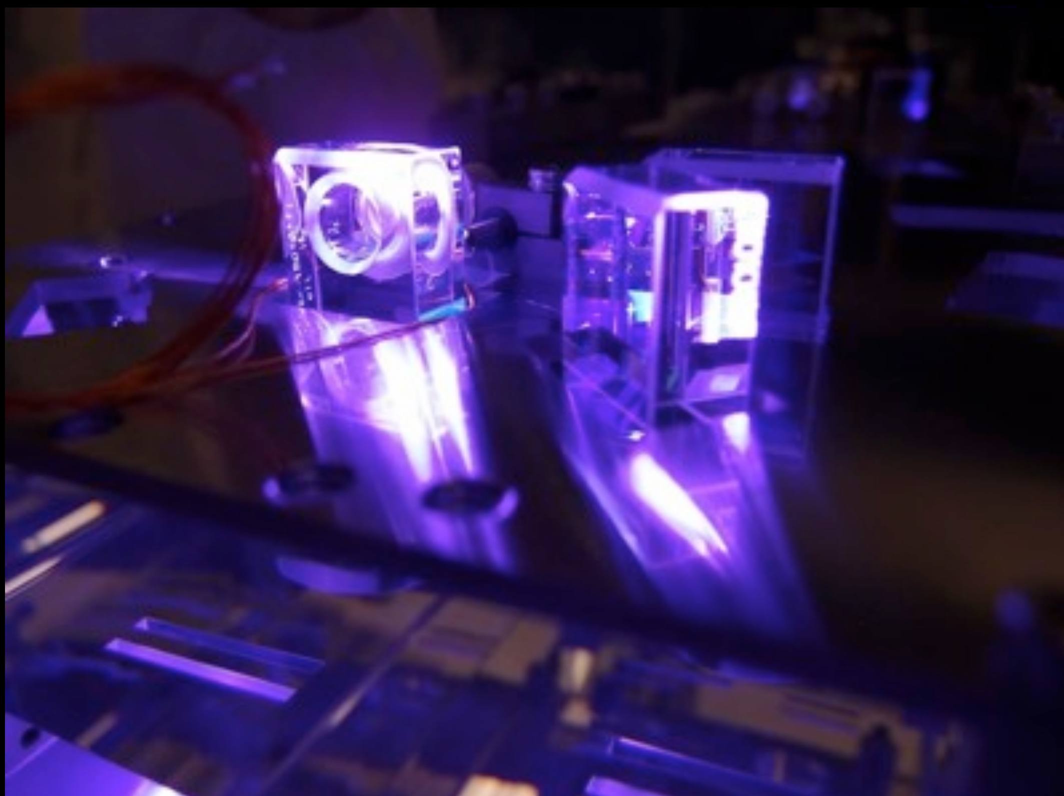
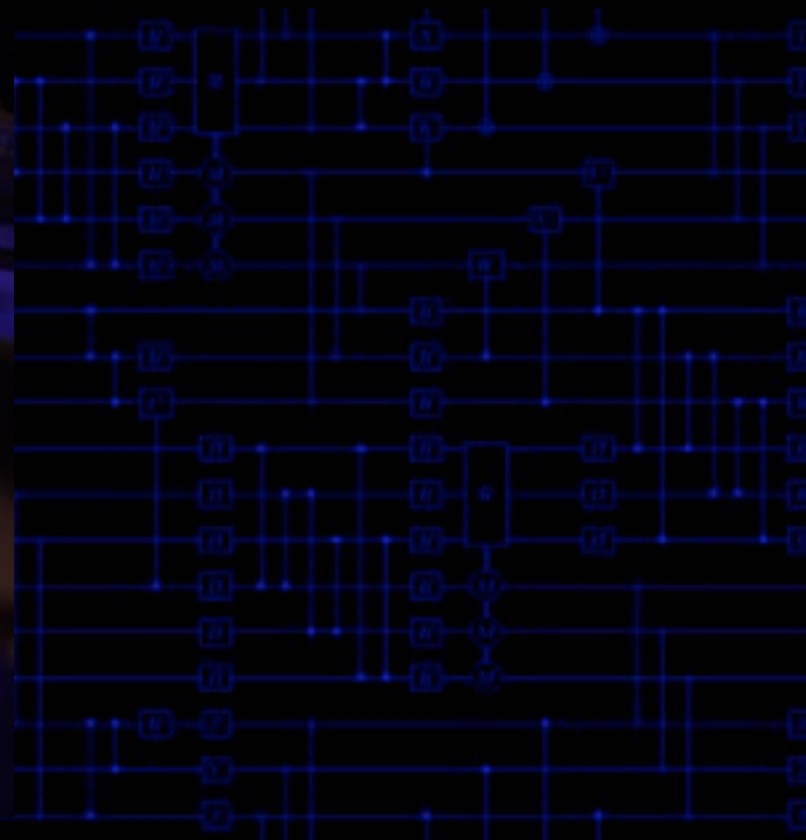
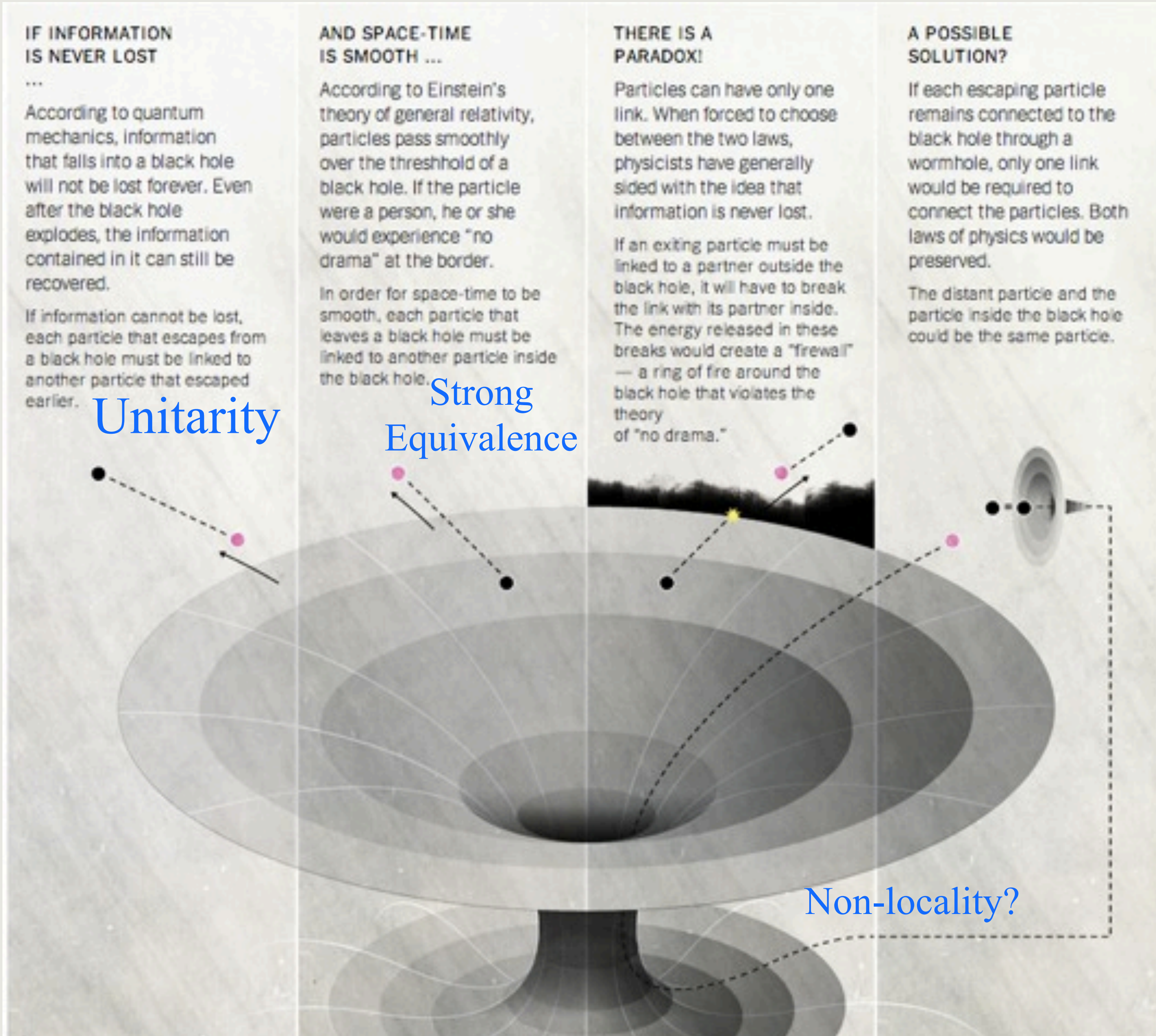
Quantum Measurement Limits in The Gravitational Wave Detectors





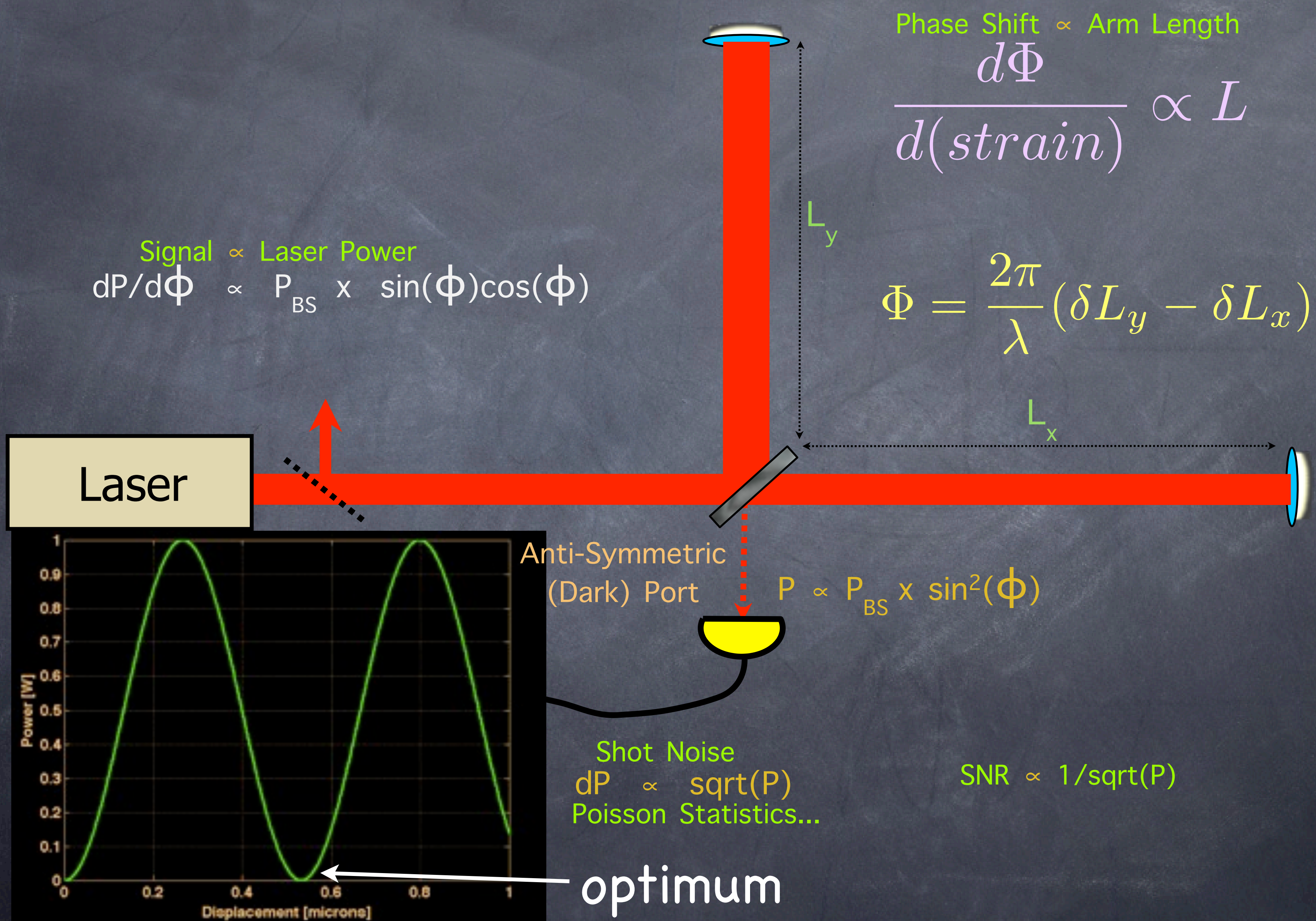
Rana X. Adhikari   ICTS / RRCAT GW School   December 2013



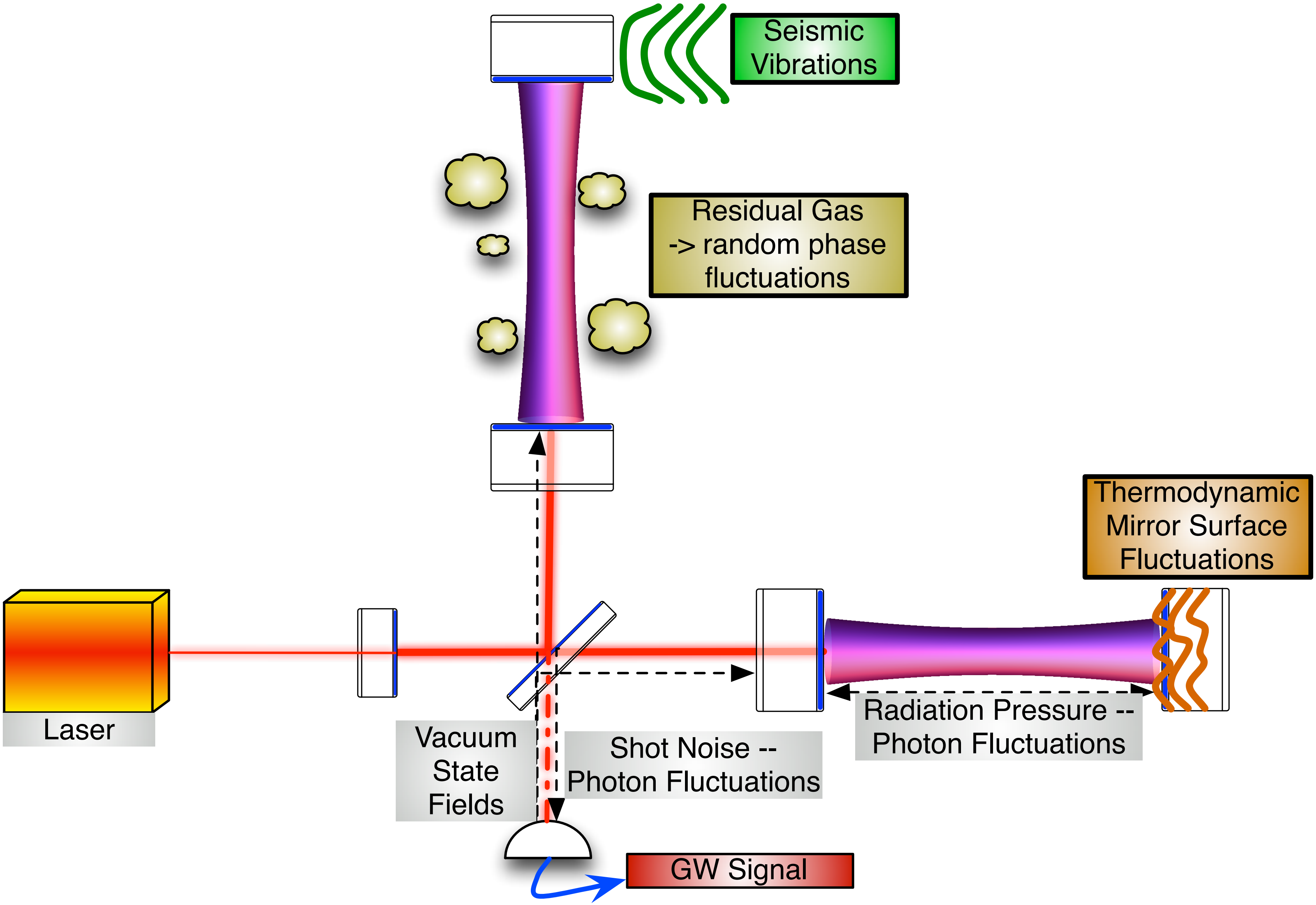
http://www.nytimes.com/2013/08/13/science/space/a-black-hole-mystery-wrapped-in-a-firewall-paradox.html

http://quantumfrontiers.com/2012/12/03/is-alice-burning-the-black-hole-firewall-controversy/

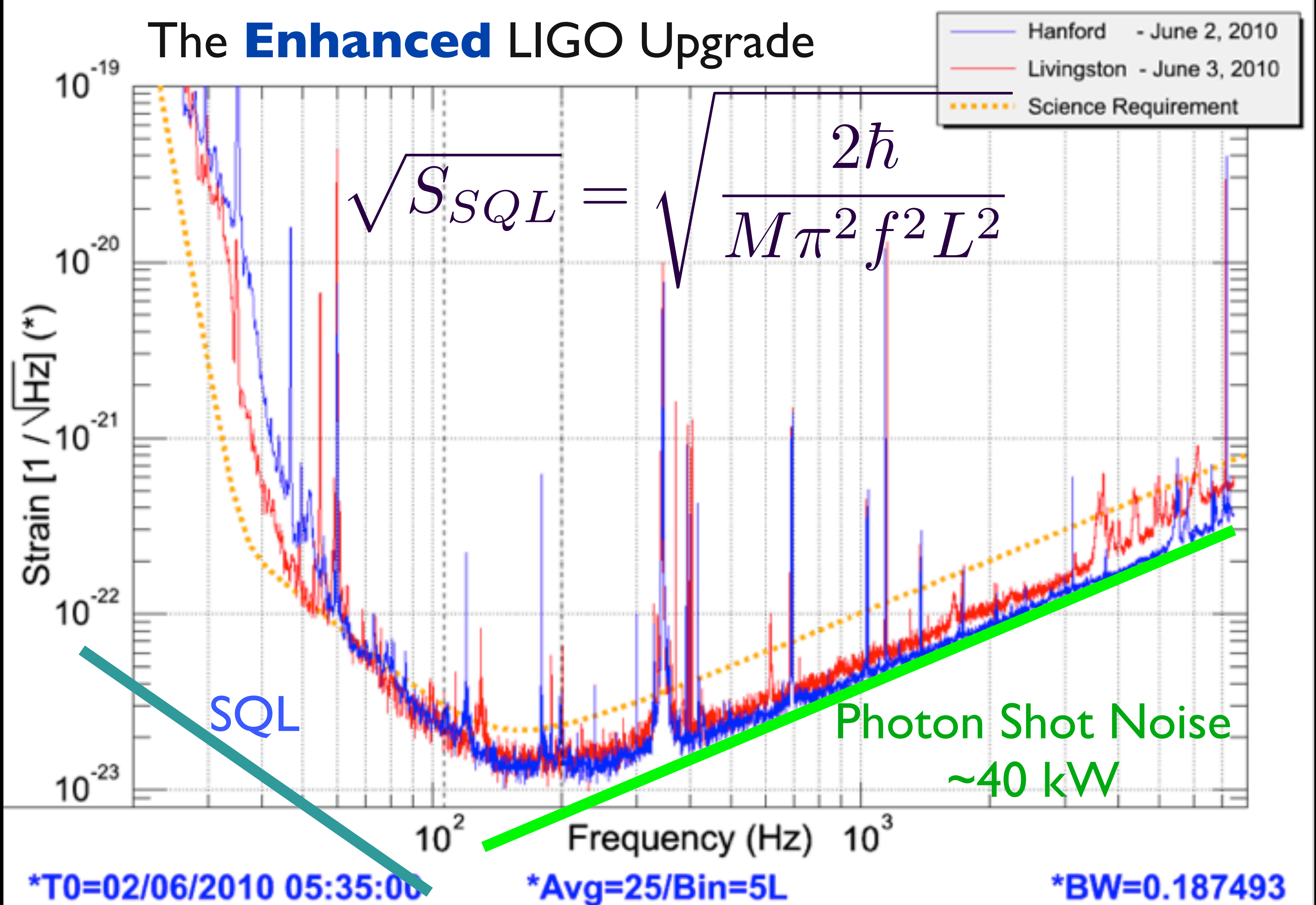
A Michelson Interferometer



LIGO: Major Sources of Noise



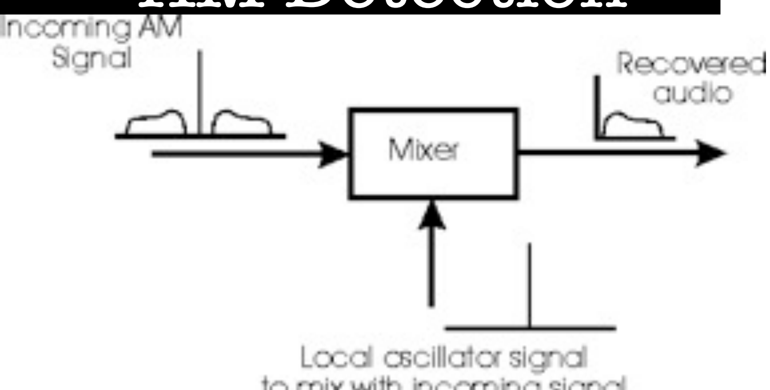
The **Enhanced** LIGO Upgrade



Lock-In Amplifier

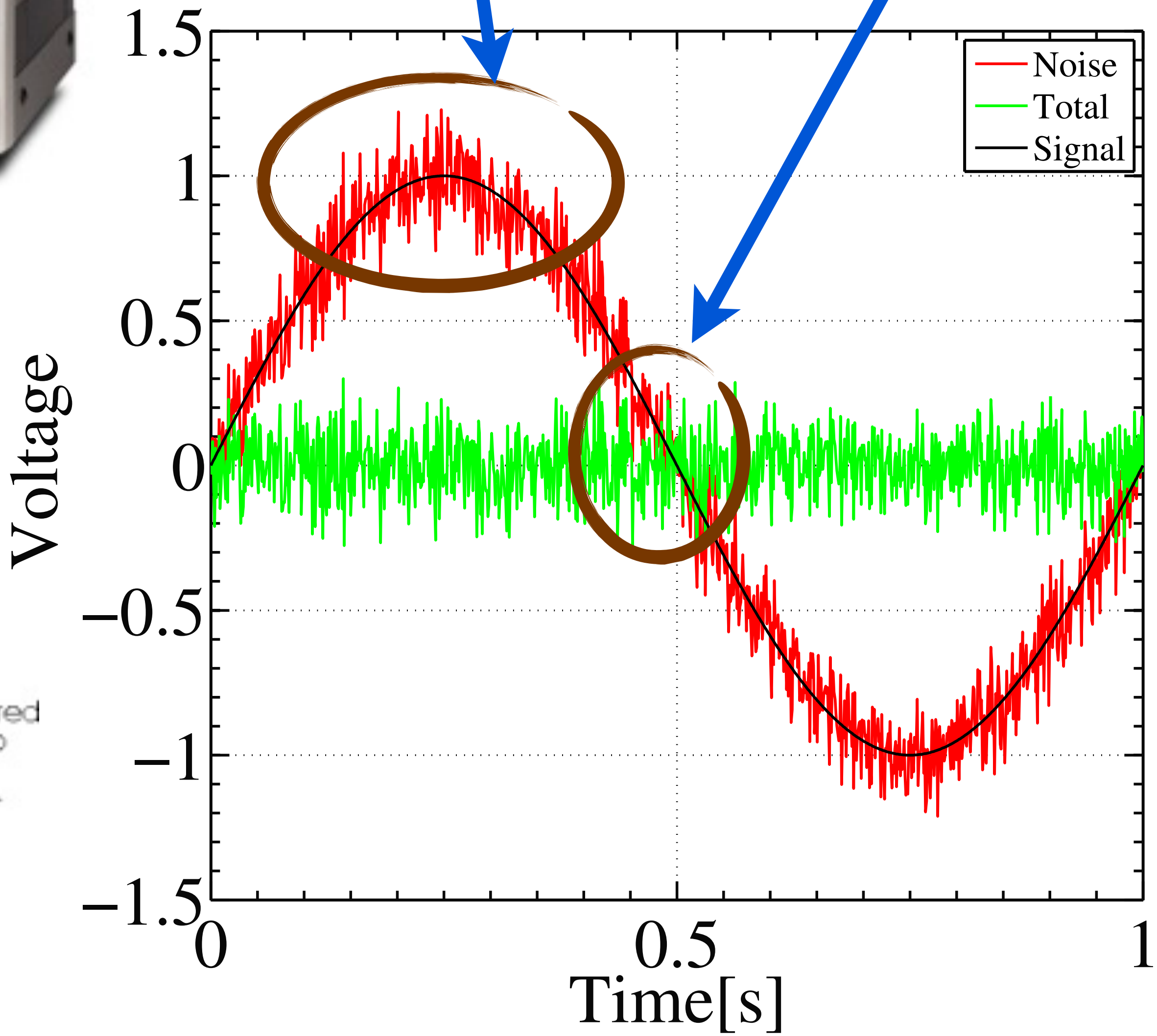
Bob Dicke, MIT/Princeton

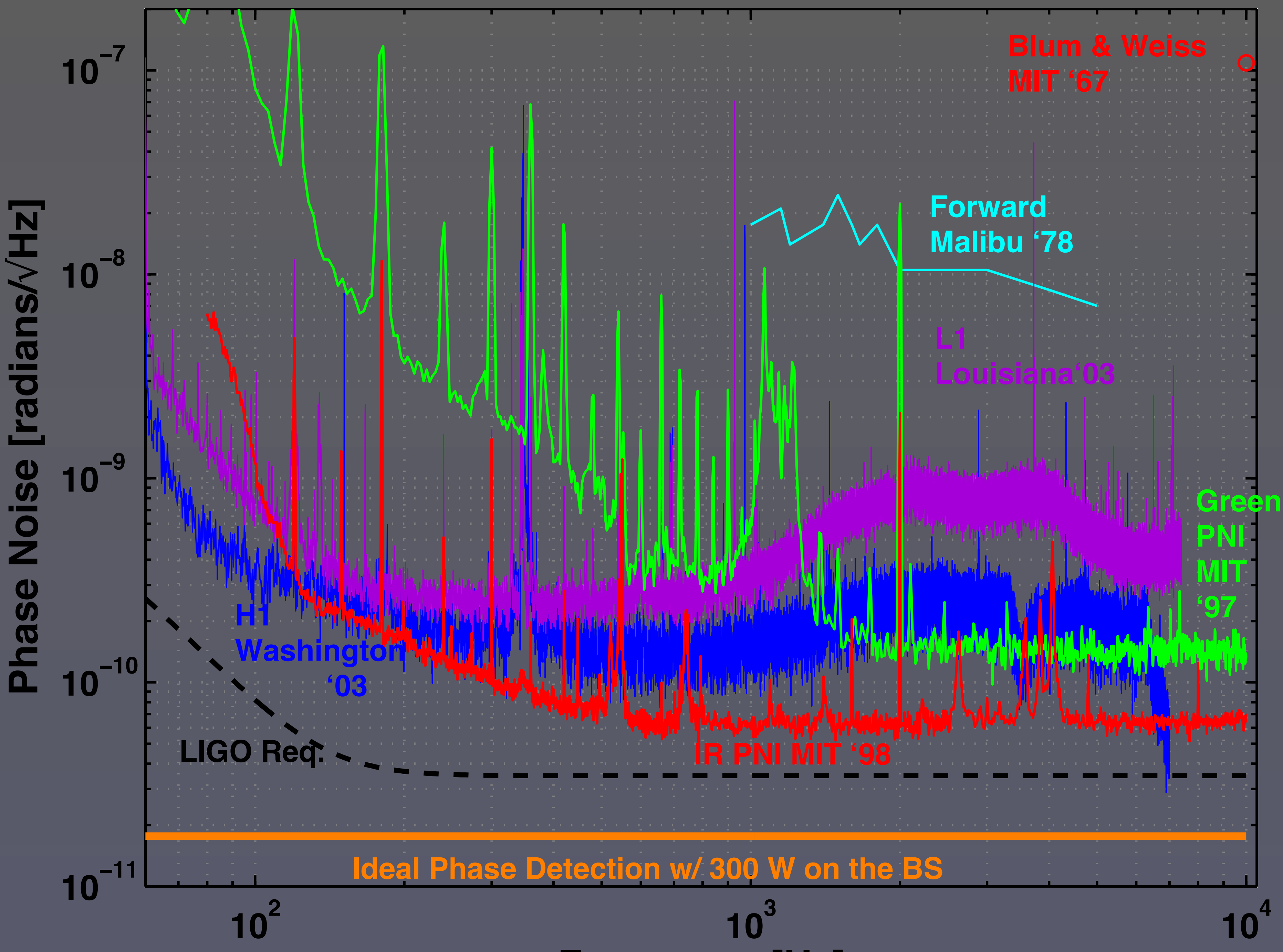
AM Detection



Amplitude Noise

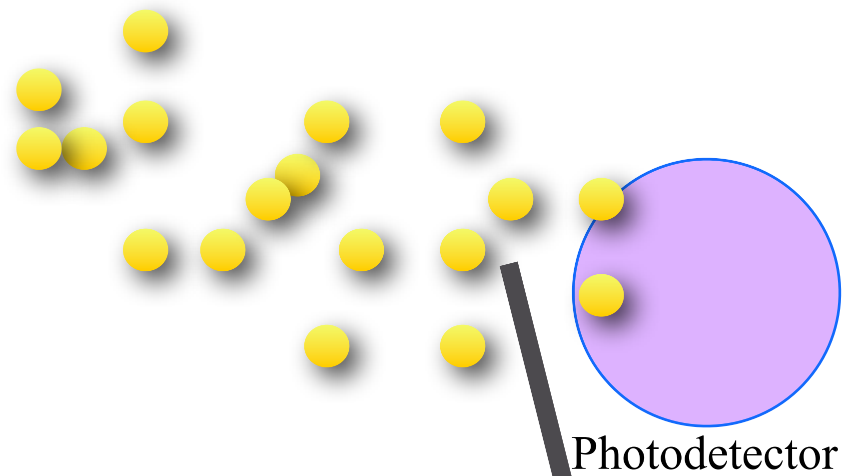
Phase Noise



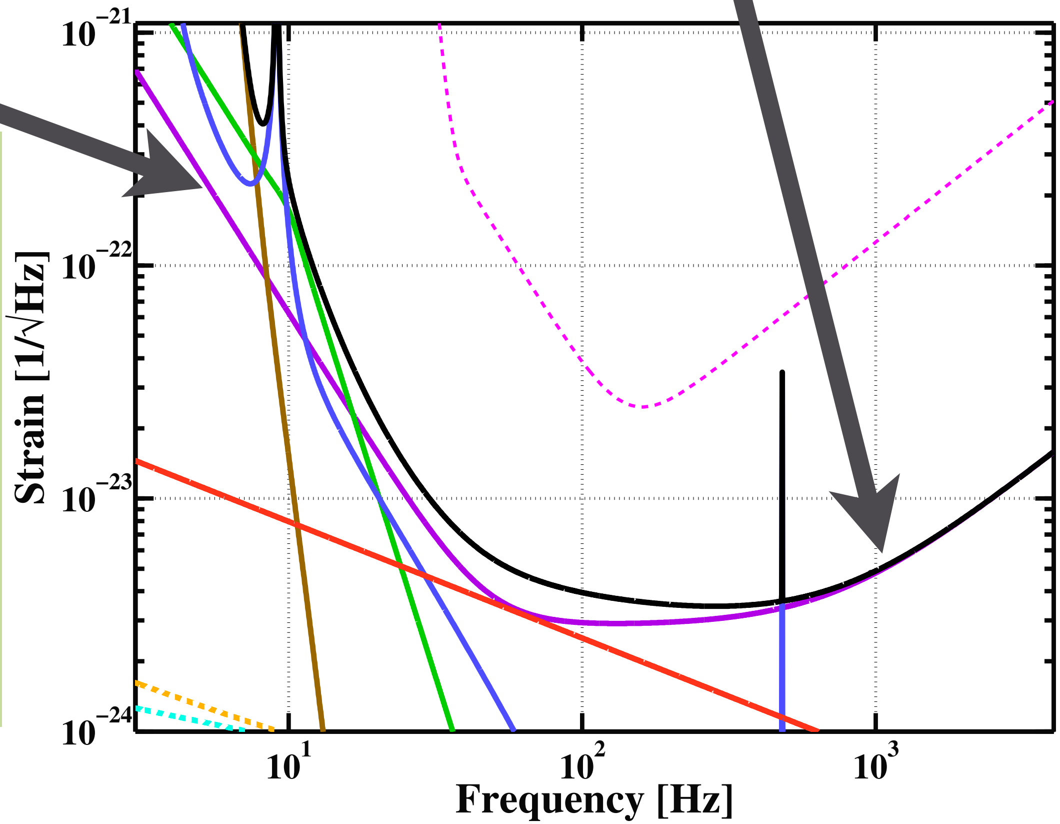

Phase Noise [radians/√Hz]
10−7
10−8
10−9
10−10
10−11
10²
10³
10⁴
Blum & Weiss
MIT '67
Forward
Malibu '78
L1
Louisiana'03
Green
PNI
MIT
'97
H1
Washington
'03
LIGO Req.
IR PNI MIT '98
Ideal Phase Detection w/ 300 W on the BS

What about this Quantum noise?

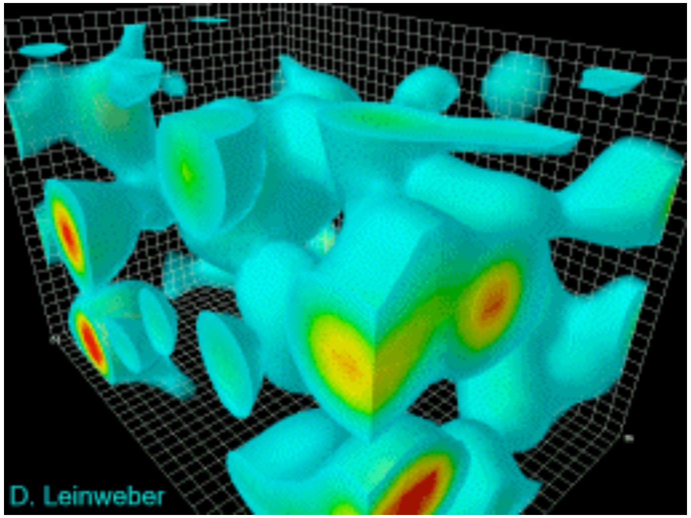
Shot Noise Picture:
Poisson statistics govern arrival time of photons at the photodetector. Also arrival times at the test mass (radiation pressure).

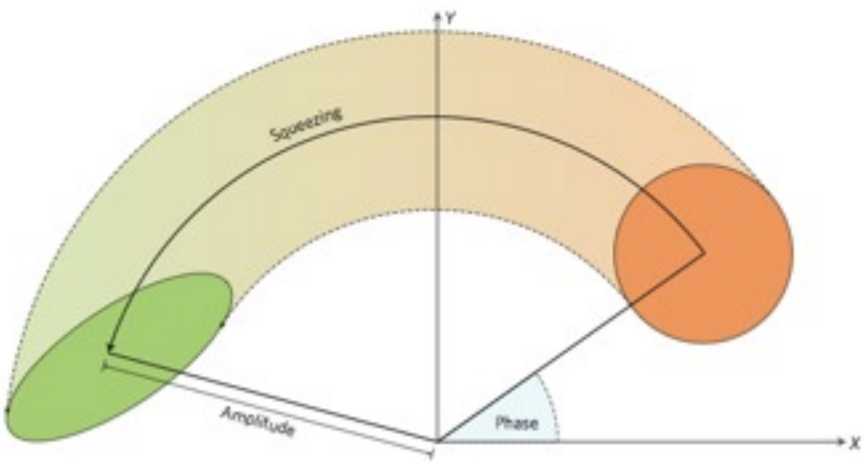


Vacuum Photon Picture:
Losses couple the fluctuating vacuum field to the interferometer. Noise is a beat between the amplitude of the vacuum field and the local field (field at the dark port or field at the test mass).

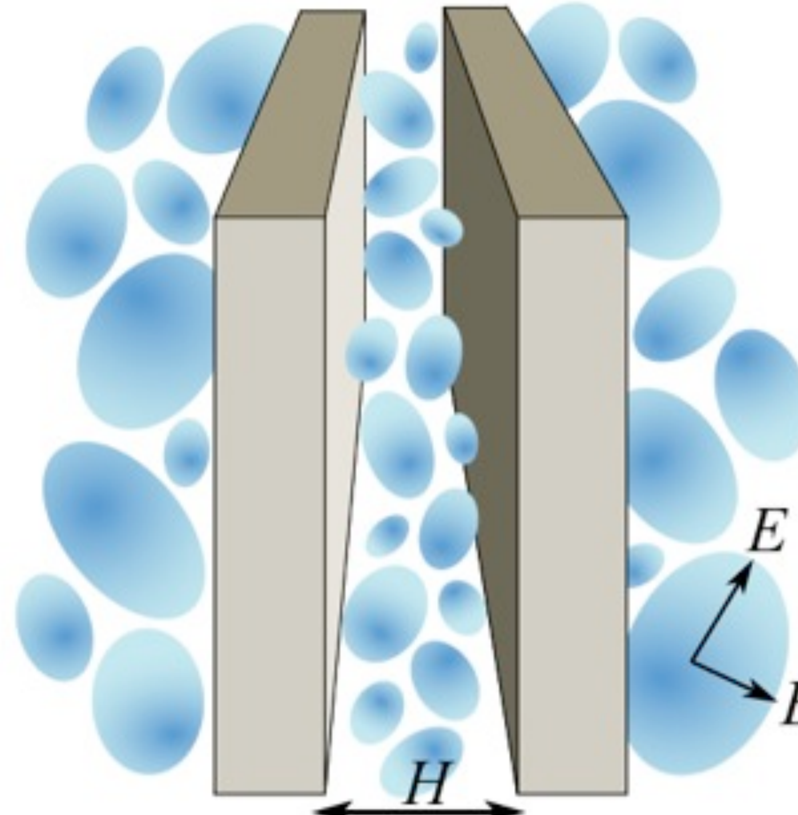


Vacuum State Fluctuations





Warwick Bowen, Nature Photonics (2013)



http://www.mit.edu/~kardar/research/seminars/Casimir2010/talks/Francqui/Casimir.html

[1] C. M. Caves, Physical Review A **31**, 3068 (1985).
[2] H. Miao and Y. Chen, “Adv. Grav. Wave Detectors (2010)

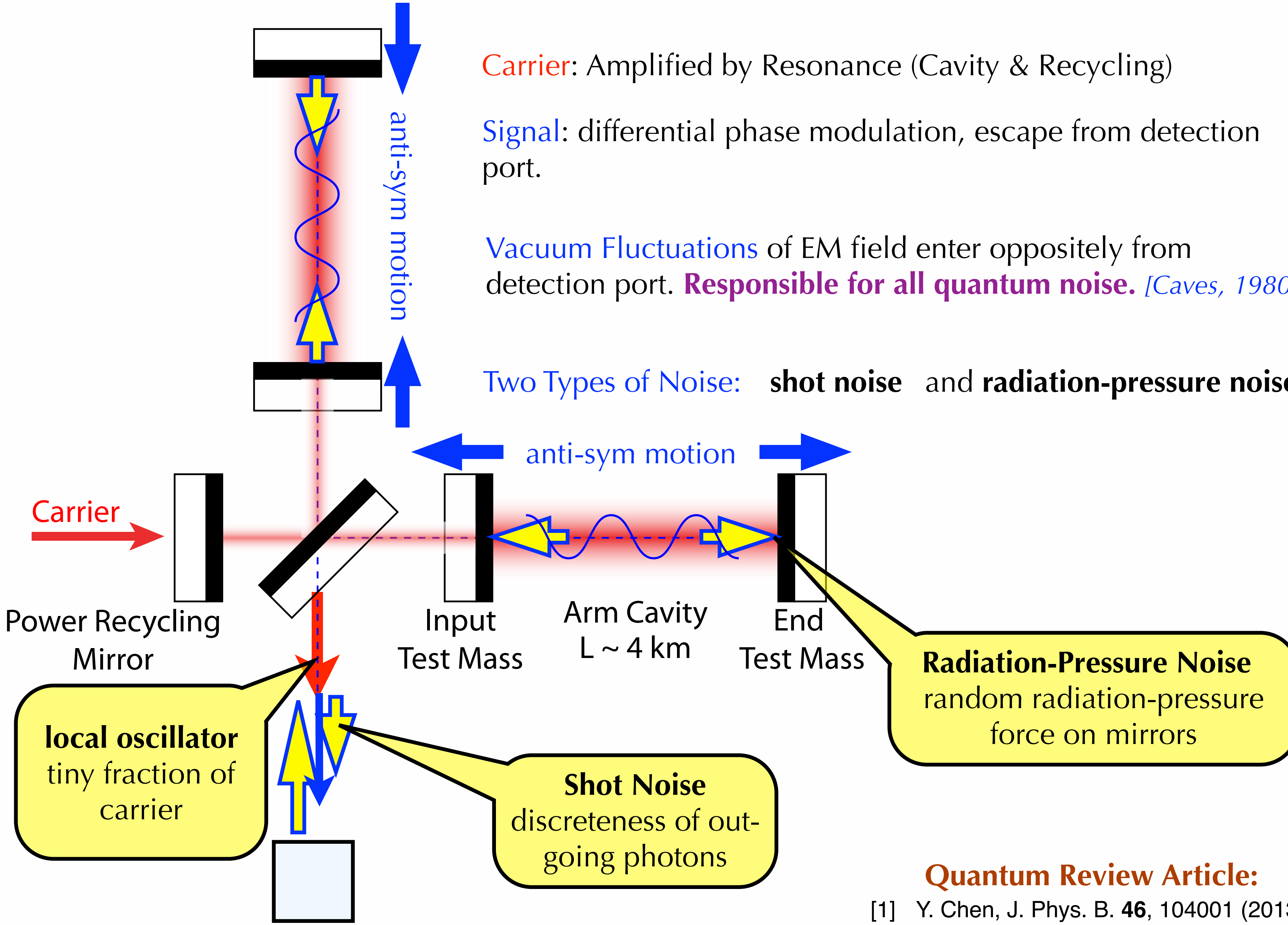
An *Ideal* Fabry-Perot Michelson Interferometer [1]

Carrier: Amplified by Resonance (Cavity & Recycling)

Signal: differential phase modulation, escape from detection port.

Vacuum Fluctuations of EM field enter oppositely from detection port. **Responsible for all quantum noise.** *[Caves, 1980]*

Two Types of Noise: **shot noise** and **radiation-pressure noise**

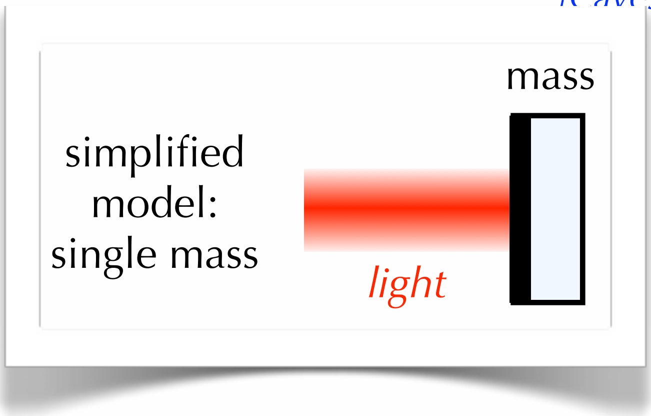


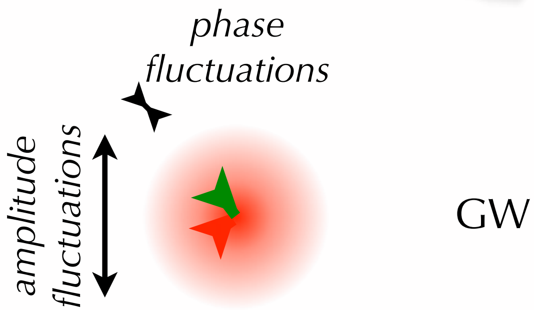
Quantum Review Article:

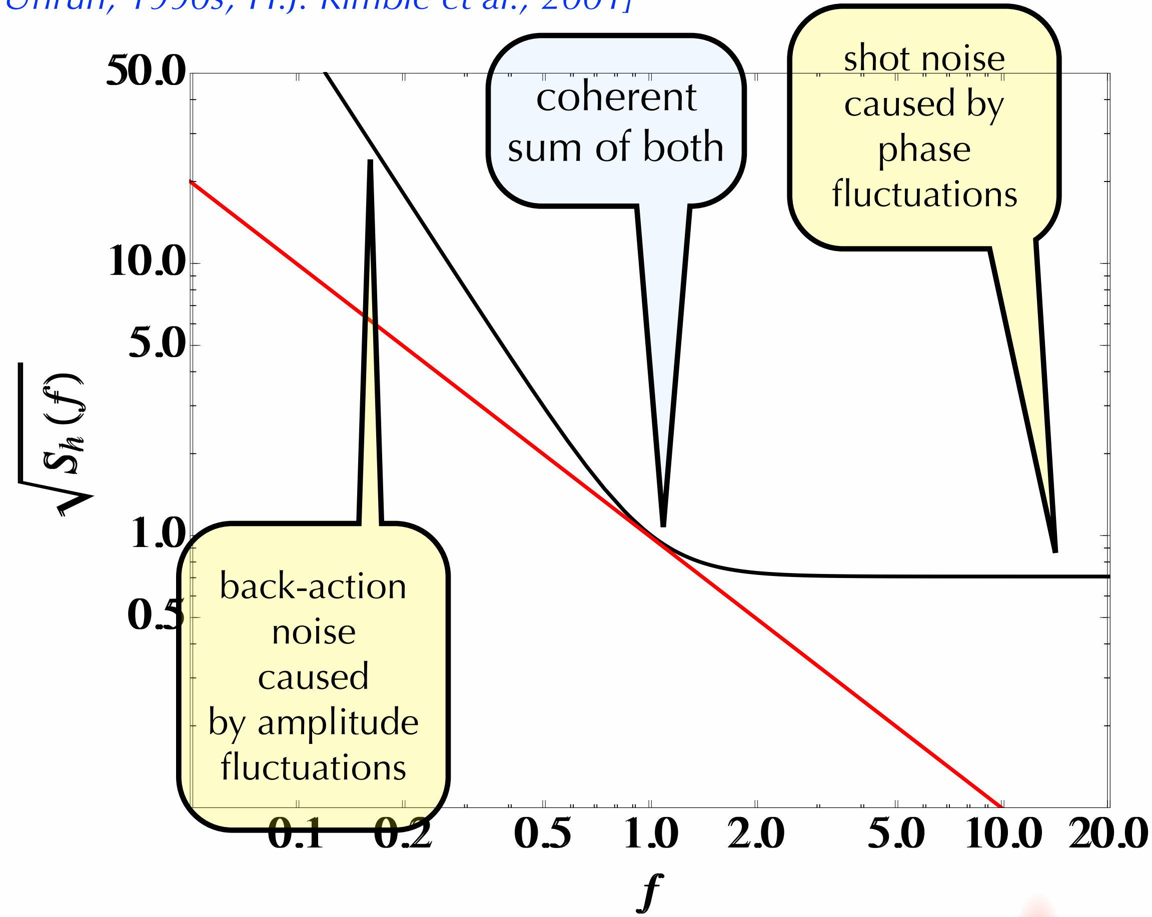
[1] Y. Chen, J. Phys. B. **46**, 104001 (2013).

Building the Necessary Correlation

[Caves, Unruh, 1990s; H.J. Kimble et al., 2001]

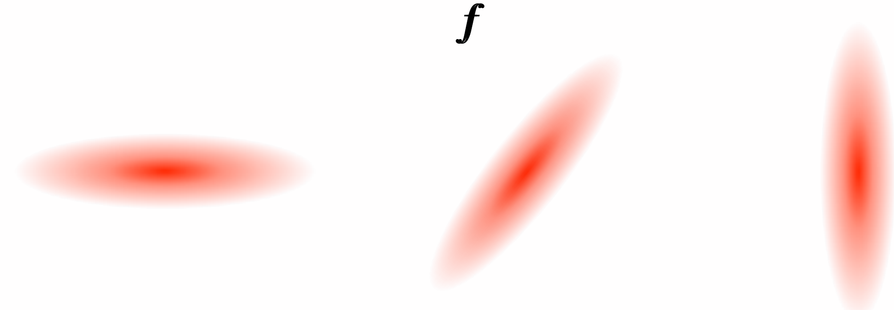






EM field can be prepared into "squeezed states"

Wu, Xiao & Kimble, 1987
R. Schnabel, N. Mavalvala, D.E. McClelland & P. K. Lam, 2010



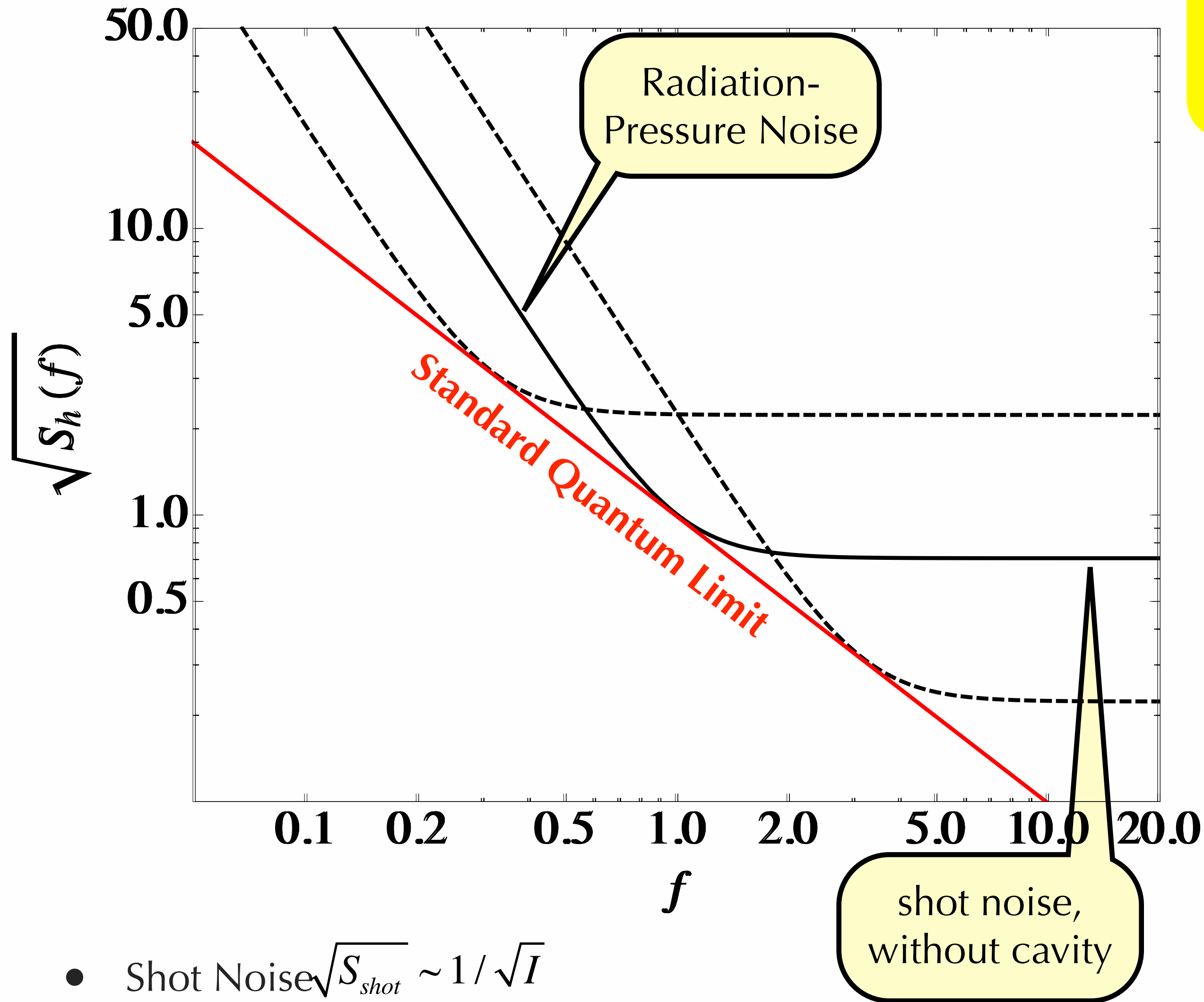
amplitude squeezed

generic squeezed *(with correlation!)*

phase squeezed

Standard Quantum Limit

[Braginsky 1960s, Braginsky and Khalili (1980)]



$S_h(f)$
Noise Spectral Density
(noise power/frequency band)

$\sqrt{f \cdot S_h(f)}$
r.m.s. noise
for broadband signal.

Standard Quantum Limit

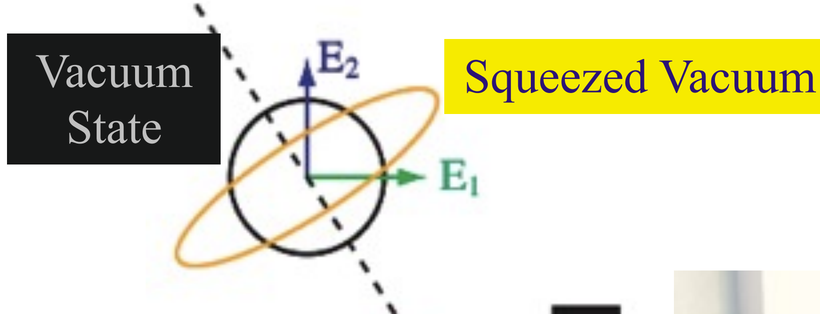
$$\sqrt{S_h^{SQL}} = \sqrt{\frac{8\hbar}{M\Omega^2 L^2}}$$

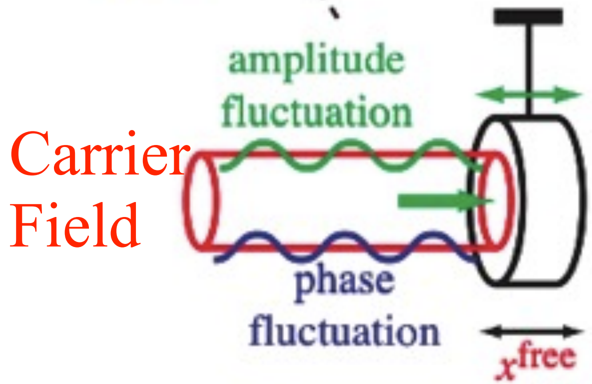
- Shot Noise $\sqrt{S_{shot}} \sim 1/\sqrt{I}$
- Radiation-Pressure Noise $\sqrt{S_{\text{rad press}}} \sim \sqrt{I}/(M\Omega^2)$

Trade-off Between Shot Noise and Radiation-Pressure Noise: **Standard Quantum Limit**

Circumventing Usual Quantum Noise

http://www.ligo.org/magazine/LIGO-magazine-issue-3.pdf





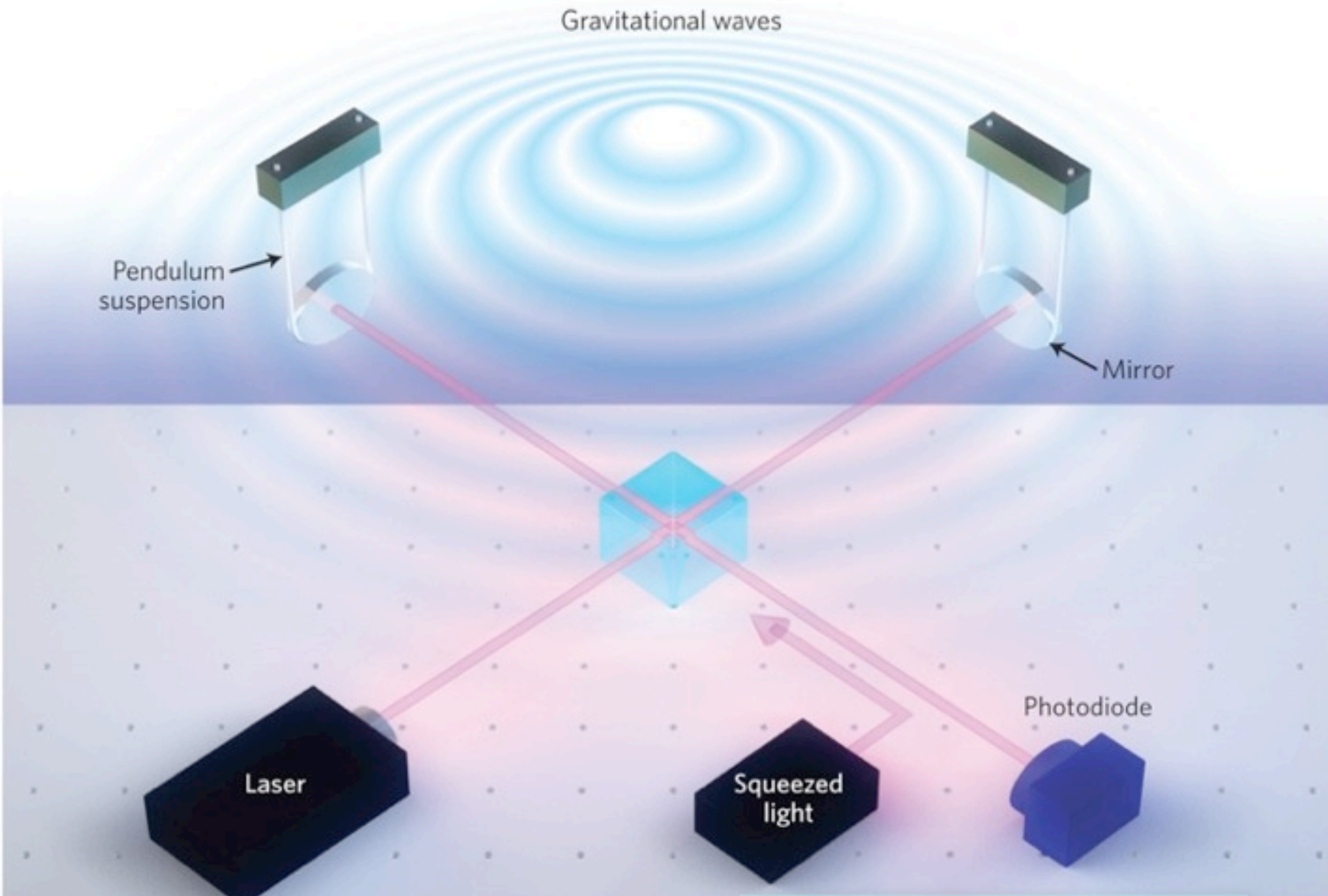
Atomic Polarization of a Dielectric Medium

$$P = \varepsilon_0(\chi^{(1)}E + \chi^{(2)}E^2 + \chi^{(3)}E^3 + \ldots)$$

Braginsky, Vorontsov and Thorne, Science (1980)

C. M. Caves, PRD (1981)

Wu, Kimble, Hall, Wu, PRL (1986)

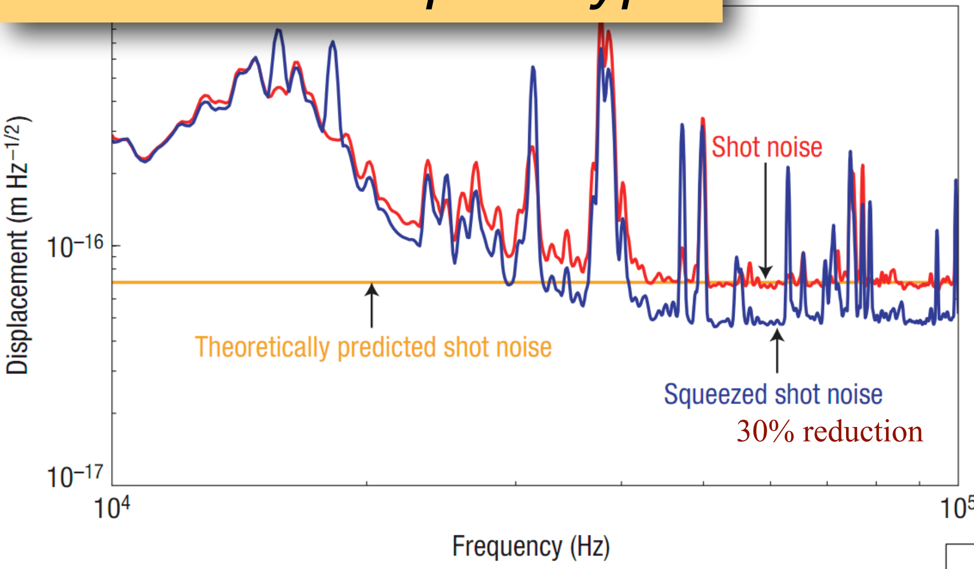


Squeezed Light Cartoon

Nature Photonics (2013)

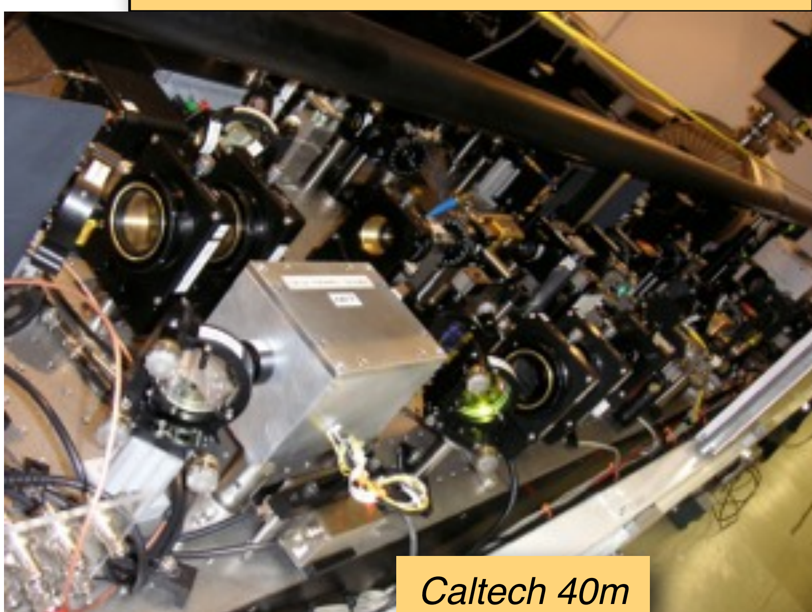
Squeezed Interferometers

Caltech 40 m prototype

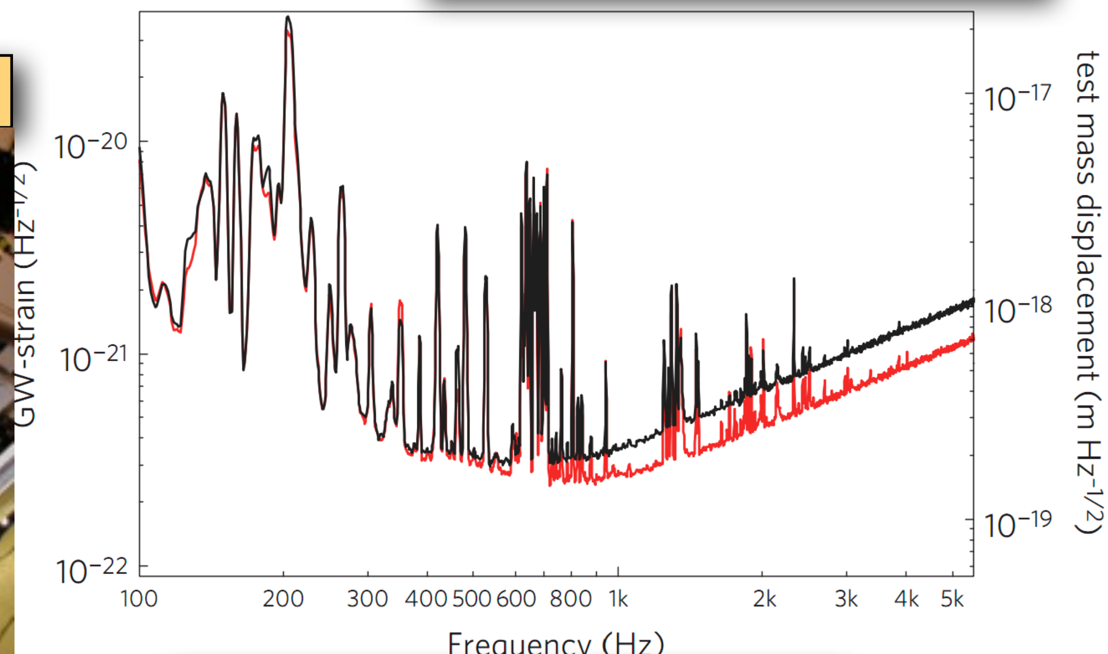


K. Goda, et al., Nature Physics (2008)

GEO Squeezer (Hannover)

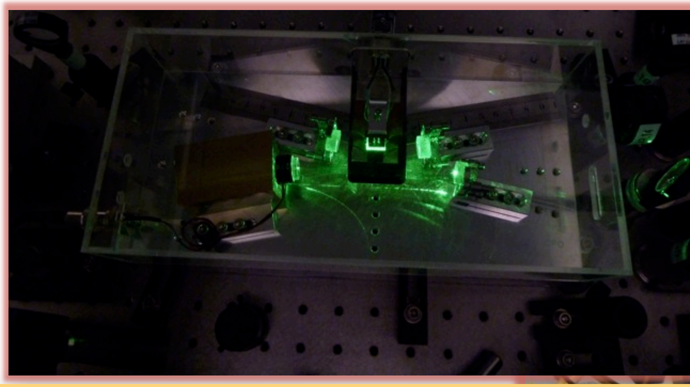


Caltech 40m



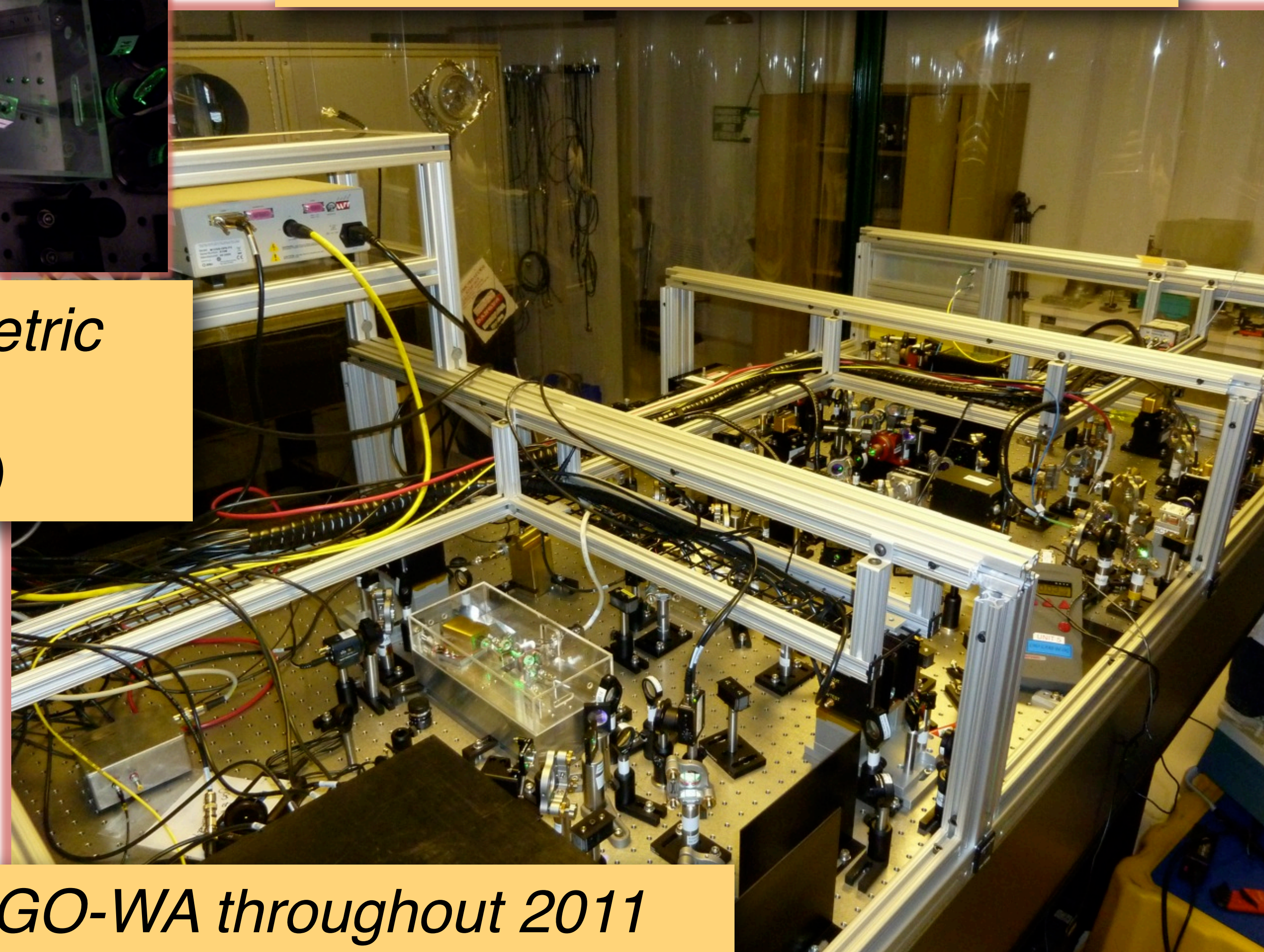
LIGO, Nature Physics (2011)

Squeezed Light in Action: LIGO 4km



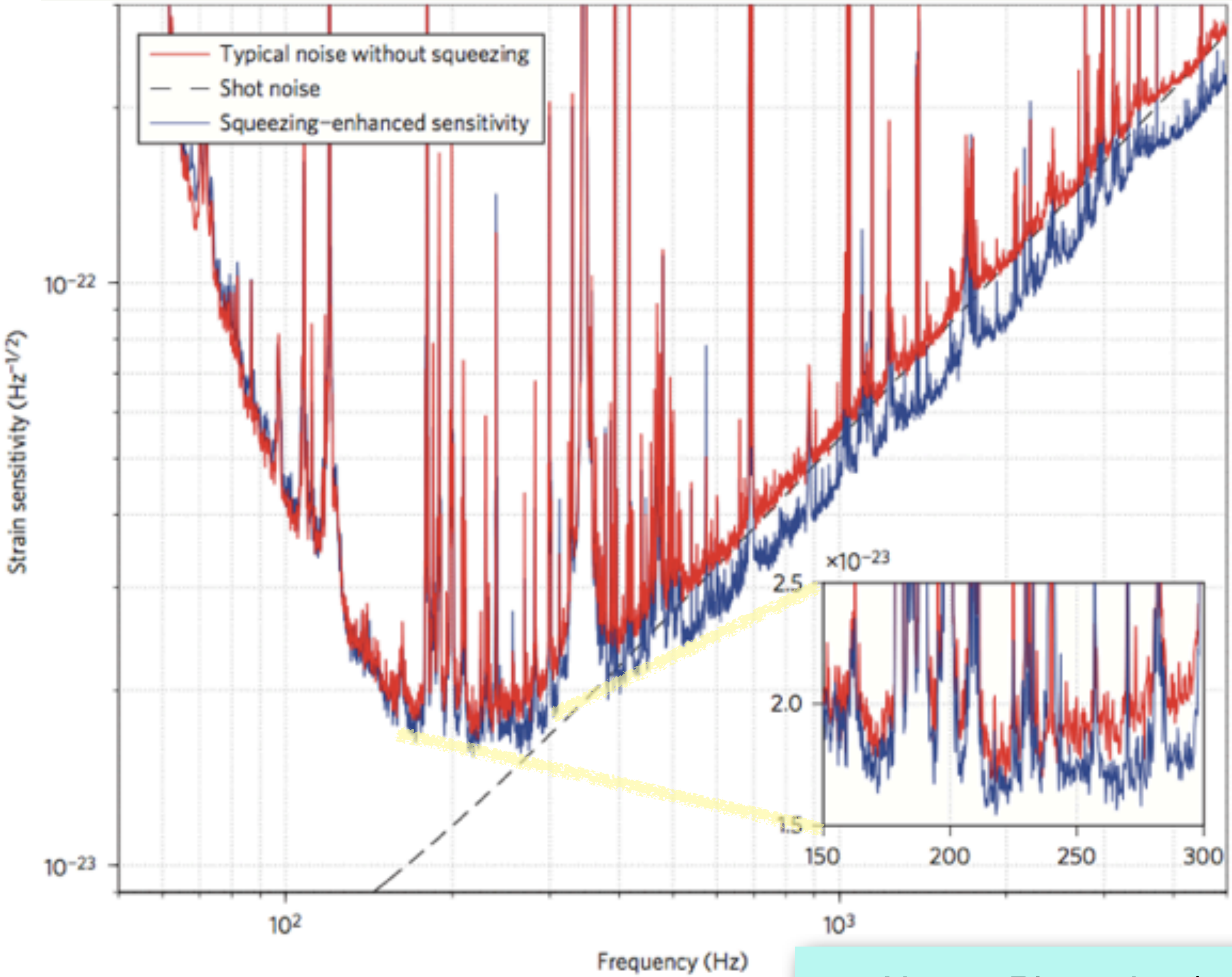
Optical Parametric Oscillator (from ANU)

Squeezed Light Injection Table



Installed at LIGO-WA throughout 2011

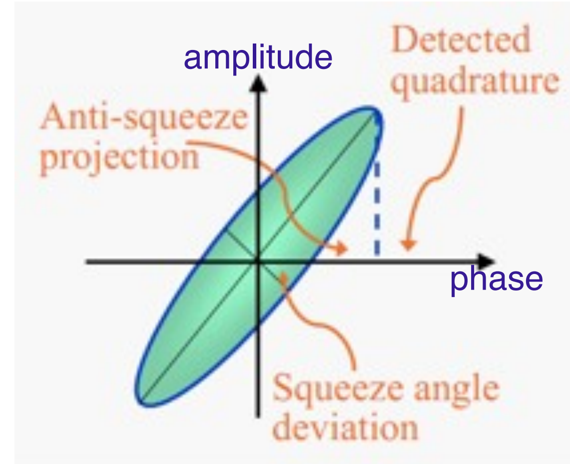
Squeezed Light in Action: LIGO 4km

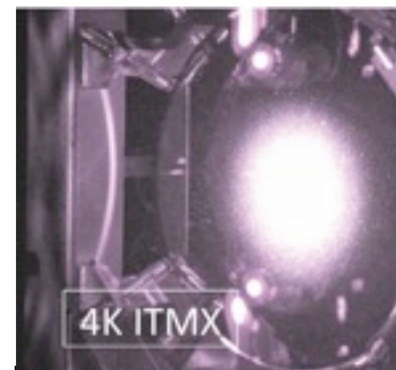


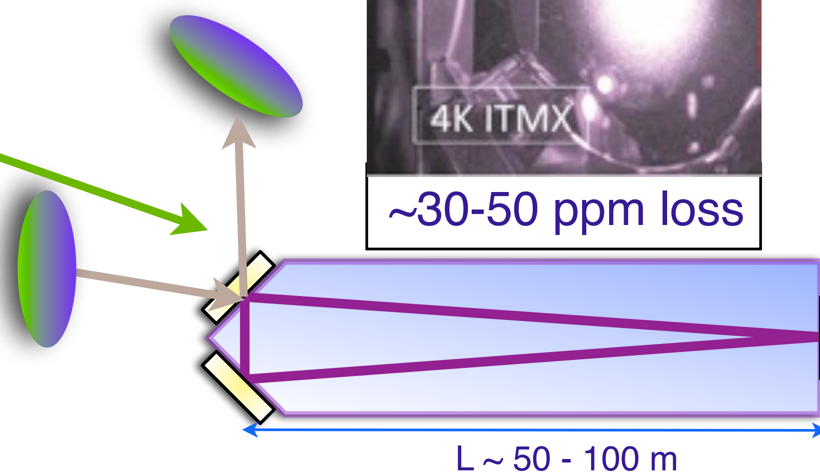
Nature Photonics (2013)

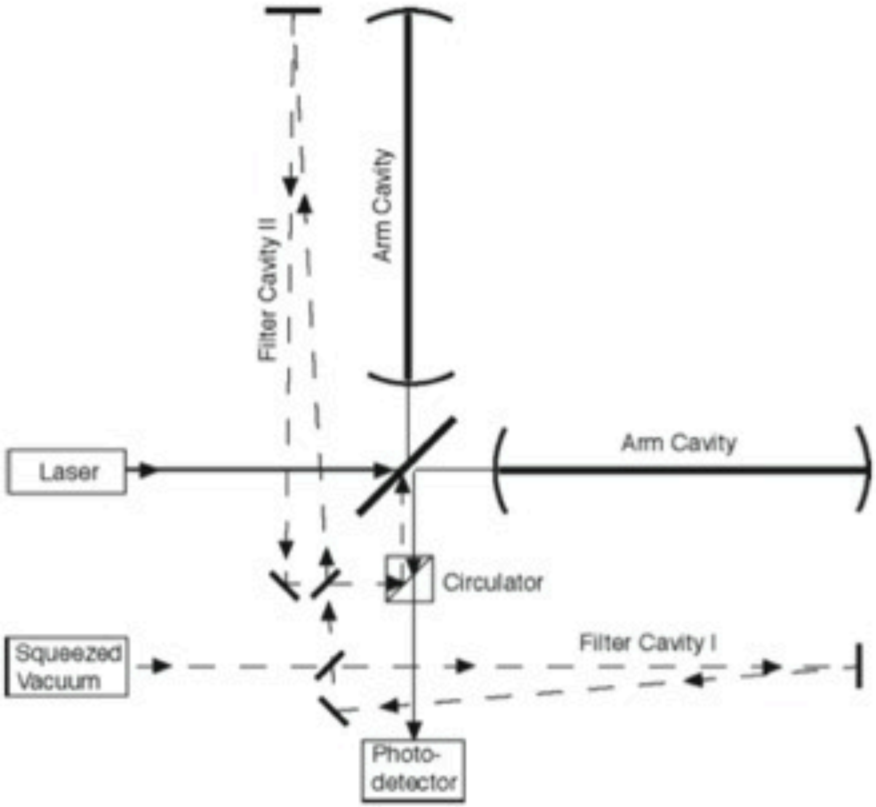
Beyond the Conventional Squeezing

- Shot Noise limits at high frequency
- Quantum Radiation Pressure fluctuations limit at low frequencies
- Laser power ‘knob’ allows for a trade off; limited by interferometer thermal instability on the high power end
- **Squeezed Light Injection** can re-allocate the quantum noise (phase noise v. amplitude noise)
    - Demonstrated on IFOs at GEO600, LIGO Hanford
- ***Frequency Dependent*** Squeeze Angle
    - Long cavities act as optical phase shifters
- **Needs:**
    - **Ultra-low loss optics (~10 ppm / bounce)**
    - 10 dB of squeezing *into the interferometer*
    - Low loss viewports, isolators, etc.



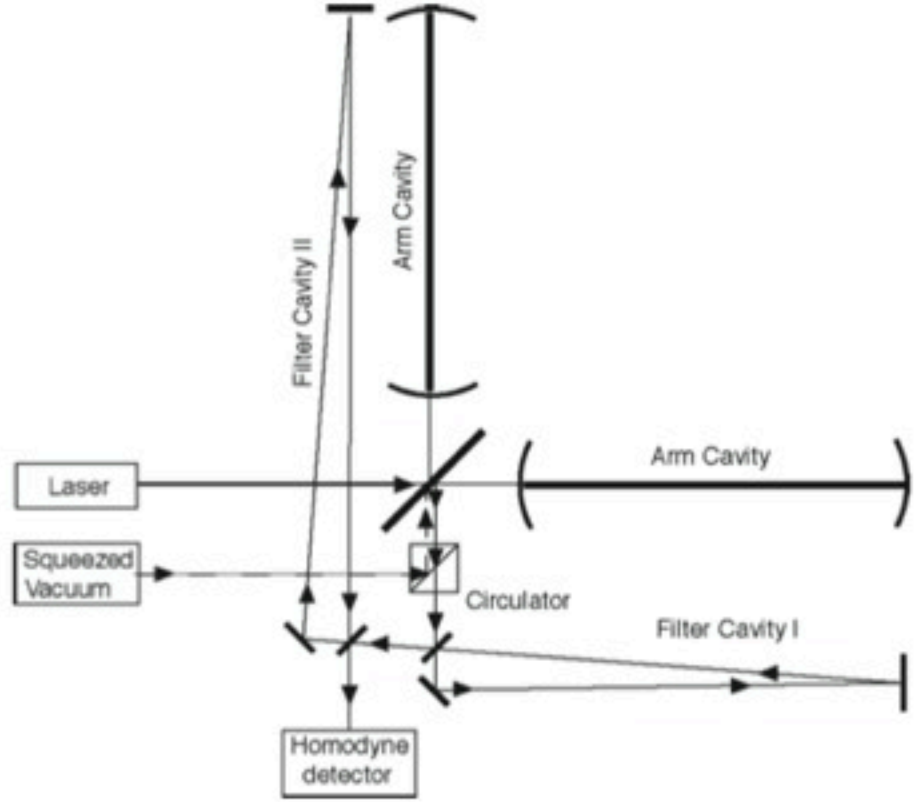






Squeezed Input

frequency dependent
input squeezing quadrature



Variational Readout

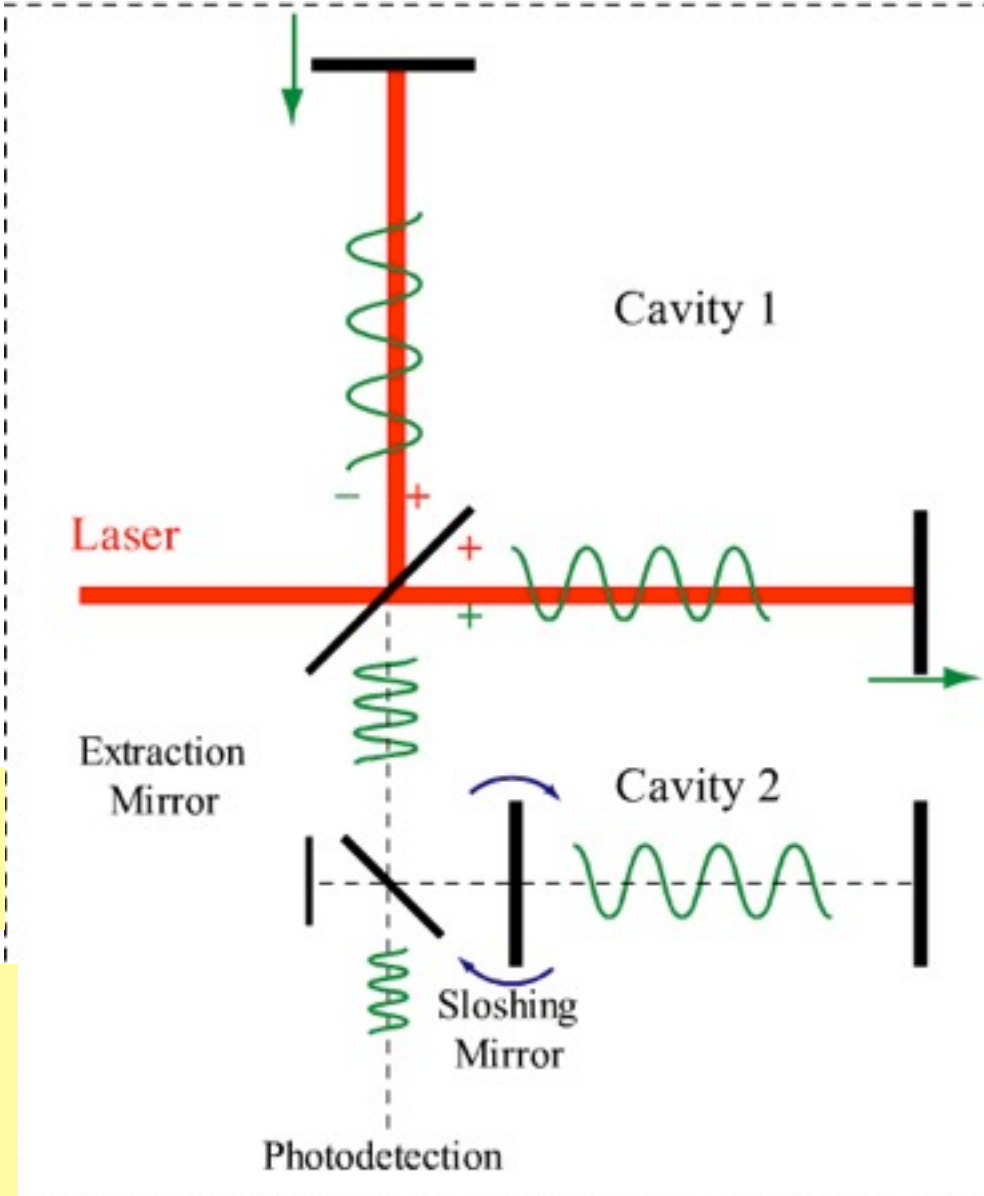
frequency dependent
readout quadrature

QND via momentum

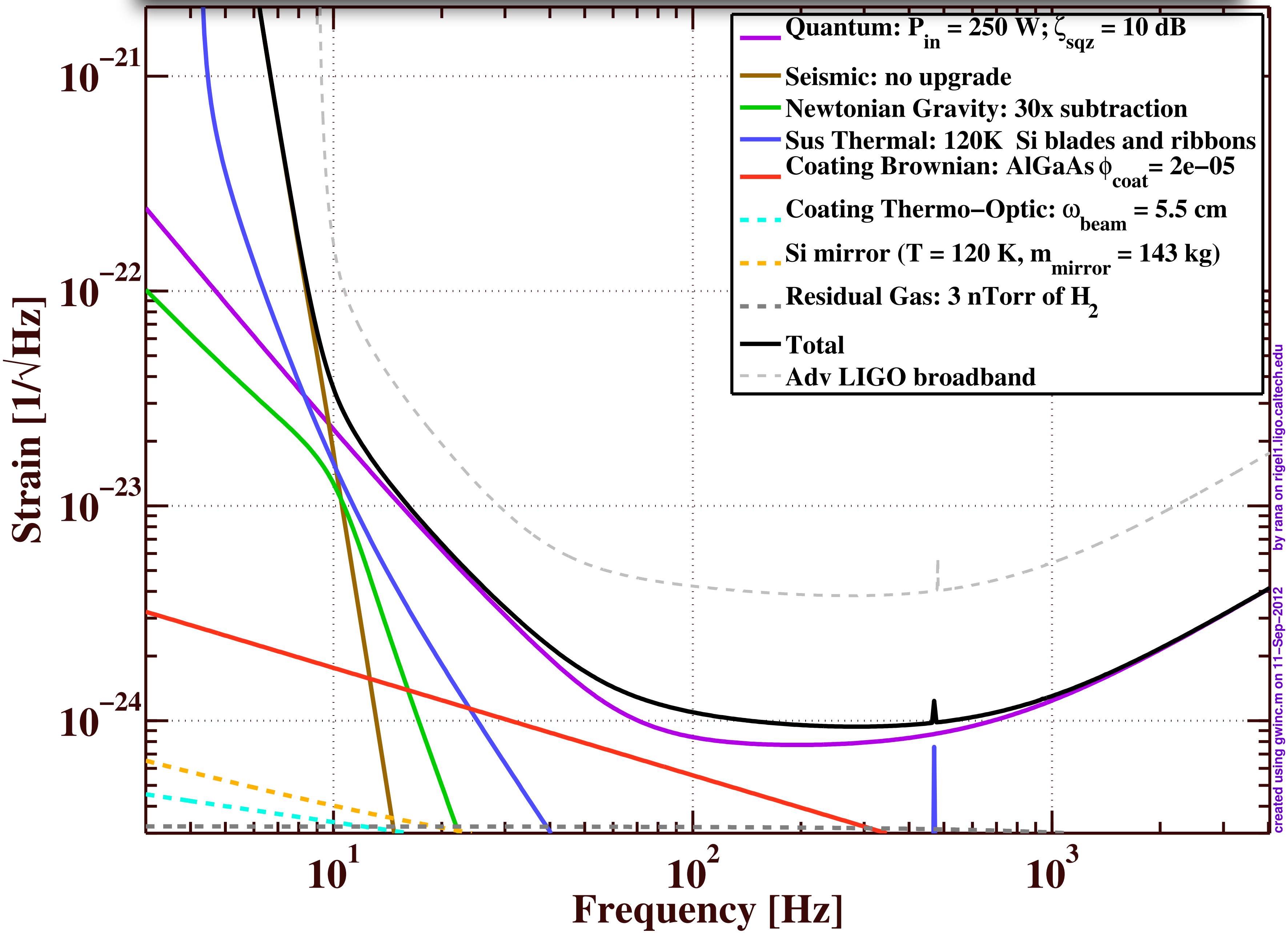
- Radiation pressure noise from dark port
- Some light experiences delay via the sloshing cavity
- Delay leads to phase flip for momentum kicks
- **Broadband Speedmeter**
  - req. low loss optics
  - **req. very long cavities**

Momentum is a QND observable

Observe momentum, perturb position. Position noise doesn't influence momentum.



3rd Generation LIGO



SUMMARY

- Quantum Measurement limits due quantization of the light, not the test mass.
- Quantum Noise comes from quantization of the electromagnetic field, *not* from the statistical nature of the beamsplitter or statistics of the laser itself.
- Empty space (the EM ground state) has EM fluctuations. **This is the source of Quantum noise**.
- Non-classical fields can be generated with modified variance.
- These non-classical fields can improve measurement sensitivity.