Discussion Questions

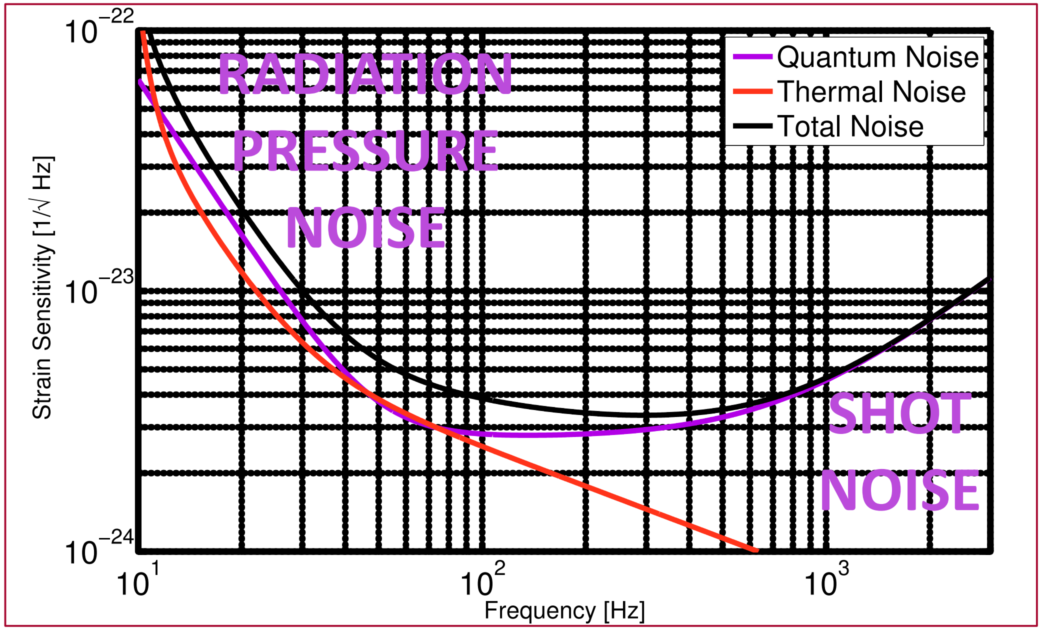
- How many detections before we pick a direction?
- downtime for improvements
  - can we take the detectors down for 6 months to make upgrades? (after detection!)
  - post detection time-volume calculus?
- what is the impact of duty cycle, lock length?
  - work on seismic system…

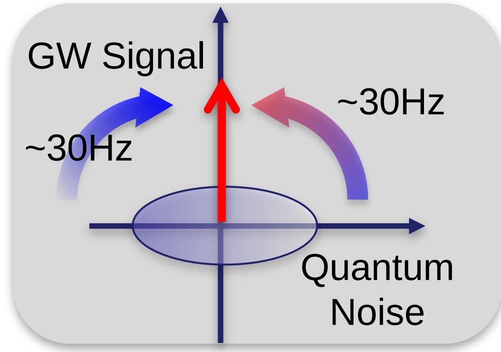
Discussion Questions

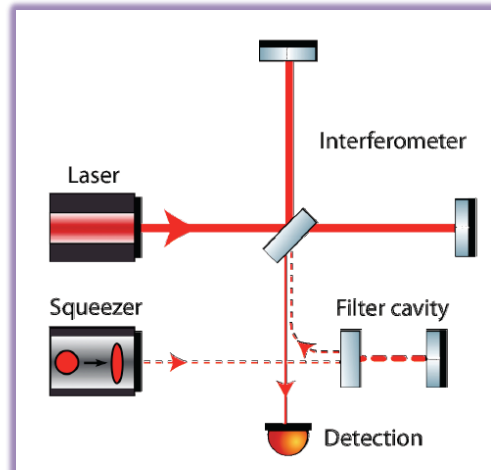
- how fast can we make progress on coating thermal noise?
  - funding limited?
  - manpower limited?
- bigger mirrors, bigger beams
  - alignment trouble, bigger BS PR3 SR3?
- cool to 200K for modest CTN improvement?
- more squeezing?
  - I/O loss reduction, readout noise, squeezer limit
- squeeze tracking?

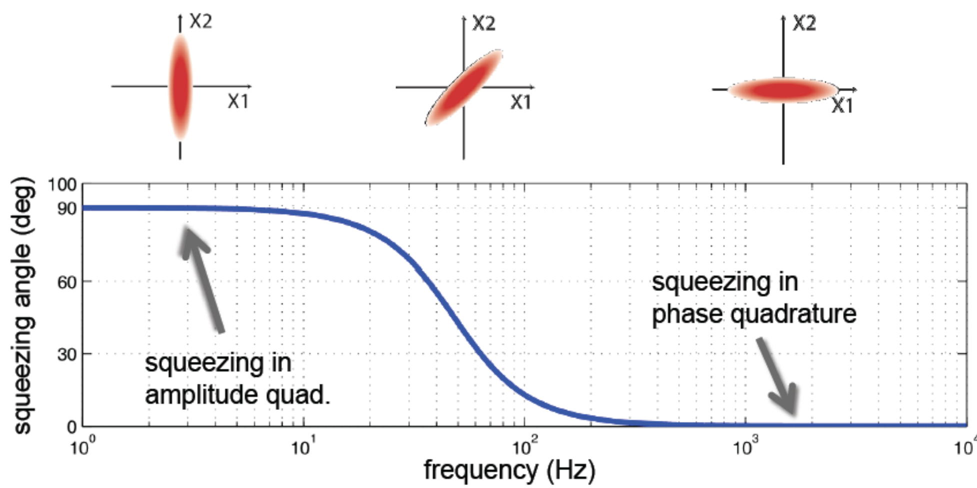
Extra Slides

Frequency Dependent Squeezing - I





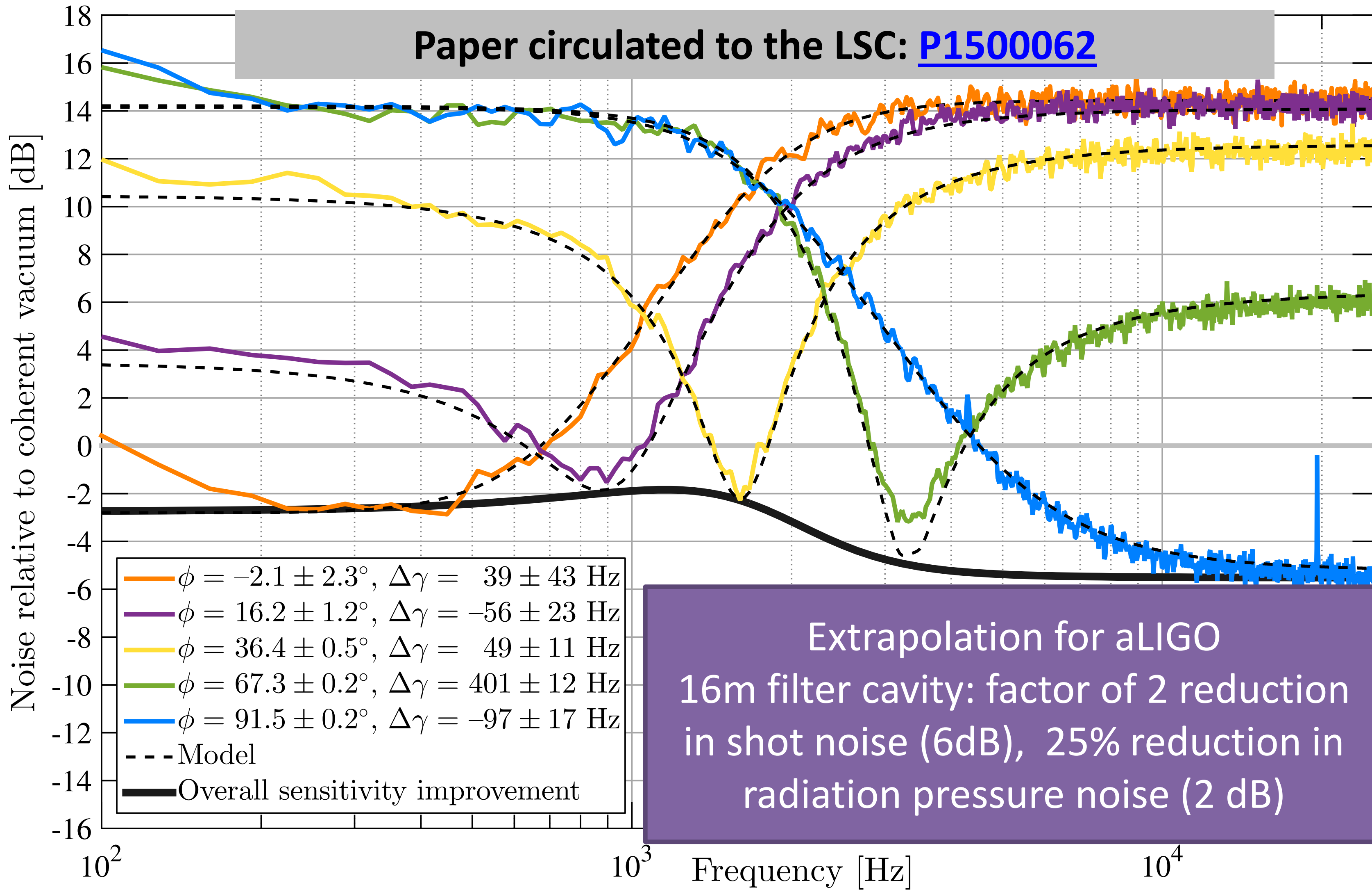




High finesse detuned **“filter cavity”** which rotates the squeezing angle as function of frequency

Frequency dependent squeezing with a 2 m filter cavity @ MIT

Paper circulated to the LSC: [P1500062]



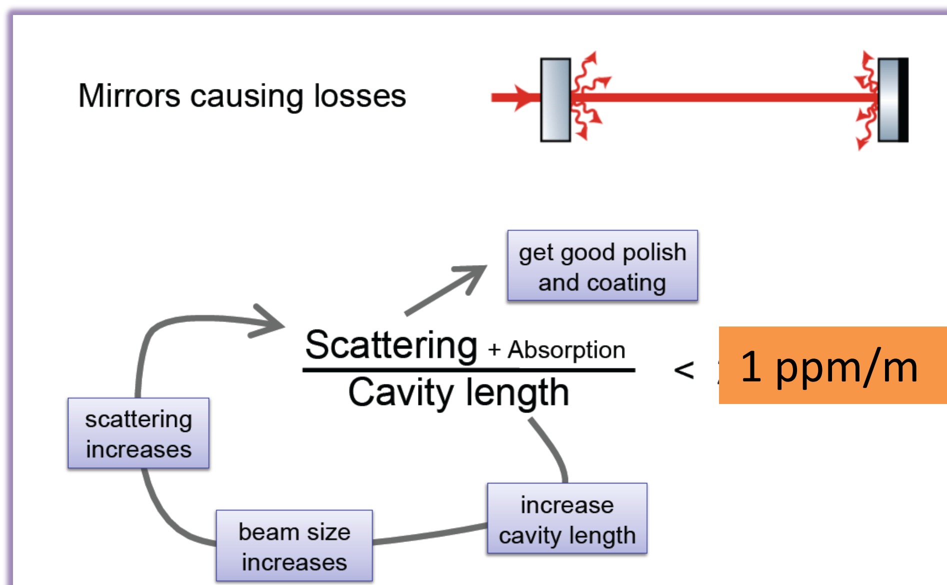
Extrapolation for aLIGO
16m filter cavity: factor of 2 reduction in shot noise (6dB), 25% reduction in radiation pressure noise (2 dB)

Long vs Short filter cavity (Nothing comes cheap)

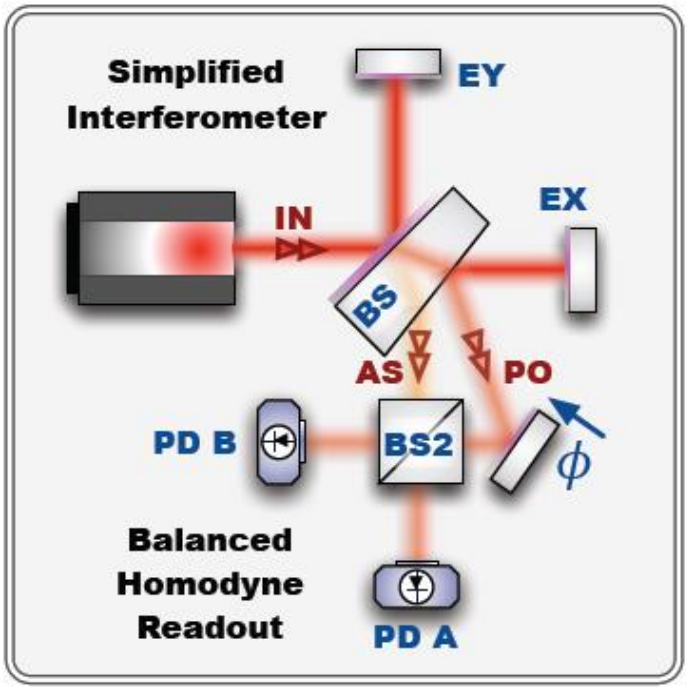
- Advanced LIGO needs a a filter cavity with 50 Hz bandwidth
- Losses in a filter cavity deteriorate, if too high, make the filter cavity useless…

$$\text{Total Loss } E = \frac{4\epsilon}{T} = \frac{\epsilon}{L}\frac{c}{\gamma_{filter}}, \qquad \gamma_{filter} = \frac{Tc}{4L}$$

Per-round-trip loss depends on the beam spot size (big beam size → higher scatter losses), which depends on L



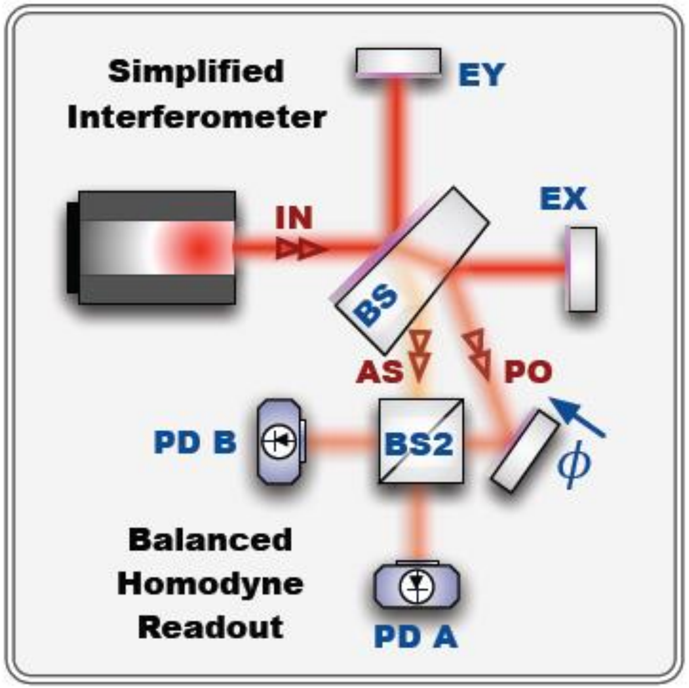
Balanced Homodyne Detection



Optics Express Vol. 22, Issue 4, pp. 4224-4234 (2014)

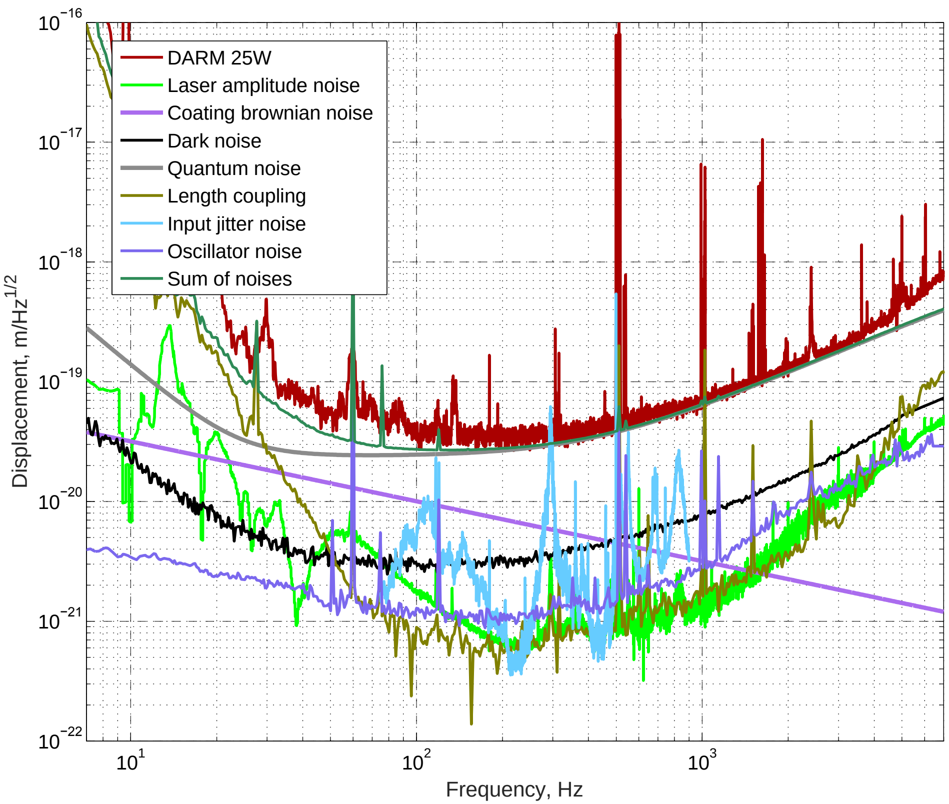
- ✧ Standard technique in table top squeezing experiments
- ✧ It has advantages compared to DC readout when applied to large scale interferometers
- ✧ Main advantage: remove static carrier field at the anti-symmetric port

Balanced Homodyne Detection

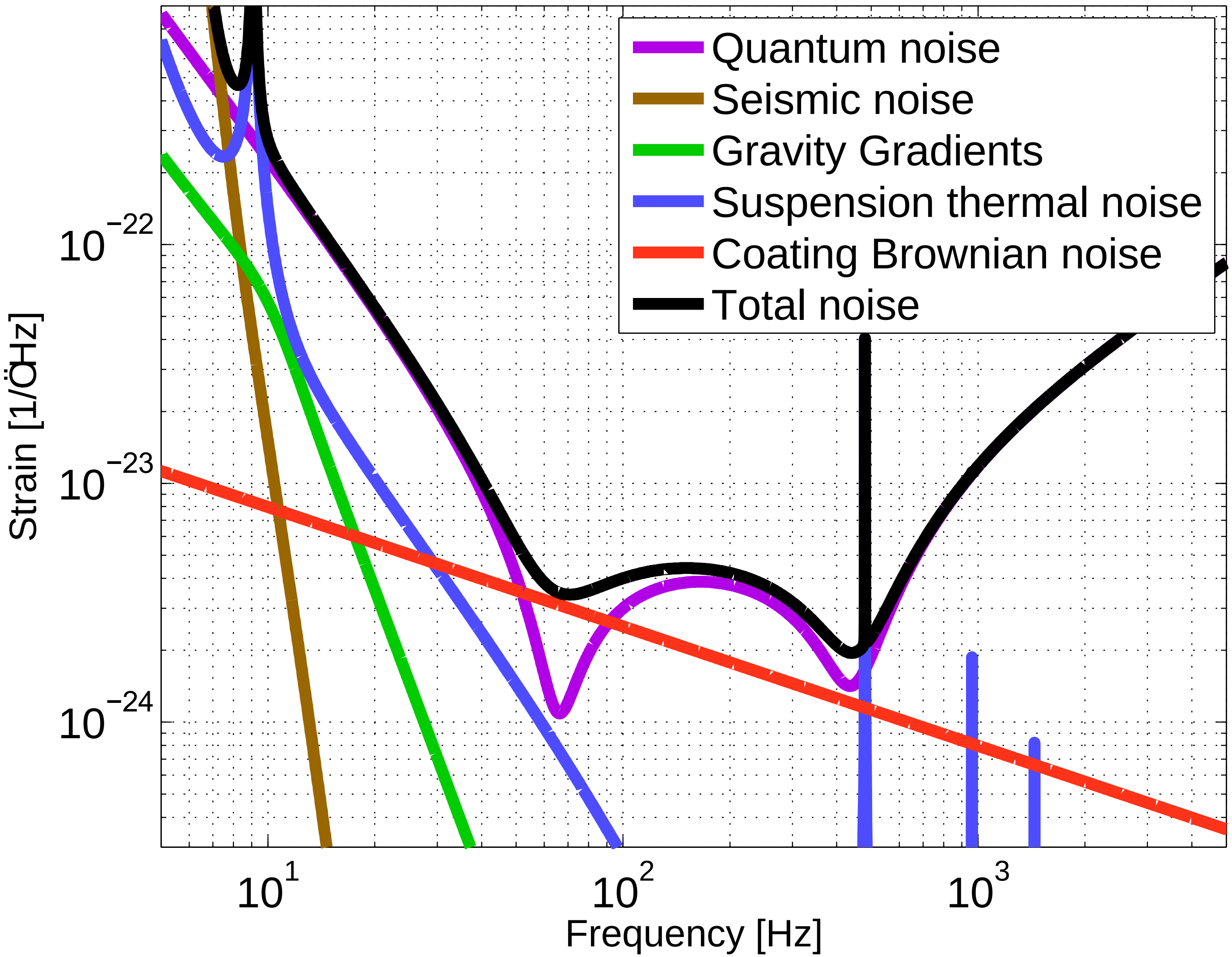


Optics Express Vol. 22, Issue 4, pp. 4224-4234 (2014)

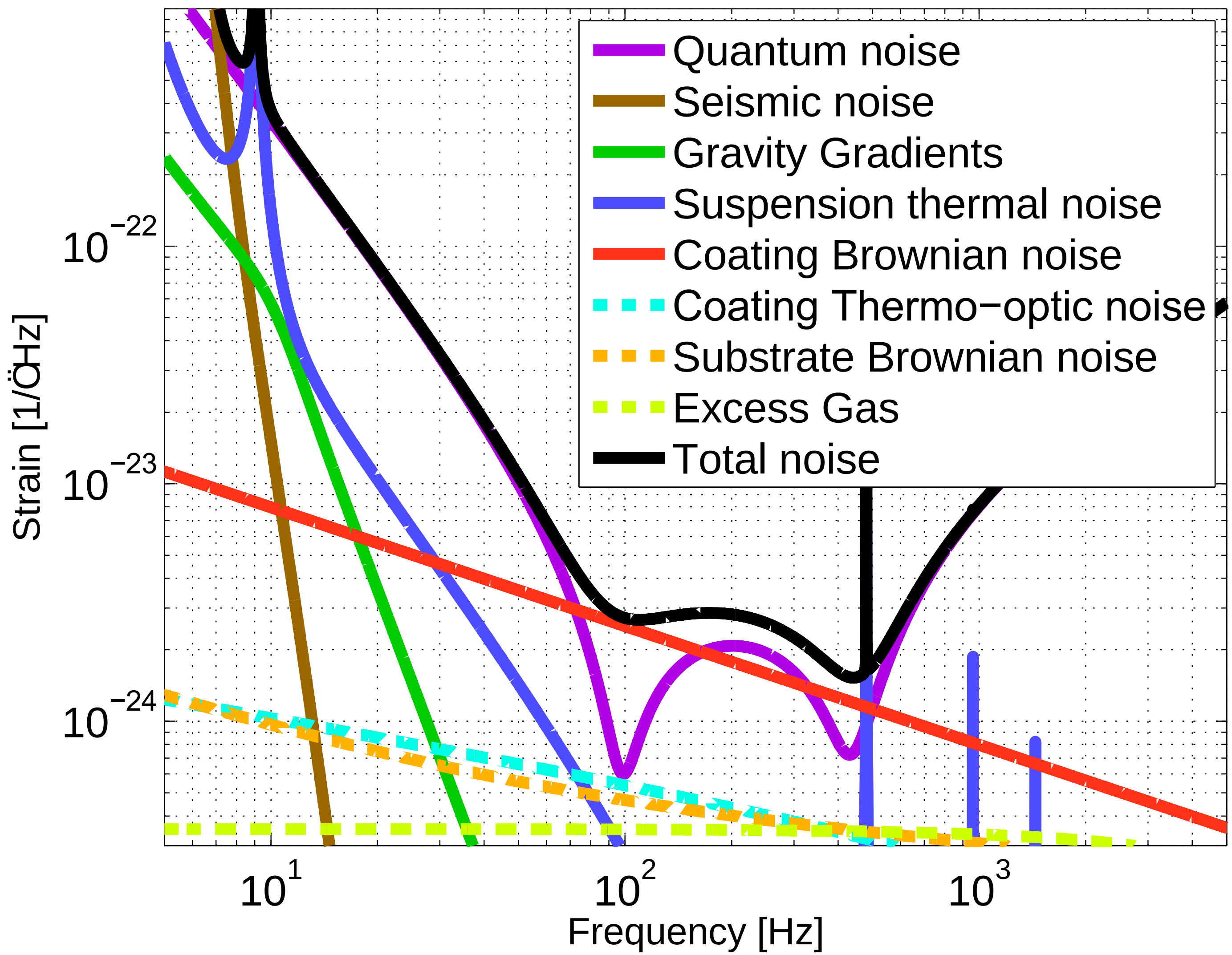
L1 current high frequency noise budget



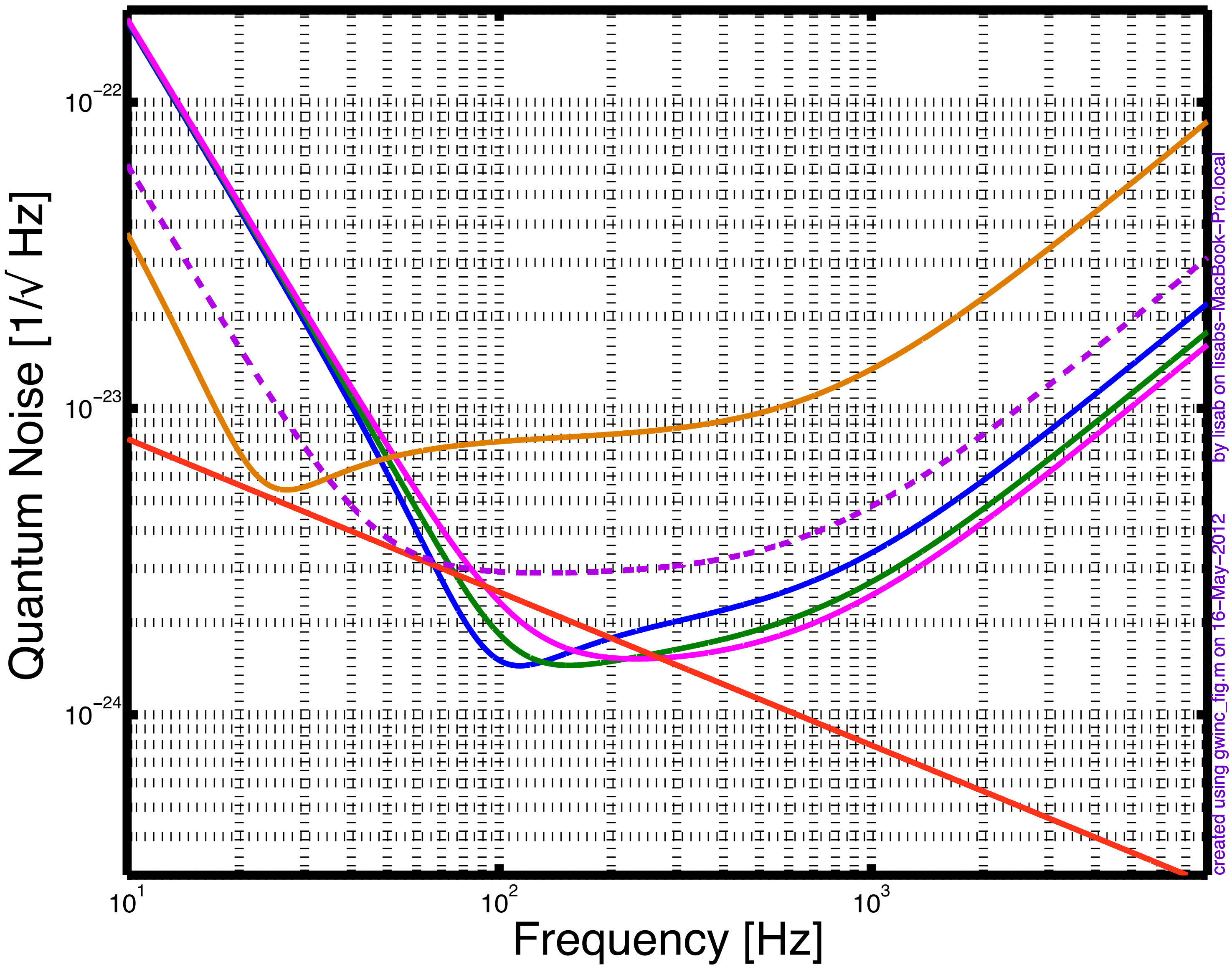
Signal Recycling Detuning with frequency independent squeezing



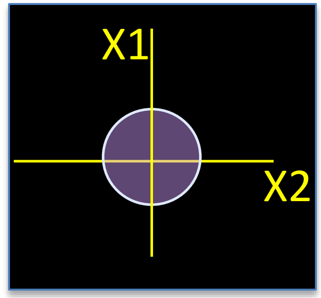
Signal Recycling Detuning with frequency independent squeezing, low loss

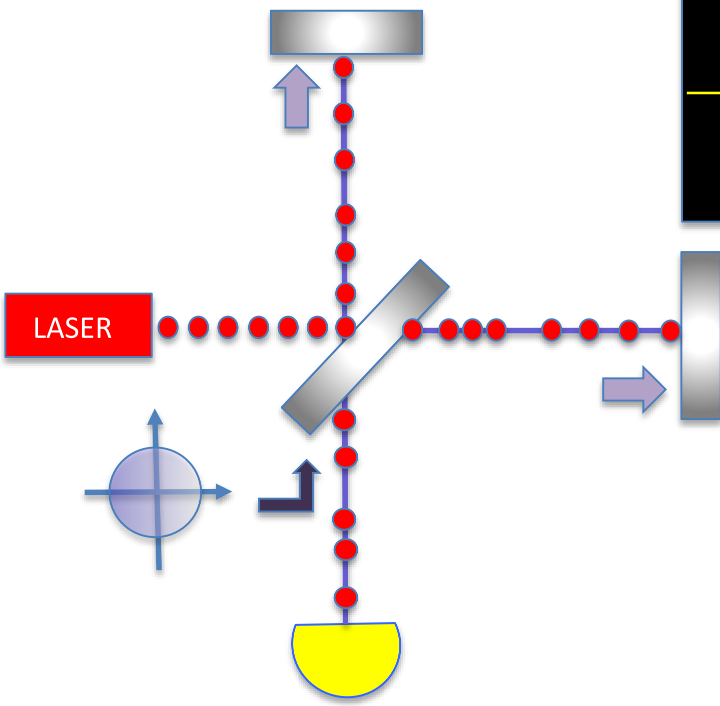


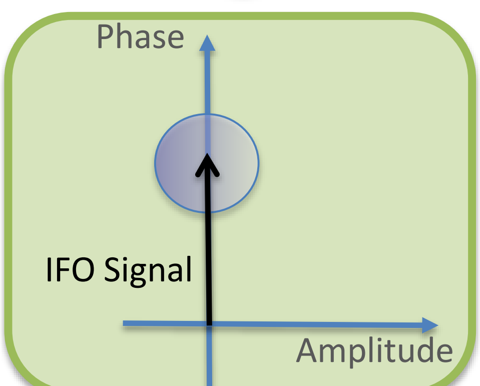
Quantum noise shaped by squeezed angle



Quantum Noise and Vacuum







- ✧ Quantization of the electro-magnetic field
- ✧ When average amplitude is zero, the variance remains
- ✧ Heisenberg uncertainty principle:

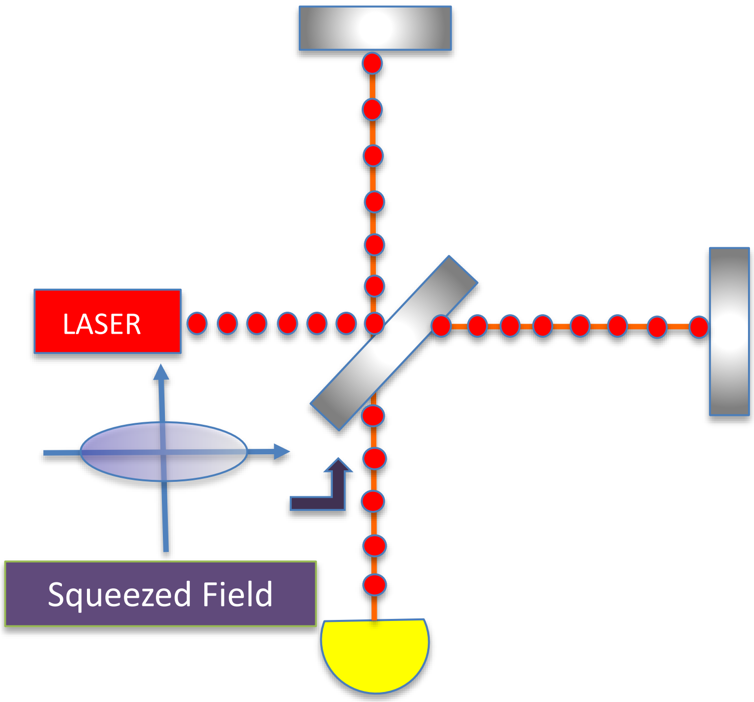
$$\Delta X_1 \, \Delta X_2 \geq 1$$

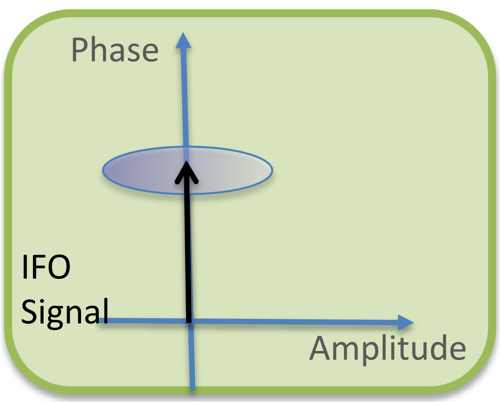
- ✧ Vacuum fluctuations are everywhere that classically there is no field….
- ✧ …like at the output port of your interferometer!

- ✧ Quantum noise is produced by vacuum fluctuations entering the open ports

- ✧ Vacuum fluctuations have equal uncertainty in phase and amplitude:
  - ❖ Phase: Shot-Noise (photon counting noise)
  - ❖ Amplitude: Radiation Pressure Noise (back-action)

Vacuum Getting Squeezed





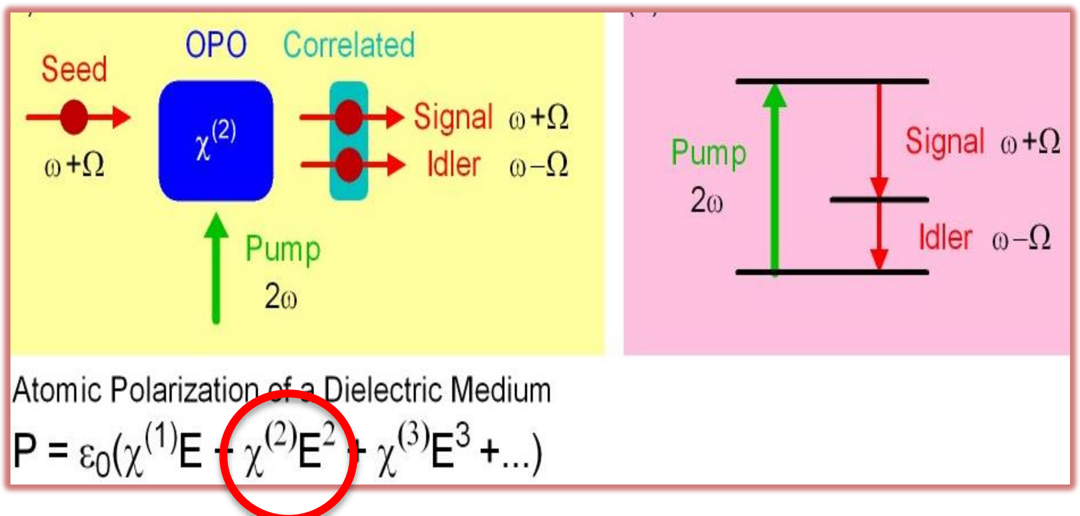
- Reduce quantum noise by injecting squeezed vacuum: less uncertainty in one of the two quadratures
- Heisenberg uncertainty principle: if the noise gets smaller in one quadrature, it gets bigger in the other one
- One can choose the relative orientation between the squeezed vacuum and the interferometer signal (squeeze angle)

C. M. Caves, Phys. Rev. Lett. 45, 75 (1980).
C. M. Caves, Quantum-mechanical noise in an interferometer. Phys. Rev. D 23, p. 1693 (1981).

How to make squeezed fields..

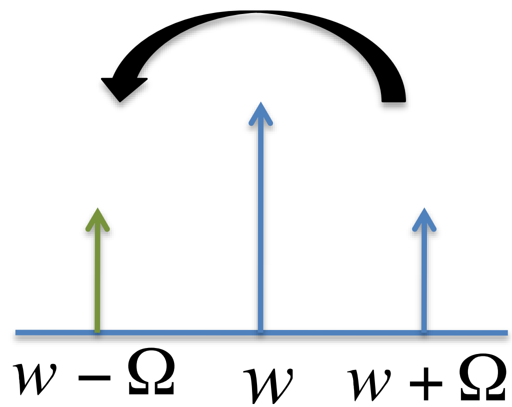
…. in theory

- ✧ Non linear medium with a strong second order polarization component
- ✧ Correlation of upper and lower quantum sidebands



$$P \propto (Ee^{-i2wt} + Ee^{-i(w+\Omega)t})^2$$

$$\Rightarrow Ee^{-i(w-\Omega)t}$$



The OPO makes a "copy" of the quantum sideband, and it correlates the sidebands

How to make squeezed fields..

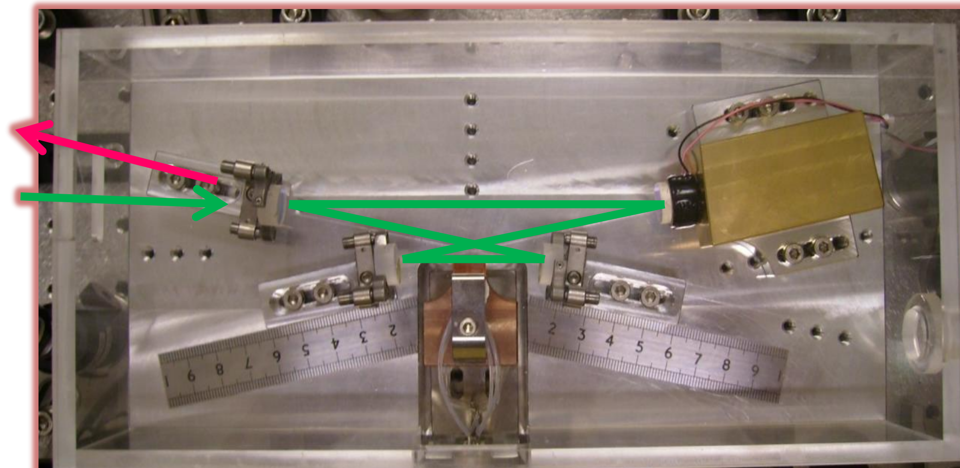
…. in practice

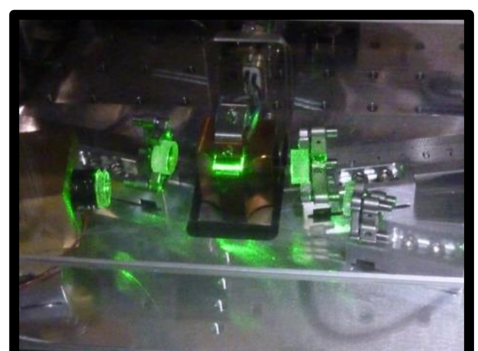
World-wide effort in the last 10 years to make squeezing in the audio-frequency band

✧ Lasers, mirrors, control loops,..

Courtesy of Alexander Khalaidovski (AEI)

The Squeezer of the GEO600 detector

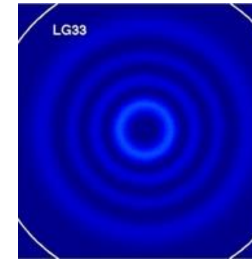




The Optical Parametric Oscillator
of the LIGO squeezer
(ANU design)

Extra slides

Improving Coating Brownian Noise - 4



- Other geometries:
  - Laguerre-Gaussian beams
    - Larger averaging area for same Gaussian beam size
      - (Phys. Rev. Lett. 105, 231102)
    - But difficult to maintain good contrast defect (degeneracy)
      - (Phys. Rev. D 84, 102001)
  - Folded arm cavities
    - Ampl TN improvement of x 0.5 possible
      - (Phys. Rev. D 88, 062004)
    - Requires significant suspension and optics changes

aLIGO Risk mitigation?

- What is the actual thermal noise?
  - No direct TN measurement of LIGO optics yet
  - Best measurement so far: *Metrologia* **52** 17 (2015)
    - But different type of coating
- Reducing Coating Thermal noise could become top priority…