Opening our eyes to QND technical issues (workshop and open forum)

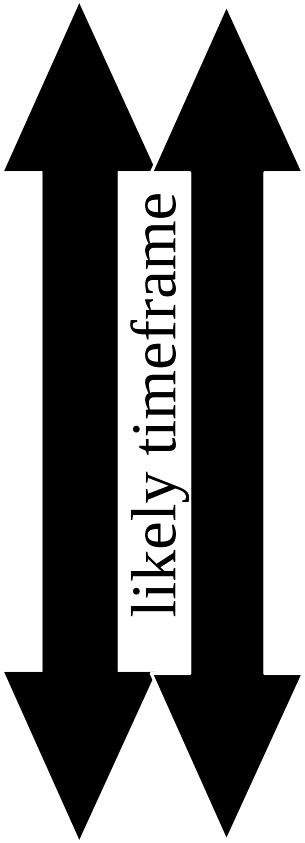
“It’ll be the blind leading the blind” - Stan Whitcomb

“You can see a lot by looking” - Yogi Berra

Relevant advanced interferometer technologies

Beating the SQL

- Ponderomotive squeezing
  - DC readout
  - RF readout from single sideband
  - Homodyne detection
  - Frequency dependant readout
  - Speedmeters
- Optical Springs
- Multi-phase detection
- Input squeezing
  - Frequency independent squeezing
  - Frequency dependant squeezing



Near future

likely timeframe

distant future

Avoiding radiation pressure

- High mass ($M>M_{max}$)
- multiple interferometers
- Reaction mass as a radiation pressure monitor

Some troublesome issues

When thinking about new interferometer configurations we usually assume all technical noise can be infinitely suppressed. We then analyze the sensitivity limited only by quantum noise

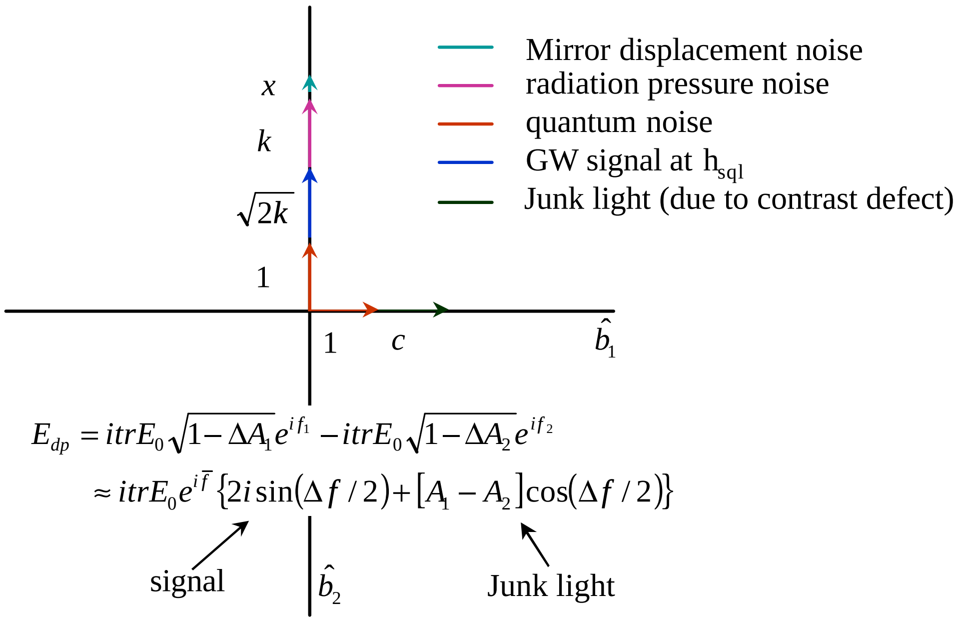
In reality there are many issues that could invalidate this assumption:

- Residual in-phase technical noise near the signal level (especially at low frequencies)
- Inability to suppress quadrature-phase noise making non-zero readout phases noisy
- Phase noise pickup from unbalanced sidebands in a detuned configuration
- Shot-noise level in feedback servos & cross couplings
- Inability to set or keep the demodulation angle within precise tolerances

Perhaps we would be better served to include these issues earlier in our analysis sooner rather than later

Picture of ponderomotive squeezing (Yanbei)

- Signal and all optical noise can be shown in a phase diagram
- signal to noise for mirror displacement noise is constant and unaffected by detection phase
- Radiation pressure noise is correlated to quantum noise on the b$_1$ axis
- All other noise sources are uncorrelated
- detection phase ζ (measured from b$_2$) chooses the axis that the vectors are projected onto for detection



$$E_{dp} = itrE_0\sqrt{1-\Delta A_1}e^{if_1} - itrE_0\sqrt{1-\Delta A_2}e^{if_2}$$
$$\approx itrE_0 e^{i\bar{f}}\{2i\sin(\Delta f/2) + [A_1 - A_2]\cos(\Delta f/2)\}$$

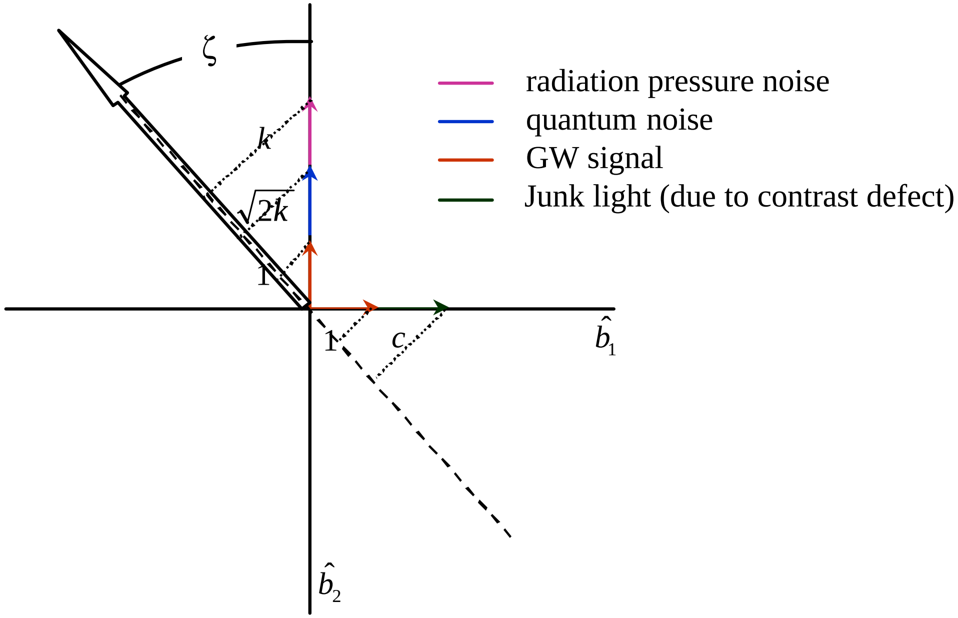
Phase quadrature diagram at dark port

$$k(w) \equiv \left(\frac{I}{I_{sql}}\right)\frac{2g^4}{w^2(w^2+g^2)}$$

γ-cavity pole frequency

Picture of ponderomotive squeezing (Yanbei)

- For proper readout phase the radiation pressure can be cancelled by the (correlated) quantum noise on axis b$_1$



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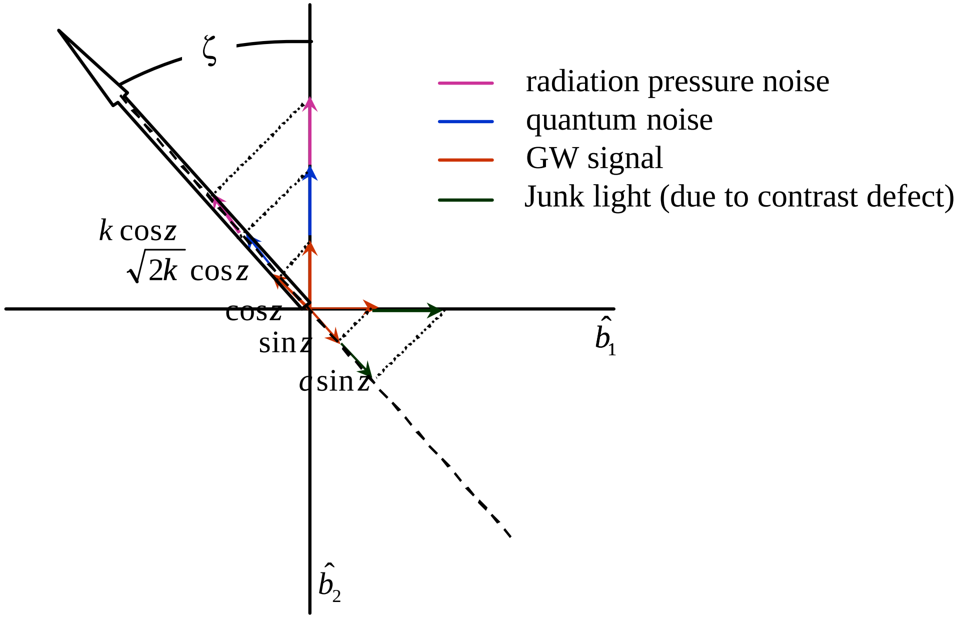

Phase quadrature diagram at dark port

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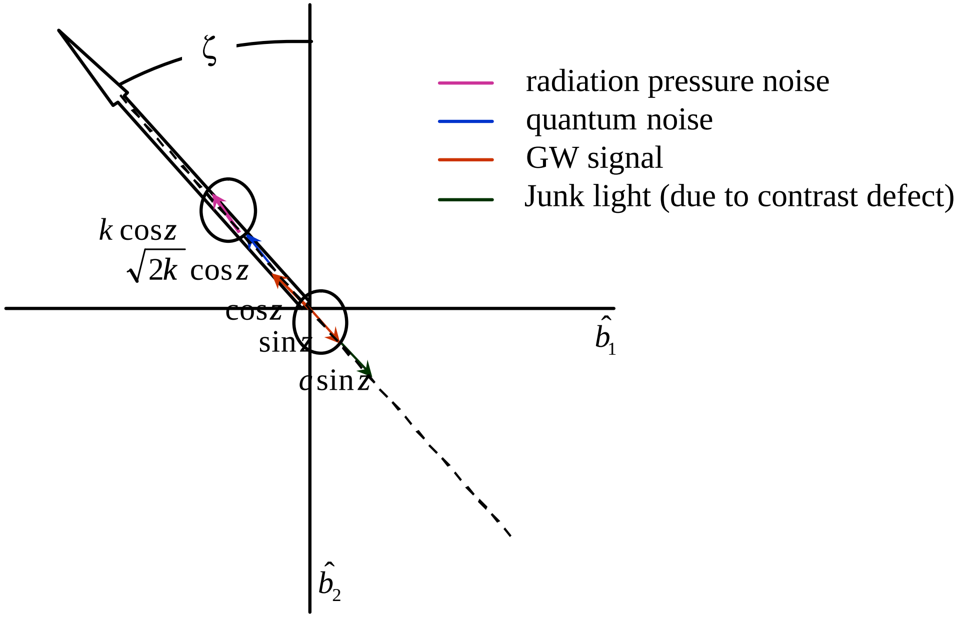


Phase quadrature diagram at dark port

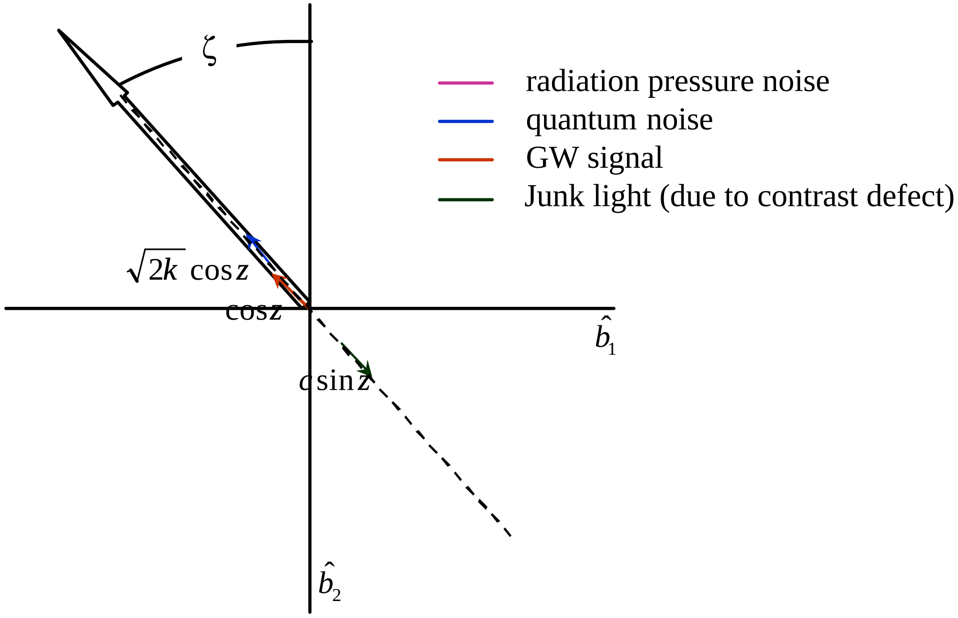
Effect of technical noise on SNR with ponderomotive squeezing

- For proper readout phase the radiation pressure can be cancelled by the (correlated) quantum noise on axis b_1
- signal to noise is:

$$SNR_{QND}^{2}(z) = \frac{2k\cos^2 z}{\cos^2 z + (k\cos z - \sin z)^2 + c^2 \sin^2 z}$$

$$(k\cos z_0 - \sin z_0)^2 = 0 \quad z_0 \equiv \tan^{-1} k$$

$$SNR_{QND}^{2}(z_0) = \frac{2k\cos^2 z_0}{\cos^2 z_0 + c^2 \sin^2 z_0} = \frac{2k}{1+c^2k^2}$$



Phase quadrature diagram at dark port

Compare to readout at ζ=0

$$SNR_{non-QND}^{2}(0) = \frac{2k}{1+k^2}$$

if c>1 QND readout at ζ_o *decreases* sensitivity

Effect of technical noise on SNR with ponderomotive squeezing

- Ignoring technical noise ponderomotive squeezing allows the removal of radiation pressure noise
- Consider simply ignoring radiation pressure noise the signal to noise would be:

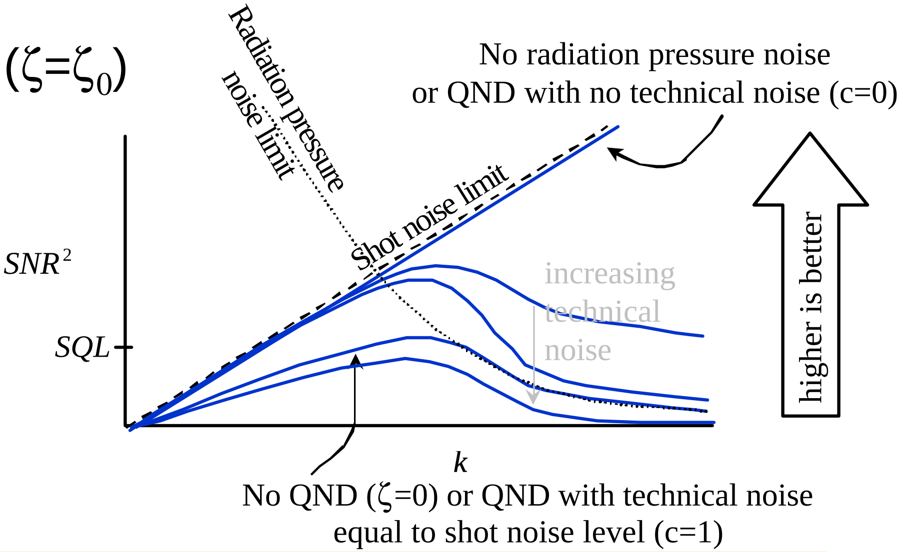
$$SNR^2_{noRP}(0) = 2k$$

Compare to non QND (ζ=1) and QND (ζ=ζ_0)

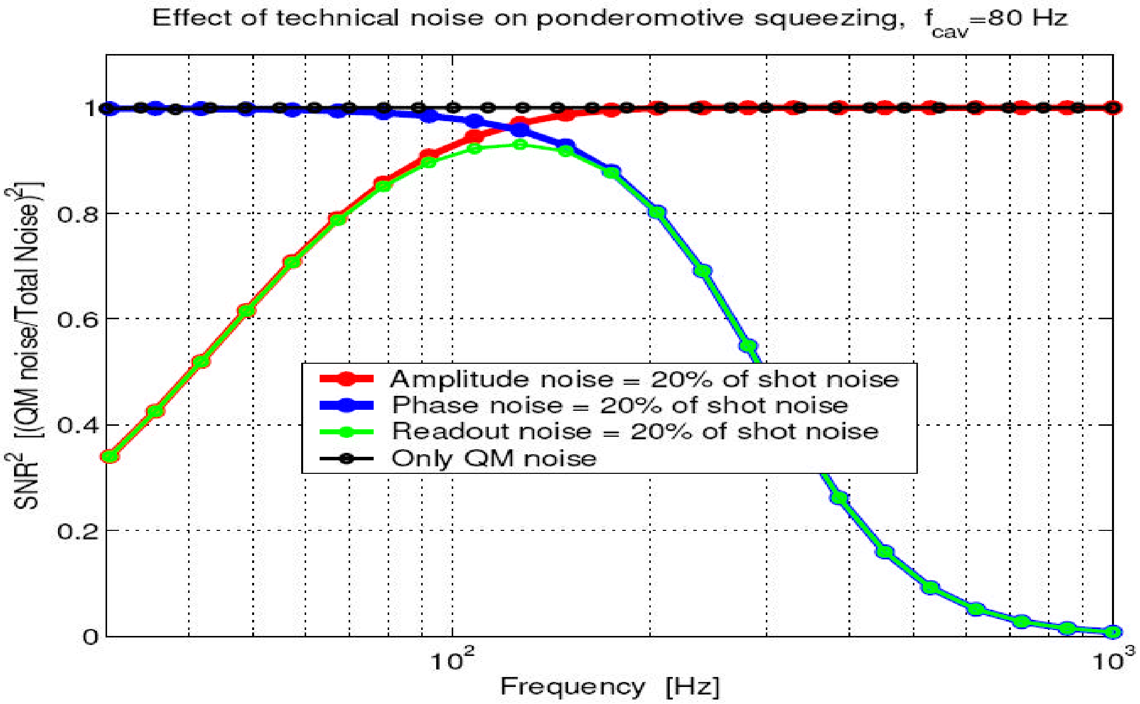
$$SNR^2_{noRP}(0) = 2k$$

$$SNR^2_{QND}(z_0) = \frac{2k}{1+c^2k^2}$$

$$SNR^2_{non-QND}(0) = \frac{2k}{1+k^2}$$



Effect of technical noise on SNR with ponderomotive squeezing

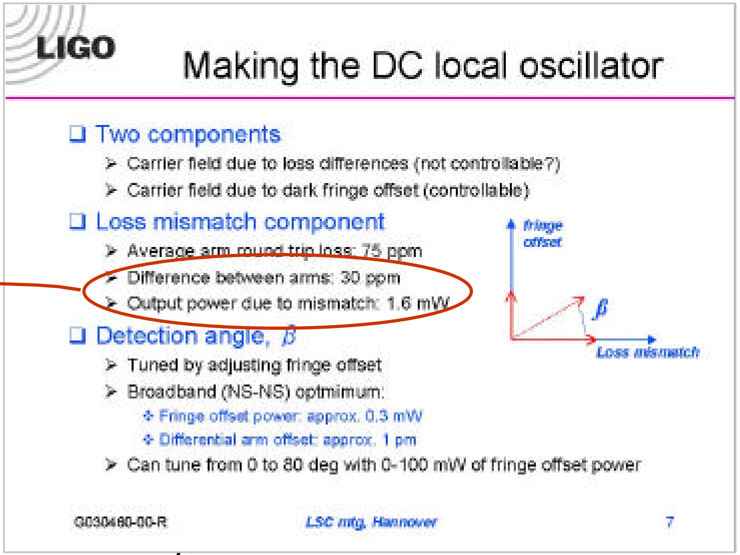


higher is better

Plot by Andri Gretarsson

Estimating the technical noise level

- Pondermotivce squeezing is only beneficial when the technical noise is kept below the shot noise (in both quadratures!)
- Estimation of c
    - Arm loss mismatch $\Delta A \approx 30\ 10^{-6}$
        - E-field of junk light $\Delta E/E_{in} \approx 3\ 10^{-5}$
    - in-band RIN of laser $I(\omega)/I_0 \approx 10^{-8}$
        - E-field fluctuations are $E(\omega)/E_0 \approx\ I(\omega)/I_0 = 10^{-8}$
    - Noise of junk light E-field $E_{junk}(\omega) \approx 3\ 10^{-13}\ E_{in}$
    - Shot noise limited phase sensitivity for 1kW on beamsplitter is $\phi_{SN} \approx 10^{-11}$ so $E_{SN} \approx 10^{-11}\ E_{in}$
    - $c \equiv E_{junk}(\omega)/\ E_{SN} \approx 0.03$

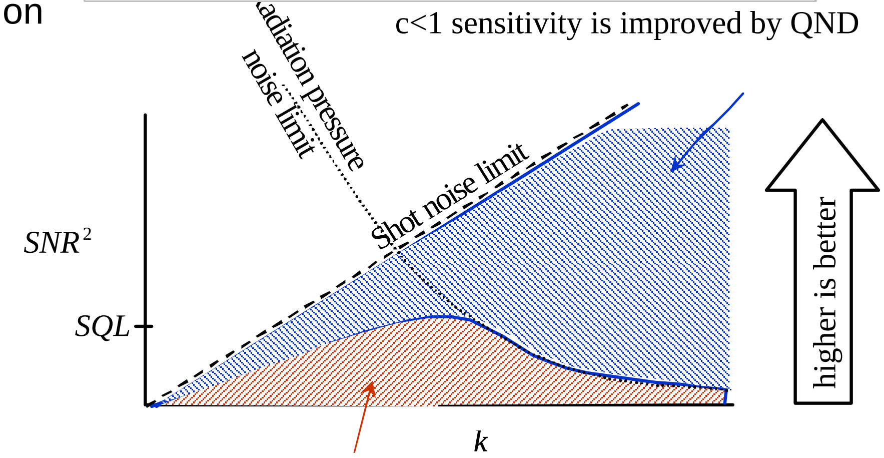


LIGO

Making the DC local oscillator

- ❑ Two components
    - Carrier field due to loss differences (not controllable?)
    - Carrier field due to dark fringe offset (controllable)
- ❑ Loss mismatch component
    - Average arm round trip loss: 75 ppm
    - Difference between arms: 30 ppm
    - Output power due to mismatch: 1.6 mW
- ❑ Detection angle, β
    - Tuned by adjusting fringe offset
    - Broadband (NS-NS) optmimum:
        - Fringe offset power: approx. 0.3 mW
        - Differential arm offset: approx. 1 pm
    - Can tune from 0 to 80 deg with 0-100 mW of fringe offset power

G030480-00-R LSC mtg, Hannover 7

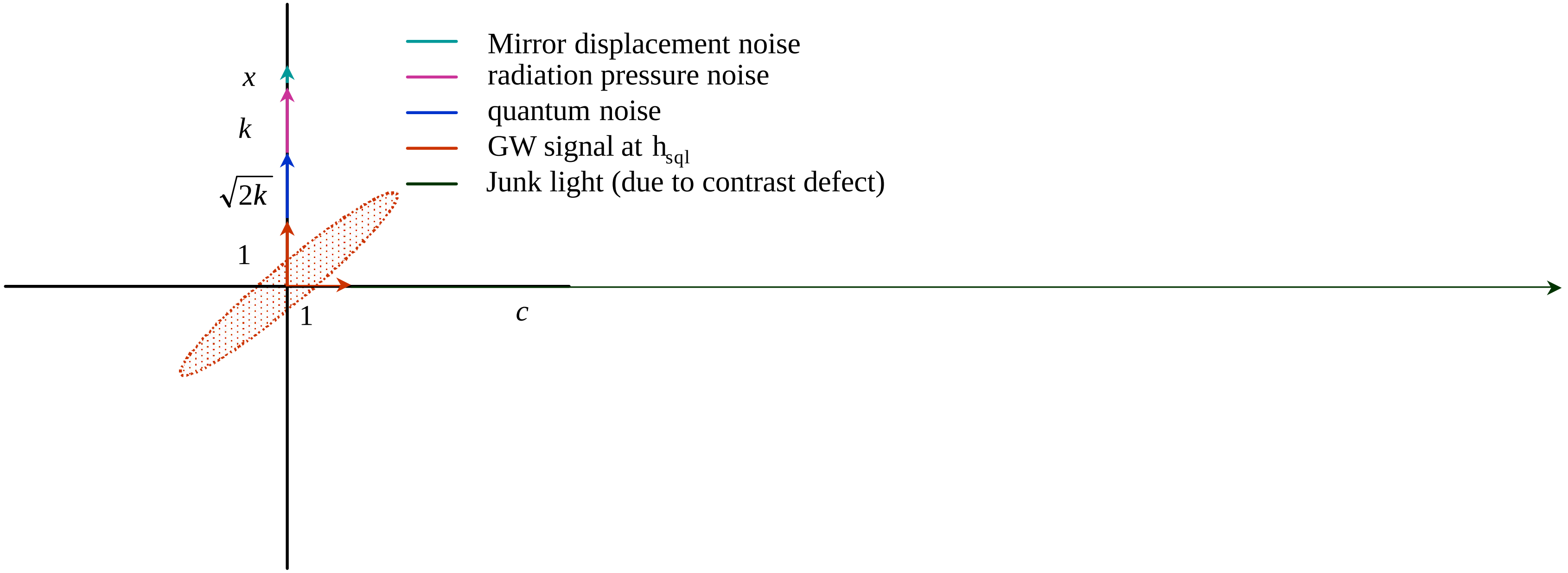


c<1 sensitivity is improved by QND

c>1 sensitivity is degraded by QND

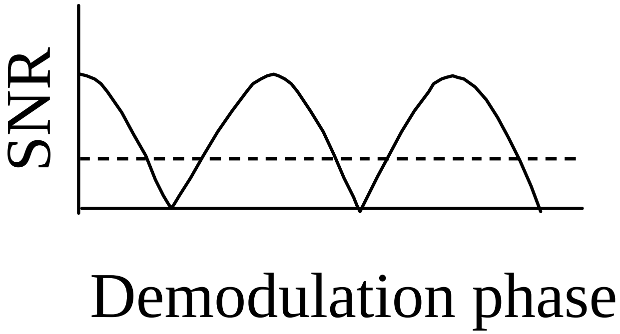
Readout with high technical noise

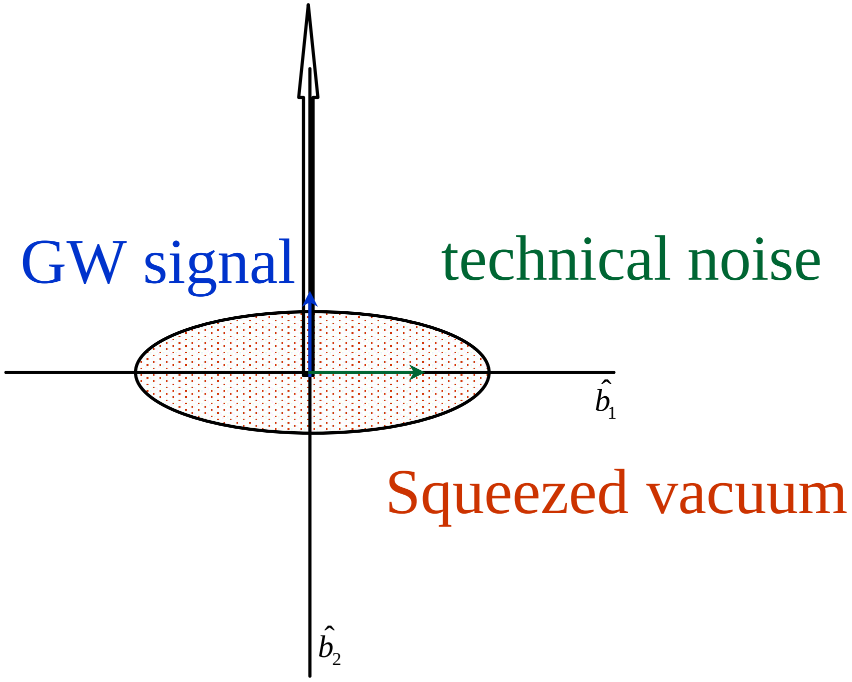
- For c>>1 regardless of the ponderomotive squeezing, the lowest noise readout is at 0 degrees



Review of Input Squeezing (Nergis)

- Use input squeezing to increase the effective laser power
- choose demodulation phase where quantum noise is most squeezed





Phase quadrature diagram at dark port

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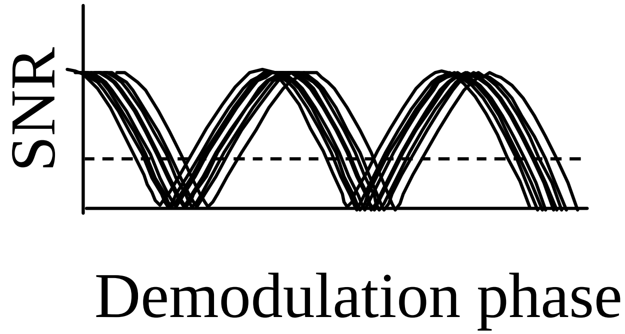
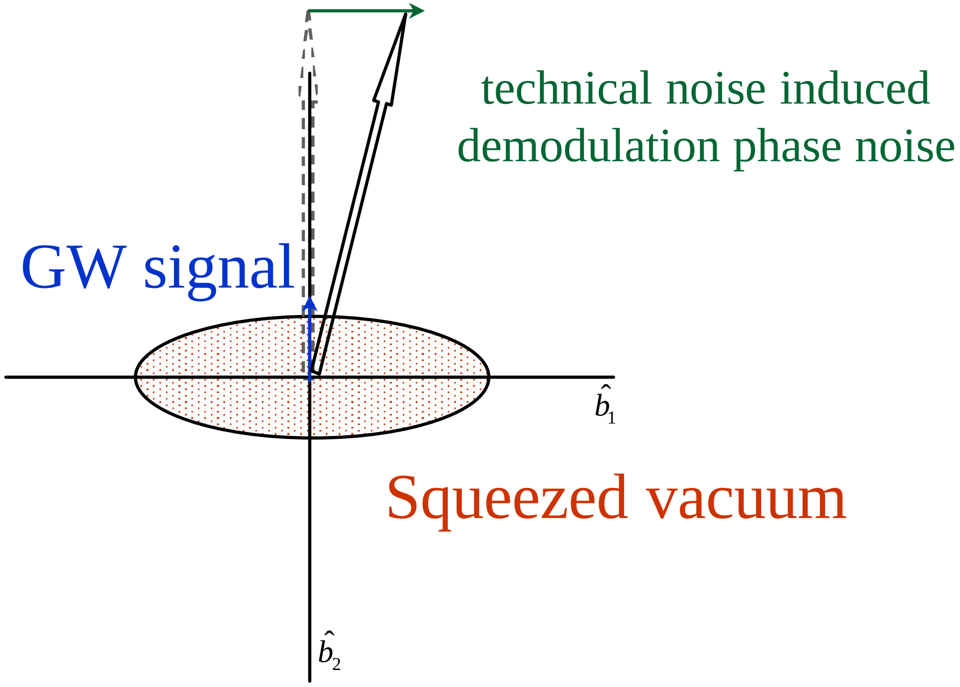




Phase quadrature diagram at dark port

If we can’t beat the SQL then...

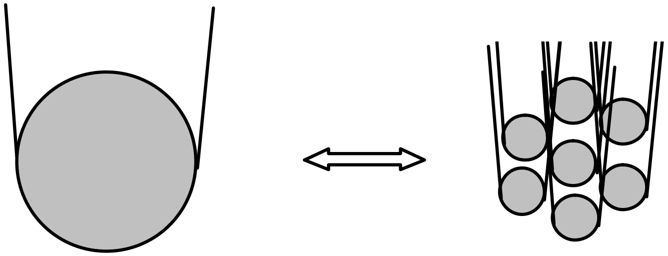
- Ways to avoid the SQL
  - Radiation pressure monitor with reaction mass
  - High mass (Ricardo, Warren’s session Saturday)
  - High frequency and low frequency optimized detectors
  - interferometer arrays

Interferometer arrays to reduce noise

- To reduce radiation pressure noise we want **massive** mirrors
- LIGO mirror sizes are at the limits of today’s fabrication technology
- Consider 1 interferometer with mirrors of mass m_o and laser intensity i_o
- Consider the signal and noise for the interferometer

Interferometer arrays to reduce noise

- For the maximum mirror mass and laser power make many low powered interferometers instead of one high powered interferometer
- signal adds coherently
- noise adds incoherently (except gravity gradient)



Number of mirrors	Mirror mass	intensity	Signal level	Radiation pressure noise	thermal noise	shot noise
1	M	i_0	h_0	r_0	t_0	s_0
1	M/n	i_0	h_0	$n\ r_0$	t_0	s_0
1 of n	M/n each	i_0/n	h_0/n	$r_0/\sqrt{n}$	t_0/n	$s_0/\sqrt{n}$
array of n	M total	i_0	h_0	r_0	$t_0/\sqrt{n}$	s_0

Questions to discuss

- When should we start to include technical noise analysis with quantum noise analysis in QND configurations?
- Can technical noise be suppressed enough for QND measurements?
- Is junk light noise in 1st generation detectors a useful indicator of noise in future detectors?
- How far can we lower technical noise curves below quantum noise?
- How accurately and stably can we set demodulation phases?
- Should we try to avoid the SQL rather than beat it?