Enhancing sensitivity of gravitational wave antennas, such as LIGO, via light-atom interaction

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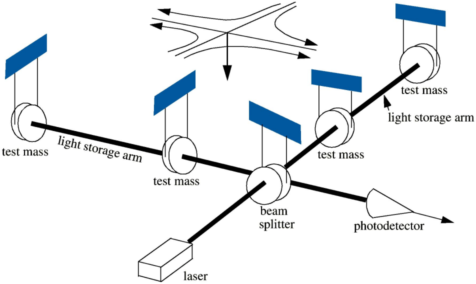
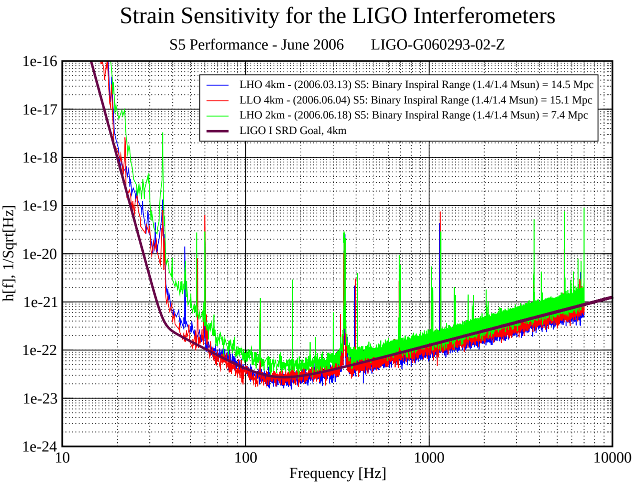
New Laser Scientists, 24 October 2014

Laser Interferometer Gravitational-wave Observatory

- $L = 4$ km
- $h \sim 2 \times 10^{-23}$
- $\Delta L \sim 10^{-20}$ m



LIGO sensitivity, S5 run, June 2006



Inspiral search range during S5 is 14Mpc

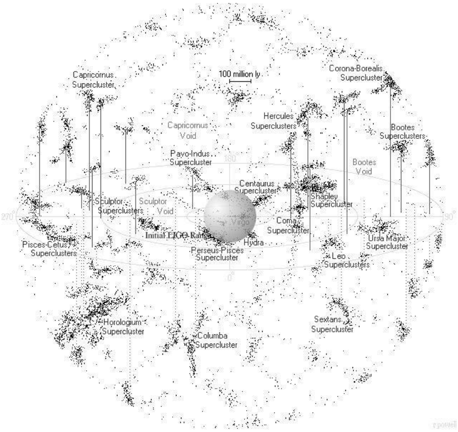
Upgrade to advanced LIGO

Goals

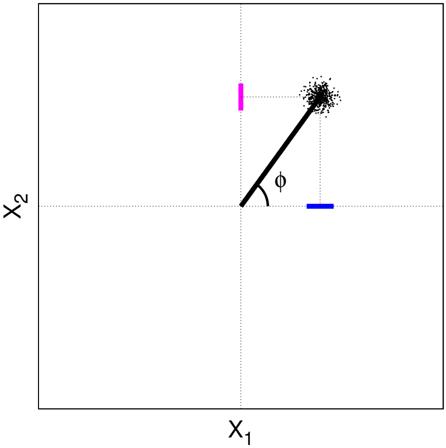
- Factor of 15 increase in sensitivity
- inspiral range from 20 Mpc to 350 Mpc
- Factor of 3000 in event rate
  One day > entire 2-year initial data run

How

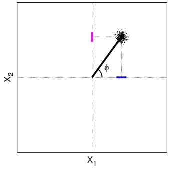
- better seismic isolation
- decreasing thermal noise
- higher laser power
- injection of squeezed state



Squeezed quantum states zoo



Unsqueezed coherent



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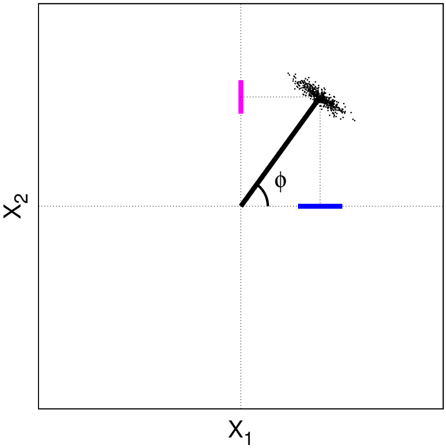

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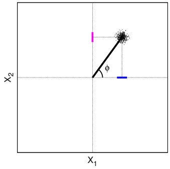
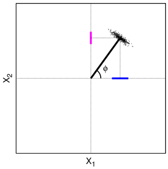


Amplitude squeezed



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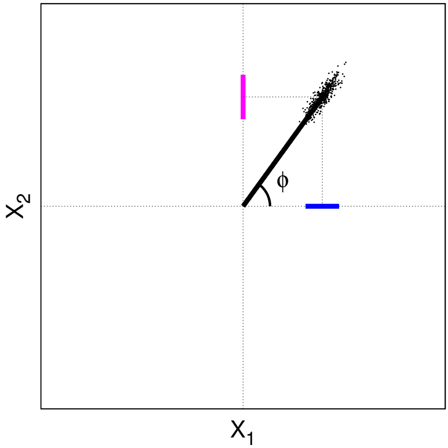

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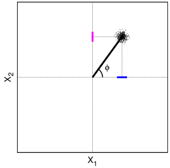

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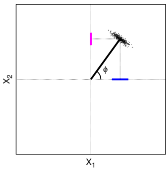
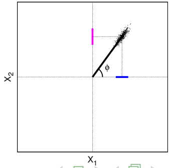


Phase squeezed



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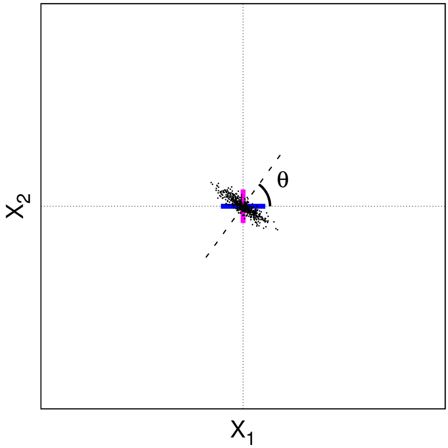
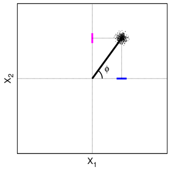
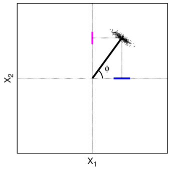


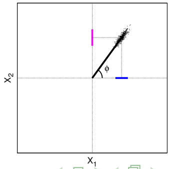
Unsqueezed coherent



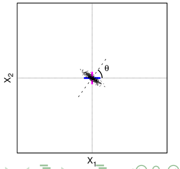
Amplitude squeezed



Phase squeezed

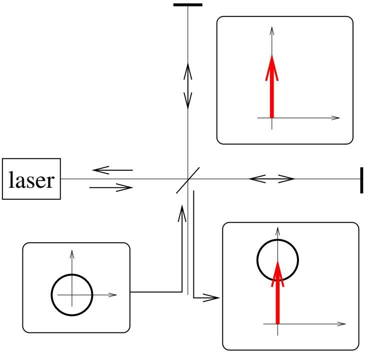


Vacuum squeezed



Squeezing and interferometer

Vacuum input



Squeezing and interferometer

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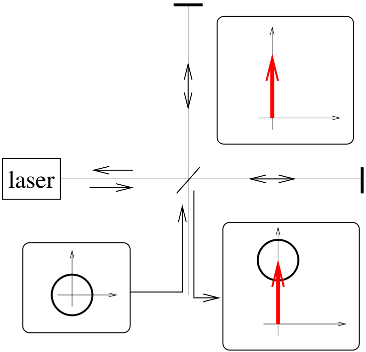
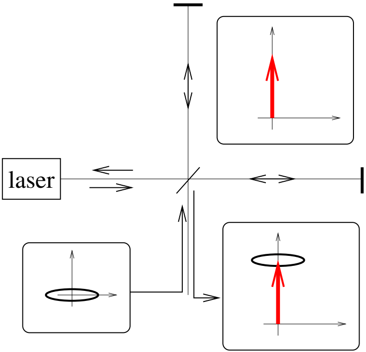


Squeezed input



Limiting noise - Quantum Optical noise

Next generation of LIGO will be
quantum optical noise limited at almost all detection frequencies.

shot noise

Uncertainty in number of photons

$$h \sim \sqrt{\frac{1}{P}} \quad (1)$$

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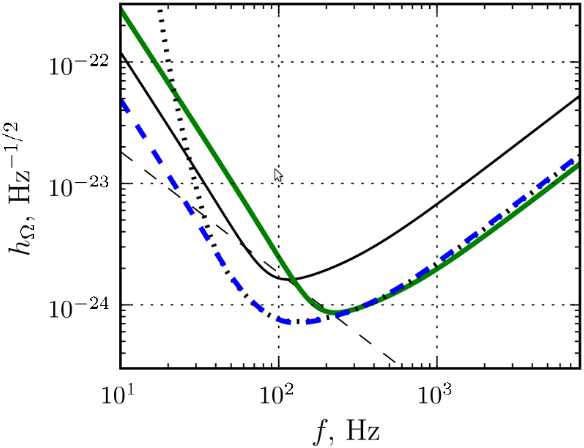
There is no optimal light power to suit all detection frequency.
Optimal power depends on desired detection frequency.

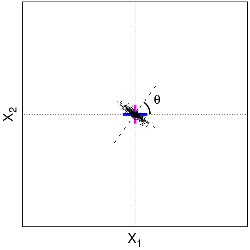
Interferometer sensitivity improvement with squeezing

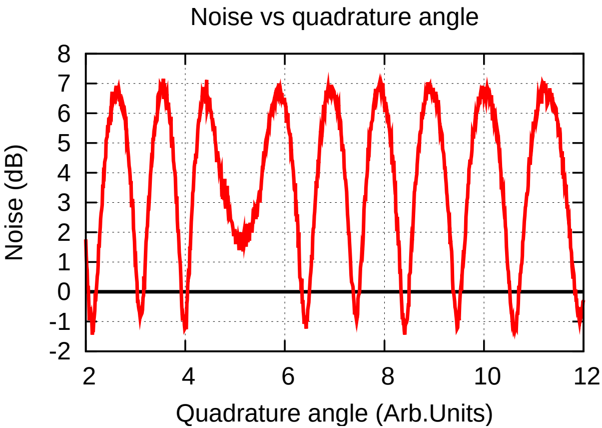
Projected advanced LIGO sensitivity



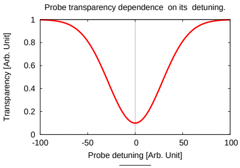
F. Ya. Khalili Phys. Rev. D 81, 122002 (2010)

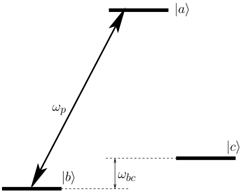
Squeezing and detection noise quadratures





Electromagnetically Induced Transparency (EIT) filter





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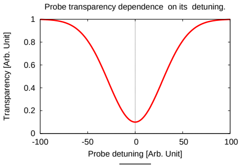
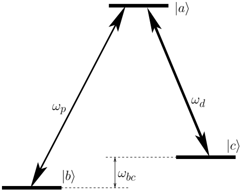
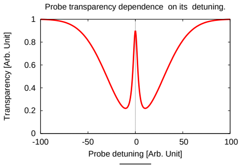


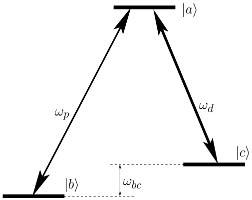


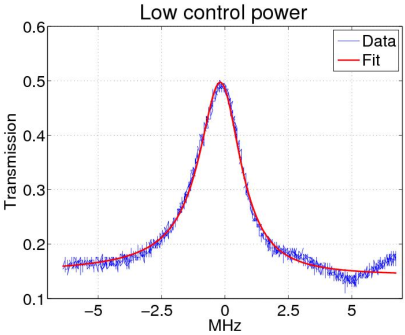


Squeezing and EIT filter

$$\begin{pmatrix} V_1^{out} \\ V_2^{out} \end{pmatrix} = \begin{pmatrix} A_+^2 & A_-^2 \\ A_-^2 & A_+^2 \end{pmatrix} \begin{pmatrix} V_1^{in} \\ V_2^{in} \end{pmatrix} + \left[1 - \left(A_+^2 + A_-^2\right)\right] \begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

$$A_\pm = \frac{1}{2}(T_+ \pm T_-)$$





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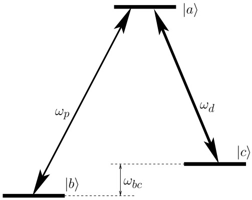

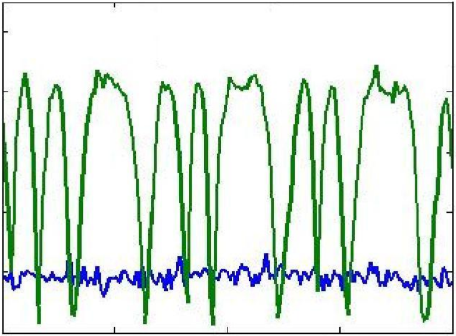

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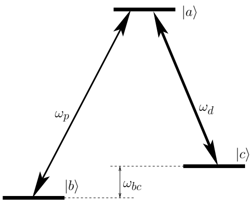

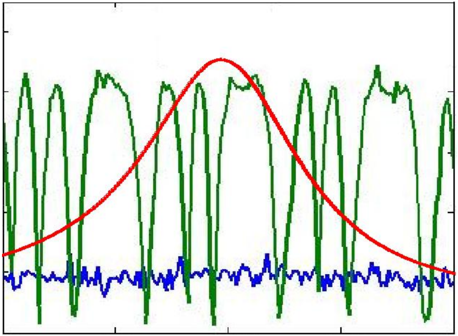

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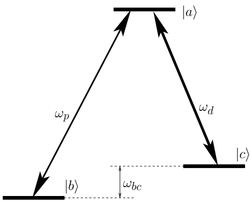
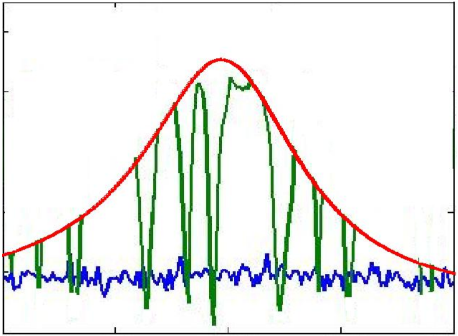
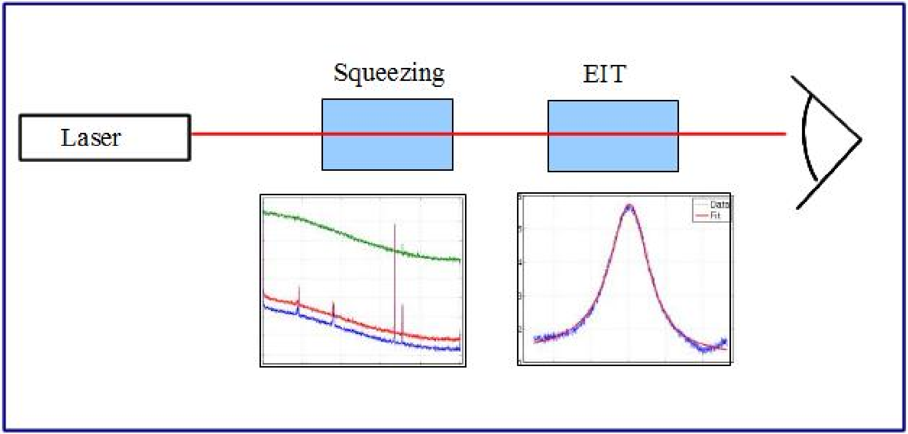




Squeezing and EIT filter setup



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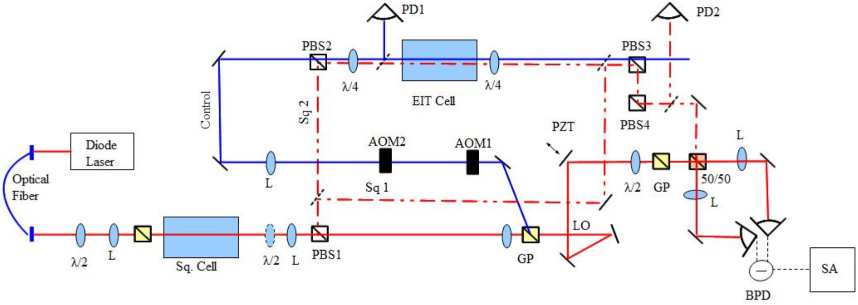
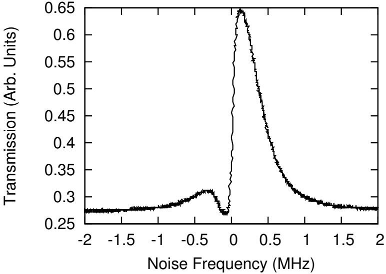
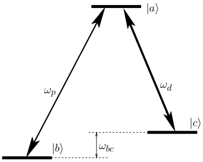


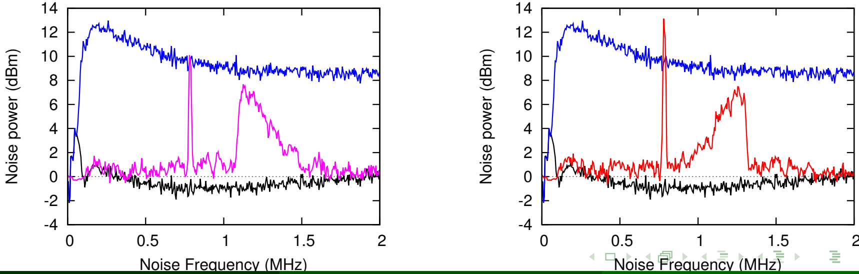
EIT filter and measurements without light



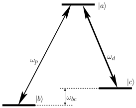
Coherent signal

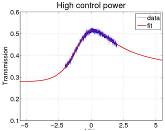


Signal in the noise quadratures

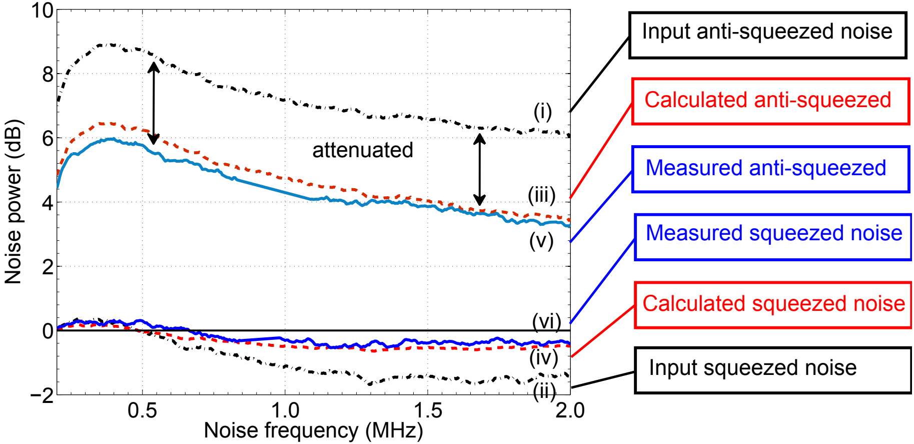


Wide EIT filter and squeezing

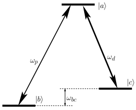


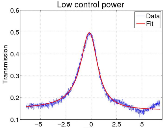


- Peak transmission = 52%
- FWHM= 4MHz

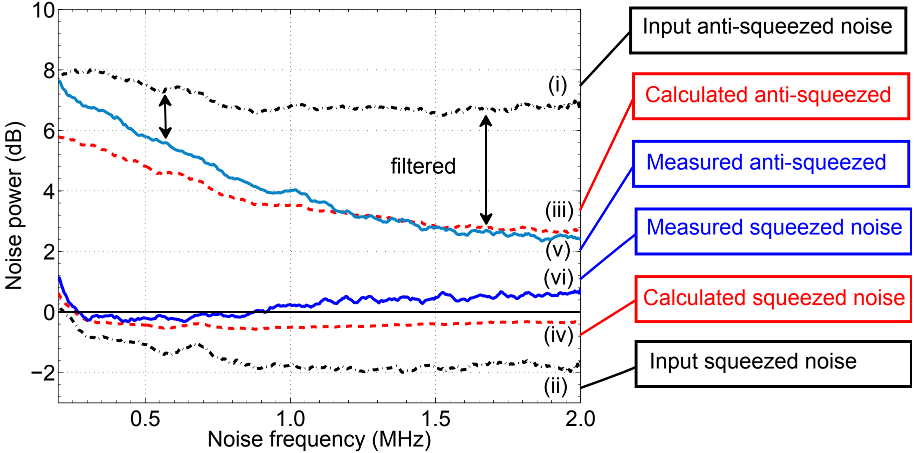


Narrow EIT filter and squeezing

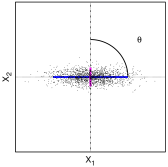


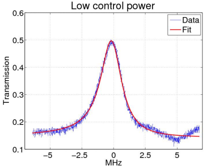


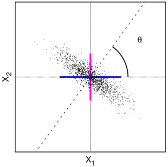
- Peak transmission = 50%
- FWHM= 2MHz



Squeezing angle rotation







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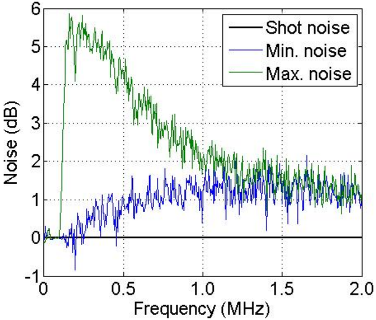
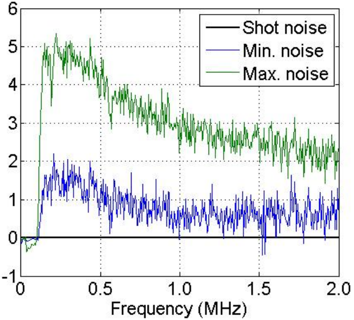
Locked at 300kHz



Locked at 1200kHz



Summary

It is possible to boost sensitivity of gravitational wave antennas via light-atom interaction.

Proposed work

- narrow EIT resonance/filter
- maintain high transmission
- match squeezing filter to LIGO $\lambda = 1064$ nm
  - find atomic media which is resonant to 1064 nm
  - use existing methods to up convert atom-filtered squeezing λ from 795 nm to 1064 nm