Quantum Non-Demolition in Advanced Gravitational Wave Interferometers

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People Involved

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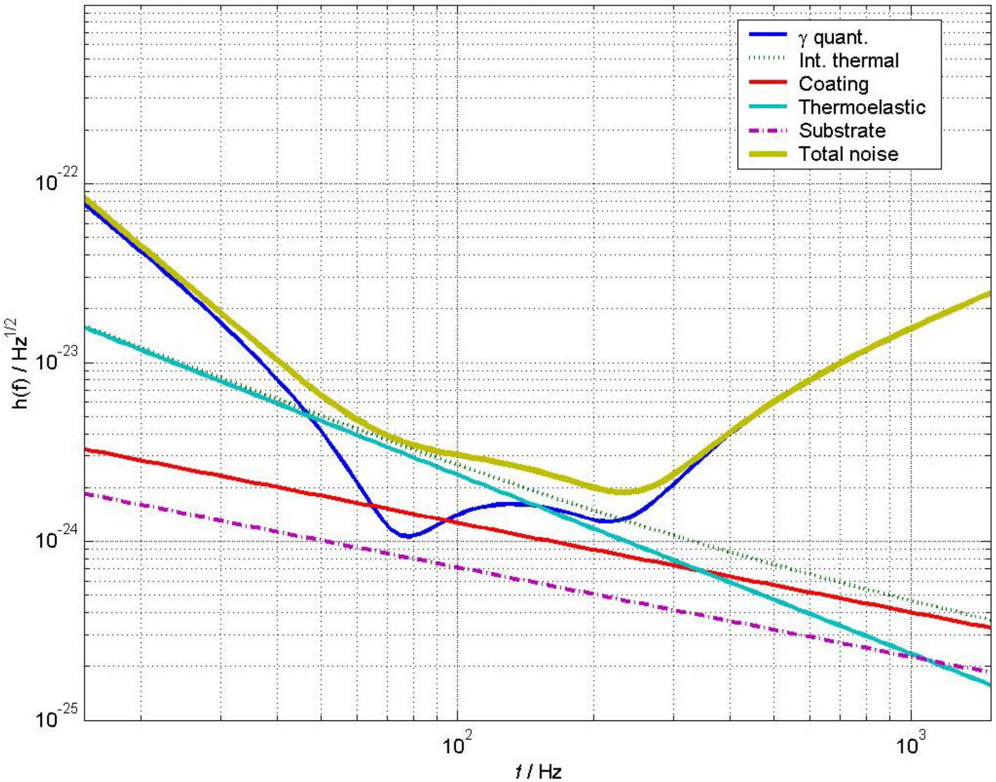
Overview of Talk

- Advanced LIGO and the implications of quantum noise
- The Standard Quantum Limit (SQL)
- A discussion of quantum noise
- Ideas for beating quantum noise
- Current limits on QND performance
- Ideas and experiments to explore and beat the standard quantum limit with bench top experiments
- The potential gain for Advanced LIGO

Advanced LIGO Sensitivity

- Predicted sensitivity for Sapphire interferometer
- Predominantly limited by thermoelastic noise and quantum noise
- Assumes a solution to coating thermal noise is found



- Low frequency optical noise => Radiation pressure noise
- High frequency optical noise => Shot Noise

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

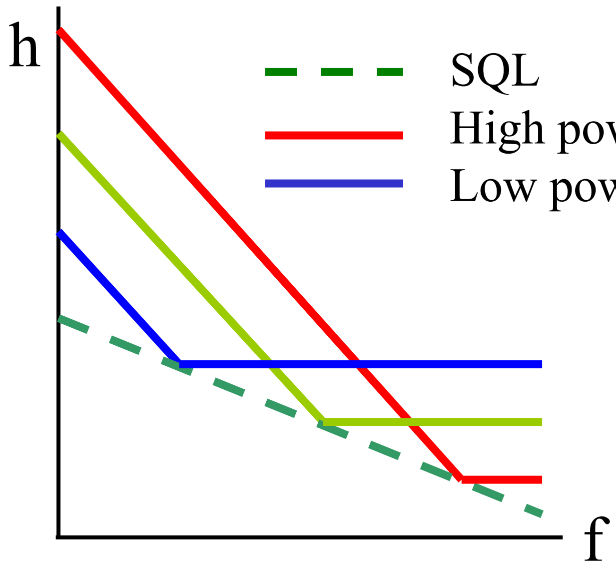
- Shot Noise
  - Uncertainty in number of photons detected ⇨

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

  - (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 (SQL)



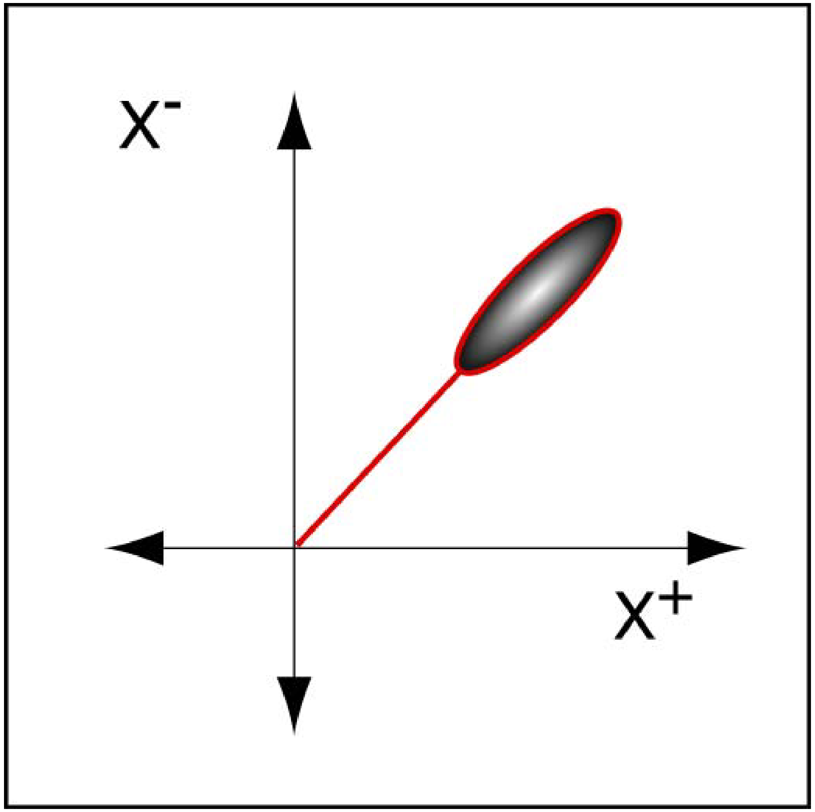
$$h_{SQL} = \frac{1}{L}\sqrt{\frac{h}{2M\pi^{3/2}}}\frac{T_{ifo}(\tau_s, f)}{f}$$

$$P_{bs} = \frac{c\lambda\pi^{3/2}}{8F^2}\frac{f^2}{T_{ifo}(\tau_s, f)^2}$$

- Minimum noise achieved when $h_{shot}=h_{rp}$ for a given frequency f
- Assumes that radiation pressure noise and shot noise add it quadrature
- No correlations and hence no noise cancellations considered

‘Ball on stick’ representation

- Analogous to the phasor diagram
- Stick → dc term
- Ball → fluctuations
- Common states
  - Coherent state
  - Vacuum state
  - Amplitude squeezed state
  - Phase squeezed state



How to increase sensitivity beyond Advanced LIGO ??

Two options for increasing the sensitivity:

Classical approach: Get a bigger hammer !!

- Increase the mass of the test mass and increase the laser power

QND approach:

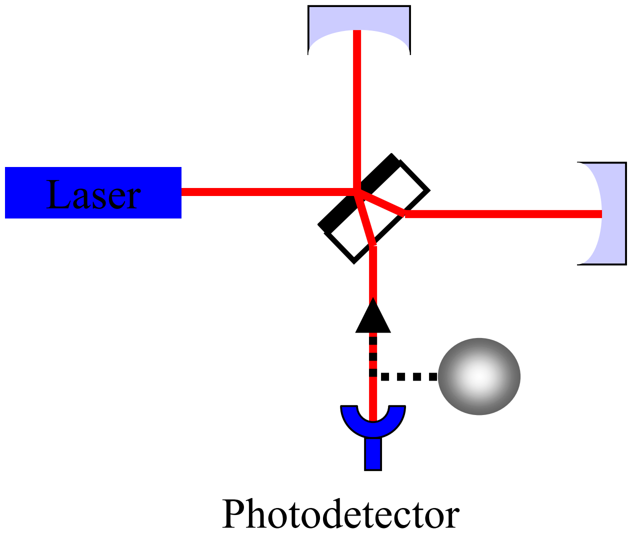
- Plug open output port of the beam splitter with squeezed vacuum

=> Improved high frequency noise without power increase

- Cancel out the radiation pressure fluctuations effects on TM
- Combination of both

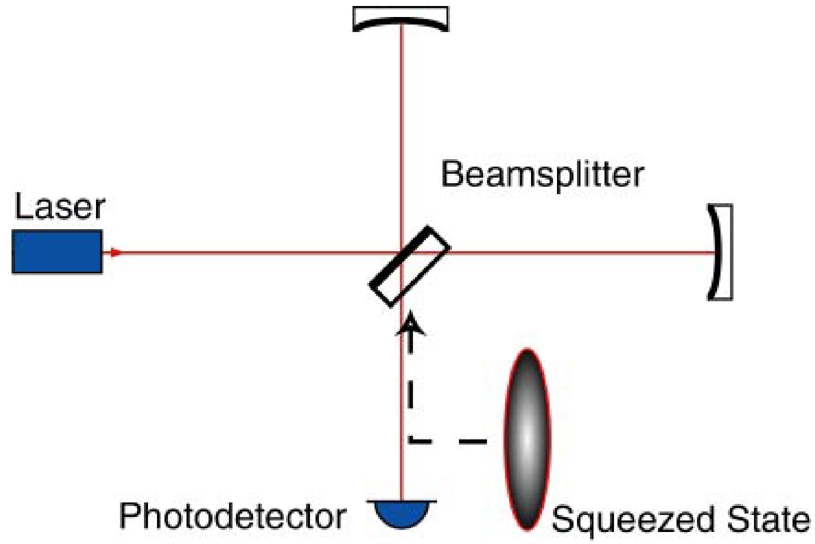
Vacuum State in a Michelson

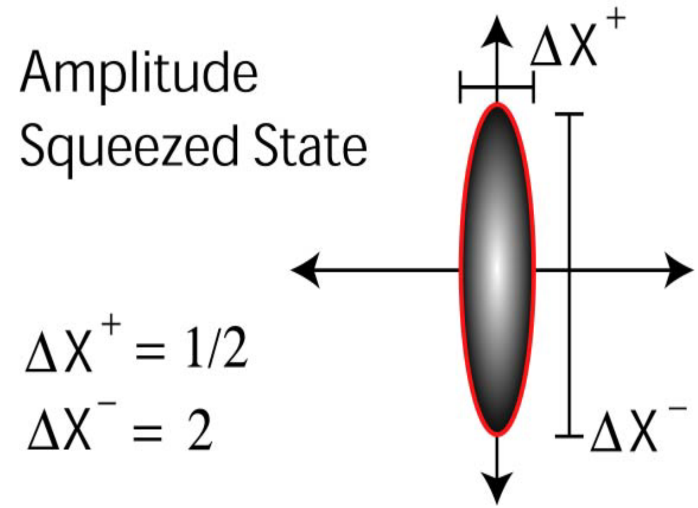
- Michelson on dark fringe ➔ laser contributes only correlated noise
- GW signal from anti-correlated effect ➔ phase quadrature
- Vacuum noise couples in at the beamsplitter
  - Phase quadrature fluctuations: **Shot Noise**
  - Amplitude quadrature fluctuations: **Radiation Pressure Noise**



Squeezed State in a Michelson

- Inject squeezed state into the dark port of Michelson to replace vacuum
- Amplitude squeezed state oriented to reduce noise in the signal (phase) quadrature
- GW signal in the phase quadrature



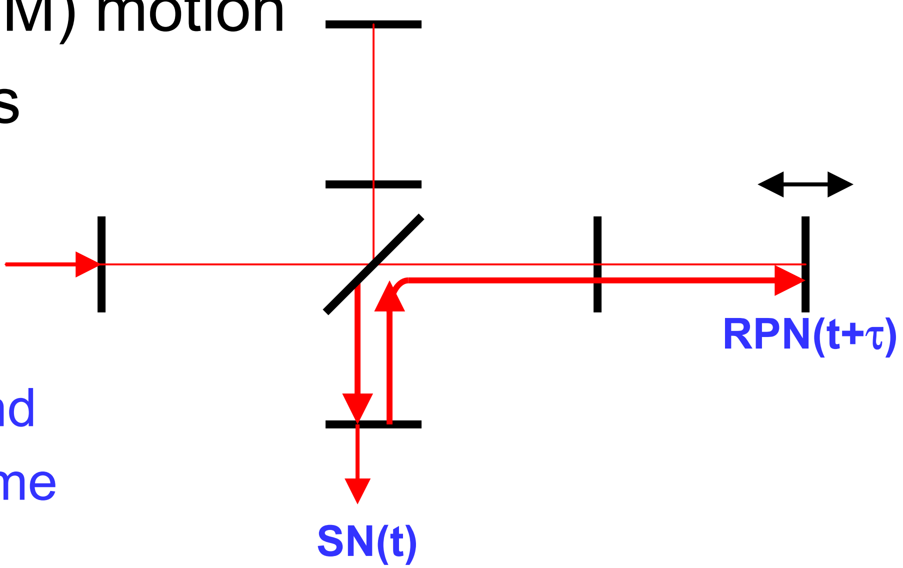


McKenzie

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

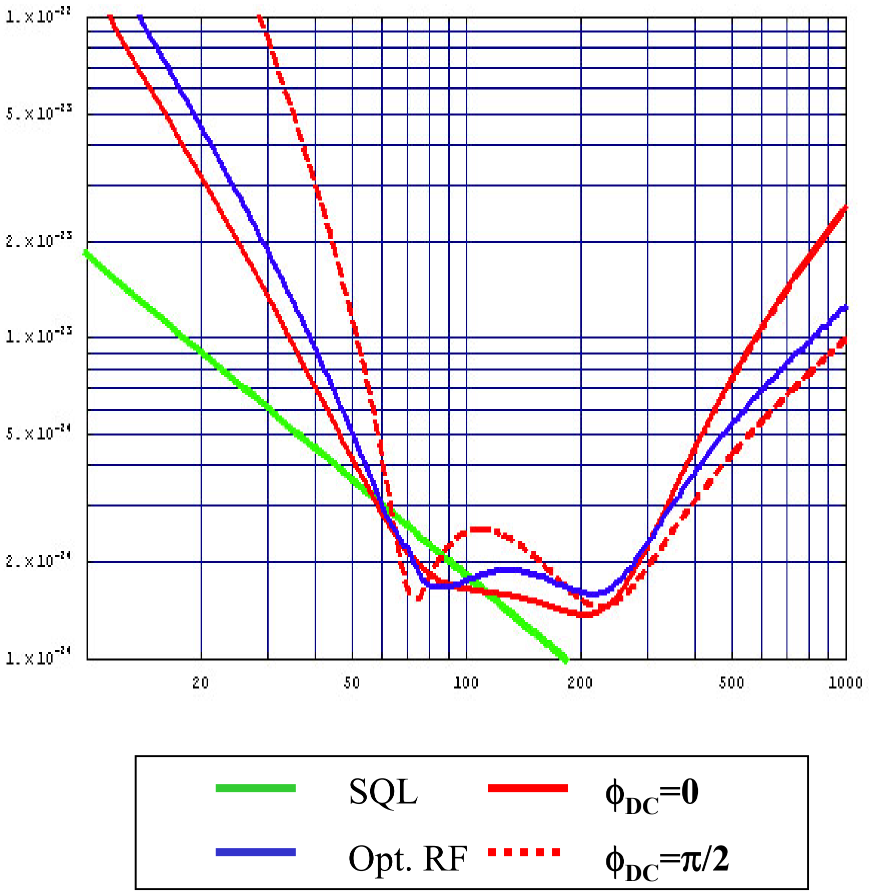


New quantum limits

- Quantum correlations ➔
  - SQL applies to free particles
  - Test masses are connected by radiation pressure
  - 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

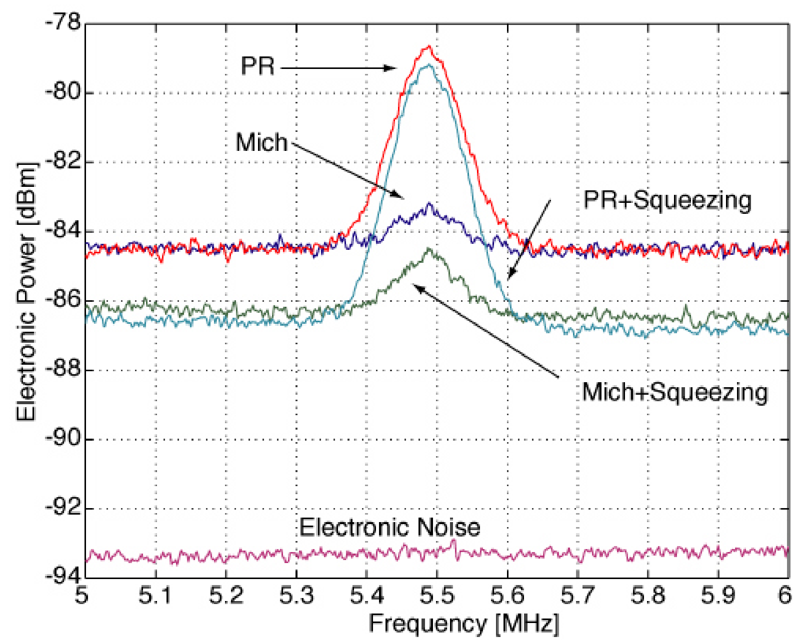
Quantum Manipulation: AdLIGO as an example

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



Quantum manipulation: Avenues for AdLIGO+

- Squeezed 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

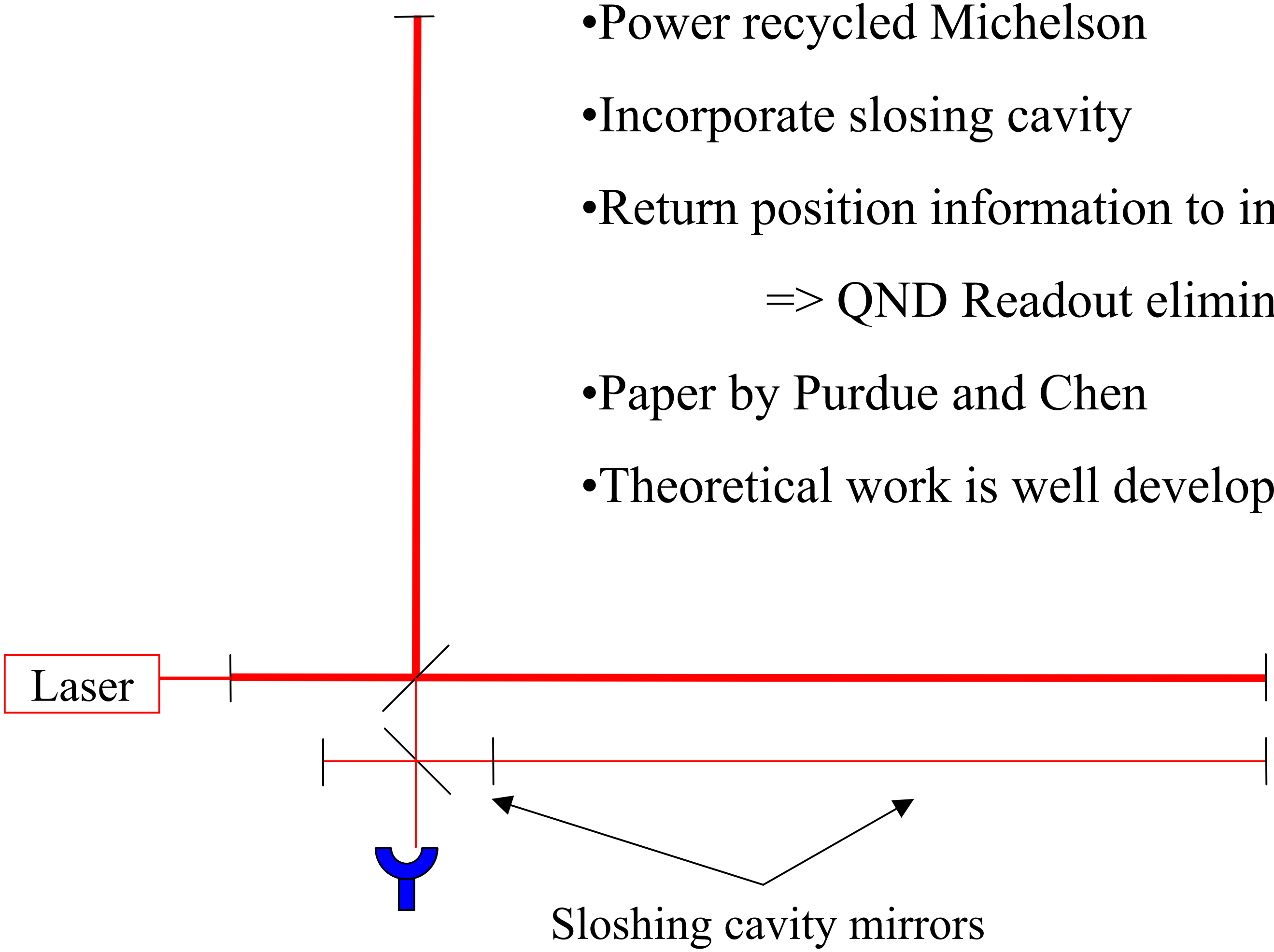


ANU, 2002

Speed Meter Example

- Power recycled Michelson
- Incorporate slosing cavity
- Return position information to interferometer

  => QND Readout eliminates back action
- Paper by Purdue and Chen
- Theoretical work is well developed



Squeezed source applications:

- Advance LIGO
  - Signal tuned
  - Quantum noise limited
  - SEM → SN and RPN correlated → QND
  - Squeezed input
  - Evaluation in the presence of other noise limits and technical noise
- AdLIGO +
  - Speedmeters
  - White light interferometers
  - All reflective interferometers
  - Ponderomotive squeezing

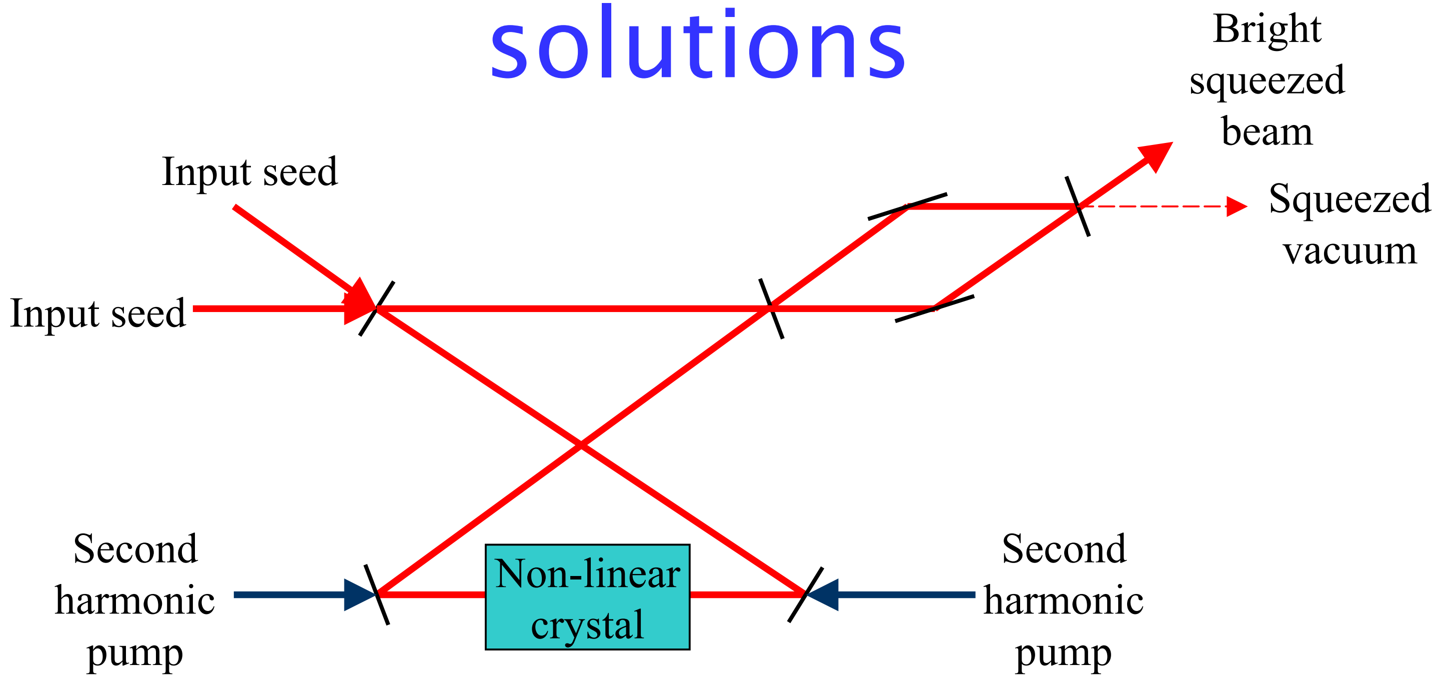
Current issues in Squeezing

- •Current squeezing is limited to around 7dB
- •Current squeezing is limited to above the near MHz region
- •Squeezing required at the level of 10 dB at100 Hz
- •How ????

10 dB Possible Solutions

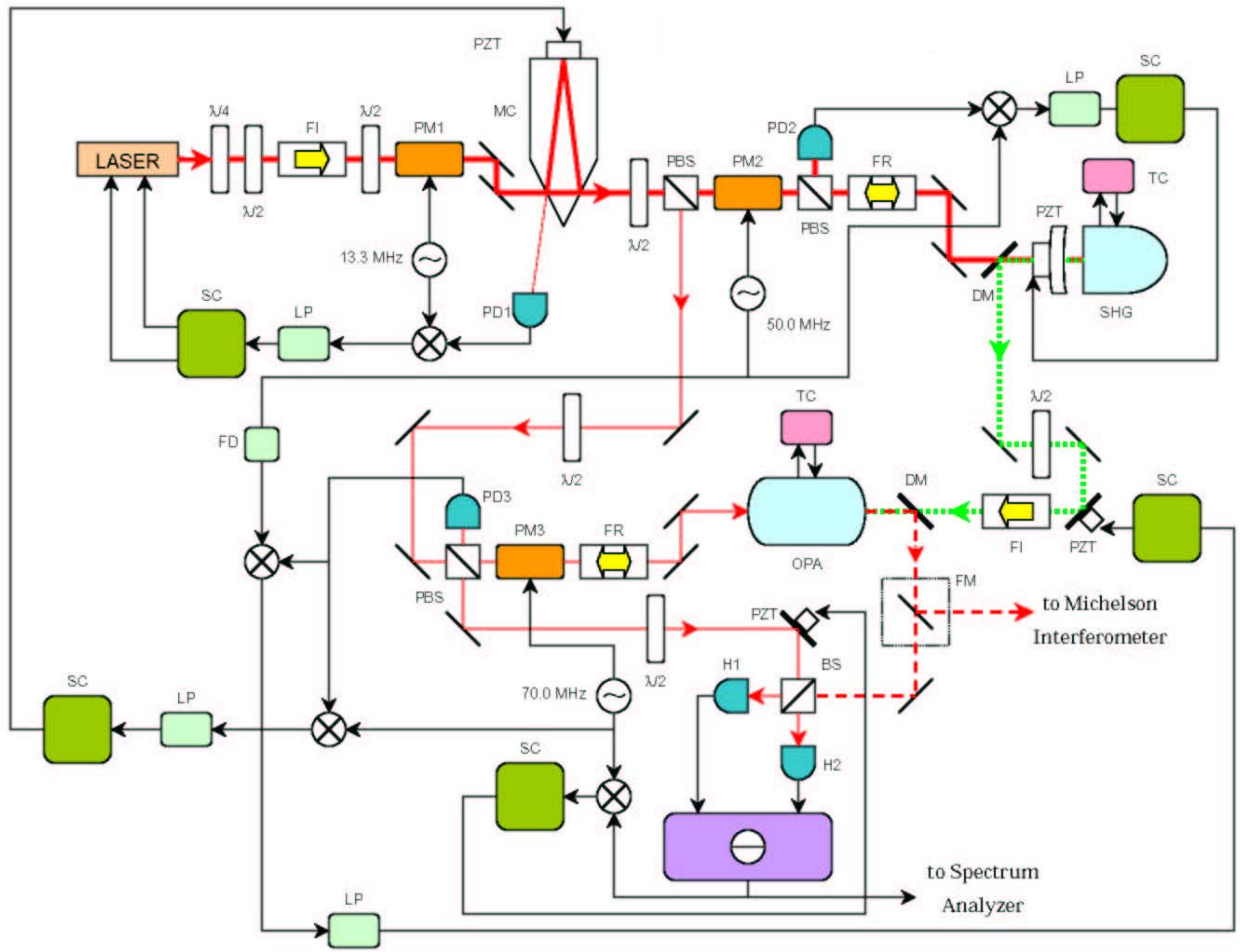
- Internal losses and interferometer injection losses
- Larger κ^2 and κ^3 non-linearities
- Increased pump power
- Improved photo-detection efficiency (different wavelength)
- 10 dB Consortium to obtain improved crystals

Low frequency squeezing solutions



- Uses two squeezers to cancel the technical noise on the seeds – shown to produce squeezing to 200 kHz by Bowen *et al*.
- Common OPO to cancel OPO technical noise
- Proposed by Bowen *et al*.

Proposed Initial MIT Squeezer



LASER: Nd:YAG 1064nm
SC: servo controller
LP: low-pass filter
PD: photodetector
FM: flipper mirror

PM: phase modulator
FI: faraday isolator
HP: high-pass filter
DM: dichroic mirror
PZT: piezoelectric transducer

OPA: optical parametric amplifier
FR: faraday rotator
λ/4: quarter-wave plate
BS: 50/50 beamsplitter
PBS: polarizing beamsplitter

SHG: second harmonic generator
H: homodyne photodetector
λ/2: half-wave plate
FD: frequency doubler
TC: temperature controller

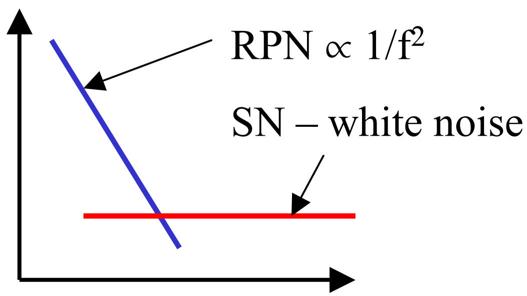
- Obtained crystals from ANU
- Uses control electronics that we already have
- Gain experience with squeezers
- Utilize existing LASTI Infrastructure
- Including 10 W PSL

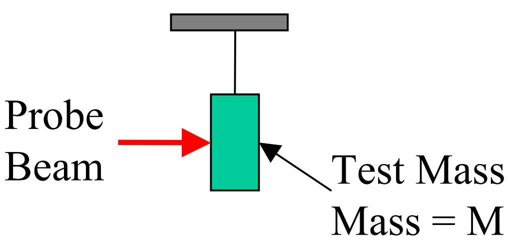
LIGO

Bench top sub-SQL experiments

- Remember:

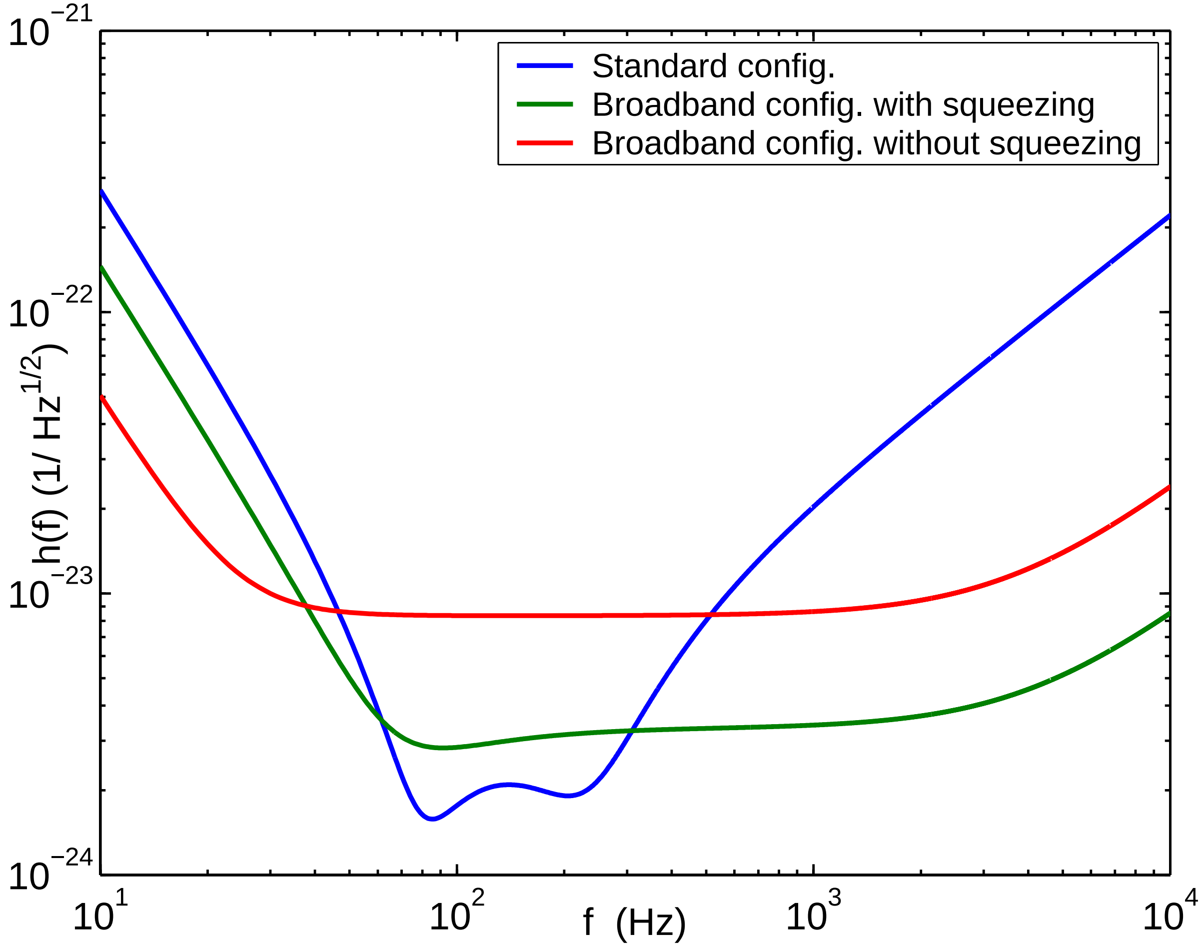
$$x_{shot}(f) = \frac{1}{L}\sqrt{\frac{hc\lambda}{8F^2 P_{bs}}}\frac{1}{T_{ifo}(\tau_s, f)} \qquad x_{RP}(f) = \frac{2F}{ML}\sqrt{\frac{2hP_{bs}}{\pi^3 c\lambda}}\frac{T_{ifo}(\tau_s, f)}{f^2}$$





- Increase SQL noise so it is larger than other noise sources at some frequency
- Increasing power decreases shot noise whilst increasing RP noise
- Make mirrors very light increases radiation pressure noise, shot noise is unchanged
- Light mirrors increases suspension thermal noise, potential solution, very low frequency pendulum
- Another knob, choice of T_{ifo}

If we succeed…



Calculation done by Corbitt using derivation by Buonanno and Chen