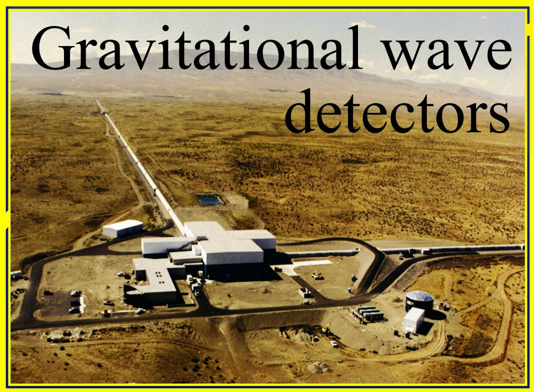
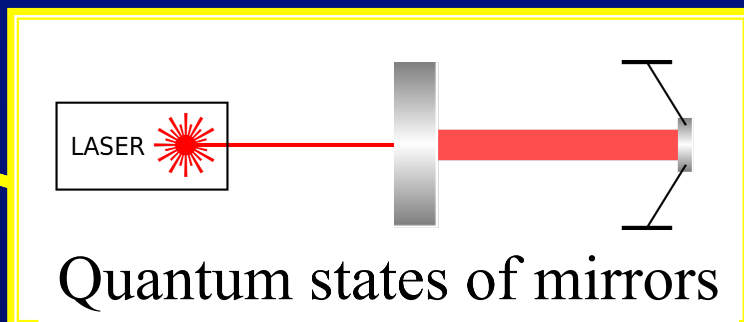
Quantum Opportunities in Gravitational Wave Detectors



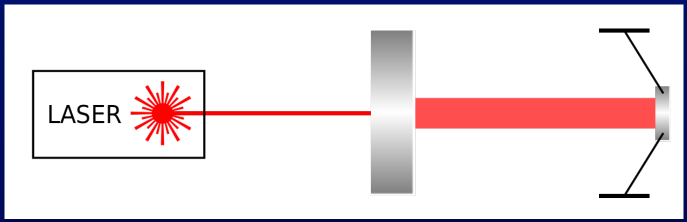


Nergis Mavalvala, MIT
@ APS, April 2011

Two revolutions

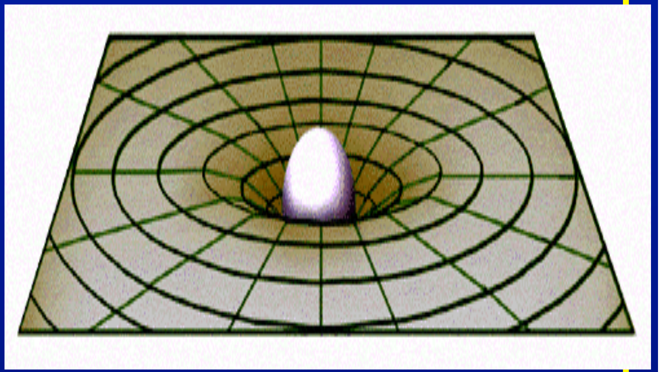
- Direct observation of gravitational waves should open a new window into the Universe
- Gravitational wave detectors are the most sensitive position meters ever constructed
- The quantum limit in gravitational wave detectors opens up a whole new field of study
- Quantum opportunities in gravitational wave detectors
  - Applications of quantum optics techniques

  - New tools for quantum measurement on truly macroscopic (human) scales



Gravitational waves (GWs)

- Prediction of Einstein's General Relativity (1916)
- Indirect detection led to Nobel prize in 1993
- Ripples of the space-time fabric
- GWs stretch and squeeze the space transverse to direction of propagation
- Emitted by accelerating massive objects
  - Cosmic explosions
  - Compact stars orbiting each other
  - Stars gobbling up stars
  - "Mountains" on stellar crusts



$$h_{GW} = \frac{\Delta L}{L}$$

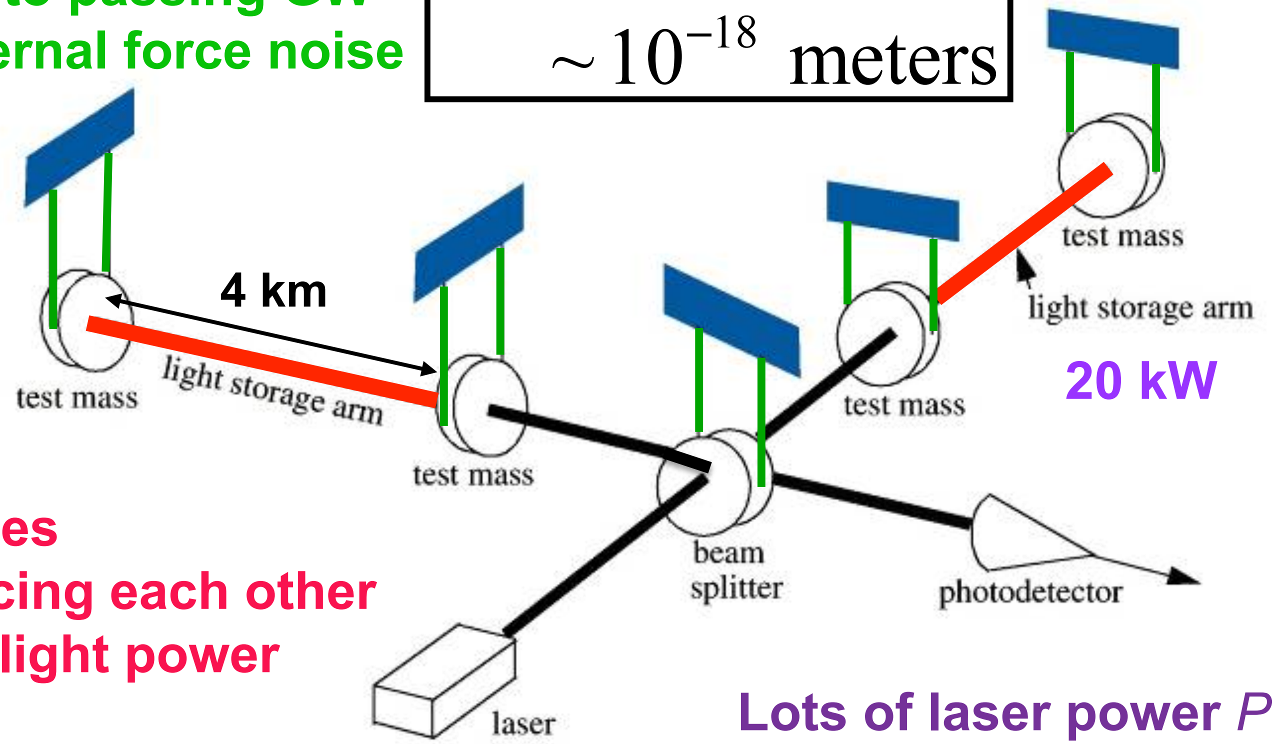
$$h_{GW} \sim 10^{-21}$$

☹

GW detector at a glance

Mirrors hang as pendulums
- Quasi-free particles
- Respond to passing GW
- Filter external force noise

$$\Delta L = h_{GW} L$$
$$= 10^{-21} \times 4000$$
$$\sim 10^{-18} \text{ meters}$$

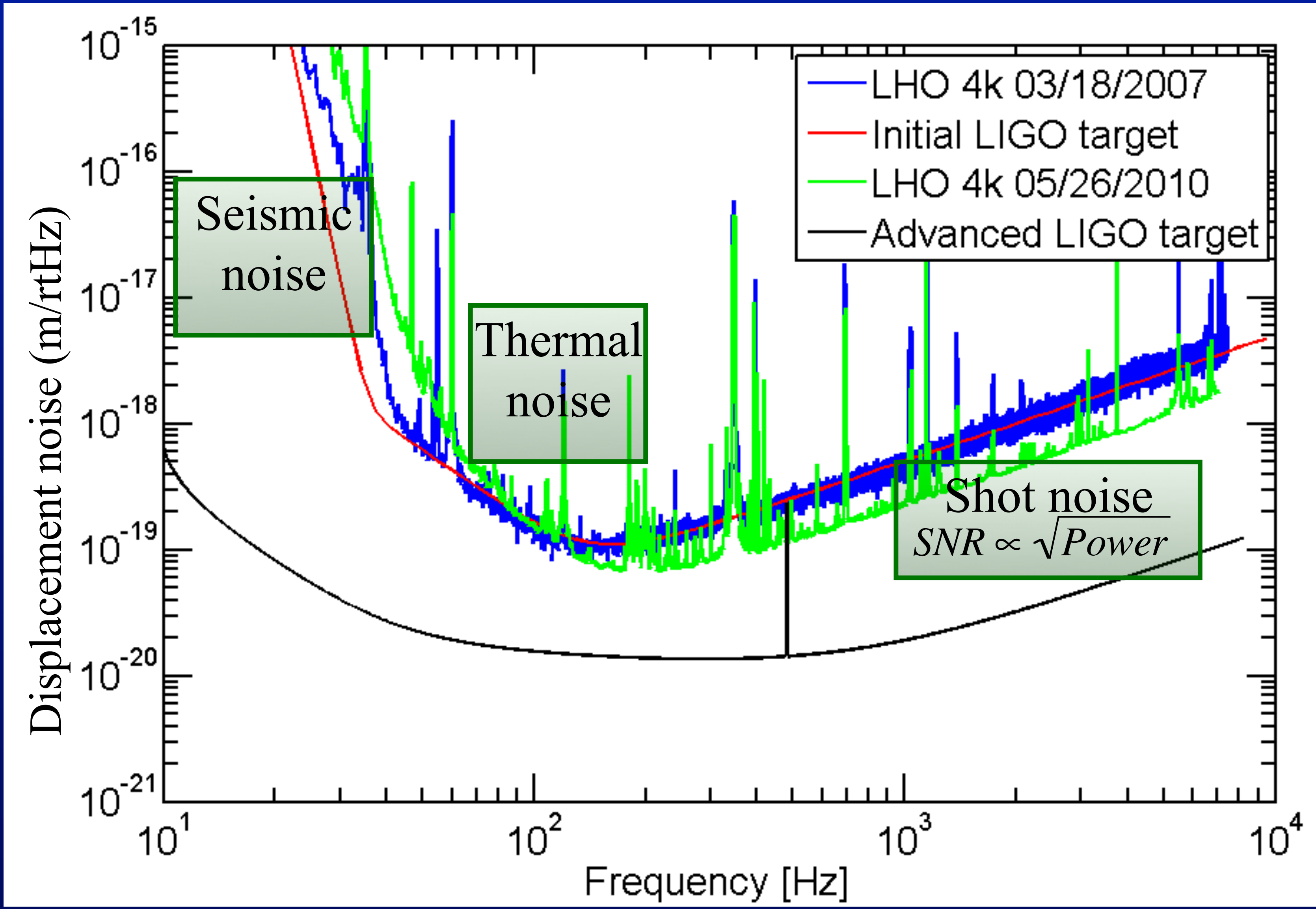


Optical cavities
- Mirrors facing each other
- Builds up light power

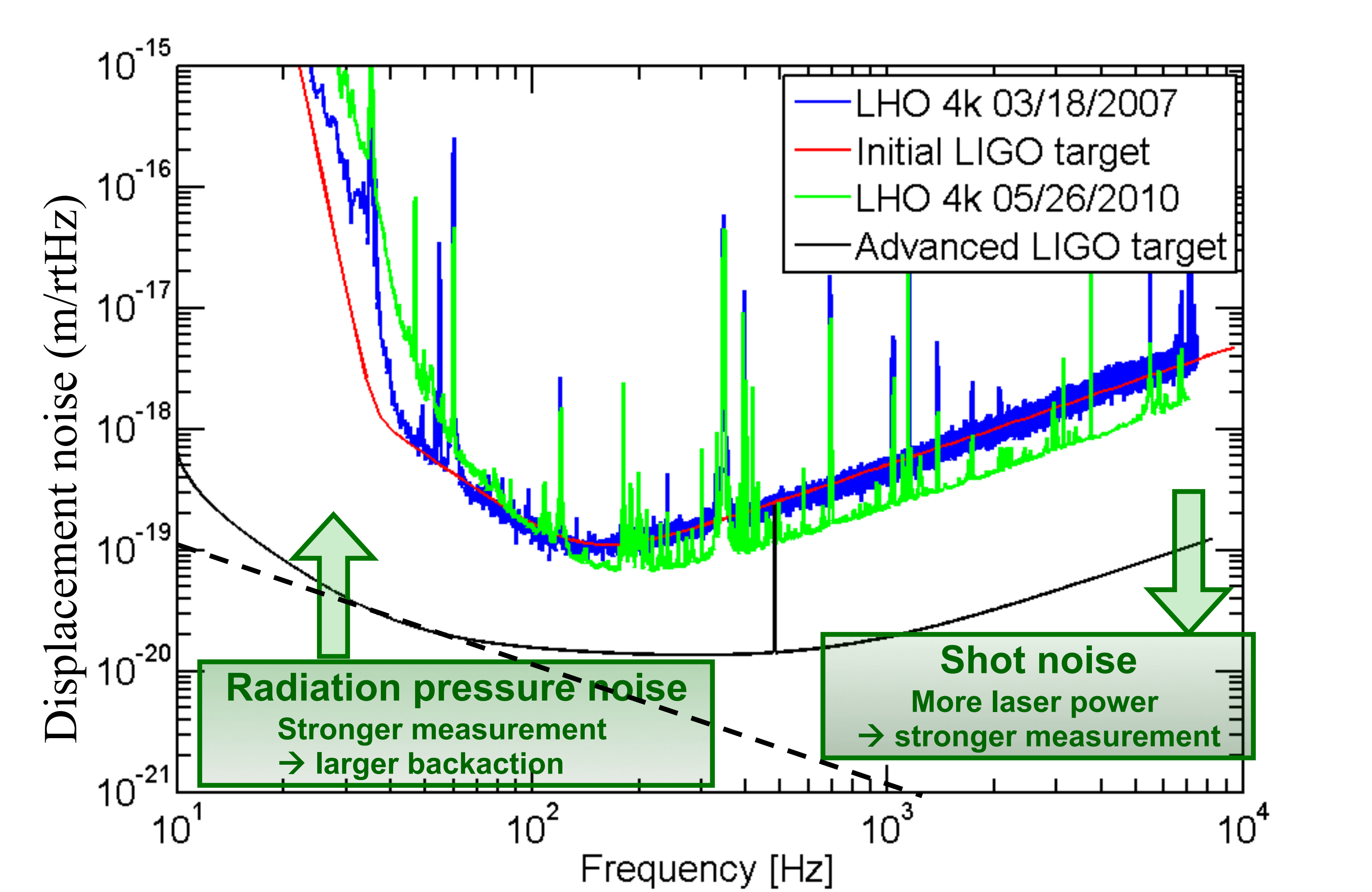
Lots of laser power *P*
- Signal α *P*
- Noise α $\sqrt{P}$

Global network of detectors

Phases of LIGO (~2000 to 2020)



Quantum noise in Initial LIGO



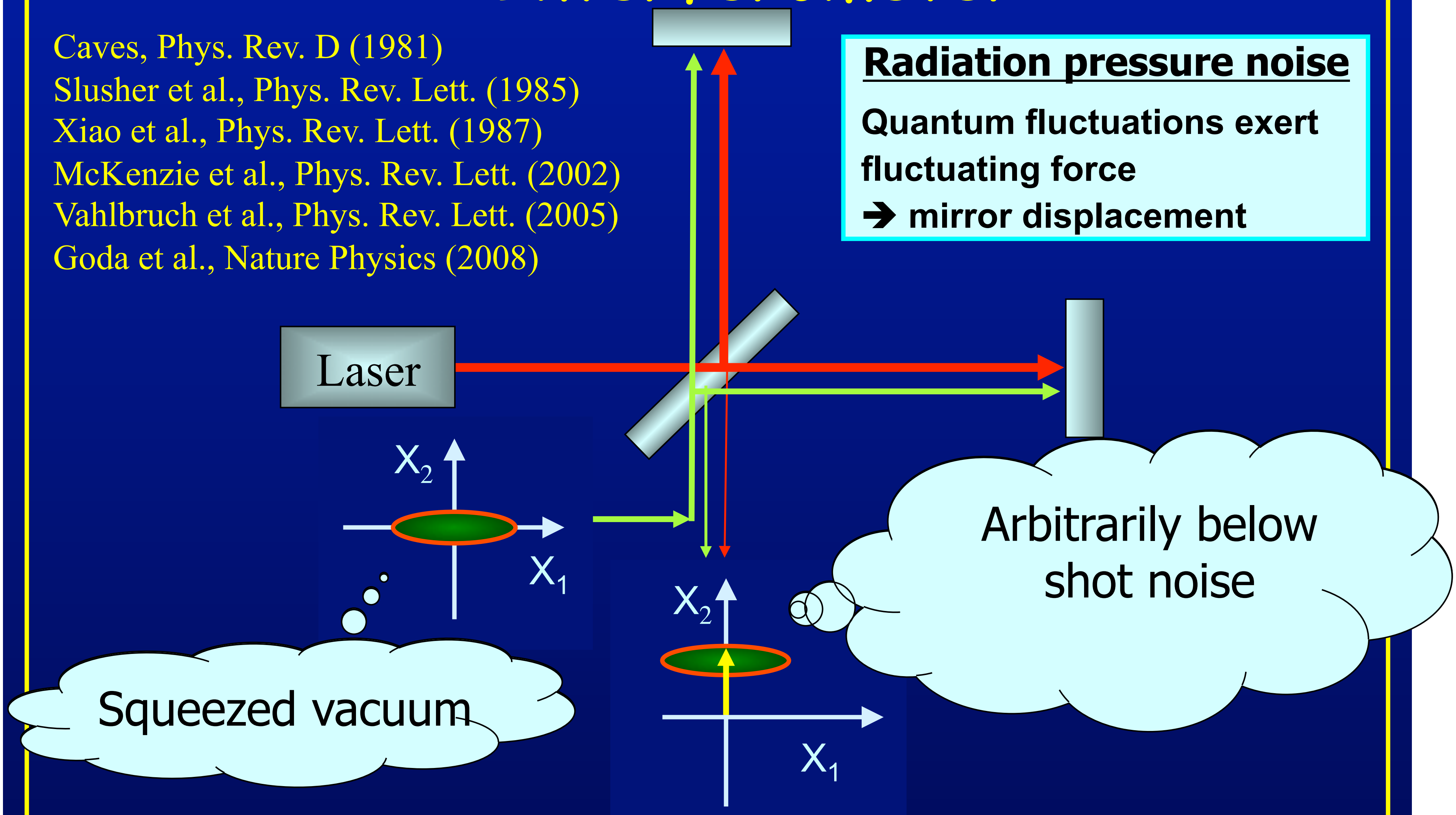
Origin of the Quantum Noise
Vacuum fluctuations

Quantum Noise in an Interferometer

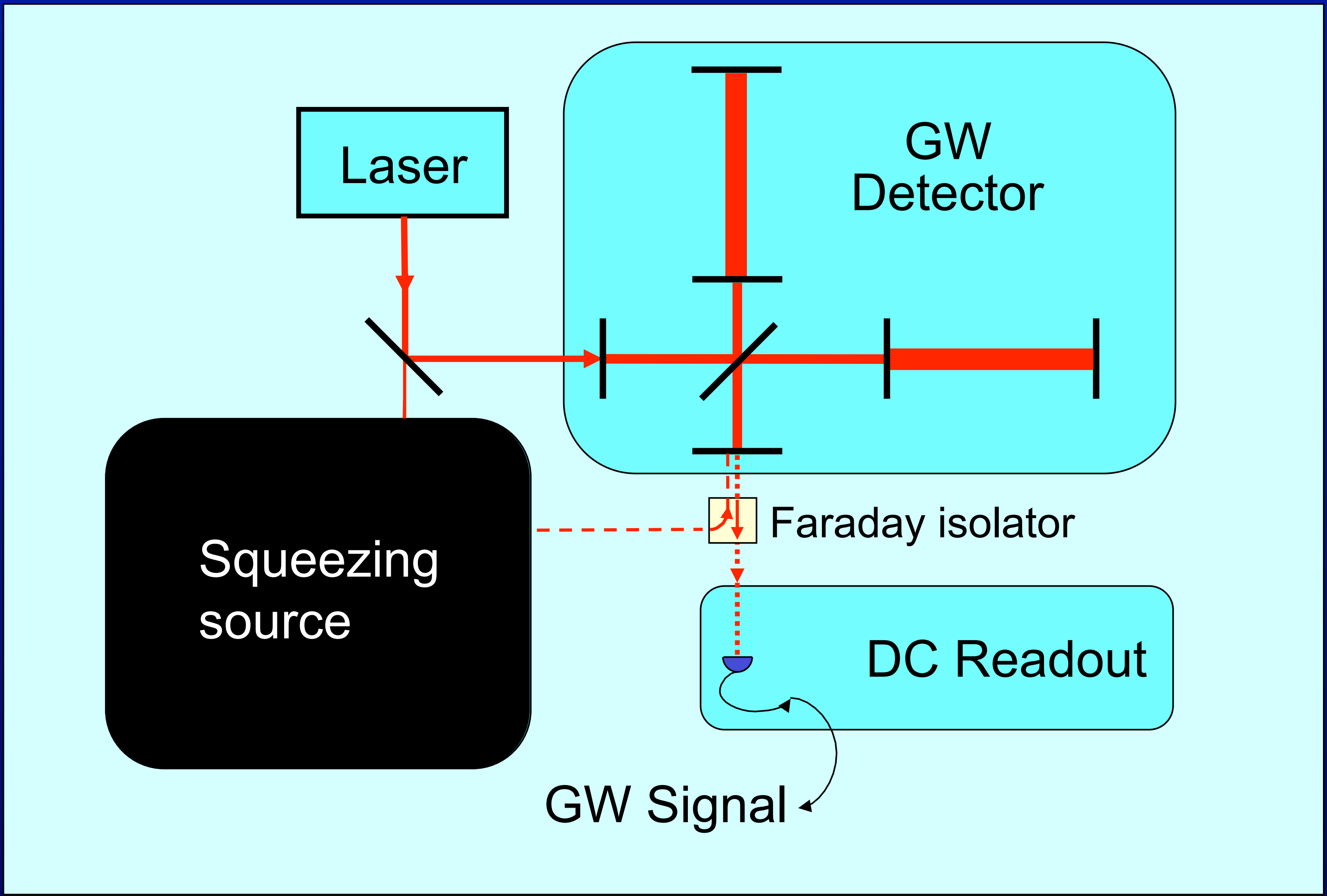
Caves, Phys. Rev. D (1981)
Slusher et al., Phys. Rev. Lett. (1985)
Xiao et al., Phys. Rev. Lett. (1987)
McKenzie et al., Phys. Rev. Lett. (2002)
Vahlbruch et al., Phys. Rev. Lett. (2005)
Goda et al., Nature Physics (2008)

Radiation pressure noise

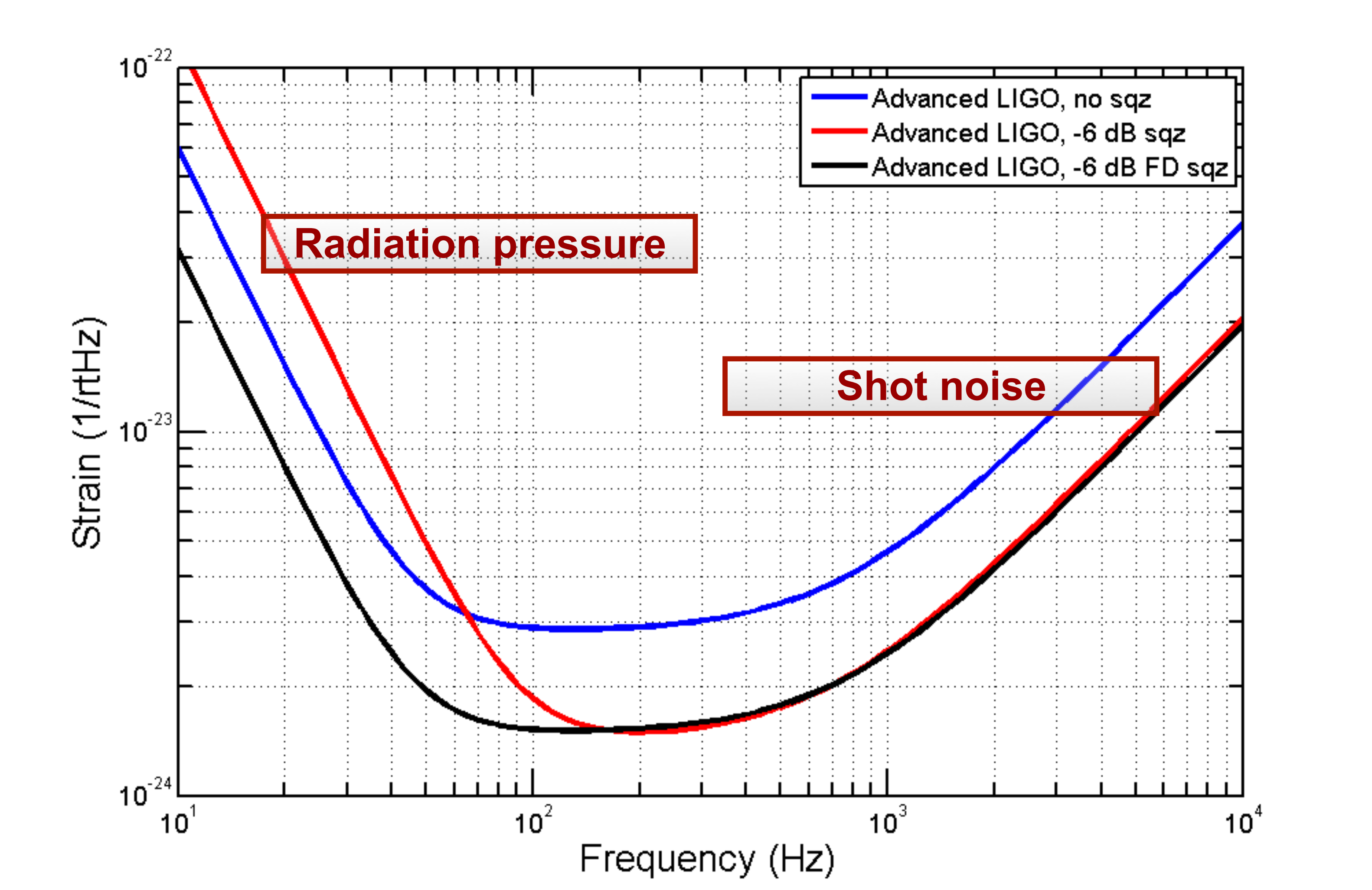
Quantum fluctuations exert fluctuating force
➔ mirror displacement



Squeezing injection in Advanced LIGO



Advanced LIGO with squeeze injection

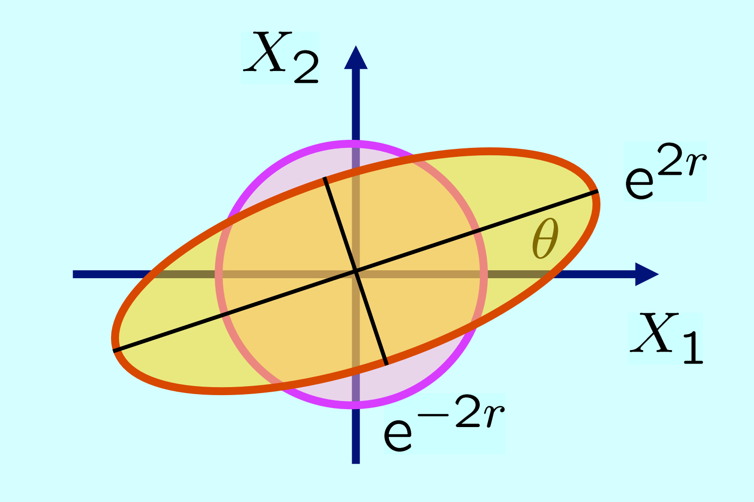


Quantum Optics &
Squeezed State Injection

How to squeeze photon states?

- Need to simultaneously amplify one quadrature and de-ampilify the other

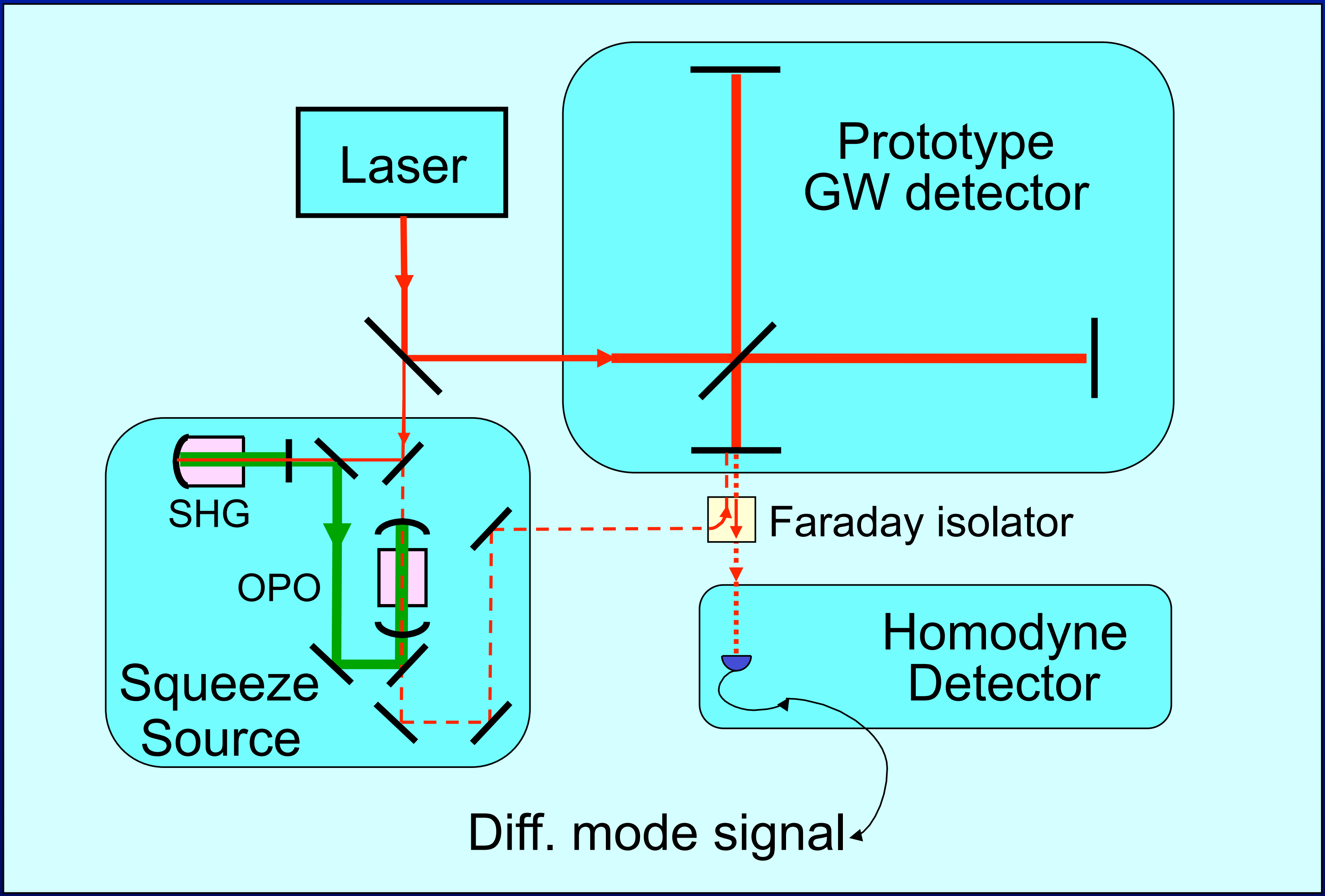
$$\langle(\Delta\hat{X}_1)^2\rangle \sim e^{-2r}$$
$$\langle(\Delta\hat{X}_2)^2\rangle \sim e^{2r}$$



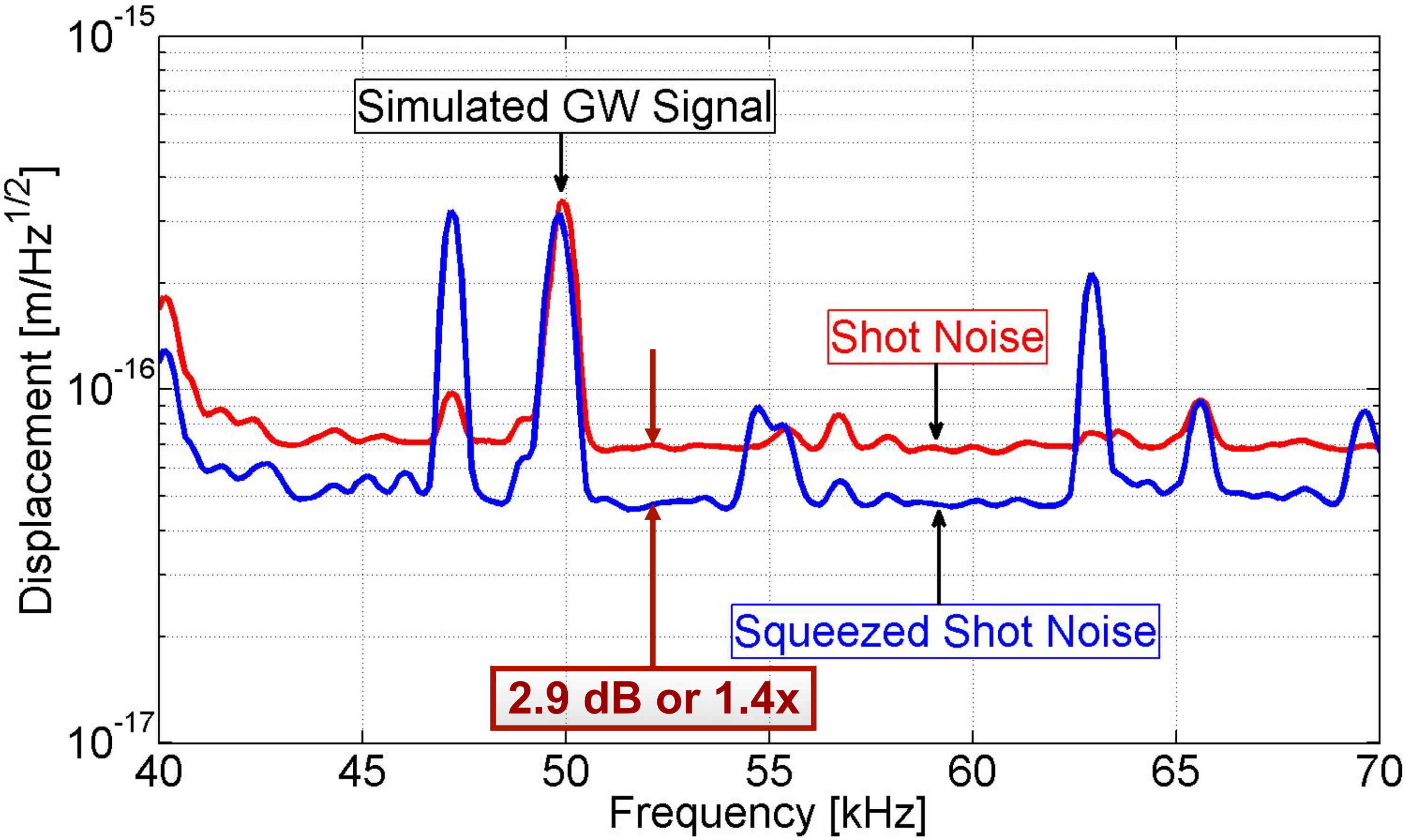
- Create correlations between the quadratures
  - Simple idea → nonlinear optical material where refractive index depends on intensity of light illumination

$$n(I) = n_0 + n_1 I + \ldots$$
$$n(I) \Rightarrow \phi(z, I)$$
$$\Delta I \Leftrightarrow \Delta\phi$$

Squeezing injection



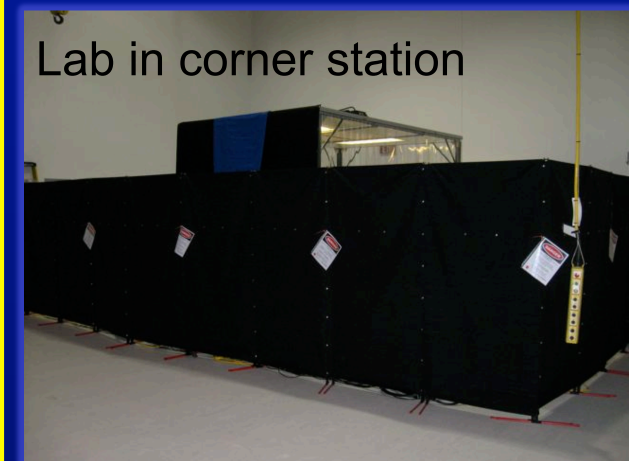
Squeezing Enhancement

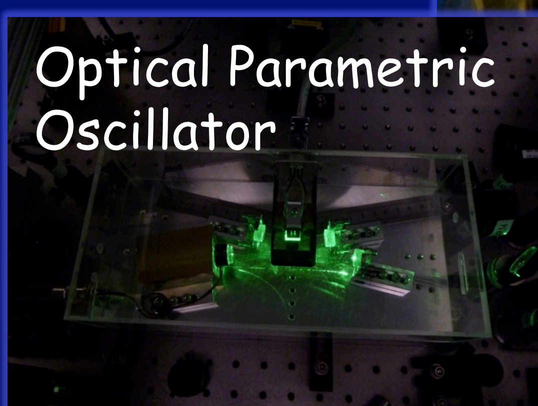


K. Goda, O. Miyakawa, E. E. Mikhailov, S. Saraf, R. Adhikari, K.McKenzie, R. Ward, S. Vass, A. J. Weinstein, and N. Mavalvala, Nature Physics **4**, 472 (2008)

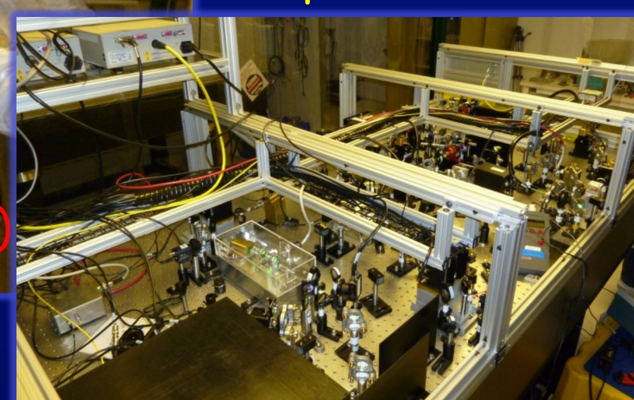
Squeezer at LIGO Hanford

ANU, AEI, MIT, LIGO collaboration

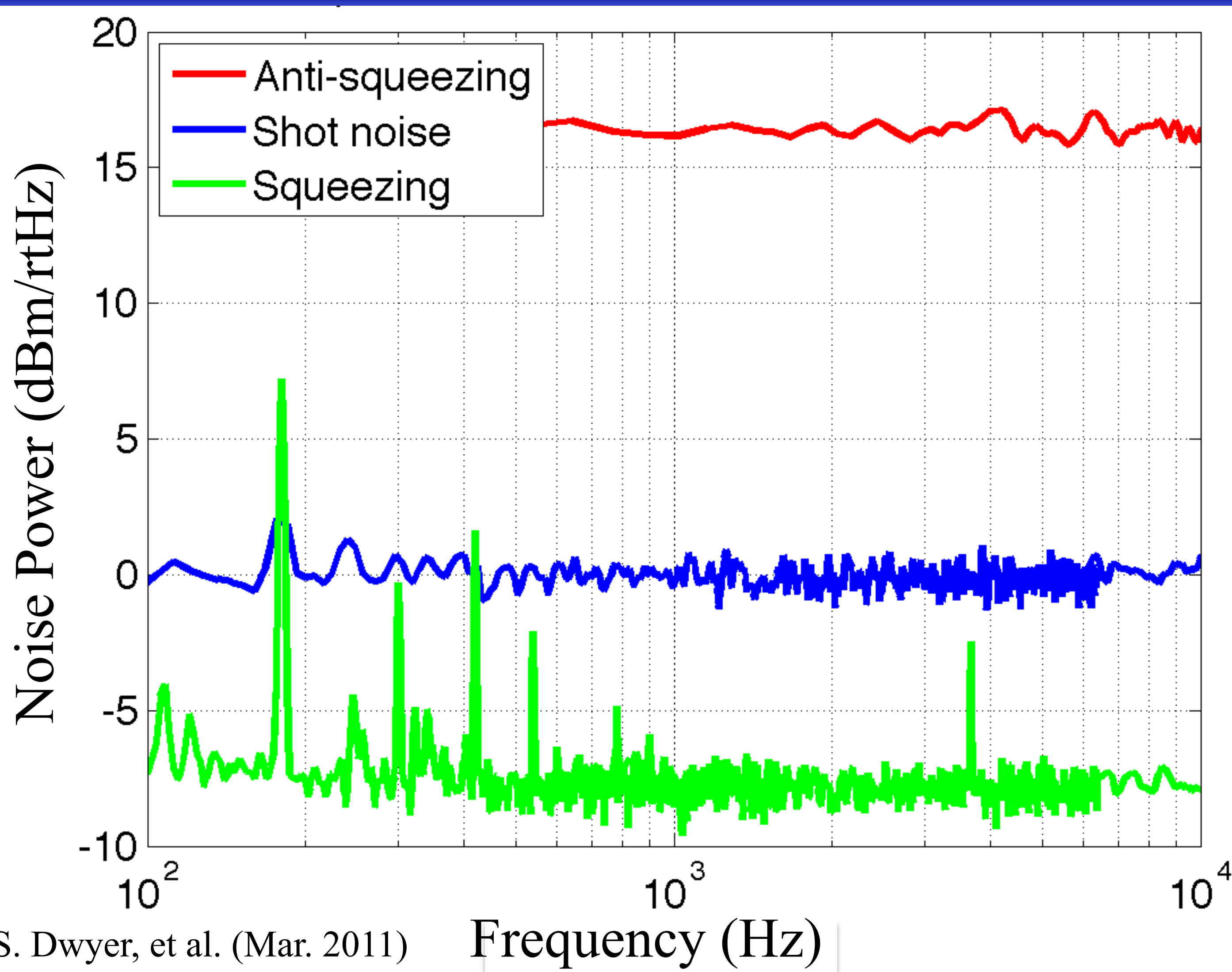




Optics Table

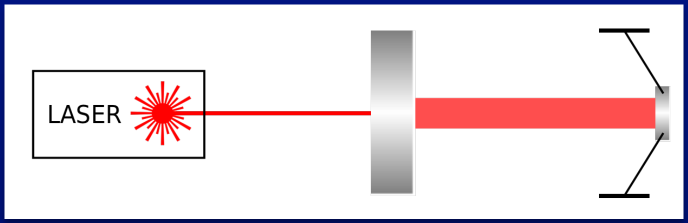


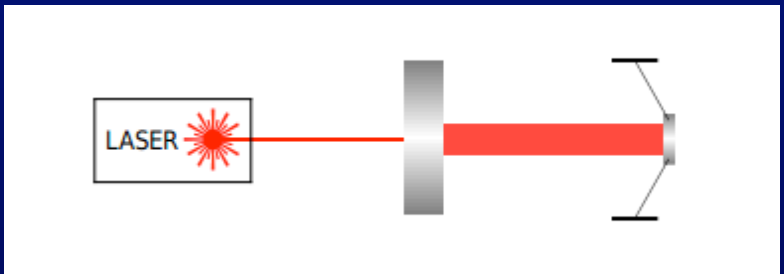
H1 Squeeze Test



S. Dwyer, et al. (Mar. 2011)

Optomechanics & Radiation Pressure





Optomechanical coupling

- The radiation pressure force couples the light field to mirror motion

Classical

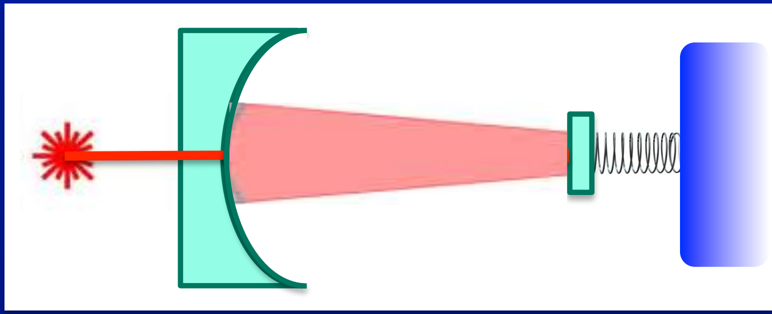
- Alters the dynamics of the mirror
  - Spring-like forces → optical trapping
  - Viscous forces → optical damping
  - Tune the frequency response of the GW detector

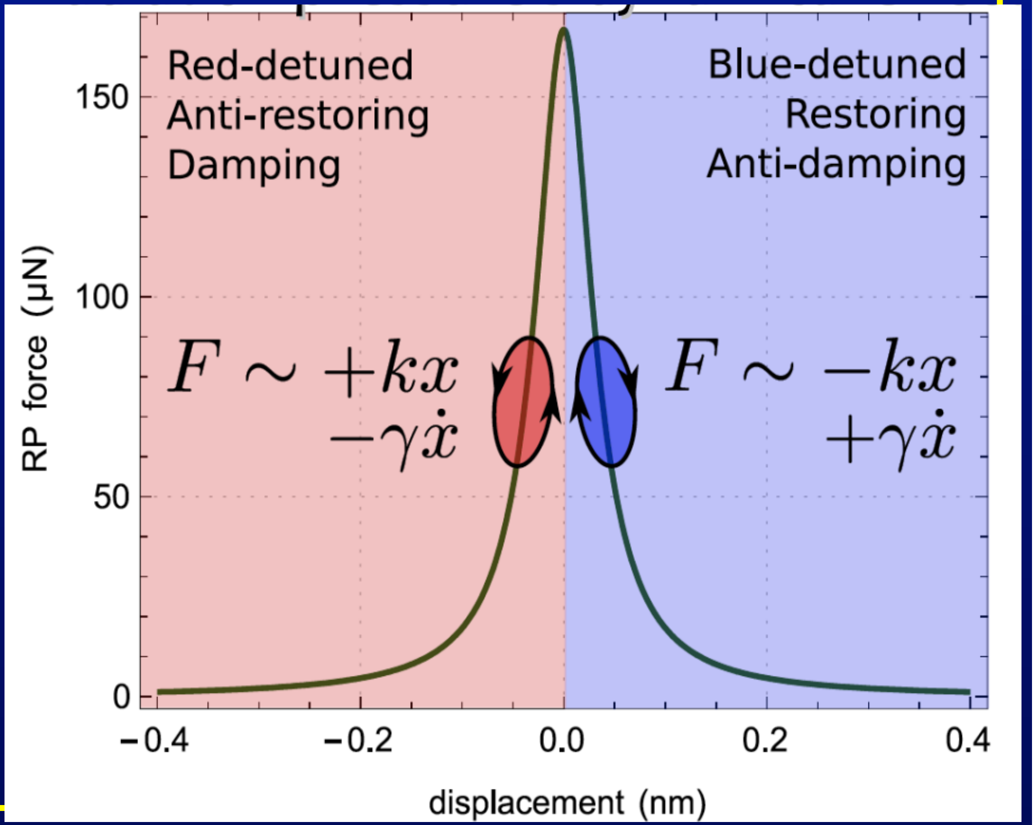
Quantum

- Manipulate the quantum noise
  - Quantum radiation pressure noise and the standard quantum limit
  - Produce quantum states of the mirrors

Classical radiation pressure forces

- Detune optical field from cavity resonance
- Change in mirror position changes intracavity power → radiation pressure exerts force on mirror
- Time delay in cavity results in cavity response doing work on mechanics





Path to the quantum regime

- For mode of oscillation of the mirror

$$k_B T < \hbar \Omega$$

- Thermodynamics

$$T_{\text{eff}} \propto T_{\text{env}} \times \frac{\Omega_{\text{mech}}}{\Omega_{\text{opt}}} \times \frac{1}{Q_{\text{mech}}}$$

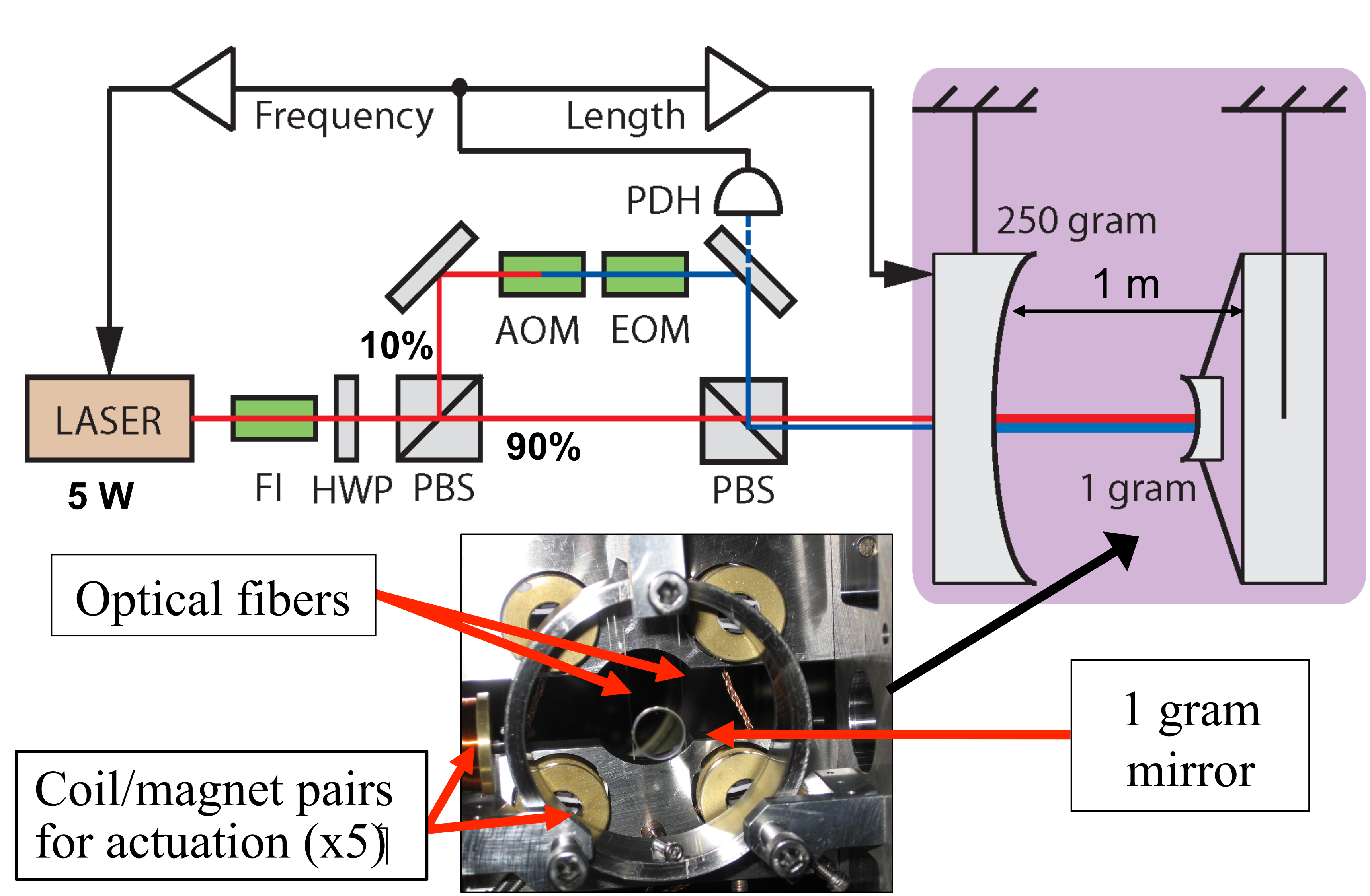
$\Omega_{\text{opt}} \gg \Omega_{\text{mech}}$

STIFF OPTICAL SPRING

$Q_{\text{mech}} \gg 1$

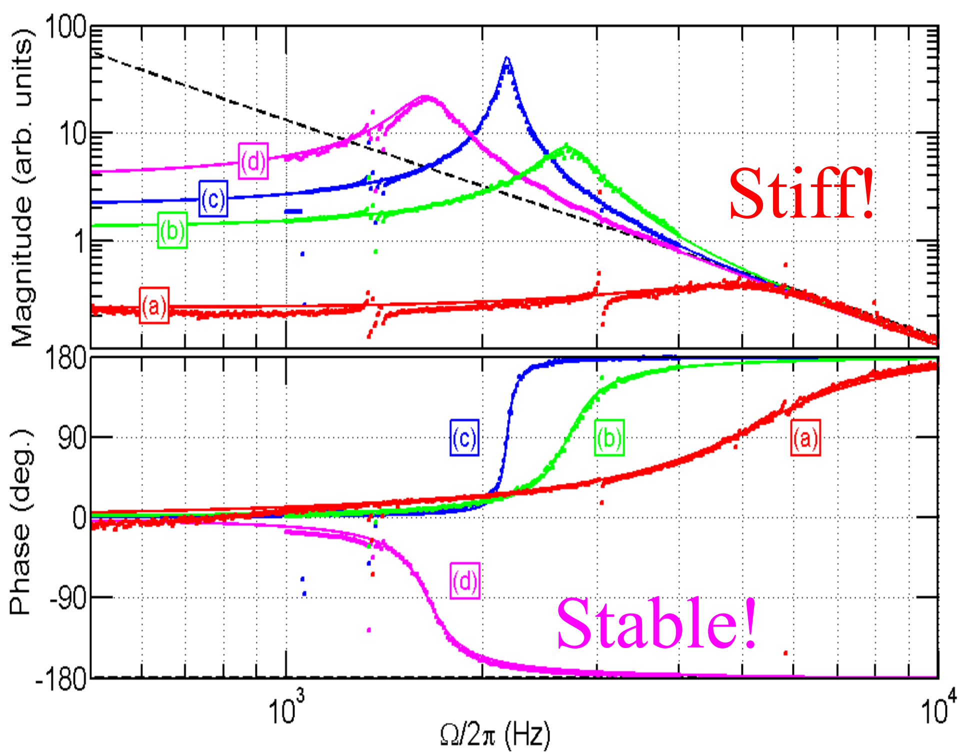
HIGH MECHANICAL Q

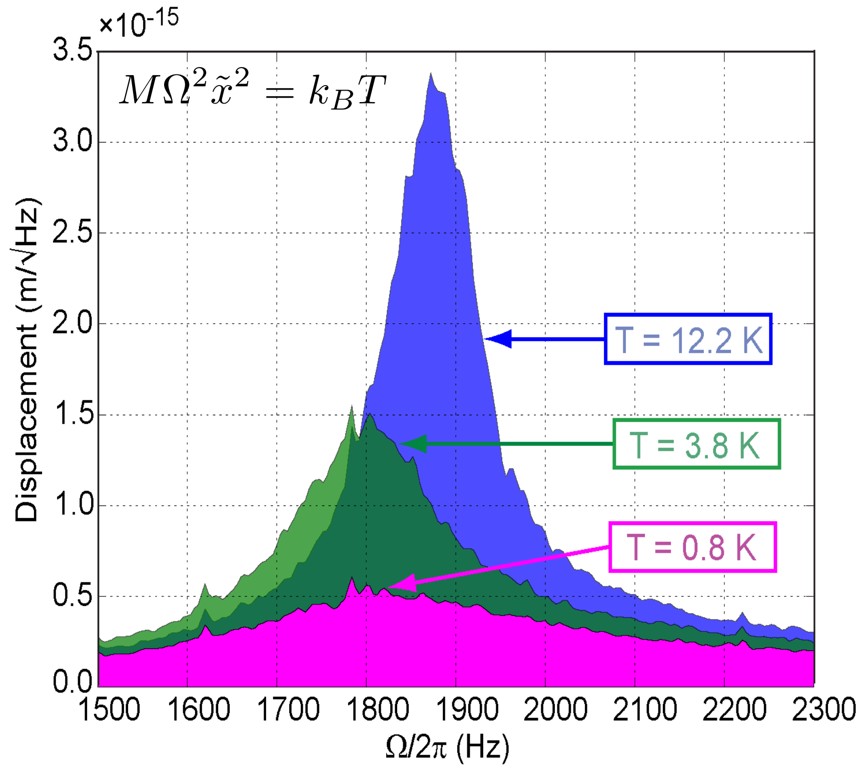
Experimental cavity setup



Trapping and cooling

- Optical trap response
- Optical cooling

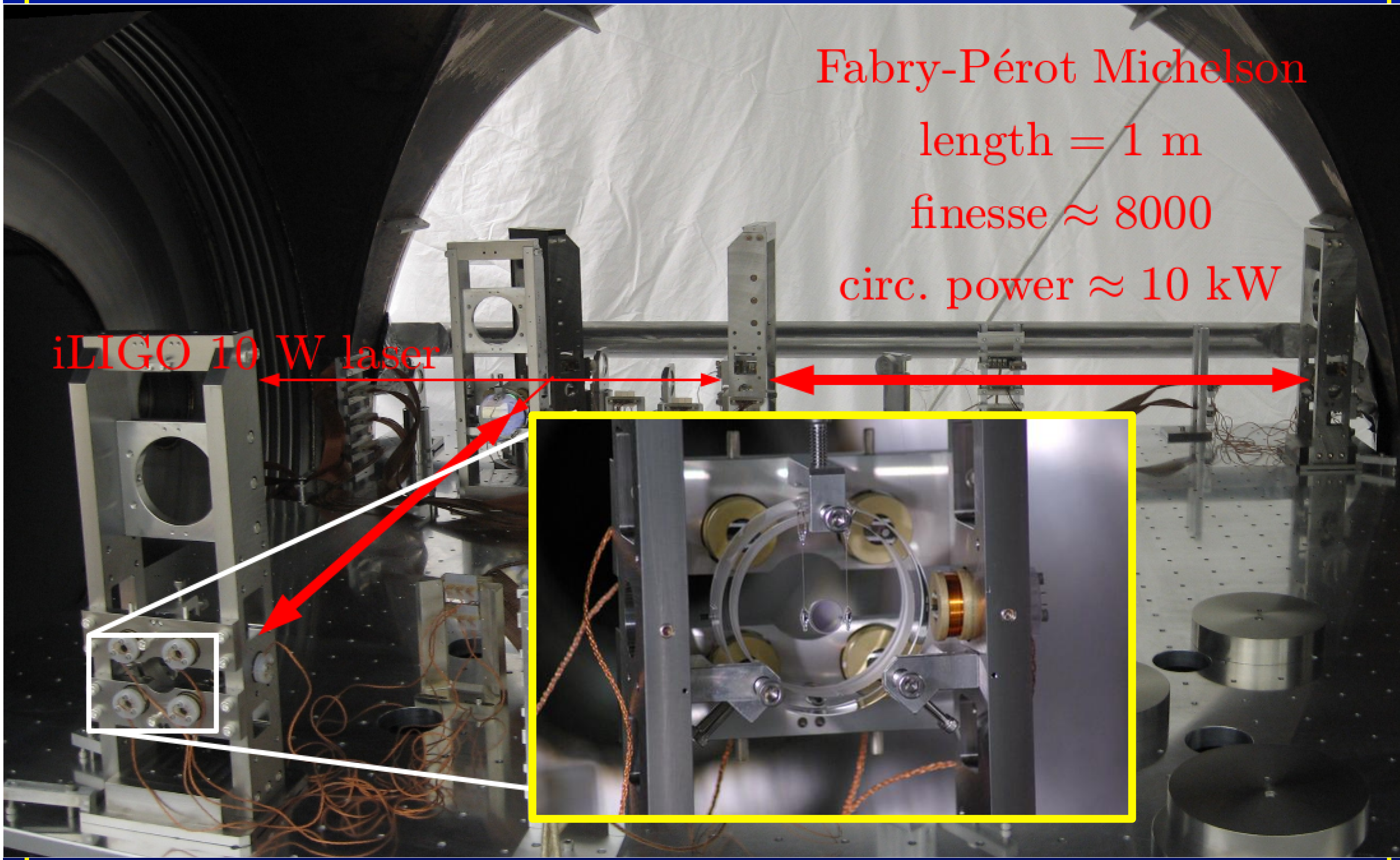




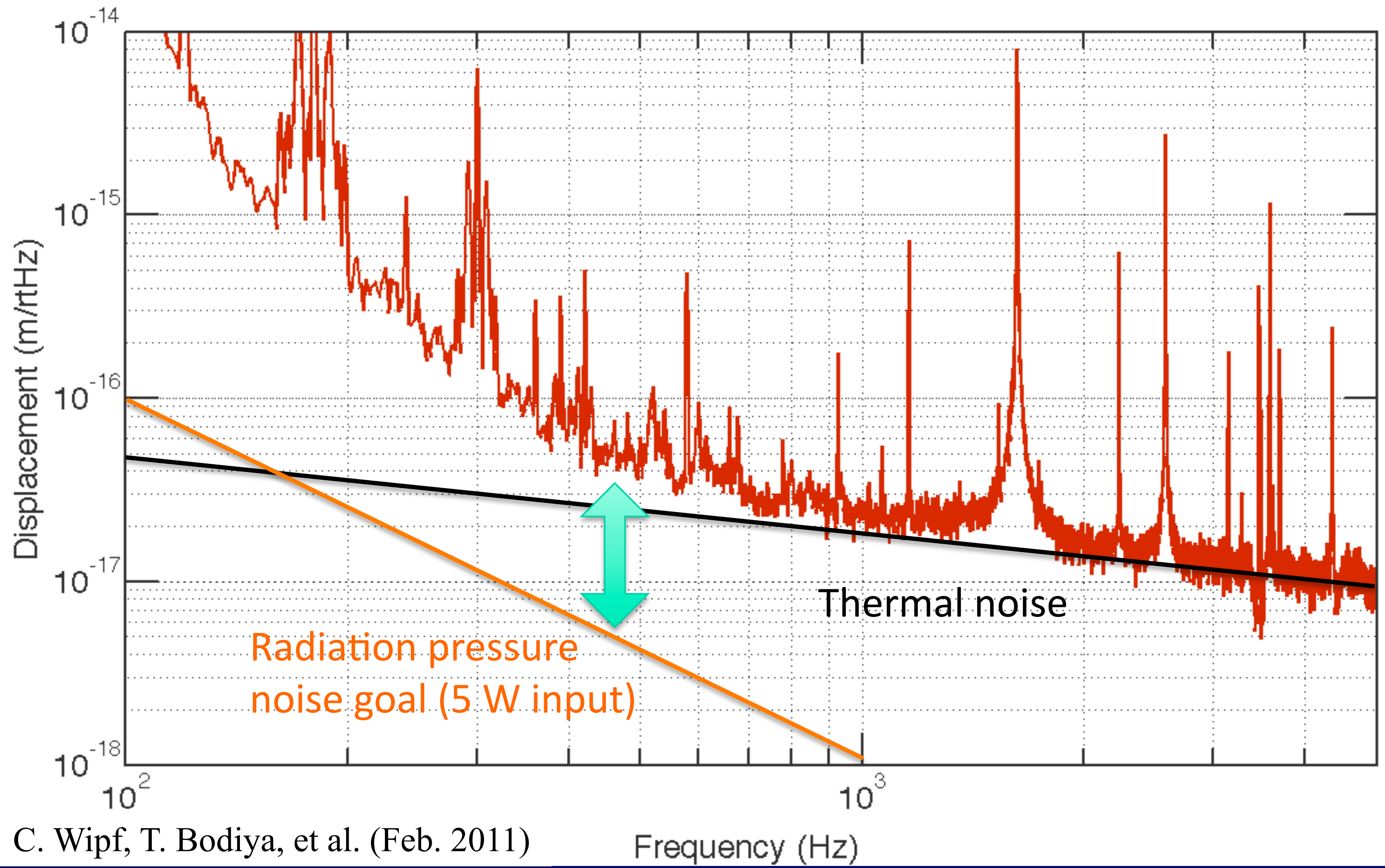
T. Corbitt et al., Phys. Rev. Lett **98**, 150802 (2007)

Quantum Radiation Pressure Effects

The experiment grows



That elusive quantum regime



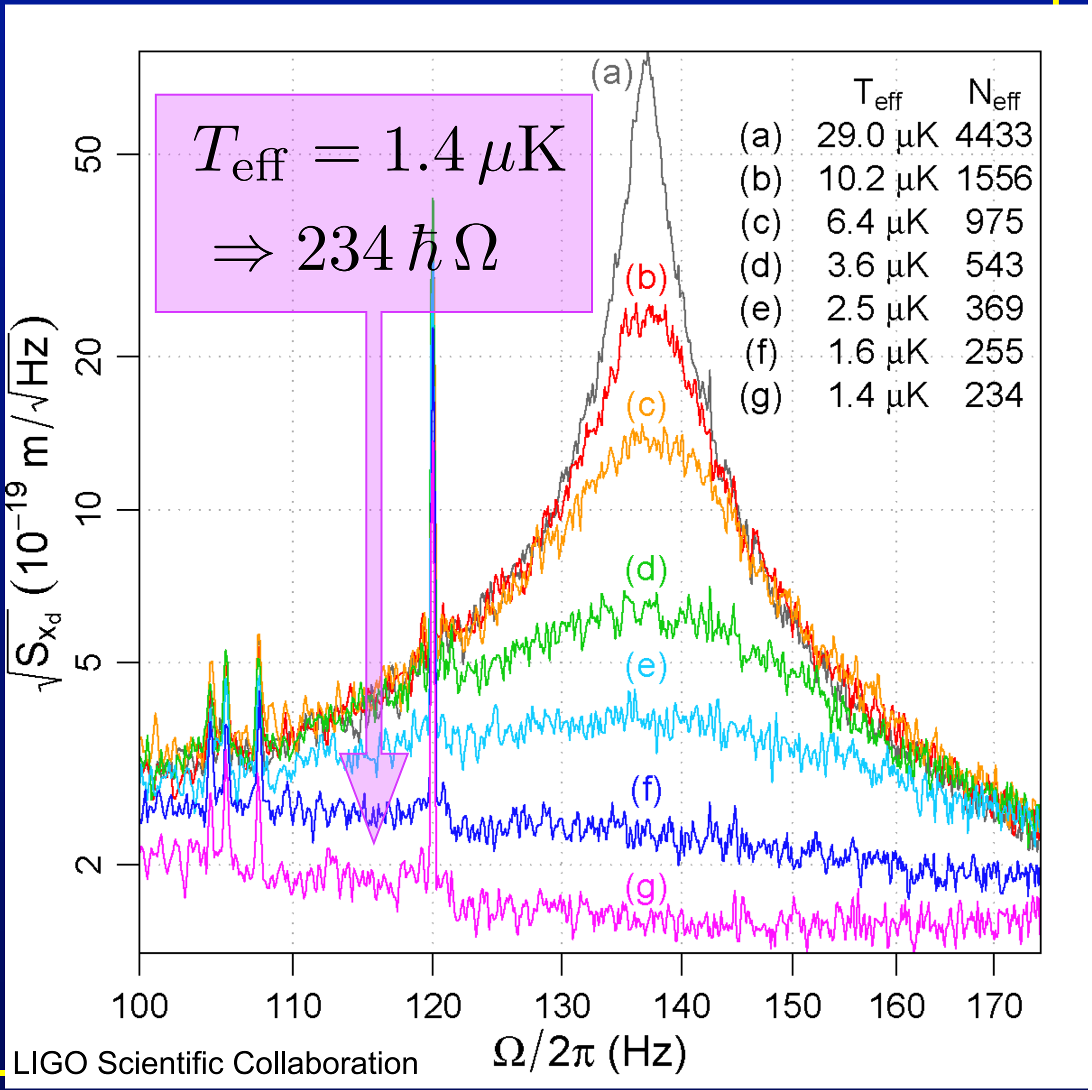
C. Wipf, T. Bodiya, et al. (Feb. 2011)

Quantumness in Initial LIGO

Cooling the kilogram-scale mirrors of Initial LIGO

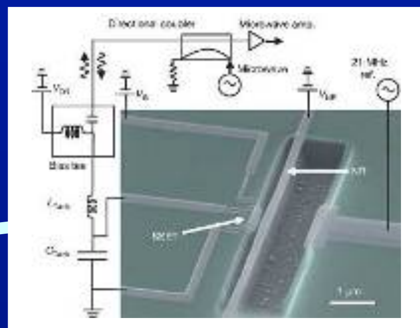
$$M_r = 2.7\,\mathrm{kg}$$

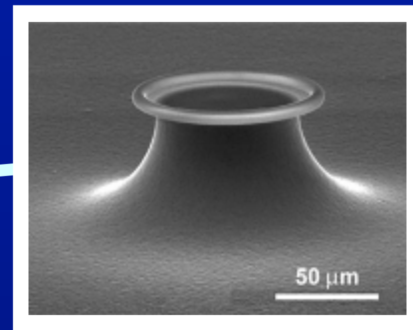
$$\Omega_{\mathrm{mech}} = 2\pi \times 0.7\,\mathrm{Hz}$$



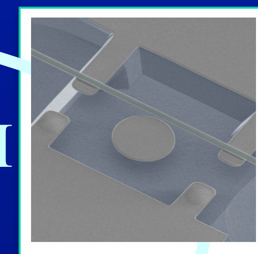
Some other cool oscillators

NEMS
→ 10^{-12} g



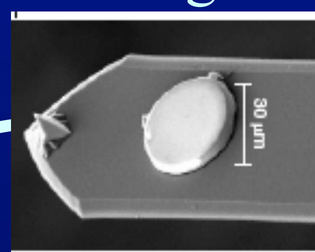


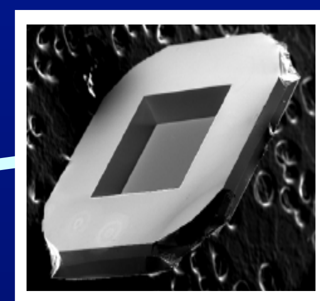
Toroidal microcavity
→ 10^{-11} g



WG-WGM
→ 10^{-11} g

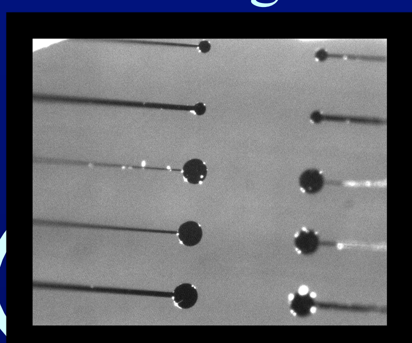
AFM cantilevers
→ 10^{-8} g

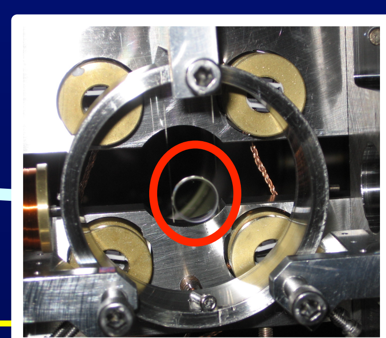




SiN_3 membrane
→ 10^{-8} g

Micromirrors
→ 10^{-7} g





Minimirror → 1 g

LIGO
→ 10^3 g

Quantum optomechanics

- Techniques for improving gravitational wave detector sensitivity
- Tools for quantum information science
- Opportunities to study quantum effects in macroscopic systems
  - Observation of quantum radiation pressure
  - Generation of squeezed states of light
  - Entanglement of mirror and light quantum states
  - Quantum states of mirrors

Amazing cast of characters

MIT

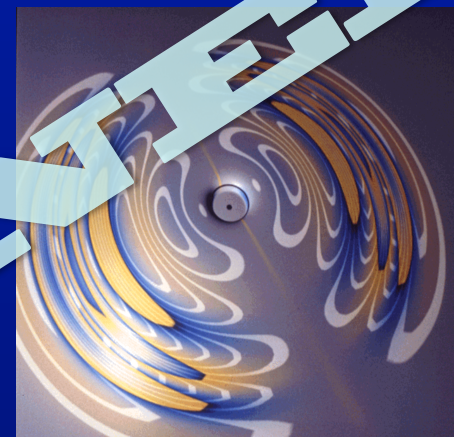
- Keisuke Goda
- Thomas Corbitt
- Christopher Wipf
- Timothy Bodiya
- Sheila Dwyer
- Lisa Barsotti
- Nicolas Smith-Lefevbre
- Eric Oelker
- Rich Mittleman
- MIT LIGO Laboratory

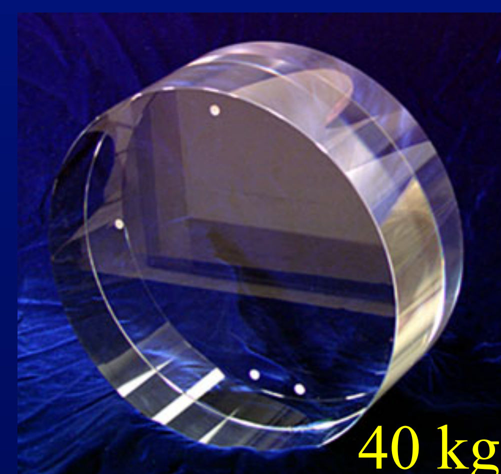
Collaborators

- Yanbei Chen & group
- David McClelland & group
- Roman Schnabel & group
- Stan Whitcomb
- Daniel Sigg
- Caltech 40m Lab team
- Caltech LIGO Lab
- Garrett Cole of Aspelmeyer group (Vienna)
- LIGO Scientific Collaboration

Capturing elusive wave…

- Tests of general relativity
  - Directly observe ripples of space-time
- Astrophysics
  - Directly observe the Black Holes, the Big Bang, and objects beyond our current imagination
- Directly observe quantum mechanics in human scale objects





STAY TUNED