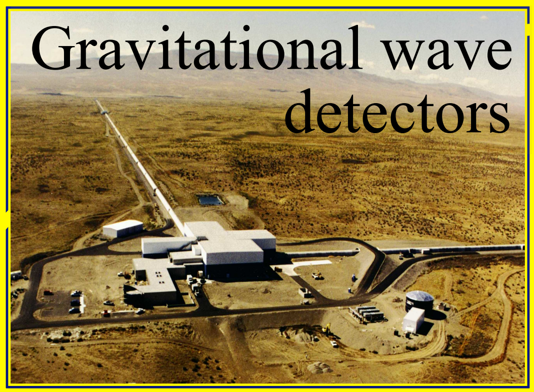
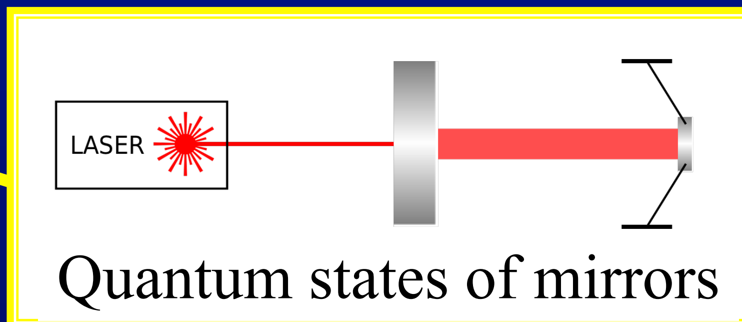
Quantum Opportunities in Gravitational Wave Detection

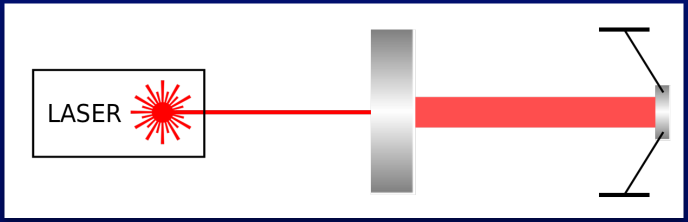




Nergis Mavalvala, MIT
@ Fermilab, March 2012

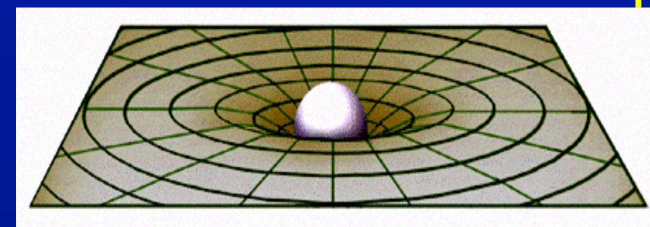
Two revolutions

- 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



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

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

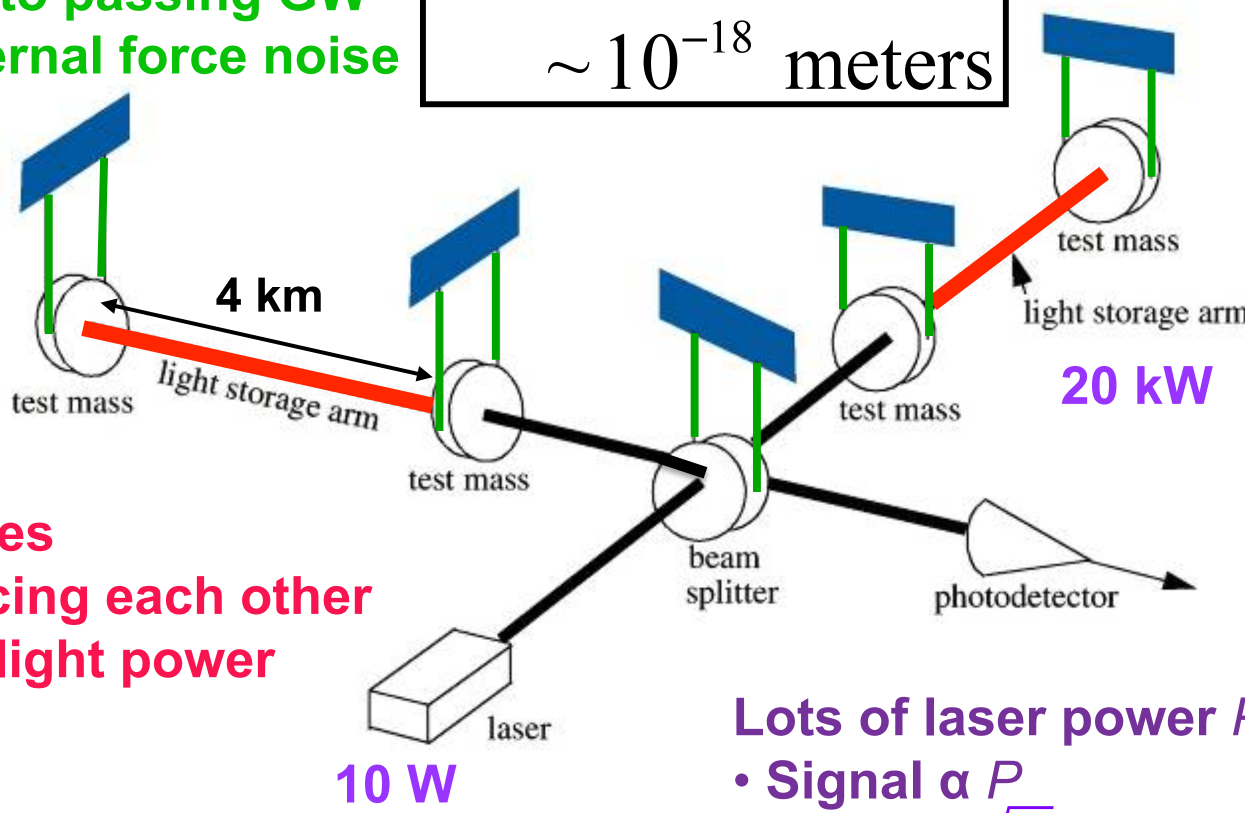
☹

Global network of detectors

GW detector at a glance

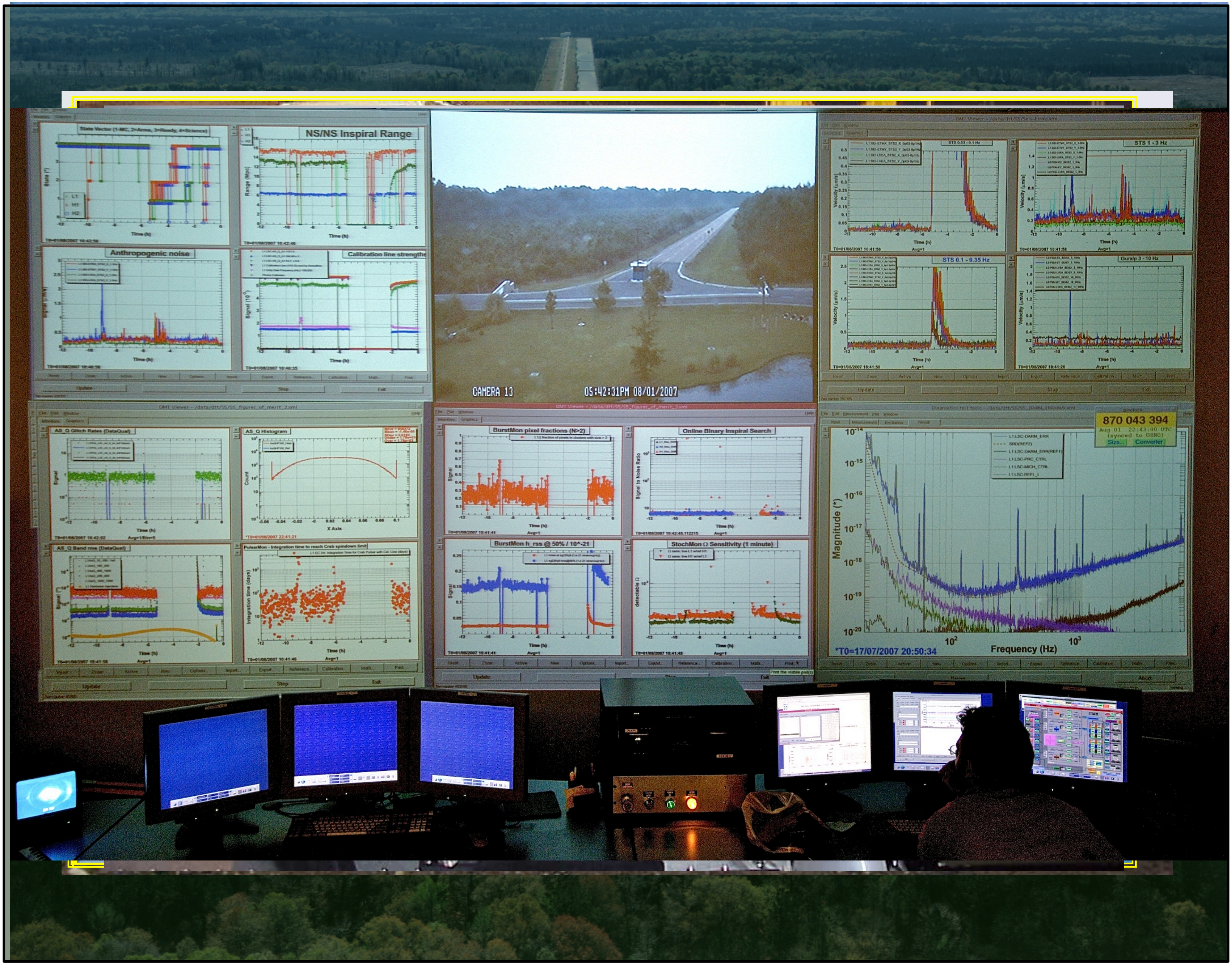
Mirrors hang as pendulums
- **Quasi-free particles**
- **Respond to passing GW**
- **Filter external force noise**

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



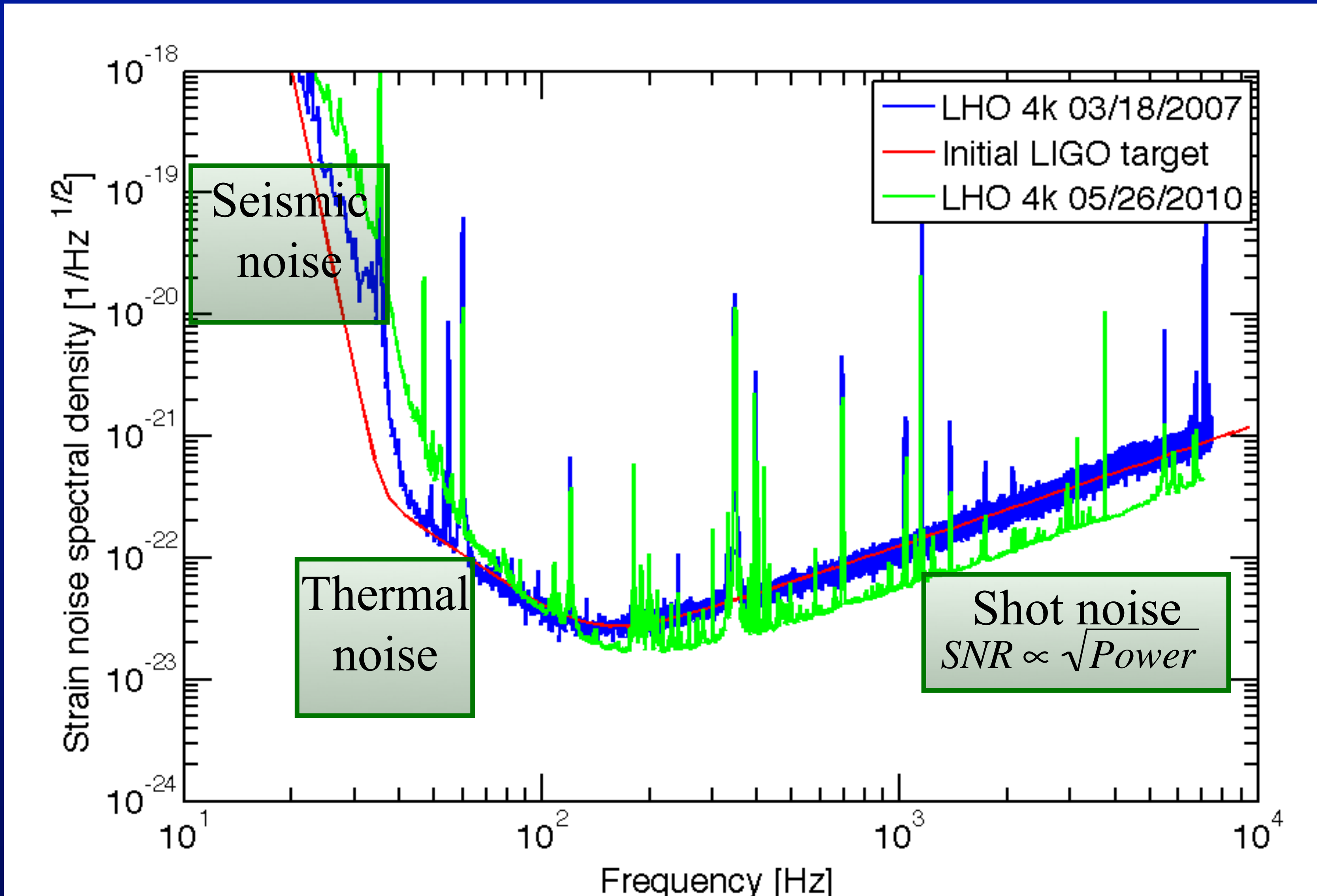
Optical cavities
- **Mirrors facing each other**
- **Builds up light power**

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



State Vector (1=MC, 2=Arms, 3=Ready, 4=Science)
NS/NS Inspiral Range
Anthropogenic noise
Calibration line strengths
CAMERA 13
05:42:31PM 08/01/2007
AS_Q Glitch Rates (DataQual)
AS_Q Histogram
AS_Q Band rms (DataQual)
BurstMon pixel fractions (N>2)
Online Binary Inspiral Search
StochMon Ω Sensitivity (1 minute)
870 043 394
Magnitude
Frequency (Hz)
*T0=17/07/2007 20:50:34

First Phase of LIGO (~2000 to 2010)



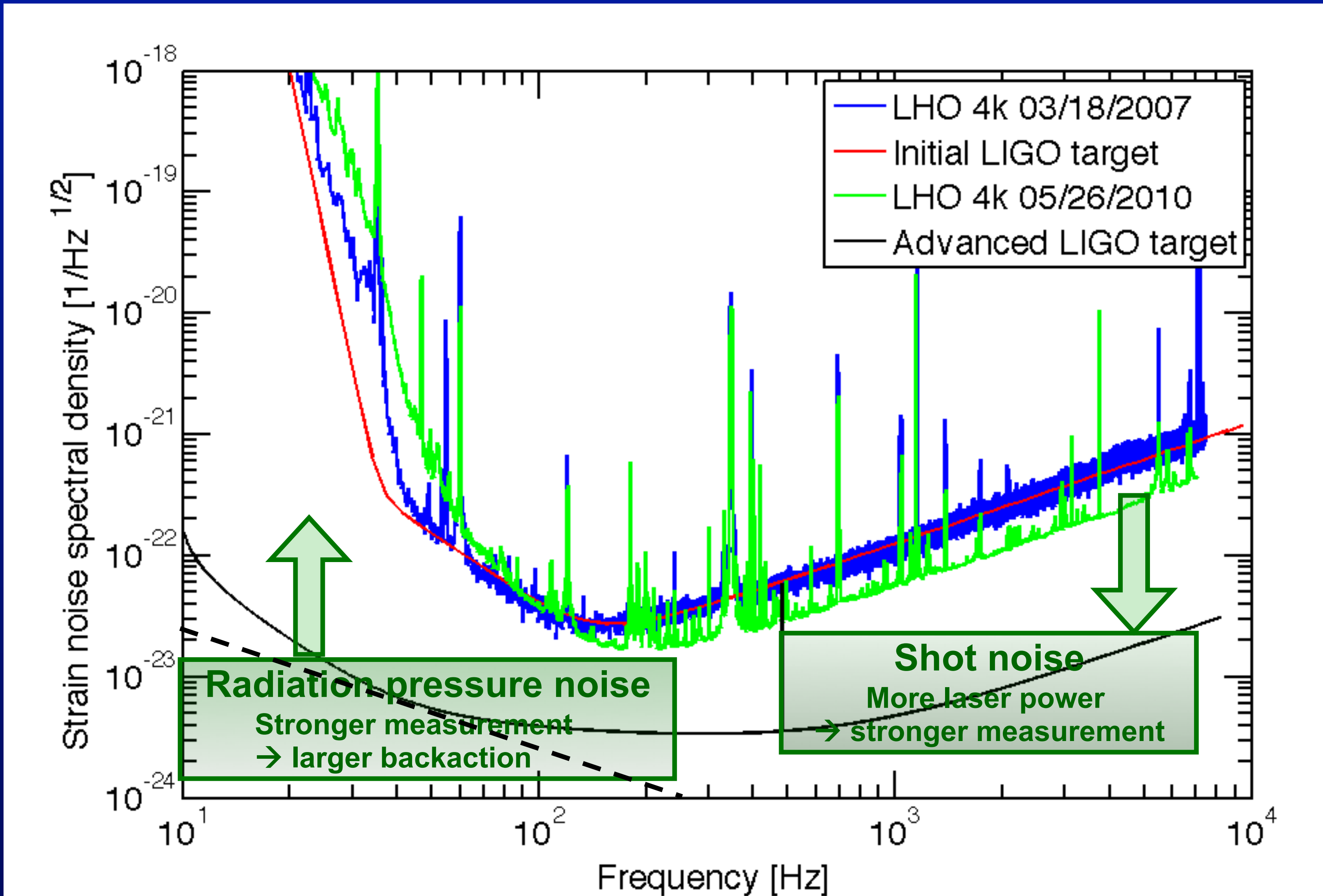
Astrophysics with first generation detectors

Over 50 published results

- Journals include
  - Physical Review
  - Astrophysics Journal
  - Nature
  - Classical and Quantum Gravity
  - New Journal of Physics
- Topics include
  - Neutron star and black hole coalescence
  - Gamma-ray bursts
  - Known pulsars (e.g . Crab)
  - Unknown pulsars
  - Transient sources ("bursts")
  - Cosmological stochastic background

No direct detections (yet)

Advanced LIGO (2011…)



Origin of the Quantum Noise
Vacuum fluctuations

Quantum states of light

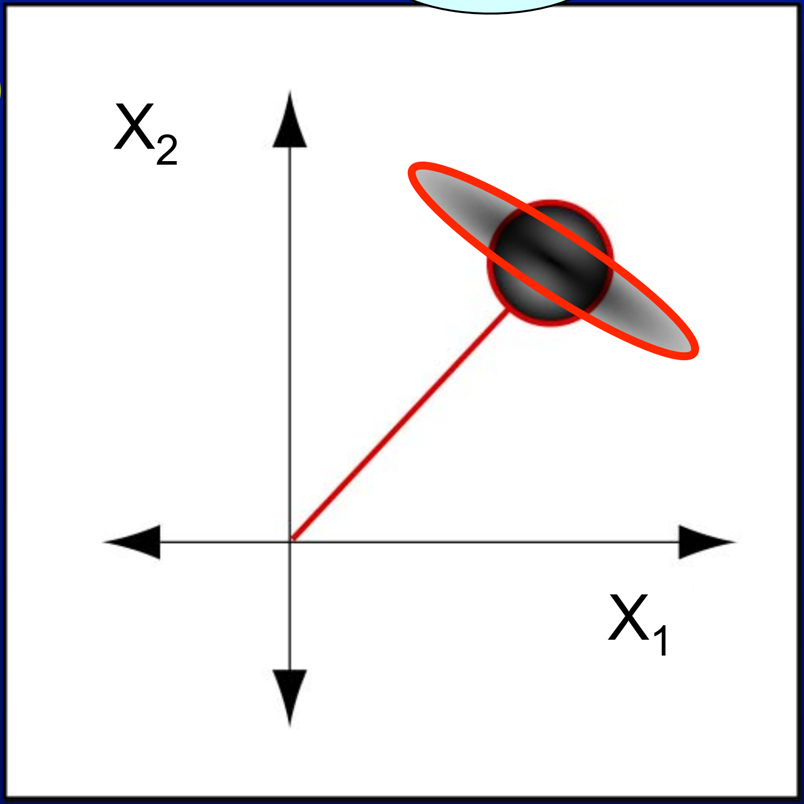
- Heisenberg Uncertainty Principle

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

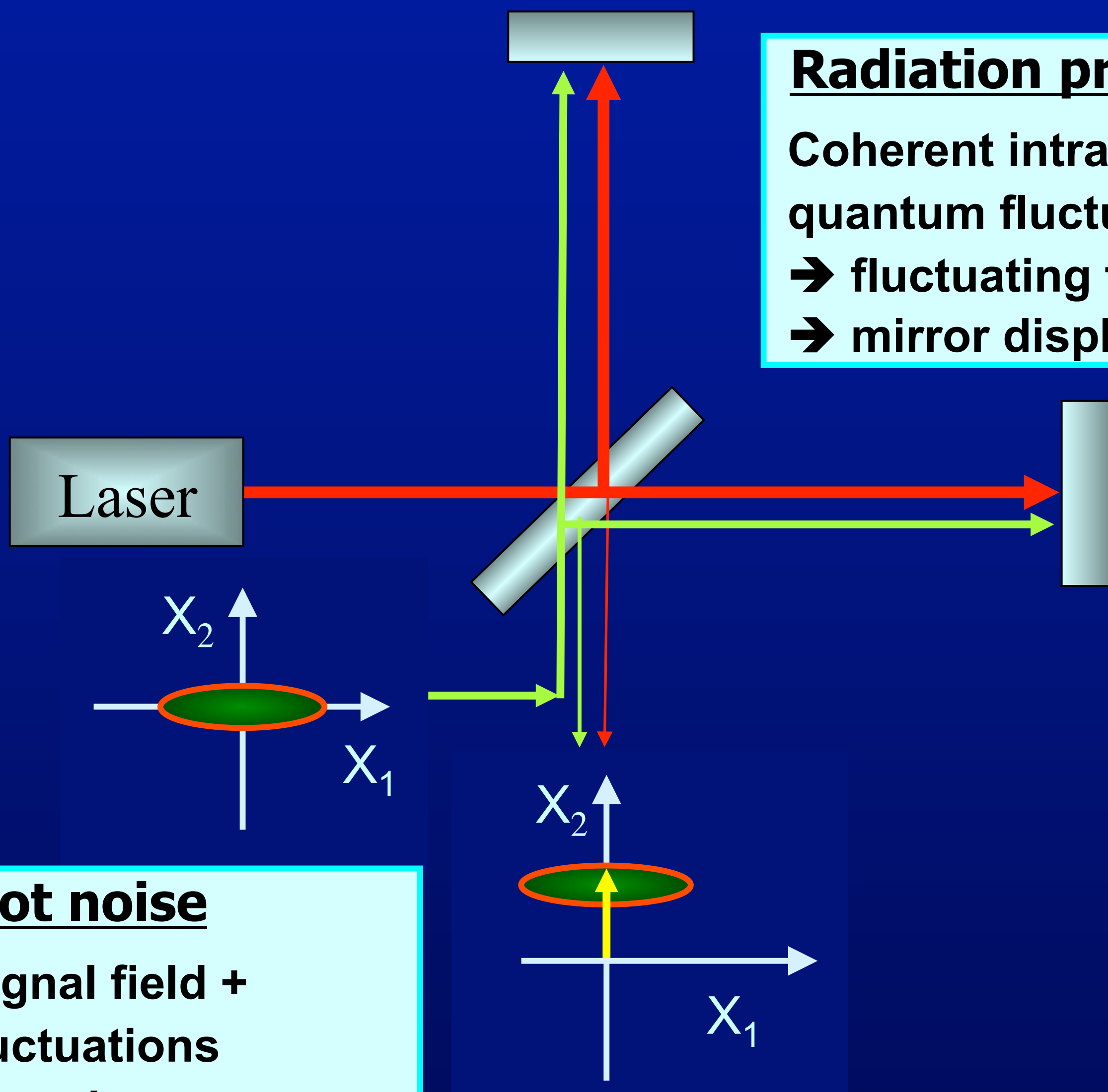
X_1 and X_2 associated with amplitude and phase

- Coherent state (laser light)
- 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



Radiation pressure noise

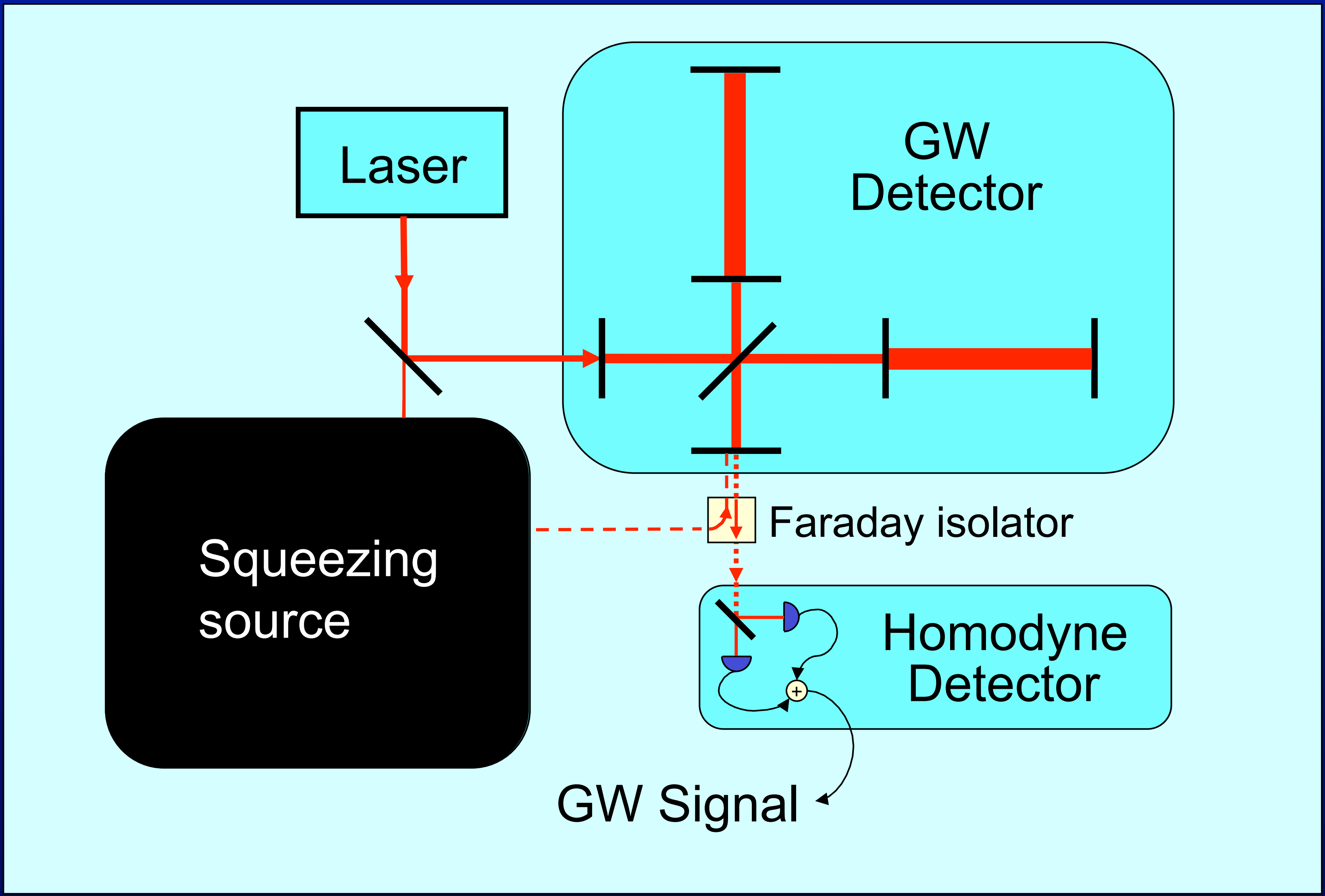
Coherent intracavity field + quantum fluctuations
➔ fluctuating force
➔ mirror displacement

Shot noise

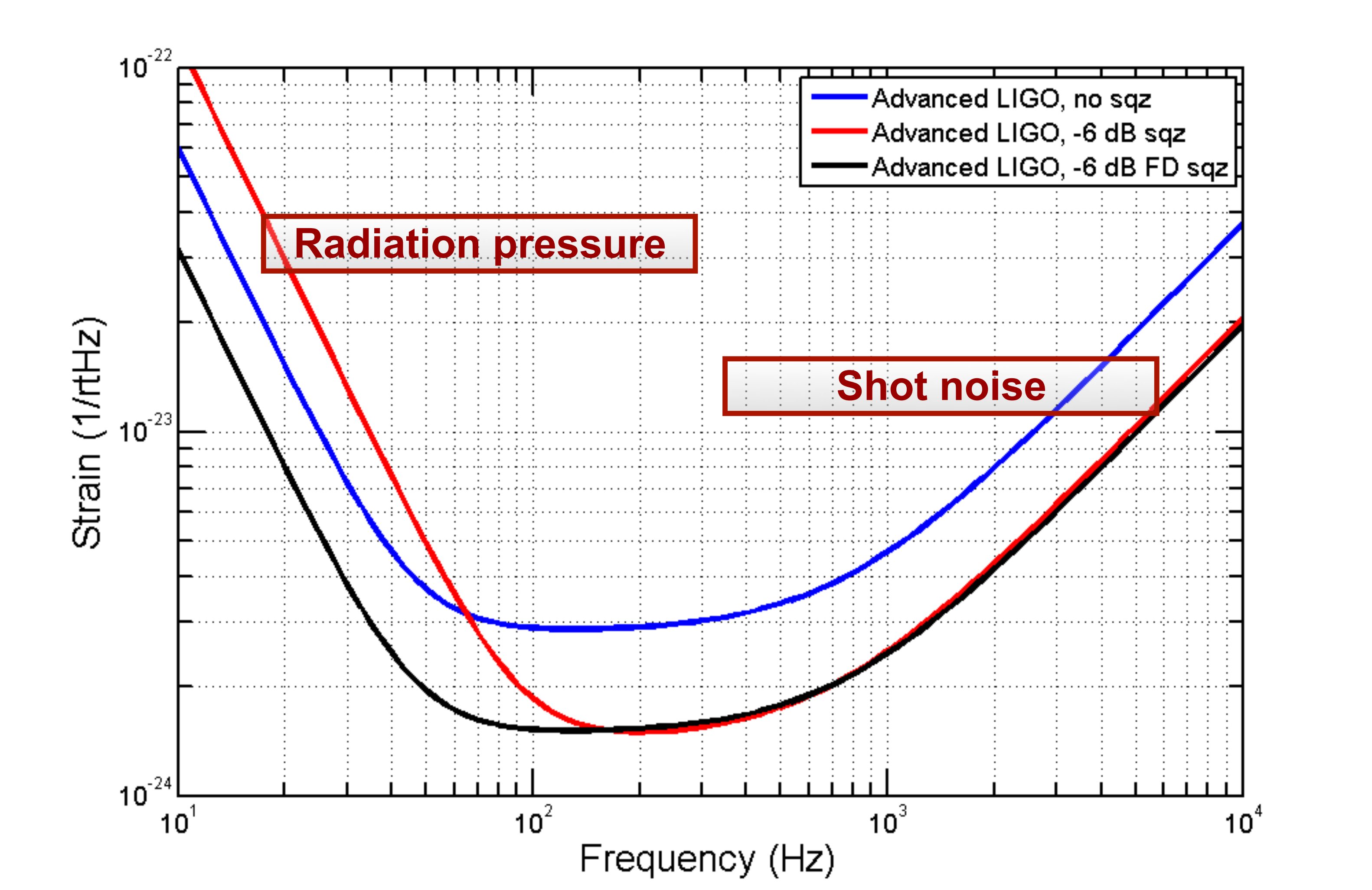
Coherent signal field + quantum fluctuations
➔ fluctuating phase

Squeezed state injection

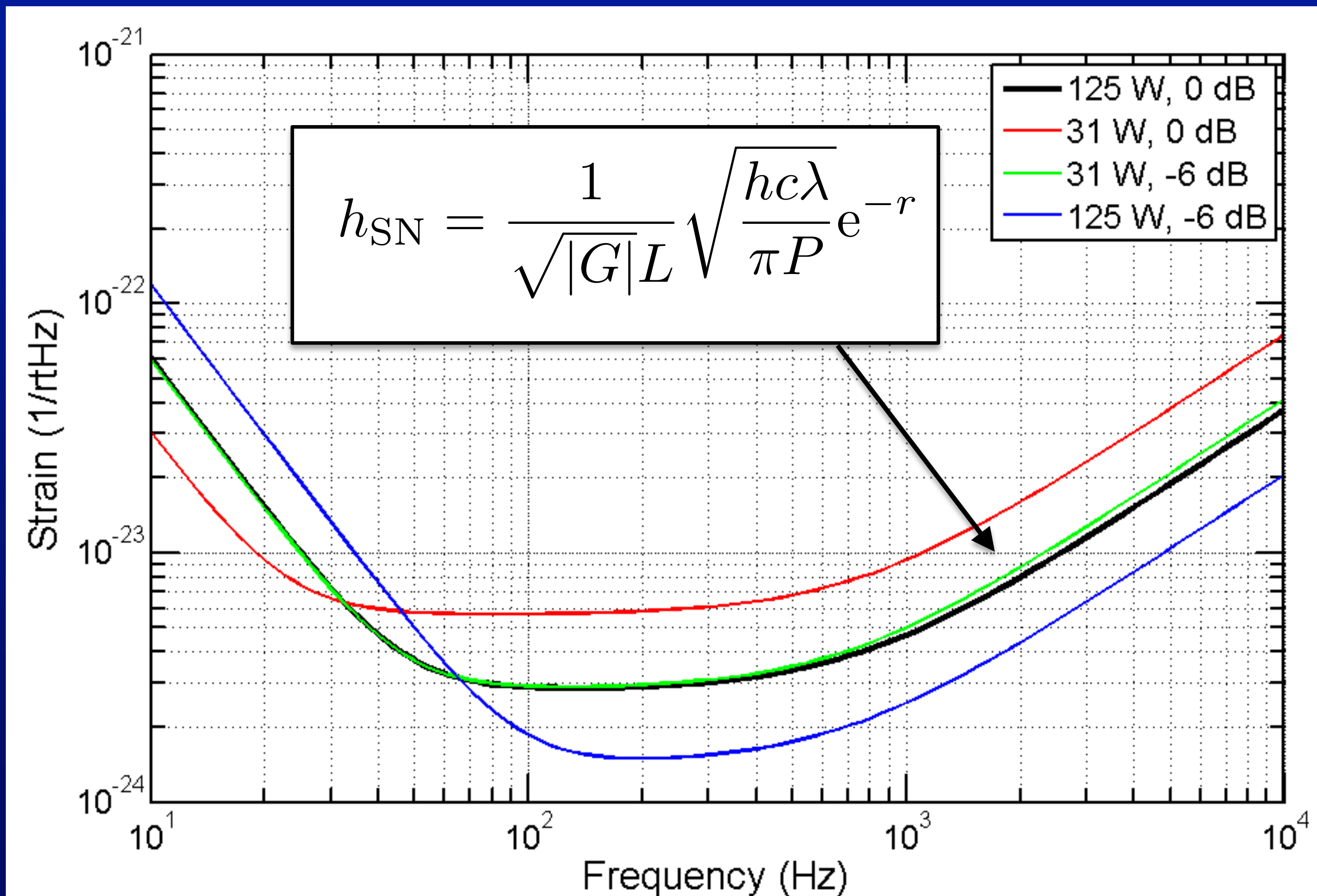
Squeezing injection in Advanced LIGO



Advanced LIGO with squeeze injection



Trading laser power with squeeze injection

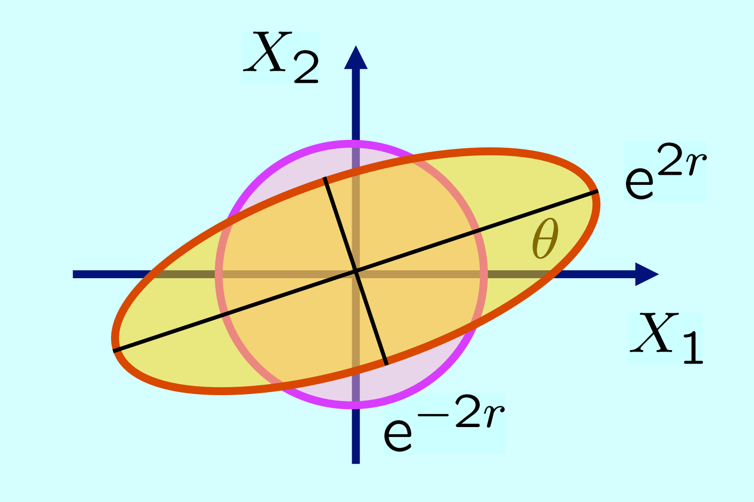


Squeezing a LIGO interferometer

How to squeeze photon states?

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

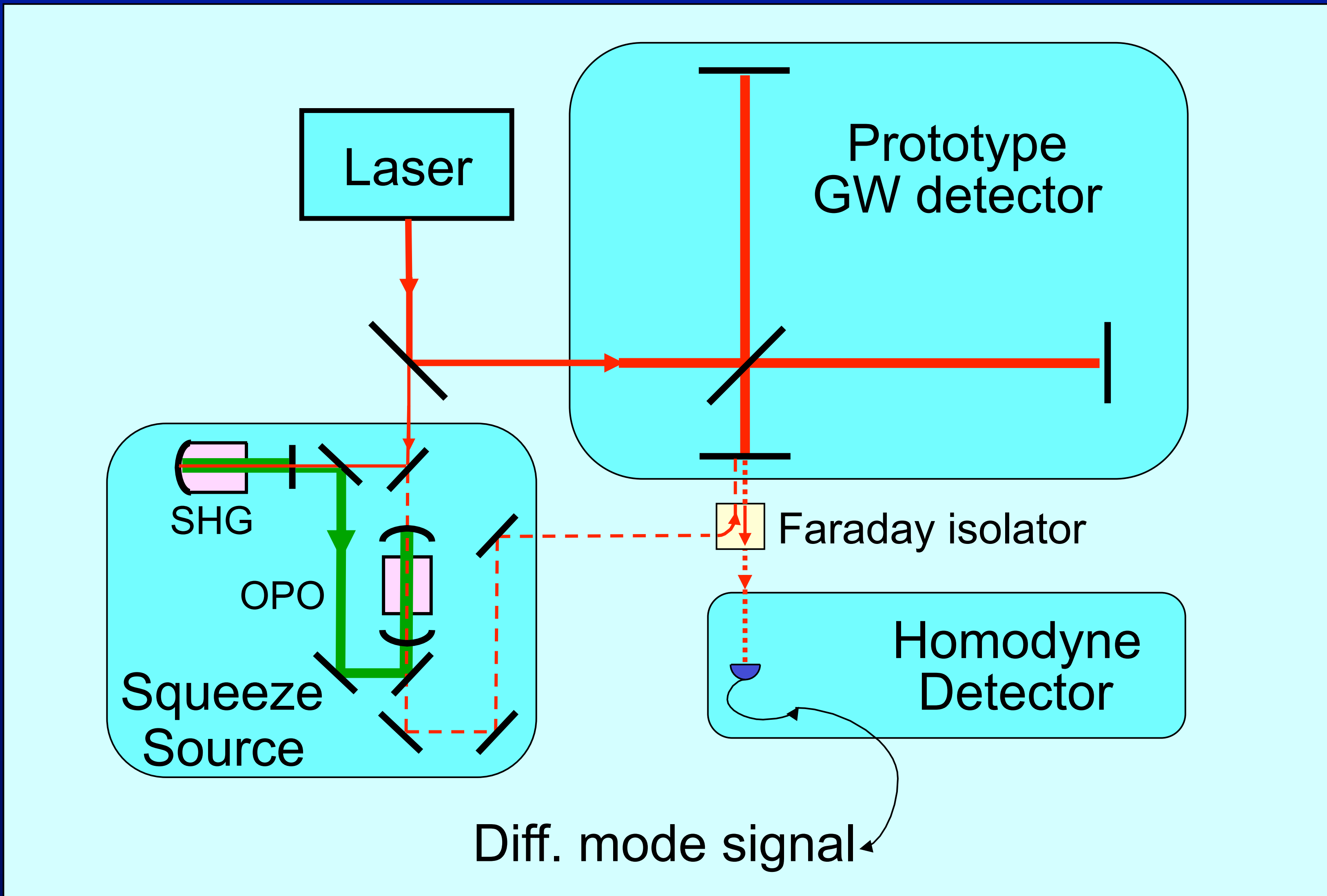
$$\langle(\Delta\hat{X}_1)^2\rangle \sim e^{-2r}$$
$$\langle(\Delta\hat{X}_2)^2\rangle \sim e^{2r}$$



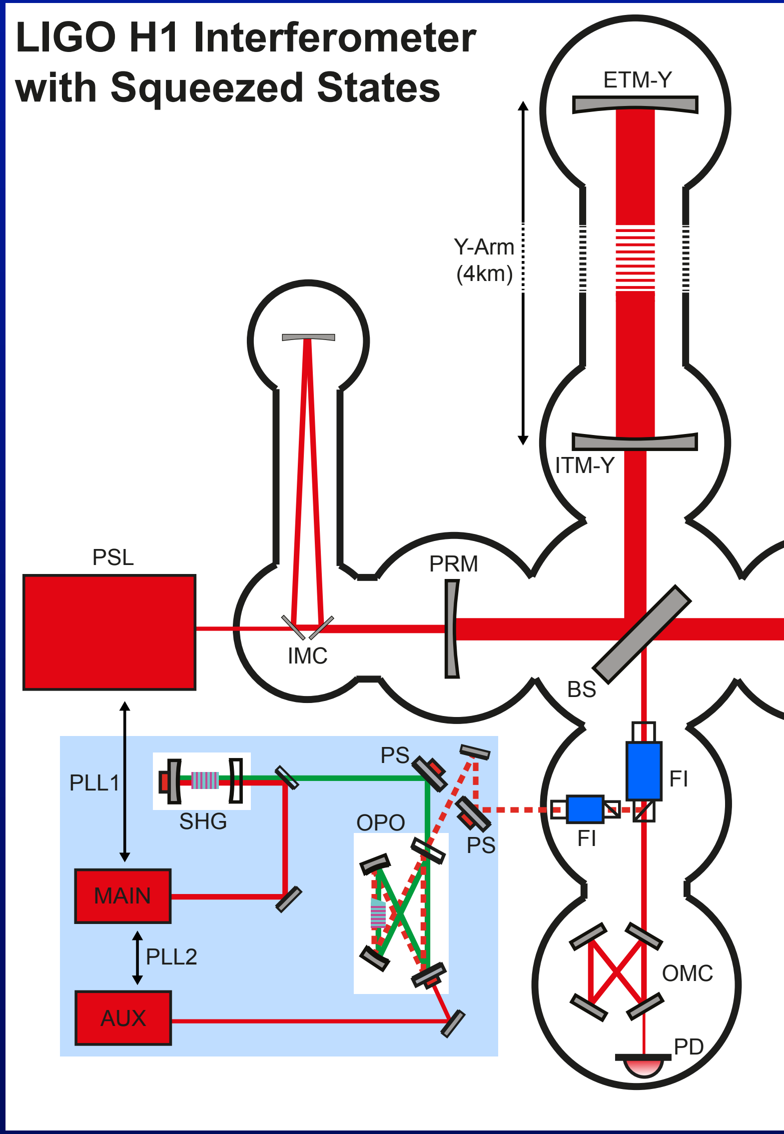
- Create correlations between the quadratures
  - Simple idea → nonlinear optical material where refractive index depends on intensity of light illumination

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

Squeezing injection



Squeezing injection in LIGO

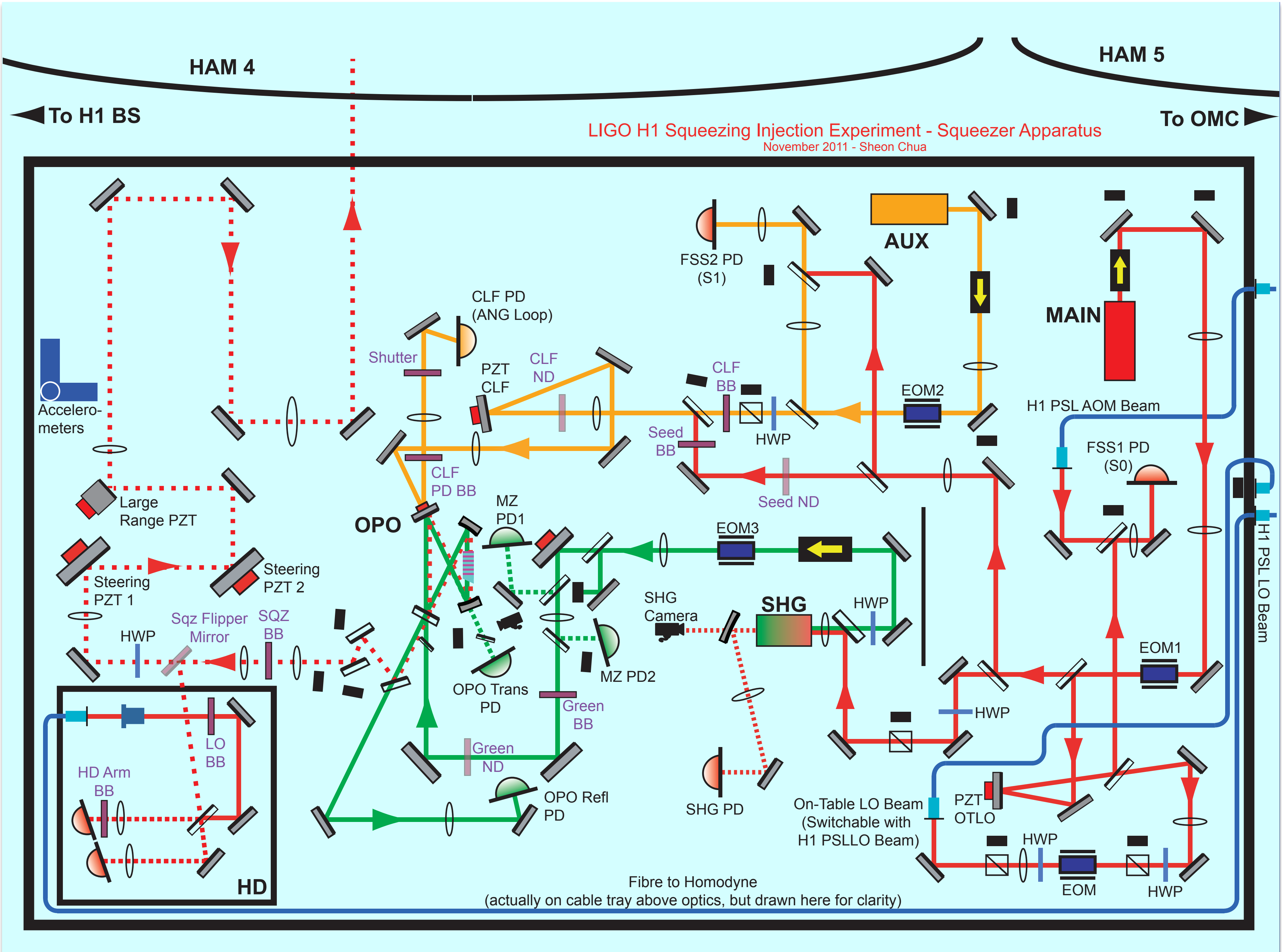


Interferometer Acronyms

- PSL - Pre-Stabilized Laser
- (thick line) - Vacuum System
- IMC - Input Mode Cleaner Cavity
- PRM - Power Recycling Mirror
- BS - Beam Splitter
- ITM - Arm Cavity Input Test Mass
- ETM - Arm Cavity End Test Mass
- FI - Faraday Isolator
- OMC - Output Mode Cleaner Cavity
- PD - Photodiode (Data Output)

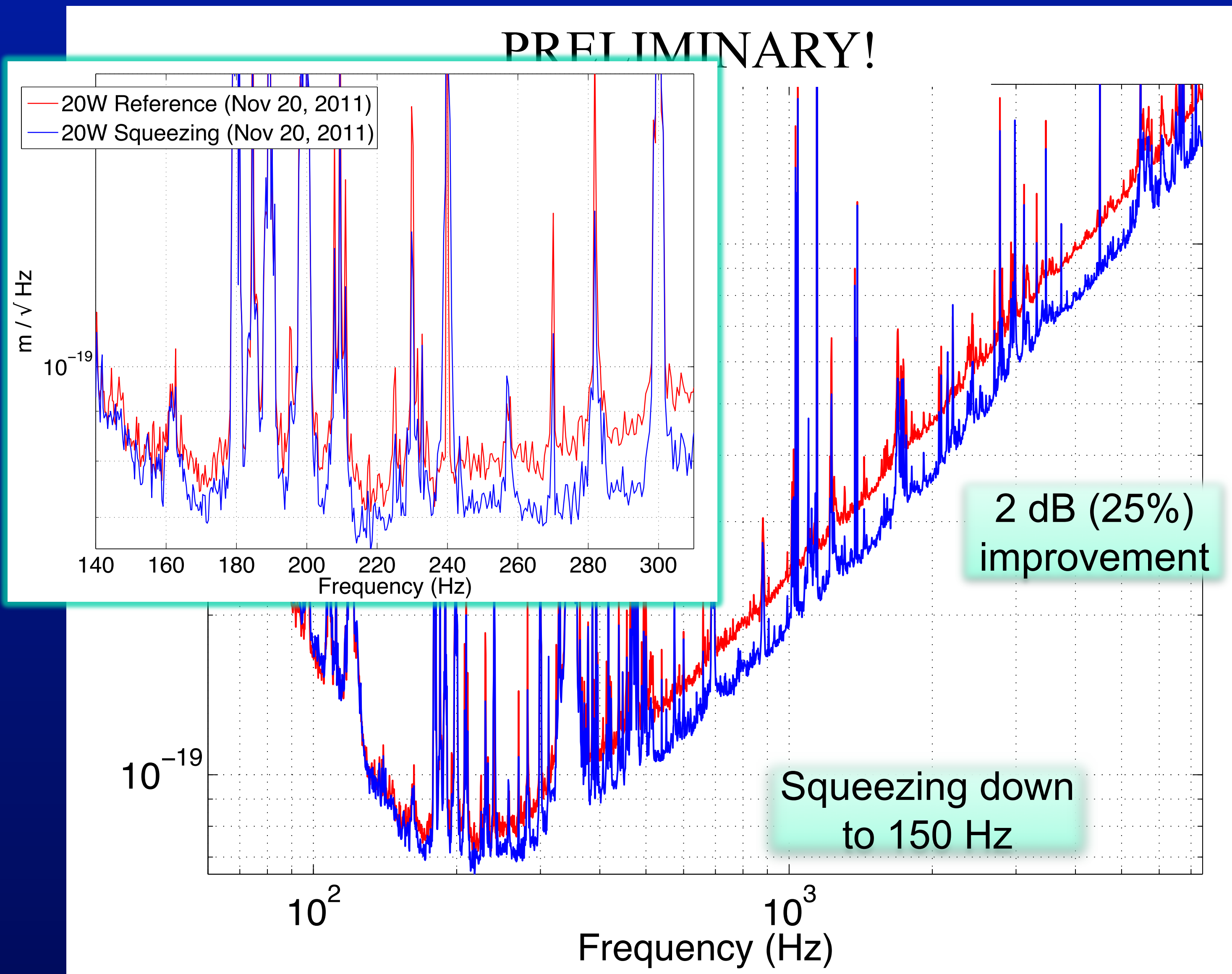
Squeezed Light Source Acronyms

- MAIN - Squeezing Main Laser
- AUX - Squeezing Auxiliary Laser
- PLL - Phase Lock Loop
- SHG - Second Harmonic Generator
- OPO - Optical Parametric Oscillator
- PS - Phase Shifter

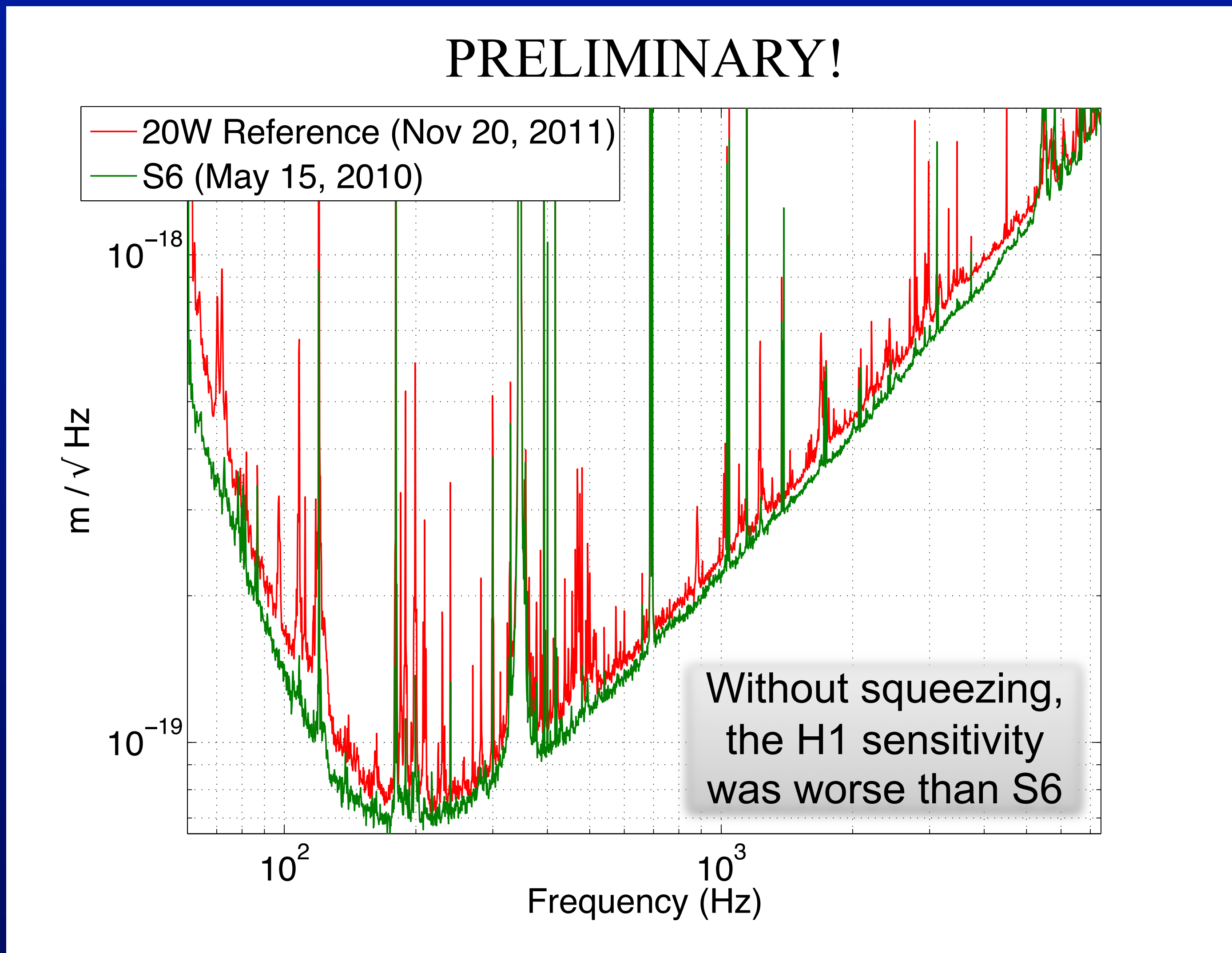


HAM 4
HAM 5
To H1 BS
To OMC
LIGO H1 Squeezing Injection Experiment - Squeezer Apparatus
November 2011 - Sheon Chua
FSS2 PD
(S1)
AUX
MAIN
CLF PD
(ANG Loop)
Shutter
PZT
CLF
CLF
ND
CLF
BB
EOM2
H1 PSL AOM Beam
HWP
Seed
BB
Seed ND
FSS1 PD
(S0)
Accelero-
meters
CLF
PD BB
OPO
MZ
PD1
EOM3
Large
Range PZT
Steering
PZT 2
Steering
PZT 1
SHG
Camera
SHG
HWP
H1 PSL LO Beam
Sqz Flipper
Mirror
SQZ
BB
HWP
MZ PD2
OPO Trans
PD
EOM1
Green
BB
HWP
LO
BB
HD Arm
BB
Green
ND
OPO Refl
PD
SHG PD
On-Table LO Beam
(Switchable with
H1 PSLLO Beam)
PZT
OTLO
HWP
EOM
HWP
HD
Fibre to Homodyne
(actually on cable tray above optics, but drawn here for clarity)

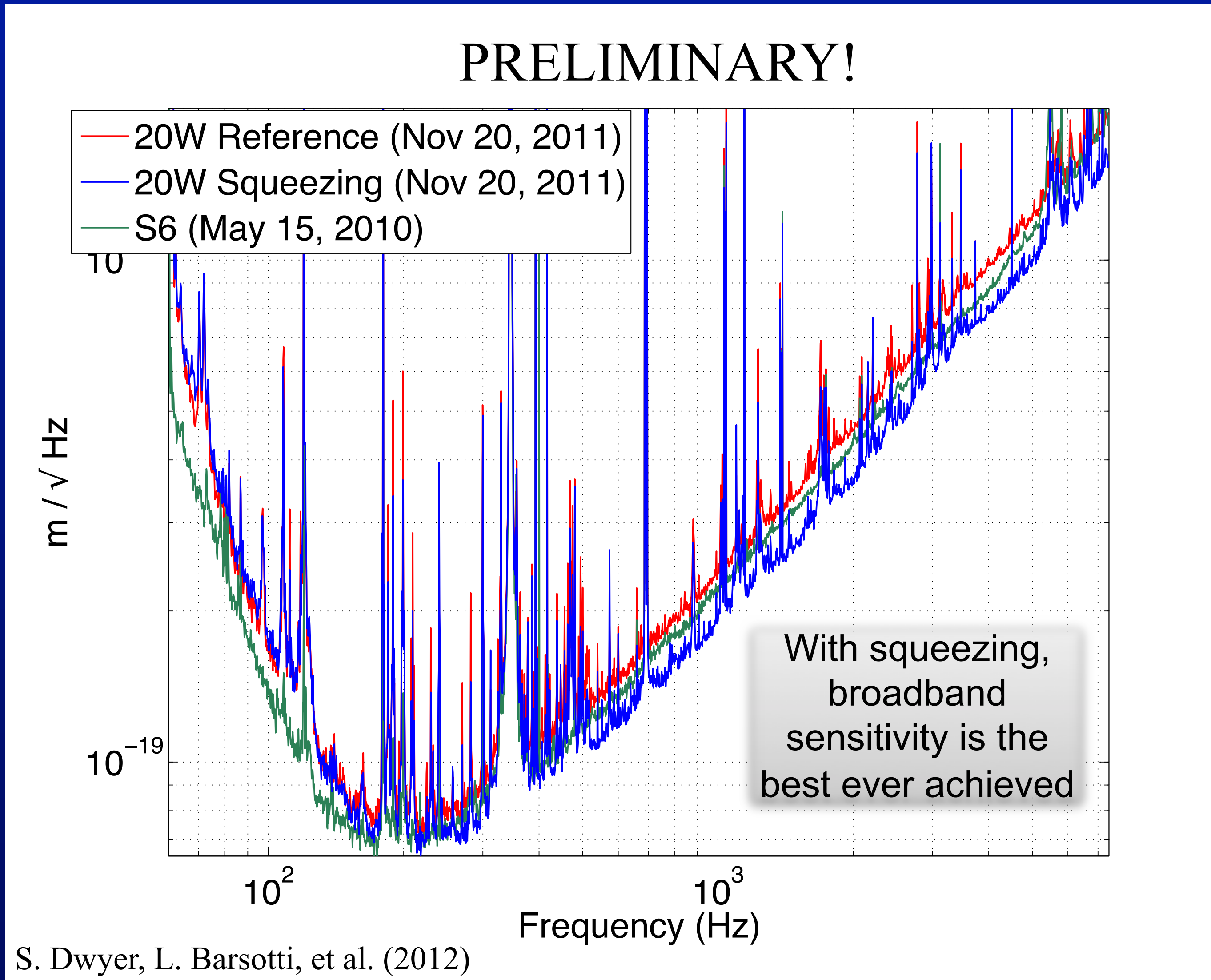
H1 Squeezed


PRELIMINARY!
20W Reference (Nov 20, 2011)
20W Squeezing (Nov 20, 2011)
m / √ Hz
10^−19
140 160 180 200 220 240 260 280 300
Frequency (Hz)
10^2
10^3
Frequency (Hz)
2 dB (25%) improvement
Squeezing down to 150 Hz

Comparison with S6

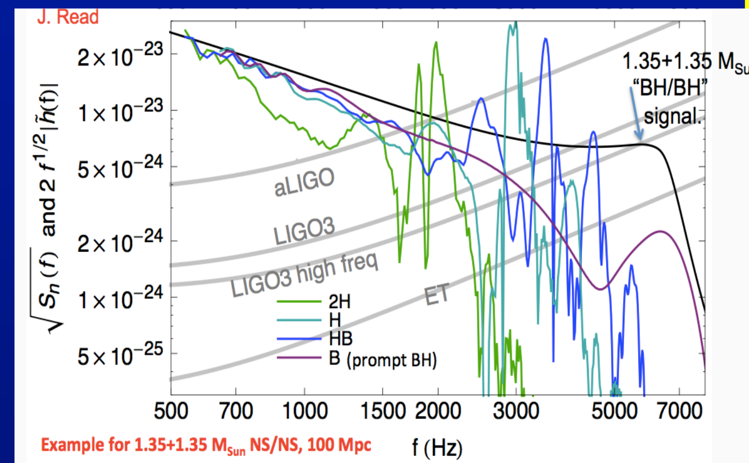


Comparison with S6



Astrophysical implications

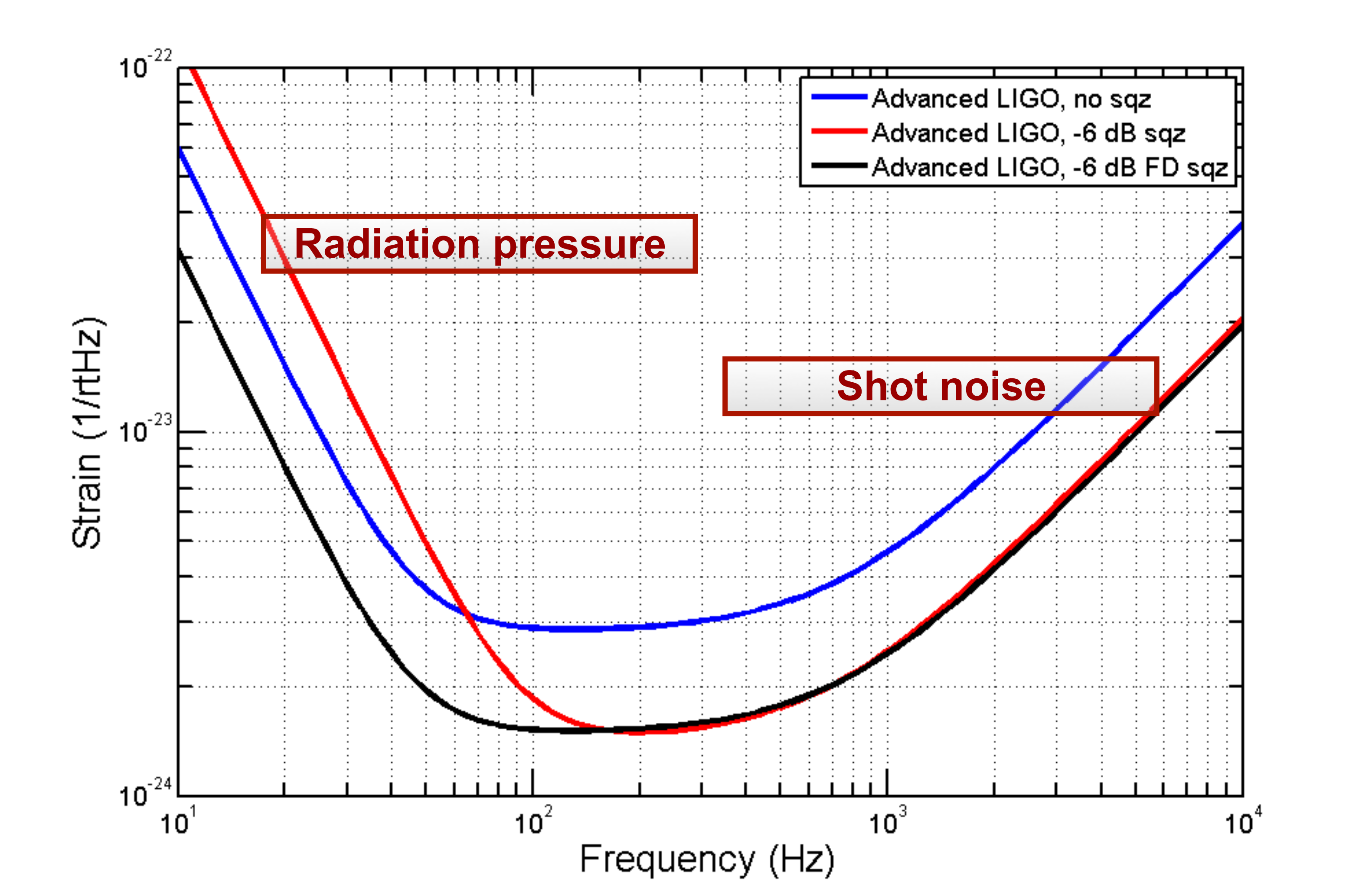
- Frequencies > 300 Hz
  - Nuclear equation of state
  - Neutron star structure
  - Core collapse supernovae, long GRBs
  - Post-merger NS/BH binaries, short GRBs



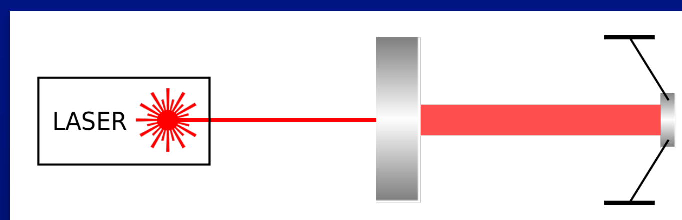
- Frequencies 50 Hz to 300 Hz
  - NS/BH binaries horizons → populations
- Frequencies < 50 Hz
  - Physical parameters of NS and BH binaries (cycles)
  - Intermediate mass BH
  - Stochastic GW background

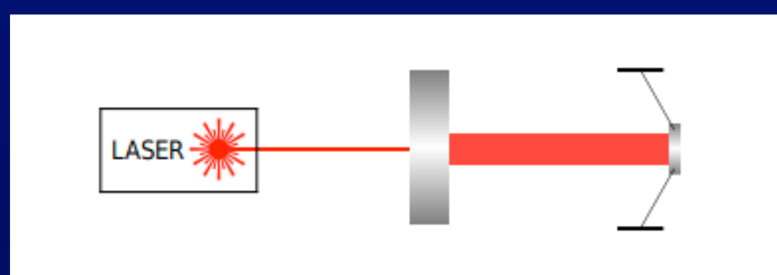
C. Ott

Advanced LIGO with squeeze injection



Optomechanics & Radiation Pressure



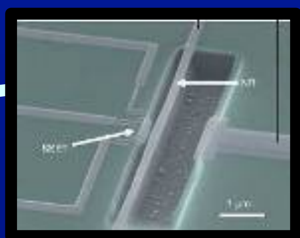


When radiation pressure dominates …

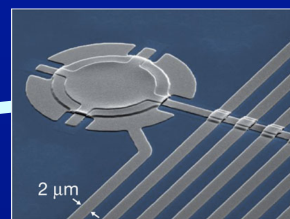
- Techniques for improving gravitational wave detector sensitivity
- Opportunities to study quantum effects in macroscopic systems
  - Observation of quantum radiation pressure
  - Generation of squeezed states of light
  - Entanglement of mirror and light quantum states
  - Quantum states of mirrors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

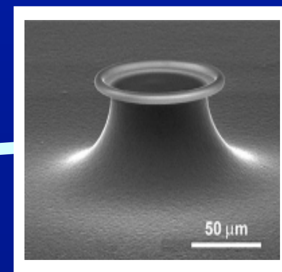
Optomechanics takes off

NEMS → 10^{-12} g

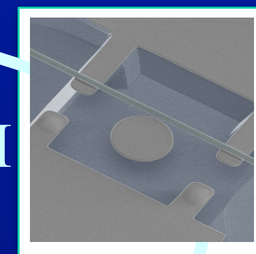


NEMS → 10^{-11} g



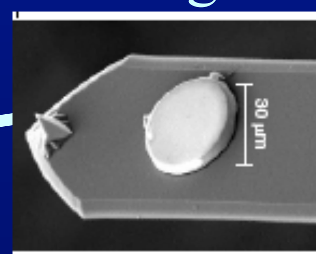


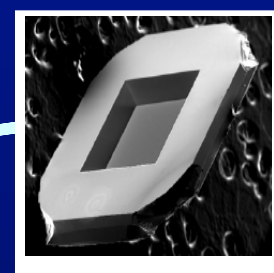
Toroidal microcavity → 10^{-11} g



WG-WGM → 10^{-11} g

AFM cantilevers → 10^{-8} g

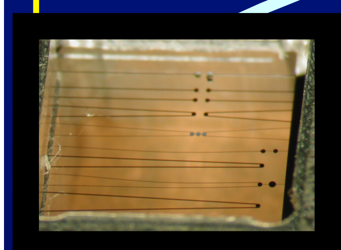




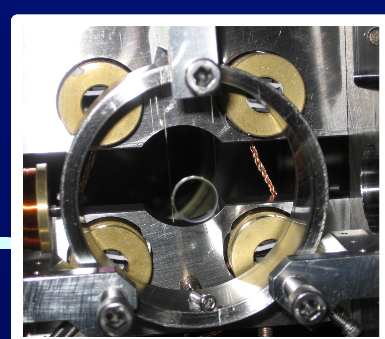
SiN_3 membrane → 10^{-8} g

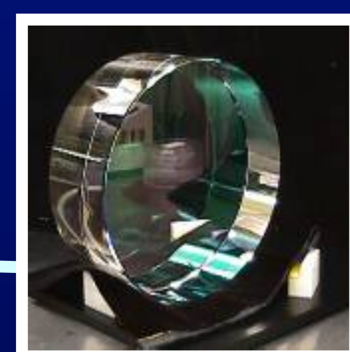
Trampolines → 10^{-7} g

Micromirrors → 10^{-6} g



Minimirror → 1 g





LIGO → 10^3 g

Optomechanical coupling

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

Classical

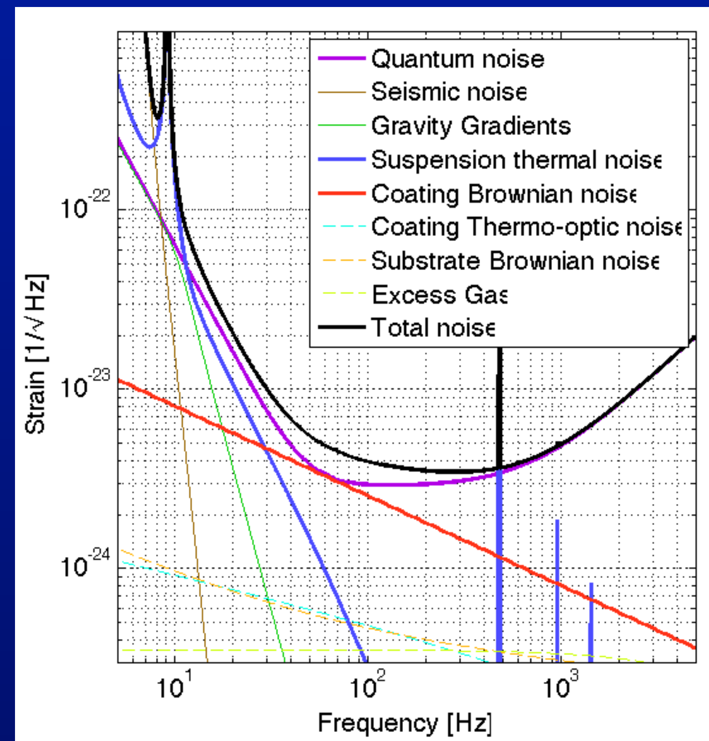
- Alters the dynamics of the mirror
  - Spring-like forces → optical trapping
  - Viscous forces → optical damping
  - Tune the frequency response of the GW detector

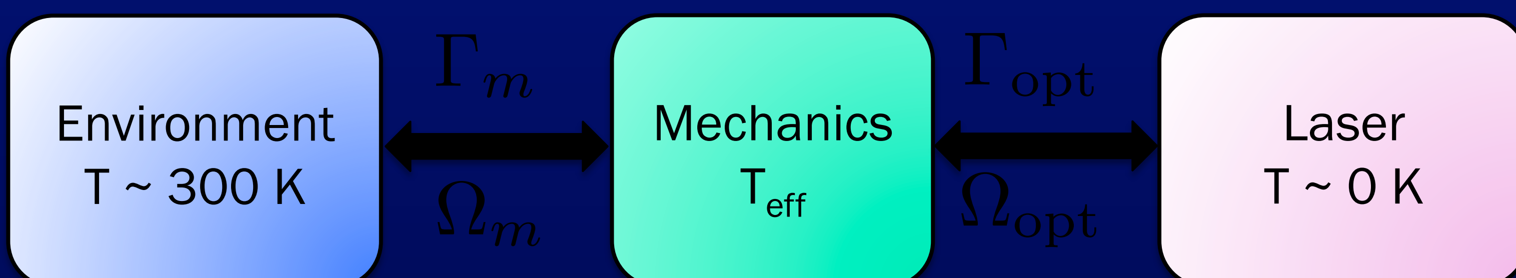
Quantum

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

Clash of Radiation Pressure and Thermal Noise

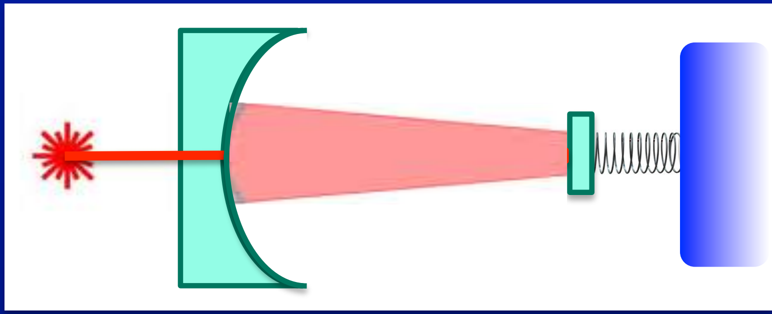
- Must eliminate all classical forces to reach the quantum radiation pressure limit
- Nemesis: Thermal noise
- Antidote: Classical radiation pressure forces
  - Intrinsically “cold”
  - Can be used to drain thermal energy from the mechanics

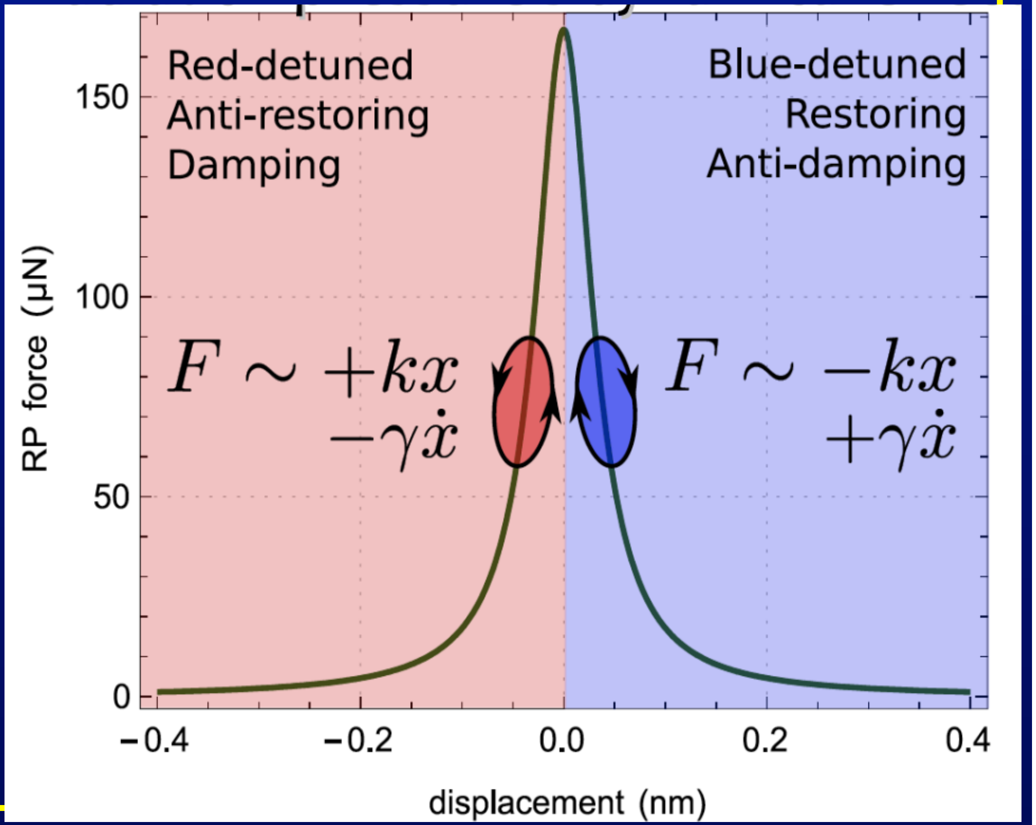




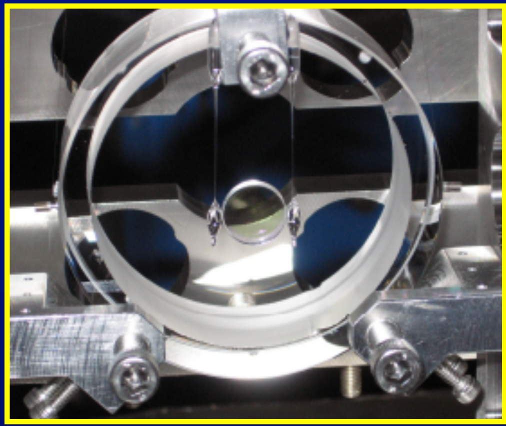
Classical radiation pressure forces

- 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

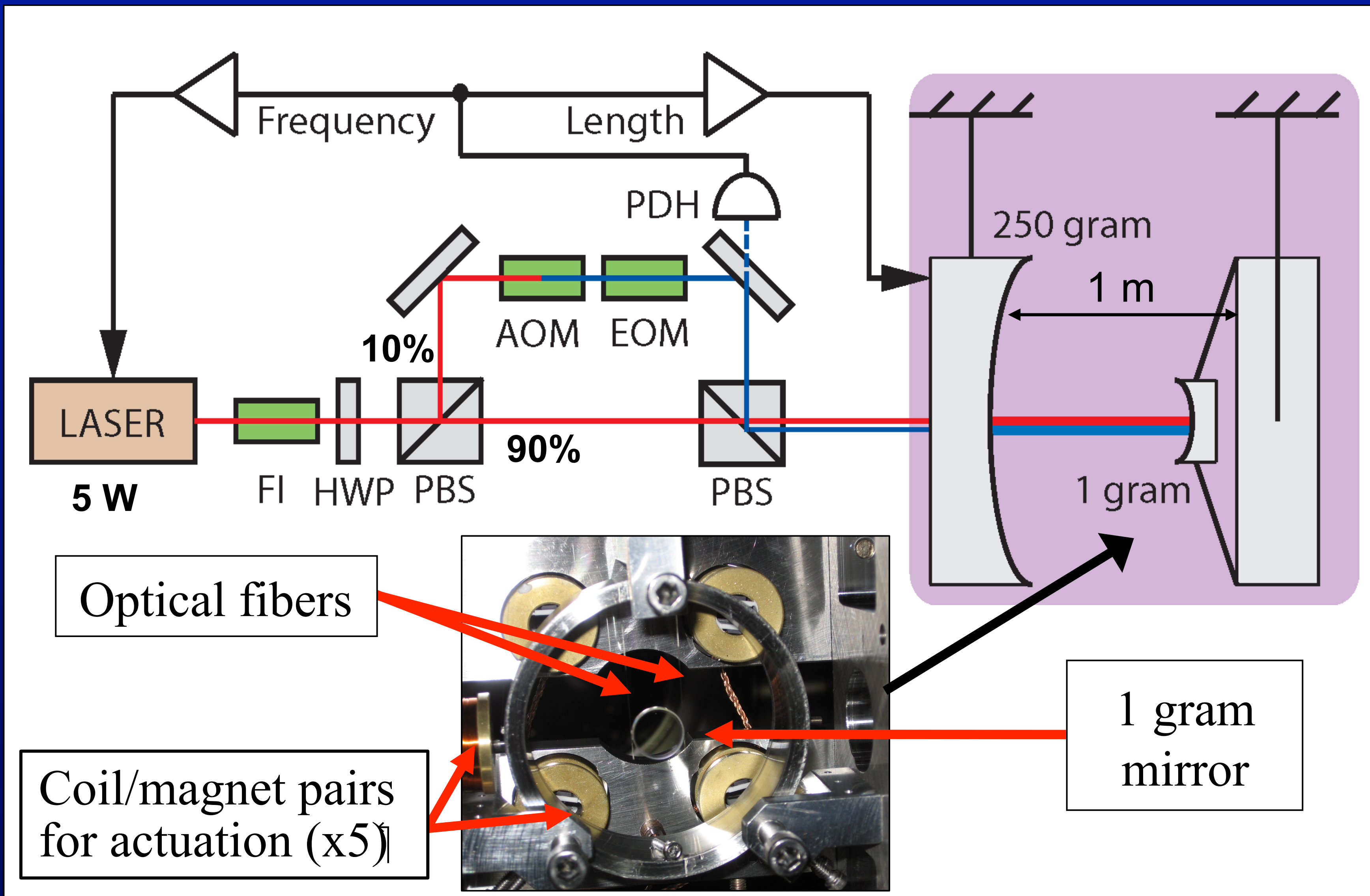




Gram-scale mirrors

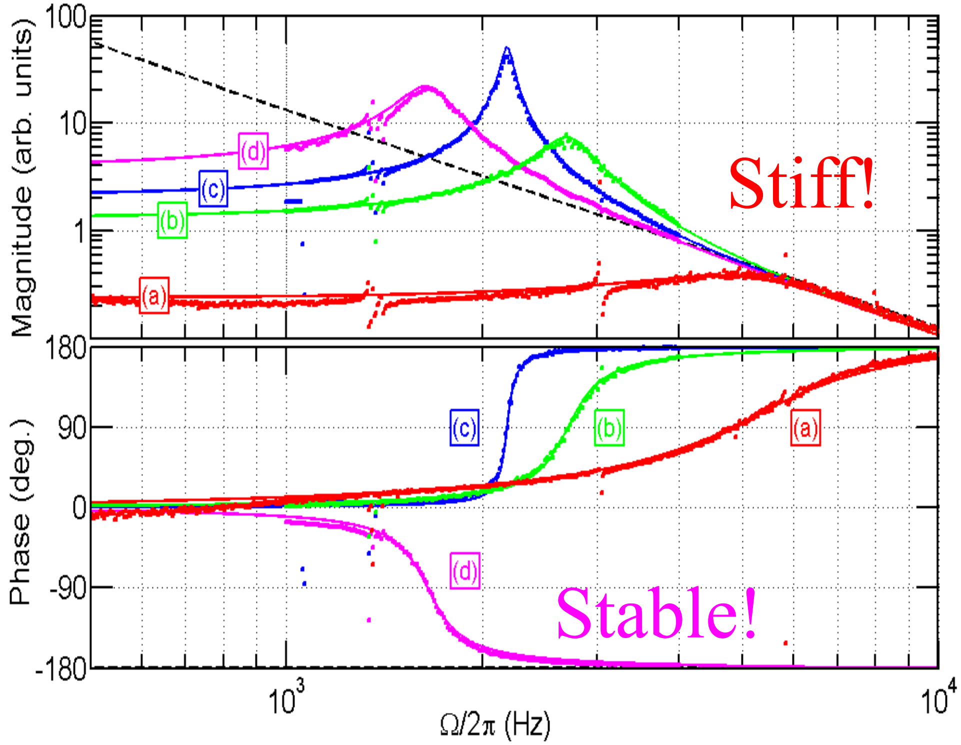


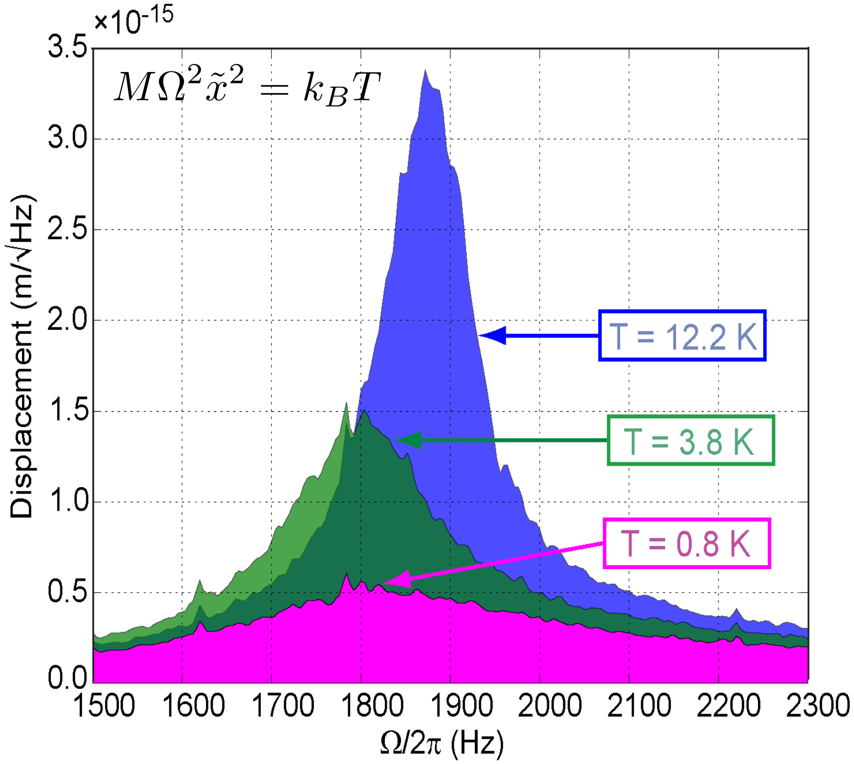
Experimental cavity setup



Trapping and cooling

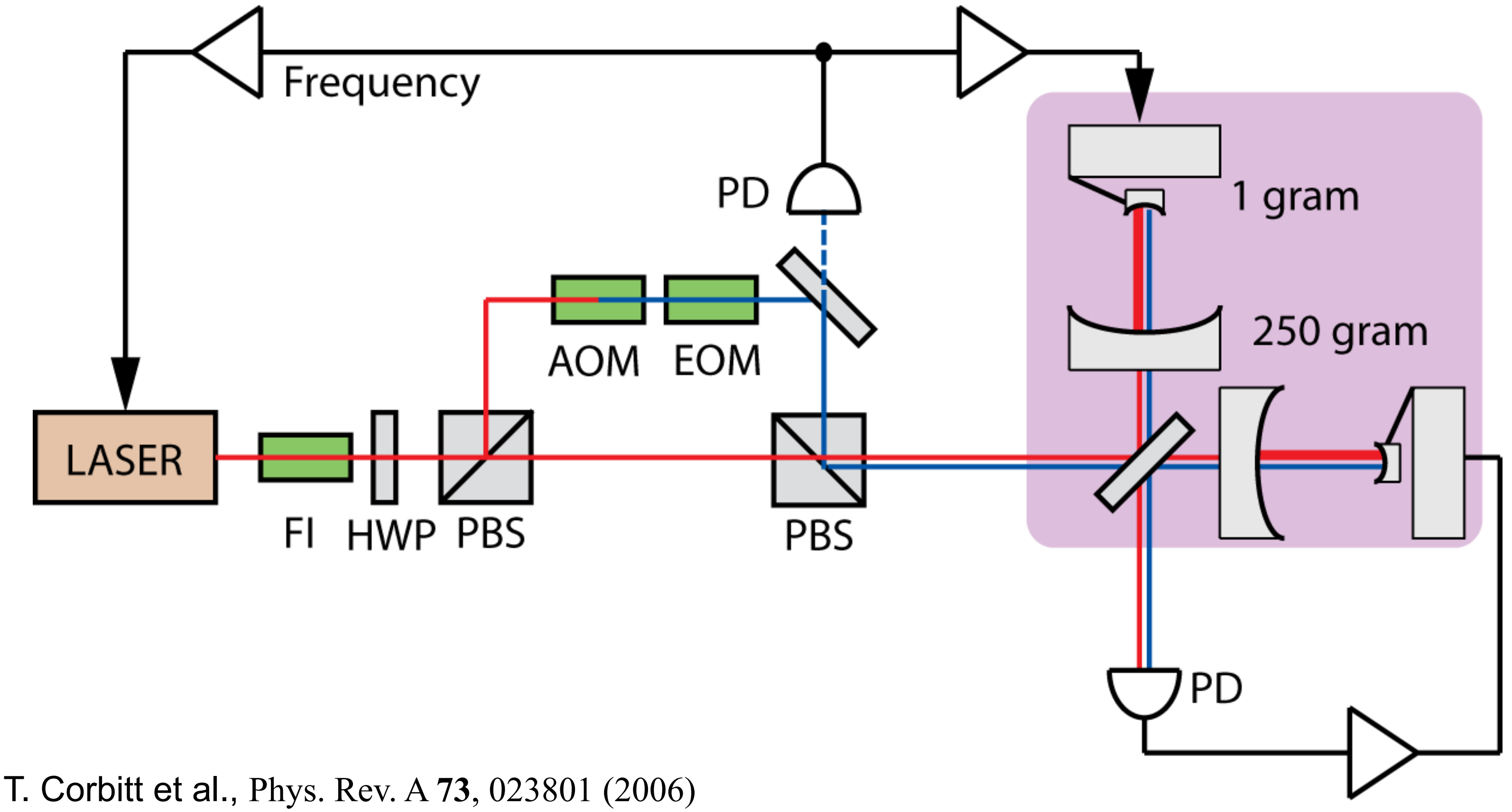
- Optical trap response
- Optical cooling





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

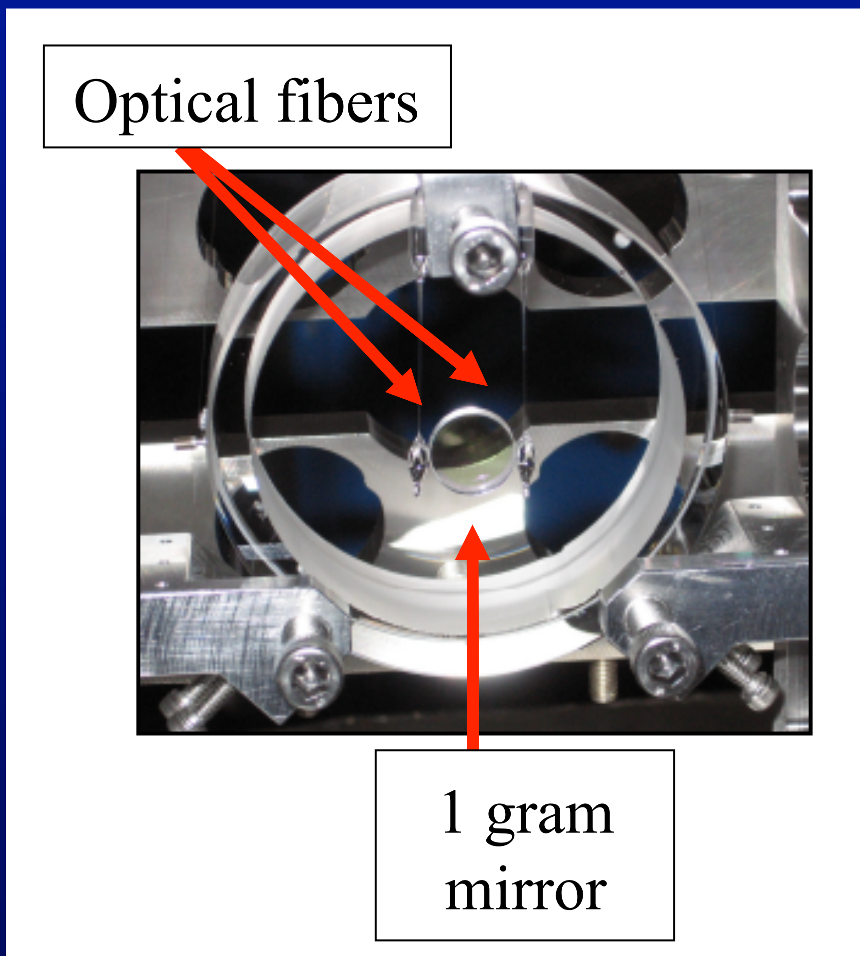
The experiment grows

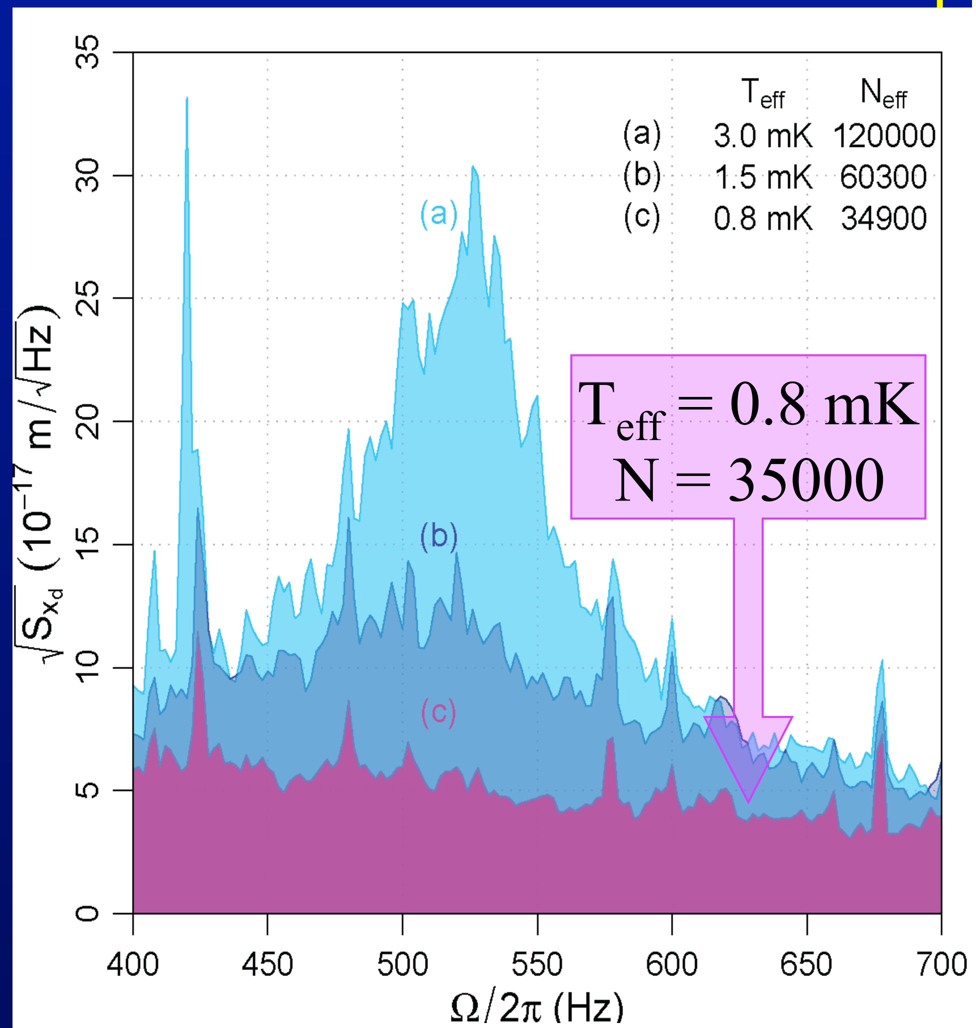


T. Corbitt et al., Phys. Rev. A **73**, 023801 (2006)

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

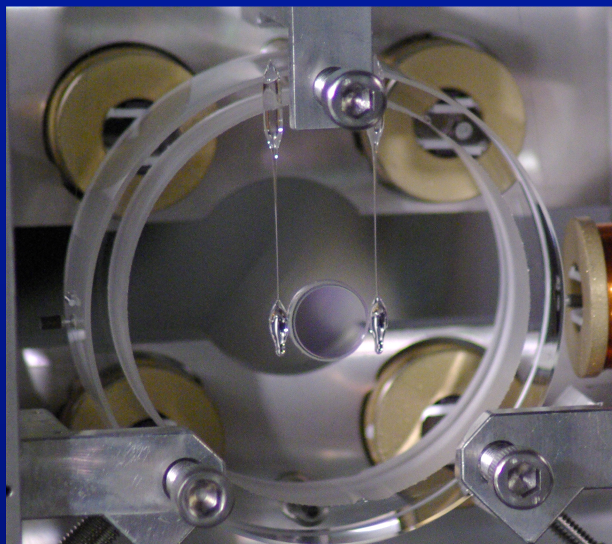
Optically trapped and cooled mirror

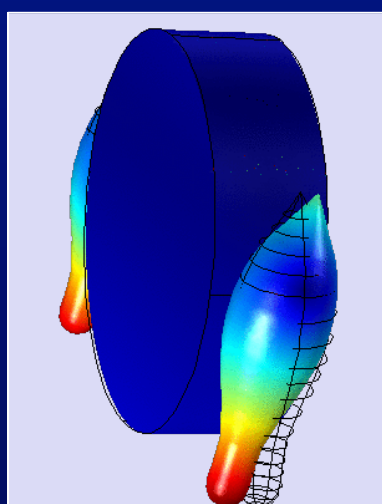


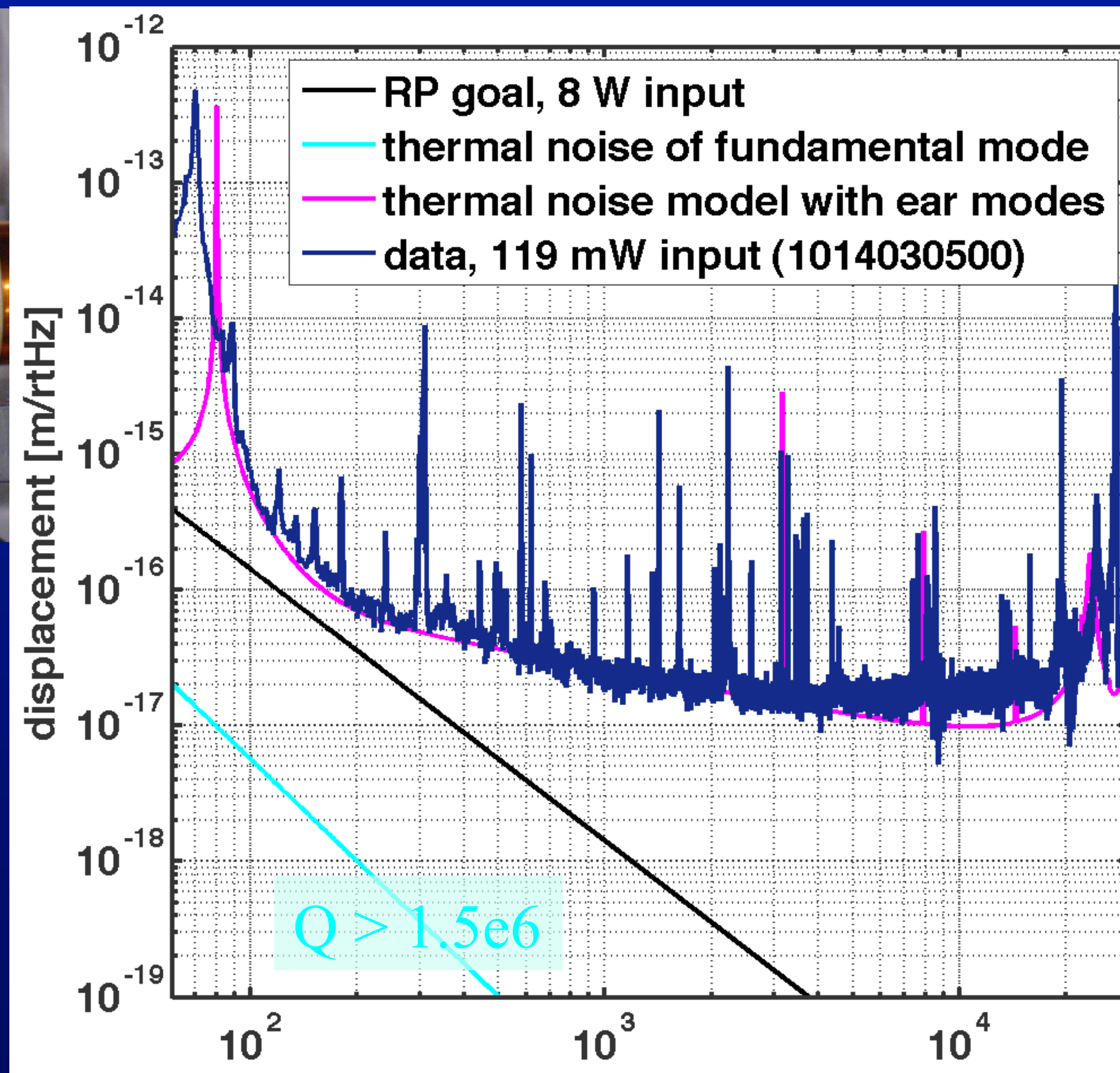


C. Wipf, T. Bodiya, et al. (March 2010)

The elusive quantum regime

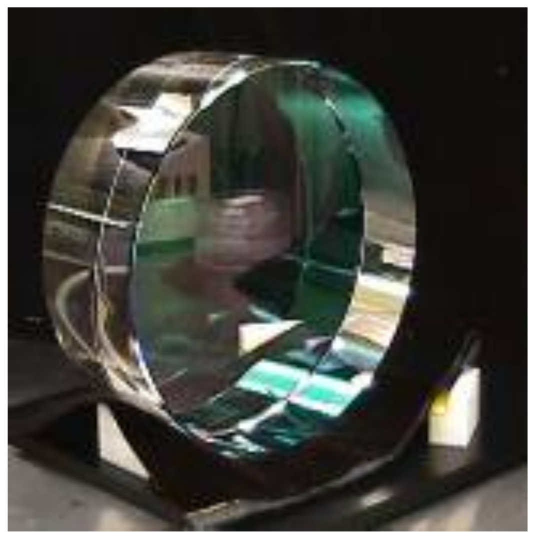






A. Neben, C. Wipf, T. Bodiya, E. Oelker, et al. (Feb. 2012)

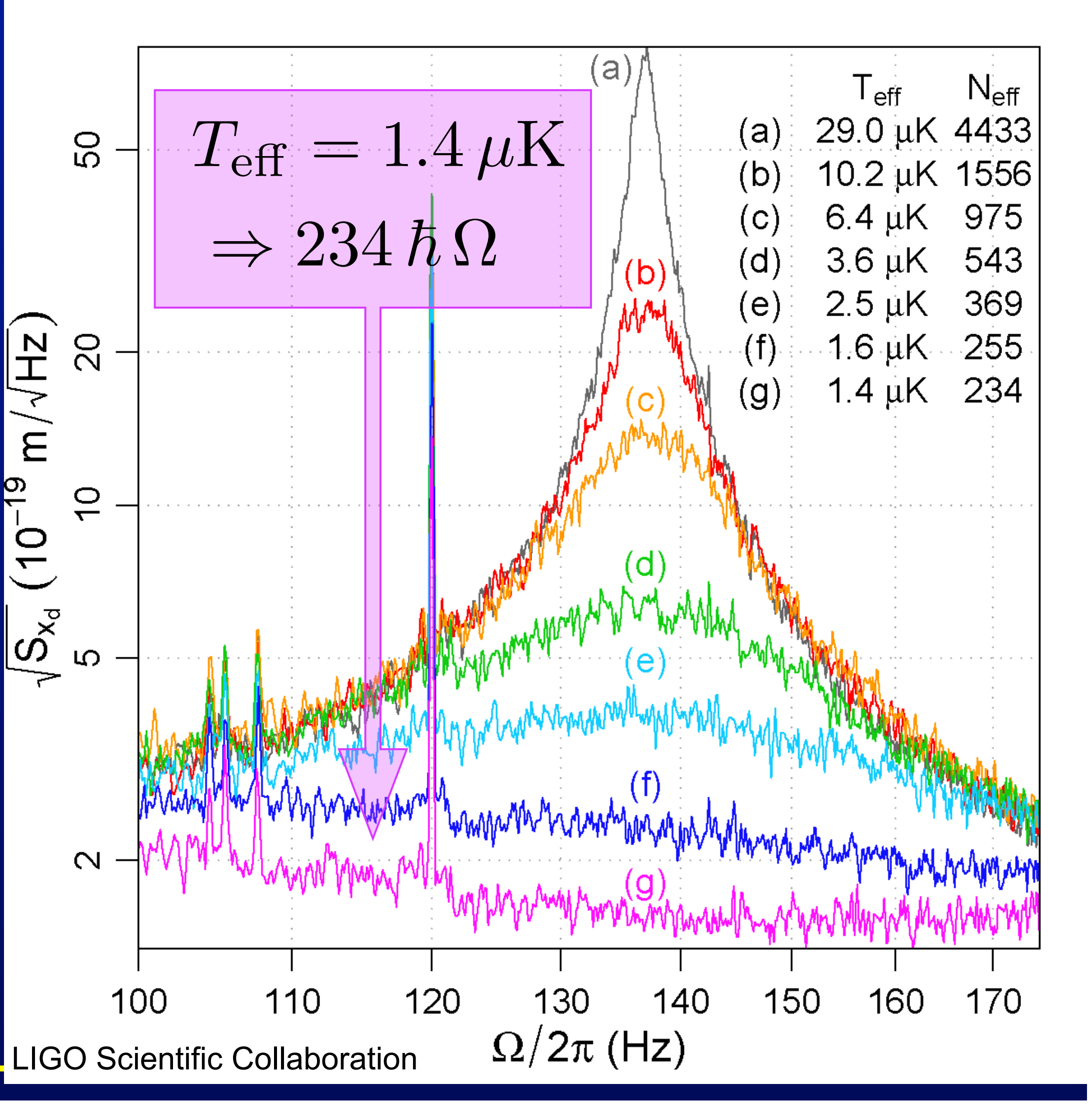
Kilogram scale mirrors



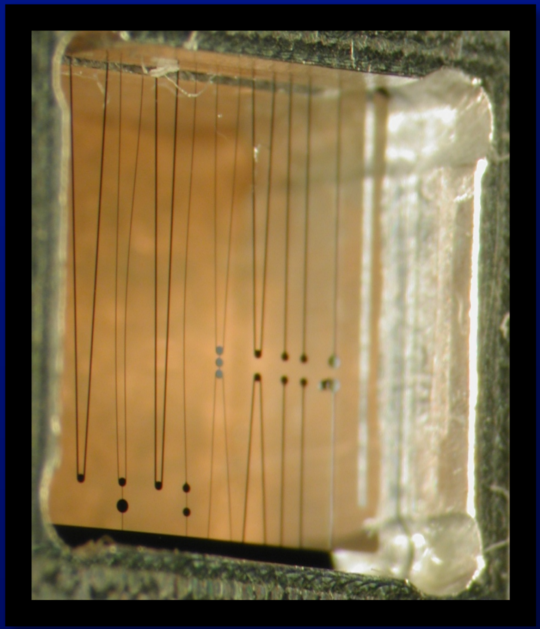
Cooling the kilogram-scale mirrors of Initial LIGO

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

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

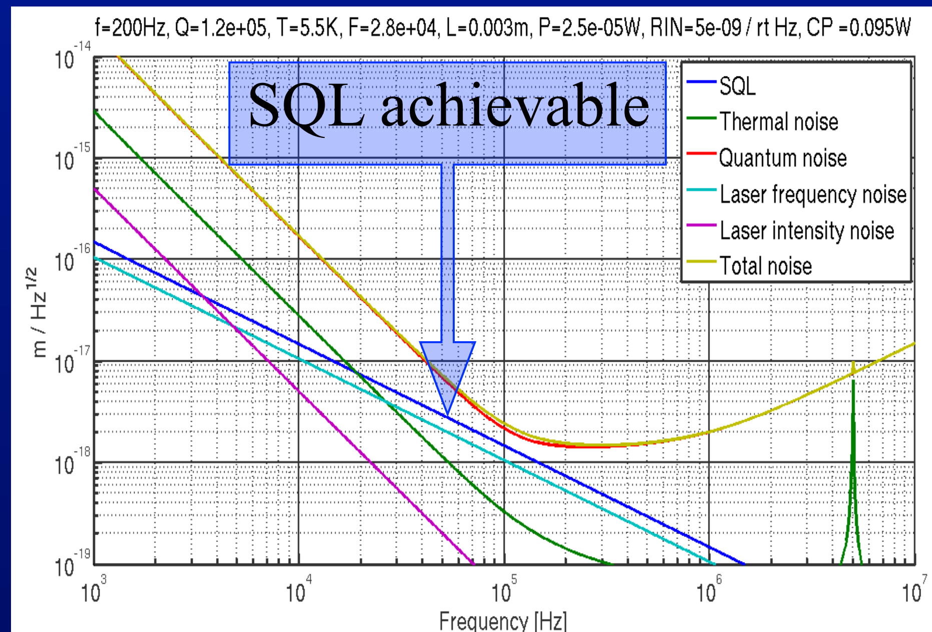


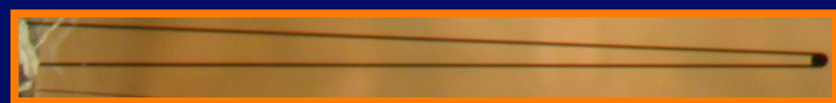
Microgram scale mirrors



Cryogenic micromirror experiment

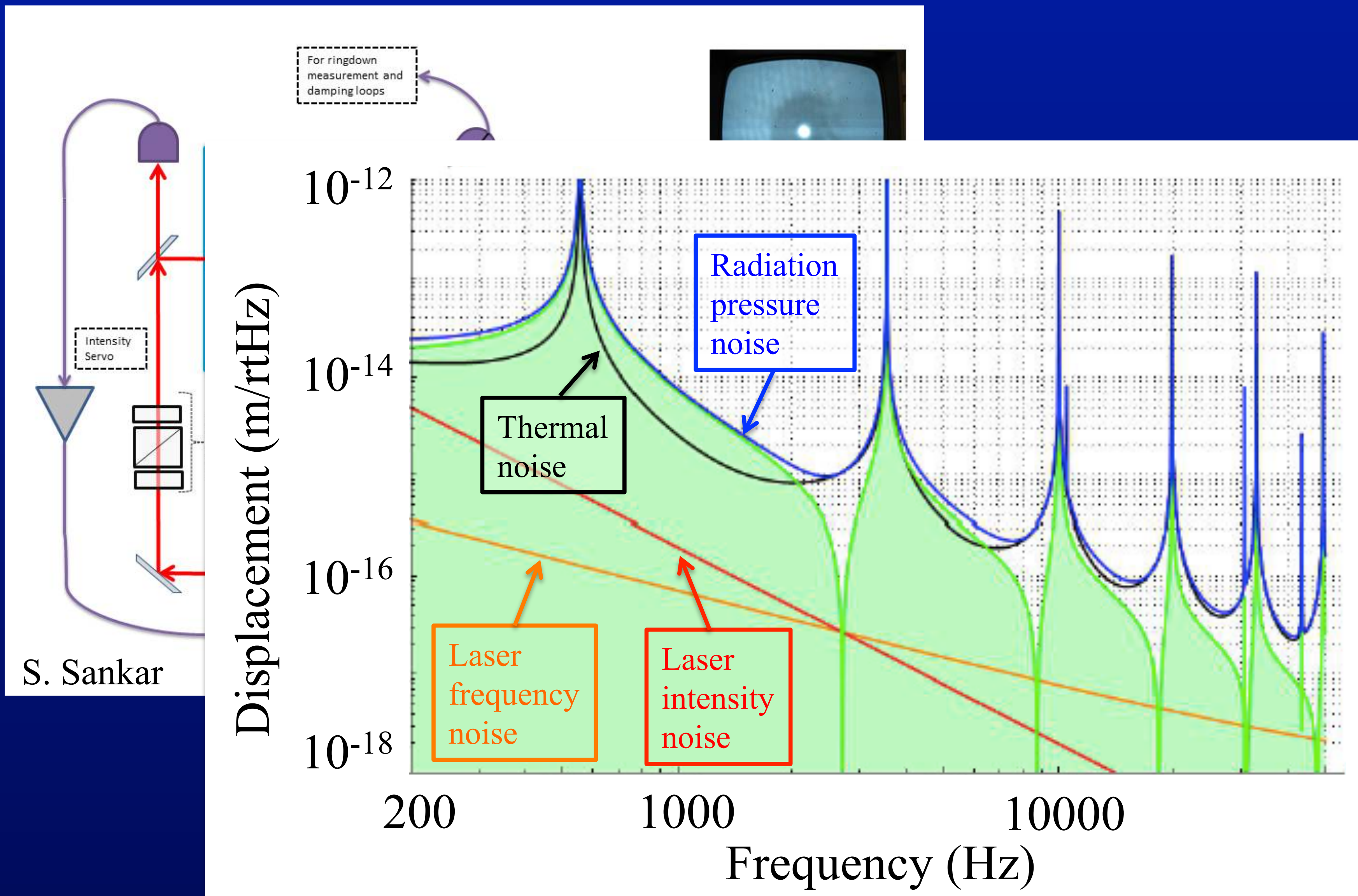
- AlGaAs layers forming a Bragg mirror
- ~ 5 mm long, ~10 µm supports, ~100 µm mirror pads
- Fundamental frequency ~ 200 Hz
- Q factor ~ 2×10^5 at 5 K
- Mass ~ 250 nanograms
- Reflectivity ~ 99.982%
- Cavity finesse ~ 20000
- Power handling:
  breaks at >100 mW of
  incident power



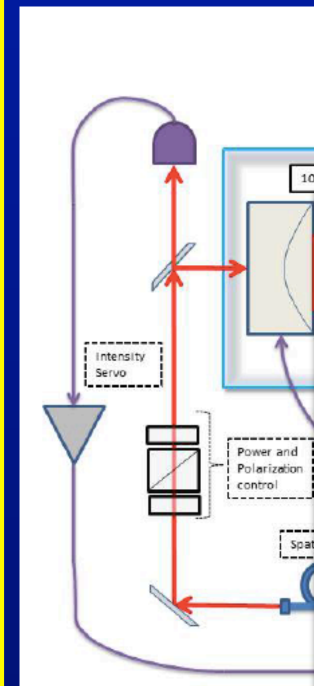


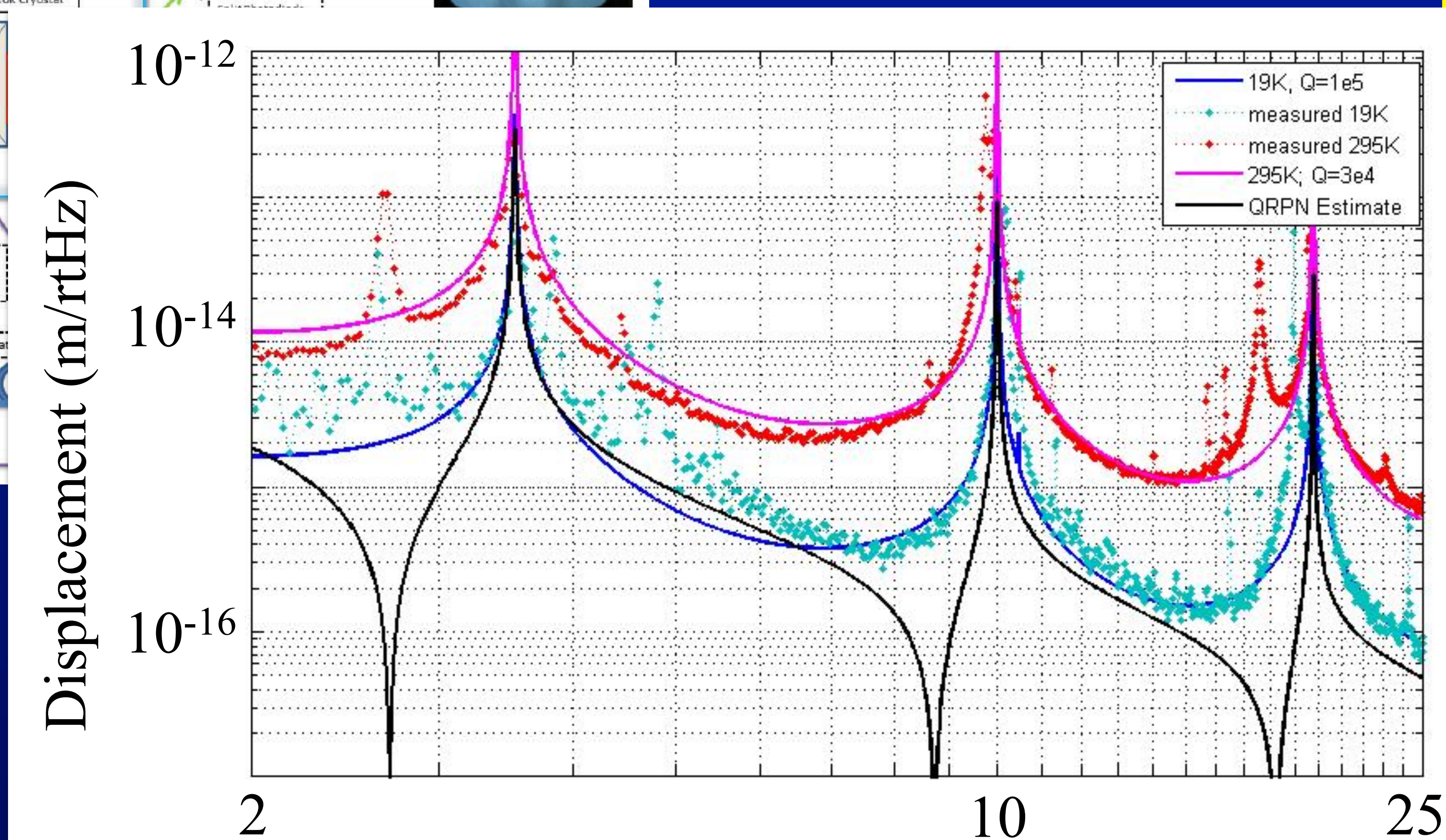
Fabricated by Garrett Cole at Univ. of Vienna

Cryogenic Micromirror Experiment



Cryogenic Micromirror Experiment





S. Sankar, T. Corbitt, G. Cole, et al. (2012)

Amazing cast of characters

MIT

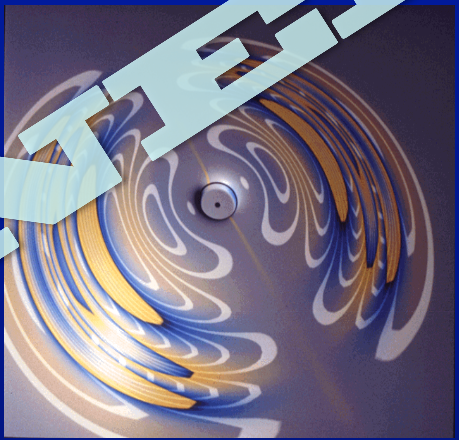
- Sheila Dwyer
- Lisa Barsotti
- Thomas Corbitt
- Christopher Wi
- Timothy Bodiya
- Nicolas Smith-L
- Shannon Sanka
- Eric Oelker
- Abraham Neben
- Rich Mittleman
- MIT LIGO Laboratory

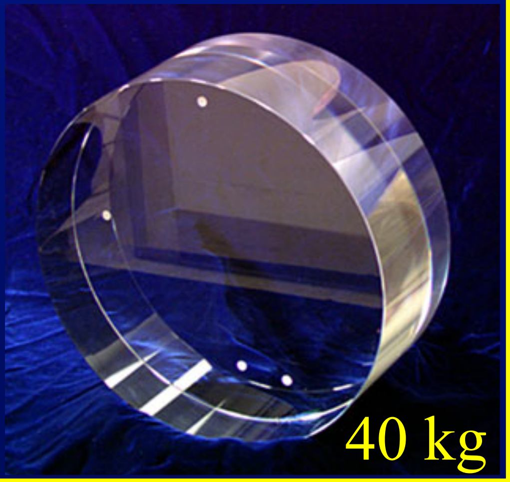
Collaborators

- Yanbei Chen & group (Caltech)
- itcomb (Caltech)
- igg (Caltech)
- cClelland and group
- Schnabel & group nnover)
- Cole (Aspelmeyer group, U. Vienna)
- LIGO Scientific Collaboration

Capturing the 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



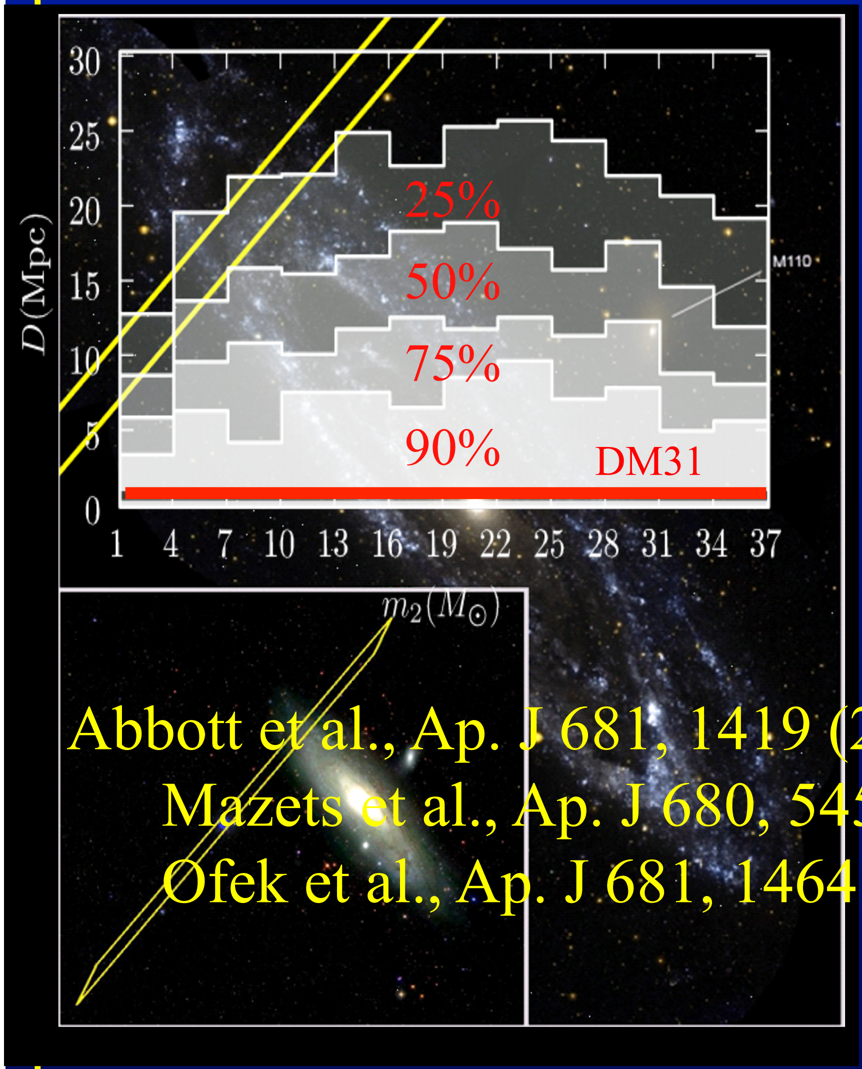


STAY TUNED

LIGO listened…

And had something to say

The search for GRB070201



Abbott et al., Ap. J 681, 1419 (2008)
Mazets et al., Ap. J 680, 545 (2008)
Ofek et al., Ap. J 681, 1464 (2008)

- GRB 070201
  - Very luminous short duration, hard gamma-ray burst
  - Detected by Swift, Integral, others
  - Consistent with being in M31
  - Leading model for short GRBs: binary merger involving a neutron star
- Looked for a GW signal in LIGO
  - **No plausible GW signal found**
  - **Can say with >99% confidence that GRB070201 was NOT caused by a compact binary star merger in M31**
- Conclusion: it was most likely a Soft Gamma Repeater giant flare in M31

Path to the quantum regime

- For mode of oscillation of the mirror

$$k_B T < \hbar \Omega$$

- Thermodynamics

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

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

STIFF OPTICAL SPRING

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

HIGH MECHANICAL Q

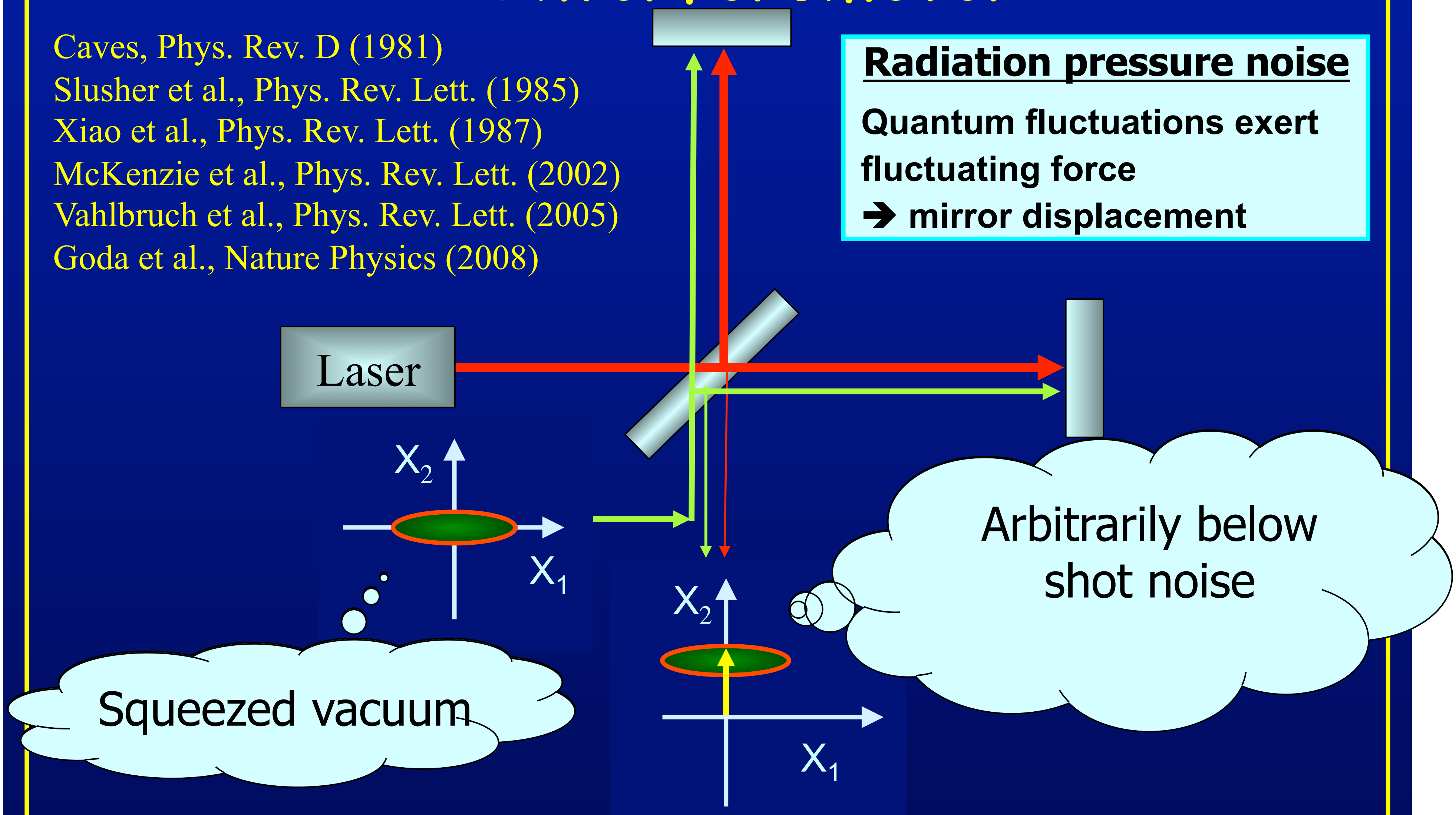
Origin of the Quantum Noise
Vacuum fluctuations

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)

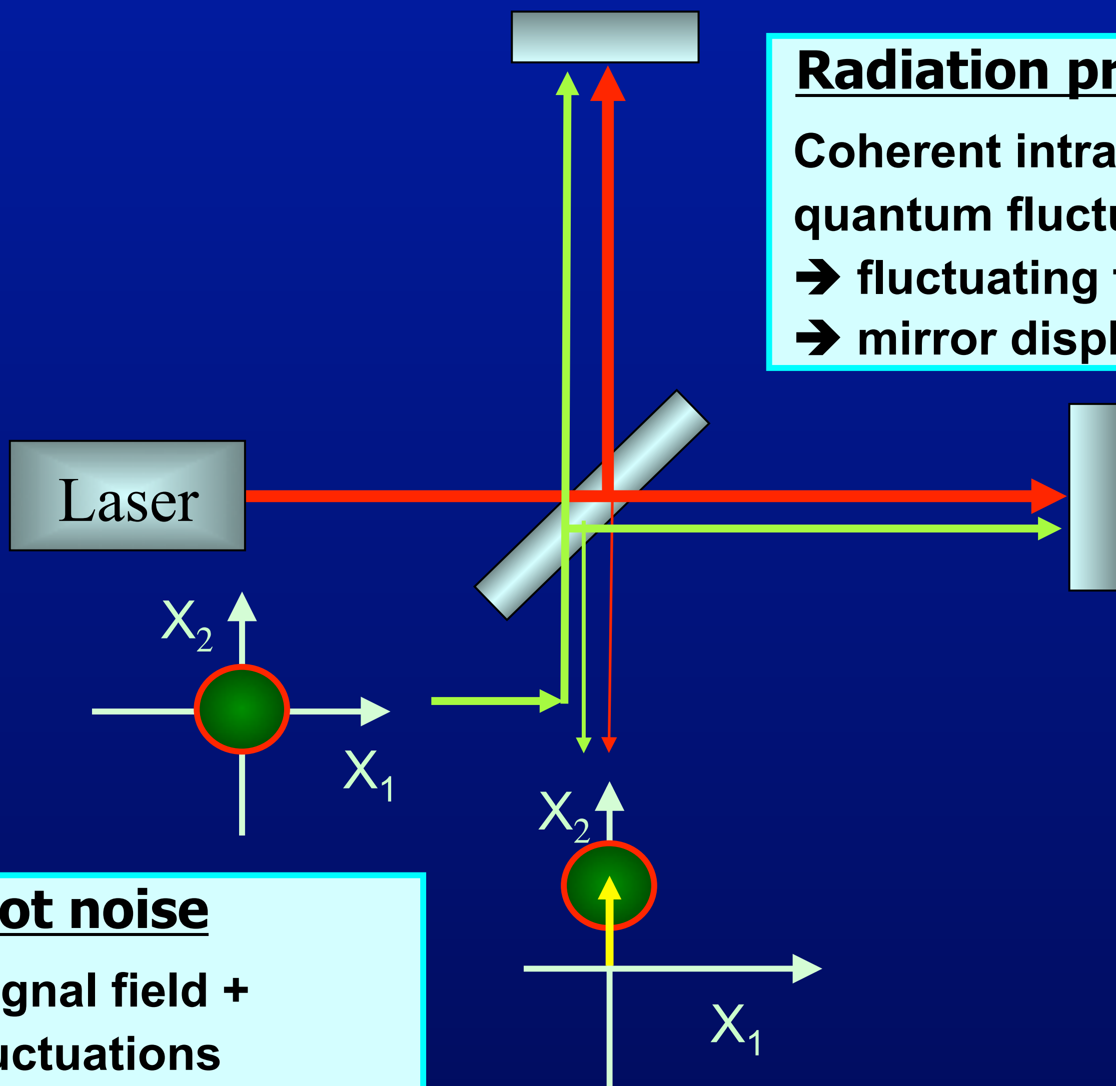
Radiation pressure noise

Quantum fluctuations exert fluctuating force
➔ mirror displacement



Quantum Optics and the Shot Noise Limit

Quantum Noise in an Interferometer



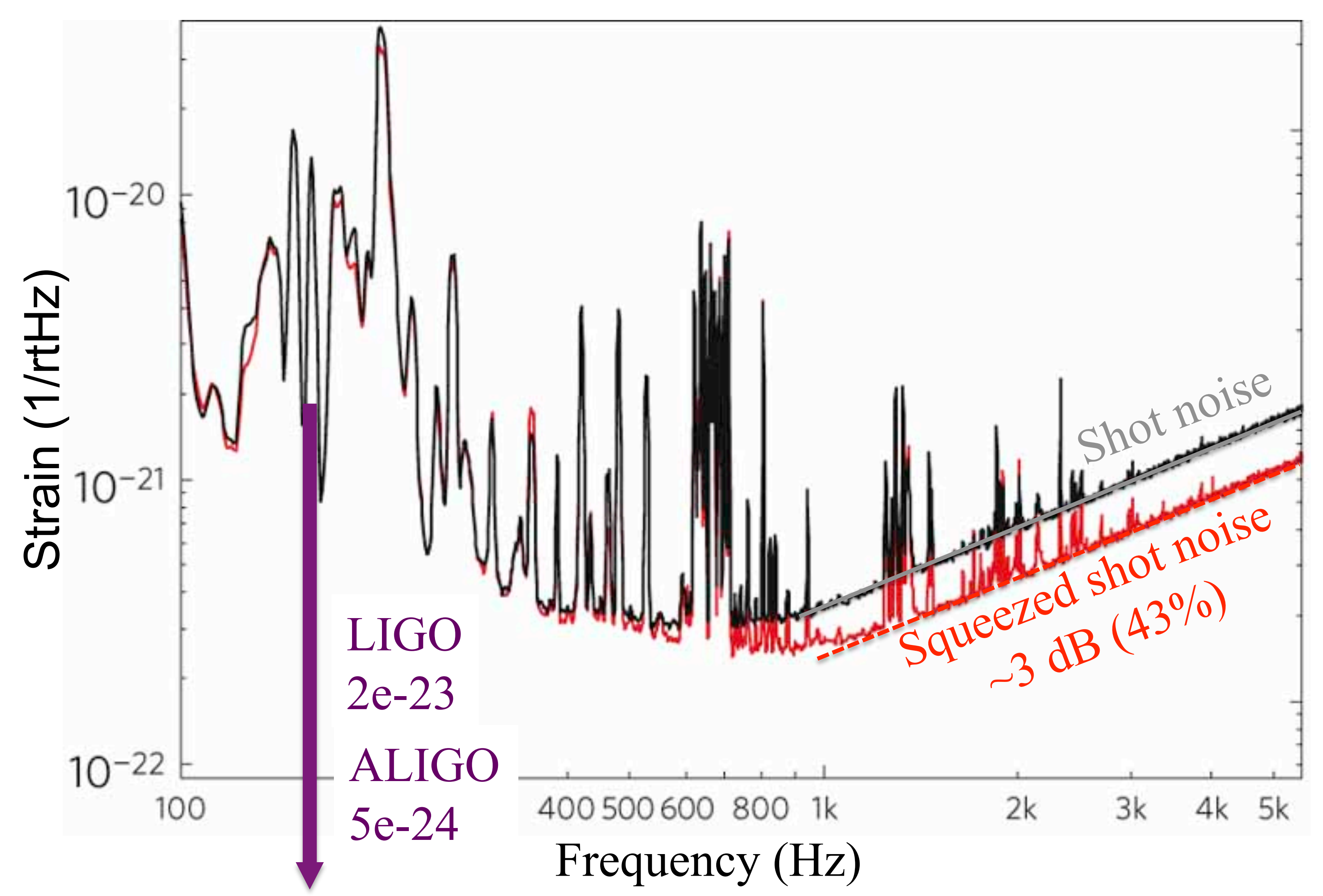
Radiation pressure noise

Coherent intracavity field + quantum fluctuations
➔ fluctuating force
➔ mirror displacement

Shot noise

Coherent signal field + quantum fluctuations
➔ fluctuating phase

Squeezing Enhancement in GEO

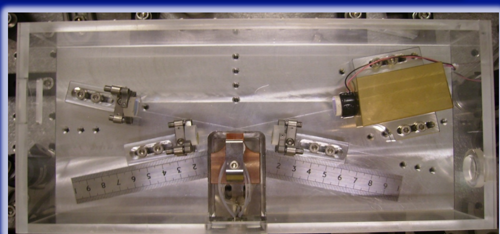


LIGO-T070265-A-D | *LIGO* | 10/9/07

Proposal for a Squeezed H1 Interferometer

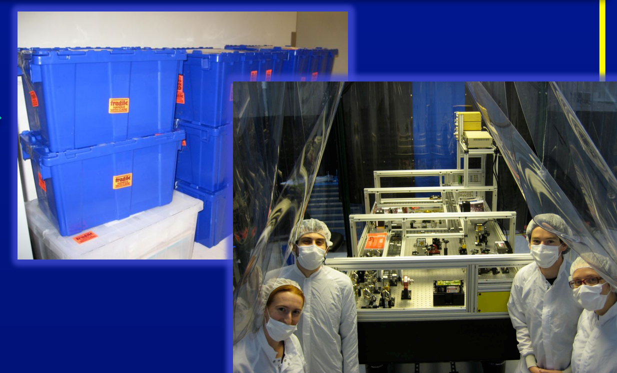
Daniel Sigg, Nergis Mavalvala, David McClelland, Ping Koy Lam, Roman Schnabel,
Henning Vahlbruch and Stan Whitcomb

Bow-tie cavity OPO design at ANU (2008)

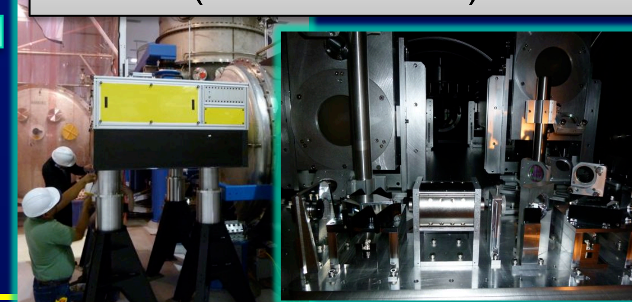


H1 Squeezer tested at MIT (2009-2010)

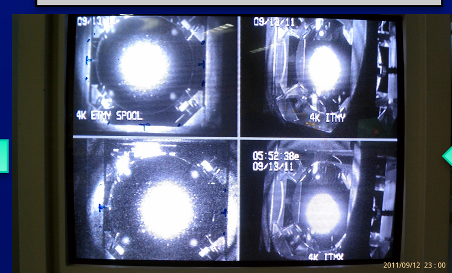
H1 Squeezer shipped to LHO (Oct 2010)



H1 Squeezer Installation (Summer 2011)



H1 Recovery (Sept 2011)



Squeeze injection in H1 (Oct 3 – Dec 4)