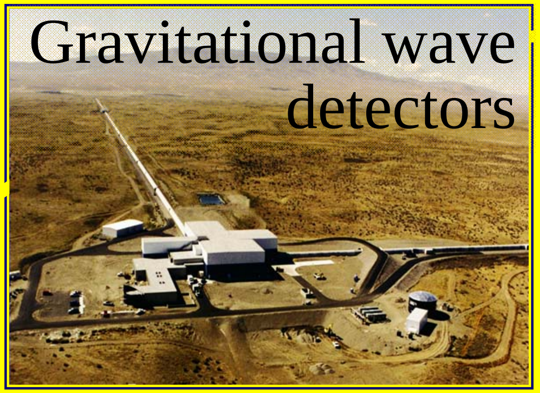
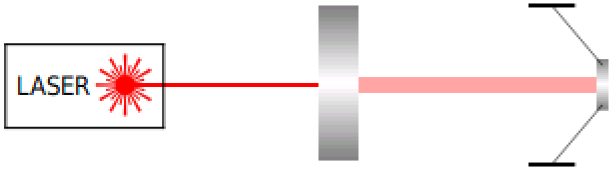
The Quantum Limit and Beyond in Gravitational Wave Detectors



Gravitational wave detectors

Quantum nature of light

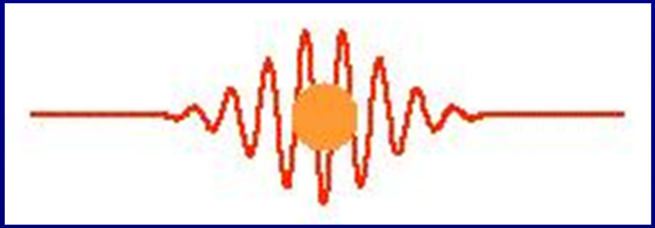


Quantum states of mirrors

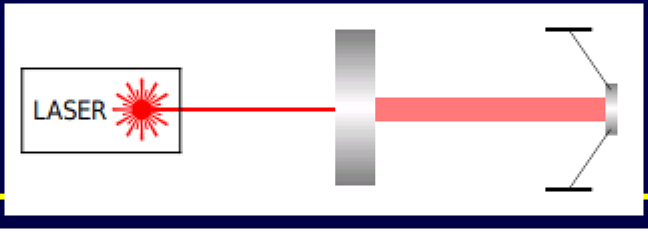
Nergis Mavalvala
GW2010, UMinn, October 2010

Outline

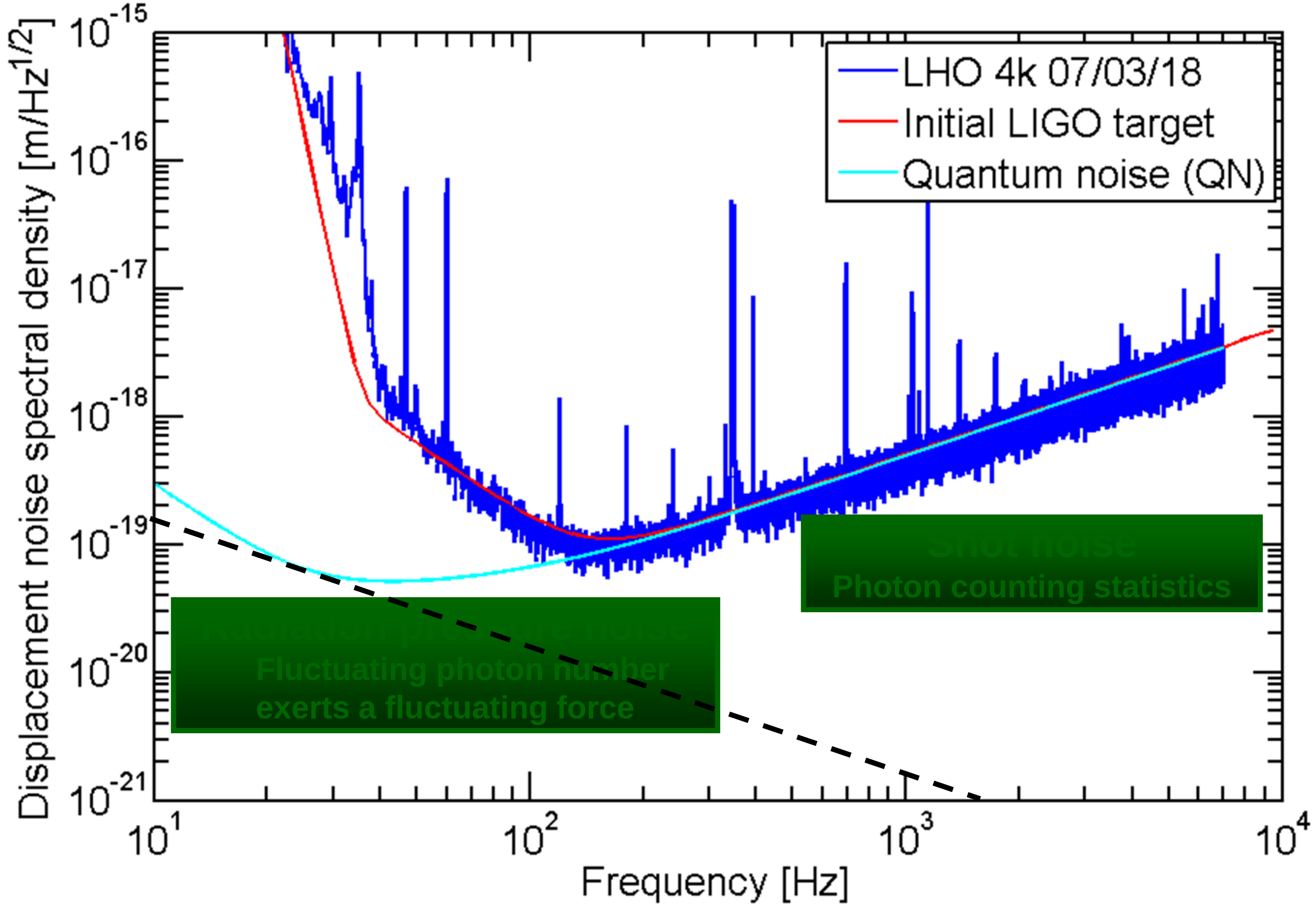
- Quantum limit for gravitational wave detectors
- Origins of the quantum limit
  - Vacuum fluctuations of the EM field



- Quantum states of light (Quantum optics)
  - Squeezed state generation and injection
- Quantum states of the mirrors (Quantum optomechanics)
  - Radiation pressure induced dynamics
  - Prospects for observing quantum effects in macroscopic objects (mirrors)



Quantum noise in Initial LIGO



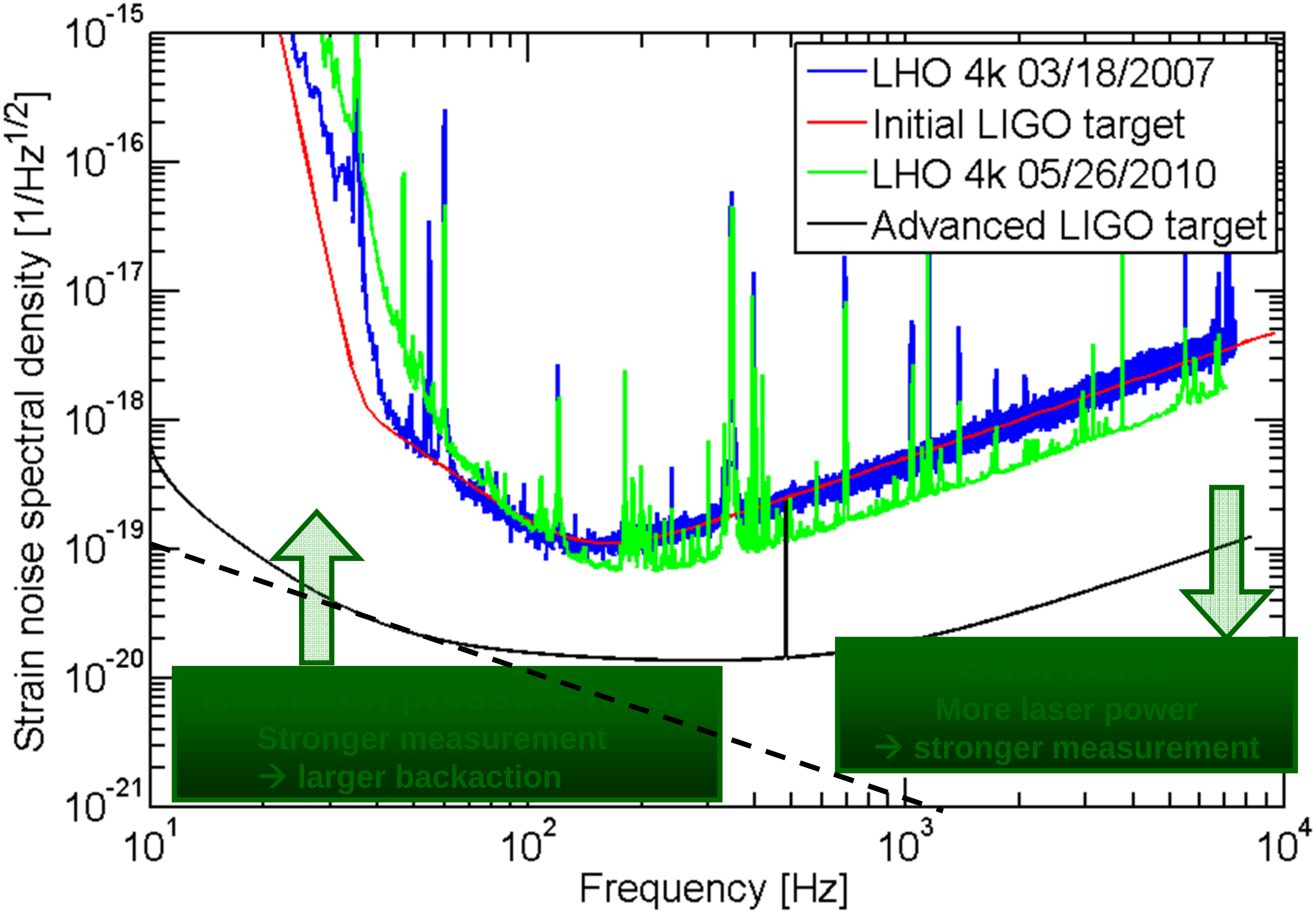
Radiation pressure noise

Fluctuating photon number exerts a fluctuating force

Shot noise

Photon counting statistics

Quantum noise in Initial LIGO



Radiation pressure noise

Stronger measurement
→ larger backaction

Shot noise

More laser power
→ stronger measurement

Origin of the Quantum Noise

Vacuum fluctuations

Quantum states of light

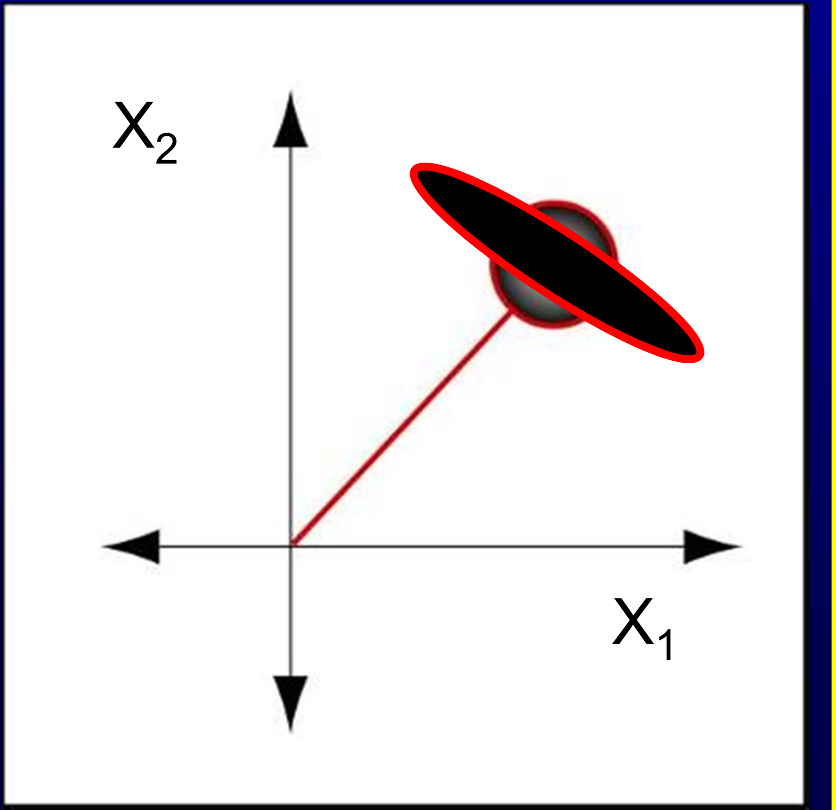
- Coherent state (laser light)

$$\langle(\Delta\hat{X}_1)^2\rangle = \langle(\Delta\hat{X}_2)^2\rangle = 1$$

X_1 and X_2 associated with amplitude and phase uncertainty

- Squeezed state
  - Two complementary observables
  - Make on noise better for one quantity, **BUT** it gets worse for the other

$$\begin{aligned}\langle(\Delta\hat{X}_1)^2\rangle &= \mathrm{e}^{-2r}\\ \langle(\Delta\hat{X}_2)^2\rangle &= \mathrm{e}^{2r}\end{aligned}$$

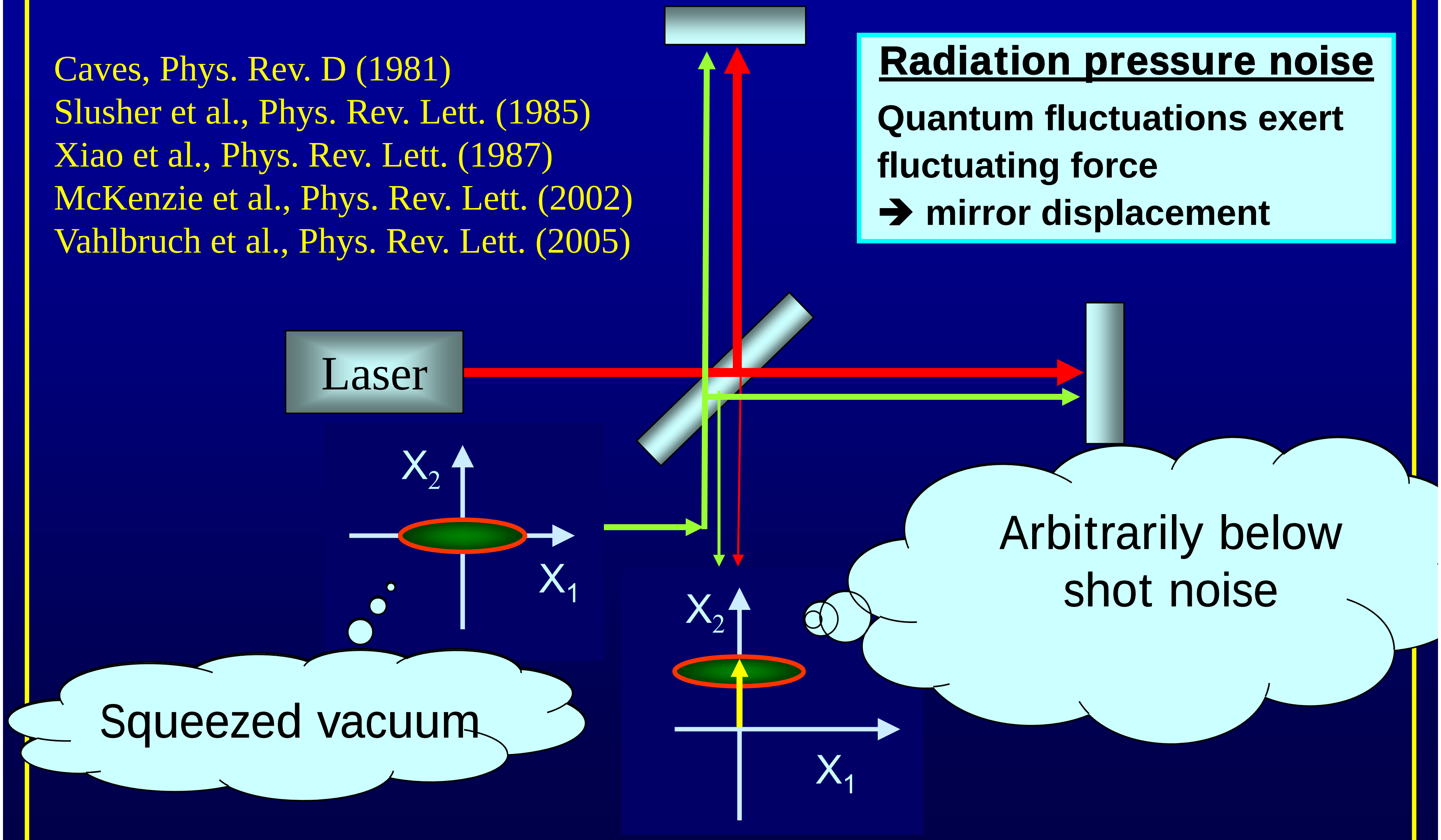


Quantum Noise in an Interferometer

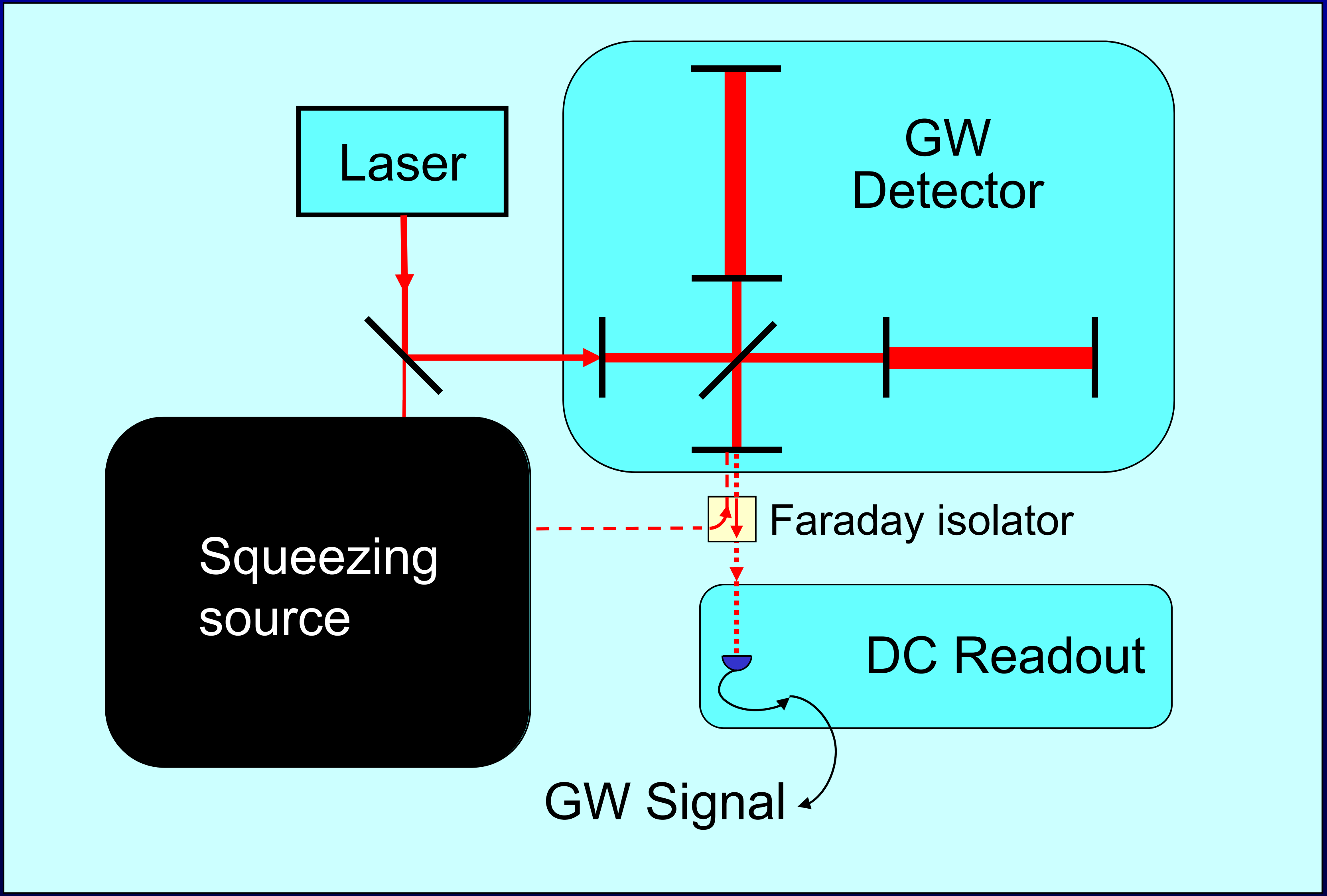
Caves, Phys. Rev. D (1981)
Slusher et al., Phys. Rev. Lett. (1985)
Xiao et al., Phys. Rev. Lett. (1987)
McKenzie et al., Phys. Rev. Lett. (2002)
Vahlbruch et al., Phys. Rev. Lett. (2005)

Radiation pressure noise

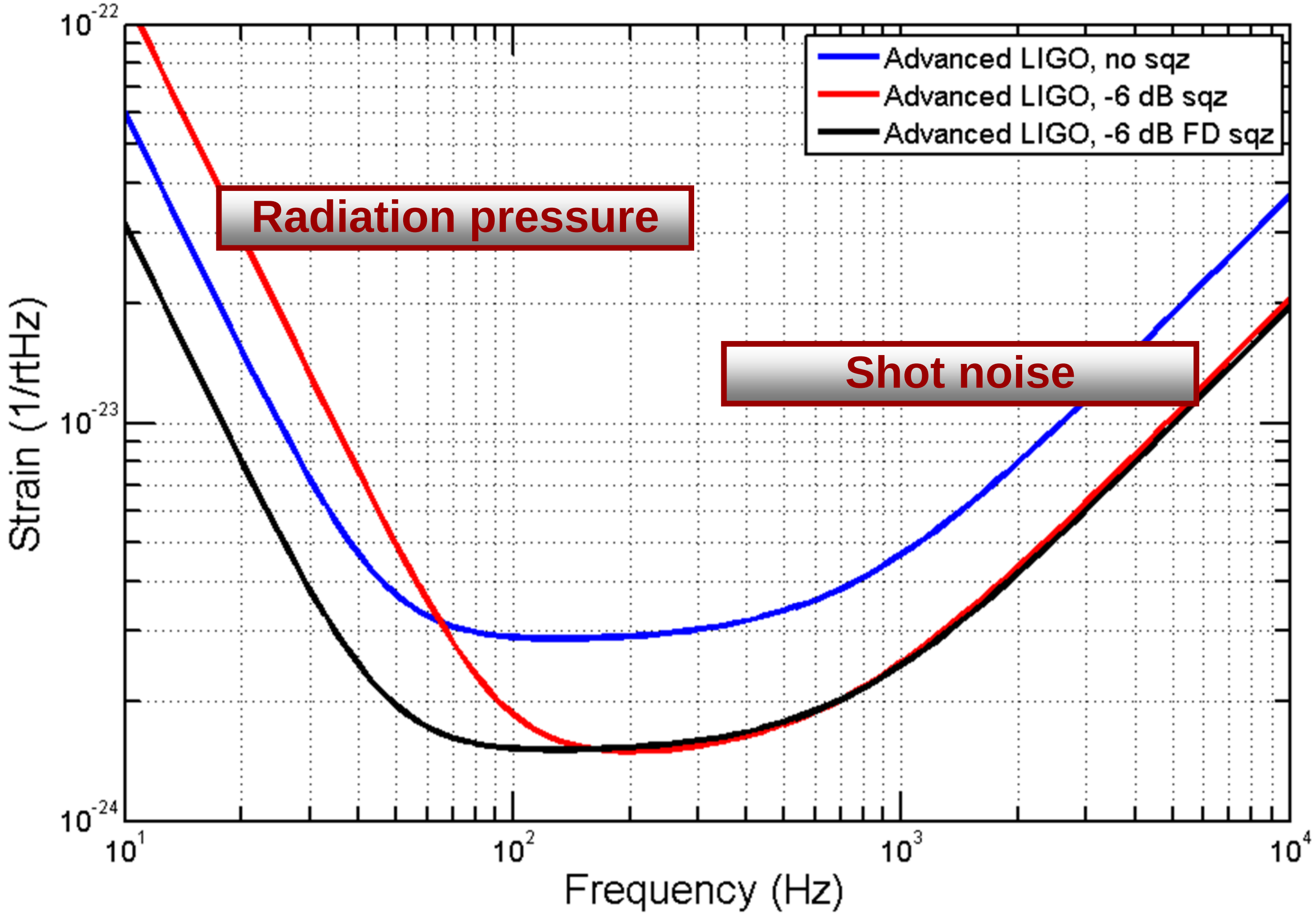
Quantum fluctuations exert fluctuating force
➔ mirror displacement



Squeezing injection in Advanced LIGO



Advanced LIGO with squeeze injection



Radiation pressure

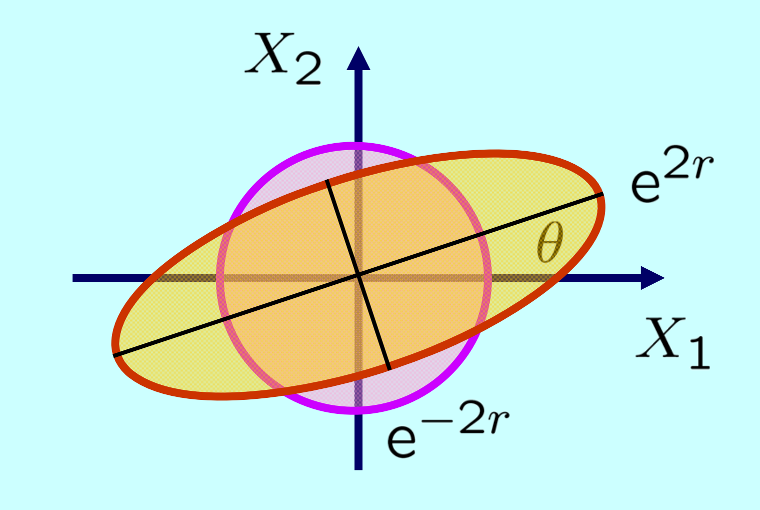
Shot noise

Squeezed state generation

How to squeeze photon states?

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

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

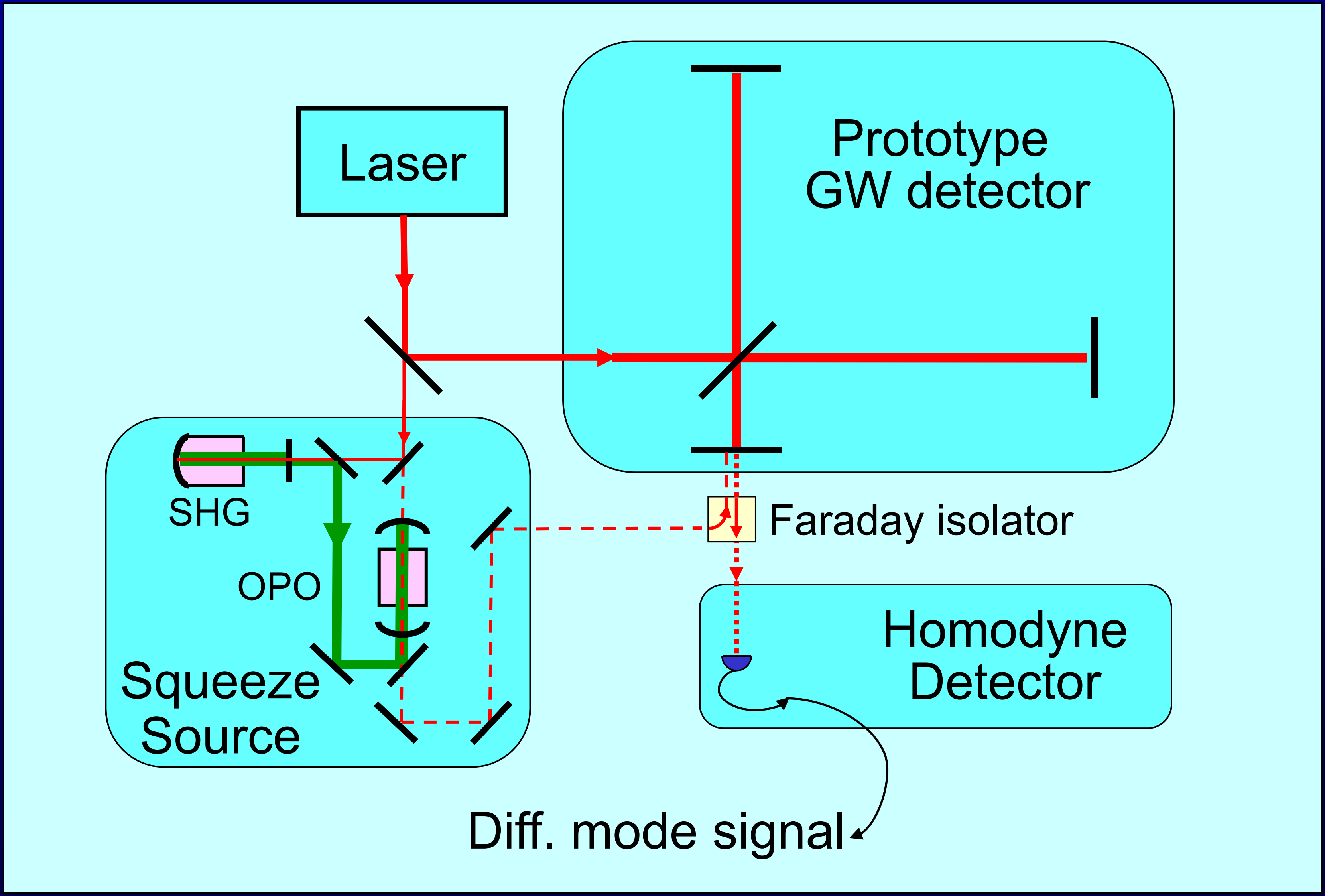


- Create correlations between the quadratures
  - Simple idea → nonlinear optical material where refractive index depends on intensity of light illumination

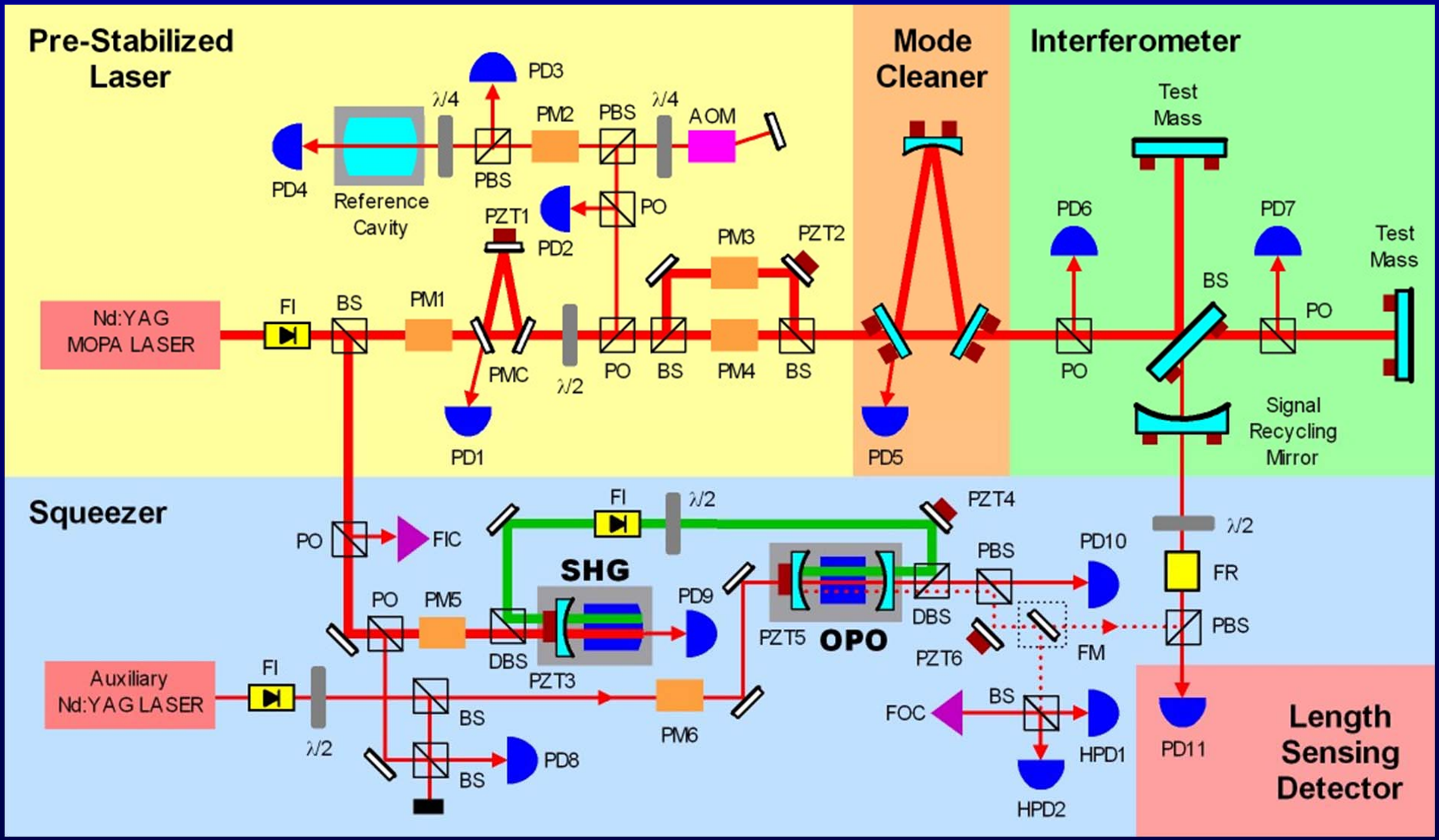
$$n(I) = n_0 + n_1 I + \ldots$$
$$n(I) \Rightarrow \phi(z, I)$$
$$\Delta I \Leftrightarrow \Delta\phi$$

Squeezing using nonlinear optical media

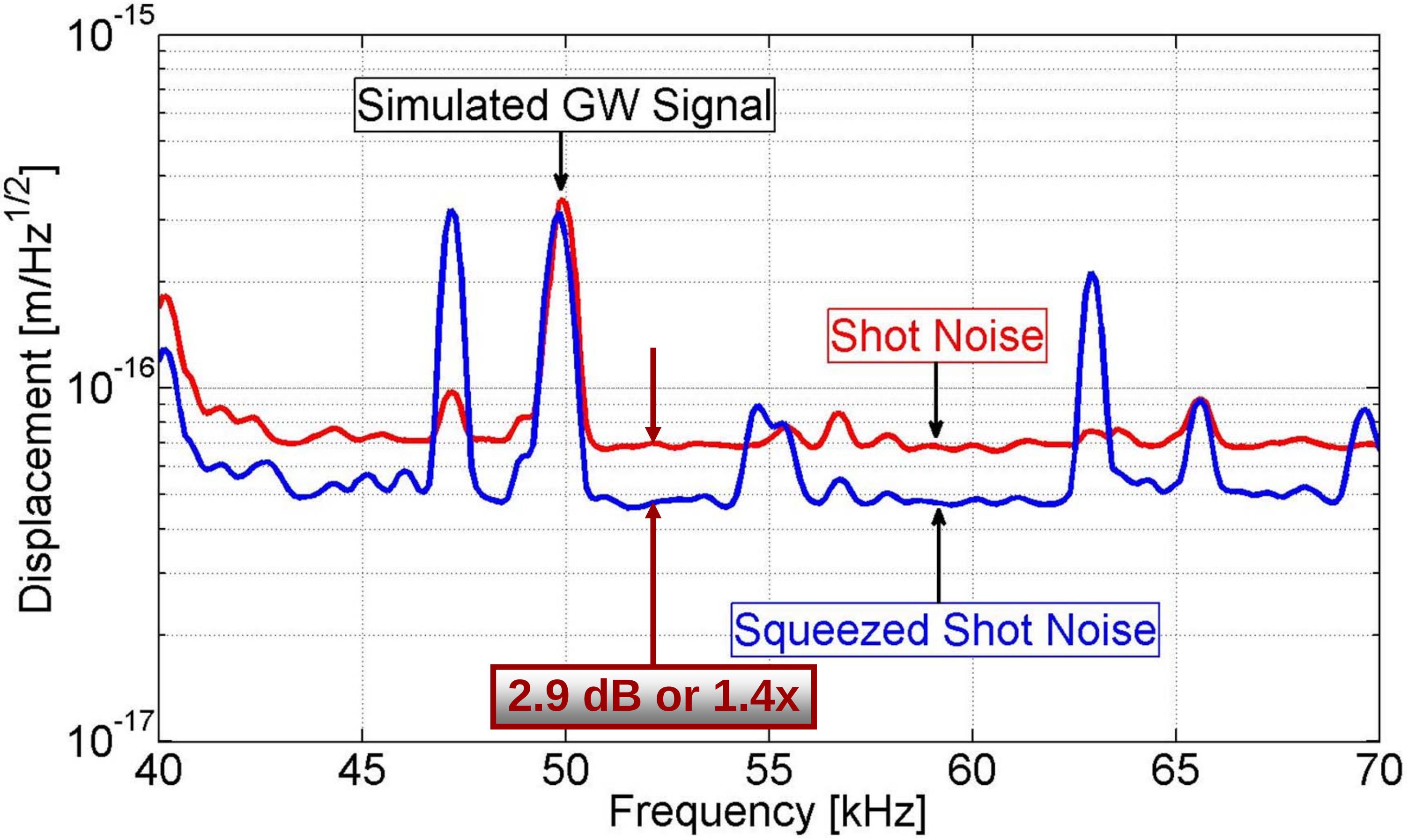
Squeezing injection in 40m prototype



Squeeze injection in a suspended-mirror interferometer: 40m prototye (Caltech)



Quantum enhancement at 40m



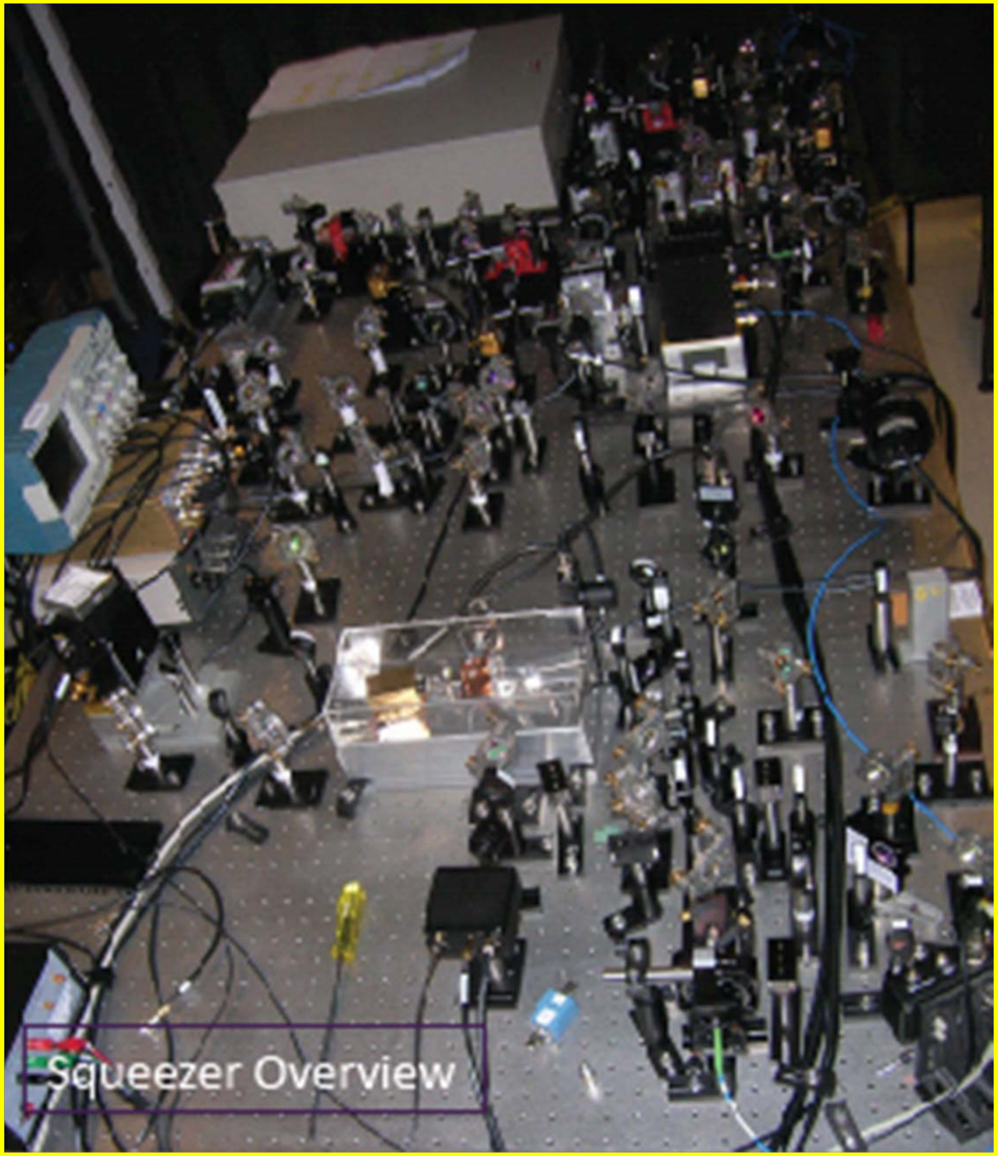
K. Goda, O. Miyakawa, E. E. Mikhailov, S. Saraf, R. Adhikari, K.McKenzie, R. Ward, S. Vass, A. J. Weinstein, and N. Mavalvala, Nature Physics **4**, 472 (2008)

Squeezed states for GW detectors

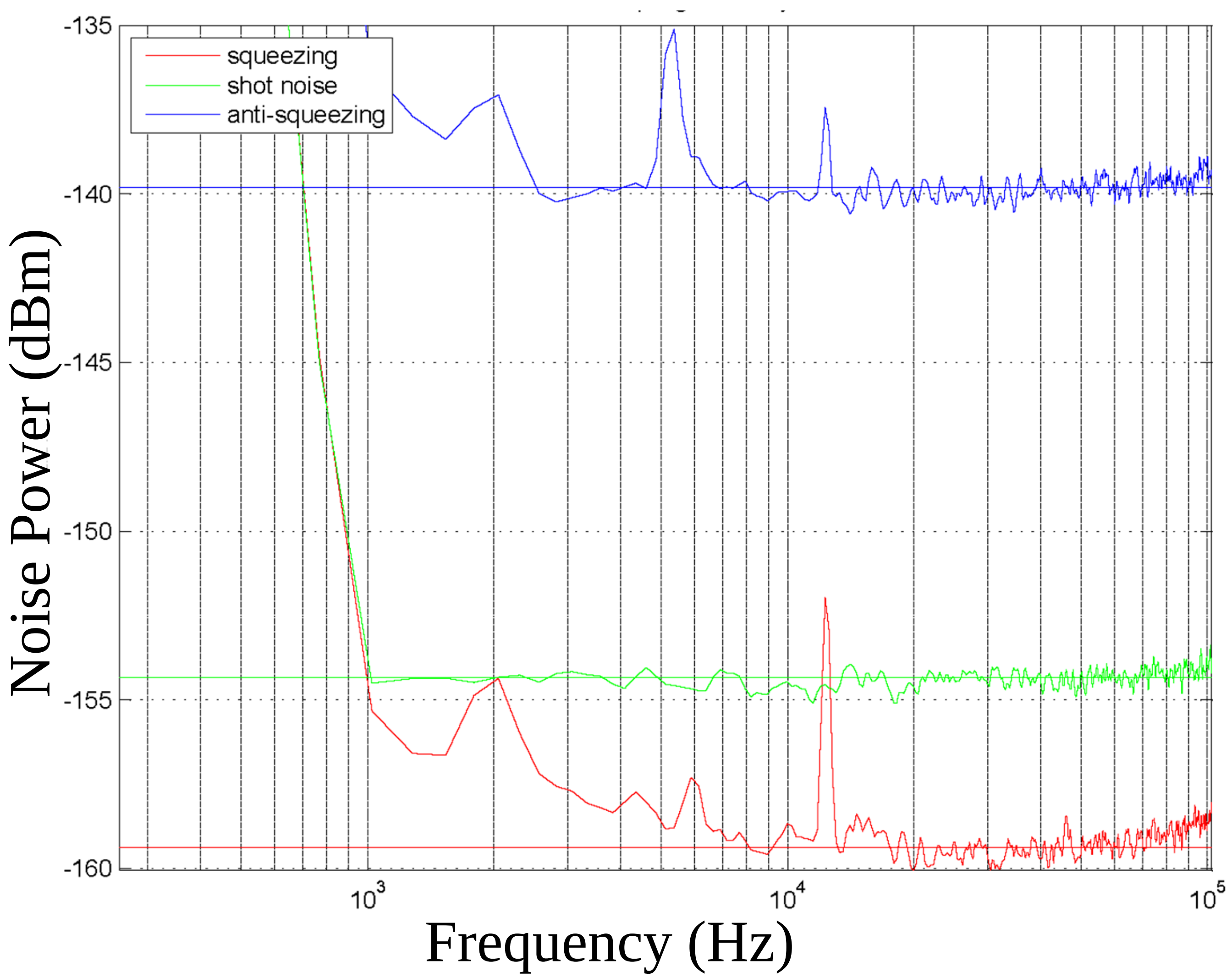
- Squeezing in the GW band
  (10 Hz to 10 kHz)
- Large squeezing factors
  (e.g. 10 dB ➔ factor of 3 improvement in strain sensitivity)
- Stable long term operation of squeezer
- Compatibility with other noise sources
  (“Do no harm” in GW band) ➔ GEOHF and H1 squeeze tests

Squeezed state injection in a LIGO interferometer (H1)

H1 Squeeze Injection Bench



H1 Squeeze Test



S. Dwyer, M. Stefszky, et al. (Sep. 2010)

Radiation pressure

the other quantum noise

Radiation pressure rules!

- Experiments in which radiation pressure forces dominate over mechanical forces
- Classical light-oscillator coupling effects (dynamical backaction)
  - Optical cooling and trapping of mirrors
- Opportunity 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 ground state of (kilo)gram-scale mirrors

Optomechanical coupling

- Detuned optical cavities give rise to coupling of radiation pressure force and mirror motion

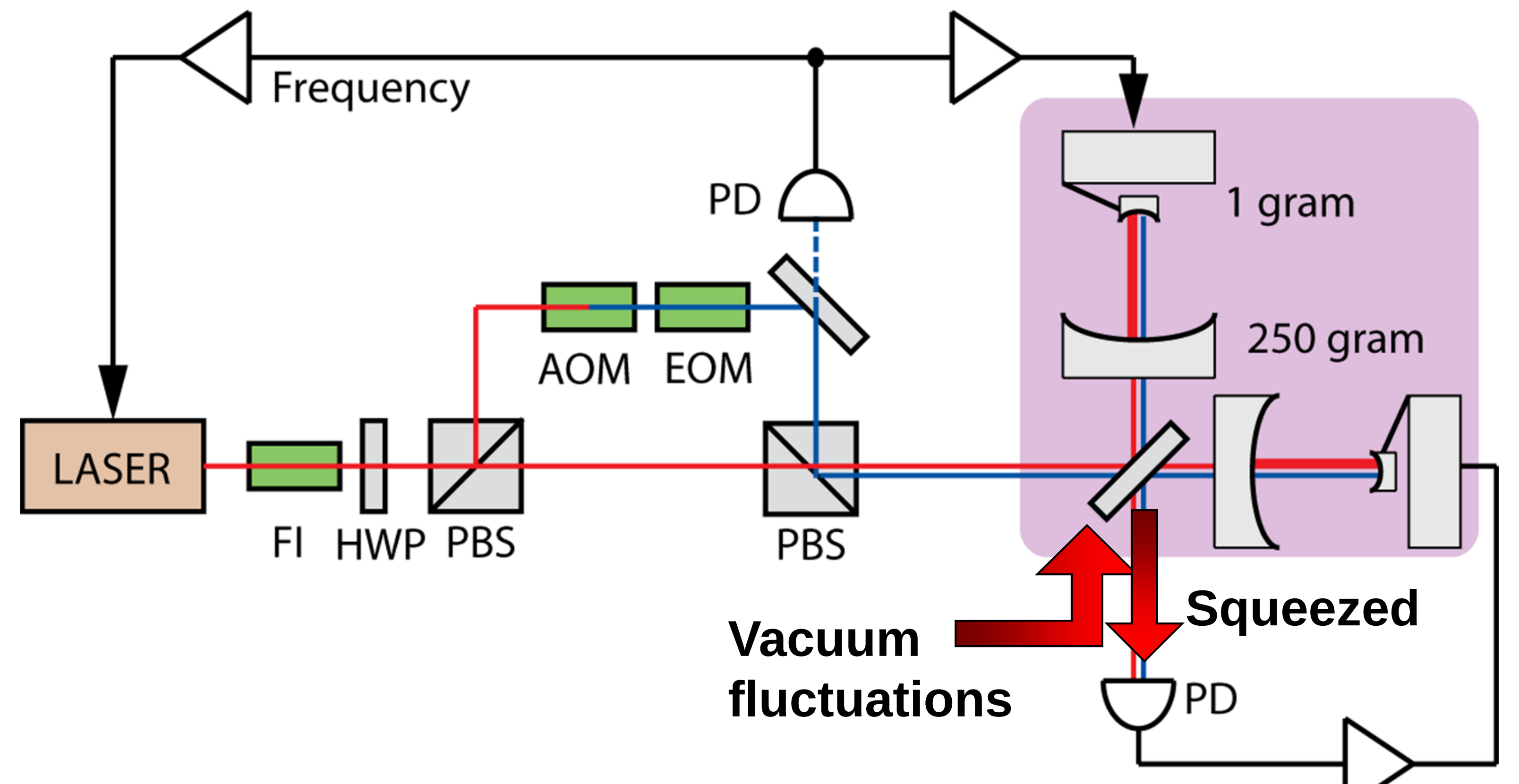
Classical

- Force linearly dependent on intracavity power → optical restoring force
  - Optical spring provides trapping potential
- Time delay in the cavity response → optical viscous damping force
  - Optical cooling

Quantum

- Amplitude noise drives mirror motion → mirror motion imprinted on phase of EM field → amplitude-phase correlations
  - Interferometer fields squeezed

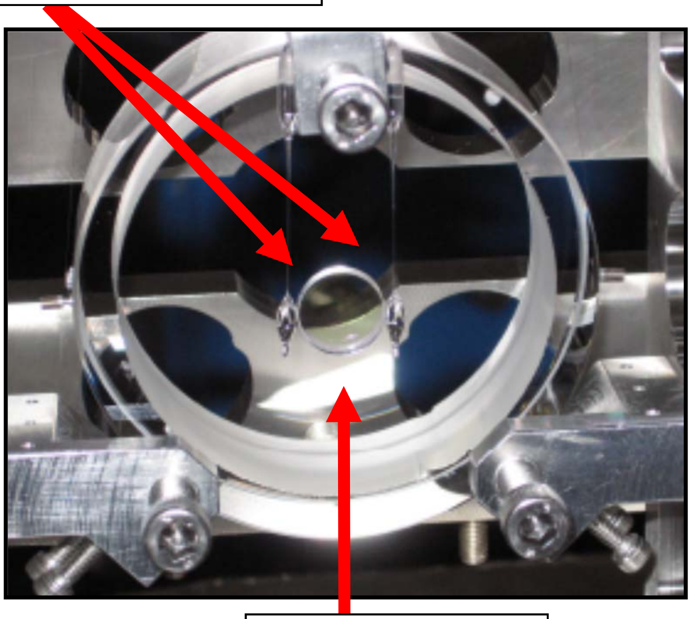
Experiment cartoon



T. Corbitt et al., Phys. Rev. A **73**, 023801 (2006)

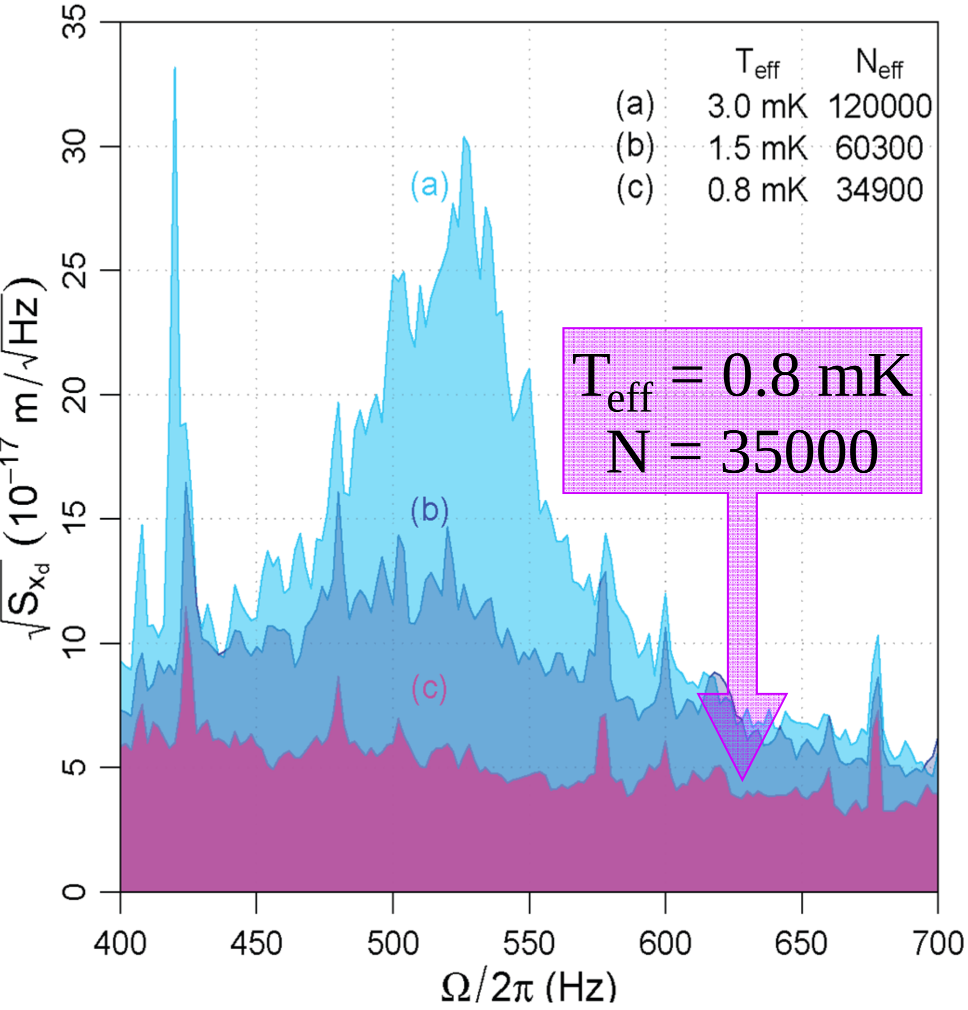
- Two identical cavities with 1 gram mirrors at the ends
- Common-mode rejection cancels out laser noise

Optically trapped and cooled mirror



Optical fibers

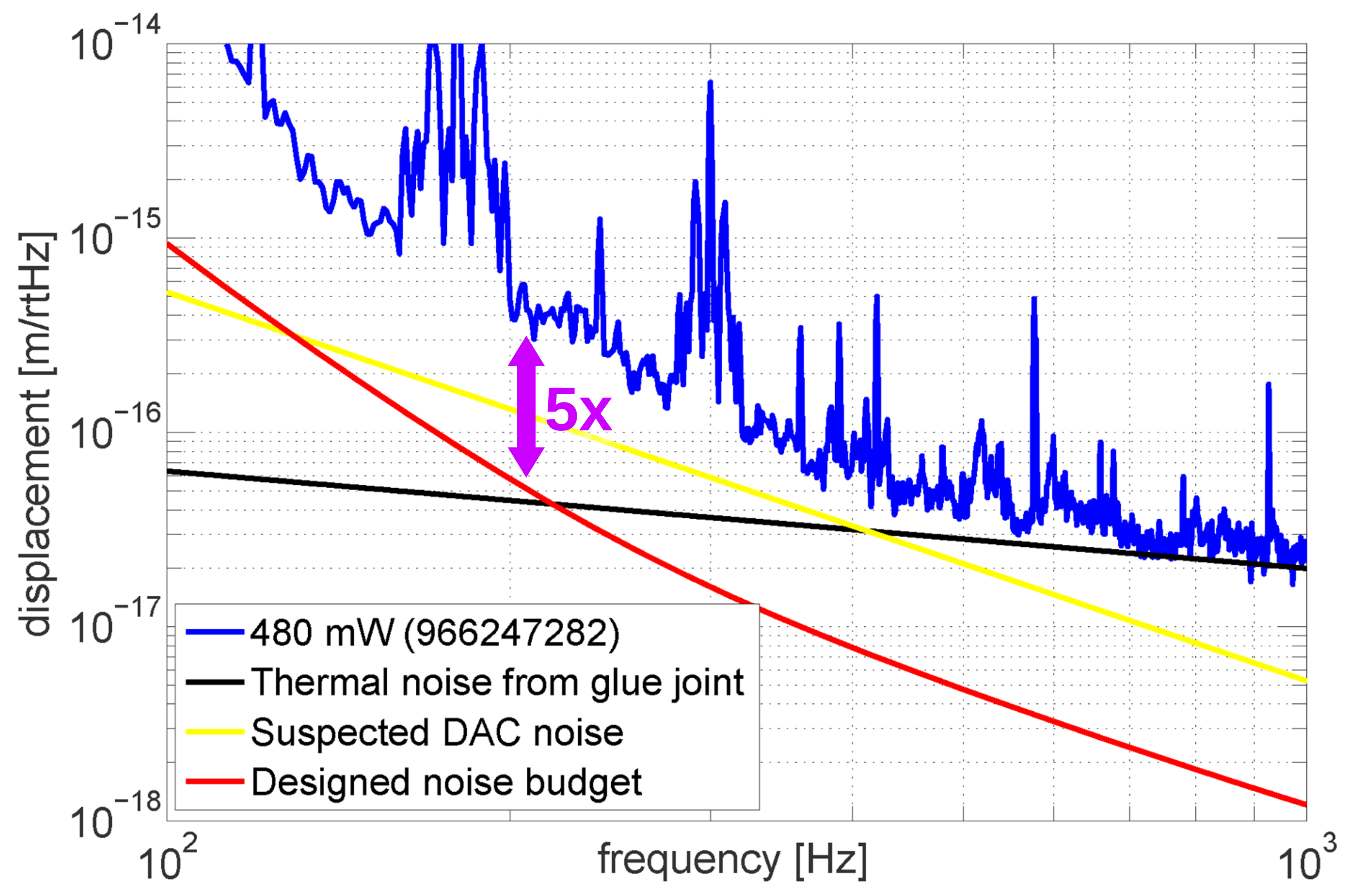
1 gram
mirror



T_{eff} = 0.8 mK
N = 35000

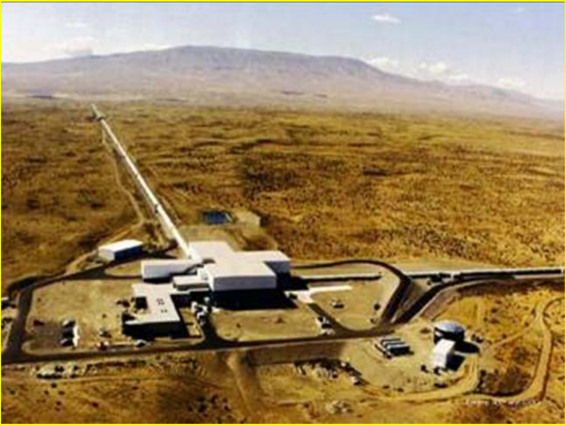
C. Wipf, T. Bodiya, et al. (March 2010)

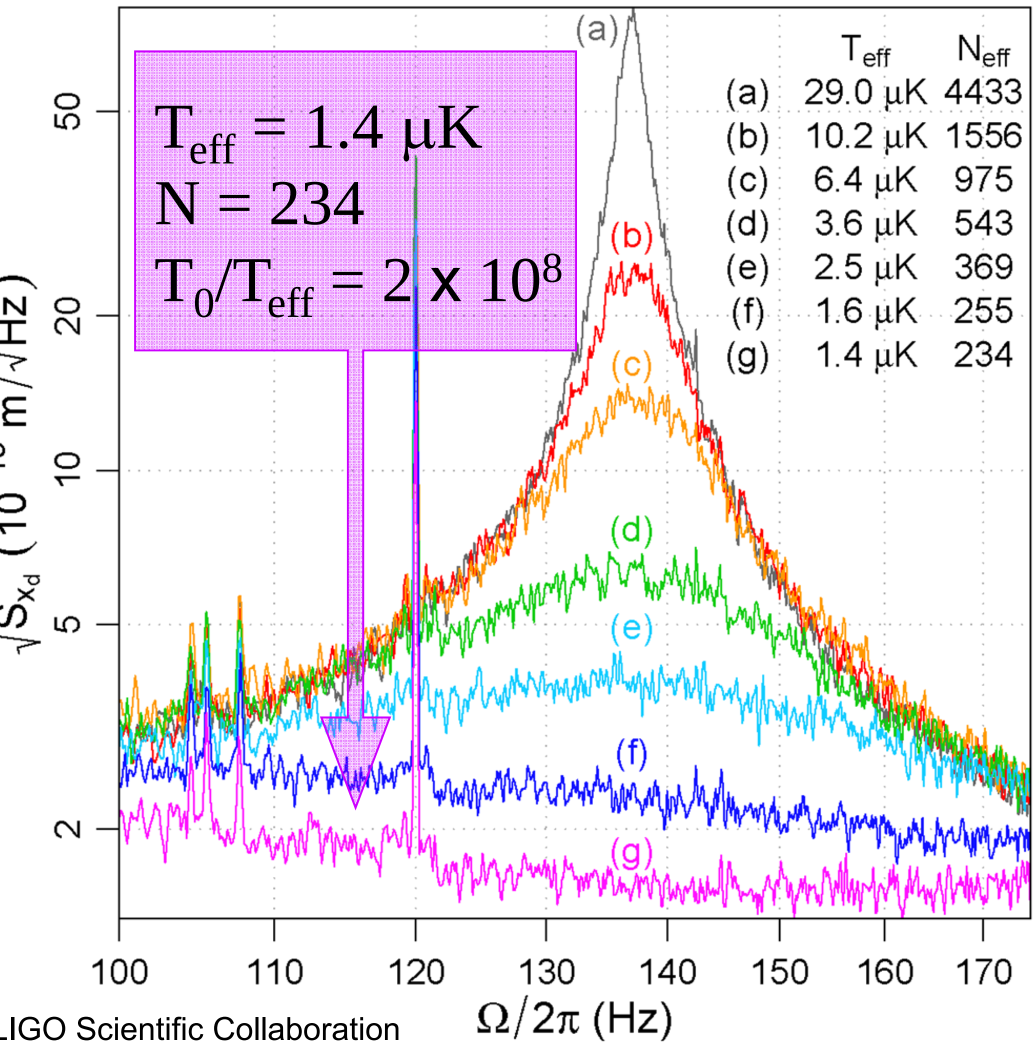
That elusive quantum regime



LIGO mirrors are so cool

Cooling the kilogram-scale mirrors of Initial LIGO





T_{eff} = 1.4 μK
N = 234
T_0/T_{eff} = 2 x 10^8

	T_{eff}	N_{eff}
(a)	29.0 μK	4433
(b)	10.2 μK	1556
(c)	6.4 μK	975
(d)	3.6 μK	543
(e)	2.5 μK	369
(f)	1.6 μK	255
(g)	1.4 μK	234

LIGO Scientific Collaboration

M_r ~ 2.7 kg ~ 10^{26} atoms
Ω_{osc} = 2 π x 0.7 Hz

GW ↔ Quantum Optics and Optomechanics

Technique	GW detection	Quantum Optomechanics
Optical spring	Resonant enhancement in sensitivity	Trapping and cooling of mirrors
Signal processing	Extract signals	Obtain conditional states in real time
Control system	Hold detector at operating point	Feedback cooling & state preparation
Squeezing	Suppress noise, improve SNR	State preparation & state tomography

Yanbei Chen, LIGO-T100075 (2010)

Closing remarks

- Quantum optics techniques deployed in GW detectors
  - Reduction of the shot noise limit with squeezed state injection
  - H1 and GEOHF tests underway
- Quantum optomechanics not yet quantum but
  - Strong optomechanical coupling → optical cooling and trapping
  - Within a factor of few in laboratory experiments
  - Advanced LIGO should operate at the SQL → Quantum ground state of many kilogram object !!!

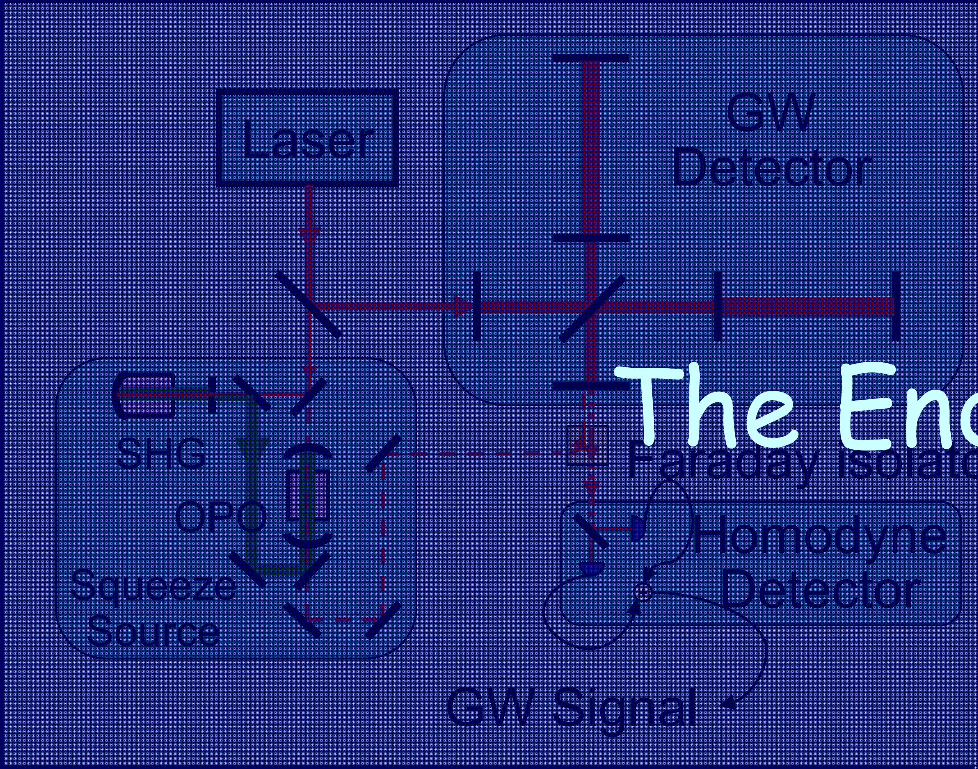
Cast of characters

MIT

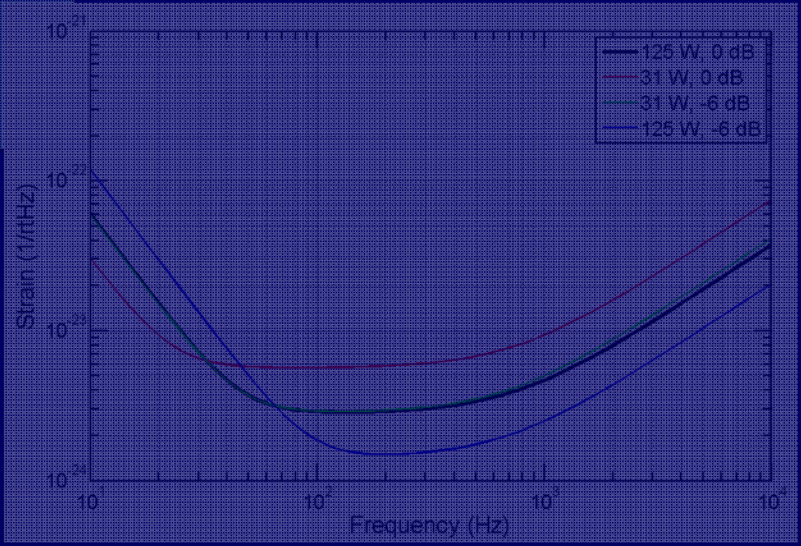
- Keisuke Goda
- Thomas Corbitt
- Christopher Wipf
- Timothy Bodiya
- Sheila Dwyer
- Nicolas Smith
- Eric Oelker
- Rich Mittleman
- LIGO Laboratory

Collaborators

- Yanbei Chen & group
- David McClelland & group
- Roman Schnabel & group
- Stan Whitcomb
- Daniel Sigg
- Rolf Bork
- Alex Ivanov
- Jay Heefner
- Caltech 40m Lab
- LIGO Scientific Collaboration


Laser
GW
Detector
SHG
OPO
Squeeze
Source
Faraday isolator
Homodyne
Detector
GW Signal

The End

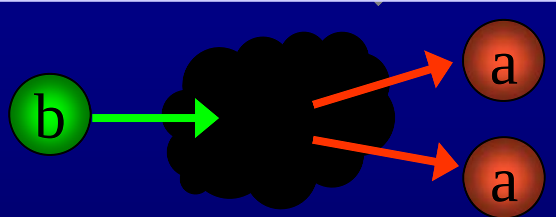

125 W, 0 dB
31 W, 0 dB
31 W, -6 dB
125 W, -6 dB
10^{-21}
10^{-22}
10^{-23}
10^{-24}
Strain (1/rtHz)
10
10^2
10^3
10^4
Frequency (Hz)

Basic principle

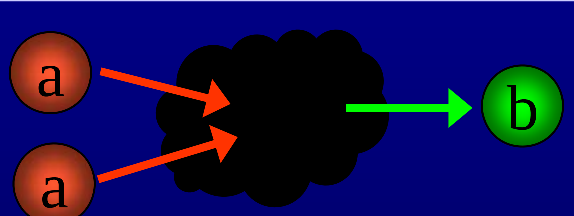
$E_a = \hbar\omega_0$

$E_b = 2\hbar\omega_0$

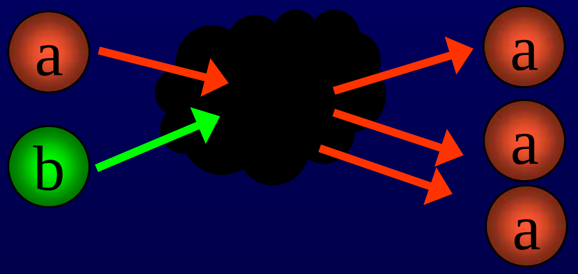
$$\hat{H} = i\,\hbar\,\kappa\left(\hat{a}^\dagger\hat{a}^\dagger\hat{b} - \hat{a}\hat{a}\hat{b}^\dagger\right)$$



Parametric oscillation



Second harmonic generation



Parametric amplification

The output photon quadratures are correlated

Typical squeezer apparatus

Second harmonic generator (SHG)

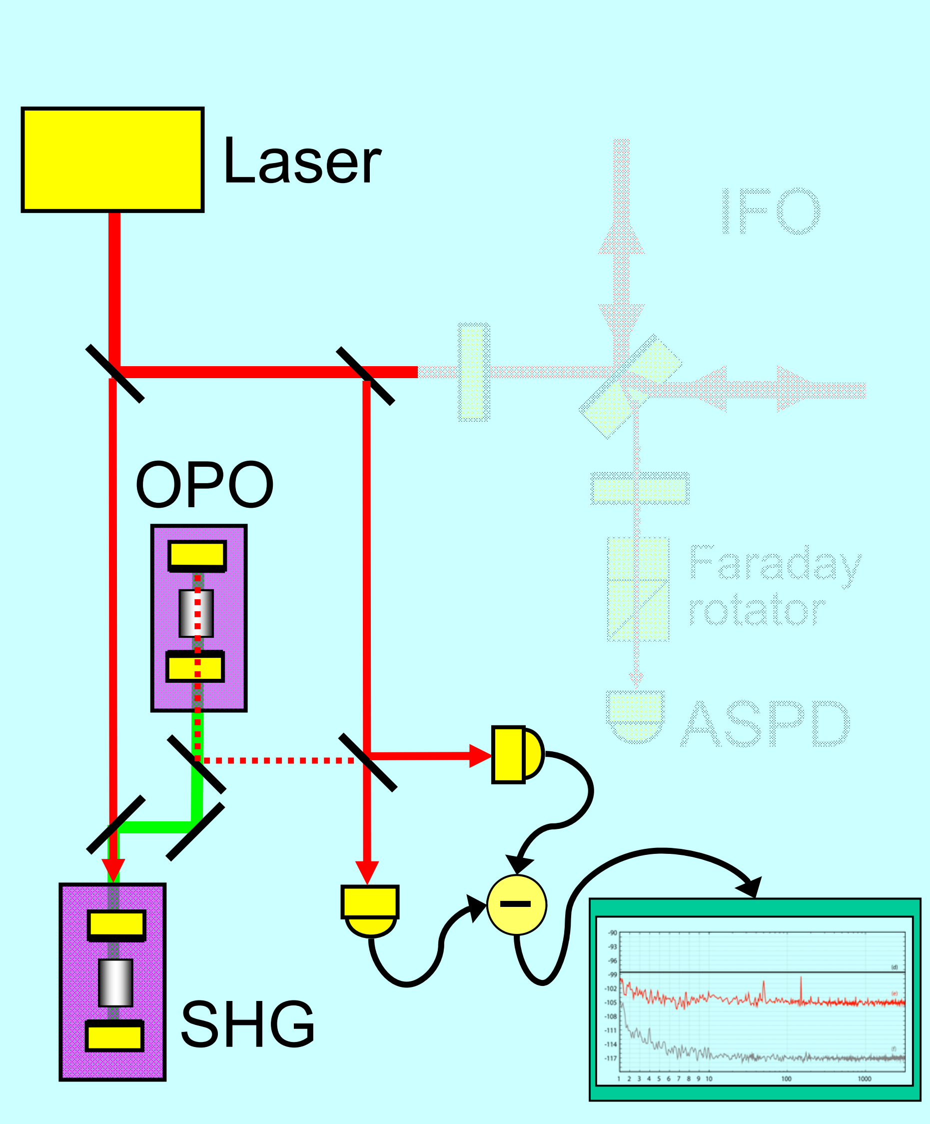
- Convert 1064 nm → 532 nm with ~50% efficiency

Optical parametric oscillator (OPO)

- Few 100 mW pump field (532 nm) correlates upper and lower quantum sidebands around carrier (1064 nm) → squeezing

Balanced homodyne detector

- Beat local oscillator at 1064nm with squeezed field



Squeezing injection

Second harmonic generator (SHG)

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