# Research Challenges as GW Detectors Enter the Quantum Regime

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# Outline

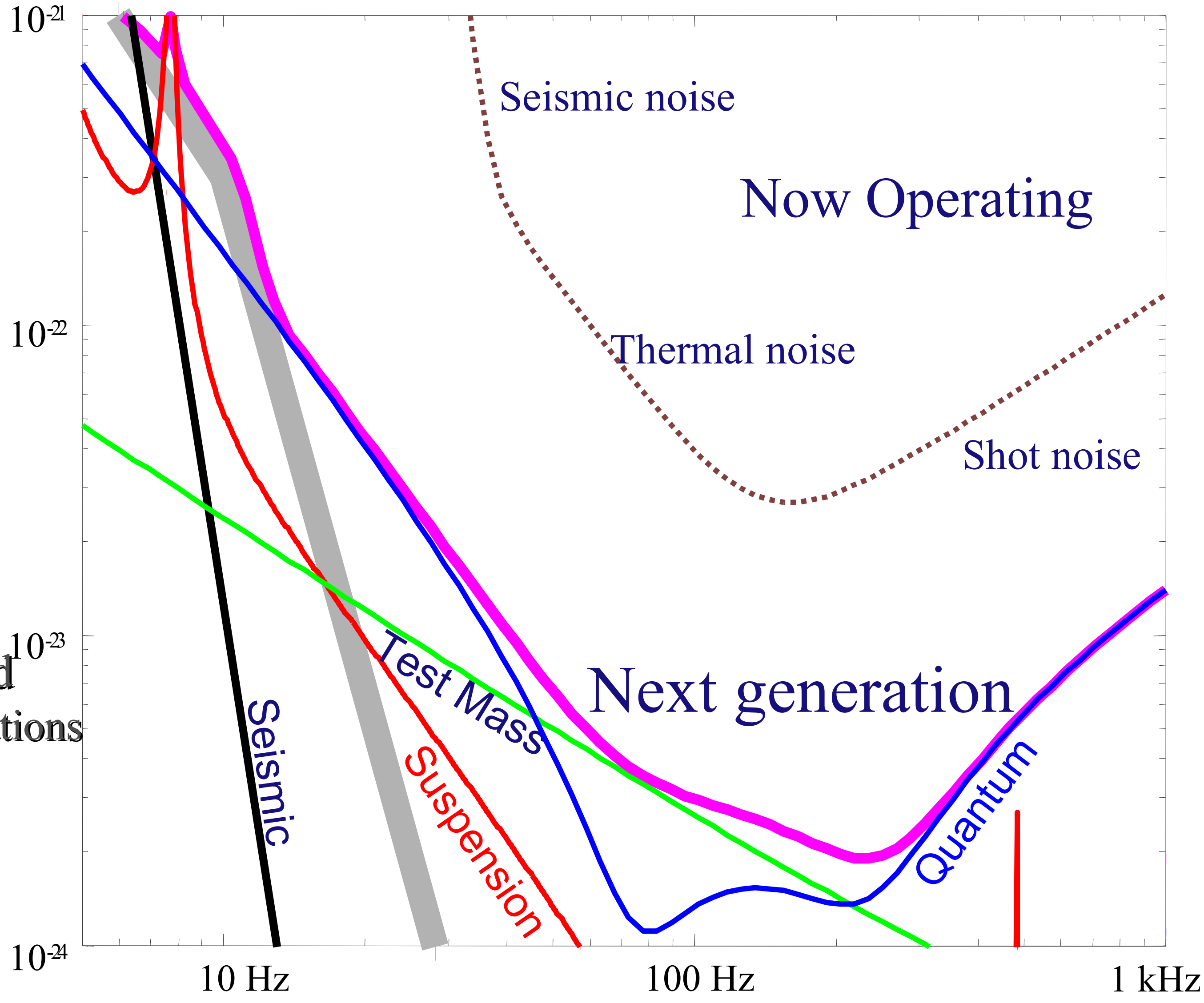
- Background
  - Engineers Approach to GW
  - Time reversal invariance
- Free mass approach
  - Good approx for initial detectors, not valid for advanced detectors
- Free mass SQL vs resonant Mass SQL
- Advanced GW detectors
- Introduction to the new physics of optical springs and quantum measurement

# Current Status of GW Detectors

- Sensitivity ~ 100 quanta
- Most sensitive* instruments ever created.
  - (*smallest amount of detected energy)
- Advanced detectors plan to reach ~ hf where f ~100Hz.
- We are already in the quantum regime.

# Improving Detector Sensitivity ΔL / L

- 
    Many stages
- Suspension thermal noise
    **Very low loss pendulums**
- Test mass thermal noise
    **Very low acoustic loss materials (sapphire, silicon or fused silica)**
- Newtonian background
    Local Gravity fluctuations
- Quantum noise
    **-uncertainty principle**
    **-high optical power**



**Factor of 10 improvement in sensitivity**

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# History of GW

- Gravitational waves proved to exist by the "sticky beads" thought experiment.
  - Bondi, Pirani, Feynman, Isaacson
- Gravitational waves in General Relativity deposit energy and hence must be real.

# Weber’s Approach

- Time Reversal Invariance
  - Symmetry between a detector and transmitter
  - Detector efficiency measured by its relaxation time for GW emission (quadrupole formula)
  - Resonant bar relaxation time ~$10^{30}$ years
  - Detector: measure the GW work done on massive resonator as a change in its acoustic state.
  - Typical engineering approach

# Cryogenic Resonant Bars

- Huge improvement over Weber’s bars by using cryogenic techniques.
- 1975 shock: Braginsky: sensitivity proposed was below the limit to measurement set by the uncertainty principle.
- Concept of the Quantum Limit and new ideas about quantum squeezing, quantum non-demolition
- Beating the Standard Quantum Limit shown to be feasible
- Bar detectors failed to sufficiently approach the SQL.

# Impedance Matching

- Electrical engineers are familiar with impedance matching.
- Impedance: force/velocity, voltage/current
- Impedance mismatches (transitions in impedance) across boundaries or between systems reduce the energy coupling
- Examples:
    - tuning forks : poor impedance matching (high quality factor).
    - Electrical power transformers (high impedance transmission line)
    - Acoustic horn

# Impedance of Free Space

- Impedance of free space to electromagnetic waves is a fundamental constant.
- $Z_0 = \mu_0 c = 376.73031$ Ohms
- Weber's demonstration of the long GW relaxation time of a perfect bar shows that the impedance of free space to GW is extremely high.
- Easy to see that $Z_G \sim c^3/G \sim 10^{35}$ Ohms

# Impedance matching for Electromagnetic Waves

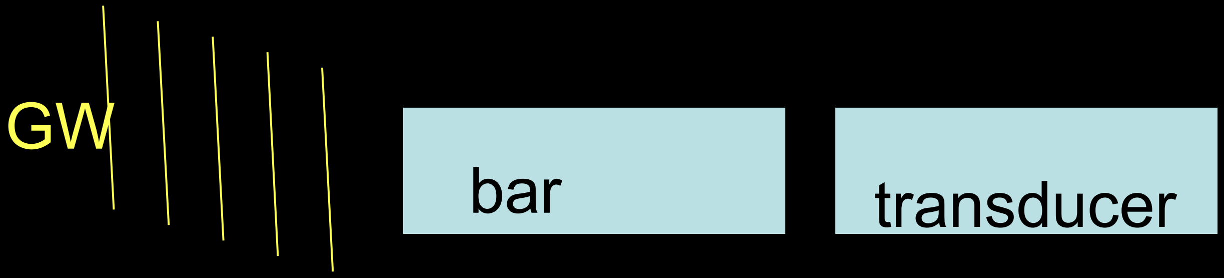
- Optical anti-reflection coatings
- Radio antennas
  - May be broadband or narrowband

# Impedance Mismatch

- In electronics high input impedance allows measurement of a weak signal with minimal extraction of energy.
  - Voltage detected is independent of system details
- Impedance mismatch between GW and GW detector means that the strain amplitude at the detector is independent of detector details

# Impedance Picture For Bars

- Resonant Bars: double impedance matching problem:



GW

bar

transducer

$Z_G \sim c^3/G$

$Z_{bar} \sim Mv_s/L$

$Z_t \sim$ Electrical energy density

- Search for suitable materials that optimised $\rho v_s^3.Q$

# Differing Approaches

- Bars: concept of energy absorption cross section

- Interferometers: concept of measuring motion of free masses
  - Good approximation in era of initial detectors
  - Bad approximation for Advanced detectors

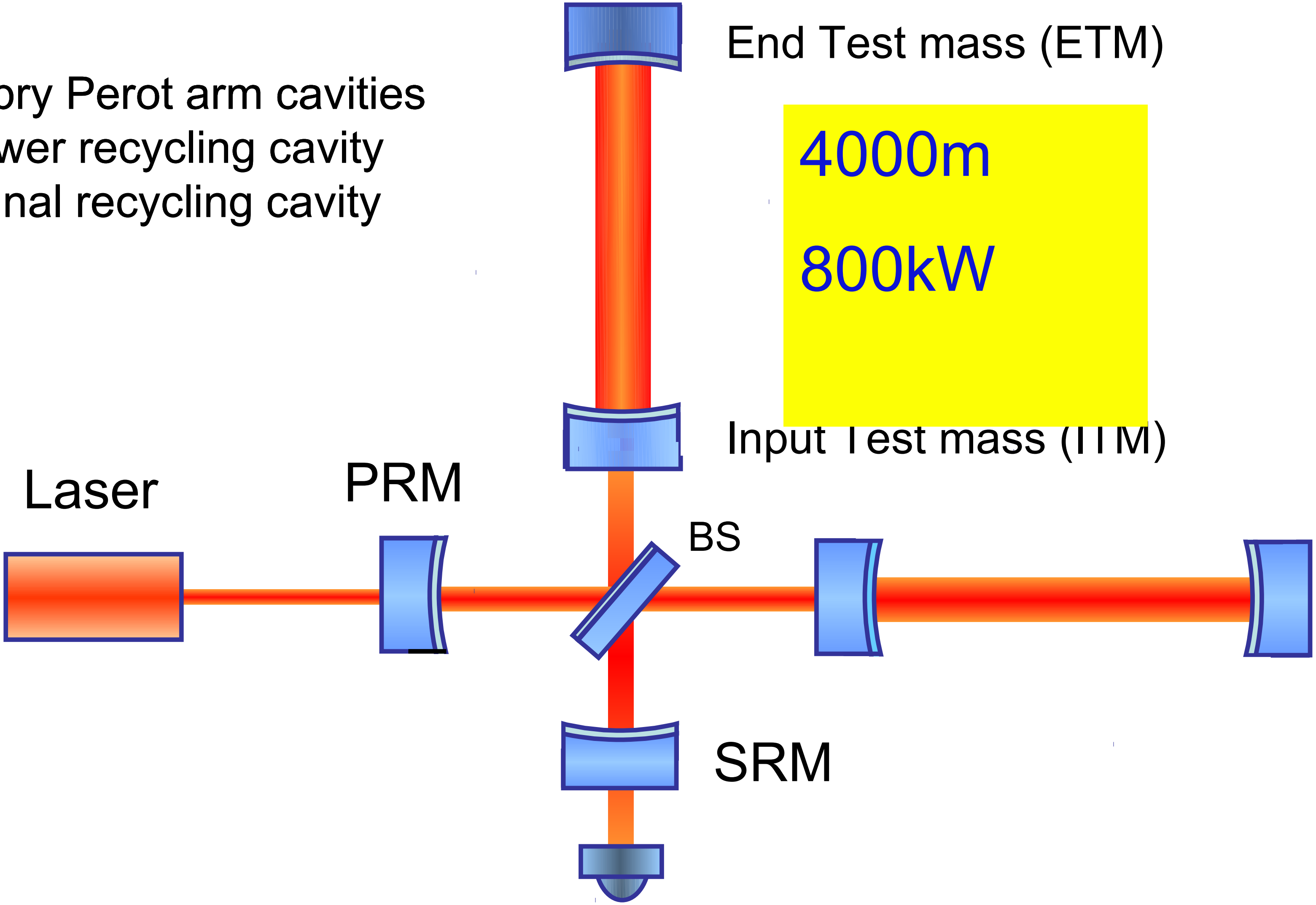
- Confusing in all cases because it implies no energy coupling
- In reality energy coupling is fundamental.
- Advanced interferometers exceed the energy coupling of bars.

# Quantum Limits

- Bar $$h_{sql} \sim \frac{1}{v_s^{2}} \sqrt{\frac{\mathrm{h}}{M}}$$
- Interferometer $$h_{sql} \sim \frac{1}{\mathrm{W}L} \sqrt{\frac{\mathrm{h}}{M}}$$
  - Normally expressed as free mass displacement sensing quantum limit

# Advanced Laser Interferometer

- Fabry Perot arm cavities
- Power recycling cavity
- Signal recycling cavity



End Test mass (ETM)

4000m

800kW

Input Test mass (ITM)

Laser

PRM

BS

SRM

Photodetector

# Optical Spring

# Estimate Spring Strength

- 1MW optical power
- Radiation pressure force =2P/c ~ 10mN
- Force acts over optical cavity linewidth ~ 1nm
- Spring constant k=F/x
- K= $10^{-2}/10^{-9}$ ~ $10^{7}$N/m
- $10^{3}$ tonnes/m

# Changing the Dynamics

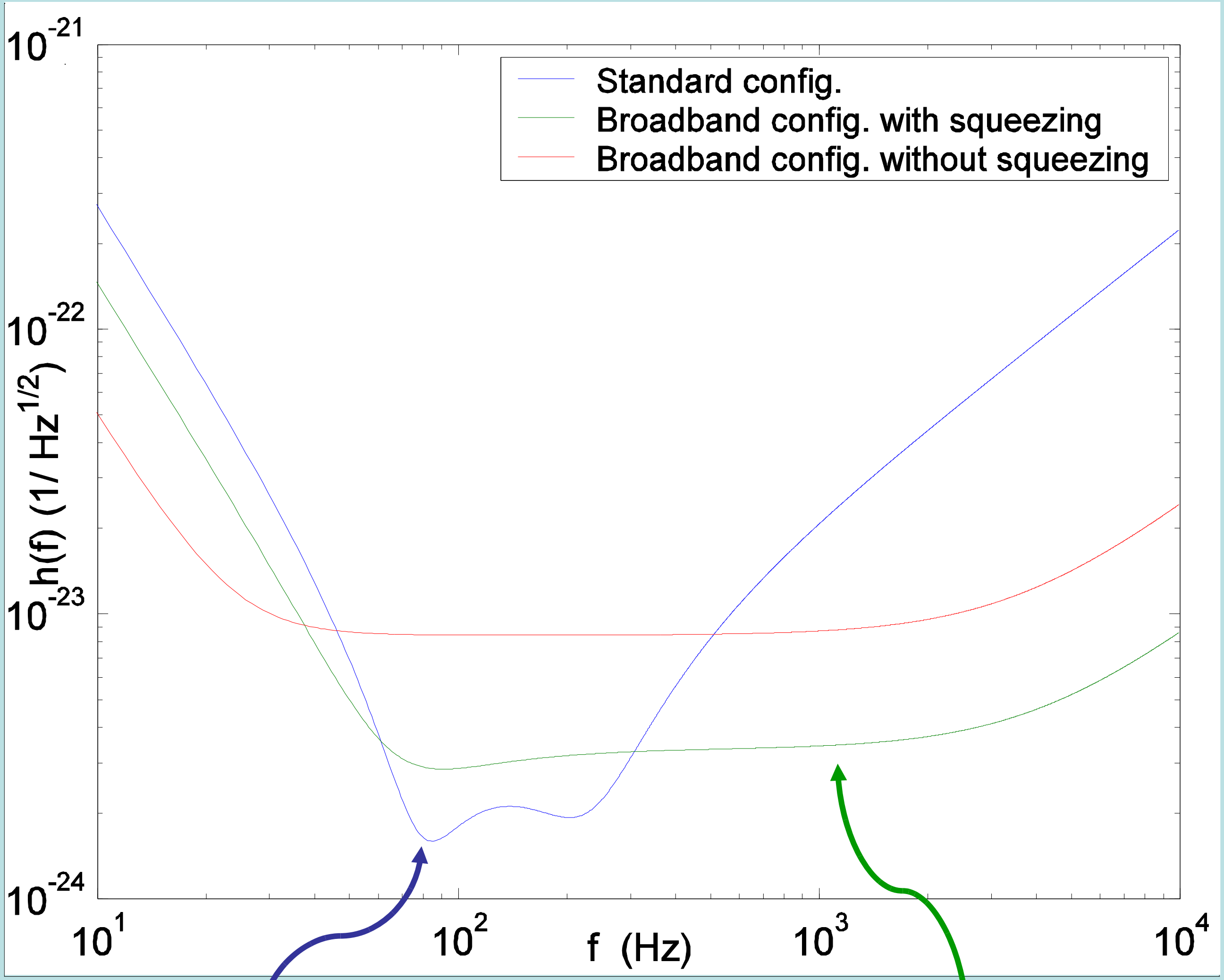
- Optical springs change detector dynamics
- They strengthen the interaction with the GW signal
  - increased energy coupling
- They change the detector response.
  - Eg: reduced sensitivity at low frequency
- The quantum limit is no longer the Free Mass SQL
- The SQL formulae for bar and interferometer are unified, but interferometer has L=4km and $v_s$ > 100km/s.

QuickTime™ and a
decompressor
are needed to see this picture.

# Quantum Measurement

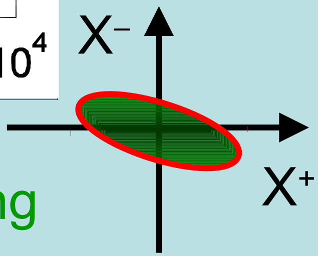
- Free Mass SQL is a convenient benchmark
- High optical power enables better impedance matching between GW and detector
- Thus sensitivity is directly increased as radiation density in the detector arms increases.
- Quantum measurement offers further improvements:
    1. Optical squeezing changing the correlation between optical quadratures
    2. Ponderomotive squeezing: radiation pressure induced correlations between $\Delta x$ and $\Delta p$
    3. Local readout: recovery of low frequency sensitivity lost by the dynamics of optical springs

# Sub-quantum-limited interferometer



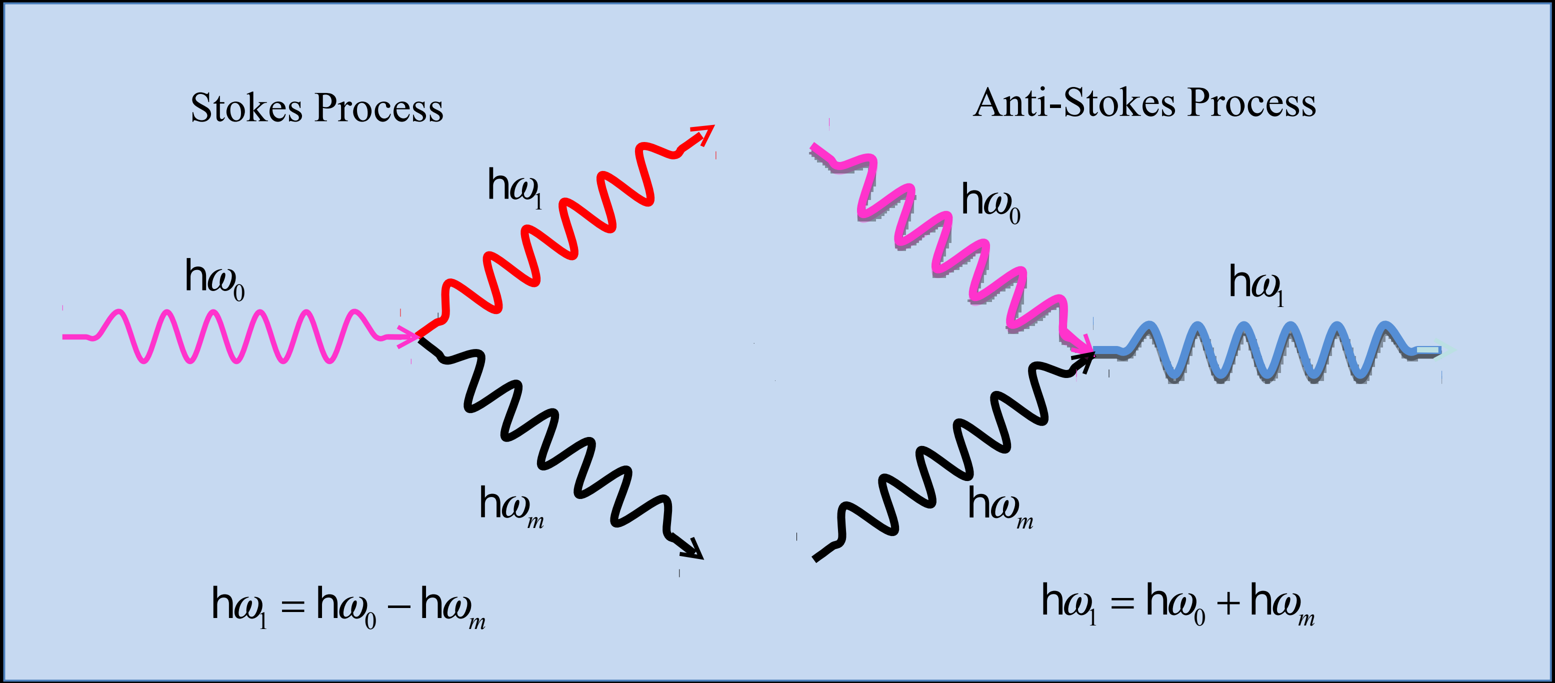
Quantum correlations
(Buonanno and Chen)

Input squeezing



Nergis Mavalvala

# Three-mode opto-acoustic parametric interactions



The conditions that enable strong optical springs also allow three mode interactions to occur.

These interactions are a threat to stability but offer both opportunities and challenges.

# Conclusion

- There is energy exchange between GW and all types of detectors
- It would be useful if this energy formalism were further developed for interferometers
- Optical springs provide a new tool for improving GW detectors by allowing a whole range of new approaches such as double optical springs. *Chunnong Zhao will discuss Thursday.*
- We are threatened by three mode interactions which could cause instability if not controlled.*Ju Li will discuss Thursday.*