Quantum Noise in Gravitational Wave Interferometers

Present status and future plans

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Quantum Noise

- Measurement process
  - Interaction of light with test masses
  - Counting signal photons with a PD
- Noise in measurement process
  - Poissonian statistics of force on test mass due to photons ➔ radiation pressure noise (RPN)
  - Poissonian statistics of counting the photons ➔ shot noise (SN)

Strain sensitivity limit due to quantum noise

- Shot Noise
  - Uncertainty in number of photons detected ⇨

$$h_{shot}(f) = \frac{1}{L}\sqrt{\frac{hc\lambda}{8F^2 P_{bs}}}\frac{1}{T_{ifo}(\tau_s, f)}$$

  - (Tunable) interferometer response ➔ T_{ifo} depends on light storage time of GW signal in the interferometer
- Radiation Pressure Noise
  - Photons impart momentum to cavity mirrors Fluctuations in the number of photons ⇨

$$h_{RP}(f) = \frac{2F}{ML}\sqrt{\frac{2hP_{bs}}{\pi^3 c\lambda}}\frac{T_{ifo}(\tau_s, f)}{f^2}$$

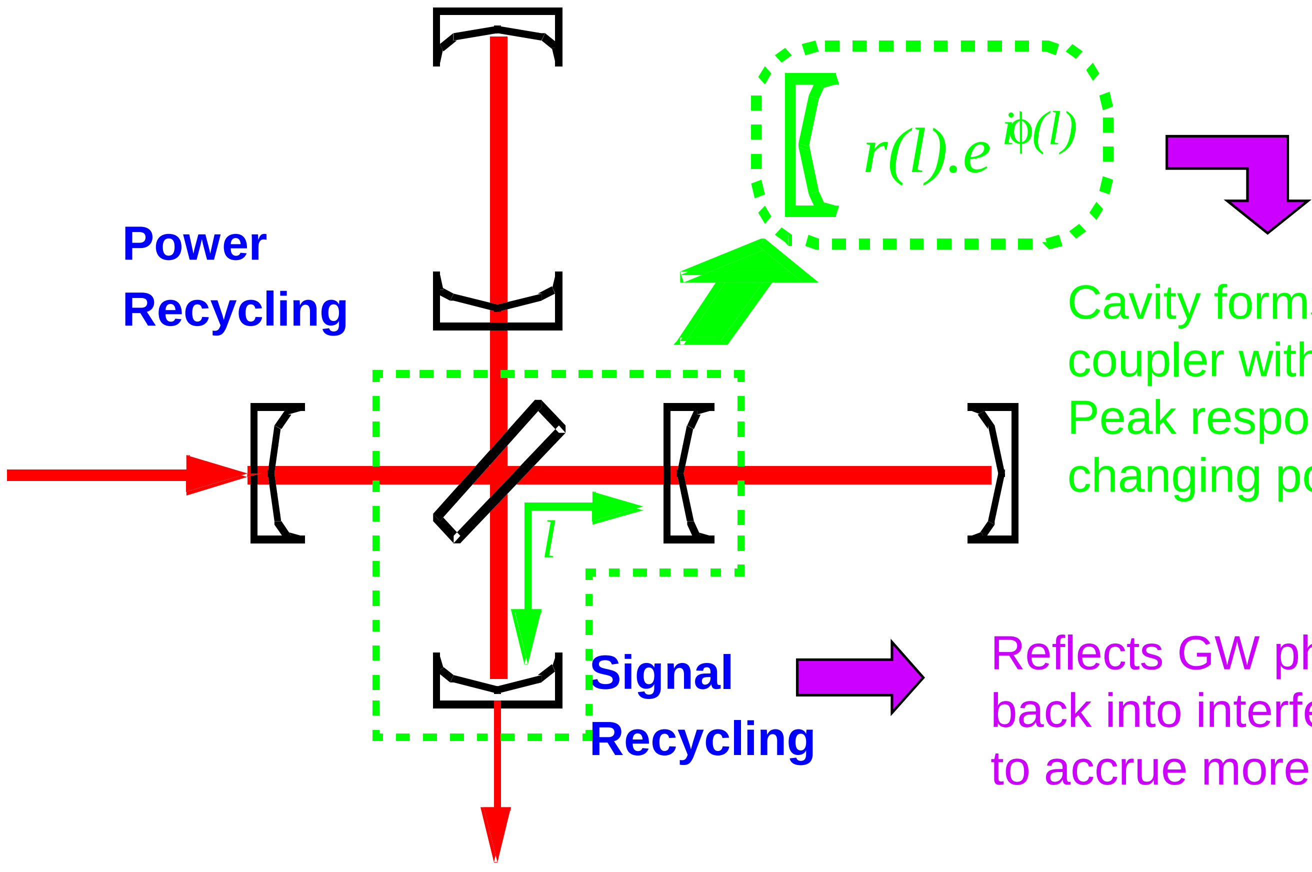
Standard Quantum Limit

- "Traditional" treatment (Caves, PRD 1980)
  - Shot noise and radiation pressure noise uncorrelated
  - Vacuum fluctuations entering output port of the beam splitter superpose $N^{1/2}$ fluctuations on the laser light
  - Optimal P_{bs} for a given T_{ifo}
- Standard quantum limit in GW detectors
  - Limit to TM position (strain) sensitivity for that optimal power for a given T_{ifo} and frequency
  - Minimize total quantum noise (quadrature sum of SN and RPN) for a given frequency and power

Heisenberg and QND

- Heisenberg ➔
  - Measure position of a particle very precisely
  - Its momentum very uncertain
  - Measurement of its position at a later time uncertain since $|x(t)\rangle = \exp(-i\frac{p^2}{2m\hbar}t)|x(0)\rangle$
- Quantum non-demolition (QND)
  - Evade measurement back-action by measuring of an observable that does not effect a later measurement
  - Good QND variables (observables)
    - Momentum of a free particle since [p, H] = 0
    - Quadrature components of an EM field

Signal Tuned Interferometer (LIGO II)



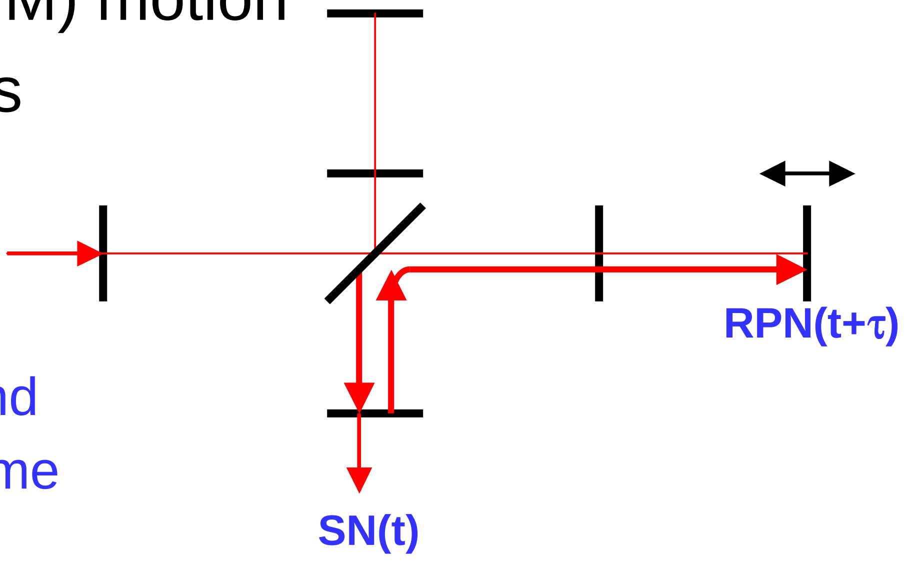
Cavity forms compound output coupler with complex reflectivity. Peak response tuned by changing position of SRM

Reflects GW photons back into interferometer to accrue more phase

Signal recycling mirror → quantum correlations

- Shot noise and radiation pressure (back action) noise are correlated (Buonanno and Chen, PRD 2001)
  - Optical field (which was carrying mirror displacement information) returns to the arm cavity
  - Radiation pressure (back action) force depends on history of test mass (TM) motion
  - Dynamical correlations

Part of the light leaks out the SRM and contributes to the shot noise BUT the (correlated) part reflected from the SRM returns to the TM and contributes to the RPN at a later time



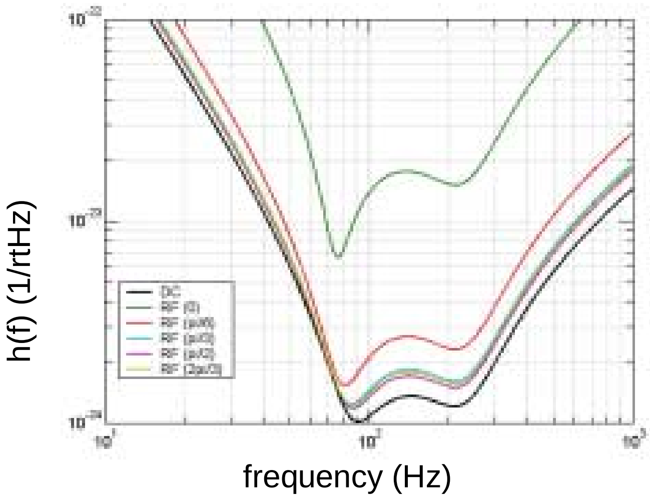
New quantum limits

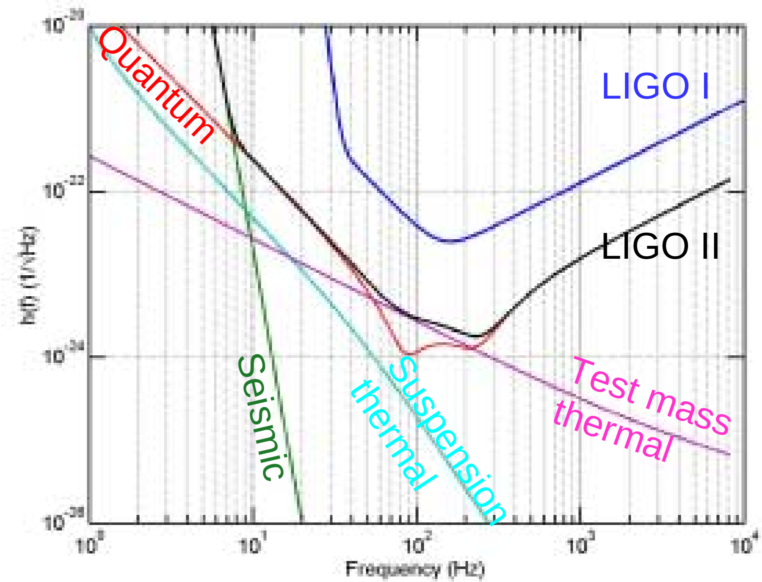
- Quantum correlations ➔
  - SQL no longer meaningful
  - Optomechanical resonance (“optical spring”)
  - Noise cancellations possible
- Quantization of TM position not important
  (Pace, et. al, 1993 and Braginsky, et. al, 2001)
  - GW detector measures position *changes* due to classical forces acting on TM
  - No information on quantized TM position extracted

Quantum Manipulation: LIGO II

- "Control" the quantum noise
- Many knobs to turn: Optimize ifo response with
  - Choice of homodyne (DC) vs. heterodyne (RF) readout
  - RSE detuning ➔ reject noise one of the SB frequencies
  - Non-classical light???

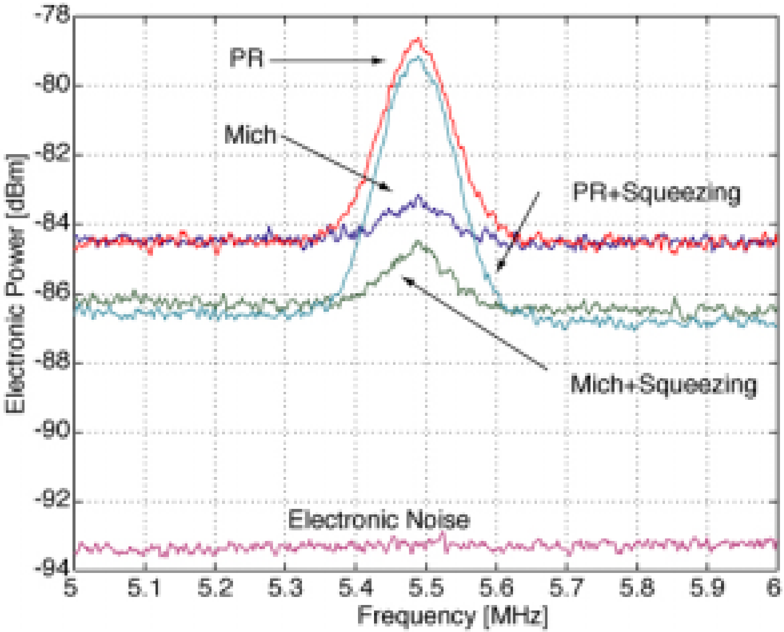
(Useful only in bands where ifo sensitivity is limited by QN ➔ trade-offs)





Quantum manipulation: Avenues for LIGO II+

- Non-classical light
  - Increased squeeze efficiency
    - Non-linear susceptibilities
    - High pump powers
    - Internal losses
    - Low (GW) frequencies
- QND readouts
  - Manipulation of sign of SN-RPN correlation terms
  - Manipulation of signal vs. noise quadratures (KLMTV, 2000)
  - Squeezed vacuum into output port



ANU, 2002

Experimental Program

- Set up a quantum optics lab at MIT
- Goals
  - Explore QND techniques for below QNL readouts of the GW signal (LIGO II+)
  - Develop techniques for efficient generation of non-classical states of light
- Trajectory → table-top scale (suspended optics?) experiments
  - Import OPA squeezer (device + expert, ANU)
  - Use in-house low loss optics, low noise photodetection capabilities to test open questions in below QNL interferometric readouts

LIGO

Programmatics: People

- People involved (drafted, conscripted)
  - 1 to 1.5 post-docs
    - Ottaway and/or TBD
  - 2 grad students
    - Goda, Betzwieser and/or TBD
  - Collaborators, advisors, sages
    - McClelland, Lam, Bachor (ANU)
    - Whitcomb (Caltech)
    - Fritschel, Weiss, Zucker, Shoemaker (MIT)
  - Visitors
    - McKenzie (ANU). Sept. to Dec. 2002
    - Buonanno (Caltech). TBD.

Programmatics: $$

- MIT seed funds
  - Available
- NSF
  - Proposal in preparation

Programmatics: where?

- Optics labs (NW17-069)
- LASTI (?)
  - Possibly share/borrow/moonlight in seismically and acoustically quiet environment for QND tests involving suspended optics
  - Share/borrow higher-power, shot-noise-limited, pre-frequency-stabilized laser

Programmatics: when?

- Summer, 2002
  - ANU visit, gain experience with OPA squeezer
- Fall, 2002 – Summer, 2003
  - Build OPA squeezer and table-top interferometer (configuration TBD)
- Beyond 2003
  - Attack open questions in the field subject to personnel, interests,funding and recent developments (and LIGO I status)