RF readout scheme to overcome the SQL

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LIGO-G040228-00-Z

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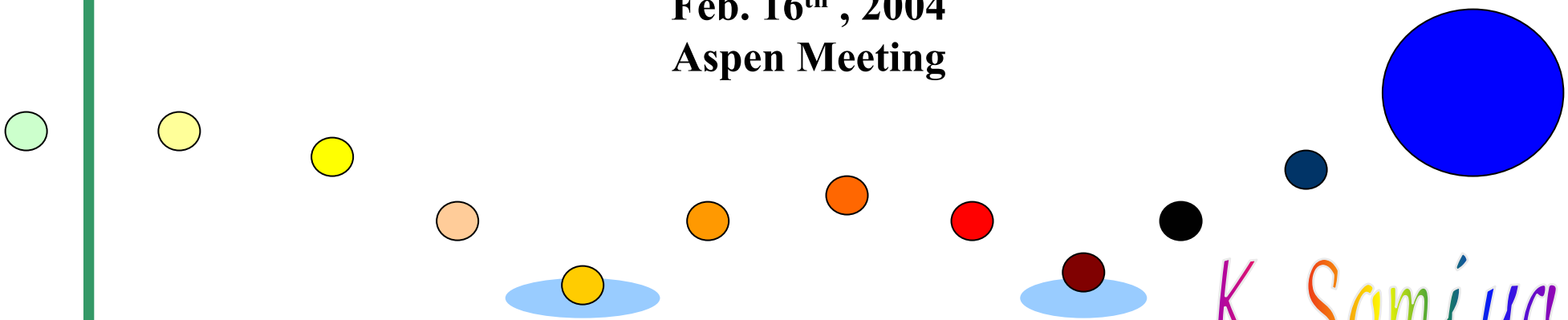
Aspen Meeting



Readout scheme

DC **or** **RF**

Commonly used in QND study

Only one readout phase

No additional quantum noise

Commonly used in GW detectors

Many readout phase can be used

(shown later)

Additional quantum noise from RF region

This noise can be hopefully removed by RF input squeezing, and the sensitivity can be better than that with DC readout !

Contents

- Short review of quantum noise
- Input squeezing and homodyne detection
- RF readout scheme (unbalanced sideband detection)
- RF input squeezing
- Multi-phase detection
- Summary and Discussion

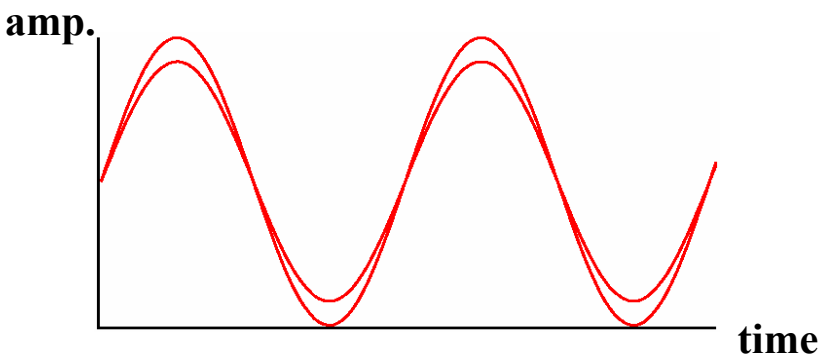
Review of quantum noise

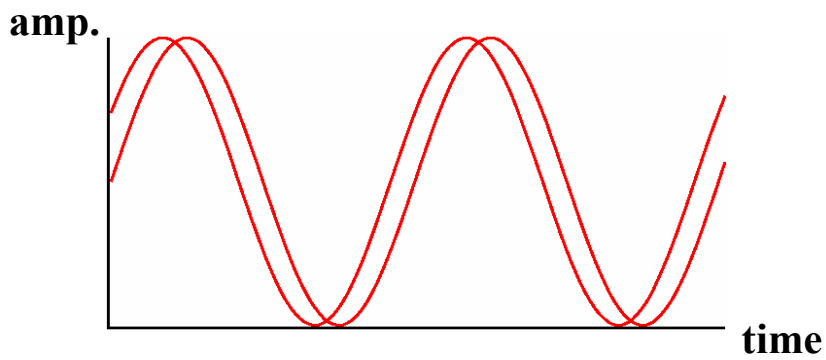
Particles
photon number

<Property>

<Fluctuation>

Waves
light phase





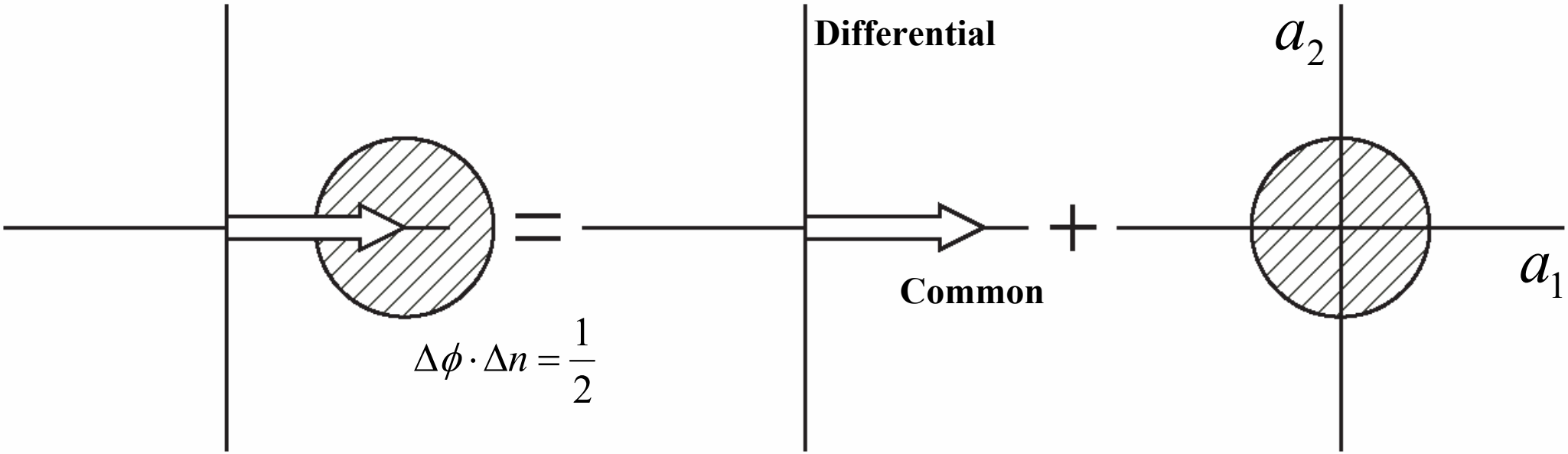
Radiation pressure noise

Shot noise

Both noise sources behave as sidebands to the classical light with or without π phase shift.

Vacuum fluctuation as SB

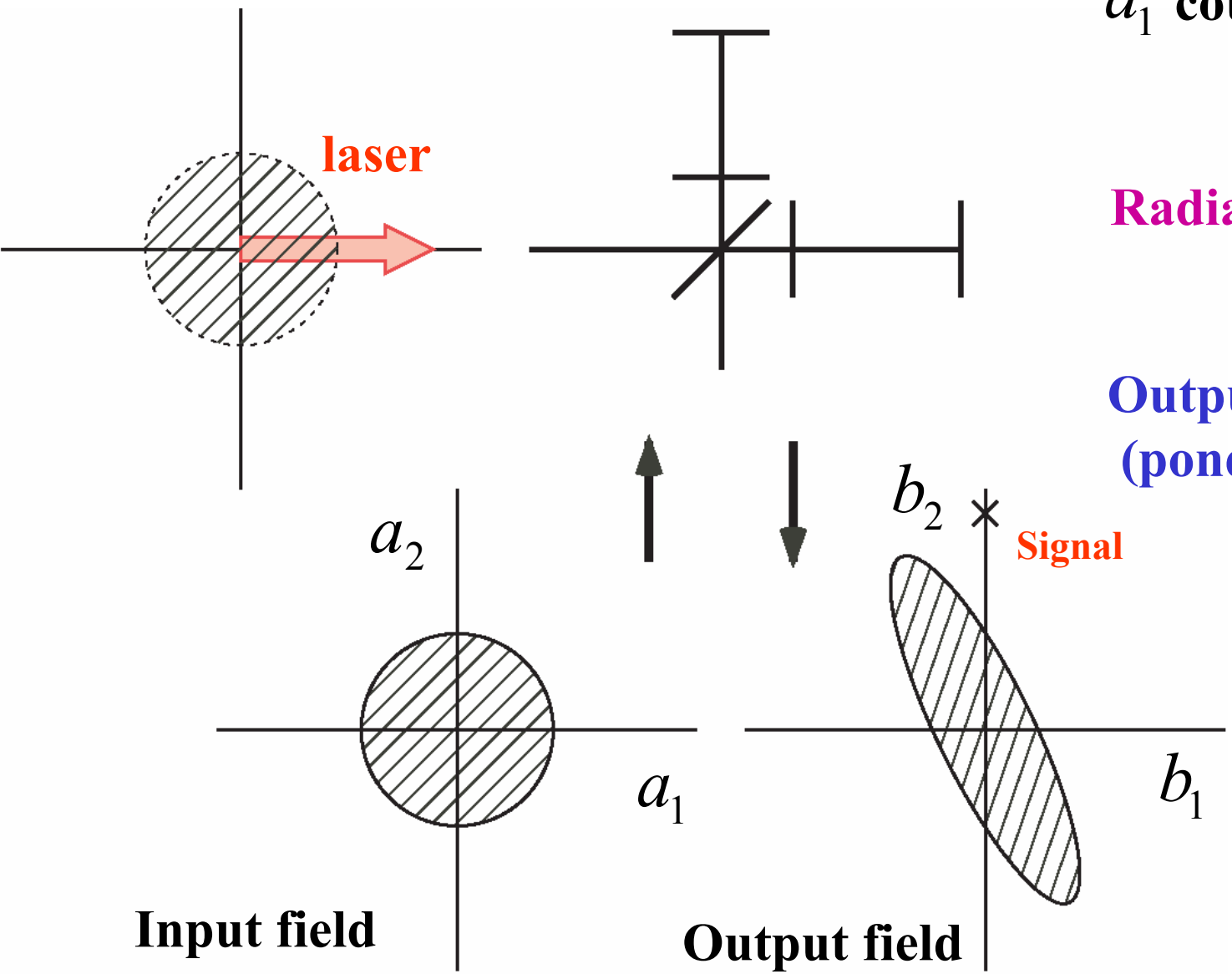
Fourier space:
relative phase to the carrier light



Laser light **Classical light** **Vacuum fluctuation**

Where does vacuum come from?

Vacuum fluctuation from DP



a_1 couples with laser light

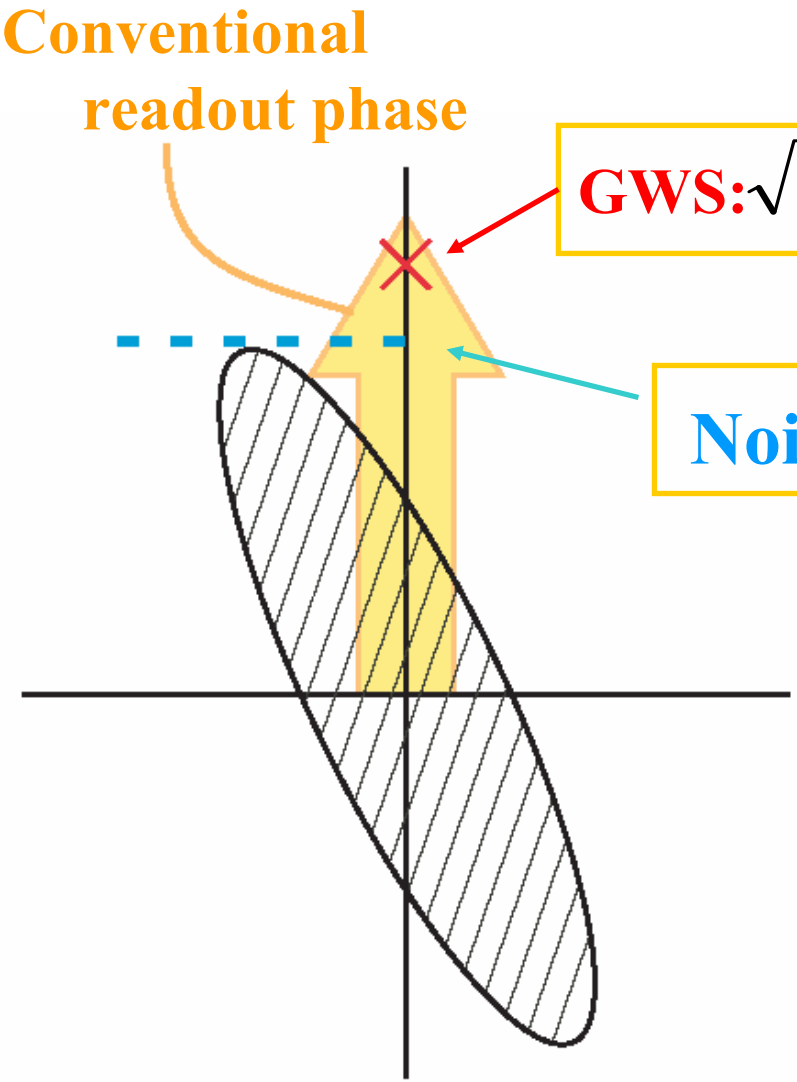
⇩

Radiation pressure noise

⇩

Output field is squeezed
(ponderomotive squeeze)

Standard Quantum Limit



$$\kappa \equiv \frac{\left(I_0 / I_{SQL}\right) 2\gamma^4}{\Omega^2\left(\Omega^2+\gamma^2\right)}$$

represents the power in the cavity.

(Ω: GW freq. , γ: cavity pole)

Total quantum noise level

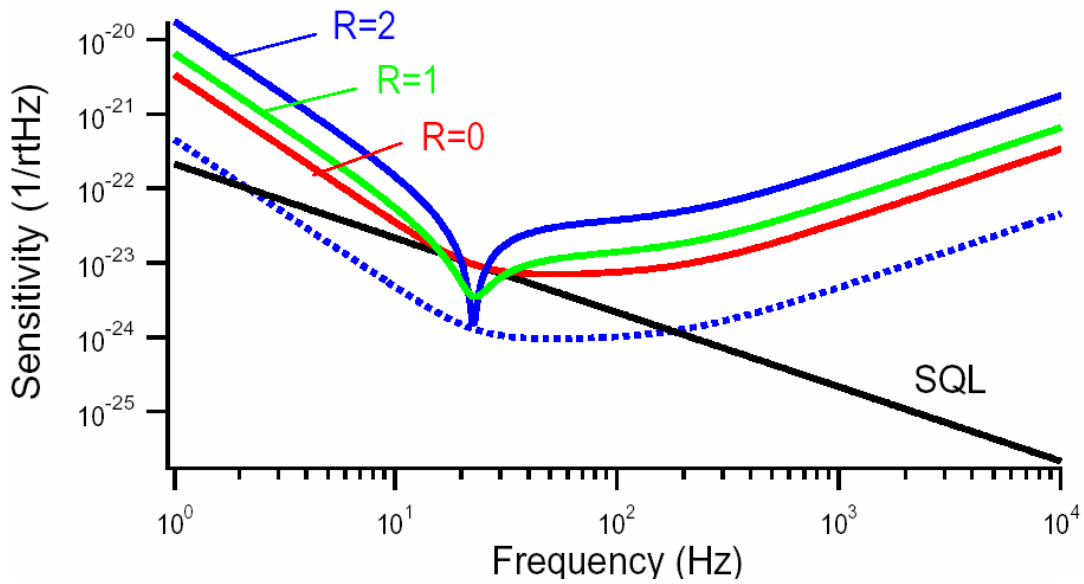
$$h_n = h_{SQL}\sqrt{\frac{\kappa^2+1}{2\kappa}} \le h_{SQL}$$

SQL is defined including this ponderomotive squeezing.

How to beat the SQL ? ~ QND techniques

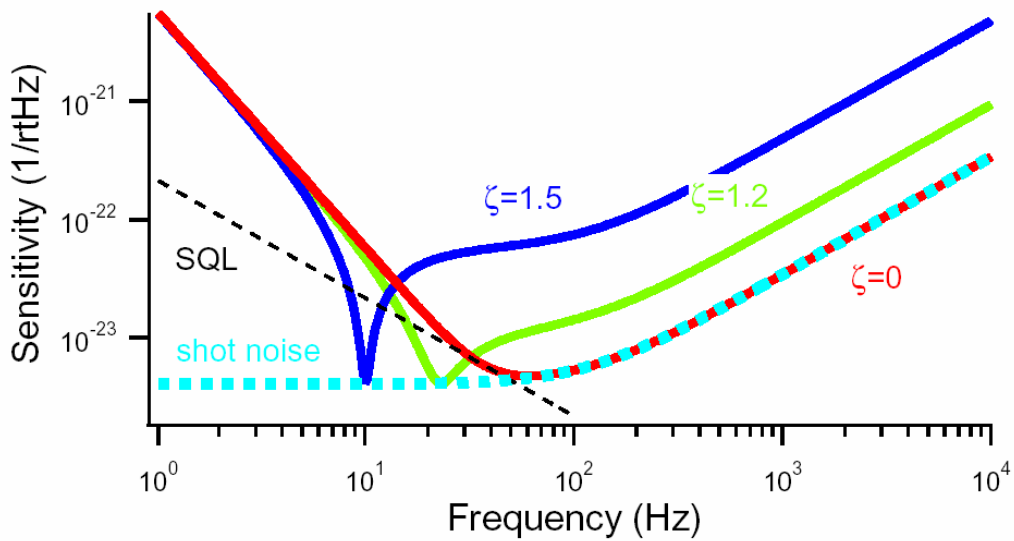
(1)Input Squeezing

With non-linear optics

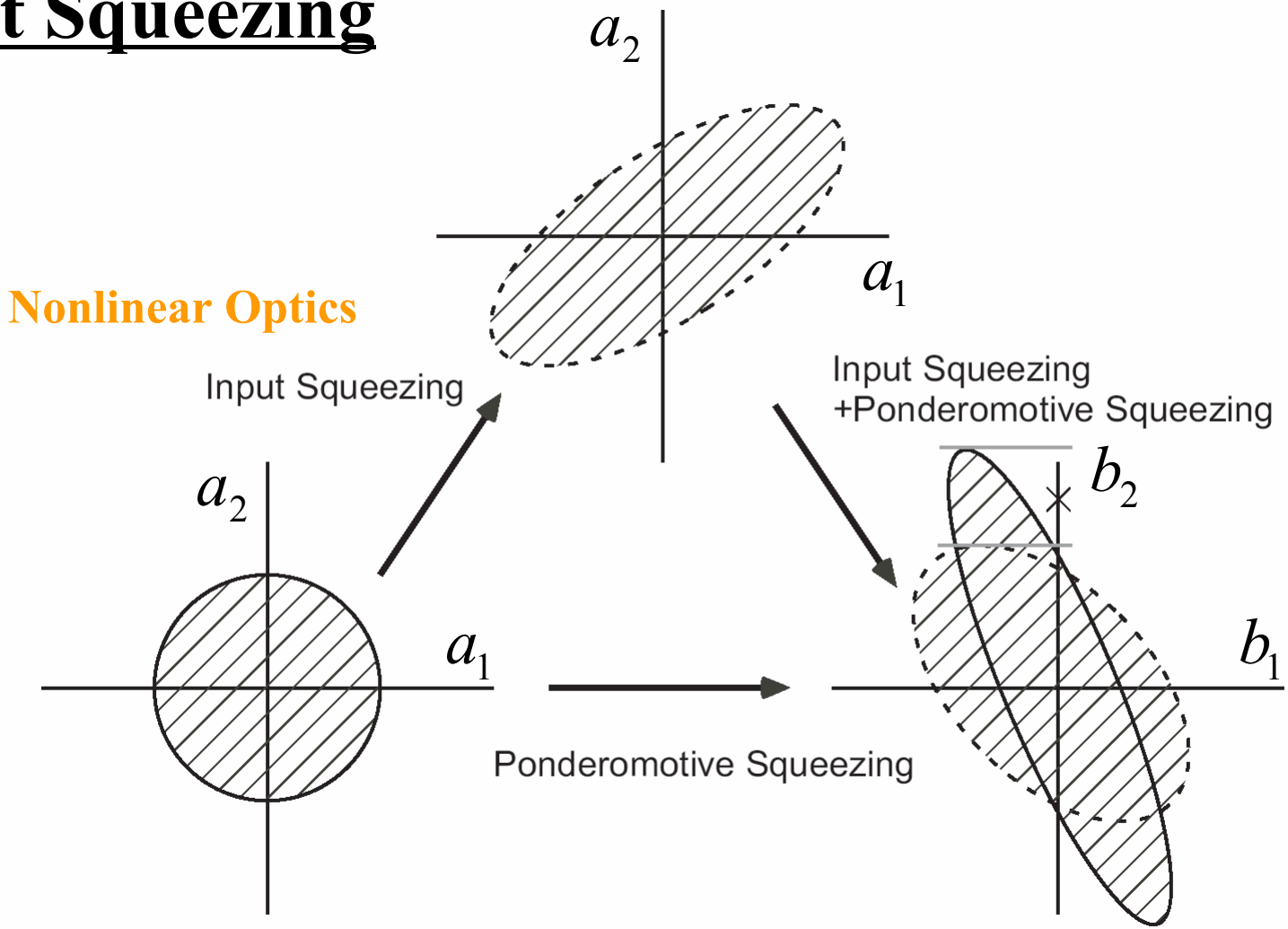


(2)Homodyne Detection

Changing readout phase



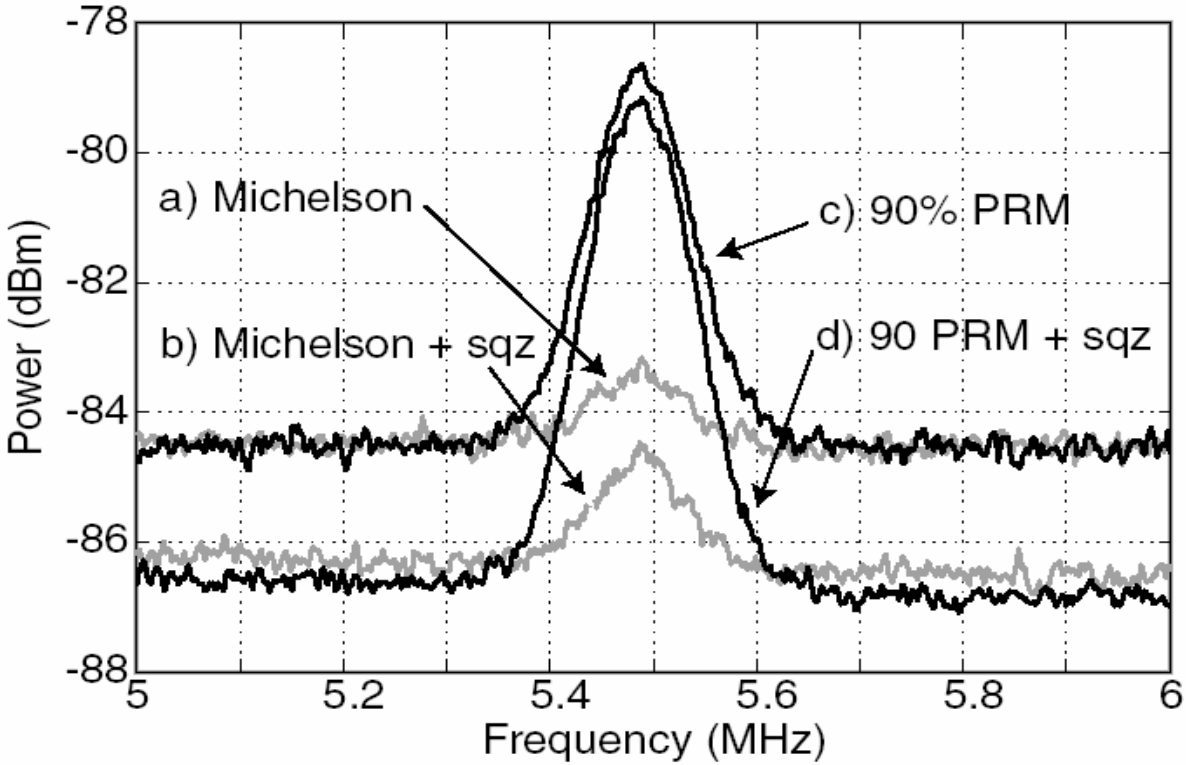
Input Squeezing



Reshape the ellipse of ponderomotive squeezing!

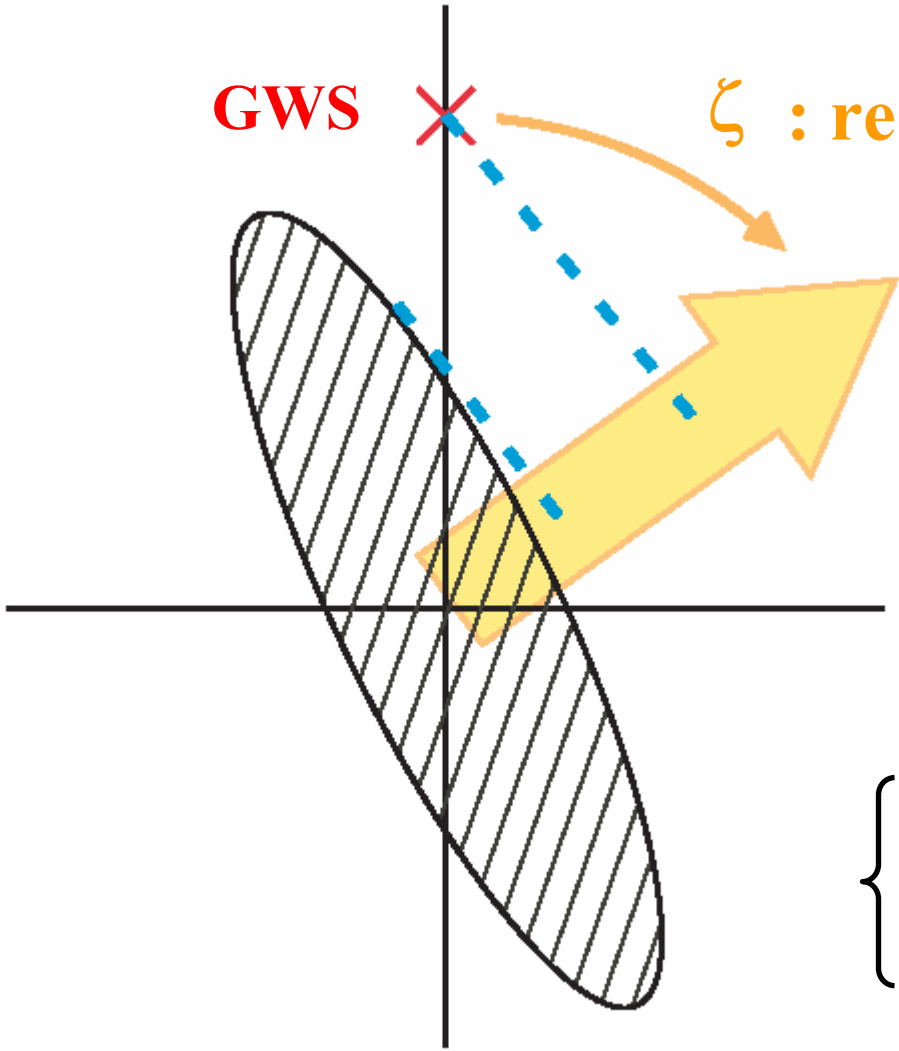
Input Squeezing Experiment in ANU

(McKenzie *et al*, Phys. Rev. Let. Vol.88 2002)



- **Successful squeezing by 7dB (R~2) in mega-hertz region**
- **Need more time for squeezing at ~100Hz**

Homodyne Detection



ζ : readout phase (homodyne phase)

Total quantum noise level

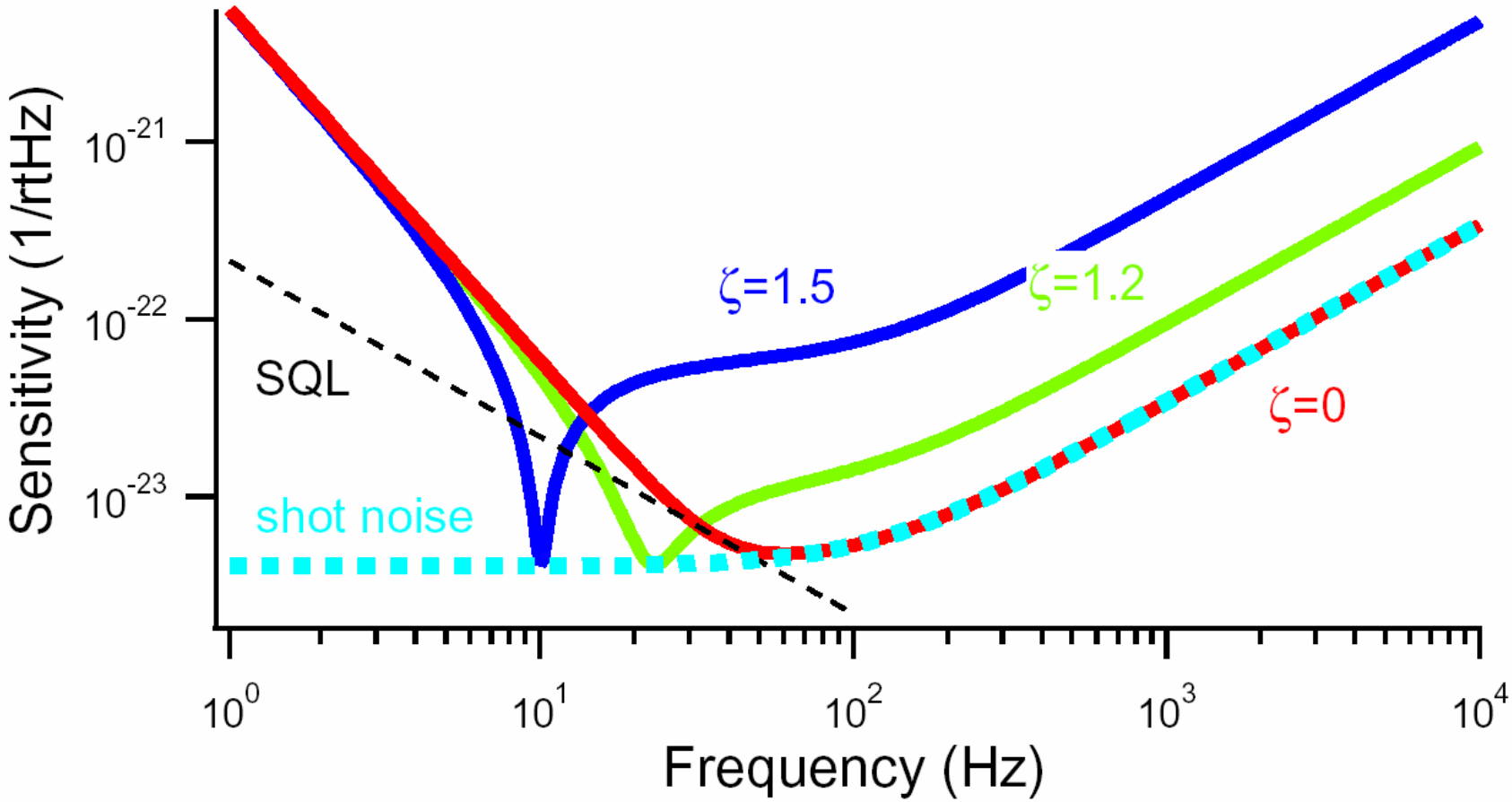
$$h_n = h_{SQL}\sqrt{\frac{(\kappa - \tan\zeta)^2 + 1}{2\kappa}}$$

- Readout phase is fixed.
- Ellipse shape depends on signal freq.

⇒ QND at particular frequency.

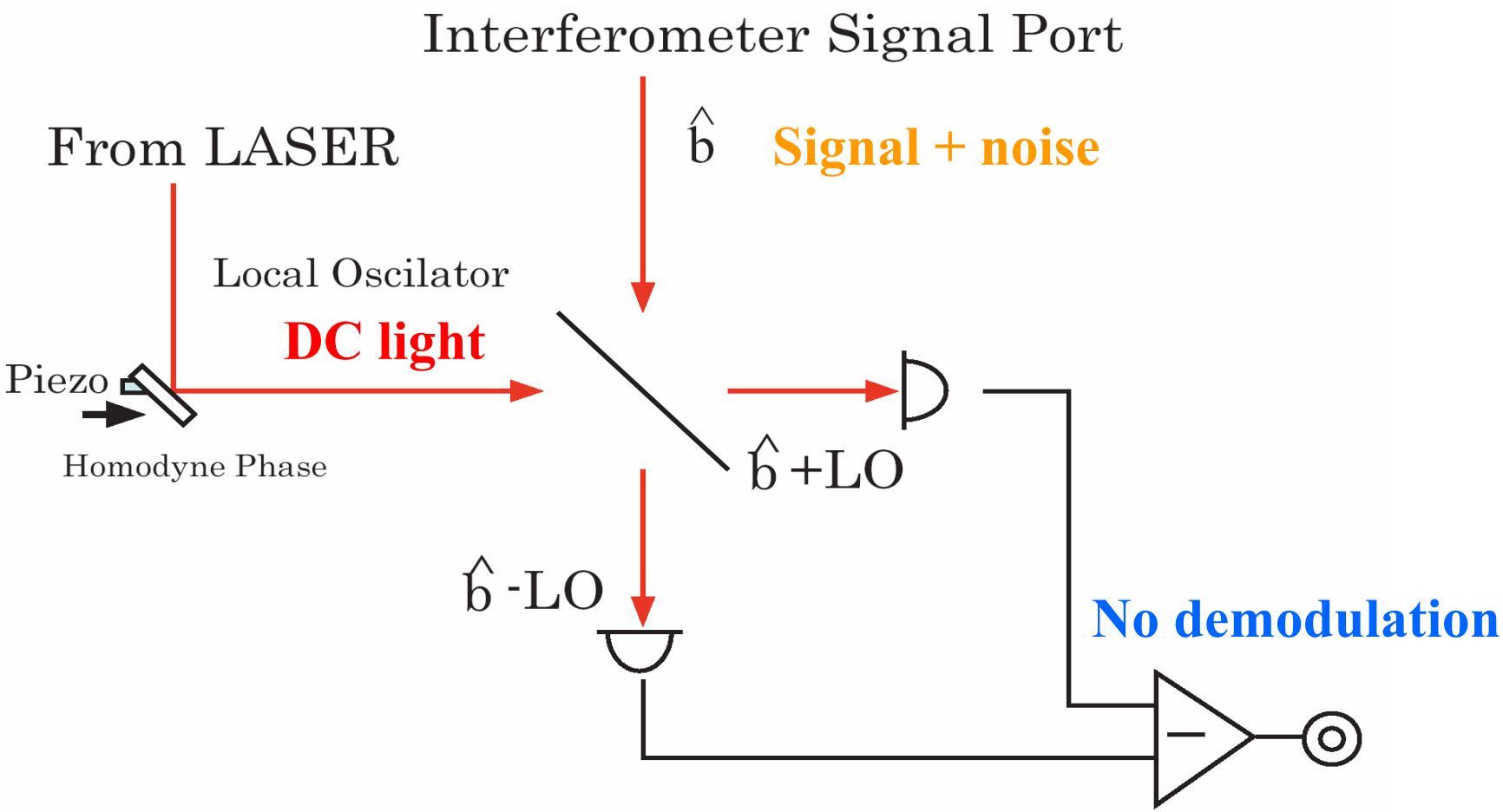
Homodyne detection spectrum

ζ : readout phase



No radiation pressure noise in narrow band.

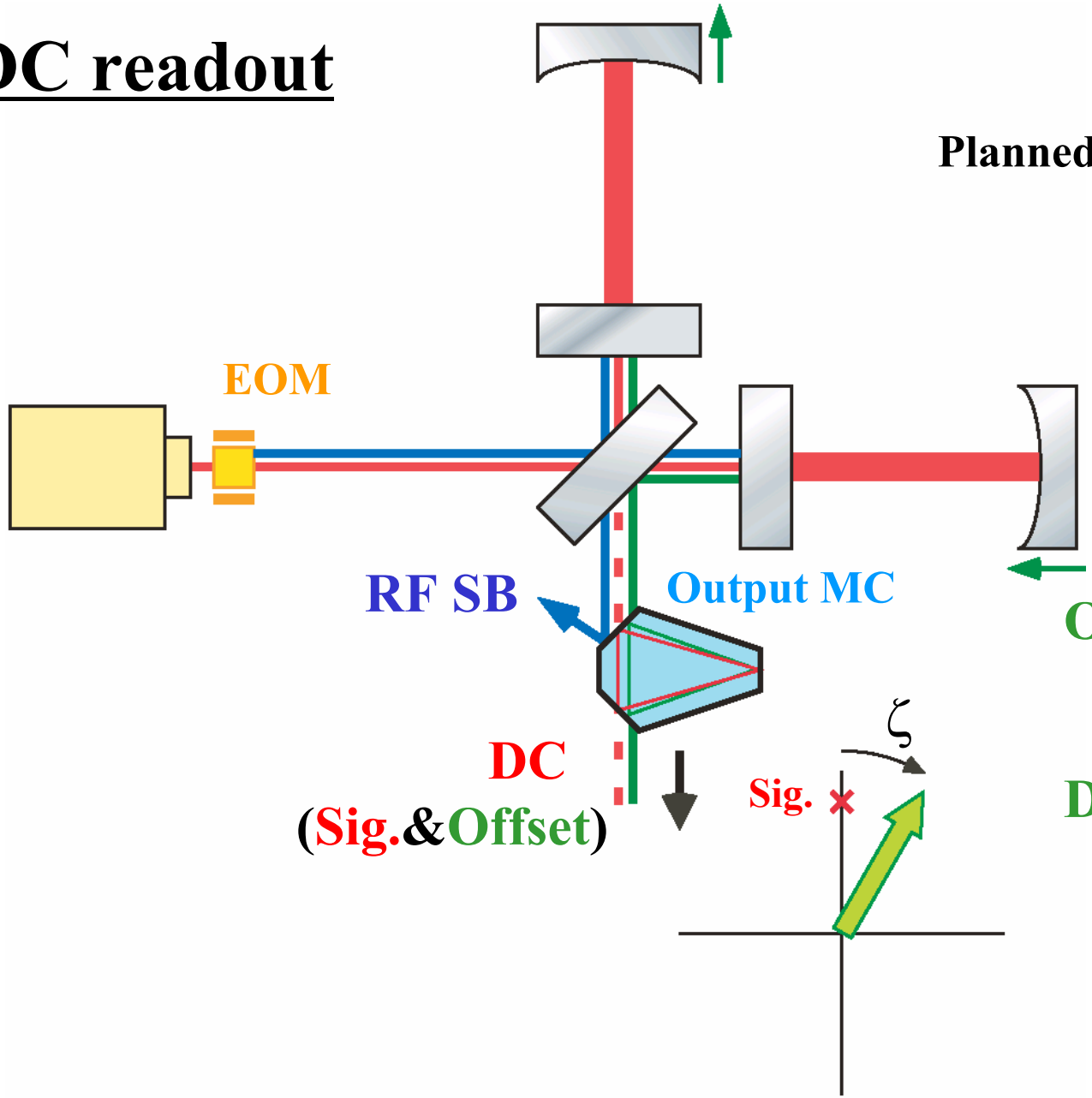
Conventional way of homodyne detection



- Additional beamsplitter would be troublesome.
- Direct coupling of AC noise might be a problem.

DC readout

Planned to be used for AdLIGO.



Offset to L-

⇓

Determines the phase ζ

Several issues should be tested at Caltech 40m.

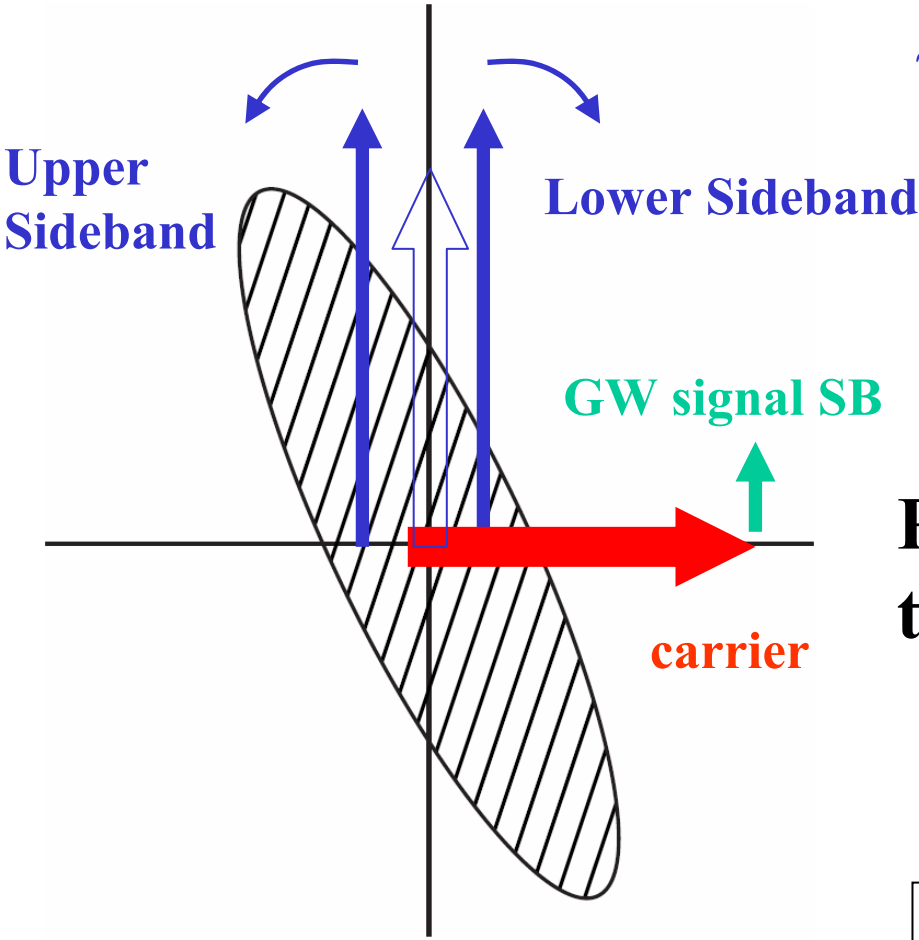
Problem of these QND techniques

1) Input Squeezing
   Only available at low frequencies so far.

2) Homodyne Detection, or DC readout
   Direct coupling of AC noise.

Isn't it possible to change the readout phase with conventional RF readout scheme?

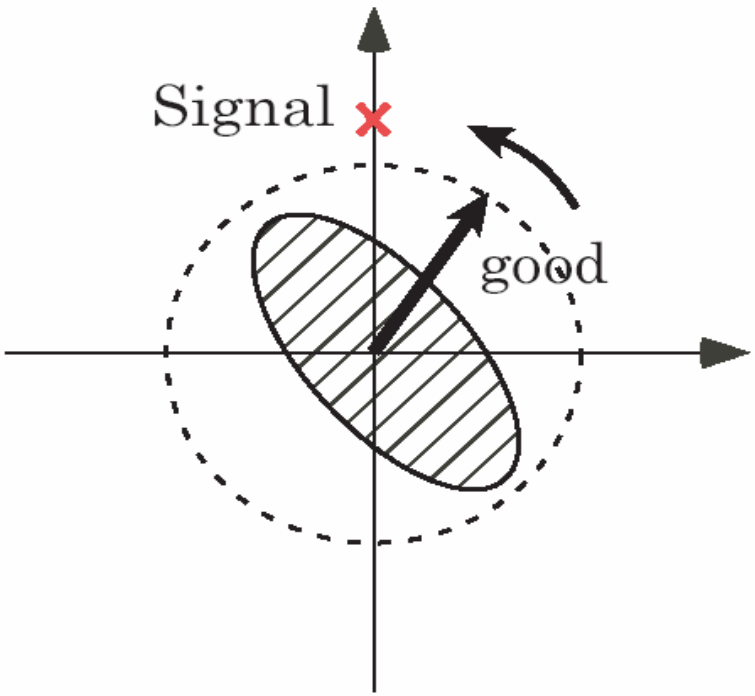
RF modulation-demodulation scheme



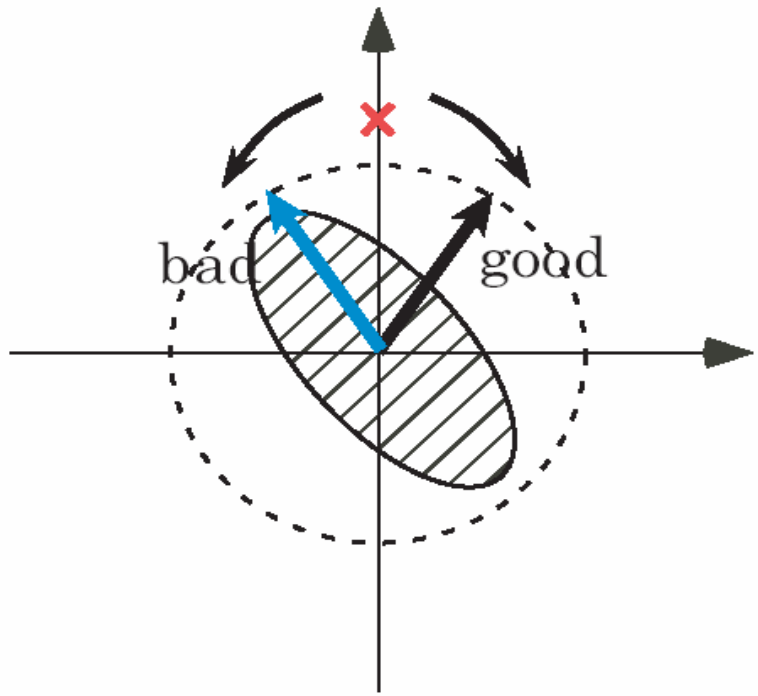
Phase modulated SB is made of the upper and the lower sidebands.

Readout phase is fixed to zero.

What if there is only a single sideband ?



Single Sideband



Dual Sidebands

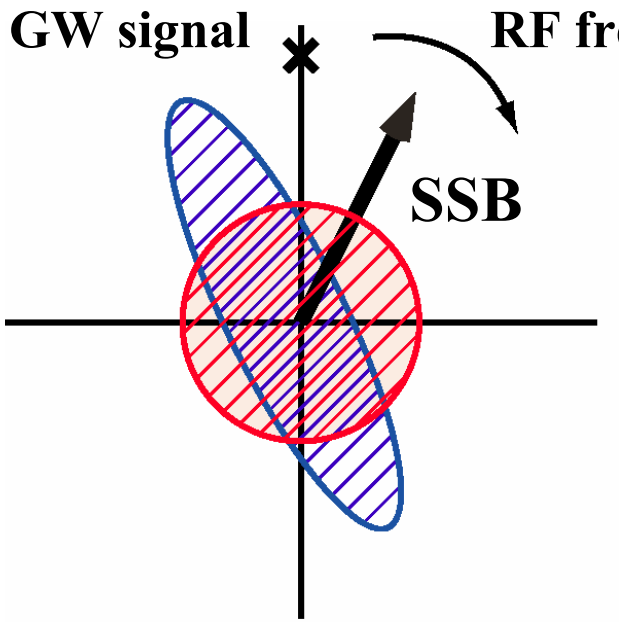
Calculated result

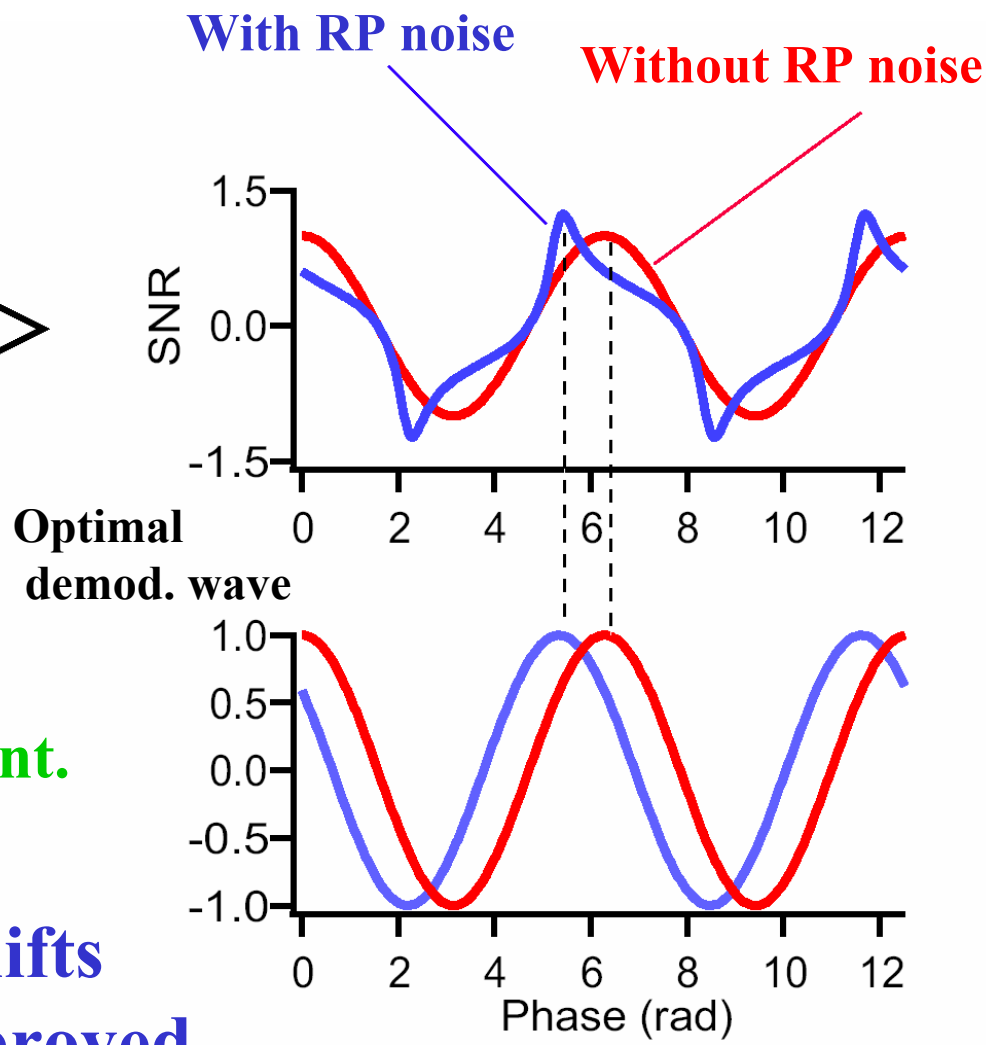
$$h_n = h_{SQL}\sqrt{\frac{(\kappa - \tan\zeta')^2 + 1}{2\kappa}}$$

(ζ'=demodulation phase)

Readout phase can be chosen by demodulation phase.

Why demodulation phase ?





Demodulation phase determines the phase of this stroboscopic measurement.

Optimal demodulation phase shifts from 0 and the sensitivity is improved.

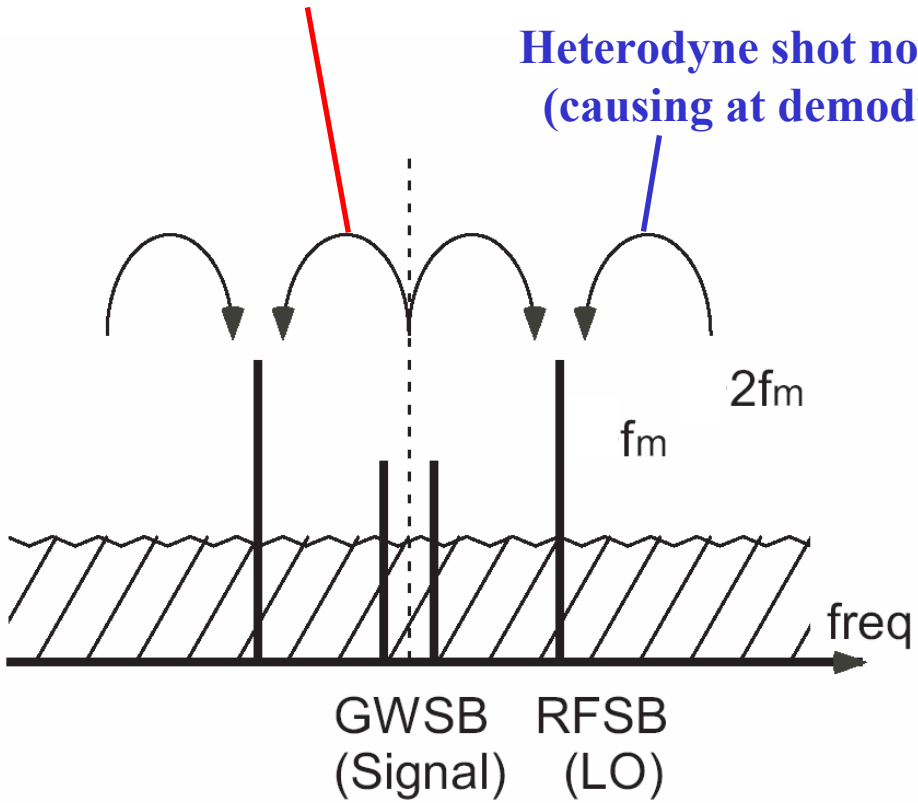
(K.Somiya, Phys. Rev. D vol.67, 2003)

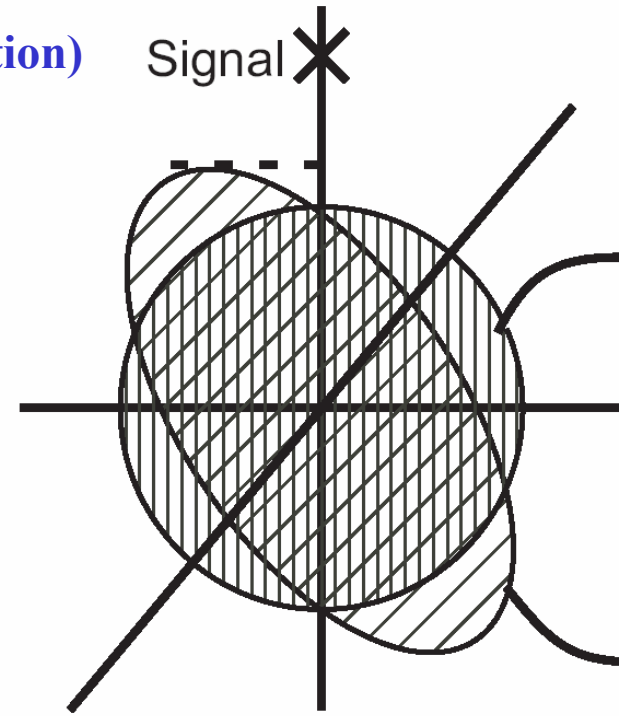
A big problem: Vacuum at 2f_m

(A.Buonanno, Y.Chen, and N.Mavalvala, Phys. Rev. D Vol.67, 2003)

Conventional shot noise

Heterodyne shot noise (causing at demodulation)



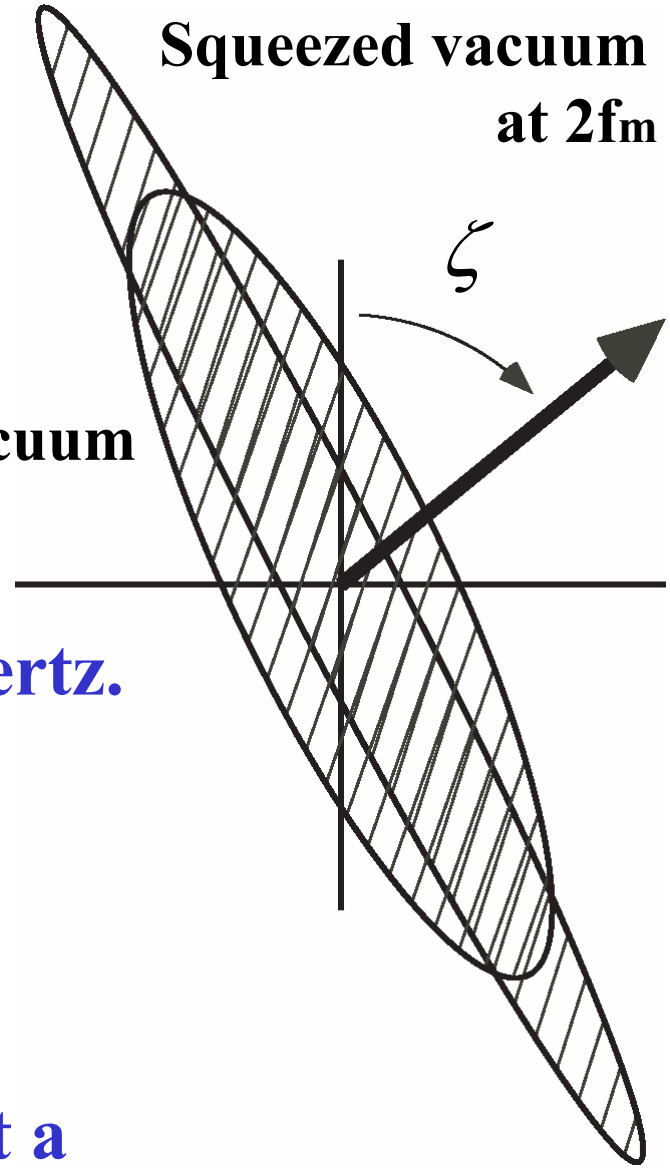


Vacuum at 2fm

Vacuum around the carrier

Vacuum at 2f_m is dominant at some readout phase.

RF Input Squeezing

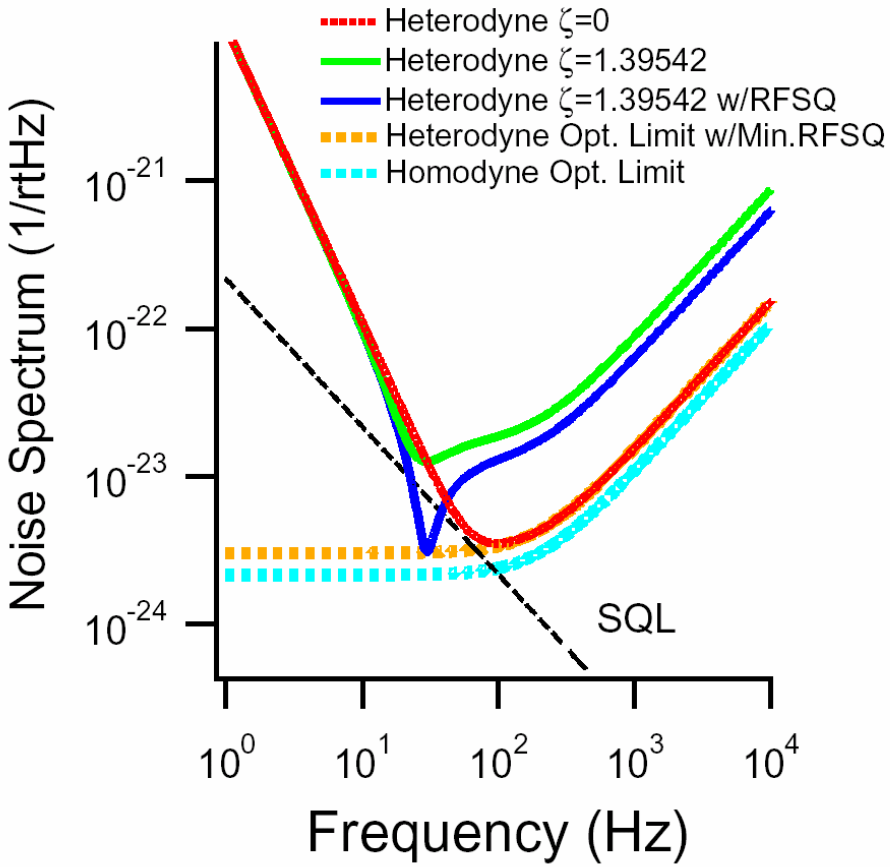


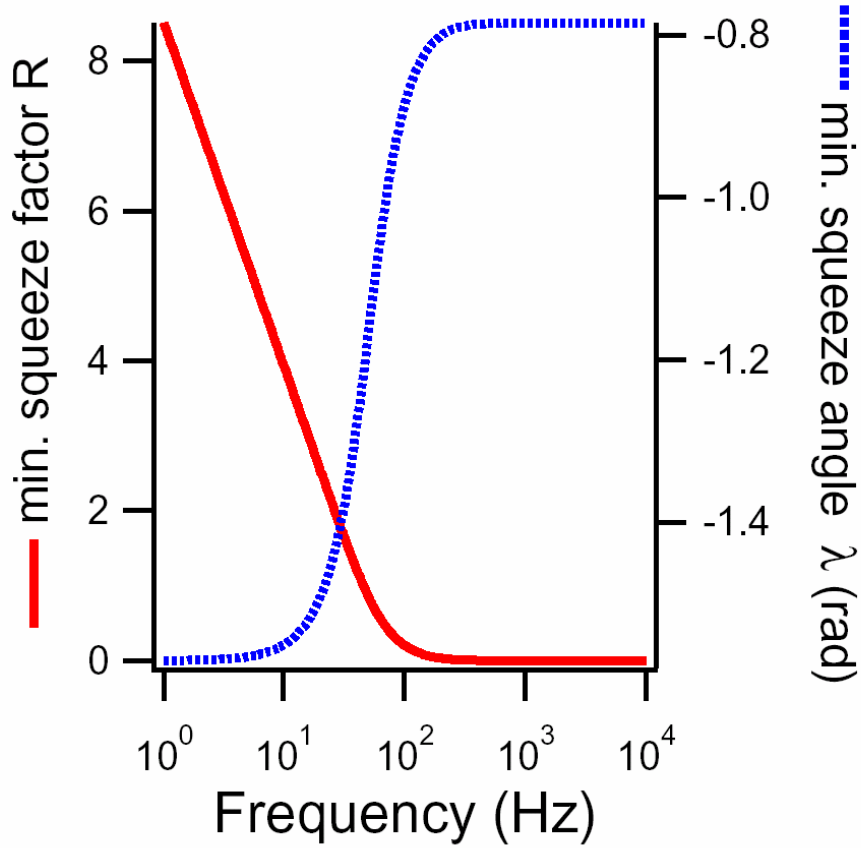
Input Squeezing is available at mega-hertz.

Squeezing at 2fm

We can reduce heterodyne shot noise at a particular frequency.

Quantum noise spectrum with RF Squeezing

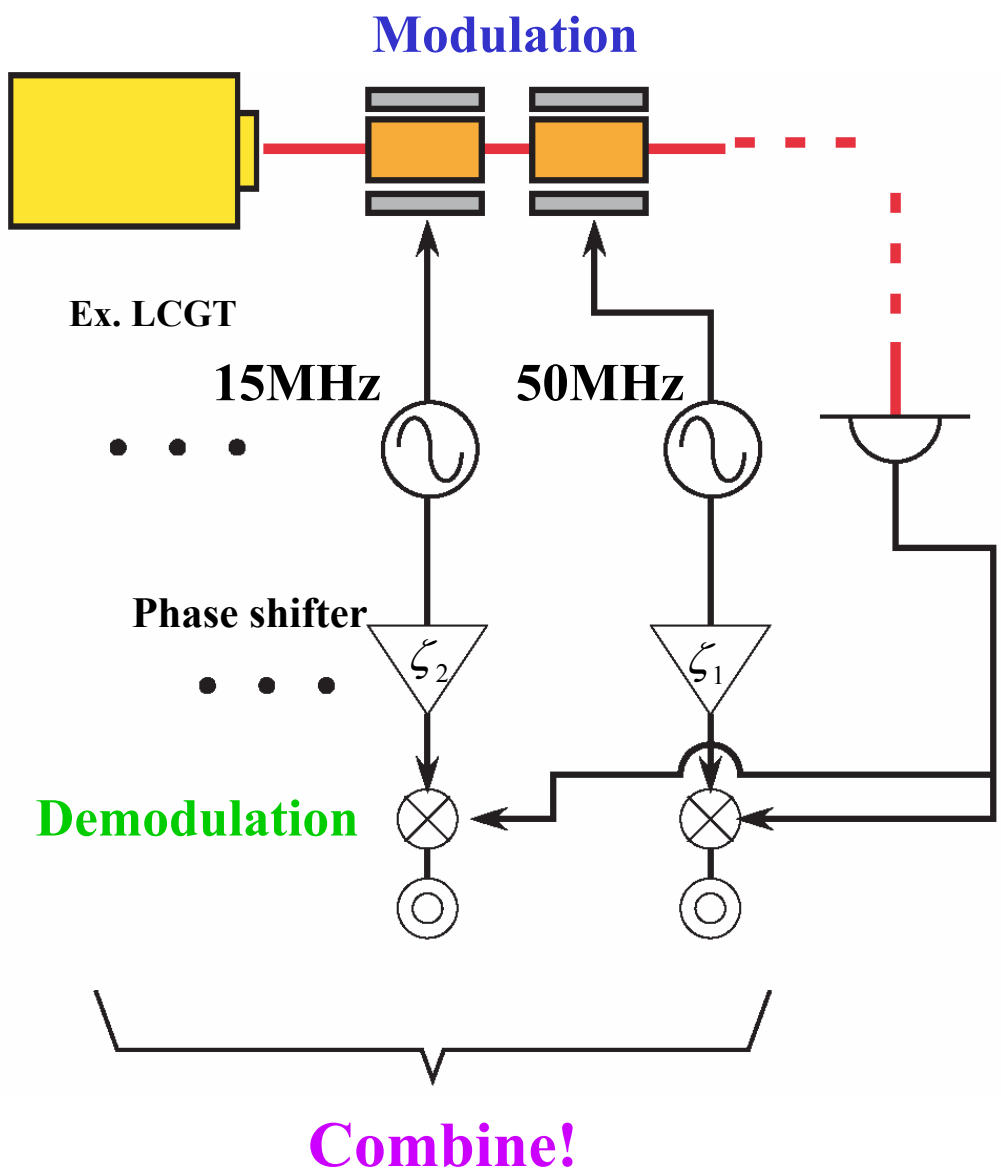




Squeeze factor R=1.76

While the peak cannot exceed the SQL with heterodyne shot noise, QND is realized with RF Squeezing !!

Multi-phase Detection



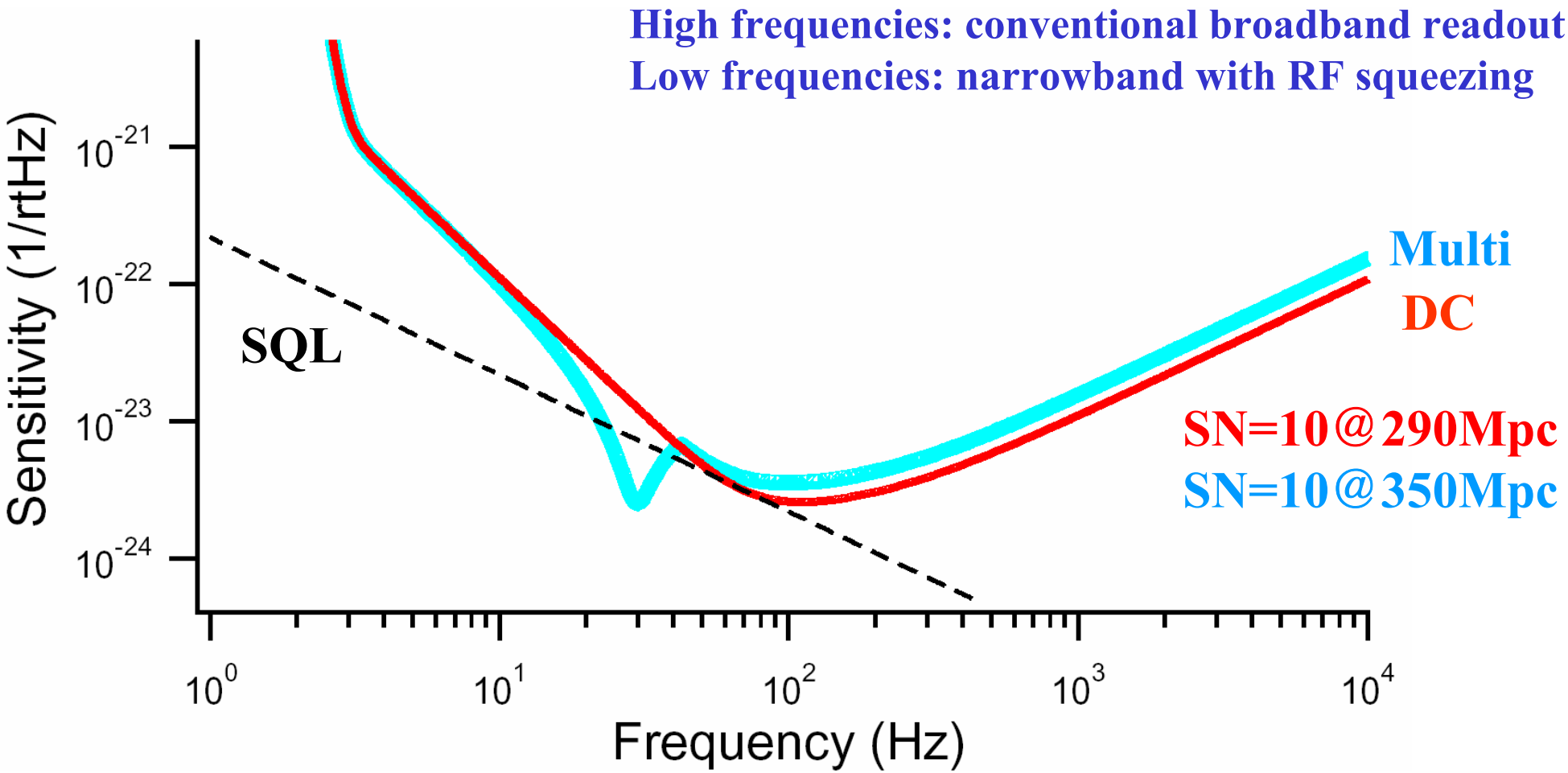
We cannot split the light not to reduce the signal amount.

But we can split the electric field without signal degeneration.

We can use all of them with different readout phase.

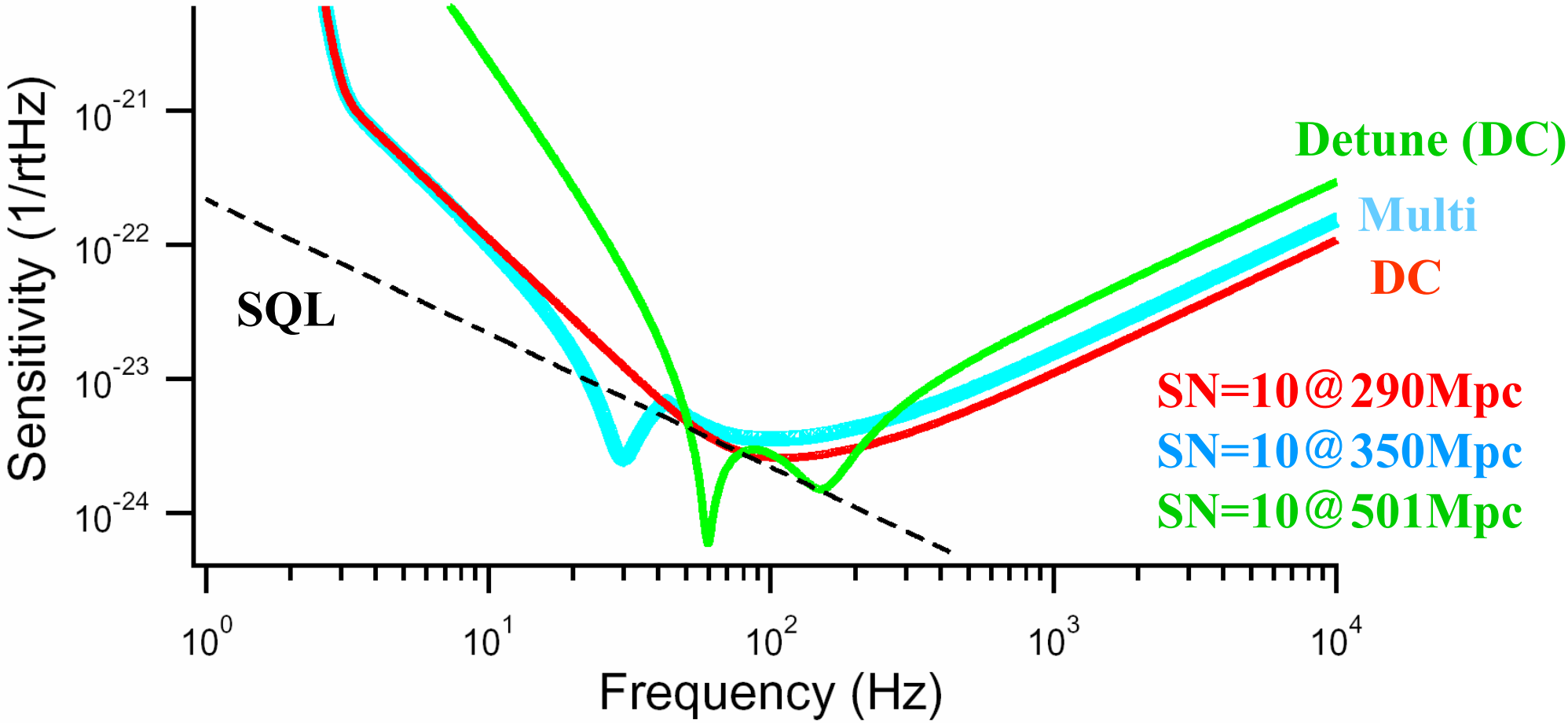
Practically two SBs will be available in a 2nd generation interferometer.

Noise spectrum with Multi-phase Detection

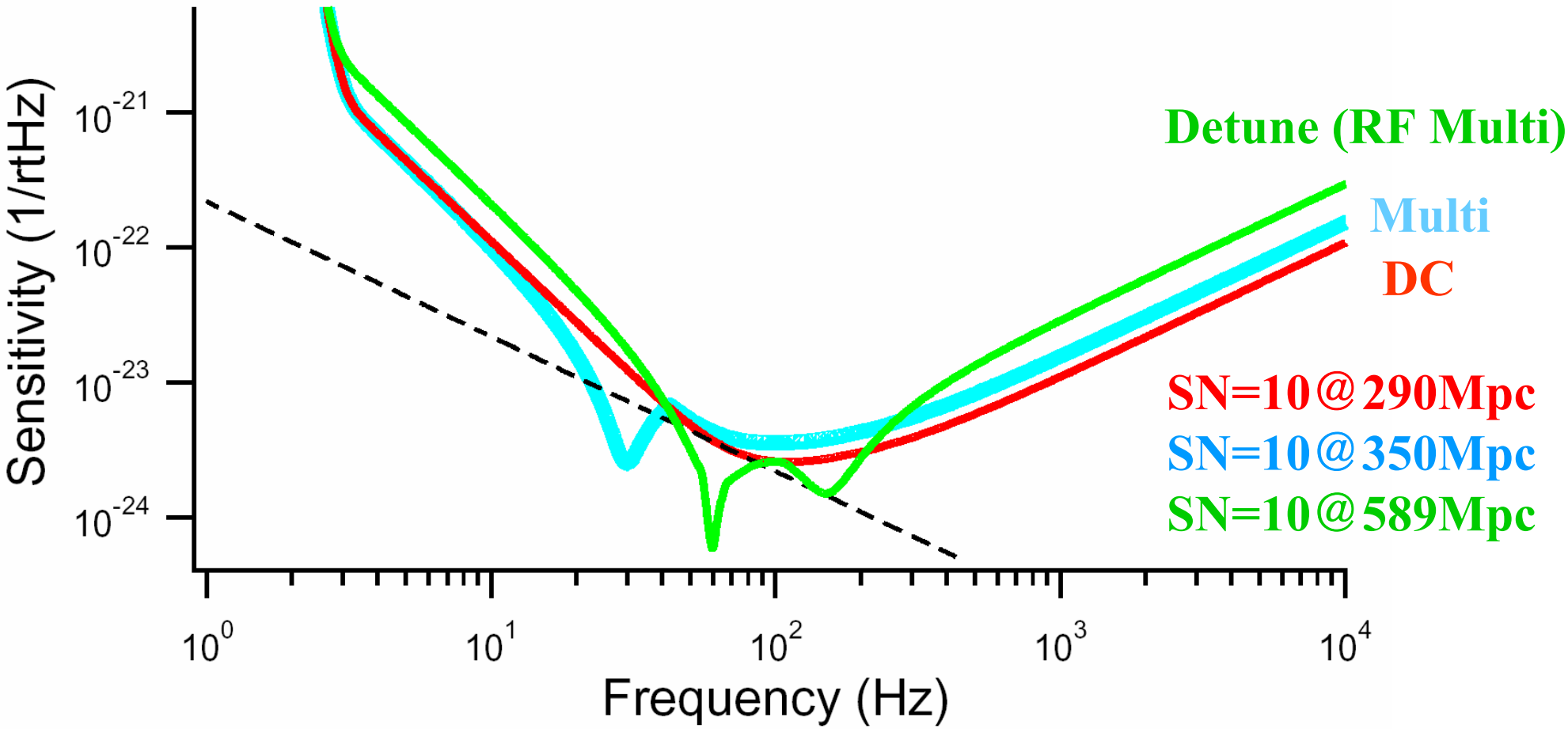


The SNR for compact binaries is improved with keeping good sensitivity in broadband.

In the case of detuned configuration



Detuned RSE + Multi-phase Detection



Very broadband detuning !!

Summary

QND techniques

Input Squeezing — Only available at very high frequency.

Homodyne Detection — DC is harder to handle.

Conventional readout scheme

RF Detection — RF is easier to handle.

→ **Obstacles for QND measurement**

- **U/L sidebands make the readout phase fixed.**
  - → **Unbalanced Sideband Detection**
- **Vacuum at $2f_m$ limits the sensitivity.**
  - → **RF Squeeze**

→ **Multi-phase detection makes the sensitivity improved and broad.**

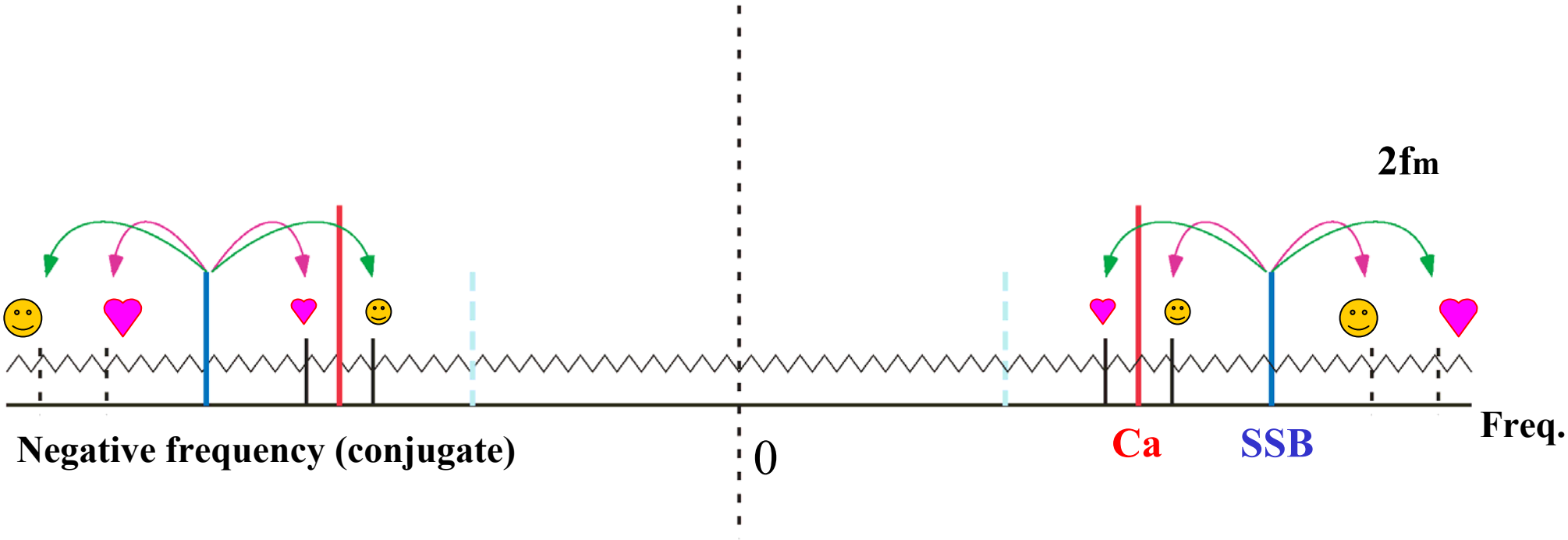
Discussion

There are several conditions necessary to realize the RF squeezing:

(1) Asymmetry factor for $2f_m$ vacuum should be a multiple of π to reflect all the input vacuum from DP to DP.

⟶ This is satisfied with a control scheme for RSE.

(2) Squeezing at $2f_m+f$ and $2f_m-f$ should be correlated (f: GWS freq.), or equivalently squeezed. **(pointed out by Y.Chen)**

⟶ This might be difficult. Need more investigation.

Discussion