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.

**Graphical Description:**
- **X-axis (Frequency [Hz]):** Shows the frequency range from $10^0$ to $10^4$ Hz.
- **Y-axis (Strain Sensitivity [1/√Hz]):** Displays the strain sensitivity ranging from $10^{-24}$ to $10^{-22}$ [1/√Hz].
- **Curves:**
  - **Purple Curve:** Represents Quantum Noise.
  - **Red Curve:** Represents Thermal Noise.
  - **Black Curve:** Represents Total Noise.

**Diagram Elements:**
- **GW Signal:** Arrows indicating the presence of GW signal at approximately 30 Hz.
- **Quantum Noise:** Represented by a curved line.
- **Interferometer:** Diagram showing the arrangement of a laser, squeezer, filter cavity, and detection system.

**Notes:**
- **RADIATION PRESSURE NOISE** and **SHOT NOISE** are labeled on the graph, indicating different noise contributions.
- **Quantum Noise** is noted to be approximately 30 Hz.
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 filter cavity with 50 Hz bandwidth
- Losses in a filter cavity deteriorate, if too high, make the filter cavity useless...

\[
\text{Total Loss} = \frac{4}{T} = \frac{c}{L_{\text{filter}}}, \quad \text{filter} = \frac{Tc}{4L}
\]

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

![Diagram showing scattering and absorption in a filter cavity](image)
Balanced Homodyne Detection

- Standard technique in tabletop squeezing experiments
- It has advantages compared to DC readout when applied to large scale interferometers
- Main advantage: remove static carrier field at the antisymmetric port
Balanced Homodyne Detection

Signal Recycling Detuning with frequency independent squeezing

- Quantum noise
- Seismic noise
- Gravity Gradients
- Suspension thermal noise
- Coating Brownian noise
- Total noise
Signal Recycling Detuning with frequency independent squeezing, low loss

- Quantum noise
- Seismic noise
- Gravity Gradients
- Suspension thermal noise
- Coating Brownian noise
- Coating Thermo-optic noise
- Substrate Brownian noise
- Excess Gas
- Total noise

Frequency [Hz]

Strain [1/ÖHz]
Quantum noise shaped by squeezed angle

Quantum Noise [1/√Hz]

Frequency [Hz]
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**)

How to make squeezed fields..

.... in theory

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

The OPO makes a “copy” of the quantum sideband, and it correlates the sidebands.

\[ P \propto (Ee^{-i2\omega t} + Ee^{-i(w+\Omega)t})^2 \]

\[ \Rightarrow Ee^{-i(w-\Omega)t} \]
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,..

The Squeezer of the GEO600 detector

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

Courtesy of Alexander Khalaidovski (AEI)
Extra slides
• 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**
LIGO 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…