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Double Optical Springs: Application to Gravitational Wave Detectors and Ponderomotive Squeezers

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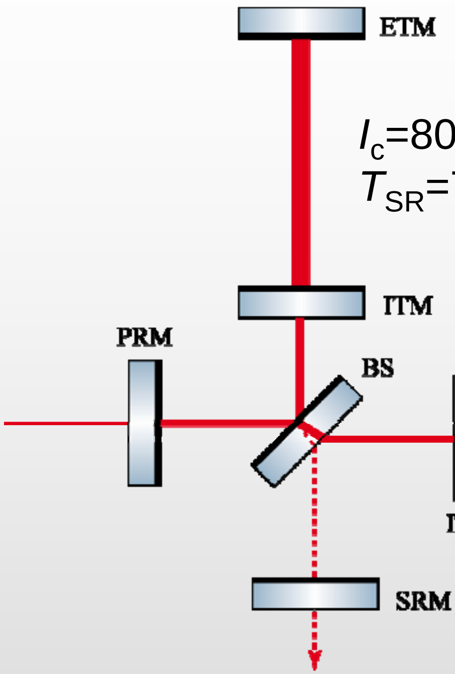
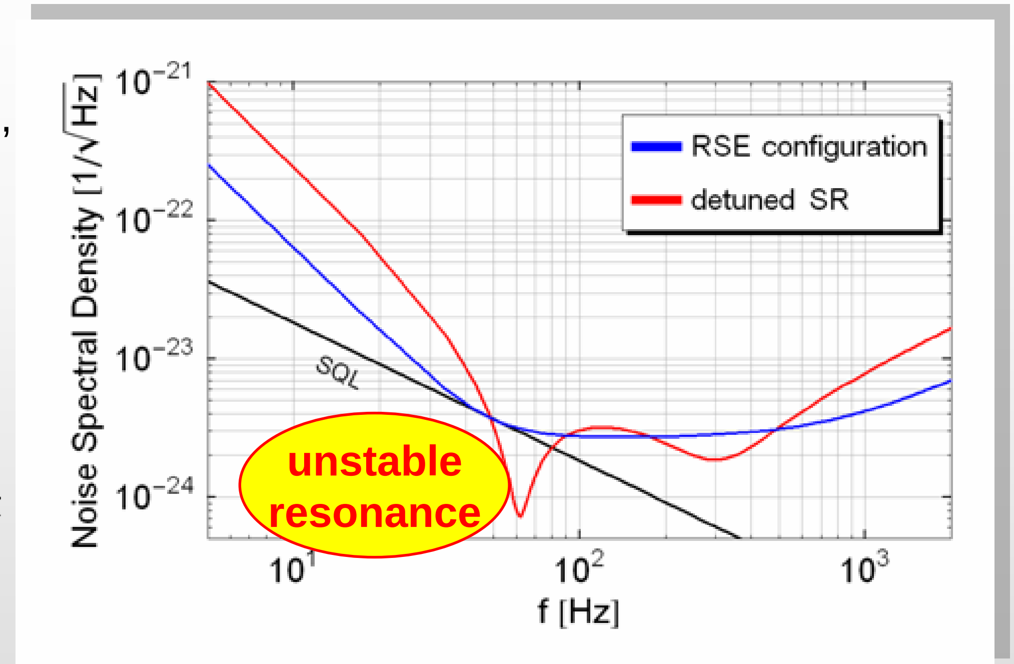
Detuned SR Interferometer



I_c=800 kW, T_{ITM}=0.5%,
T_{SR}=7%, $\phi=\pi/2-0.063$

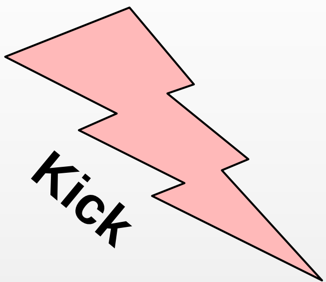
Buonanno & Chen 00,01,03

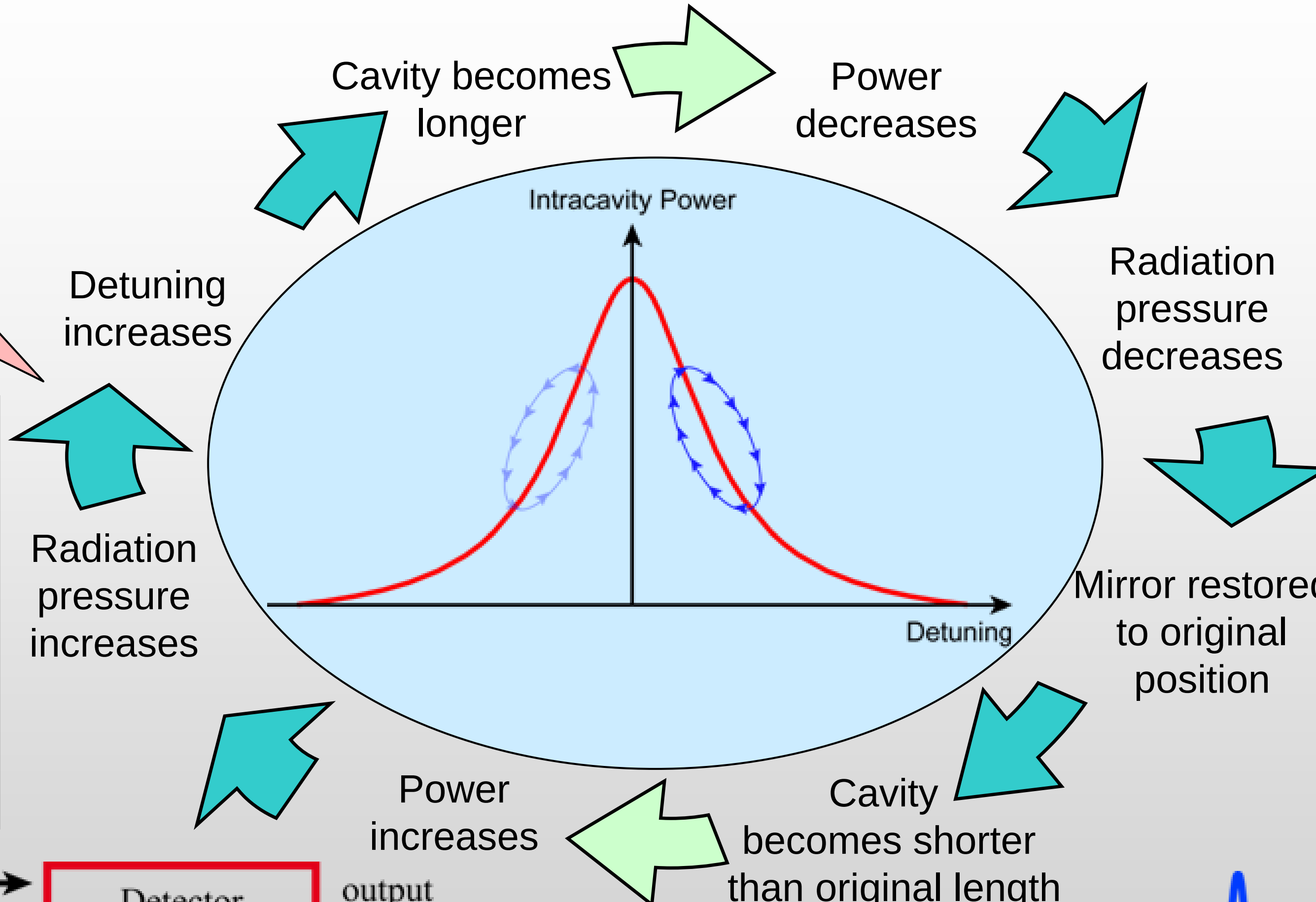


- Gain of sensitivity around optical and optomechanical resonance
- In-band control without imposing fundamental noise

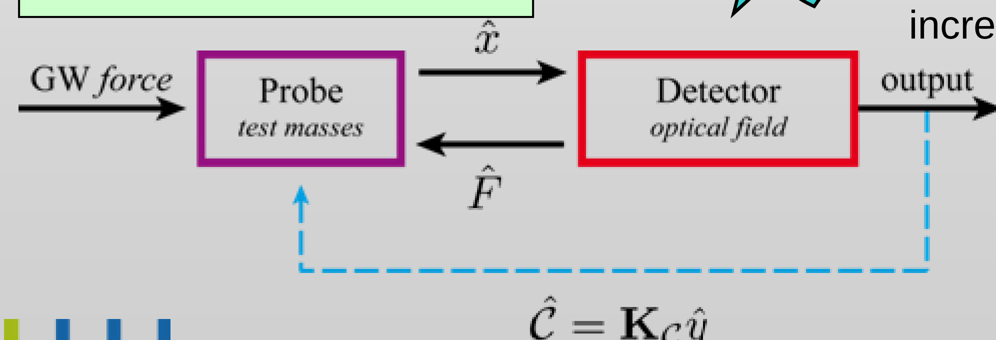
- suppressed sensitivity for frequencies below/above resonances
- Unstable optomechanical resonance

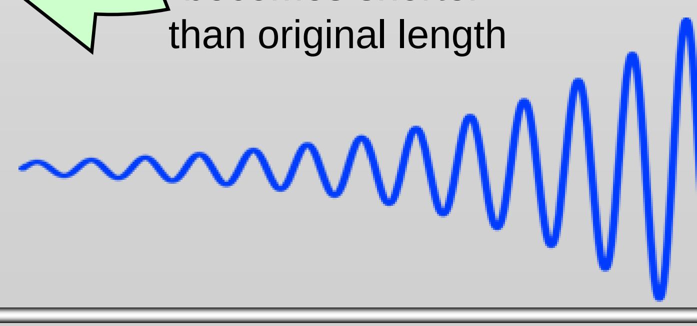
Single Optical Spring





Field response lags motion of the mirrors ⇒ restoring spring constant implies negative damping





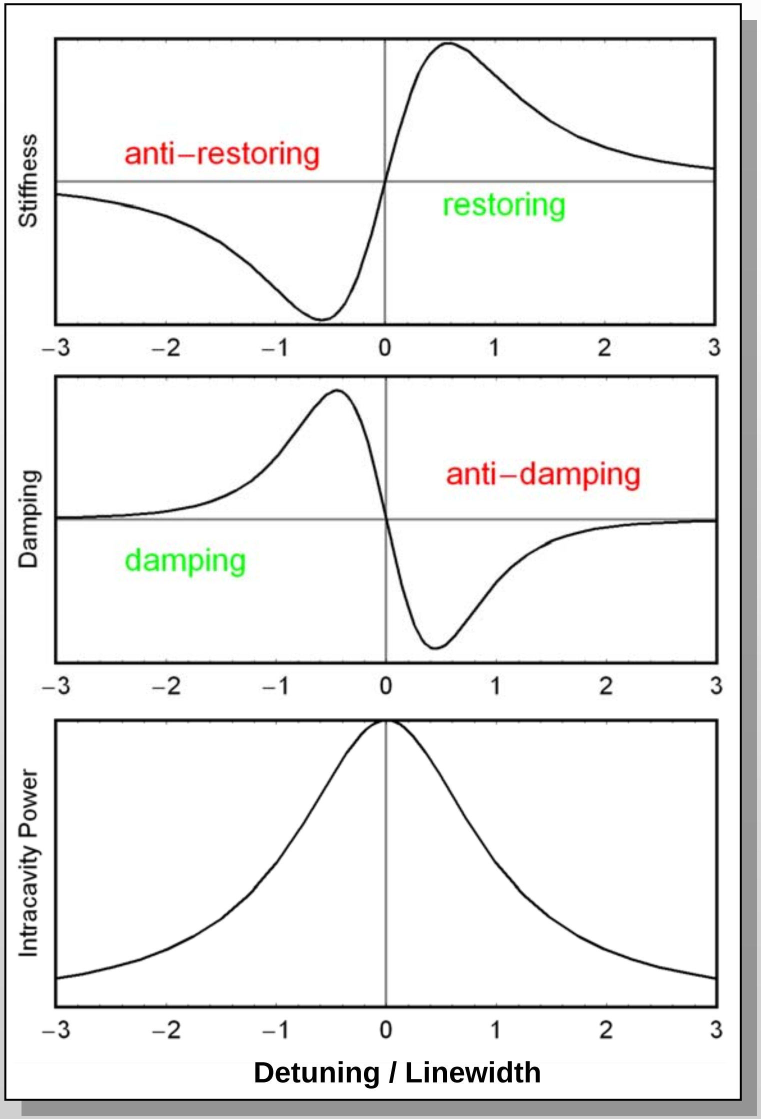
Optical Springs and Damping

- Detune resonant cavity to higher frequencies:
  - restoring optical spring (optical trapping)
  - anti-damping

unstable, feedback required

- Detune resonant cavity to lower frequencies:
  - velocity-dependent viscous damping force (cold damping)
  - anti-restoring optical spring

dynamically unstable



The Double Optical Spring

Motion of mirror:

$$\hat{x}(\Omega) = R_{xx}\left(\hat{F}_0(\Omega) + R_{FF}(\Omega)\hat{x}(\Omega)\right) + \text{GW Force}$$

For low frequencies one can split $R_{FF}(\Omega)$ into real and imaginary part

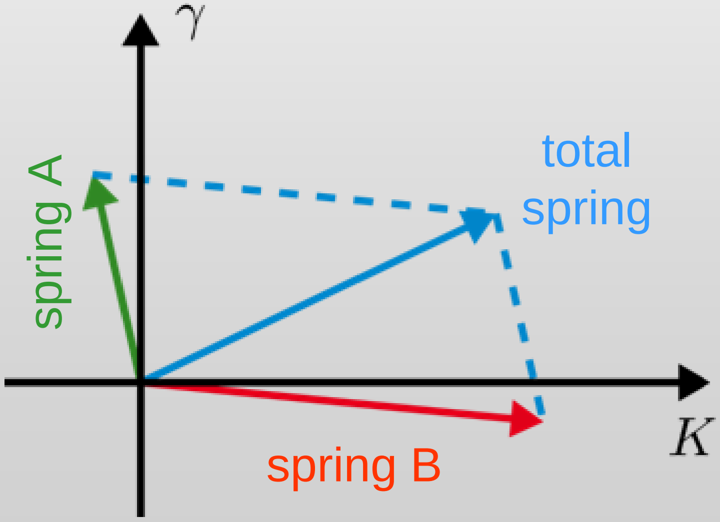
$$R_{FF}(\Omega) = -\frac{\theta^2}{4}\frac{\lambda}{(\mathrm{i}\epsilon - \lambda + \Omega)(\mathrm{i}\epsilon + \lambda + \Omega)} \approx \frac{\theta^2\lambda}{4\,(\epsilon^2+\lambda^2)}\left(1 + \mathrm{i}\frac{2\epsilon\Omega}{(\epsilon^2+\lambda^2)}\right) = K - \mathrm{i}\Omega\gamma$$

Combine good features of two optical springs:

Spring A: bad-cavity scenario: anti-restoring, damping

Spring B: good-cavity scenario: restoring, anti-damping

Total Spring: Stable system: damping, restoring



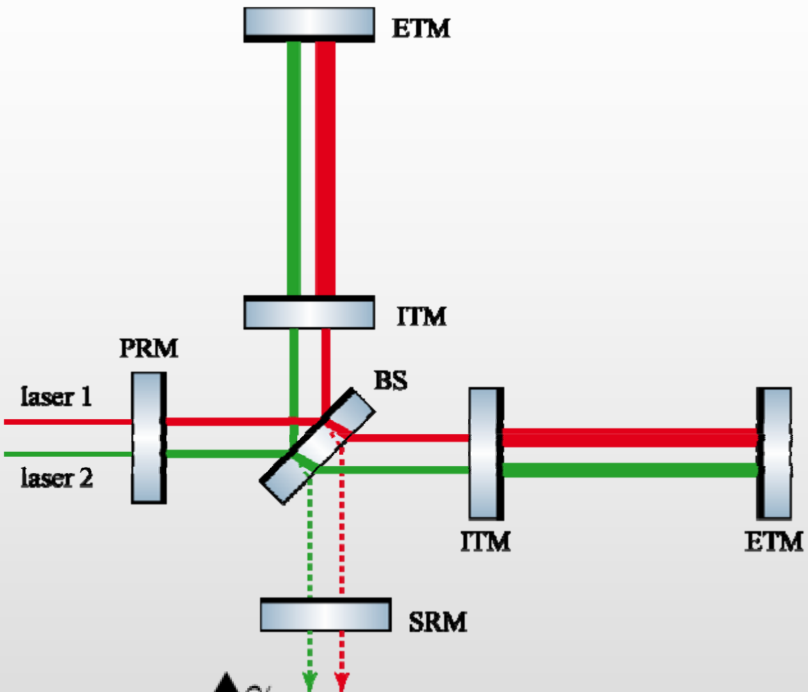
V.B. Braginsky, S.P. Vyatchanin, 02

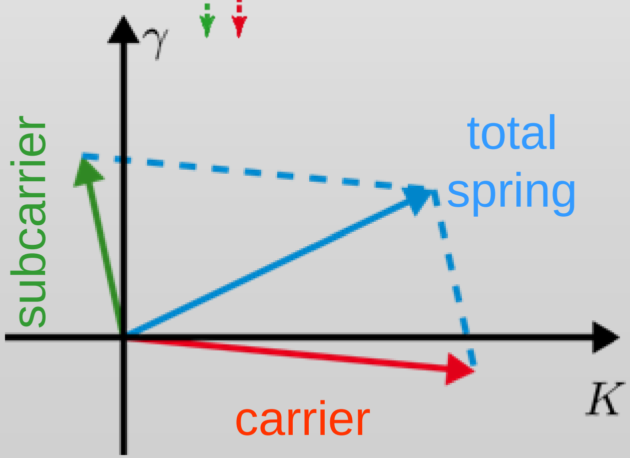
Double Optical Spring in Advanced LIGO

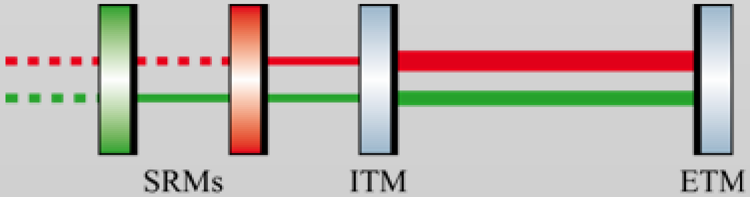
- Additional laser (subcarrier) can provide required optical spring
- Subcarrier resonates in the arms, but has different SR detuning phase [perhaps different polarization ...]
- Sensing both outputs separately improves sensitivity if appropriate filter is applied:

$$\hat{y} = K_1(\Omega)\ \hat{y}^{(1)} + K_2(\Omega)\ \hat{y}^{(2)}$$

- Second optical spring can stabilize interferometer without comprising classical noise
- Carrier and subcarrier have different SR cavities, then each equivalent to a different single detuned cavity

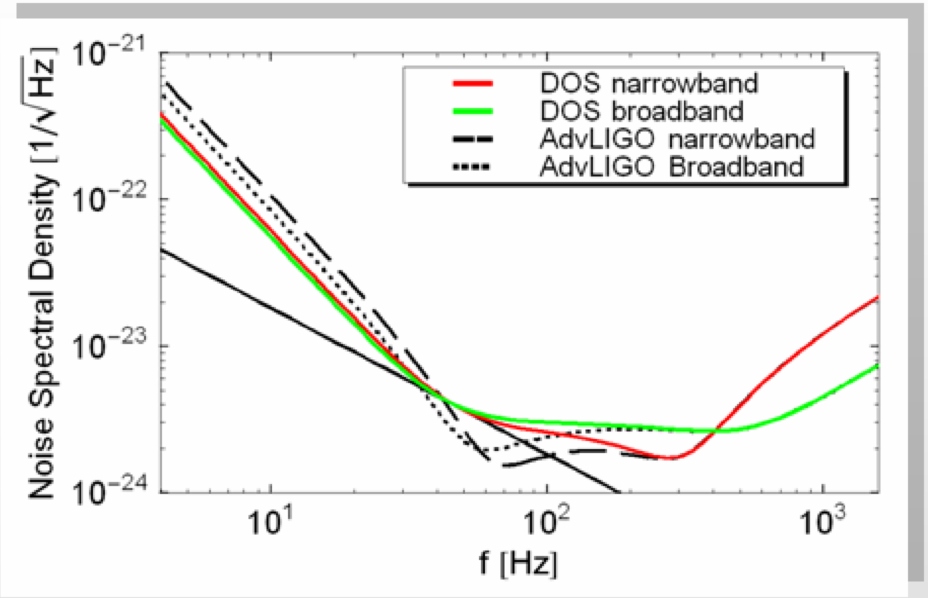


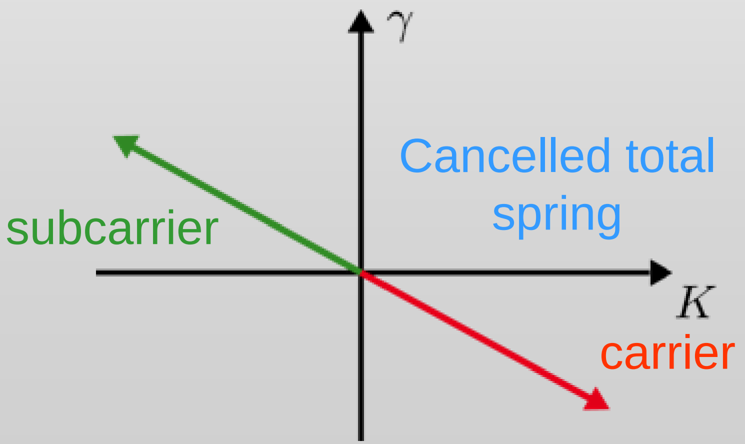




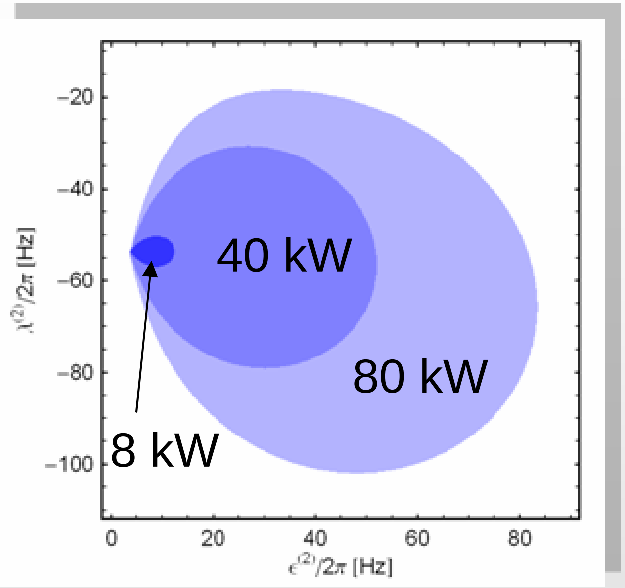
Example Configurations 1

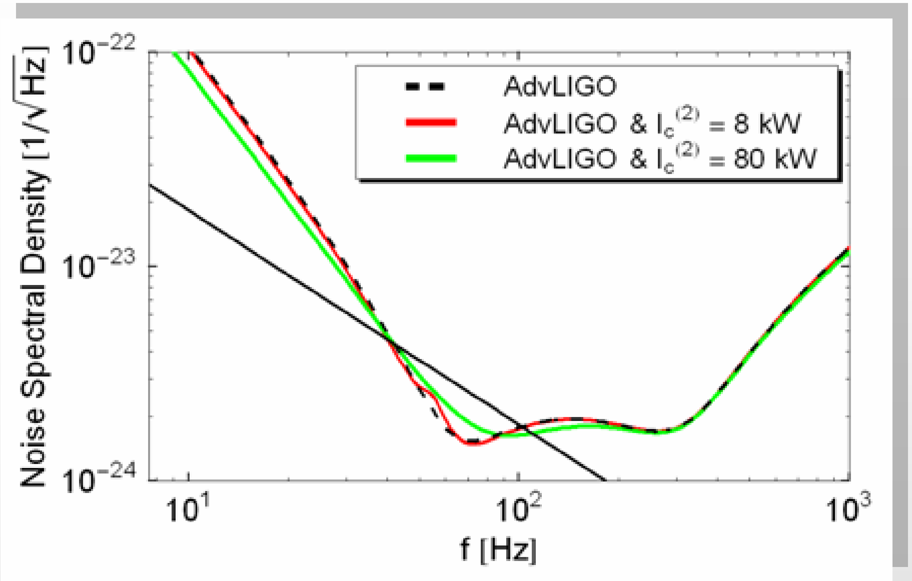
- Advanced LIGO configurations:
  narrowband scenario:
  I_c=800 kW, T_{ITM}=0.5%, T_{SR}=7%,
  $\phi=\pi/2-0.044$, $\zeta=\pi/2+0.609$
  broadband scenario:
  I_c=800 kW, T_{ITM}=0.5%, T_{SR}=7%,
  $\phi=\pi/2-0.019$, $\zeta=\pi/2+1.266$
- DOS configurations:
  carrier and subcarrier with equal power (400 kW) and detunings as above but with opposite signs.
- Optical springs cancel each other $\Rightarrow$ stable system
- Recover Advanced LIGO sensitivity above/below resonances



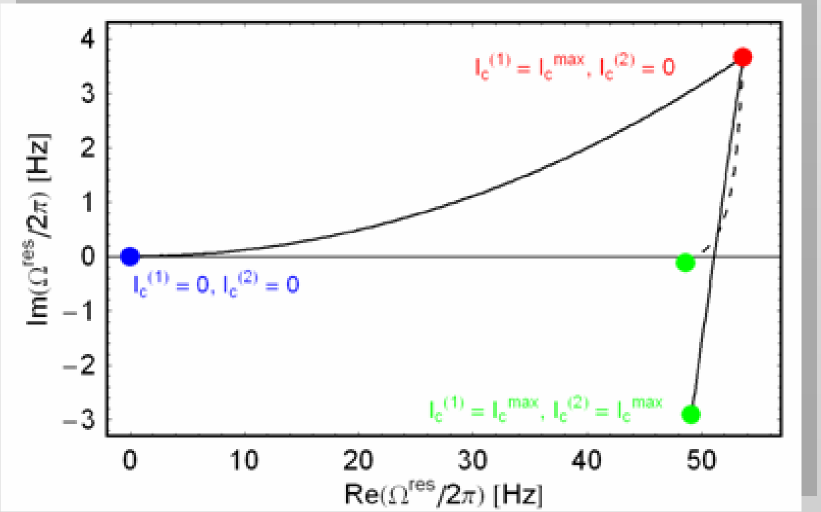


Example Configurations 2



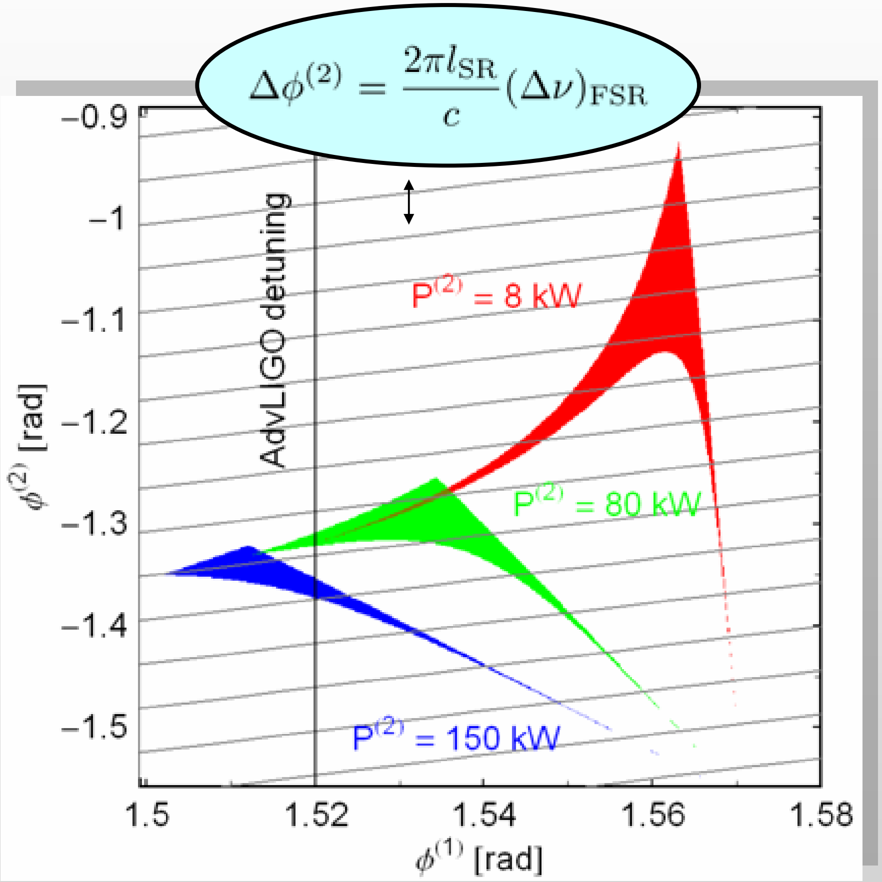


- Advanced LIGO configuration:
  narrowband scenario:
  $I_c^{(1)}$=800 kW, T_{ITM}=0.5%, T_{SR}=7%,
  $\phi=\pi/2-0.044$, $\zeta=\pi/2+0.609$
- Second carrier:
  $I_c^{(2)}$=8 kW, $\varepsilon^{(2)}=2\pi\ 5$, $\lambda^{(2)}=-2\pi\ 55$,
  $I_c^{(2)}$=80 kW, $\varepsilon^{(2)}=2\pi\ 60$, $\lambda^{(2)}=-2\pi\ 60$



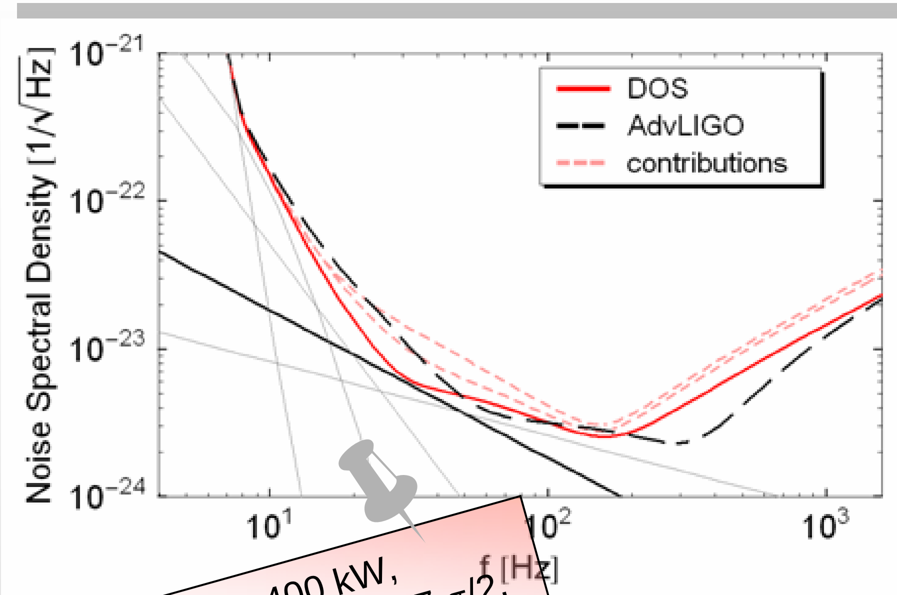
Accessible Regime and Optimization

- For comparison with Advanced LIGO we fix total power to 800 kW
- Different optimizations of DOS interferometer:
  - NS-NS binary systems (narrowband)
  - Broadband optimization
- Comparison with Advanced LIGO optimized with same algorithm



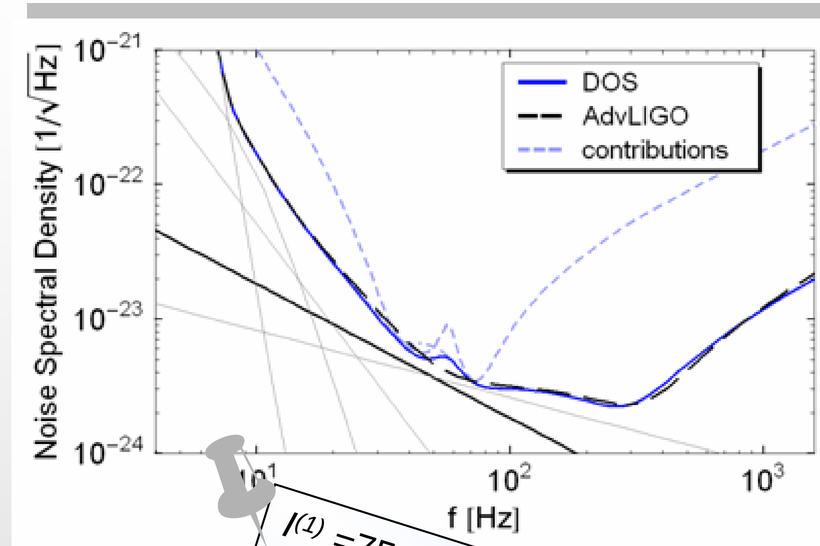
$P^{(1)}$=800 kW - $P^{(2)}$, T_{ITM}=0.5%, T_{SR}=7%

Optimized noise Spectral Densities



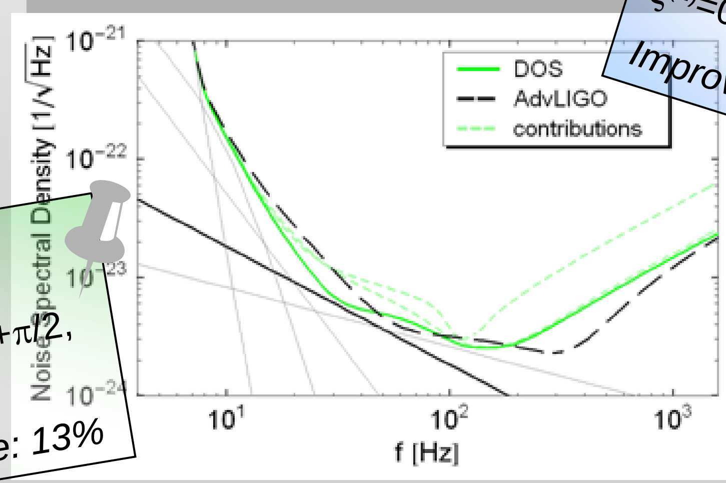
$I^{(1)}{}_c$=400 kW, $I^{(2)}{}_c$=400 kW,
T_{SM}=0.87, $\phi^{(1)}= \phi^{(2)}$=, 0.1047-$\pi/2$,
$\zeta^{(1)}$=1.15192+$\pi/2$, $\zeta^{(2)}=\pi$

Improvement in event rate: 15%



$I^{(1)}{}_c$=750 kW, $I^{(2)}{}_c$=50 kW,
T_{SM}=0.93, $\phi^{(1)}$=-0.0514+\pi/2
$\phi^{(2)}$=0.25354-$\pi/2$,
$\zeta^{(1)}$=0.872665+$\pi/2$, $\zeta^{(2)}=\pi$

Improvement in event rate: 4%

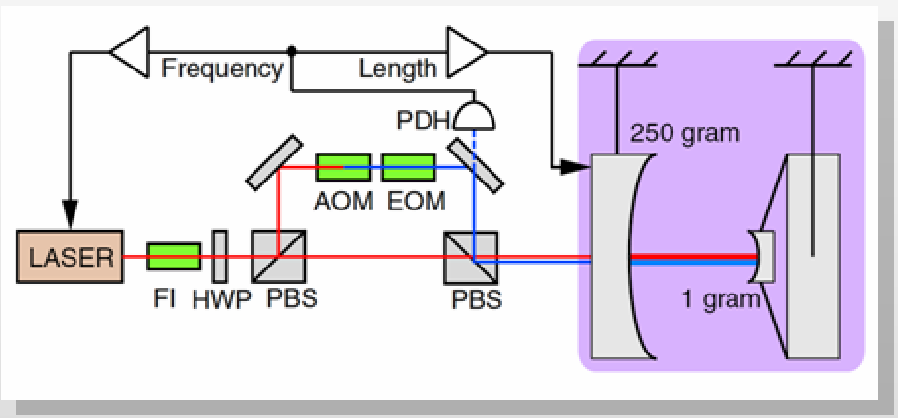


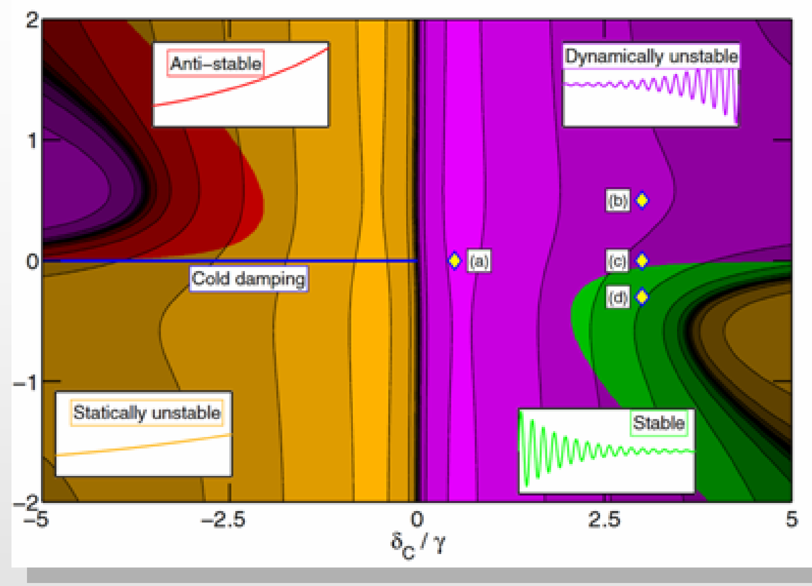
$I^{(1)}{}_c$=500 kW, $I^{(2)}{}_c$=300 kW,
T_{SM}=0.87, $\phi^{(1)}$=-0.092+$\pi/2$,
$\phi^{(2)}$=0.1517-$\pi/2$, $\zeta^{(1)}$=1.414+$\pi/2$,
$\zeta^{(2)}$=0.9425+$\pi/2$

Improvement in event rate: 13%

The Double Optical Spring Experiment

“An All-Optical Trap for Gram-Scale Mirror”





Thomas Corbitt, Yanbei Chen, Edith Innerhofer, Helge Müller-Ebhardt, David Ottaway,Henning Rehbein, Daniel Sigg, Stanley Whitcomb, Christopher Wipf, and Nergis Mavalvala,
PRL **98**, 150802 (2007)

Route to Ponderomotive Squeezing

Amplitude fluctuations of laser light

Test mass motion

Phase shift of reflected light

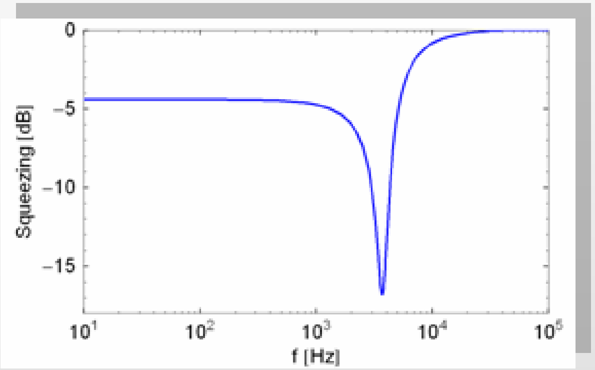
Phase shift proportional to amplitude fluctuations

Correlations between amplitude and phase

Squeezing

Advantage of using an optical spring [Corbitt et al., PRA **73**, 023801 (2006)]:

- Squeezing with constant factor and quadrature phase
- Less susceptible to classical noises



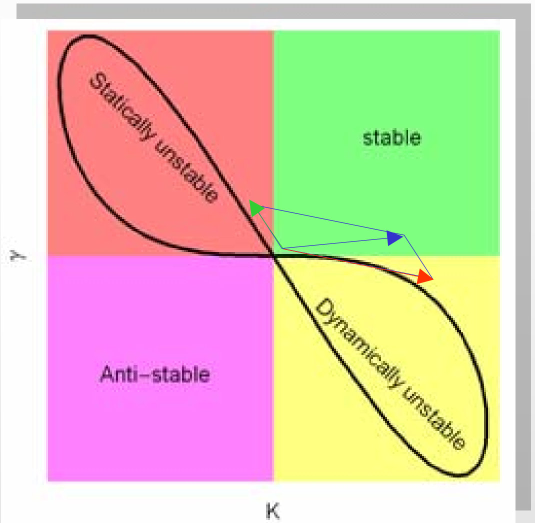
P_{in}=3W, γ=10kHz, ϕ=10kHz, m =1g, $\Omega_{os}/2\pi$ =3.7+0.3i kHz

$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 2\epsilon/\lambda & 1 \end{pmatrix} \cdot \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} + \sqrt{2}\sqrt{m/\hbar}\frac{\Omega^2}{\Omega_{os}}\sqrt{\frac{\epsilon}{\lambda}}F_x$$

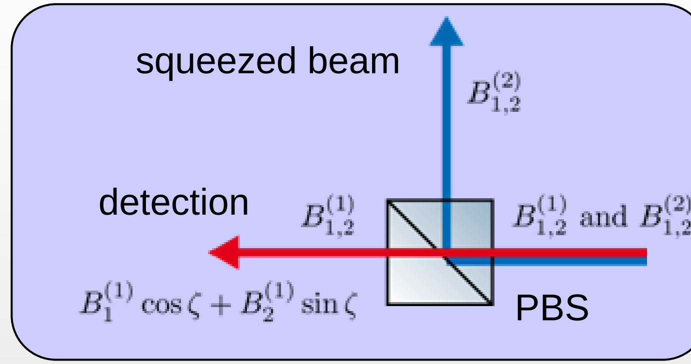
$$\Omega_{os} = \sqrt{\frac{\theta^2\lambda}{4m(\epsilon^2+\lambda^2)}}$$ Optomechanical resonance frequency

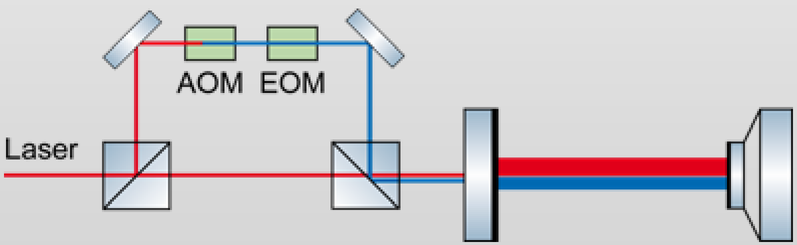
$$\theta = \sqrt{\frac{8P\omega_0}{Lc}}$$ Optomechanical coupling strength

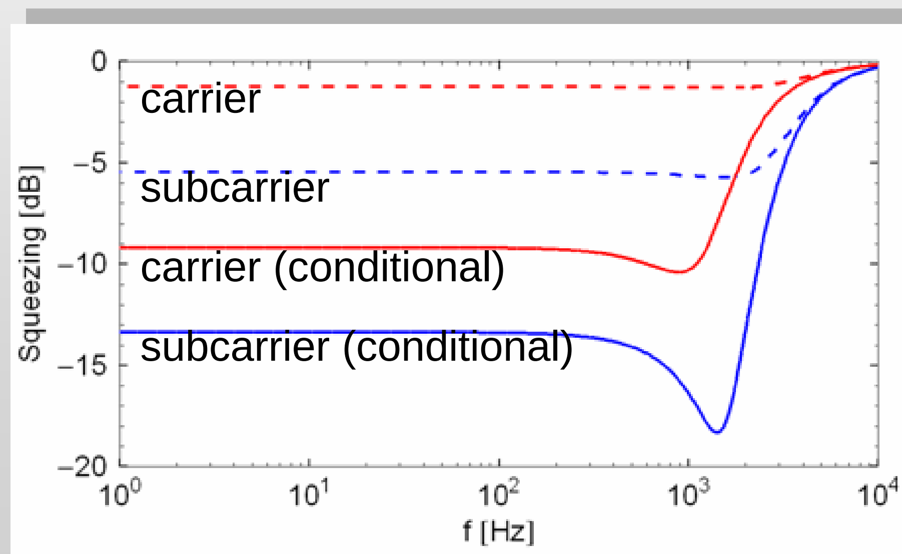
Stabilization and Squeezing



Subcarrier much more squeezed than carrier!







P_1=2.85W, P_2=0.15W, L=0.9m, m=1g, T=800ppm, $\lambda_1/2\pi$=30kHz, $\lambda_2/2\pi$=-5kHz, $\varepsilon/2\pi$ =10kHz

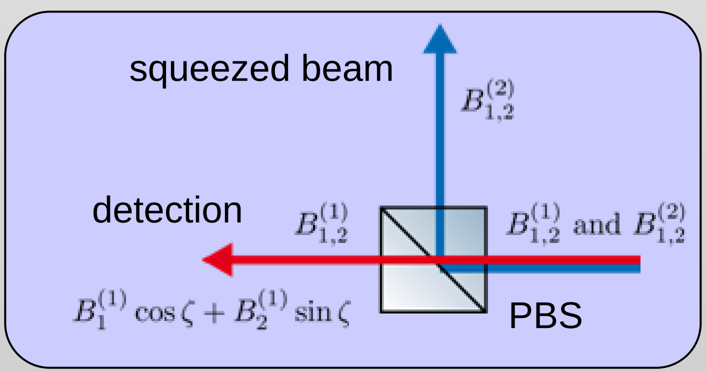
Conditional Squeezing

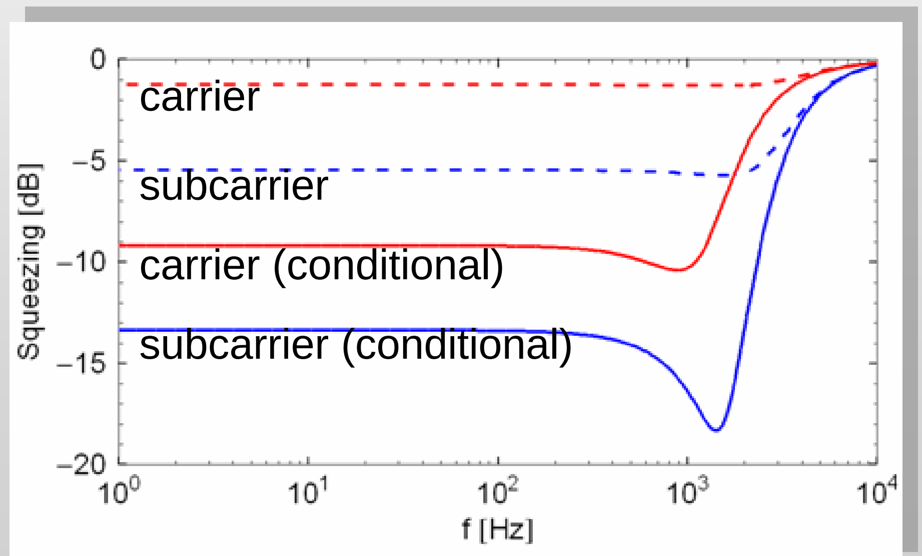
- $B_{1,2}^{(1)}$: mixed state
  $B_{1,2}^{(2)}$: mixed state
  $B_{1,2}^{(1)}$, $B_{1,2}^{(2)}$: pure state!!!
- Entanglement between carrier and subcarrier
- Conditioning recovers pure state
- Conditioning allows much more squeezing
- Conditional squeezing equivalent to “real” squeezing

squeezing entanglement

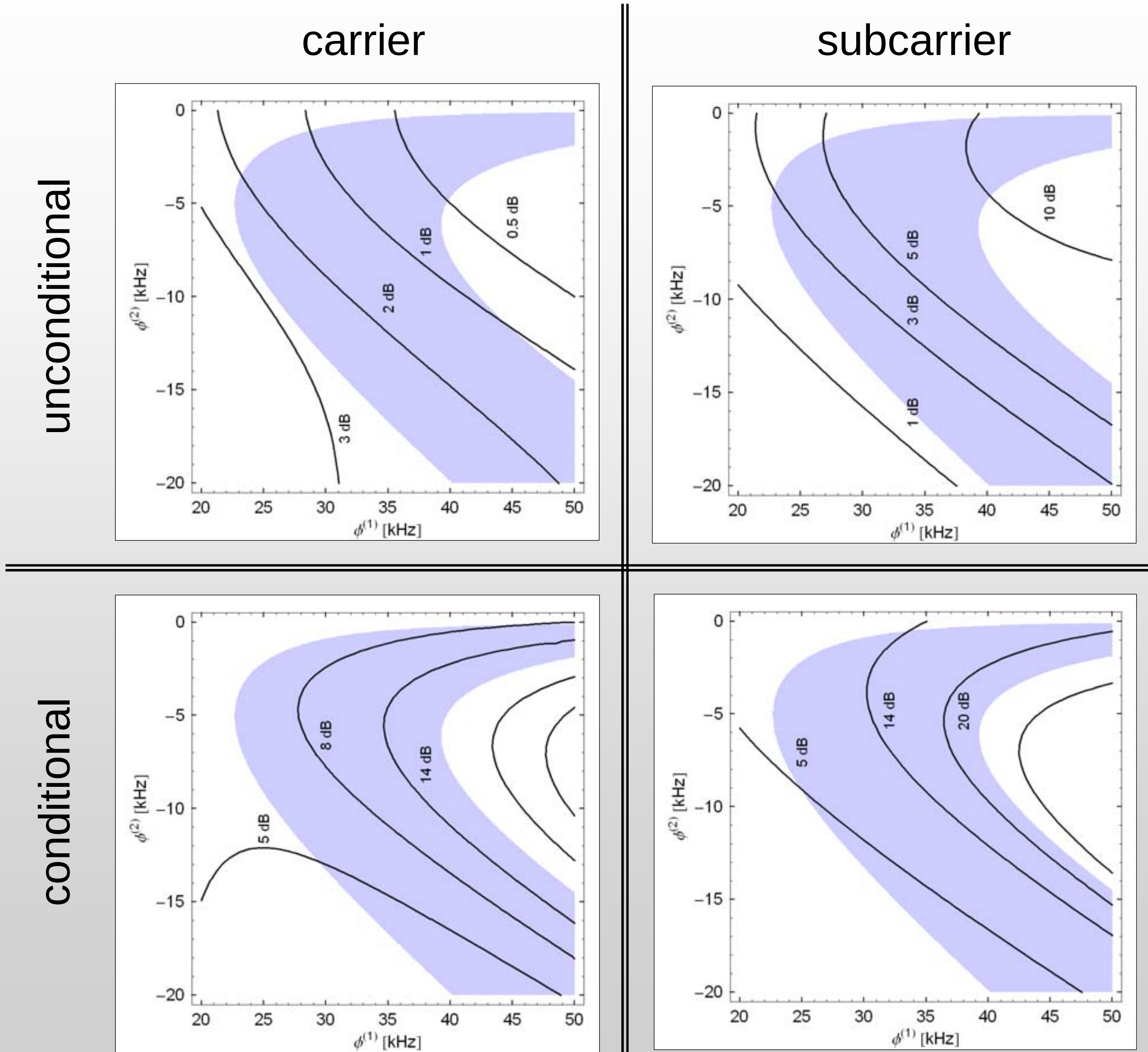
$$\begin{bmatrix} B_1^{(1)} \\ B_2^{(1)} \\ B_1^{(2)} \\ B_2^{(2)} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 2\alpha_1^2 & 1 & 2\alpha_1\alpha_2 & 0 \\ 0 & 0 & 1 & 0 \\ 2\alpha_1\alpha_2 & 0 & 2\alpha_2^2 & 1 \end{bmatrix} \cdot \begin{bmatrix} A_1^{(1)} \\ A_2^{(1)} \\ A_1^{(2)} \\ A_2^{(2)} \end{bmatrix}$$

entanglement squeezing



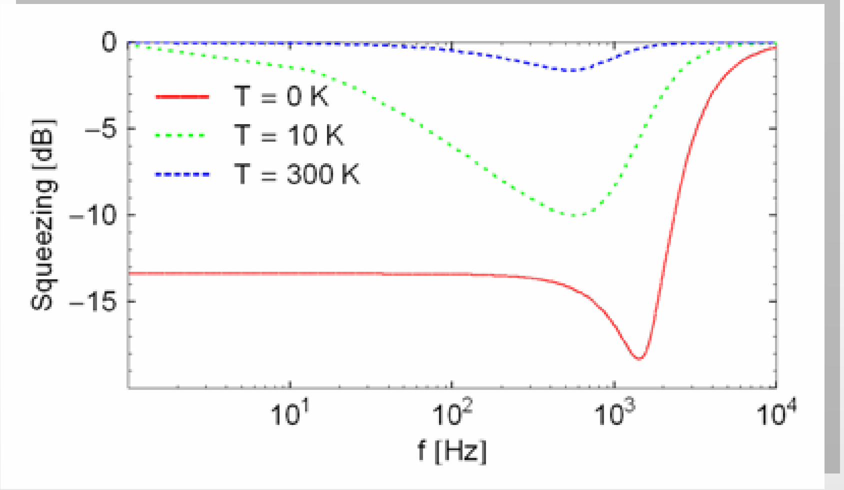


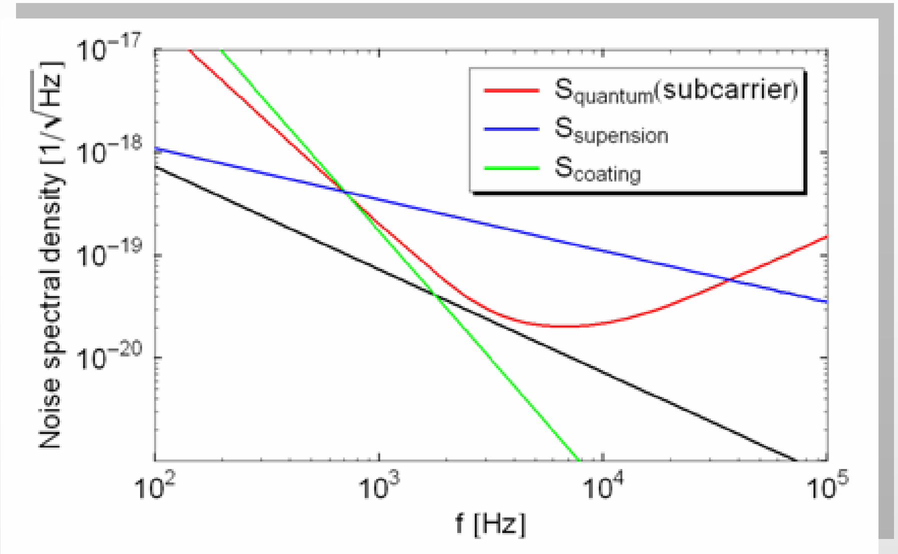
Conditional vs. Unconditional

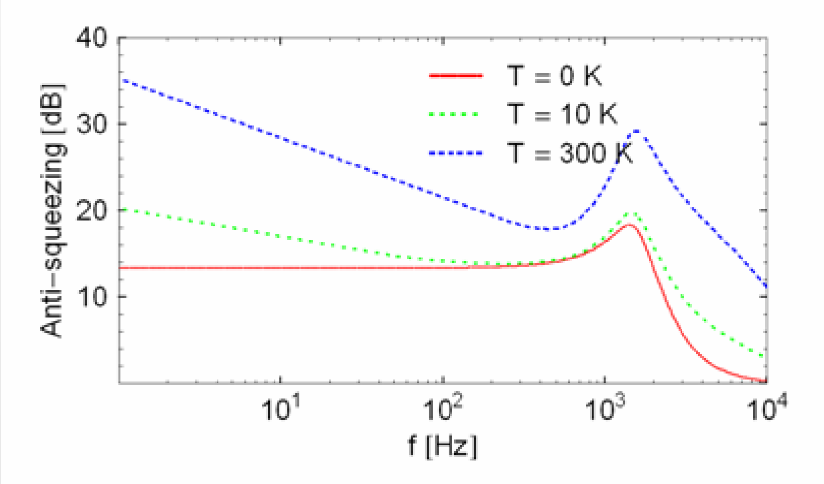


- Subcarrier always much more squeezed than carrier
- Conditioning recovers strong squeezing

Squeezing with Classical Noise

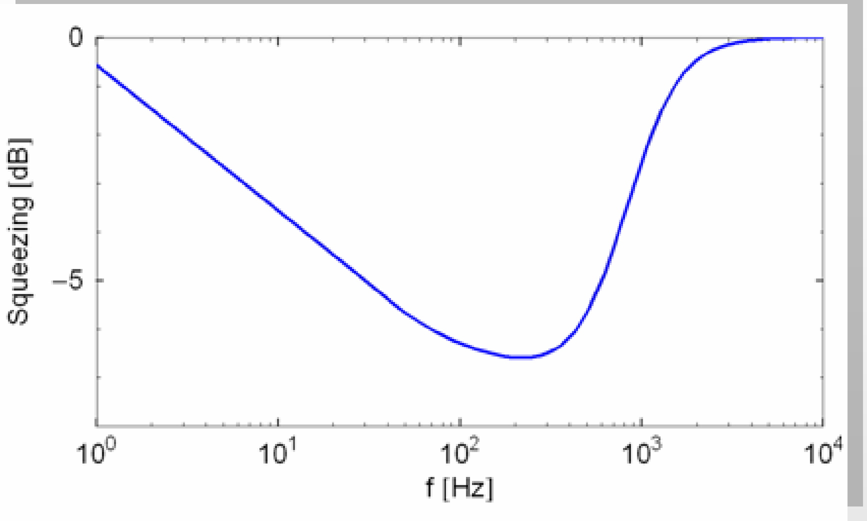




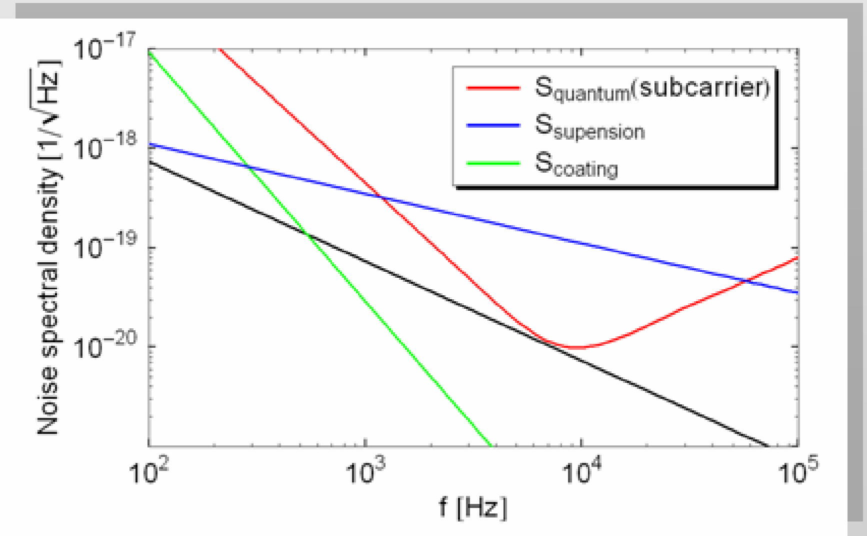


P_1=2.85W, P_2=0.15W, L=0.9m, m=1g, T=800ppm, $\lambda_1/2\pi$=30kHz, $\lambda_2/2\pi$=-5kHz, $\varepsilon/2\pi$ =10kHz, $\omega_m=2\pi$ 6 Hz, Q=10^5

How to Improve Squeezing



- Increase optical power
- Higher mechanical Q-factor
- Lower pendulum eigenfrequency
- Lower temperature



P_1=2.85W, P_2=0.15W, L=0.9m, m=1g, T=800ppm, $\lambda_1/2\pi$=30kHz, $\lambda_2/2\pi$=-5kHz, $\varepsilon/2\pi$ =10kHz, $\omega_m=2\pi$ 6 Hz, Q=10^5,T=300K

↓

P_1=11.4W, P_2=0.6W, L=0.9m, m=1g, T=800ppm, $\lambda_1/2\pi$=24kHz, $\lambda_2/2\pi$=-6kHz, $\varepsilon/2\pi$ =10kHz, $\omega_m=2\pi$ 1 Hz, Q=10^5, T=300K

Conclusion and Outlook

- Second optical spring can stabilize Advanced LIGO and improve sensitivity
- Classical electronic feedback mechanism replaced by quantum control
- Our proposed upgrade for Advanced LIGO should be realizable with low effort
- Combinable with other QND schemes, e.g. injection of squeezed vacuum
- Double optical spring helps to built efficient ponderomotive squeezing source
- Conditional measurement can remove entanglement between the two carrier fields