LIGO-G1200769

# Squeezing in Gravitational Wave Detectors

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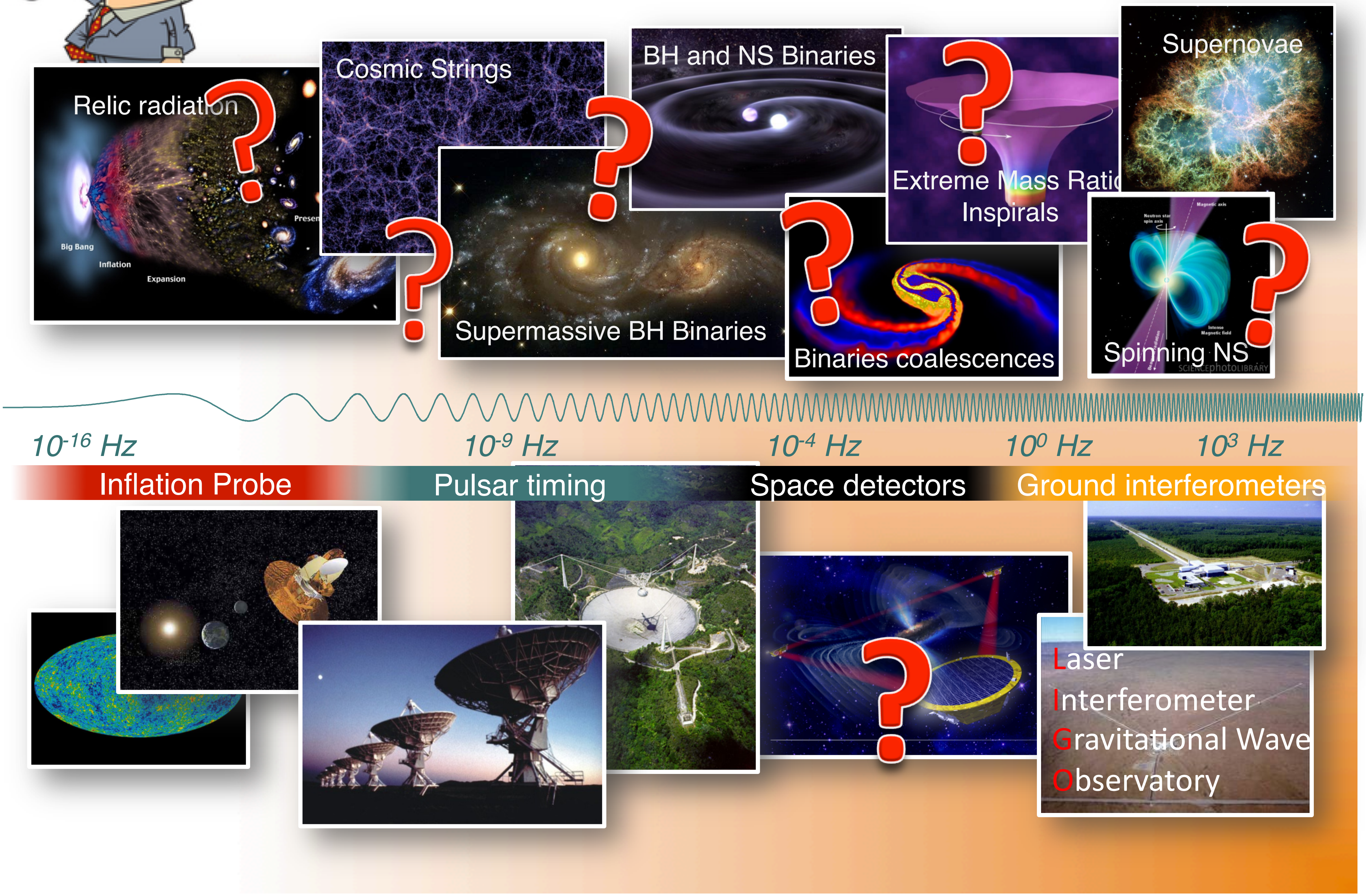
Fermilab Particle Astrophysics Seminars

June 25th, 2012

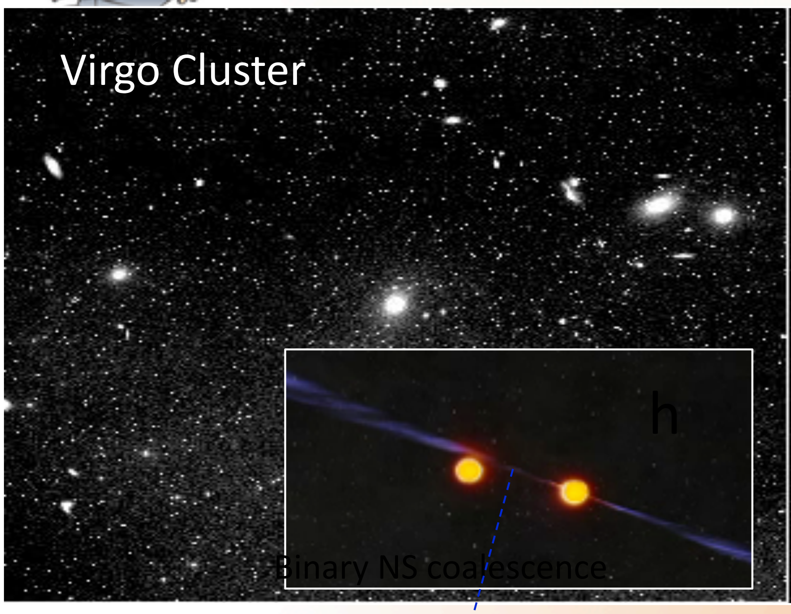
# Outline

- ✧ Gravitational waves and their detection
- ✧ Quantum noise in GW ground-based interferometric detectors
- ✧ Squeezed states of light
- ✧ The LIGO H1 squeezing experiment
  - ✧ Squeezing in GEO600
- ✧ Squeezing in next generation of detectors

# Gravitational Waves



# Ground Based Detection




$$h_{\mu\nu} = \frac{2G}{c^4}\frac{1}{r}\ddot{I}_{\mu\nu}$$

$$h \approx \frac{4\pi^2 GMR^2 f_{orb}^2}{c^4 r}$$

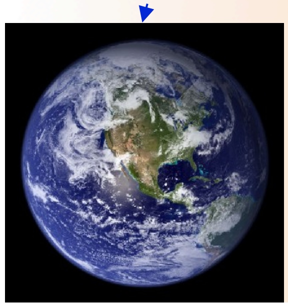
r ~ 18 Mpc

$M \approx 1.4M_{\odot}$

$R \approx 20$ km

$f_{orb} \approx 400$ Hz

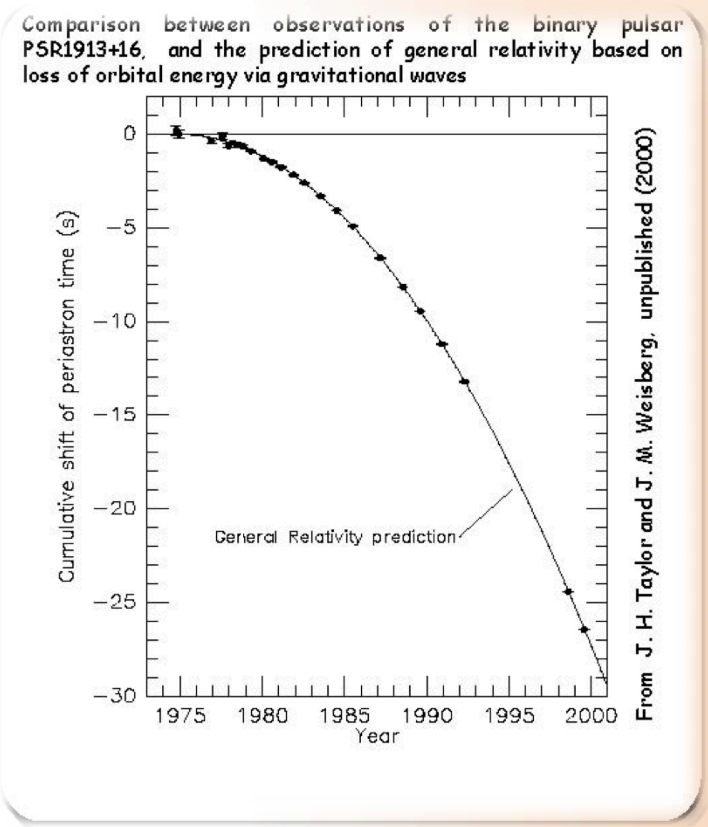
➔ $h \sim 10^{-22}$



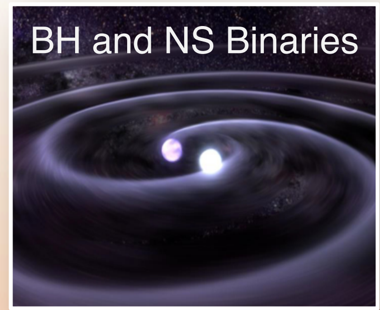
# Gravitational Waves Detection

Indirect measurement

Hulse & Taylor (Nobel Prize 1993)

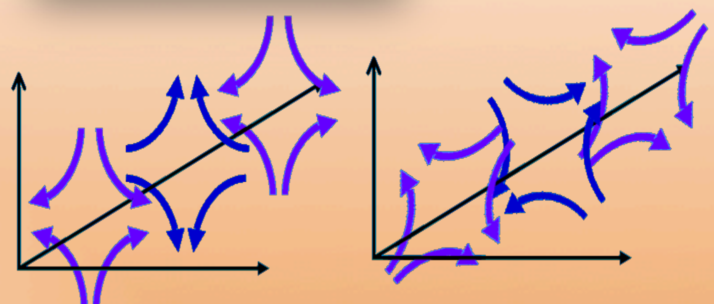


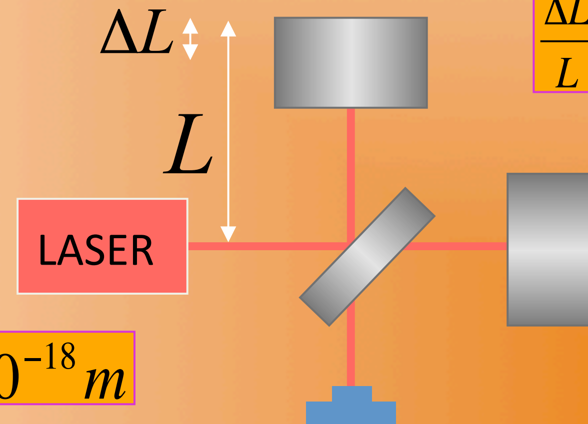

Seeking for a direct measurement




Gravitational waves: ripples in the space-time propagating at the speed of light

h = GW amplitude

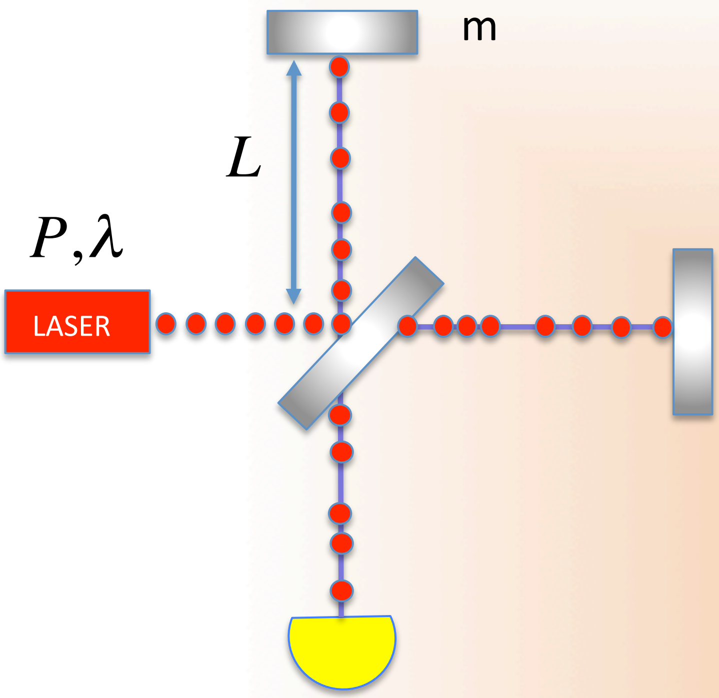





$$\frac{\Delta L}{L} = h$$

$$\Delta L = hL \sim h \times 4km \sim 10^{-18} m$$

# Quantum noise



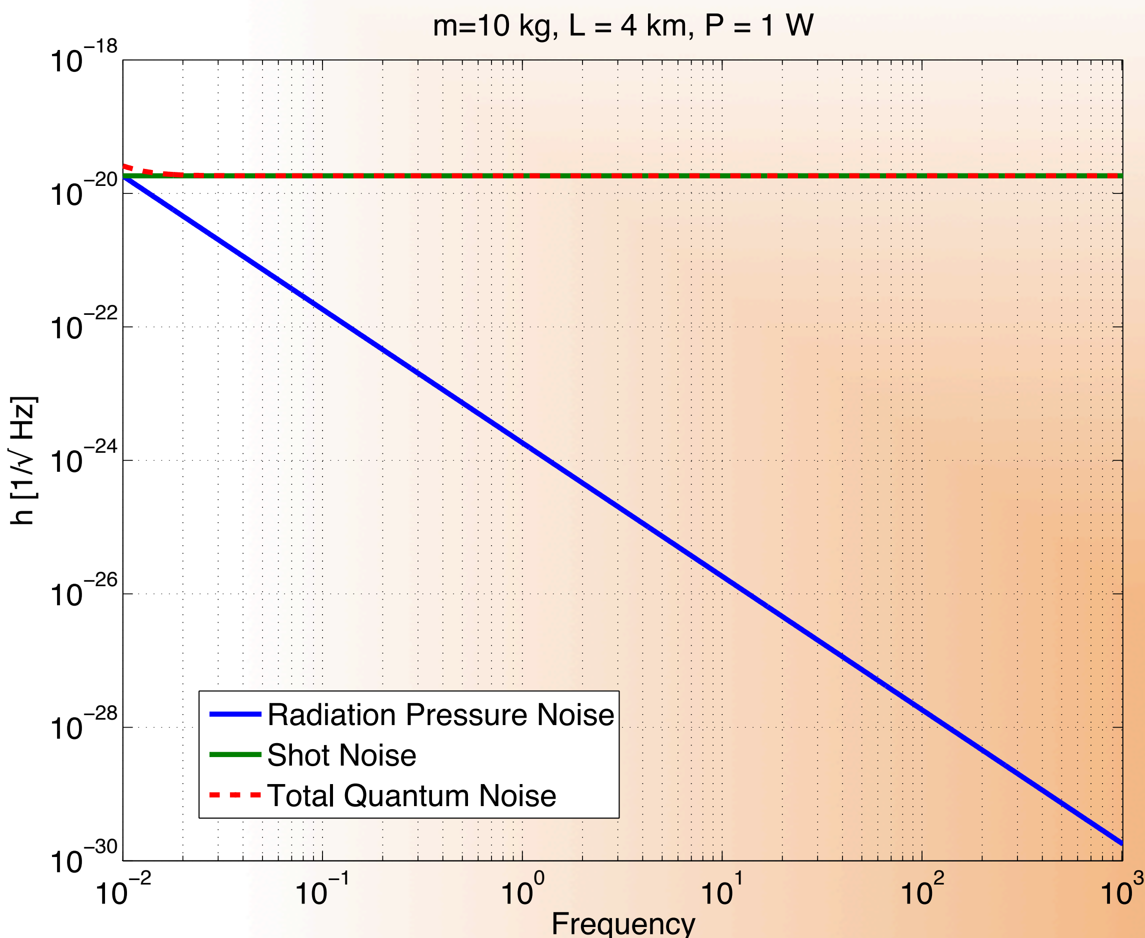

✧ SHOT NOISE: Photon counting noise produced by the uncertainty in the arrival time of the photons on a photo-detector (Poissonian statistics):

$$h_{SHOT}(f) = \frac{1}{L}\sqrt{\frac{\hbar c\lambda}{2\pi P}}$$

✧ RADIATION PRESSURE NOISE: Back-action noise caused by fluctuations in the power impinging on the mirrors:

$$h_{RAD}(f) = \frac{1}{m(2\pi)^2 f^2 L}\sqrt{\frac{8\pi\hbar P}{c\lambda}}$$

# Quantum noise

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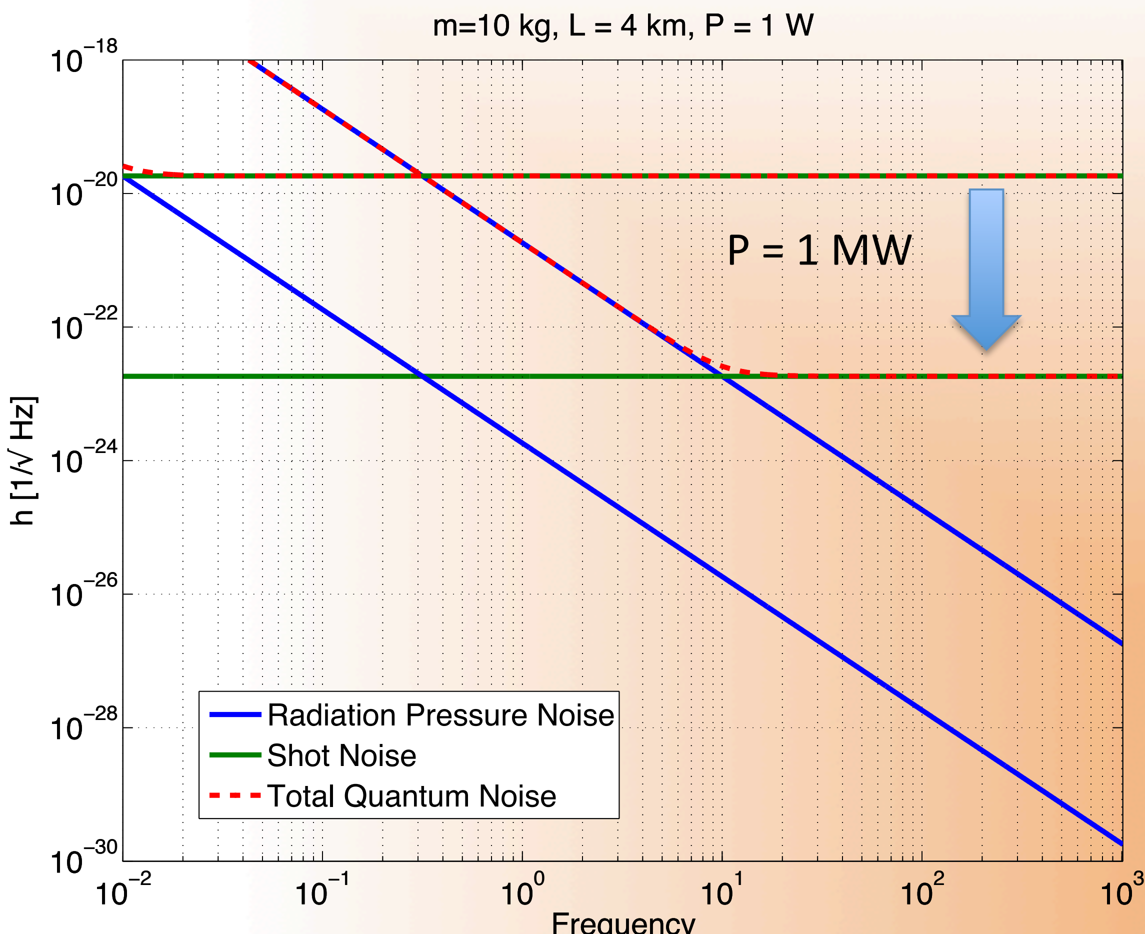
# Quantum noise

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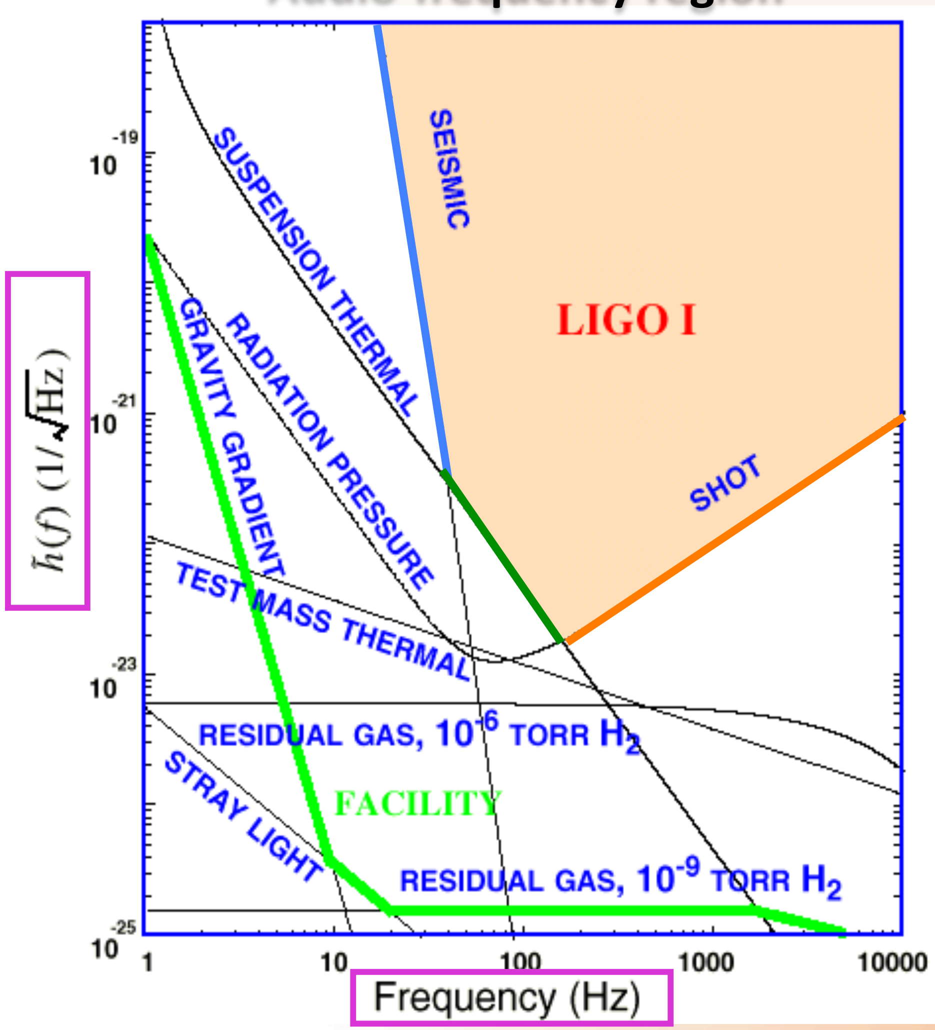
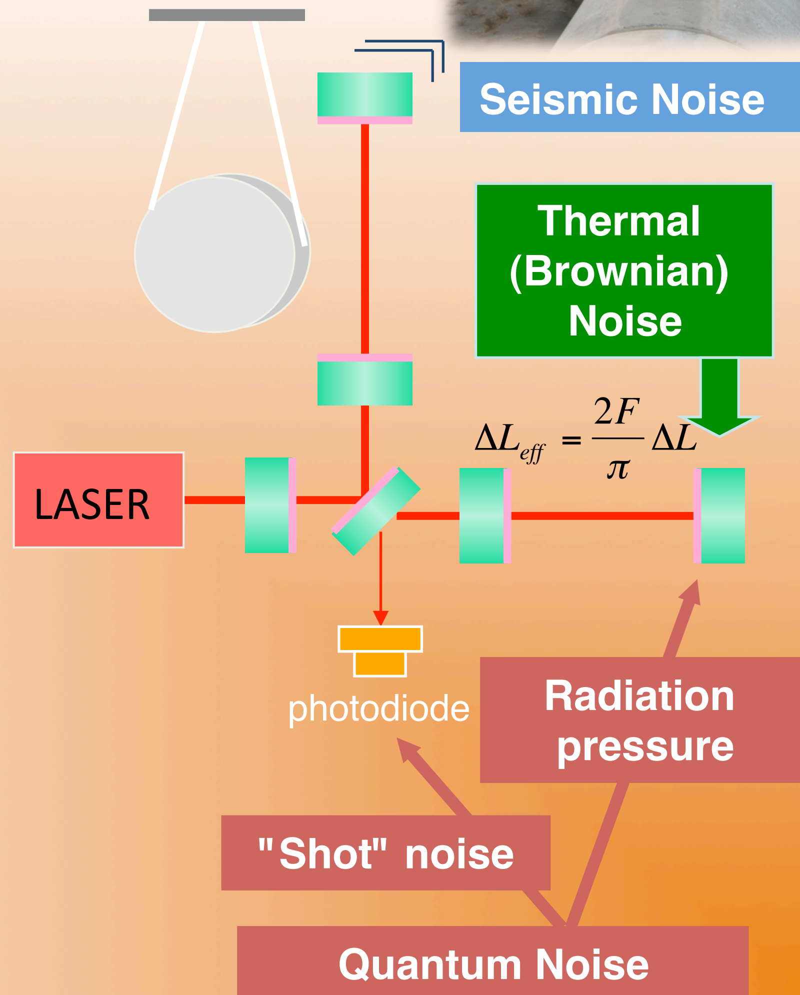
# The LIGO detector

## Audio-frequency region







# How to reduce quantum noise

- ✧Increase the power to reduce shot noise (and increase the mirror mass to minimize radiation pressure noise)
- ✧More complex optical configuration which shapes the interferometer optical response

D. E. McClelland, N. Mavalvala, Y. Chen, and R. Schnabel, “Advanced interferometry, quantum optics and optomechanics in gravitational wave detectors", Laser and Photonics Rev.5, 677-696 (2011)

- ✧ Re-think of where quantum noise comes from…

# Quantum States

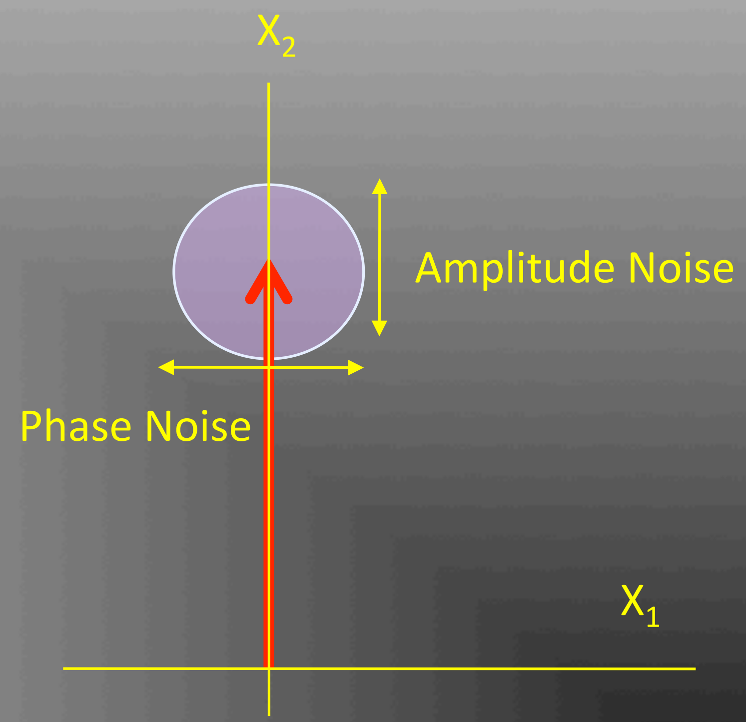
✧ Quantization of the electro-magnetic field

Quadrature Field Amplitudes

$$\hat{E} = \hat{X}_1 \cos \omega t + i \hat{X}_2 \sin \omega t$$

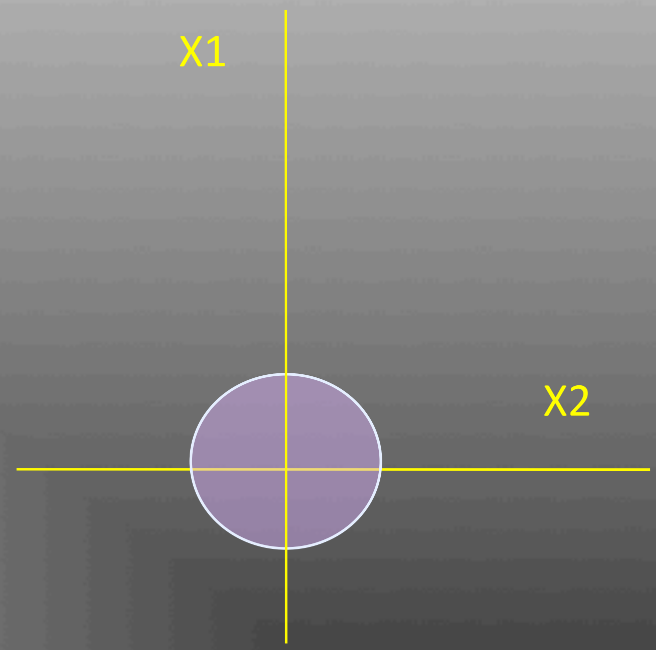
Heisenberg uncertainty principle:

$$\Delta X_1 \, \Delta X_2 \geq 1$$

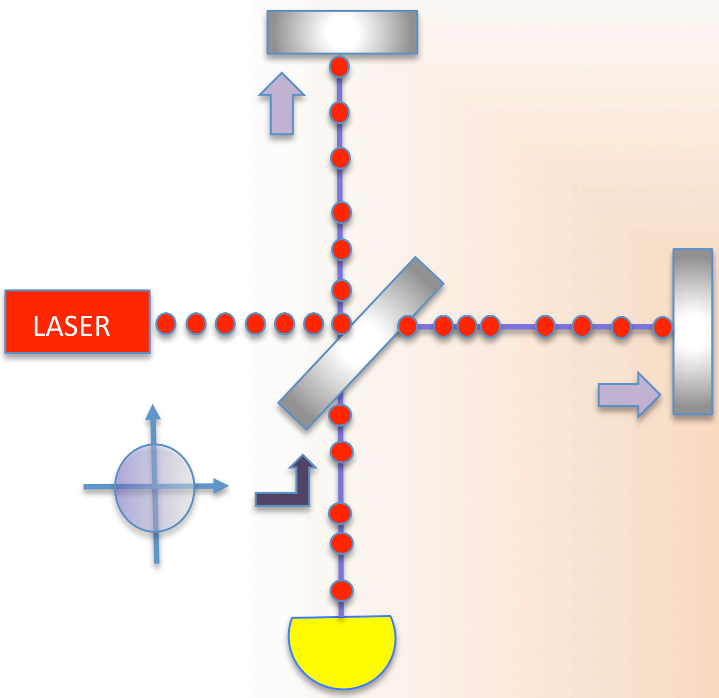


# Vacuum Fluctuations

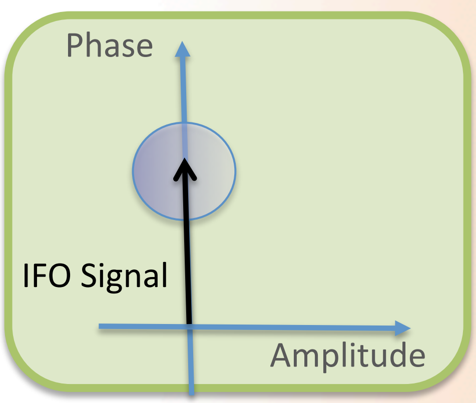
- When average amplitude is zero, the variance remains
- Vacuum fluctuations are everywhere that classically there is no field….
- …like at the output port of your interferometer!



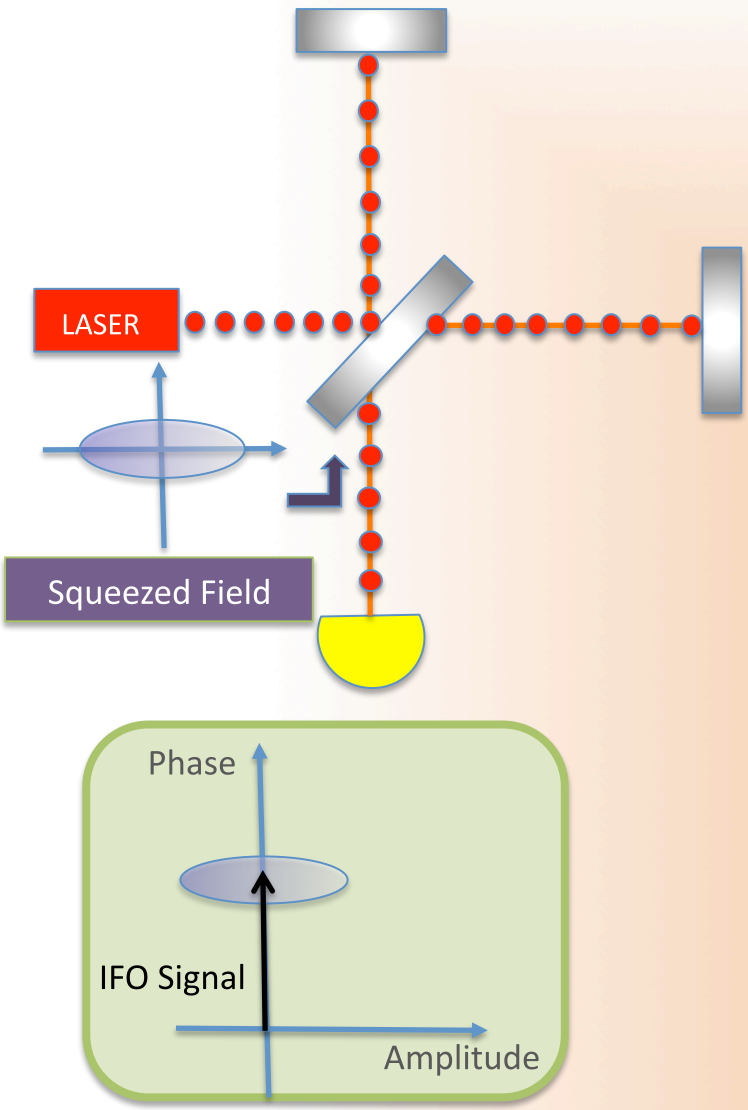
# Quantum Noise and Vacuum




- Quantum noise is produced by vacuum fluctuations entering the open ports
- Vacuum fluctuations have equal uncertainty in phase and amplitude:
  - Phase: Shot-Noise (photon counting noise)
  - Amplitude: Radiation Pressure Noise (back-action)



# Vacuum Getting Squeezed



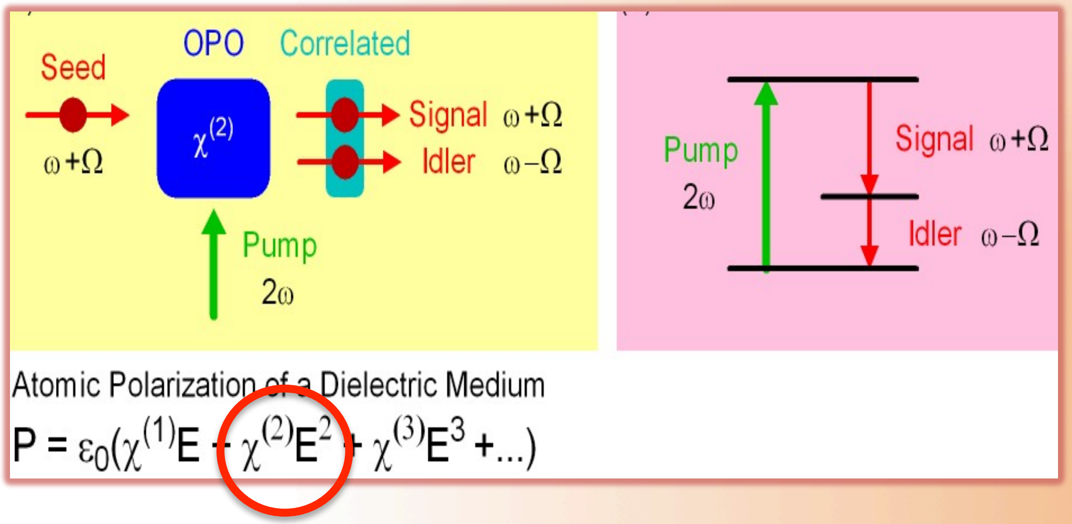

- Reduce quantum noise by injecting squeezed vacuum: less uncertainty in one of the two quadratures
- Heisenberg uncertainty principle: if the noise gets smaller in one quadrature, it gets bigger in the other one
- One can choose the relative orientation between the squeezed vacuum and the interferometer signal (squeeze angle)


C. M. Caves, Phys. Rev. Lett. 45, 75 (1980).
C. M. Caves, Quantum-mechanical noise in an interferometer. Phys. Rev. D 23, p. 1693 (1981).

# How to make squeezed fields..

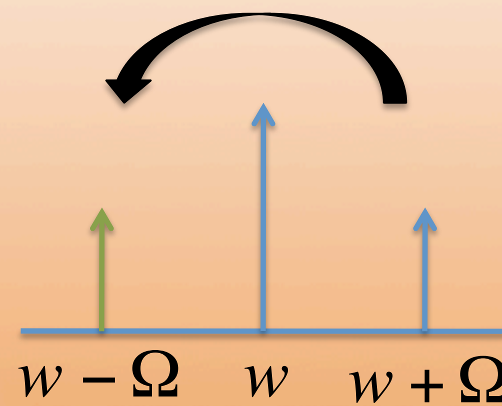
.... in theory

- ✧ Non linear medium with a strong second order polarization component
- ✧ Correlation of upper and lower quantum sidebands




$$P \propto (Ee^{-i2wt} + Ee^{-i(w+\Omega)t})^2$$

$$\Rightarrow Ee^{-i(w-\Omega)t}$$




The OPO makes a "copy" of the quantum sideband, and it correlates the sideband

# How to make squeezed fields..

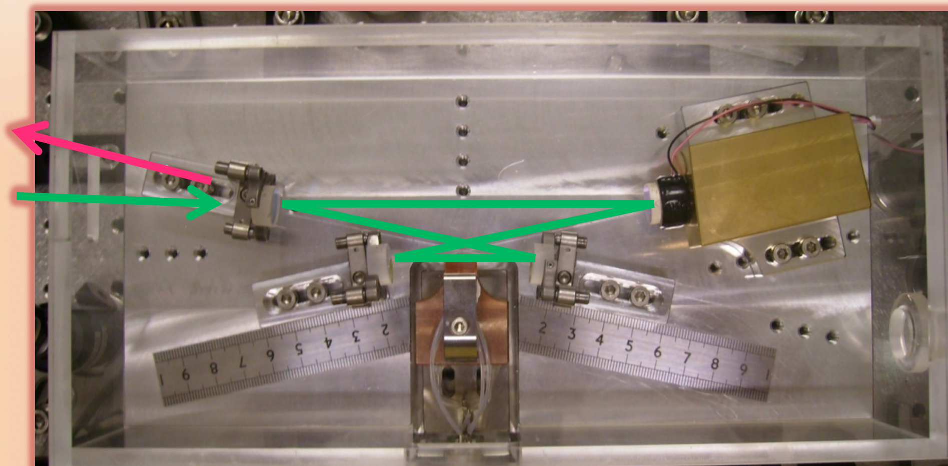
## .... in practice

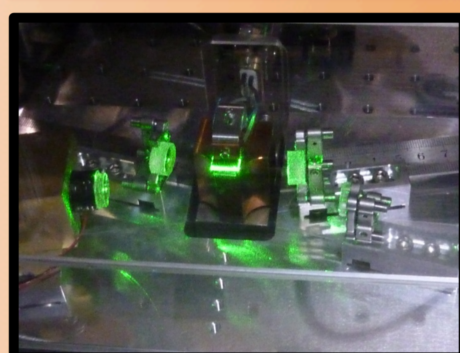
AEI, ANU, MIT, Caltech → big effort in the last 10 years to make squeezing in the audio-frequency band

✧ Lasers, mirrors, control loops,..

Courtesy of Alexander Khalaidovski (AEI)

The Squeezer of the GEO600 detector

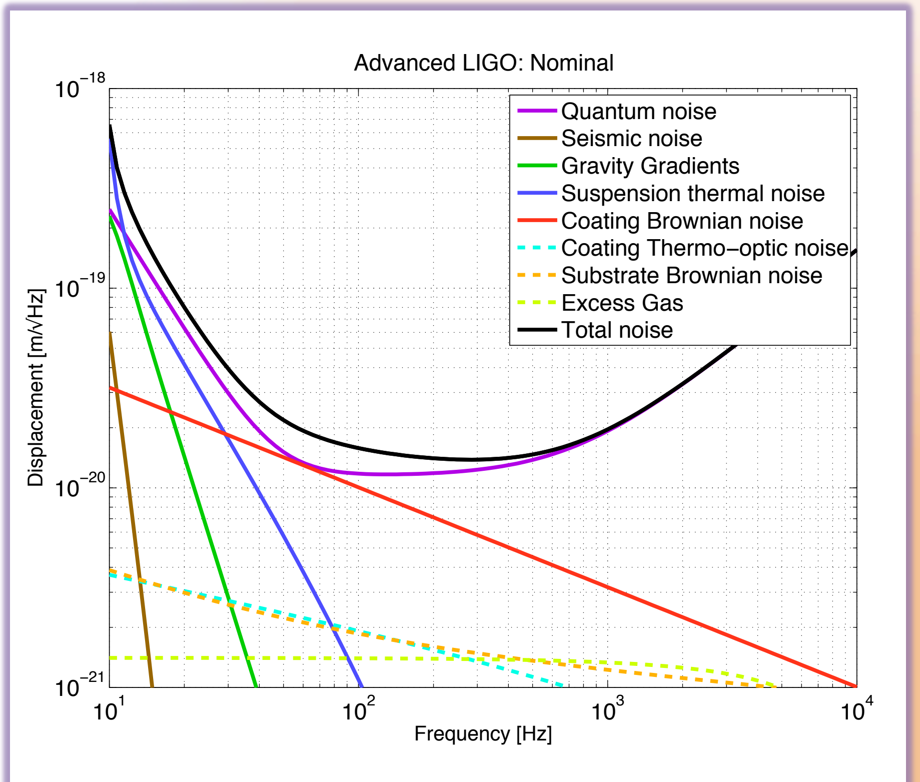


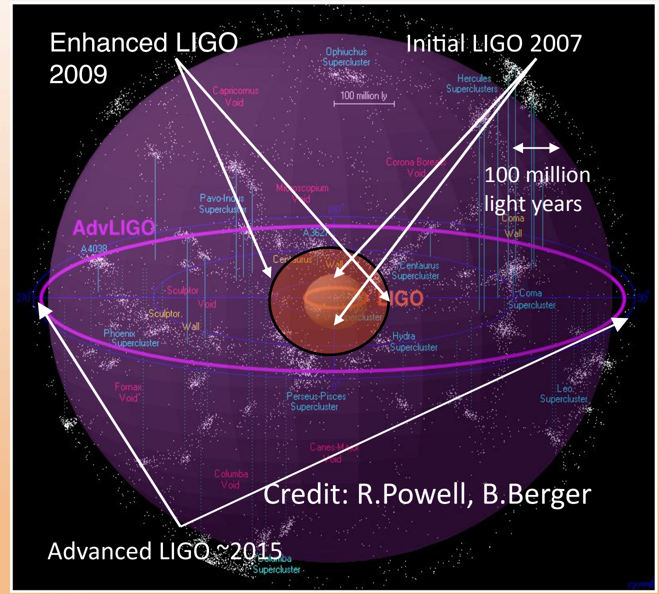


The Optical Parametric Oscillator of the LIGO squeezer

# Quantum Noise will limit the Sensitivity of GW Detectors for a long time…

2nd Generation (Advanced LIGO)

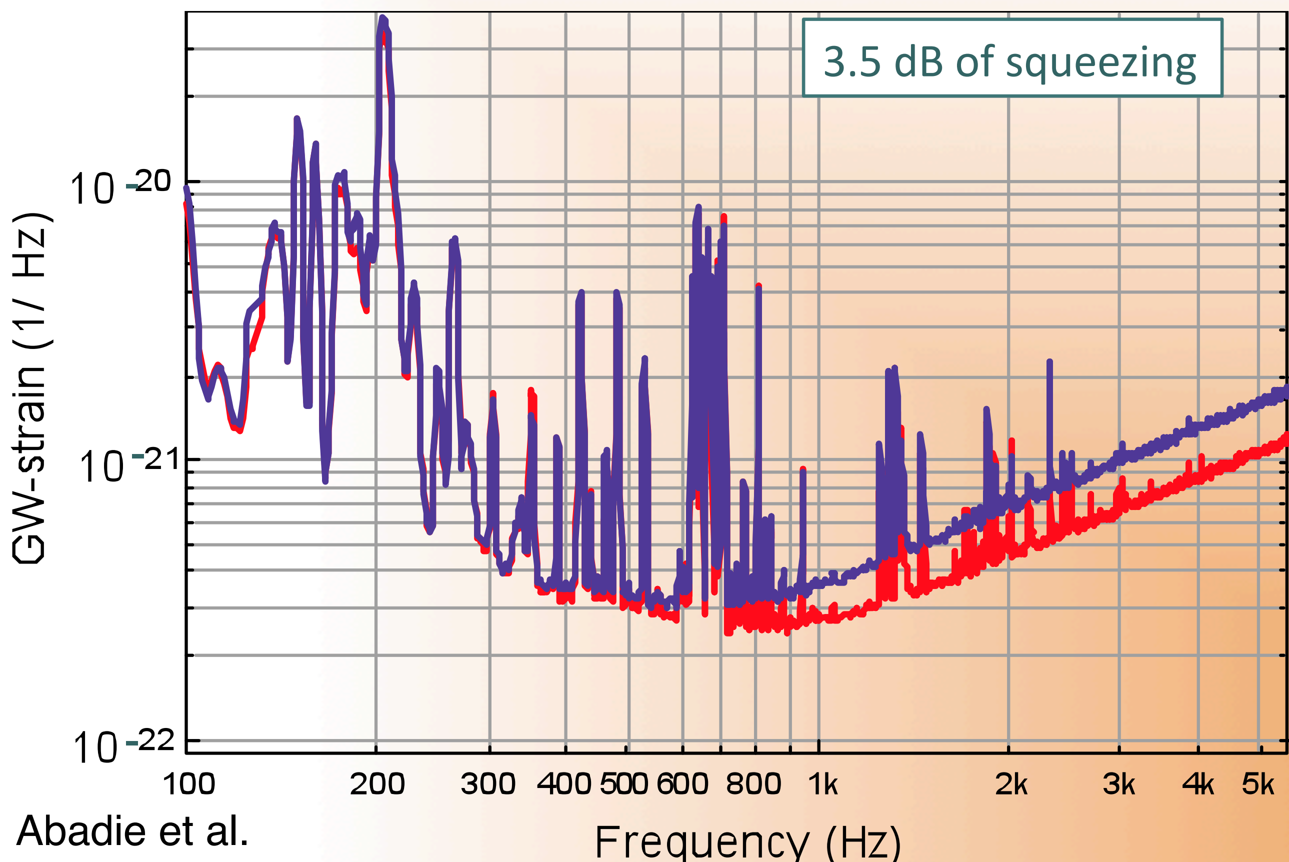



x10 better sensitivity
X1000 detection rate

Squeezing can reduce quantum noise..let's try!

# Squeezing at GEO600 (Germany)



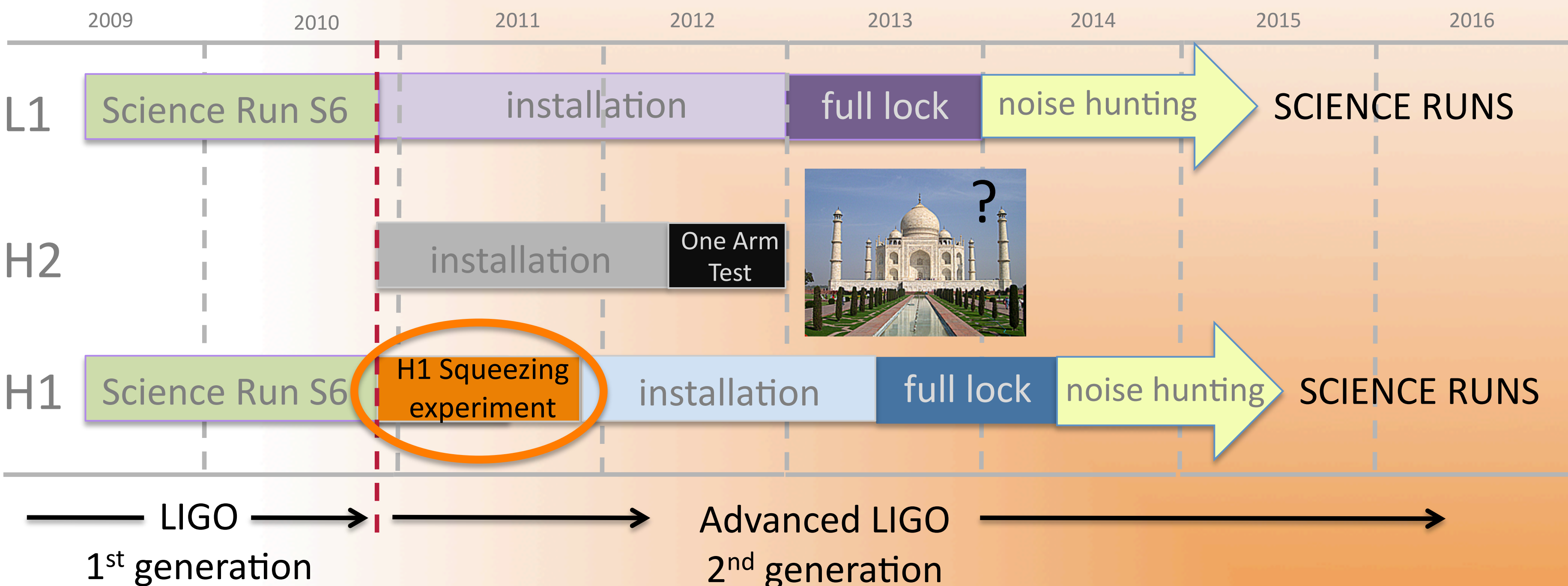

Abadie et al.
Nature Physics 7, 962 (2011)

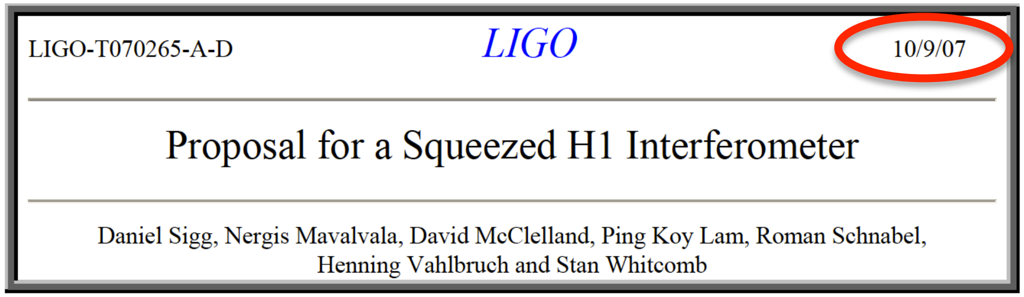
✧First implementation of squeezing in a GW observatory

✧ 3.5 dB of squeezing measured!

✧ Not close to quantum limit in the 200 Hz region ➔ injection in a LIGO detector as well

# LIGO Past & Future

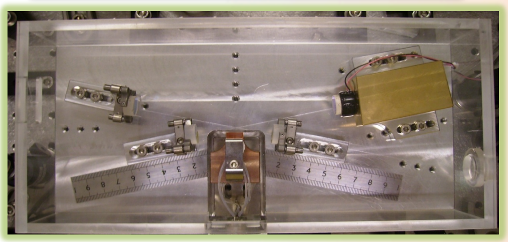



LIGO-T070265-A-D LIGO 10/9/07

Proposal for a Squeezed H1 Interferometer

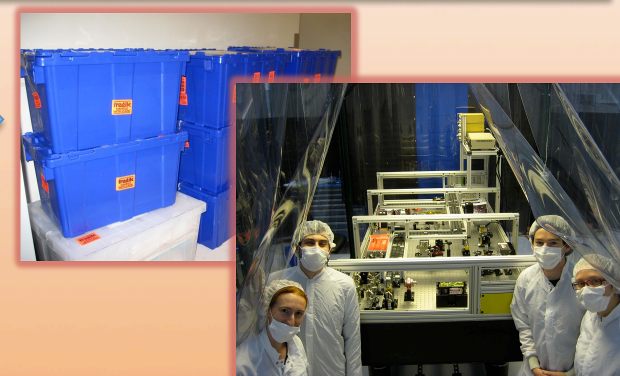
Daniel Sigg, Nergis Mavalvala, David McClelland, Ping Koy Lam, Roman Schnabel, Henning Vahlbruch and Stan Whitcomb

Bow-tie cavity OPO design at ANU (2008)

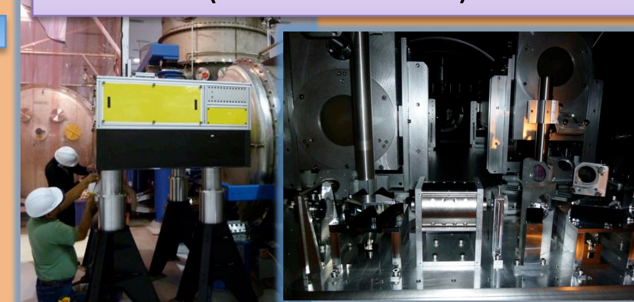


H1 Squeezer assembling at MIT (2009-2010)

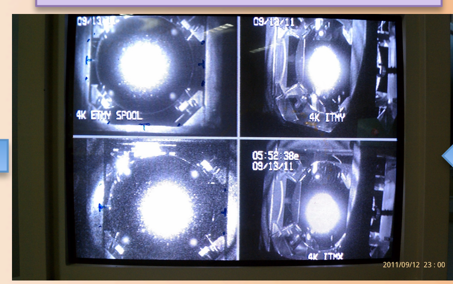
H1 Squeezer parts shipped to LHO (Oct 2010)



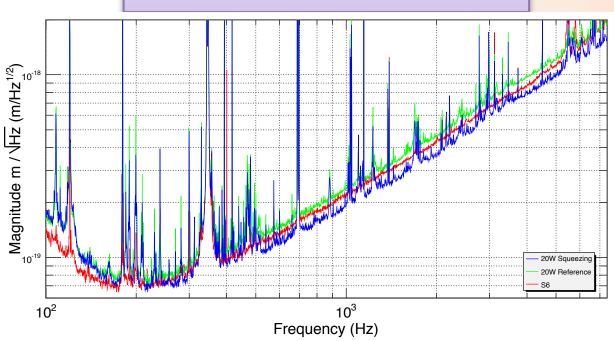
H1 Squeezer Installation (Summer 2011)



H1 Recovery (Sept 2011)

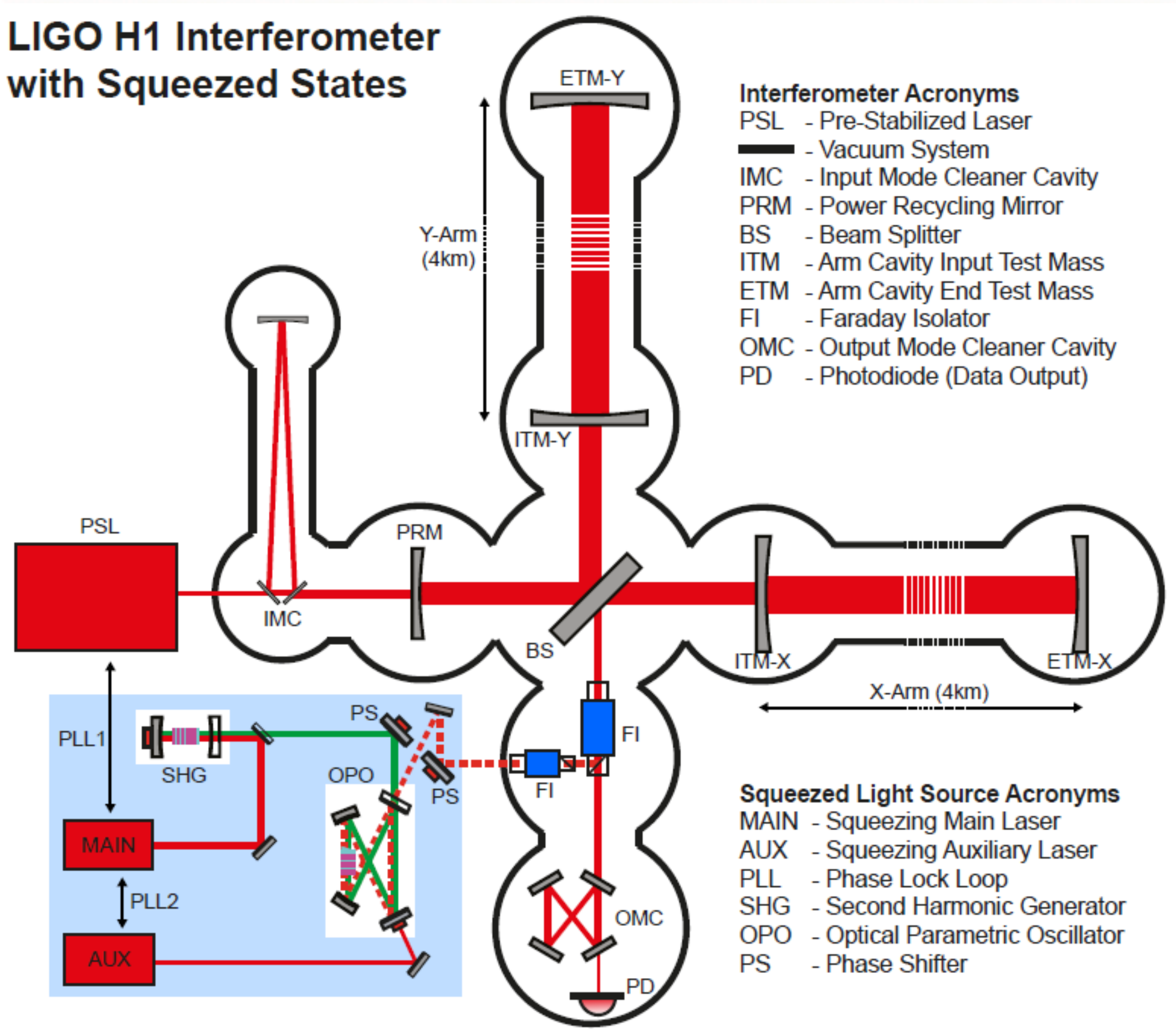


Squeezing in H1 (Oct 3 – Dec 4)

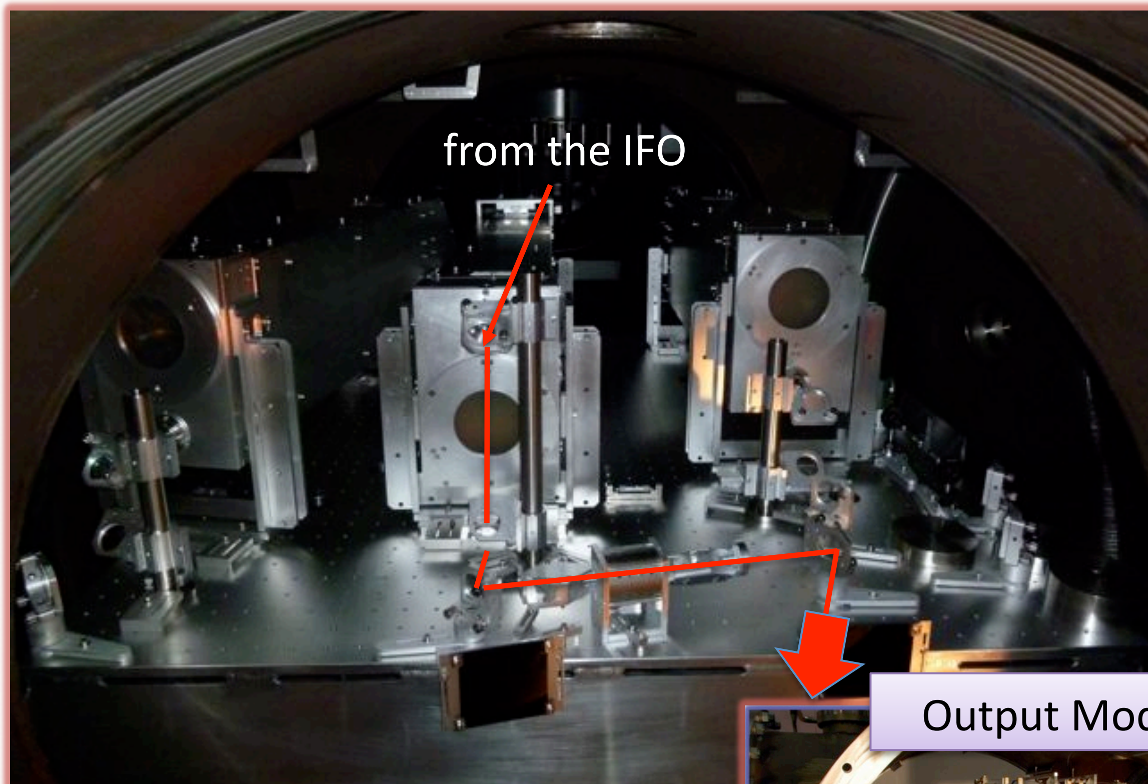


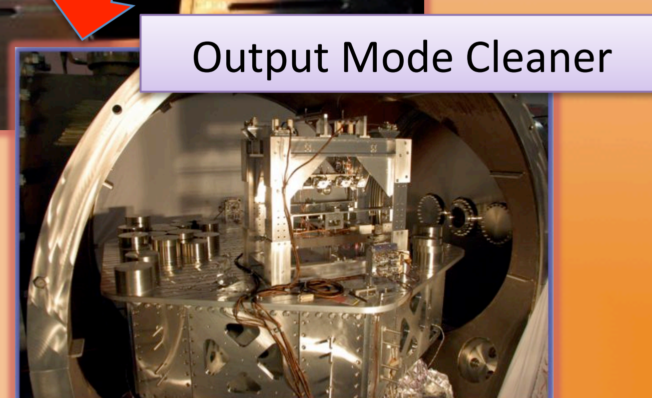

L.Barsotti

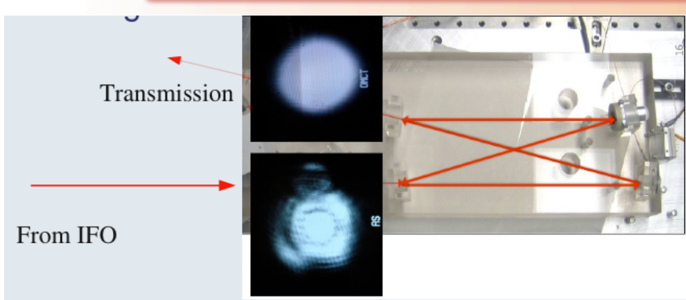
# Squeezing Injection in LIGO H1



# H1 Squeezing Experiment: (Old) Readout In-Vacuum Layout

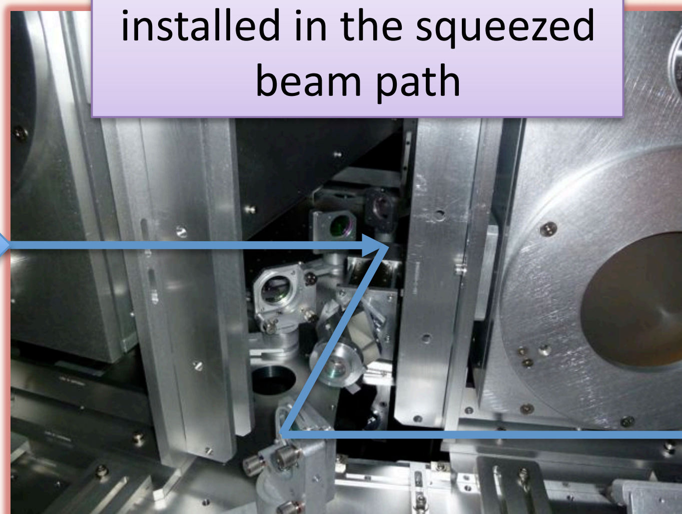


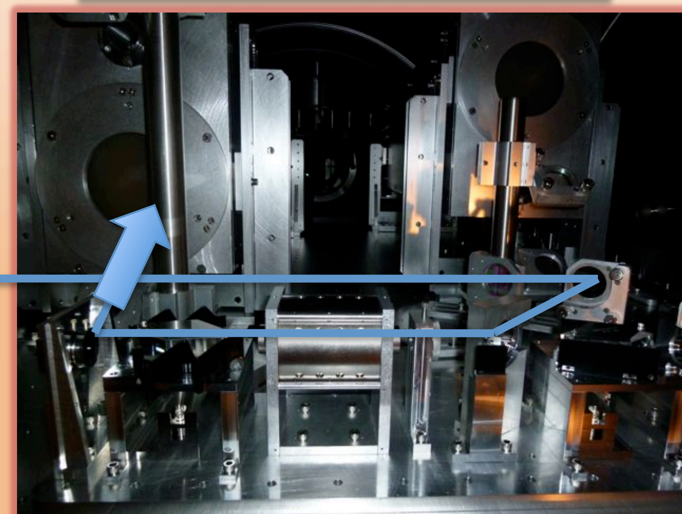
# H1 Squeezing Experiment: Squeezer Installation

Squeezer table craned to its final location

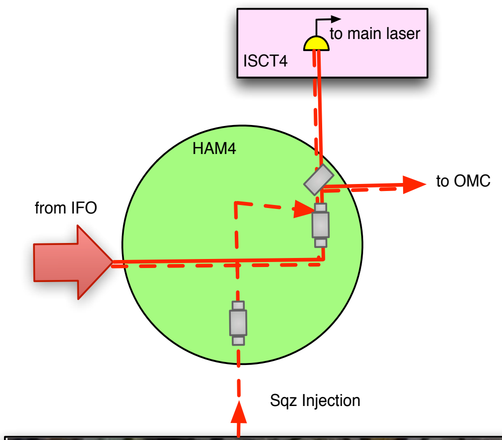


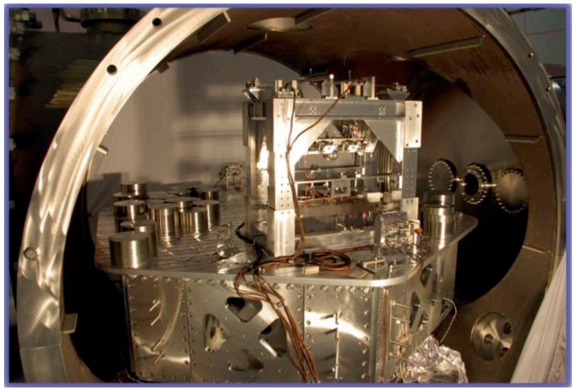
Additional Faraday installed in the squeezed beam path

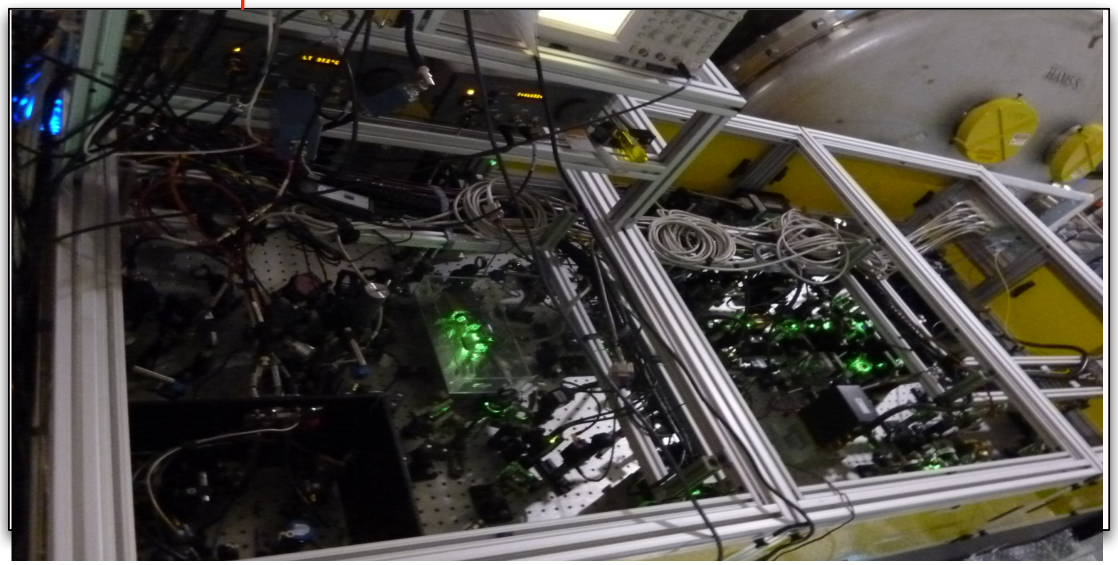
New H1 Output Faraday (first aLIGO unit)



# Squeezing Injection

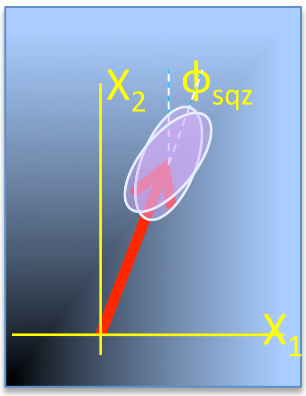


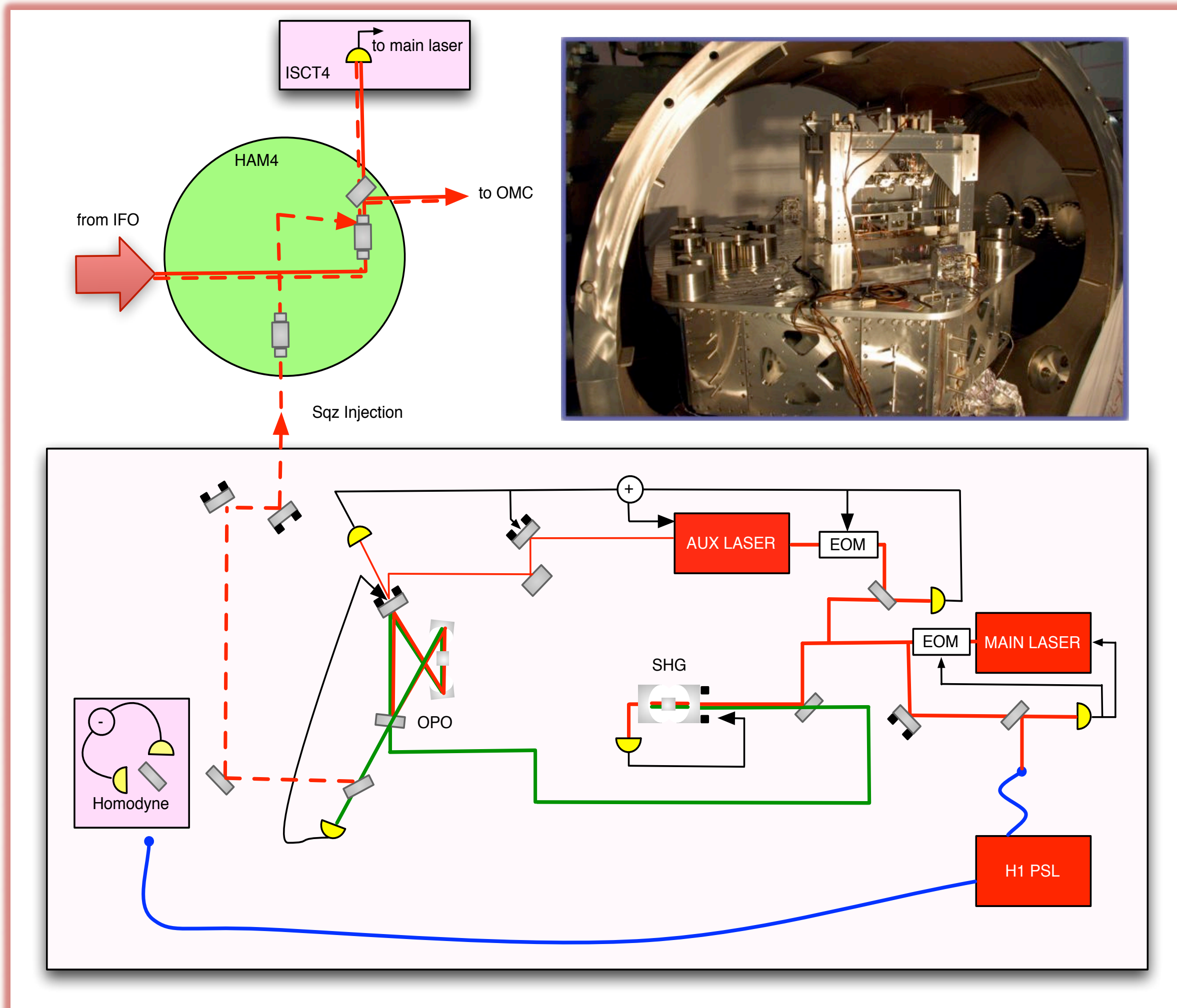





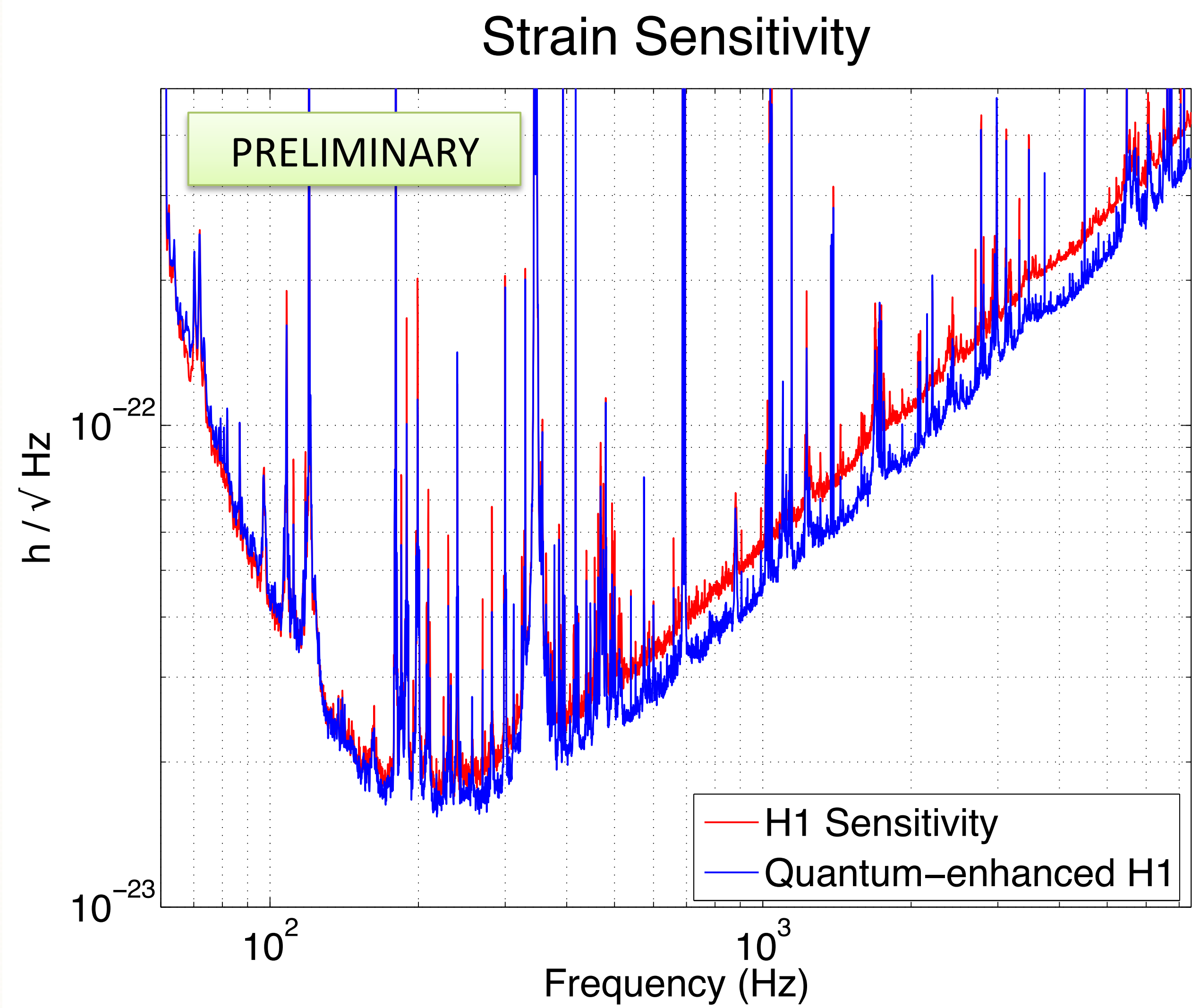
# Squeezing Injection

Coherent beam @ 29MHz injected for controlling the squeeze angle

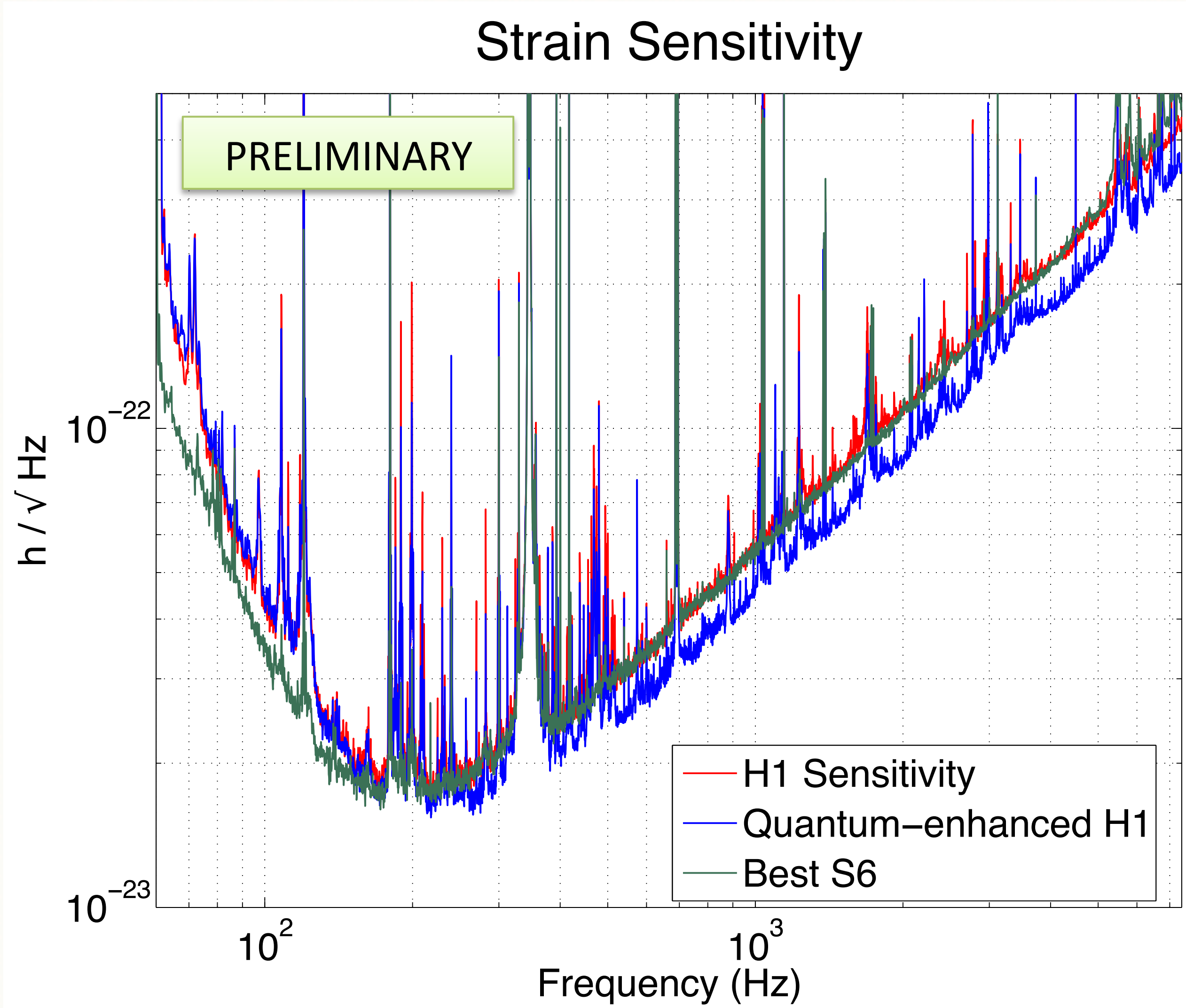


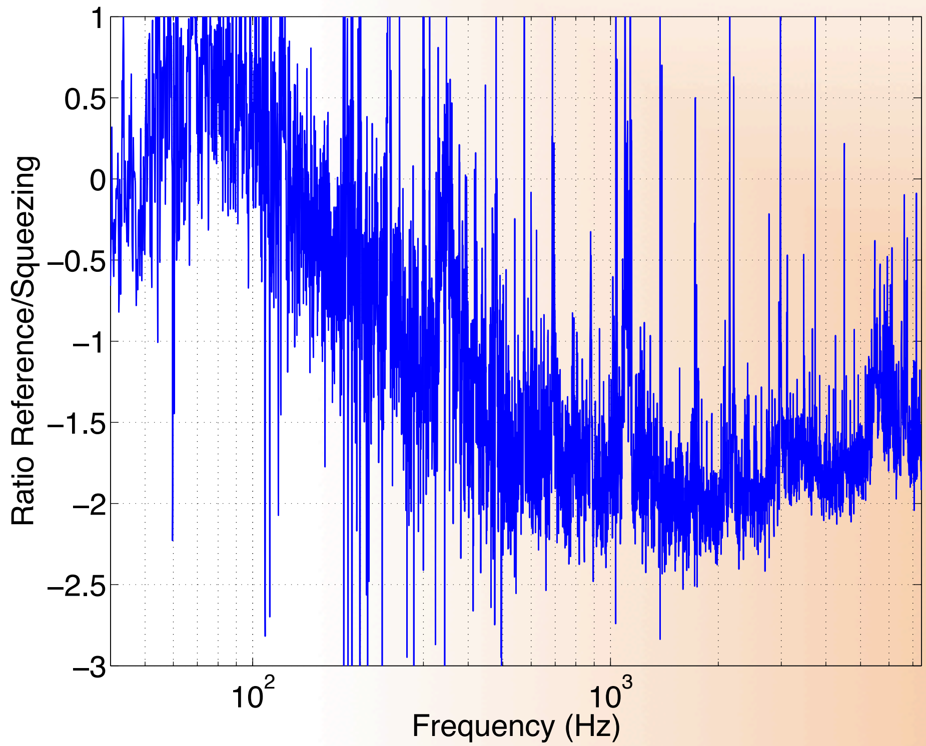
# Improving H1 with squeezing

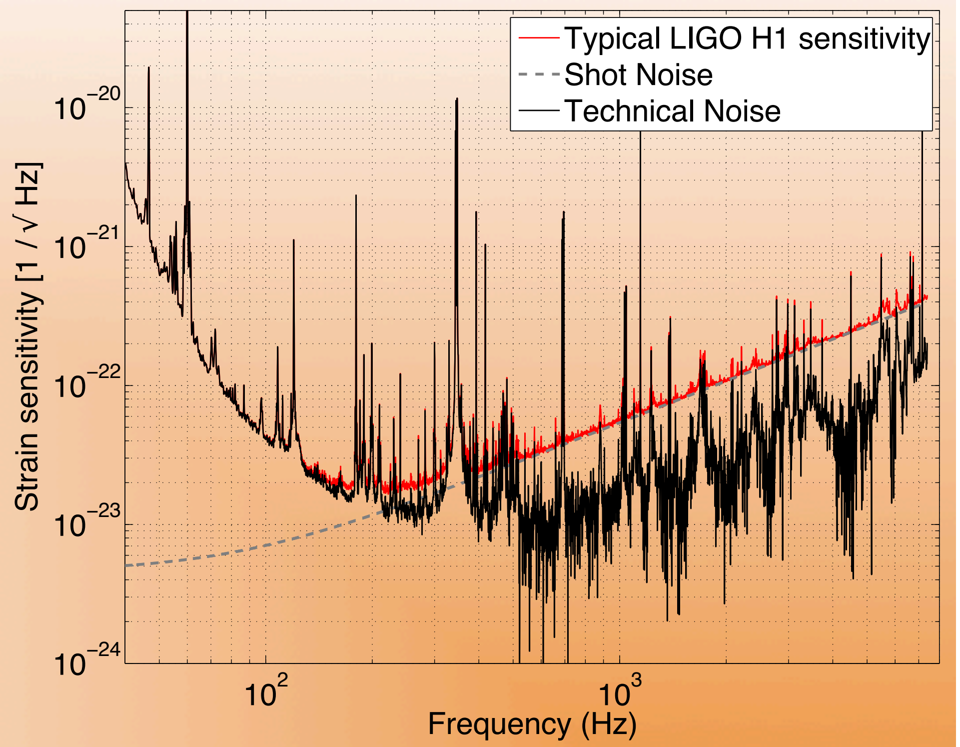


# Best broadband sensitivity ever



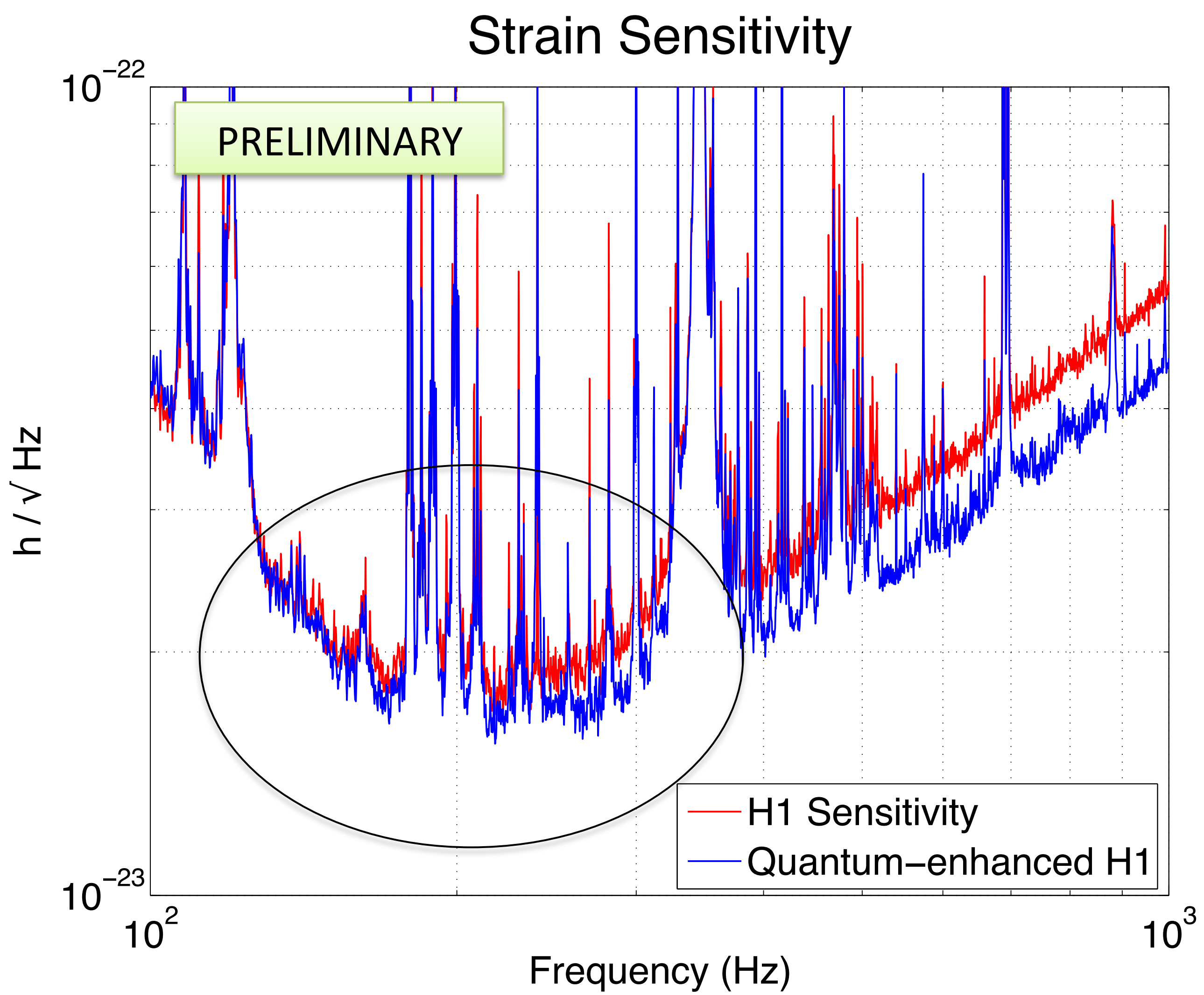
# 2.15 dB (28%) improvement over quantum noise



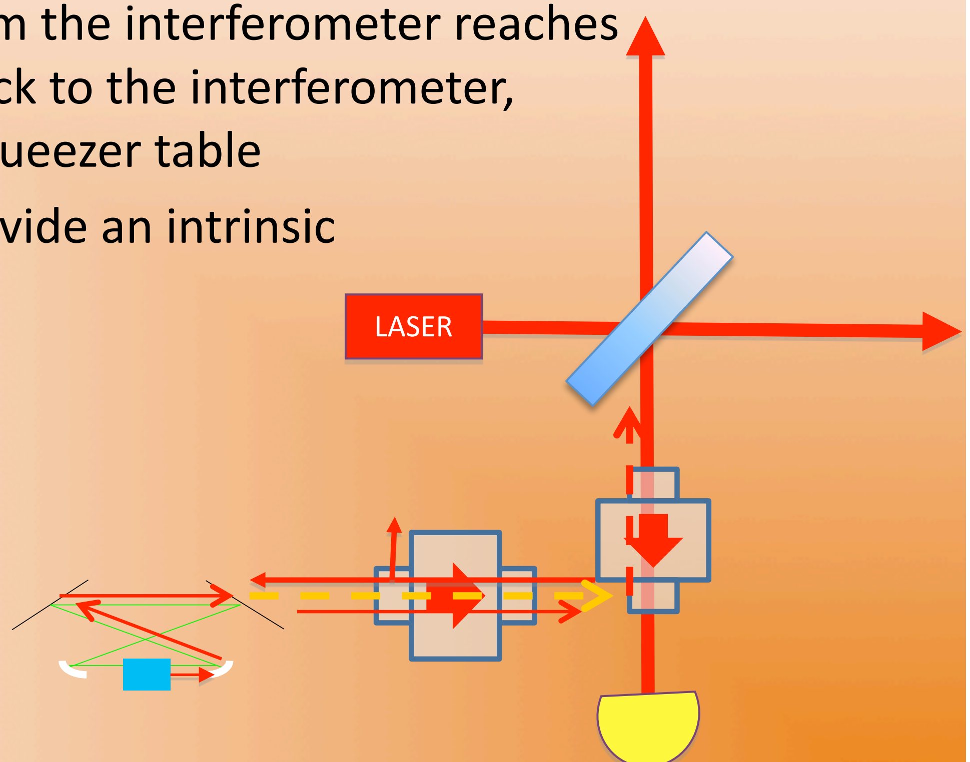

Squeezing improves only quantum noise, not other technical noises

# Improving H1 by 2 dB (28%) with squeezing ..without spoiling the sensitivity at 200 Hz



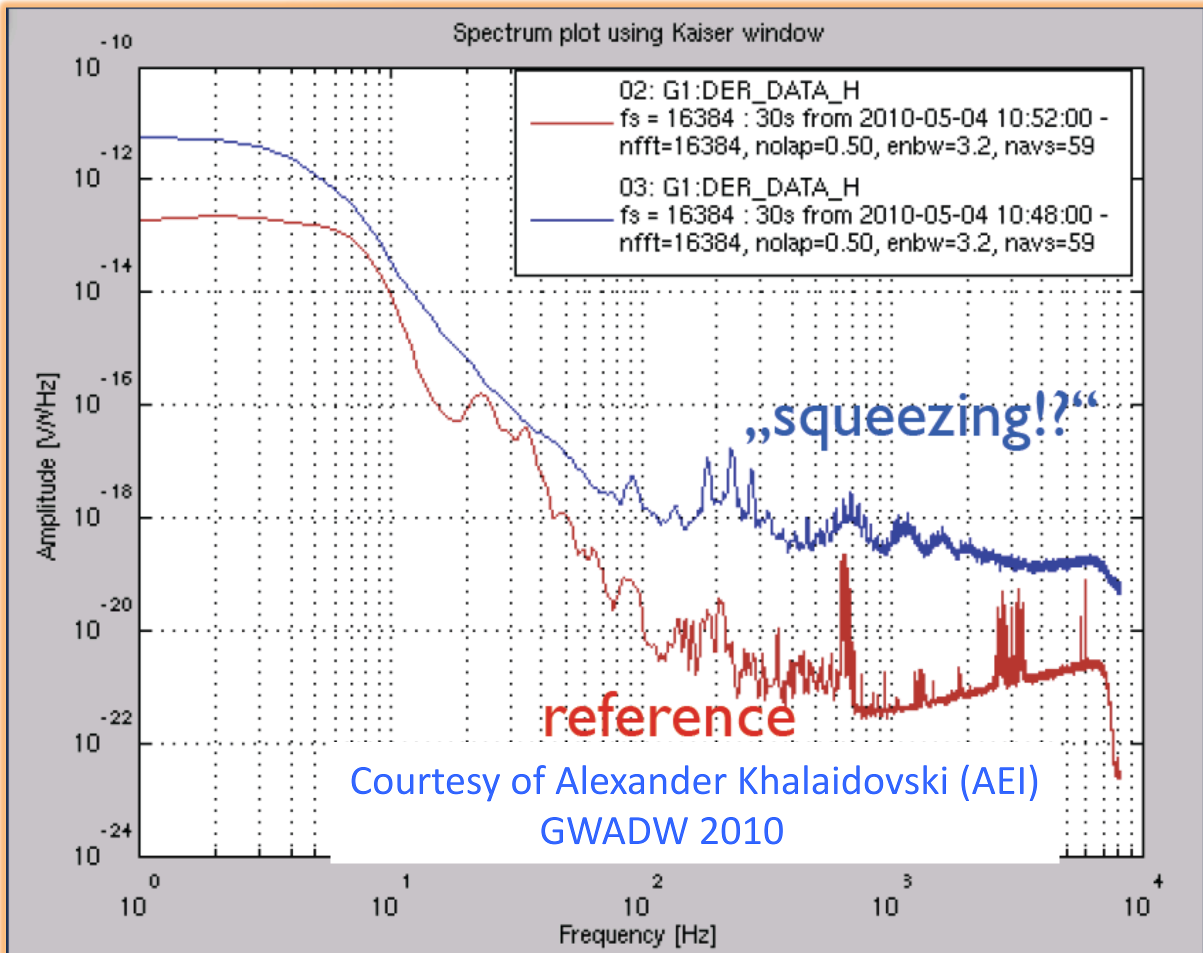
# Noise couplings

- Everything you can think of has the potential of spoiling the sensitivity of LIGO around 200 Hz
- Squeezing injection is not an exception
- One mechanism: spurious light from the interferometer reaches the squeezer, and it is scattered back to the interferometer, modulated by the motion of the squeezer table
- LIGO OPO is a bow-tie cavity to provide an intrinsic isolation to back scatter

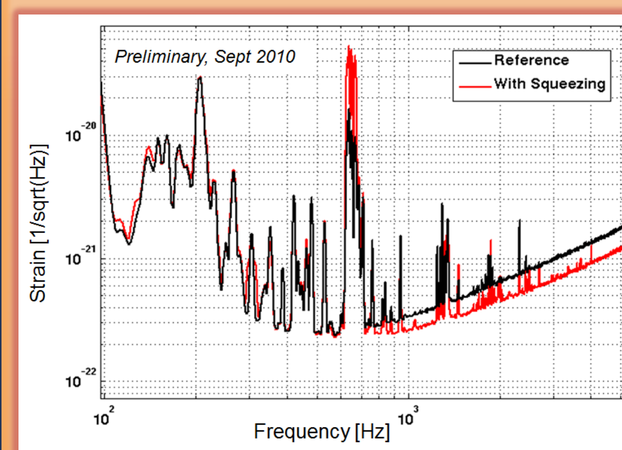



S. Chua et al., Backscatter tolerant squeezed light source for advanced gravitational-wave detectors. Optics Letters 36, 4680 (2011).

# First try at squeezing in GEO

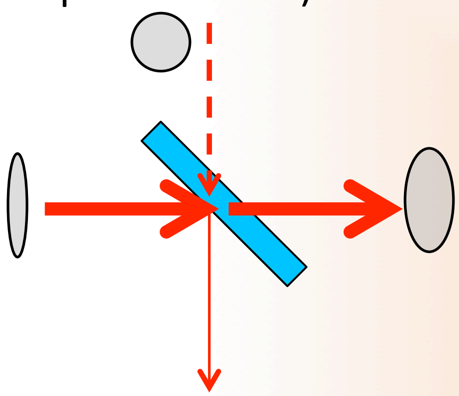



- ✧ First squeezing injection: back scattered noise limits the sensitivity
- ✧ Additional Faraday to reduce back scattering and measure squeezing

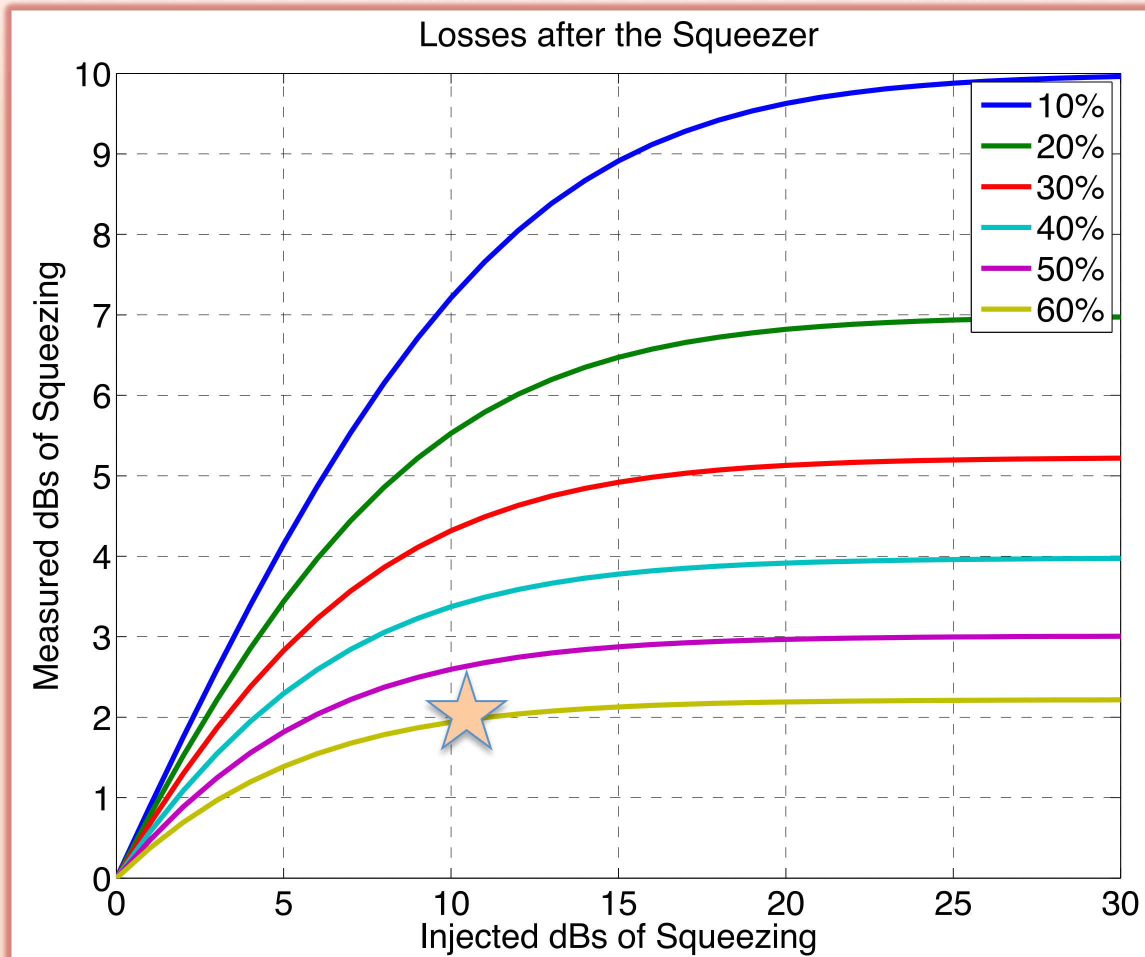


# Why only 2 dB? Losses…

✧ Losses degrade squeezing ("un-squeezed" vacuum gets in causing dechoerence of the squeezed state)



✧Vacuum fluctuations destroy the squeezed states
✧At some point it doesn't matter how much squeezing you can produce…you can't measure it!
✧ During the H1 squeezing experiment, we measured a total of **56% losses,** and we **injected 10 dB**…so it makes sense!



# Where the main losses came from

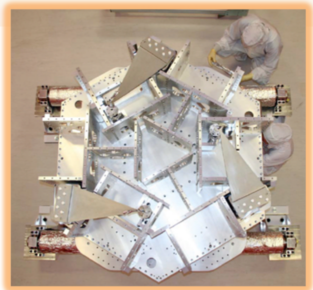
- ✧ Mode matching (~30% losses)
- ✧ Faradays (3 passes ~ 20% losses)
- ✧ OMC transmission (18% losses)

➔ “Technical” problems, total losses should be down to 10-15% in aLIGO

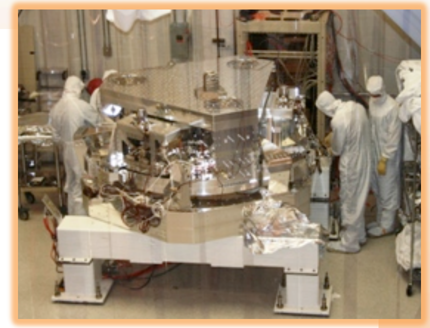
# Advanced LIGO configuration

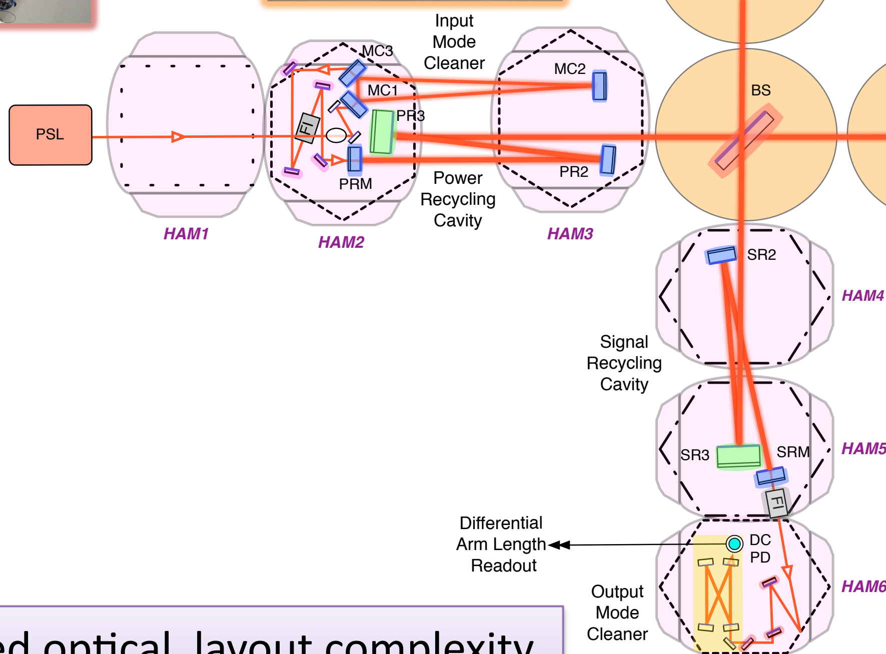
PSL

HAM-ISI

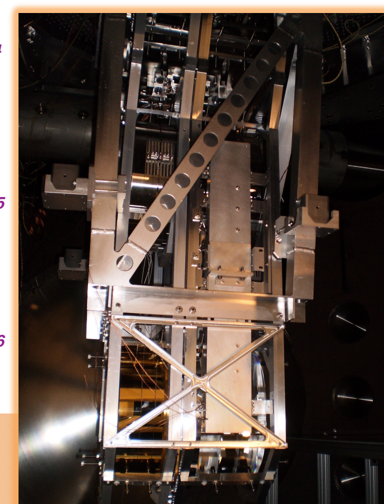


BSC-ISI

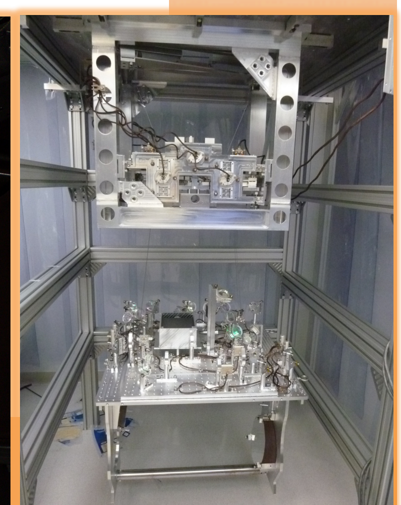




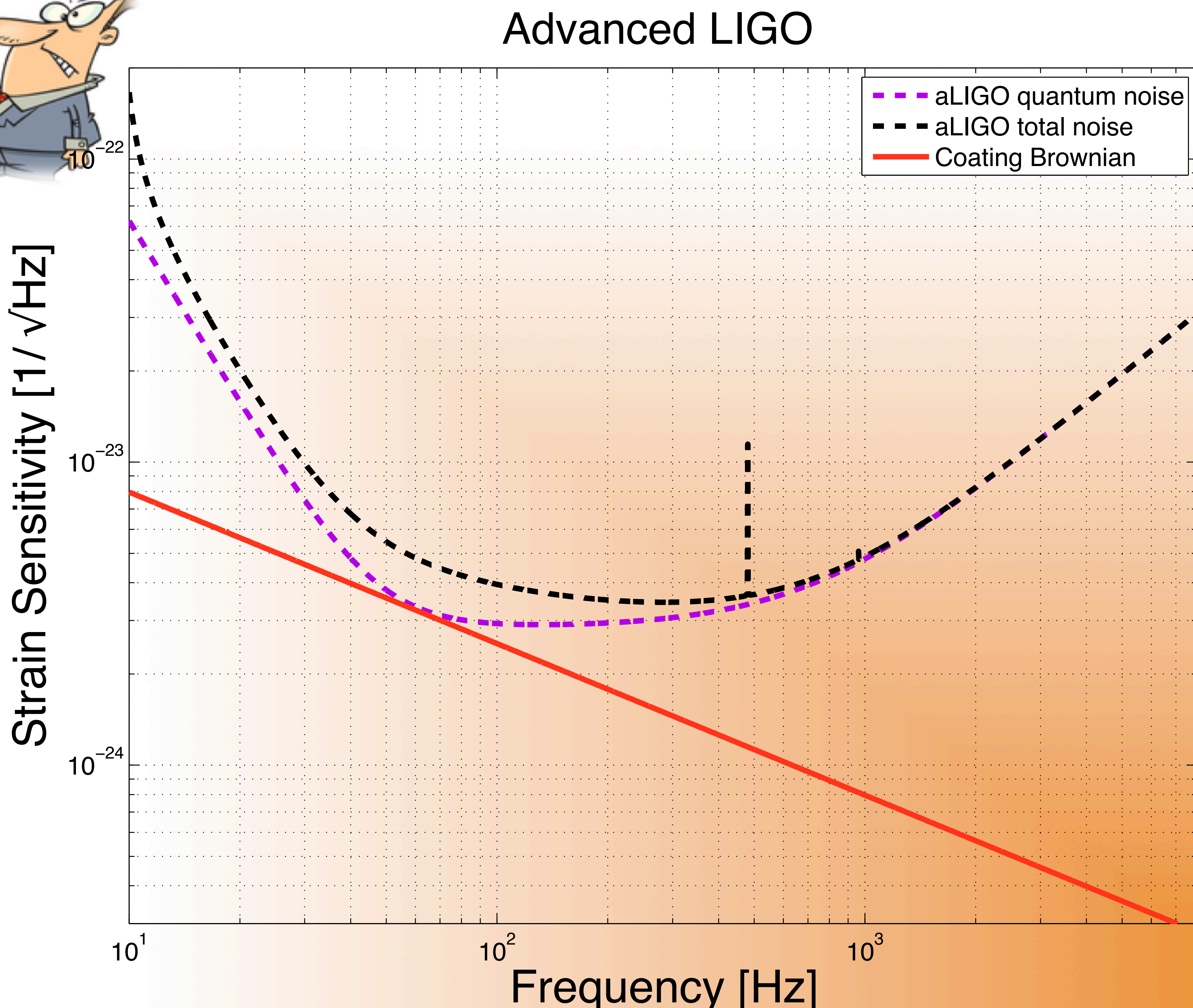

QUAD



TRANSMON

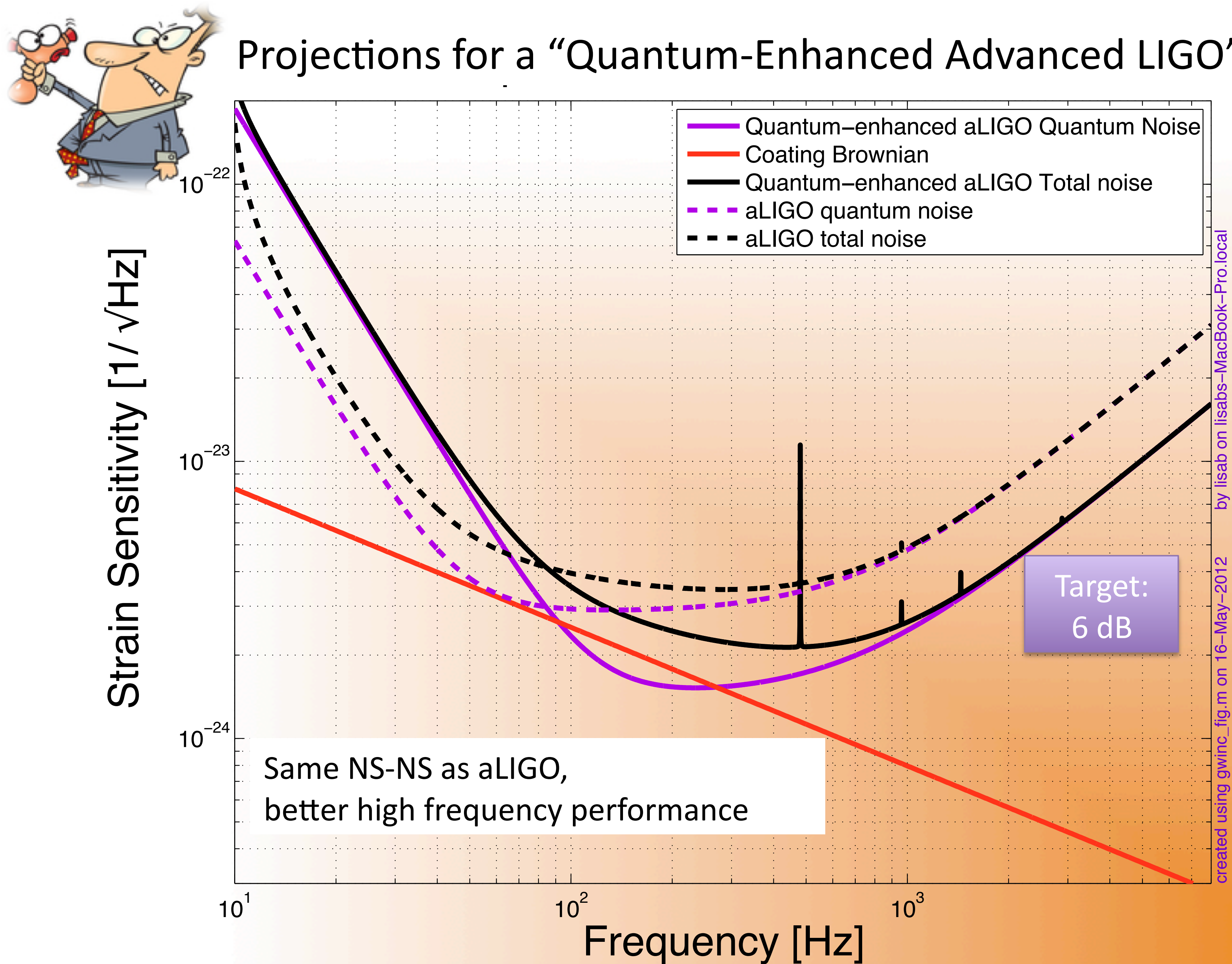


✧Increased optical layout complexity
✧Up to 125W input power

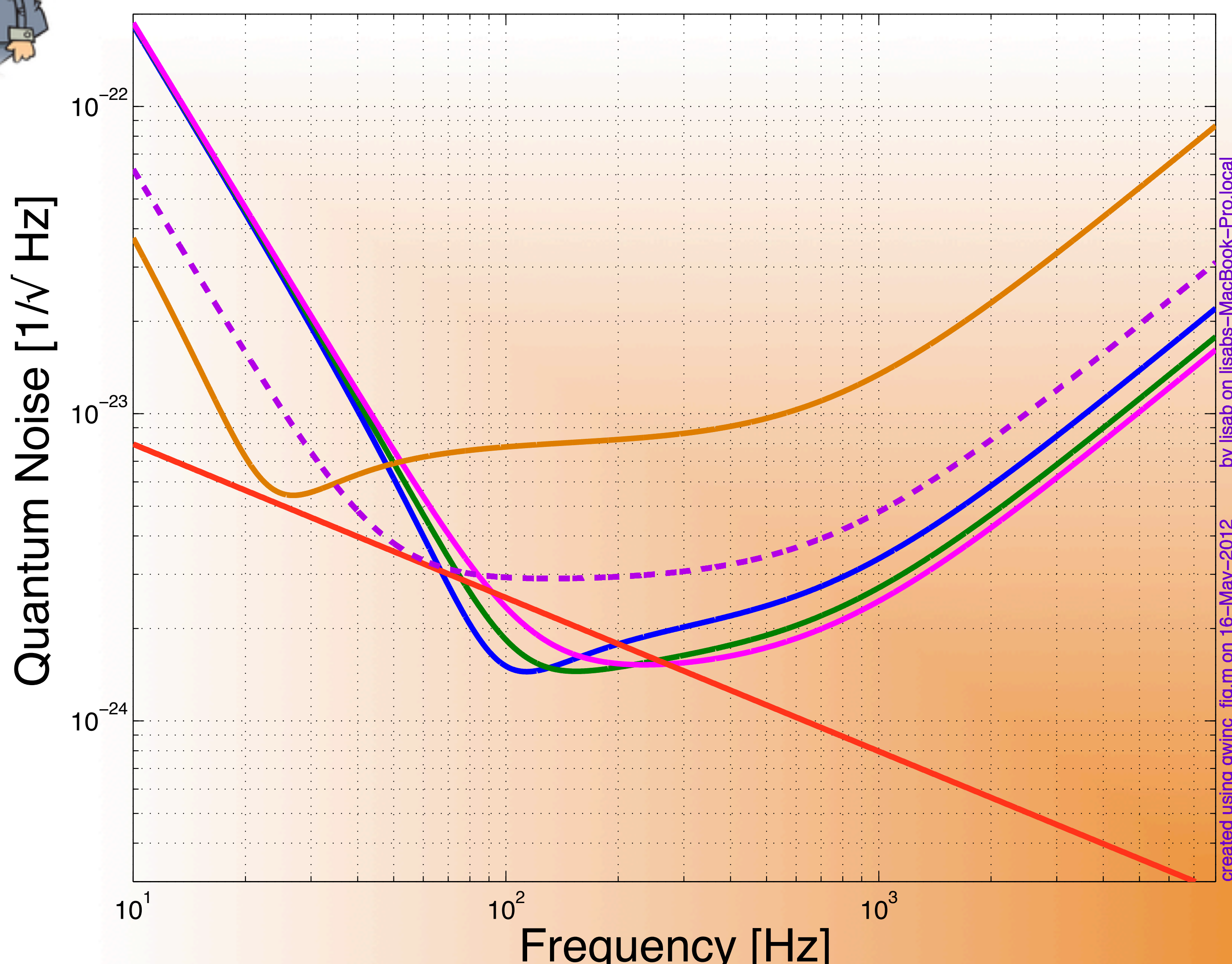


Advanced LIGO
aLIGO quantum noise
aLIGO total noise
Coating Brownian
Strain Sensitivity [1/ √Hz]
Frequency [Hz]
$10^{-22}$
$10^{-23}$
$10^{-24}$
$10^{1}$
$10^{2}$
$10^{3}$

# Projections for a "Quantum-Enhanced Advanced LIGO"

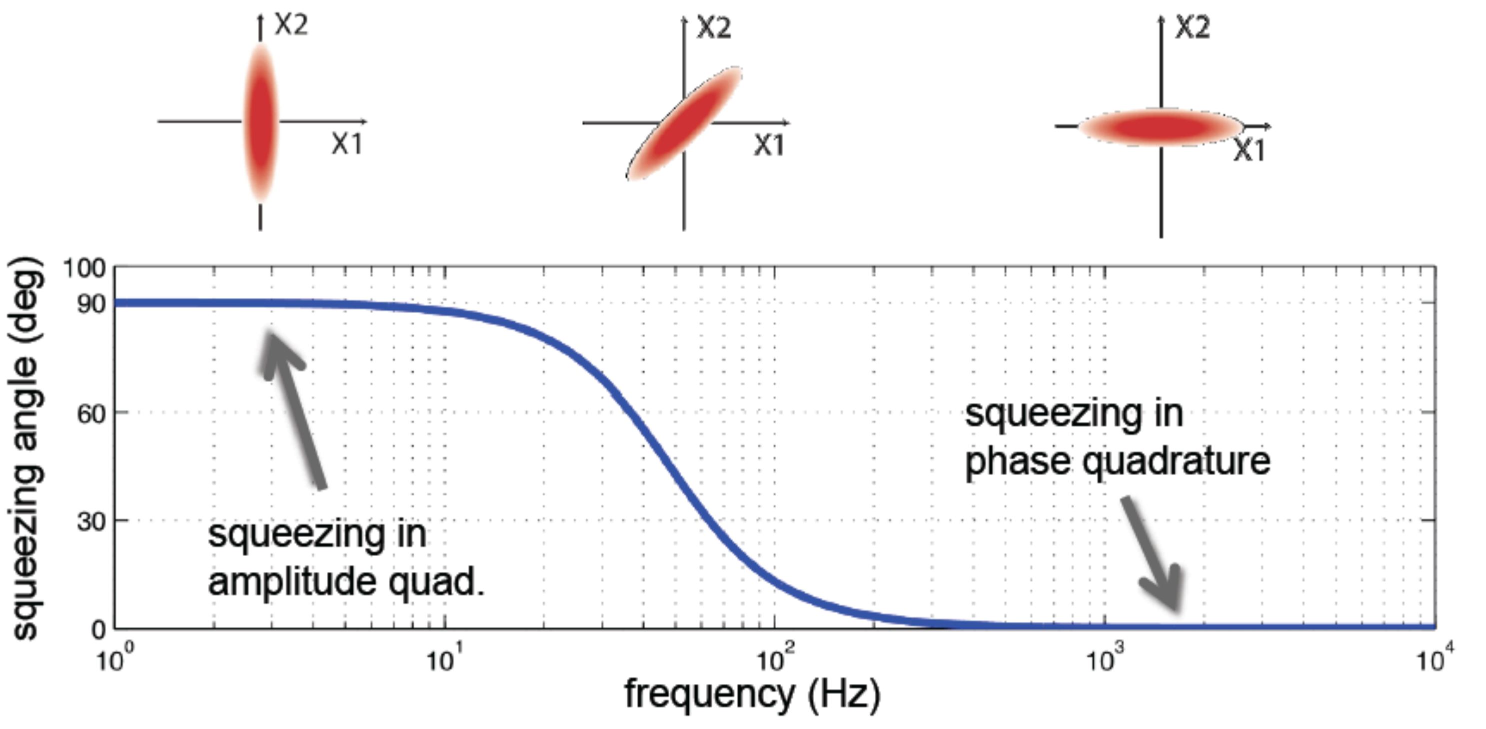


# Quantum noise shaped by squeezed angle



# Frequency Dependent Squeezing

✧ What we want is a frequency dependent rotation of the squeeze angle, to achieve a broadband improvement of the quantum noise



# Frequency Dependent Squeezing

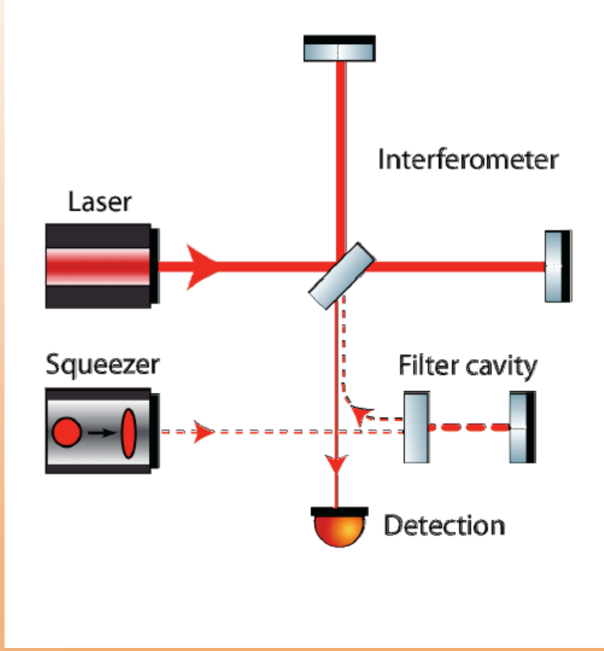
✧ High finesse detuned cavity which does the rotation for you

✧ Broadband improvement of the quantum noise

✧ Theoretically well understood, experimentally challenging

✧ Low loss needed: F ~ 50,000 for 100m scale cavities

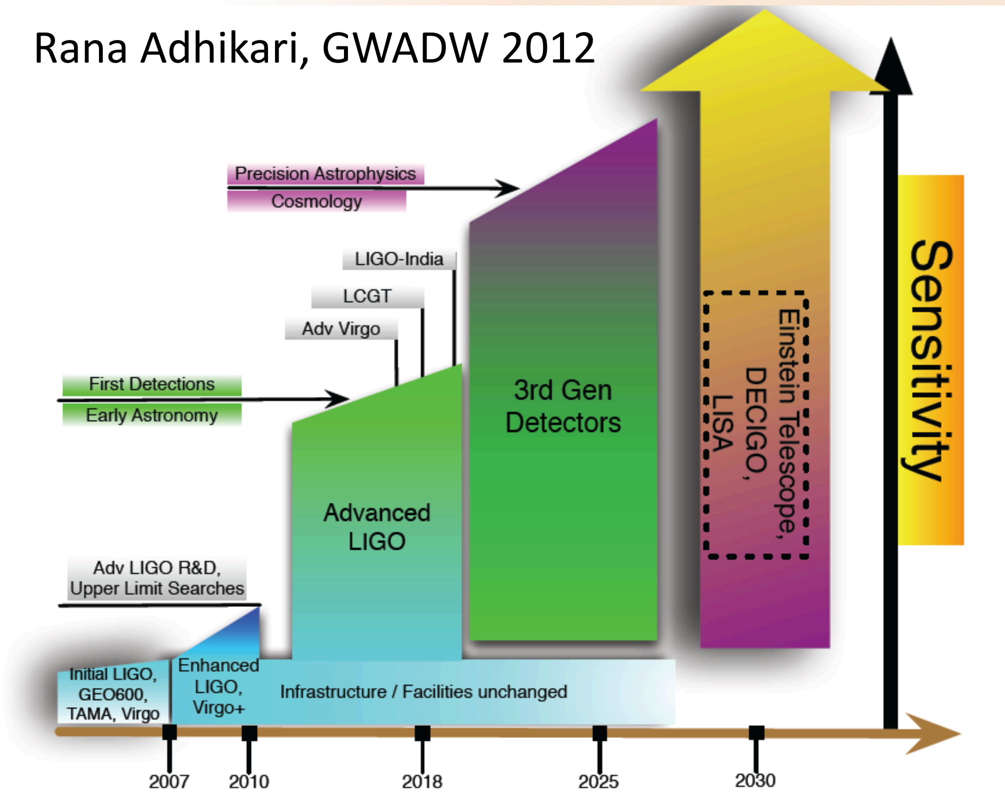
✧ R&D in progress – MIT (P. Kwee and others)
Caltech (J. Harms and others)




H. J. Kimble, Y. Levin, A. B. Matsko, K. S. Thorne and S. P. Vyatchanin, Conversion of conventional gravitational-wave interferometers into quantum nondemolition interferometers by modifying their input and/or output optics. Phys. Rev. D 65, 022002 (2001).

# Beyond aLIGO: 3rd generation
# Can we take another factor of 10 step?

Rana Adhikari, GWADW 2012




✧ Basic idea is to use the same LIGO vacuum envelope

✧ Design study happening now

✧ Still work in progress, one thing already clear:

➔ 10 dB of frequency dependent squeezing needed!

# The Message

- ✧Squeezing can reduce quantum noise, and improve the sensitivity of GW detectors
- ✧Large scale interferometers with squeezing: DONE!
  - ✧Work needed to achieve 24/7 long term stability at maximum squeezing and reduce optical losses
  - ✧H1 squeezing experiment completed, GEO600 operating with squeezing right now
- ✧In a good position to make squeezing available for Advanced detectors and beyond

# H1 Squeezing Experiment

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MIT: Sheila Dwyer, L. Barsotti, Nergis Mavalvala, Nicolas Smith-Lefebvre, Matt Evans

ANU: Sheon Chua, Michael Stefszky, Conor Mow-Lowry, Ping Koy Lam, Ben Buchler, David McClelland

AEI: Alexander Khalaidovski, Roman Schnabel