New Concepts in Gravitational Wave Detection

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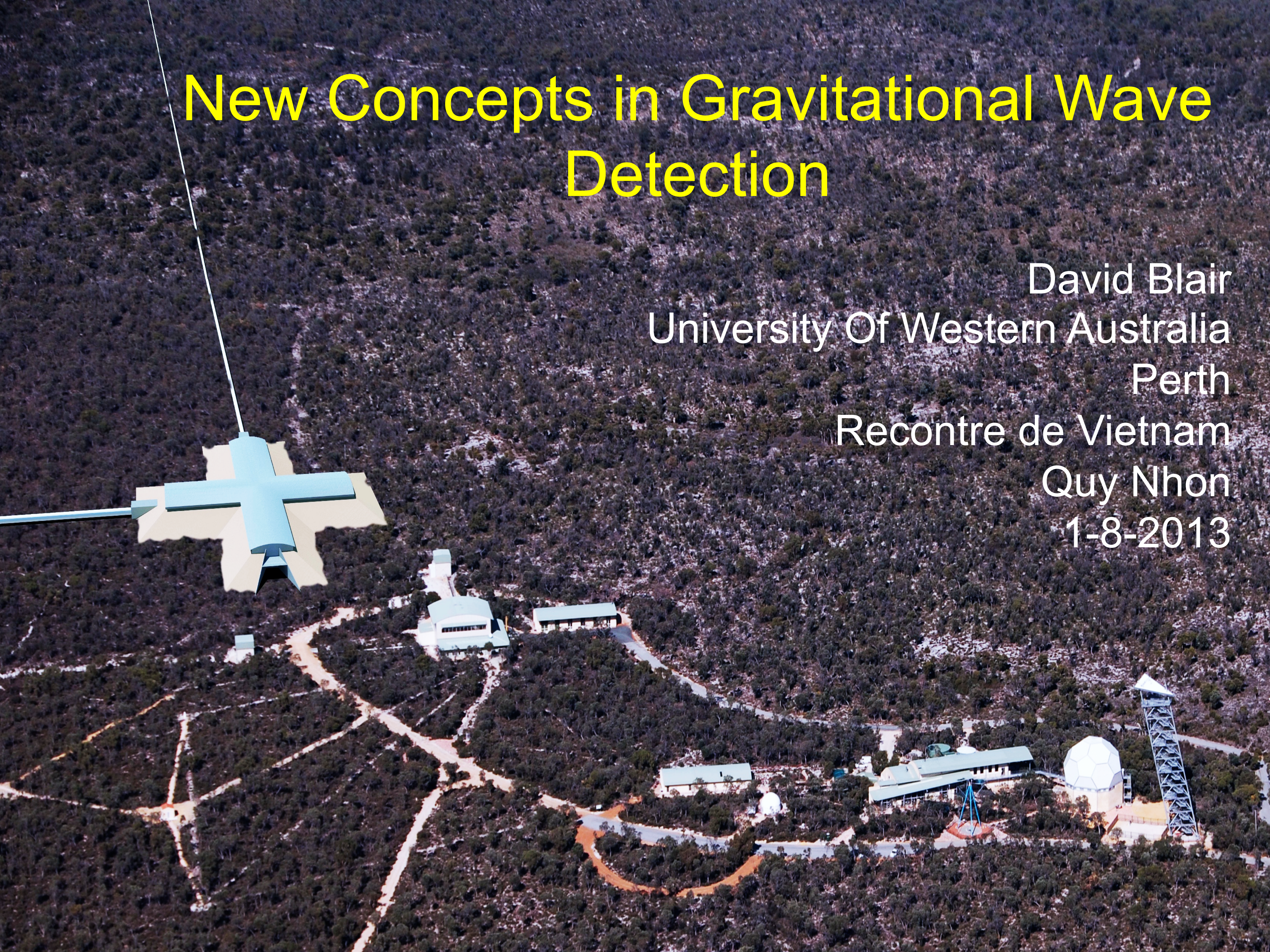
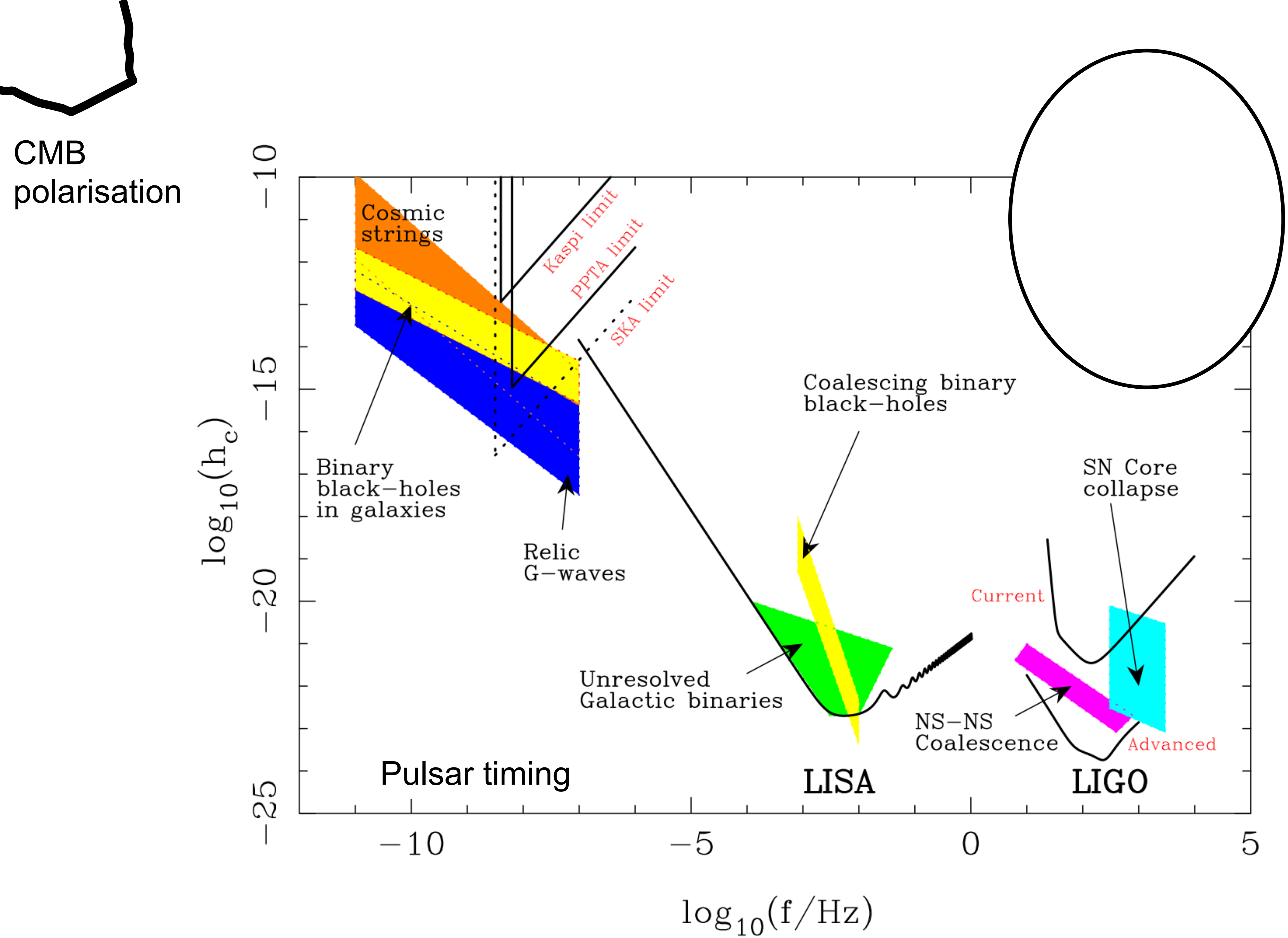
1-8-2013



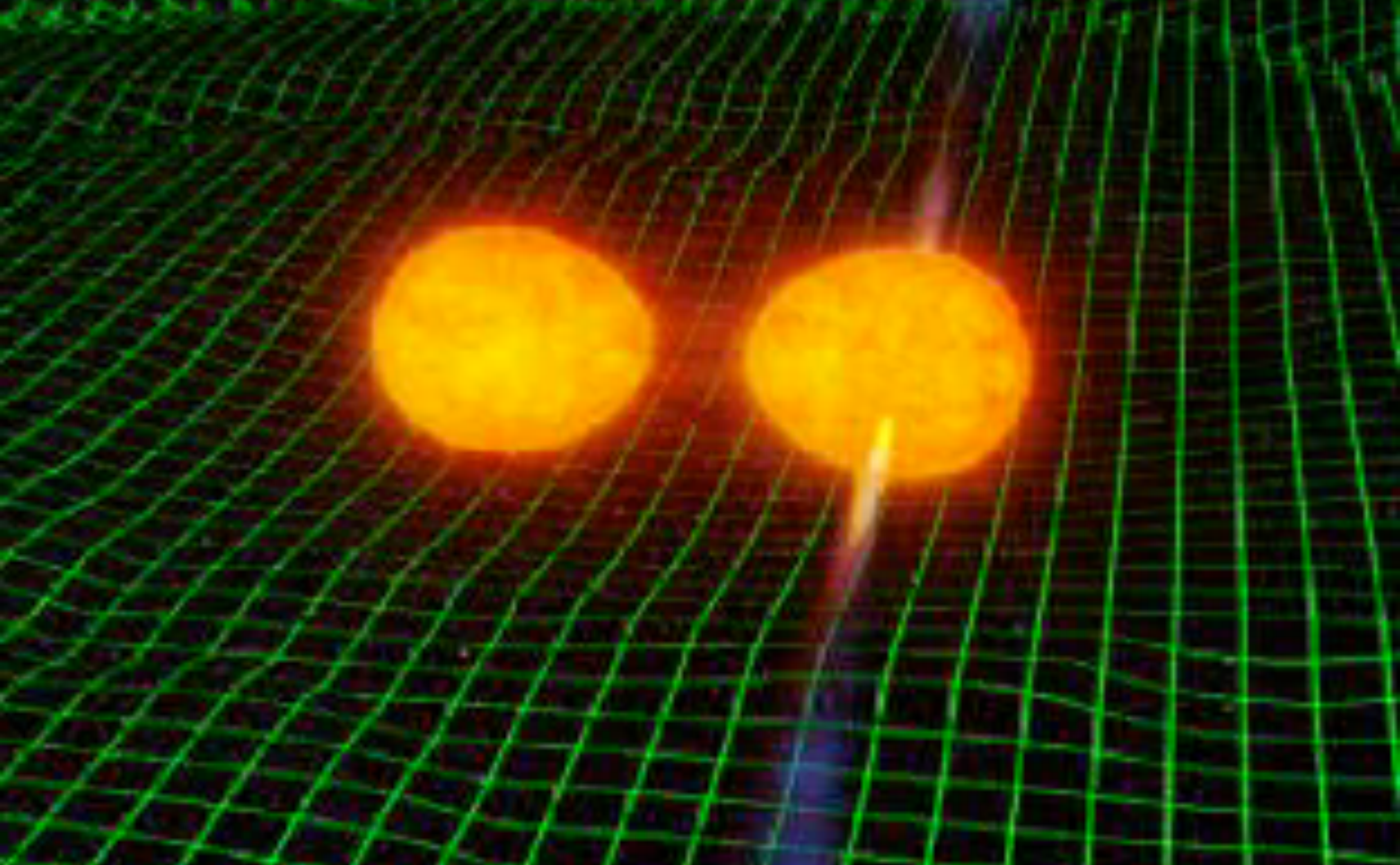

CMB
polarisation
Cosmic
strings
Kaspi limit
PPTA limit
SKA limit
Binary
black−holes
in galaxies
Relic
G−waves
Coalescing binary
black−holes
Unresolved
Galactic binaries
SN Core
collapse
Current
NS−NS
Coalescence
Advanced
Pulsar timing
LISA
LIGO
$\log_{10}(h_c)$
$\log_{10}(f/\mathrm{Hz})$
−10
−15
−20
−25
−10
−5
0
5

History of Gravitational Waves

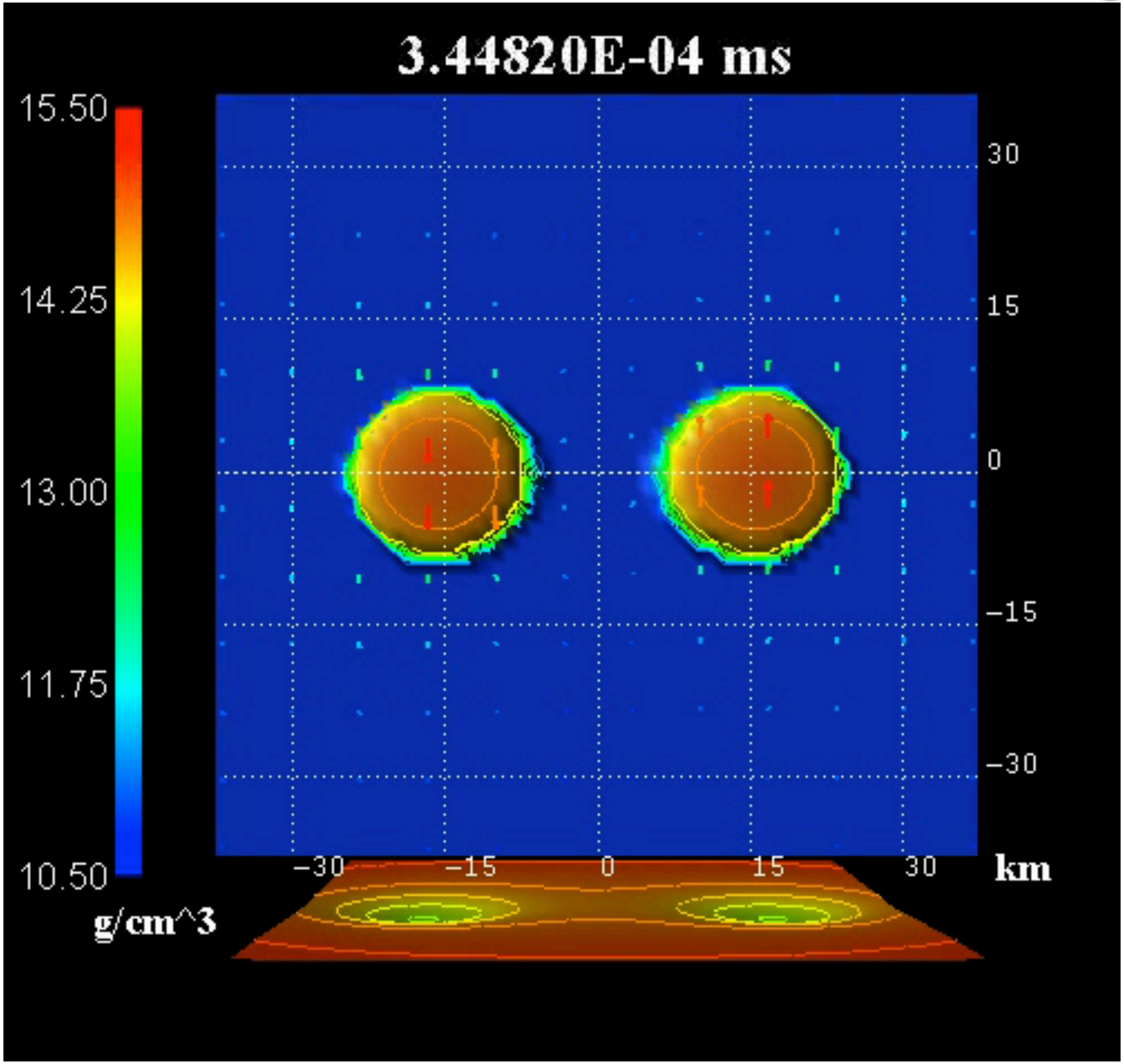
- 1916: Predicted by GR
  - of academic interest only
  - Coordinate problems: “gravitational waves travel at the speed of thought”
- 1957: Feynman and the sticky beads thought experiment.
- 1960s: Resonant Mass + Free Mass Detectors Neutron Stars and Black Holes Discovered
- 1990s: Large Interferometer Projects begin
- 2016 direct detection???

Neutron Star Binary Coalescence

known and detectable source



Numerical Simulation - Two 1.3 $M_\odot$



Shibata

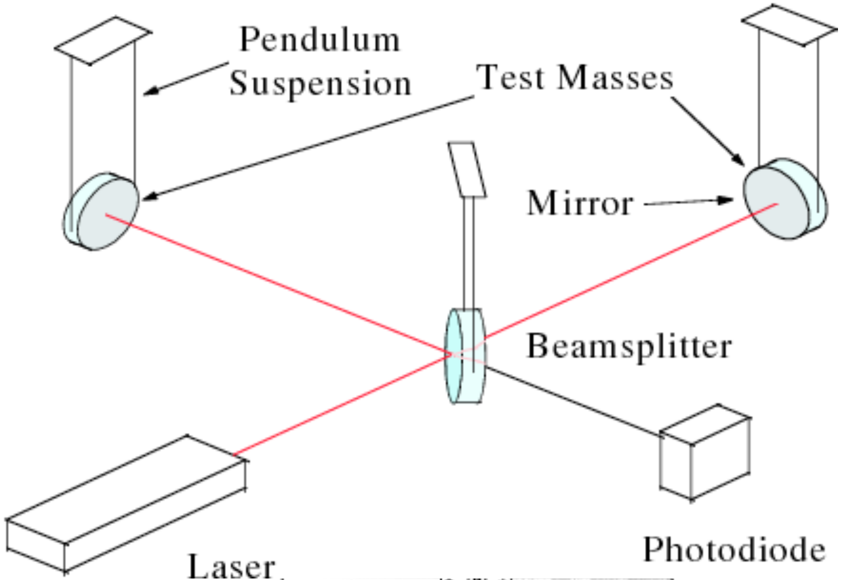
Threshold of Discovery

- Coalescing neutron star binaries
  - Known population, good rate estimates
  - new Advanced detectors designed for detection.
- Bonus sources: black hole binaries, stochastic backgrounds, spinning neutron stars
  - Less certainty (event rates/signal strengths)
- Like Higgs
  - Firm predictions, well understood detectors
  - Hopes for surprises

Detectors Today

- Most sensitive instruments of any kind ever created ~ 10^{-32} J
- Working close to limits set by the uncertainty principle
- New advanced detectors mainly limited by quantum noise.
- How can we surpass current limits?

Free Mass vs Resonant Mass



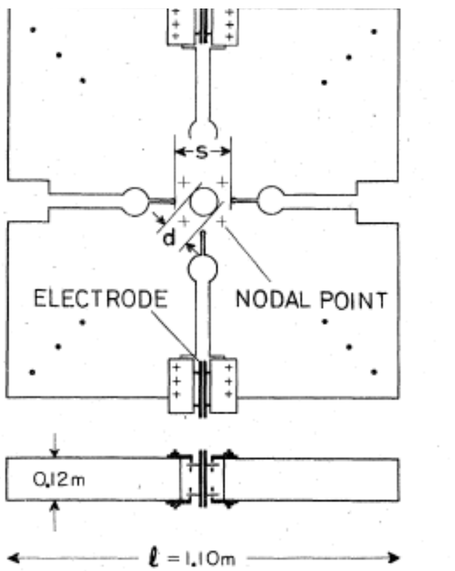


FIG. 1. 400-kg quadrupole antenna for gravitational

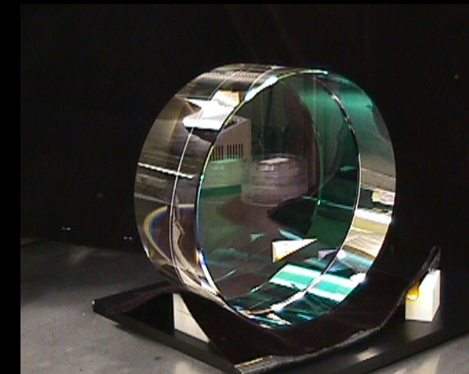
Classical Force + Quantum Detector

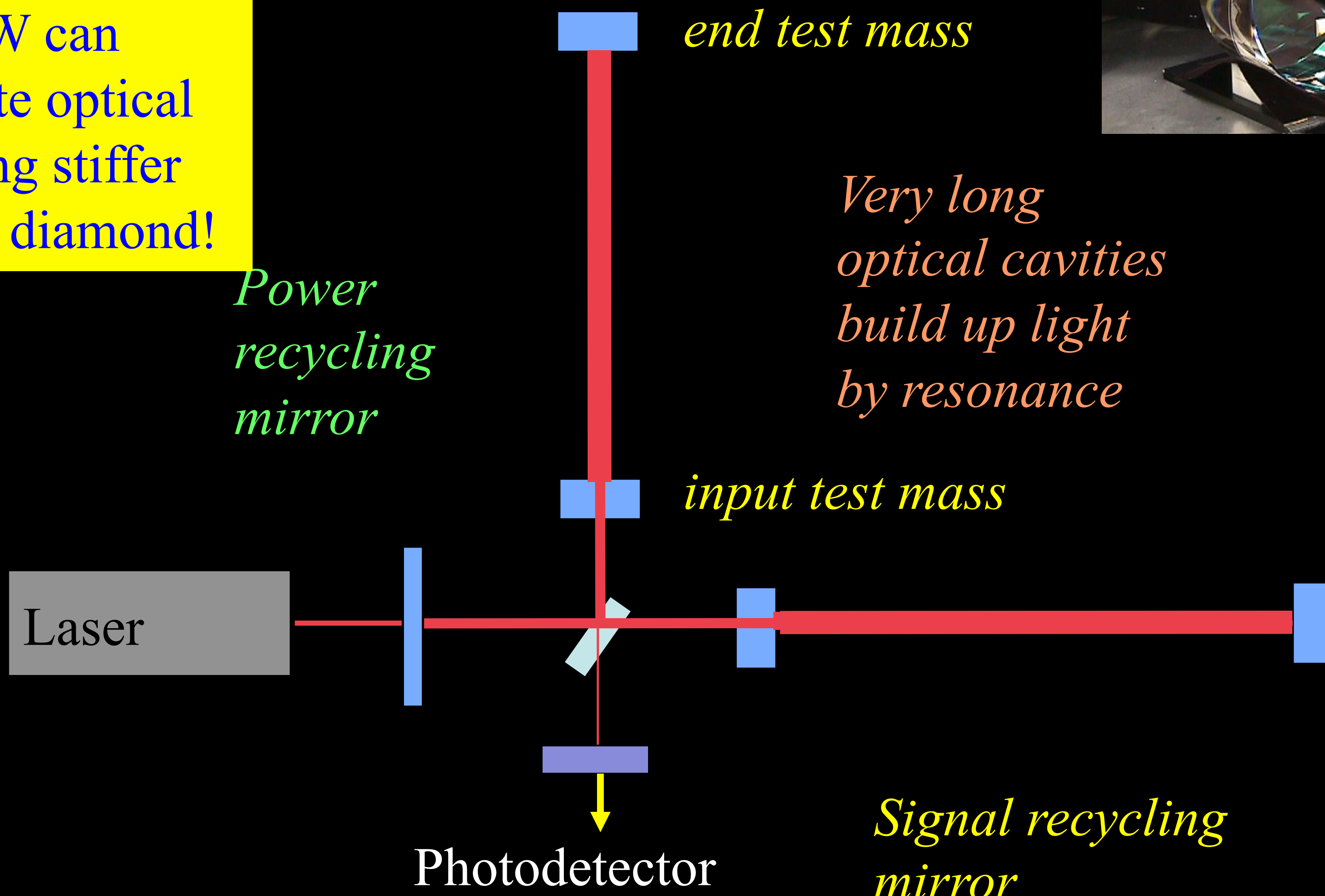
Gravitational wave is a classical wave with enormous occupation number

Detector is a Mechanical Oscillator in Quantum Regime

Gravitational Wave Interferometer

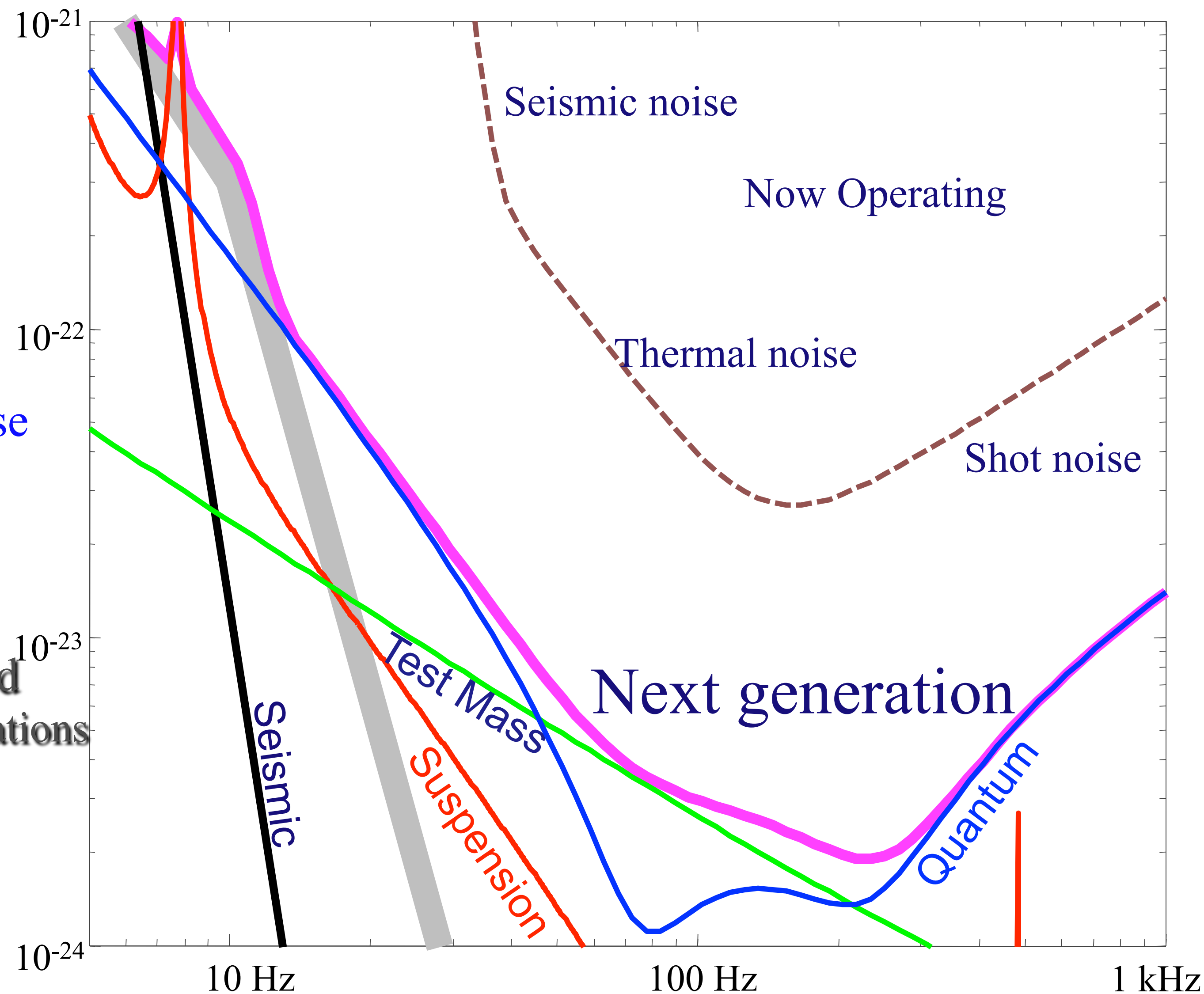
Light intensity ~MW can create optical spring stiffer than diamond!





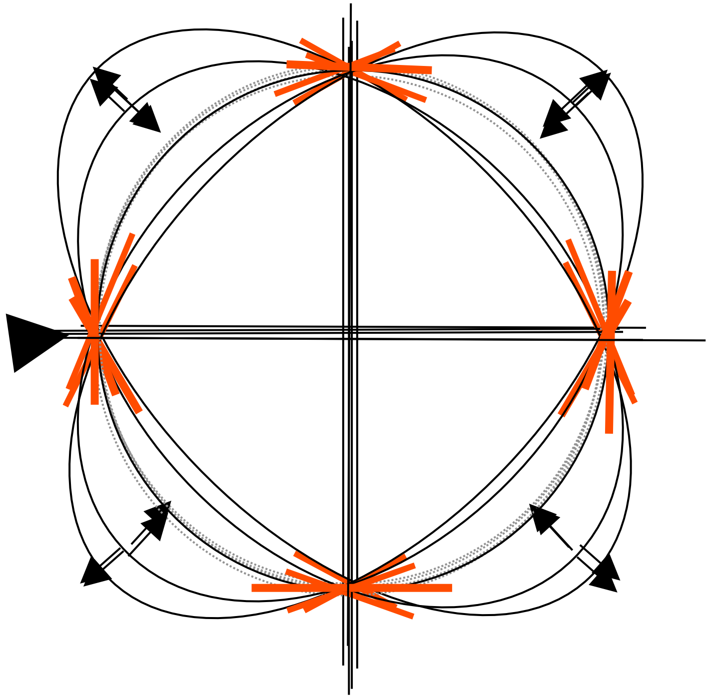
Improving Detector Sensitivity ΔL / L

- Seismic vibration
  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

GW Strains : Tilt + Linear Strain



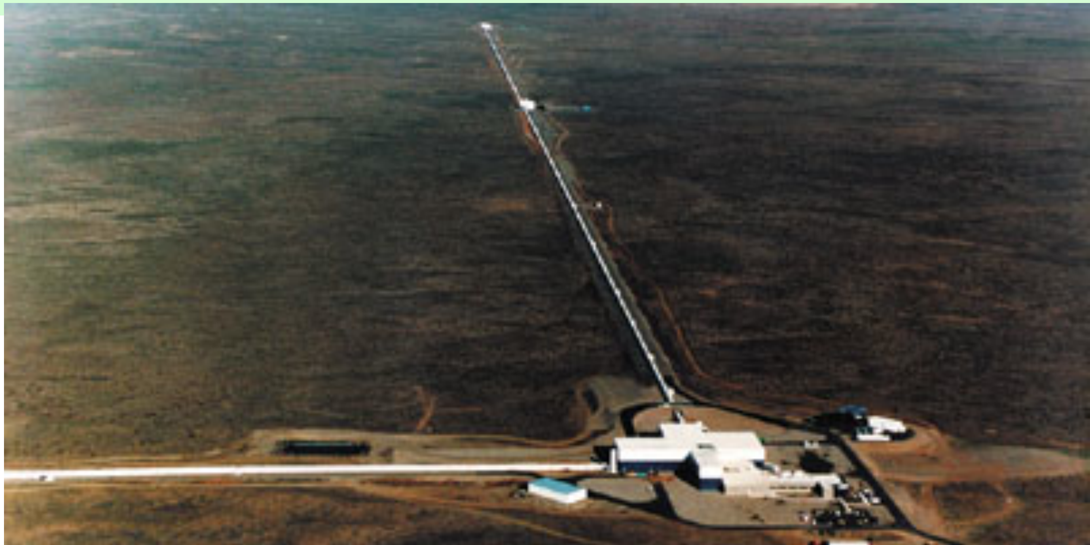
$h = \Delta L/L = \Theta$

Existing detectors are polarised
sensitive to one polarisation only.

+

X = tilt in + orientation

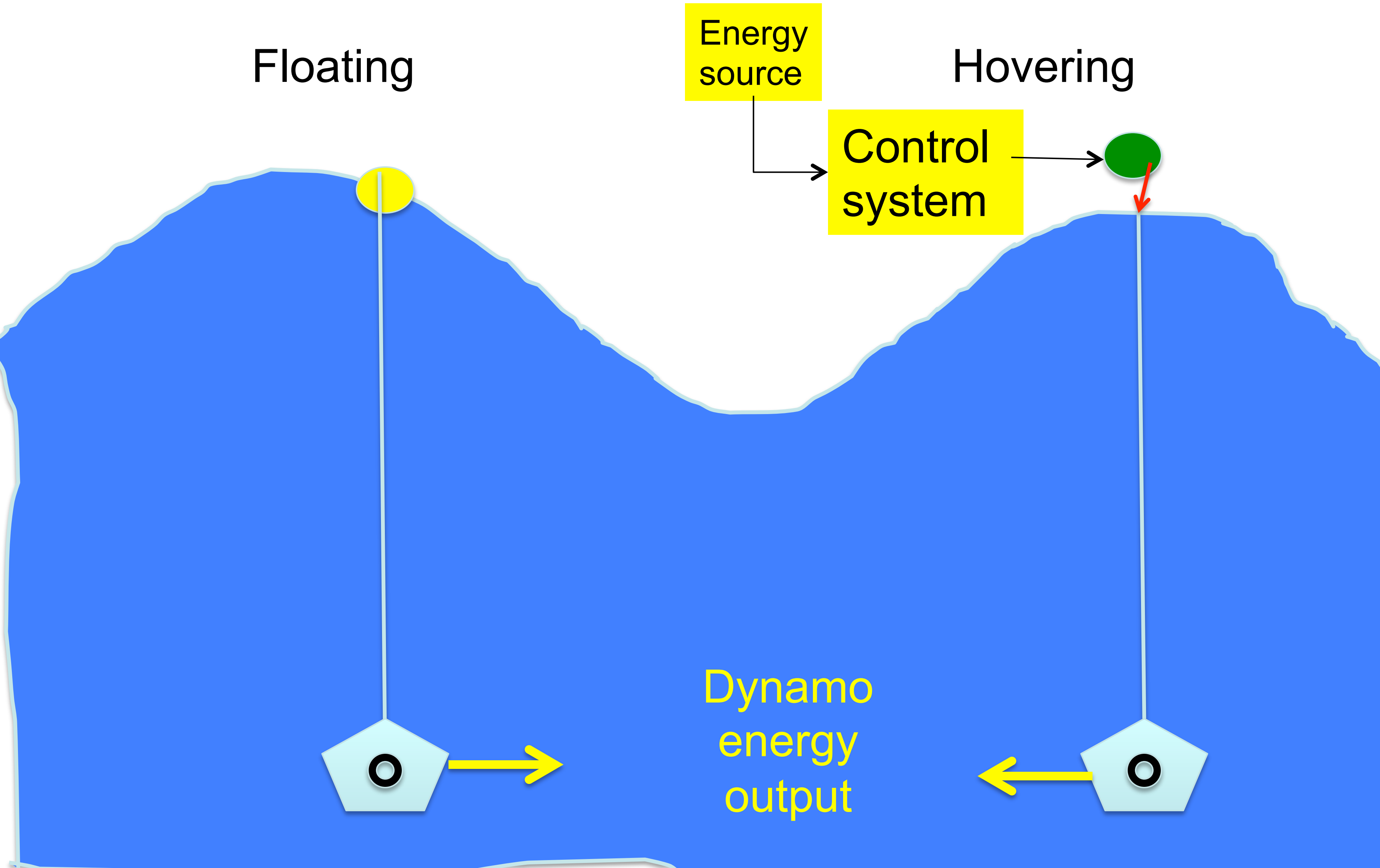
If you could add a tilt sensitive gravitational receiver to an existing beam tube you could achieve full wave form reconstruction.



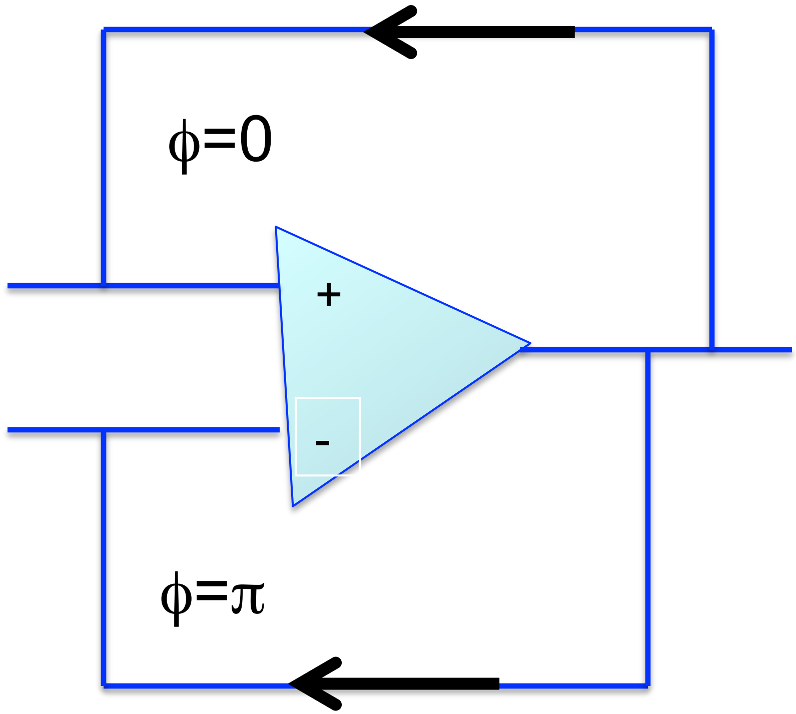
Free Mass Detectors

- Laser interferometers: free mass detectors?
- Does this not violate the need for GWs to do work?
- Is a GWD not a *receiver* of GW energy?
- Is a laser interferometer not a *transducer* for GW energy?
- Why can we measure GW without absorbing energy?
  - Can all the sideband energy come from the laser?

Example: Ocean Wave Monitor



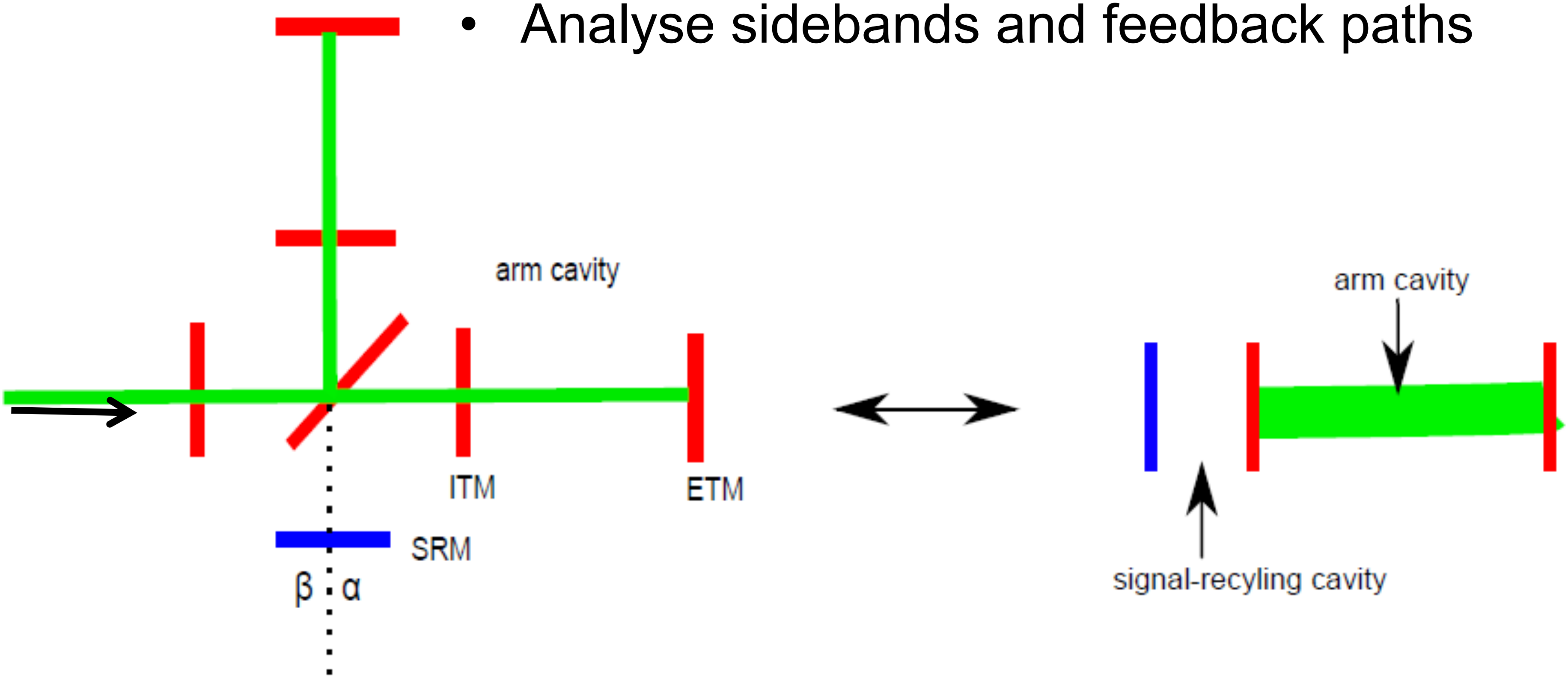
Electronic Amplifier Analog



Feedback around an amplifier: change the input impedance, change the gain.

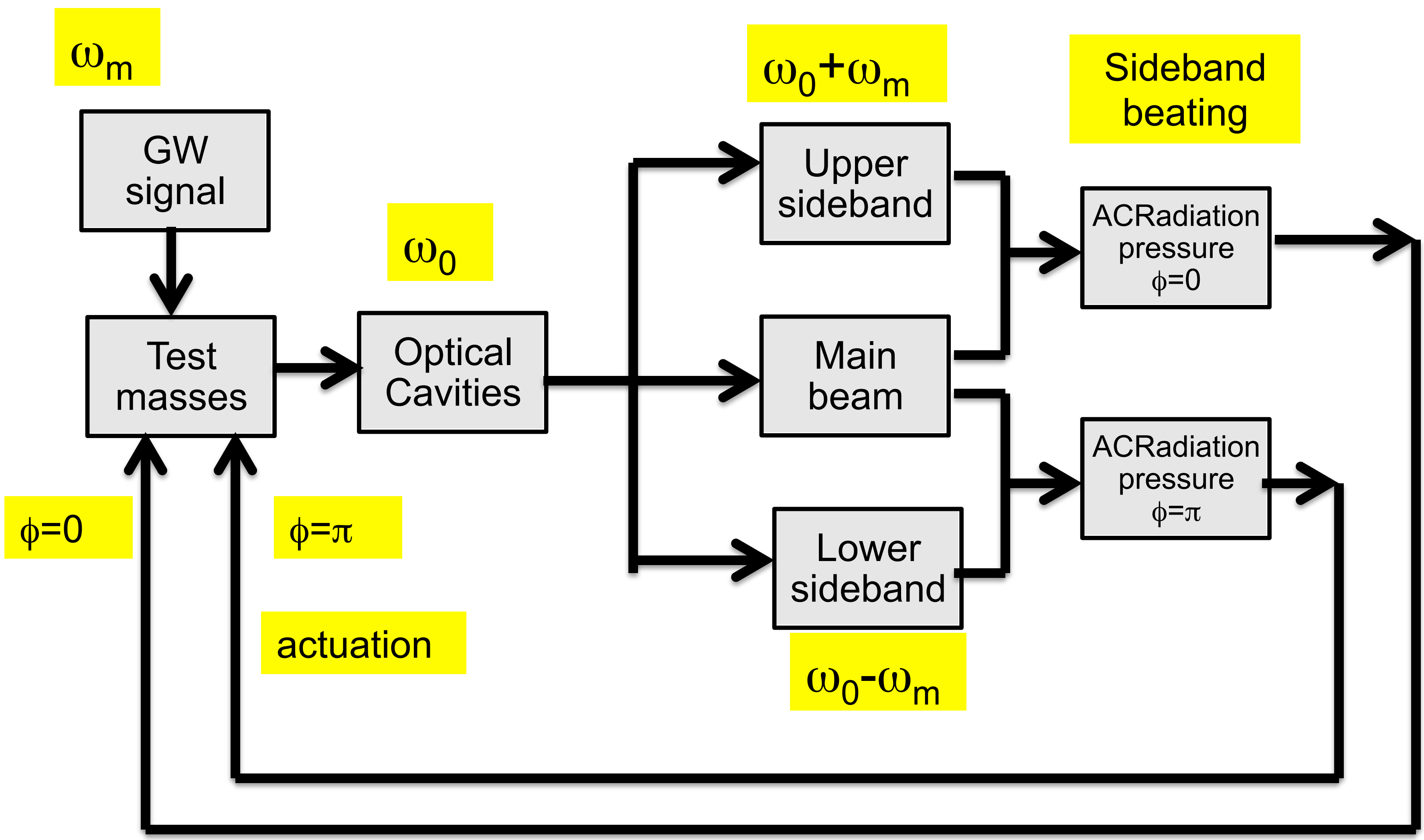
Energy Flow Analysis

- Map Laser Interferometer to a three mirror cavity.
- Quantum analysis of energy flow
- Analyse sidebands and feedback paths

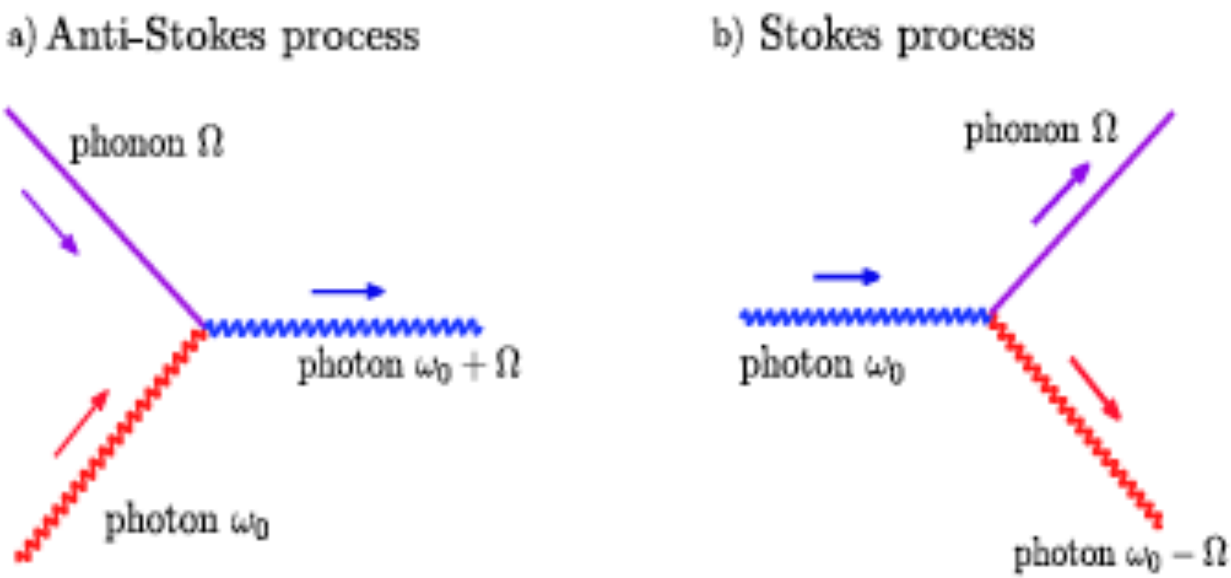


Laser frequency ω_0, gravity wave frequency ω_m creates signal sidebands at $\omega_0 + \omega_m$ and $\omega_0 - \omega_m$

GW Transducer Feedback



Quantum Picture



Creates an optical spring

Nulls the optical spring

Sideband Roles

- Upper sideband represents energy absorption from GW

- Lower sideband is a feedback circuit that nulls the dynamical response, causing the detector to have low input impedance and negligible energy absorption from the GW.

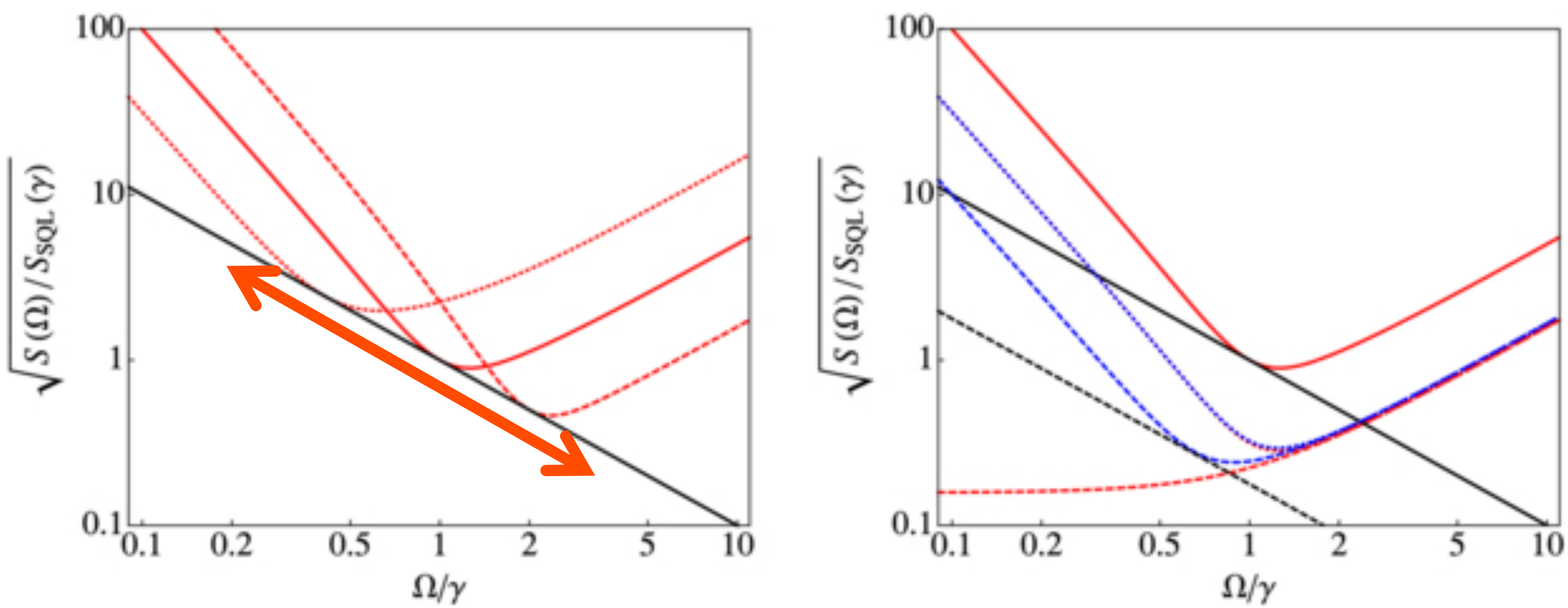
- A detector with single (upper) sideband readout maximises the energy absorption

Two approaches to improved sensitivity

1. Reduce effect of the quantum fluctuations which enter the detector at the dark port and set the standard quantum limit.

2. Increase the the gravitational wave signal by changing the detector dynamics to enable more signal to be received.

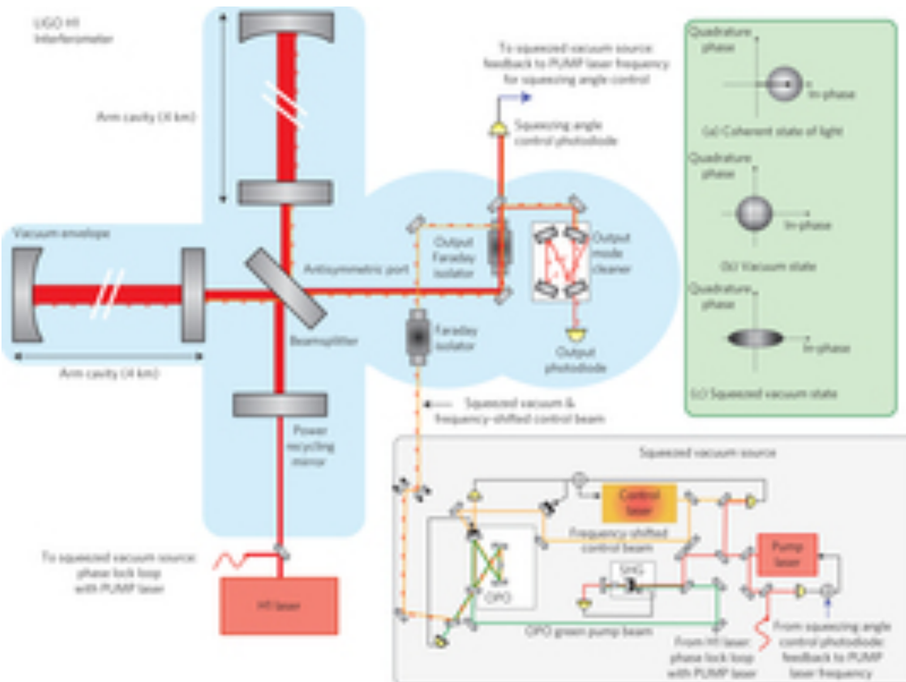
Free Mass Standard Quantum Limit

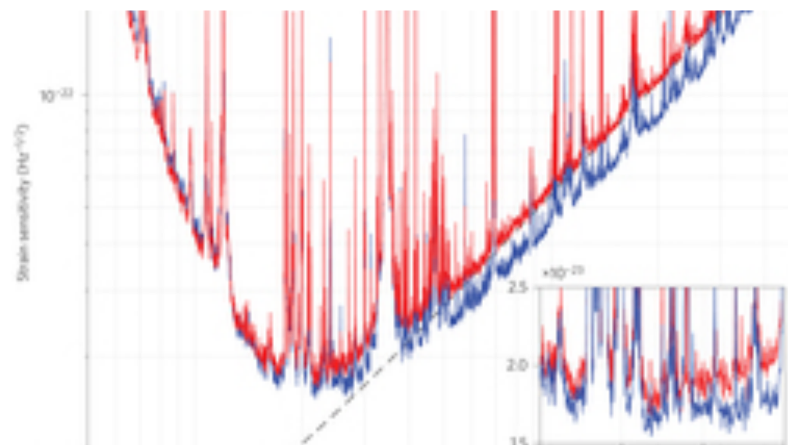


FM SQL Line is the locus of uncertainty principle measurement limit for a free mass

Yanbei Chen J Phys B 2013

Enhanced sensitivity of the LIGO gravitational wave detector by using squeezed states of light

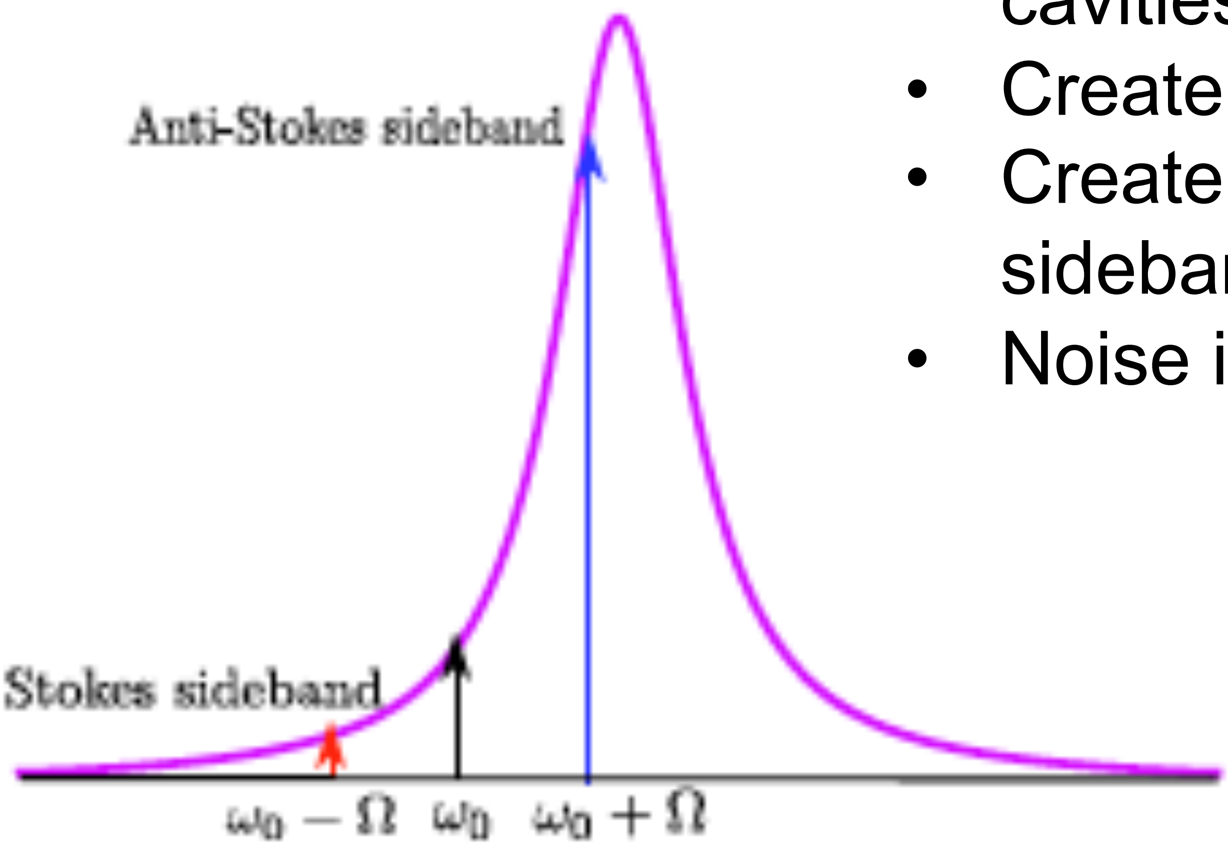




Quantum shot noise suppressed by squeezing the vacuum quantum fluctuations

Nature Photonics 21 July 2013

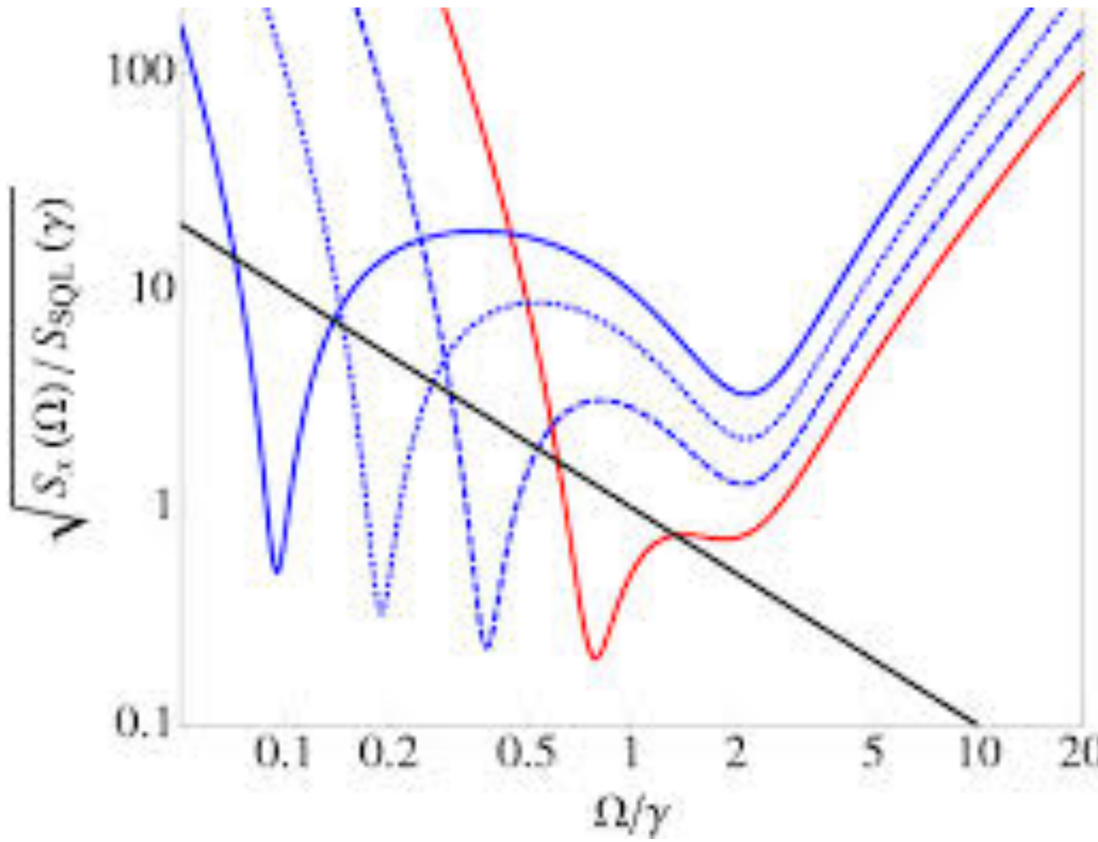
Optical Springs



- Detuning the optical cavities
- Create optical spring
- Create unbalanced sidebands
- Noise issues

Optical "Bar"

- Improved sensitivity due to opto-mechanical response of detector

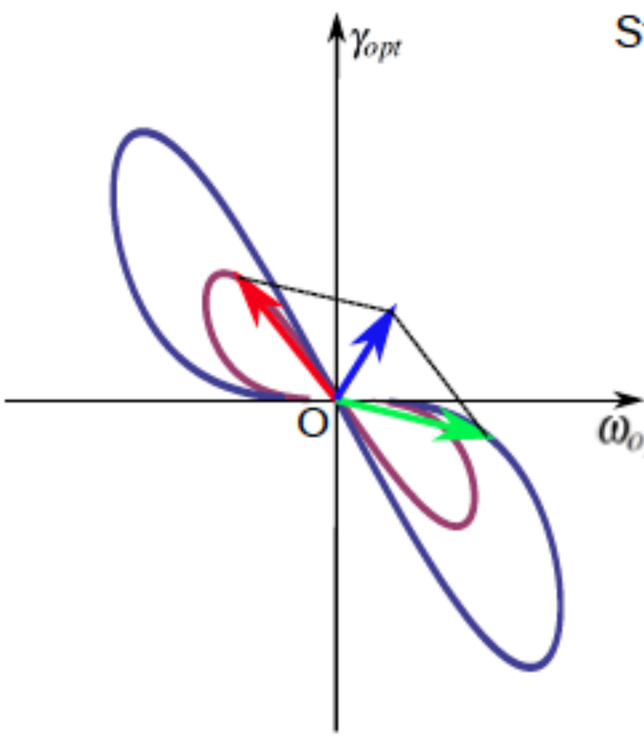


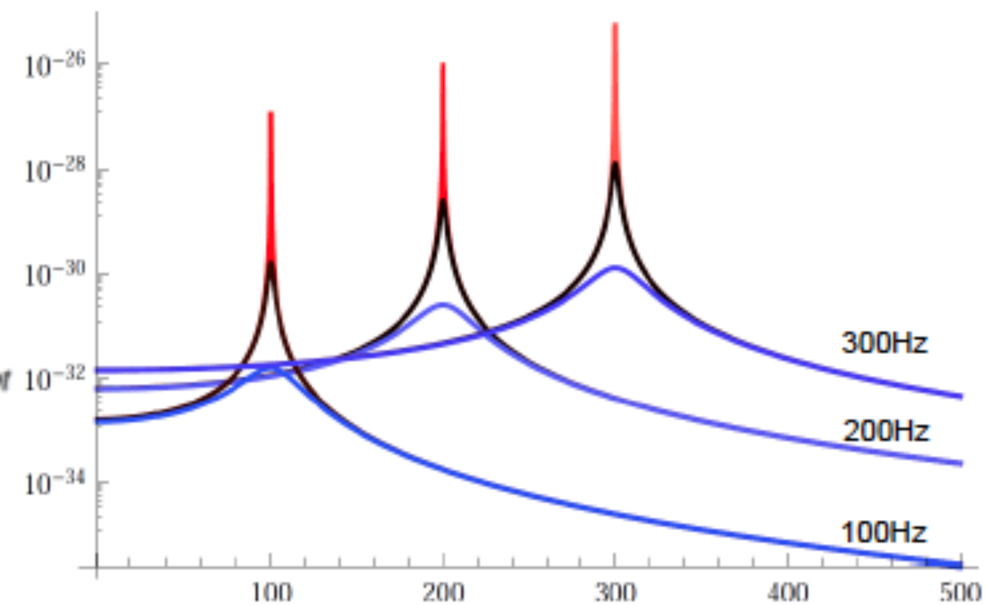
See references in Yanbei Chen J Phys B 2013

Unbalanced Sidebands – double optical spring interferometer

Unbalanced sidebands create optical spring, modify the detector dynamics and allow detection below the free mass SQL by increasing the energy coupling from the GW

>10^6 increased energy absorbed from GW





Single Sideband Tilt Interferometer

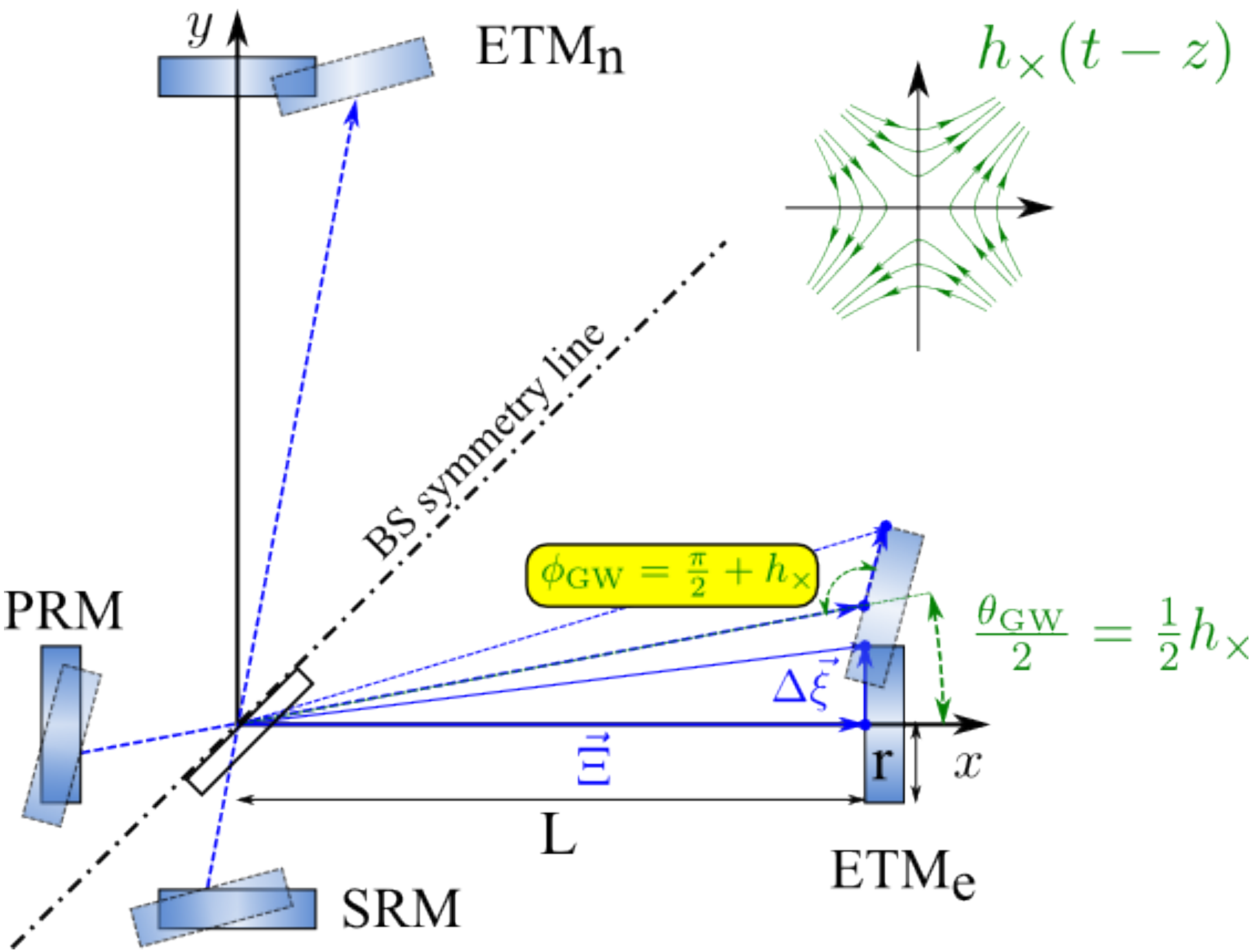
Measure second polarisation in same beam pipe

Increase the energy absorbed by GW

Tunable narrow band detector

Preliminary ideas still to be fully analysed

Tilt Interferometer



Three Mode Interactions

Gingin experiments reveal high sensitivity “angular” readout.

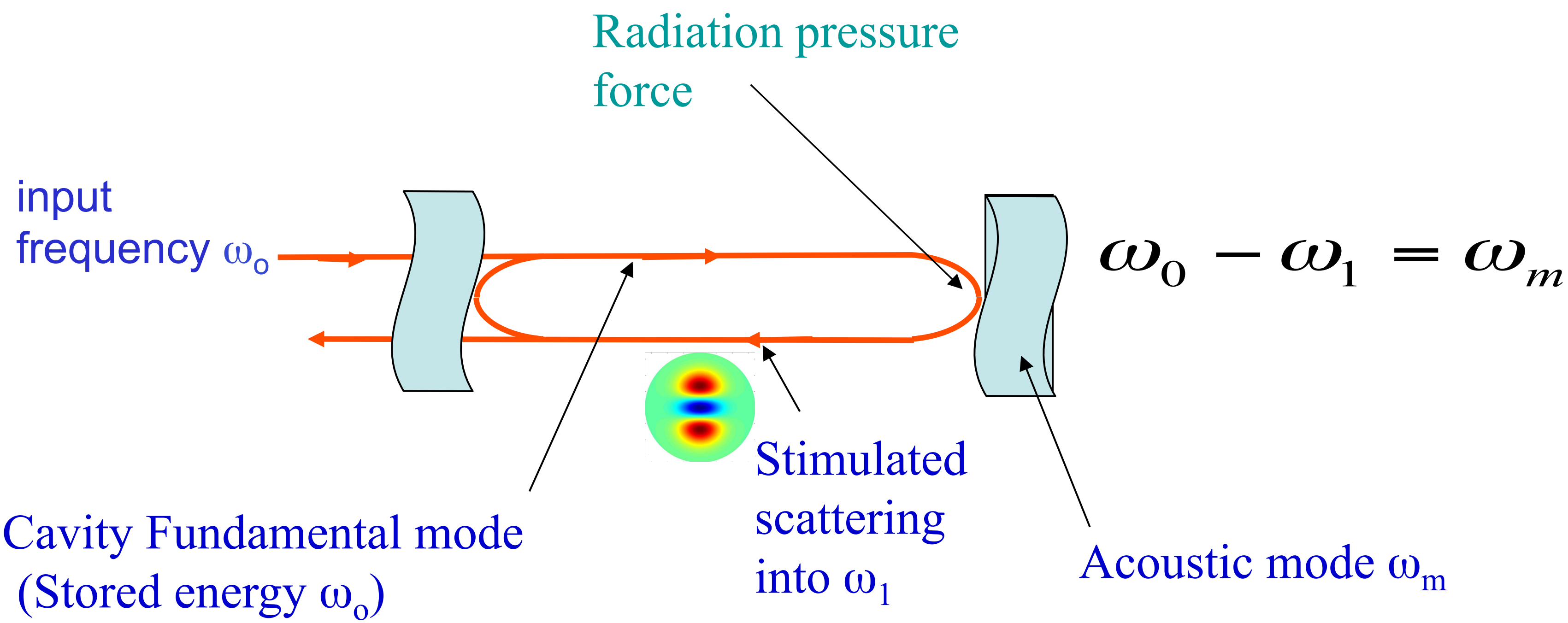
Single sideband 3-mode readout

Test mass motion excites cavity 01-mode

A GWD could use the same method to read out angular deflections due to GW.

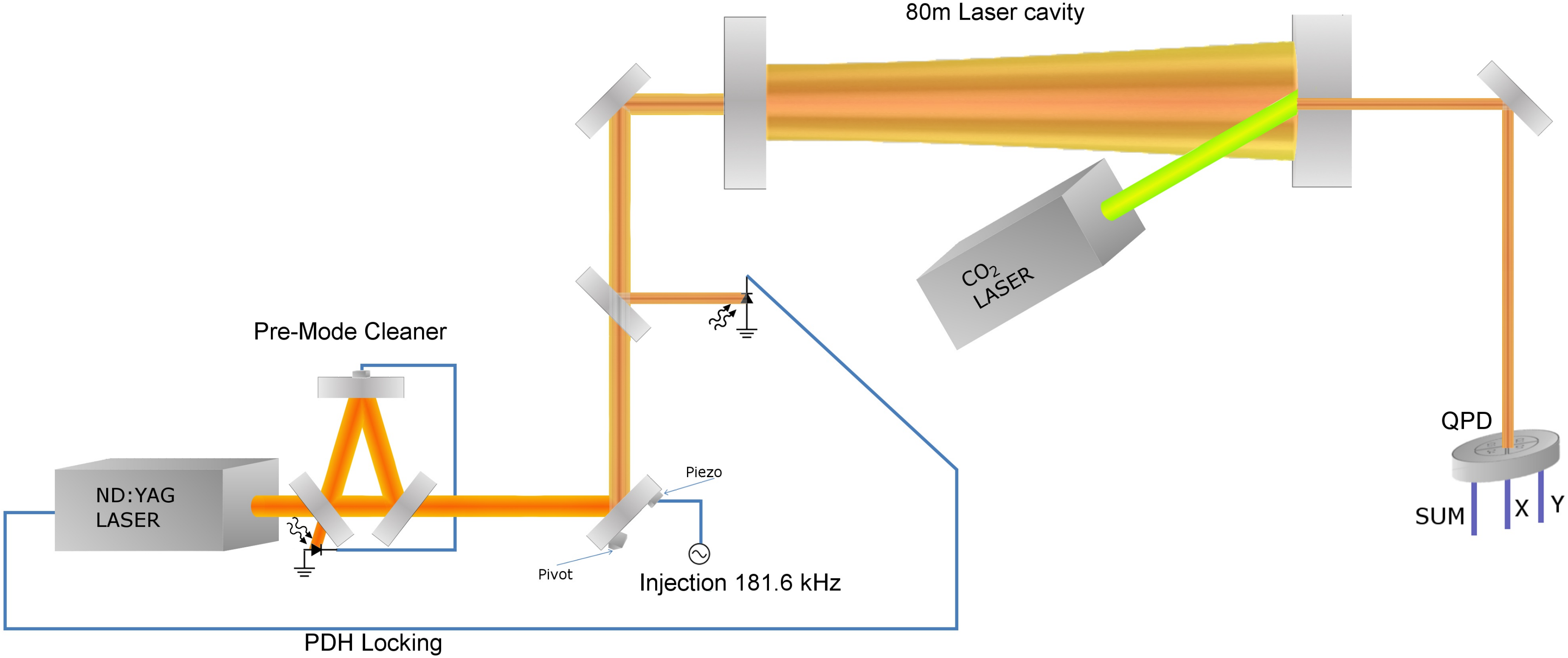
Benefit: second GW polarisation can be measured in the same vacuum tube of a displacement interferometer

Opto-Acoustic Interaction



Motivation: Gingin Experiment

1. ETM tilts : observed high sensitivity to test mass mode equivalent to a tilt vibration

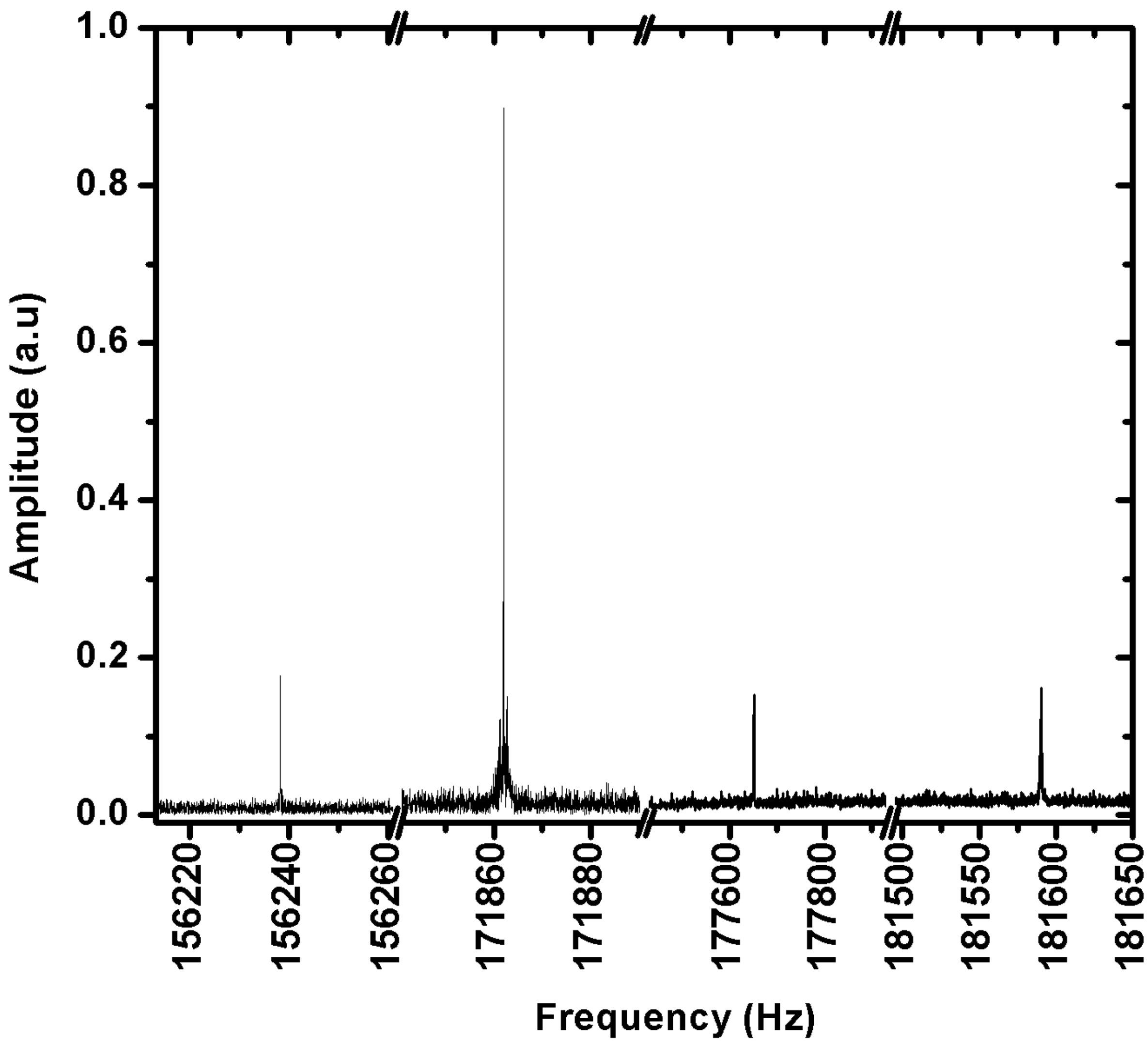


Thermally excited acoustic mode readout

Simple system very sensitive to acoustic modes in the 100kHz range.

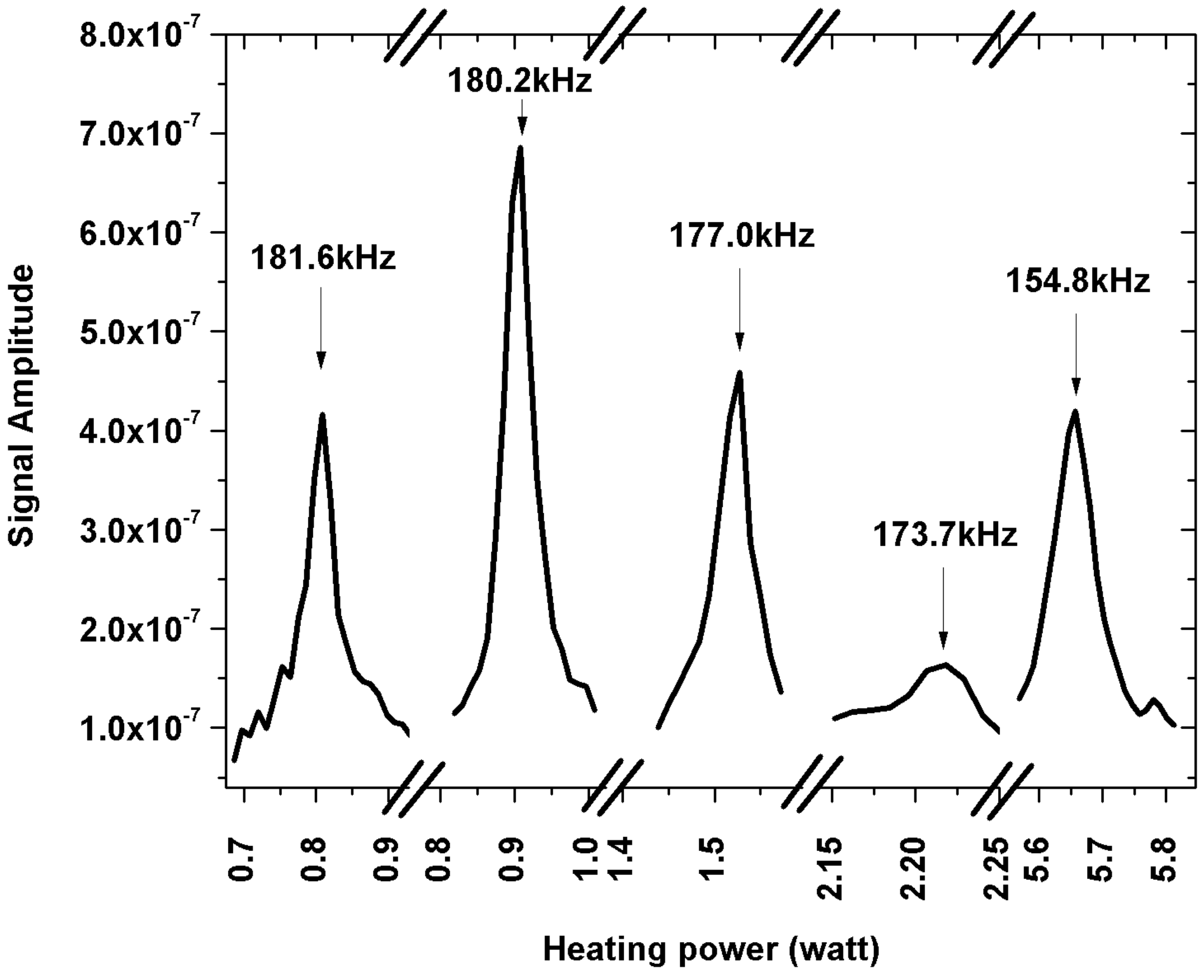
100kHz gravitational wave detector!

Accepted for publication Susmithian et al PLA 2013



Radius of curvature cavity tuning

High SNR when transverse mode is correctly tuned by CO2 laser tuning



Coupling Tilt to TEM_{01} mode

Gain

$$R = \pm \frac{2\Lambda I_0 Q_0 Q_1 Q_m}{m\omega_0 \omega_m^2 L^2}$$

Detector Concept

- GW signal tilts the mirrors;
- Equivalent to laser beam jitter with GW frequency;
- GW converts some carrier light ω_0 to upper sideband frequency $\omega_1 = \omega_0 + \omega_m$ =cavity mode TEM_{01}.
- Radiation pressure of beat note induces the torsional optical spring.
- When optical spring frequency is equal to the GW frequency, the GW induced mirror tilt motion will be resonantly amplified.

Thermal Noise Limit

- T = 1 K,
- Torsion suspension frequency: $\omega_m/2\pi$ = 1 mHz
- Q_m = 10^7
- Torsional optical spring frequency $\Omega_{\mathrm{GW}}/2\pi$ = 10^3 Hz

- $h_{\mathrm{th}} \simeq 2 \times 10^{-24}\ \mathrm{Hz}^{-1/2}$

Requirements and Limits

h_{SQL} (1kHz) ~ 10^{-27}

Optical Power: 4MW

Cavity g-factor very close to 1 to achieve TEM_{01} mode 1kHz above TEM_{00}

Nearly concentric optical cavities

ROC: 2 x 2003.5 m

Cavity Finesse: as high as possible, say 20,000.

Realisation

- Very low frequency torsion pendulum suspended test masses.
- Torsional optical spring created by beating of carrier and sideband
- 4MW required to achieve raise 1mHz pendulum frequency to 1kHz
- GW does work against the optical spring, giving high sensitivity narrow band readout.

Advantage: all cavities on-resonance

Very narrow bandwidth detector: good for GW searches from pulsars

Questions

1. Can the similar concepts be used to create a detector with broad bandwidth or a comb of narrow band sensitivities?

2. Can technical noise sources such as laser beam jitter noise be sufficiently suppressed?

3. Can instabilities in the detector be controlled.

4. Is there always a SNR benefit in being able to absorb more GW energy?

5. Is there a way to utilise 3MI in displacement interferometers?

Acknowlegements

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Australian Consortium for Gravitational Astronomy

Gingin Facility

Australian National University

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