Beyond Advanced Gravitational Wave Detectors: beating the quantum limit with squeezed states of light

Lisa Barsotti

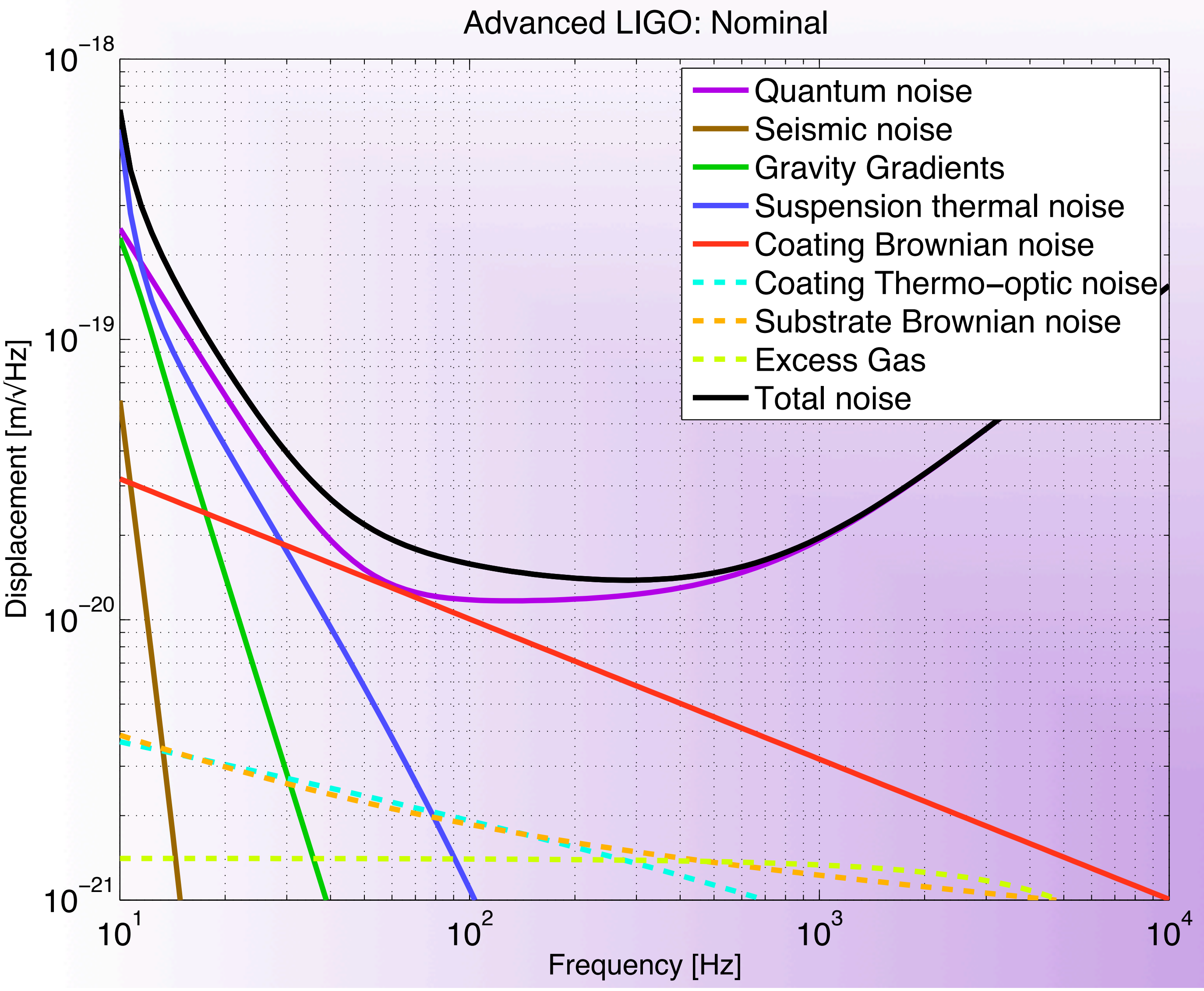
(LIGO-MIT)

GRITTS Seminar, April 3 2013

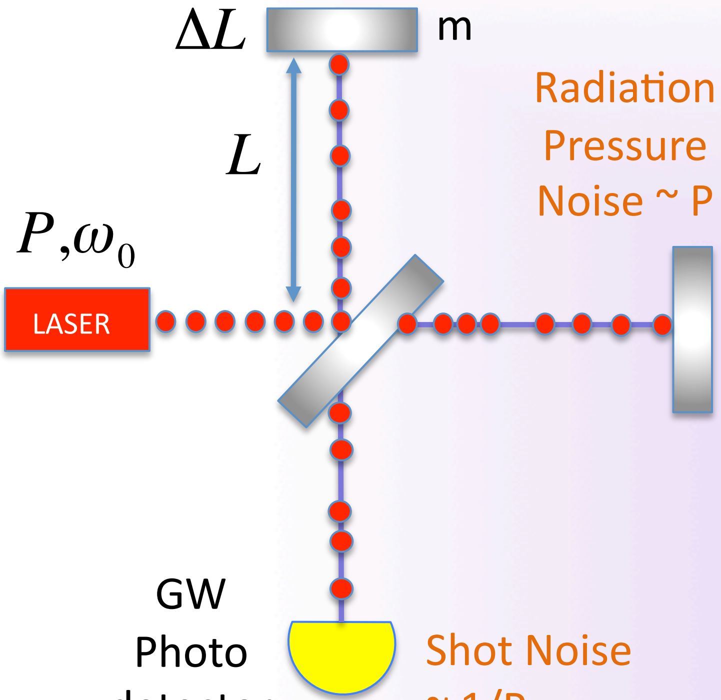
LIGO-G1300420

Why we talk about quantum noise

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



Where quantum noise comes from



ΔL m

L

P, ω_0

LASER

Radiation Pressure Noise ~ P

GW Photo detector

Shot Noise ~ 1/P

✧ SHOT NOISE: Photon counting noise produced by fluctuations of the number of photon detected at the interferometer output

➔ Limitation of the precision you can measure arm displacement

✧ RADIATION PRESSURE NOISE: Back-action noise caused by random motion of the mirrors due to fluctuations of the number of photons impinging on the mirrors

➔ Additional displacement noise

$$\Delta L_{rad} = \frac{1}{cm\Omega^2}\sqrt{8\hbar P\omega_0} \qquad \Delta L_{shot} = c\sqrt{\frac{\hbar}{2P\omega_0}}$$

$$\Delta L_{Quantum} = \sqrt{\Delta L^2{}_{rad} + \Delta L^2{}_{shot}}$$

“Standard Quantum Limit”

$$\Delta L_{Quantum} = \sqrt{\frac{4\hbar}{m\Omega^2}}\sqrt{\frac{1}{2}\left(\mathrm{K}+\frac{1}{\mathrm{K}}\right)}, \qquad \mathrm{K} = \frac{4P\omega_0}{c^2 m\Omega^2}$$

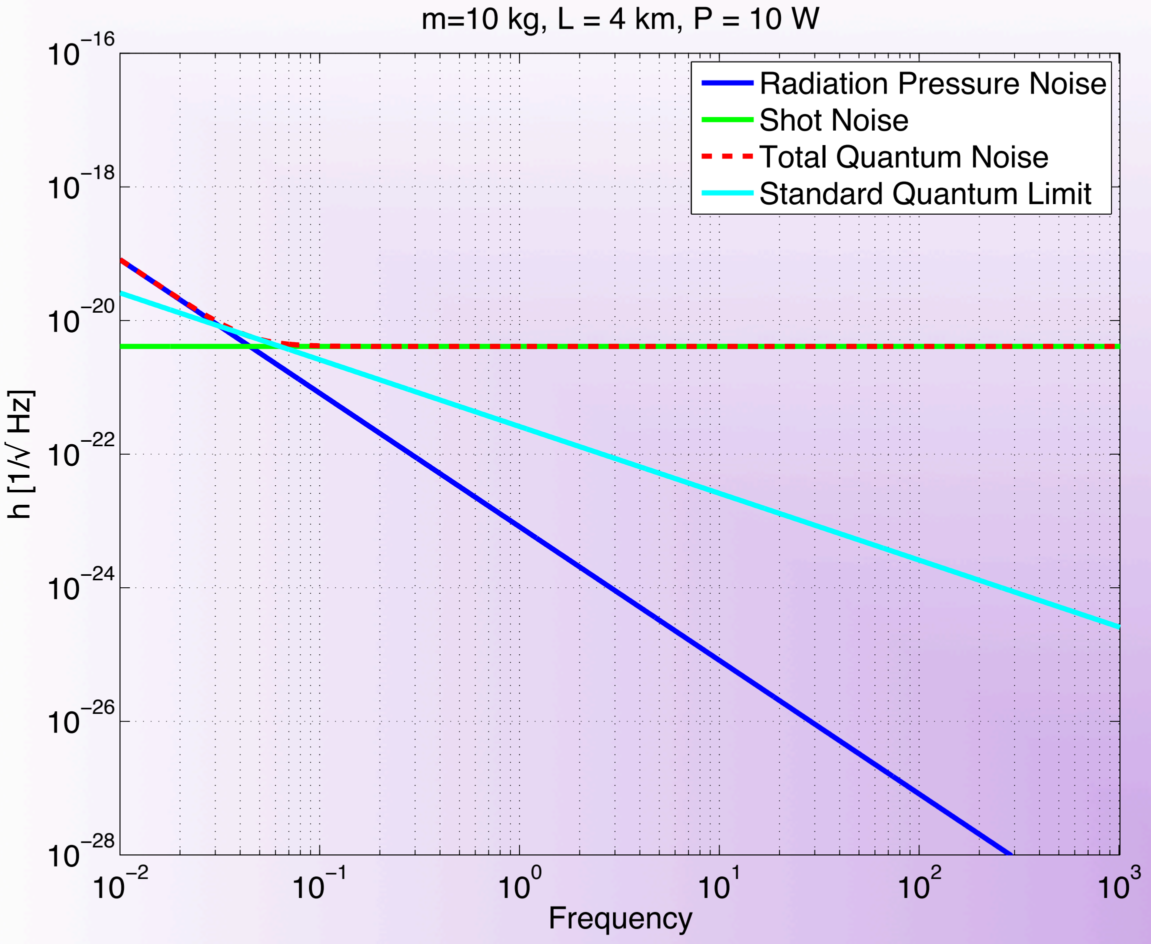
It doesn’t depend on the interferometer, just on the quantum mechanics of a harmonic oscillator mass

$$\Delta L_{SQL} \sim \sqrt{\frac{\hbar}{m\Omega^2}}$$

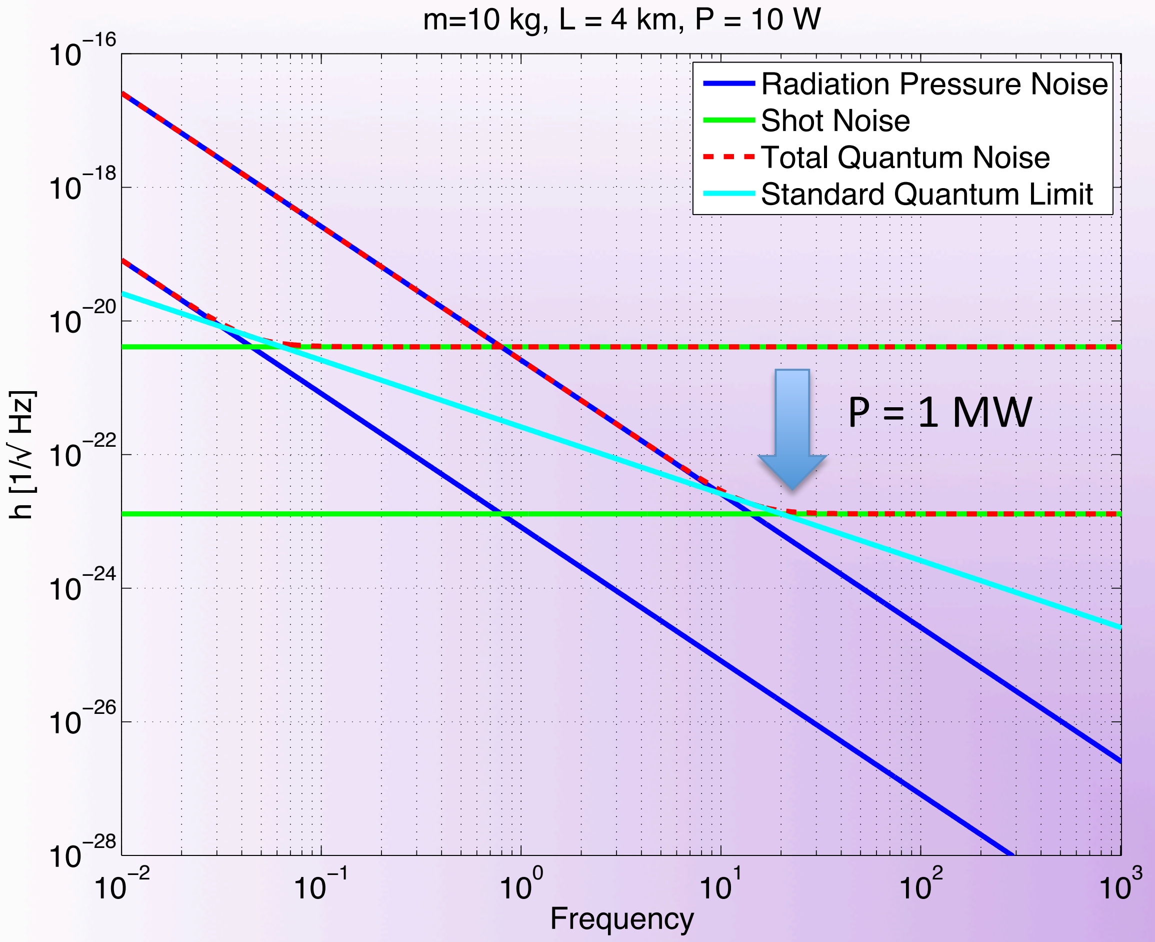
$$h_{Quantum} = \frac{\Delta L_{Quantum}}{L} = \sqrt{\frac{4\hbar}{m\Omega^2 L^2}}\sqrt{\frac{1}{2}\left(\mathrm{K}+\frac{1}{\mathrm{K}}\right)}$$

$$\mathrm{K} = 1 \;\Rightarrow\; \mathrm{P} = \frac{c^2 m\Omega^2}{4\omega_0} \qquad h_{SQL} = \sqrt{\frac{4\hbar}{m\Omega^2 L^2}}$$

Simple Michelson, P = 10 W



Simple Michelson, P = 1 MW



"Easy" ways of reducing quantum noise

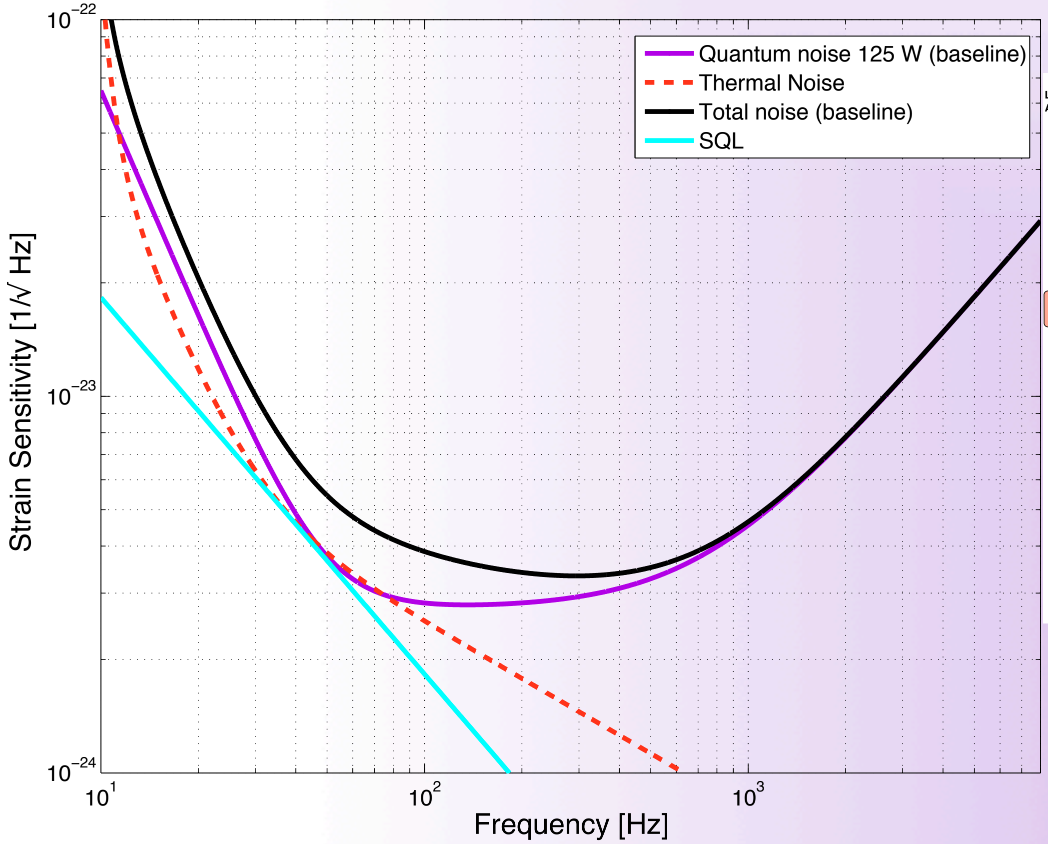
$$h_{Quantum} = \sqrt{\frac{1}{2}}\sqrt{\frac{4\hbar}{m\Omega^2 L^2}}\sqrt{\left(\mathrm{K} + \frac{1}{\mathrm{K}}\right)}, \qquad \mathrm{K} = \frac{4P\omega_0}{c^2 m\Omega^2}$$

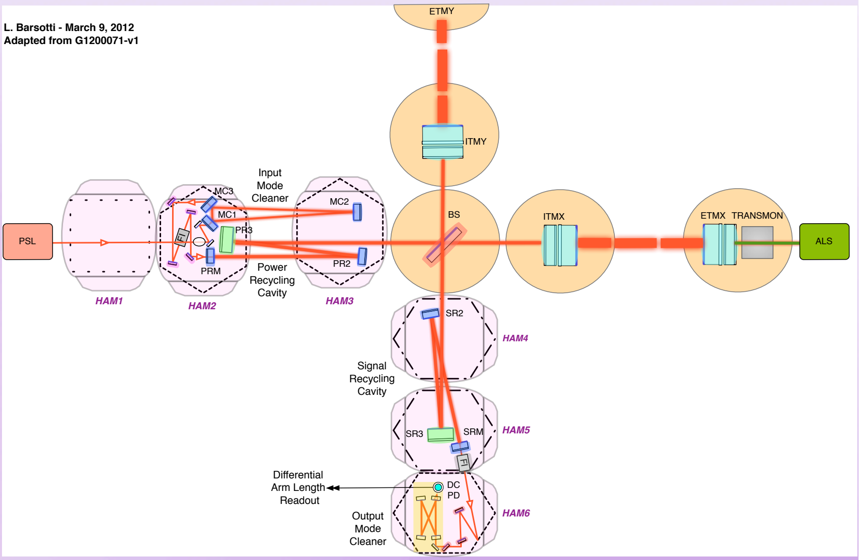
- ✧ Just make your interferometer longer
- ✧ More power to improve shot noise + heavier test masses to compensate for radiation pressure noise

$$h_{Quantum} \sim \sqrt{\left(\frac{4P\omega_0}{c^2 m^2\Omega^2} + \frac{c^2\Omega^2}{4P\omega_0}\right)}$$

More Clever: Quantum Noise in aLIGO

$$h_{Quantum} = \sqrt{\frac{1}{2}}\sqrt{\frac{8\hbar}{m\Omega^2 L^2}}\sqrt{\left(K_{SR} + \frac{1}{K_{SR}}\right)}, \qquad K_{SR} \sim \frac{8P_{Arm}\omega_0}{c^2 m\Omega^2}\frac{G_{sig}}{(1+\Omega^2/\gamma_{src}^2)}$$




L. Barsotti - March 9, 2012
Adapted from G1200071-v1

- ✧Arm cavities, power and signal recycling cavity
- ✧Up to ~800 kW of light stored in the arms

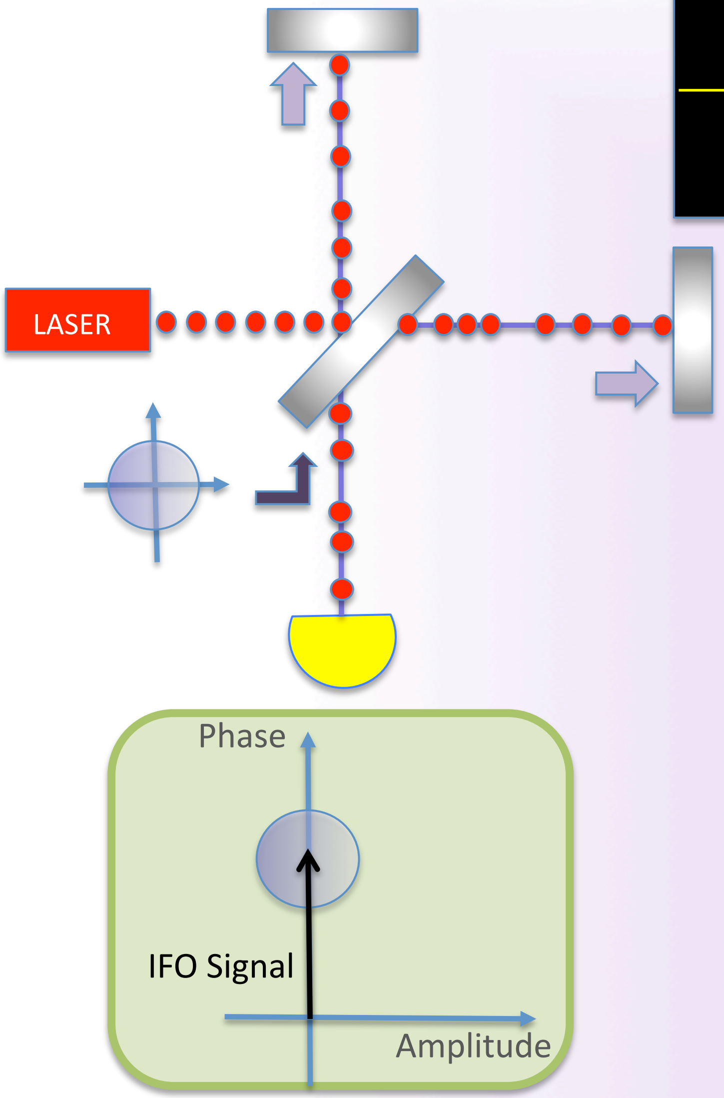
How we go beyond aLIGO

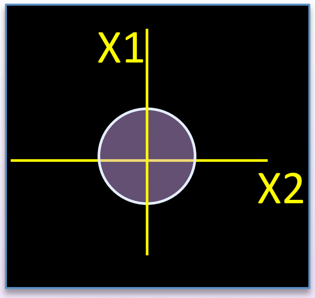
- ✧Again…make your interferometer longer!
- ✧More power + heavier test masses
  - ✧Already ~1MW in the arm cavities, need to compensate for thermal effects and instabilities
- ✧(Even) more complex optical configuration which shapes the interferometer optical response

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)

- ✧Injection of squeezed states of vacuum

Quantum Noise and Vacuum





- Quantization of the electro-magnetic field
- When average amplitude is zero, the variance remains
- Heisenberg uncertainty principle:

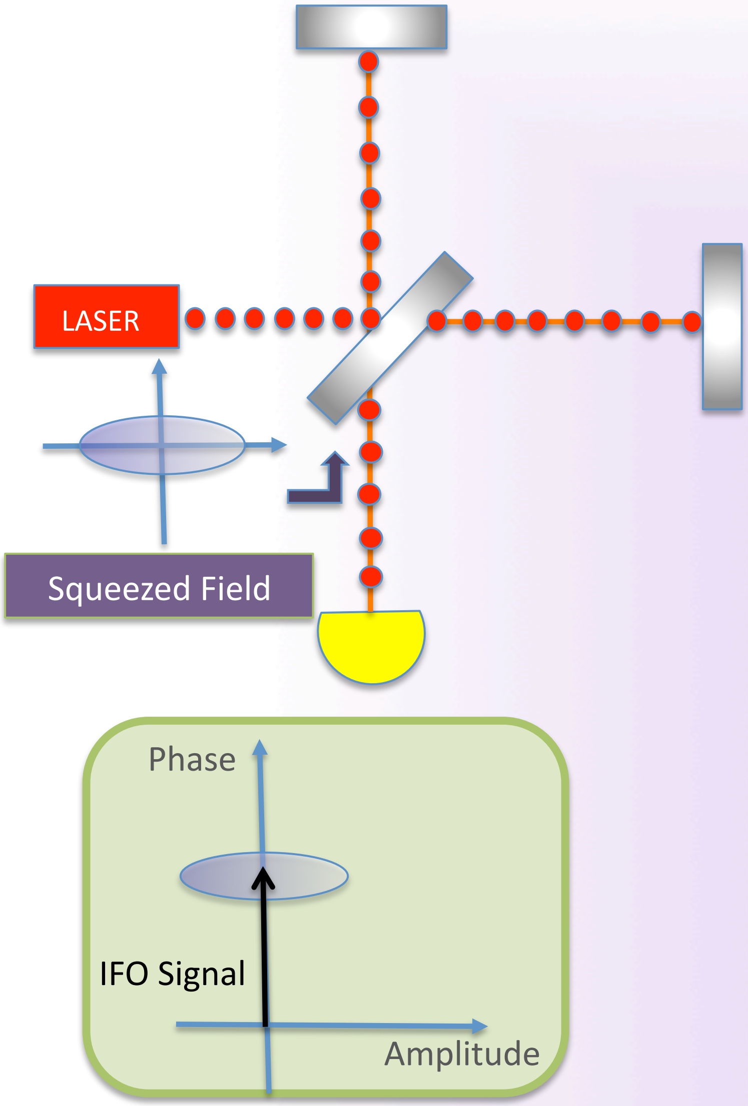
$$\Delta X_1 \, \Delta X_2 \geq 1$$

- Vacuum fluctuations are everywhere that classically there is no field….
- …like at the output port of your interferometer!

- 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



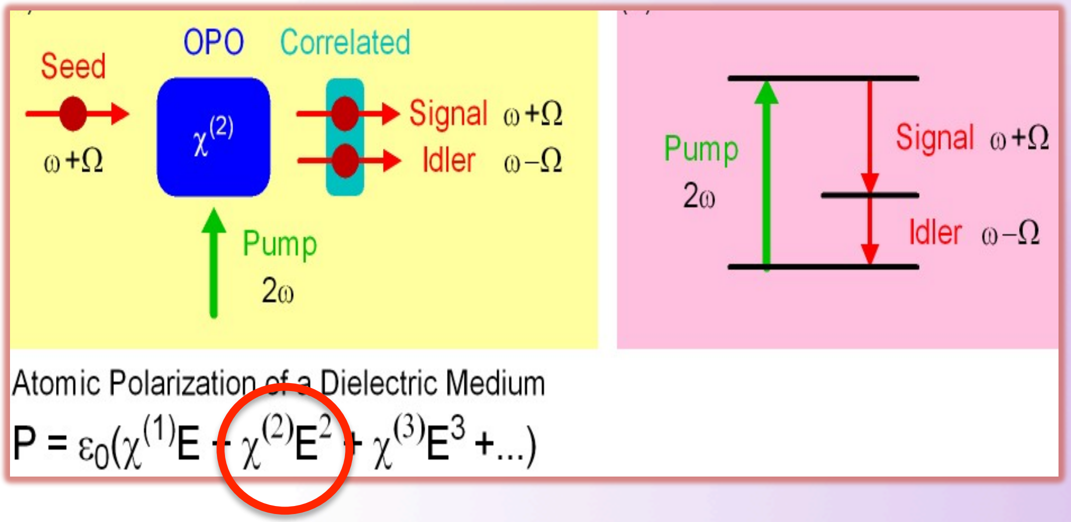
- Reduce quantum noise by injecting squeezed vacuum: less uncertainty in one of the two quadratures
- Heisenberg uncertainty principle: if the noise gets smaller in one quadrature, it gets bigger in the other one
- One can choose the relative orientation between the squeezed vacuum and the interferometer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

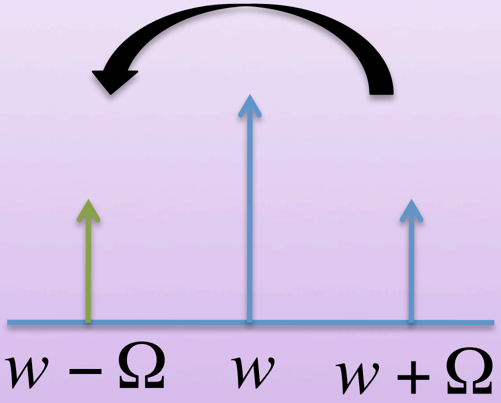
…. in theory

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



Atomic Polarization of a Dielectric Medium

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



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

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

The OPO makes a “copy” of the quantum sideband, and it correlates the sidebands

How to make squeezed fields..

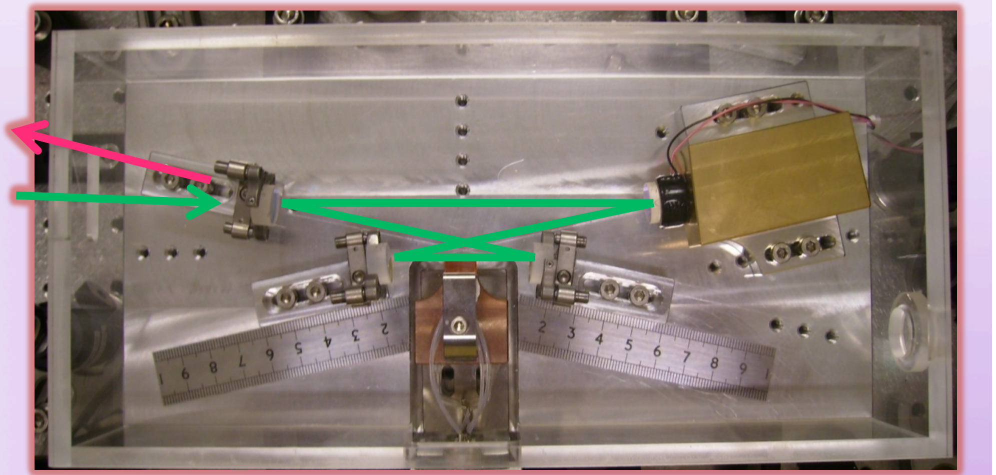
.... in practice

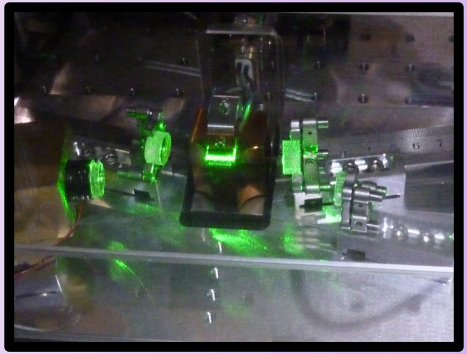
World-wide effort in the last 10 years to make squeezing in the audio-frequency band

- ✧ Lasers, mirrors, control loops,..

Courtesy of Alexander Khalaidovski (AEI)

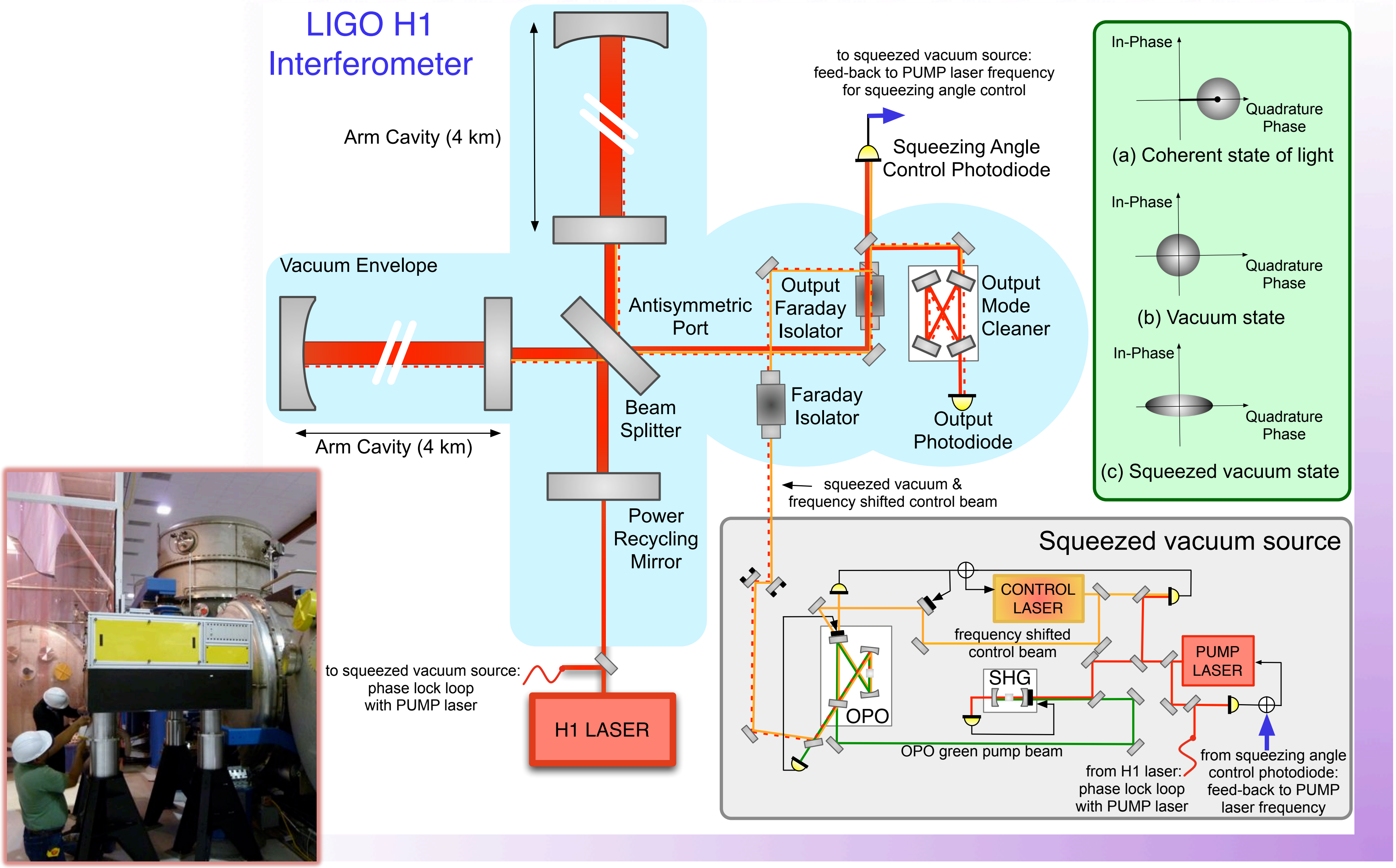
The Squeezer of the GEO600 detector





The Optical Parametric Oscillator
of the LIGO squeezer
(ANU design)

How to inject squeezed fields



LIGO H1
Interferometer

Arm Cavity (4 km)

Vacuum Envelope

Arm Cavity (4 km)

Antisymmetric Port

Beam Splitter

Power Recycling Mirror

to squeezed vacuum source:
phase lock loop
with PUMP laser

H1 LASER

to squeezed vacuum source:
feed-back to PUMP laser frequency
for squeezing angle control

Squeezing Angle
Control Photodiode

Output Faraday Isolator

Output Mode Cleaner

Faraday Isolator

Output Photodiode

squeezed vacuum &
frequency shifted control beam

In-Phase
Quadrature Phase
(a) Coherent state of light

In-Phase
Quadrature Phase
(b) Vacuum state

In-Phase
Quadrature Phase
(c) Squeezed vacuum state

Squeezed vacuum source

CONTROL LASER

frequency shifted
control beam

PUMP LASER

SHG

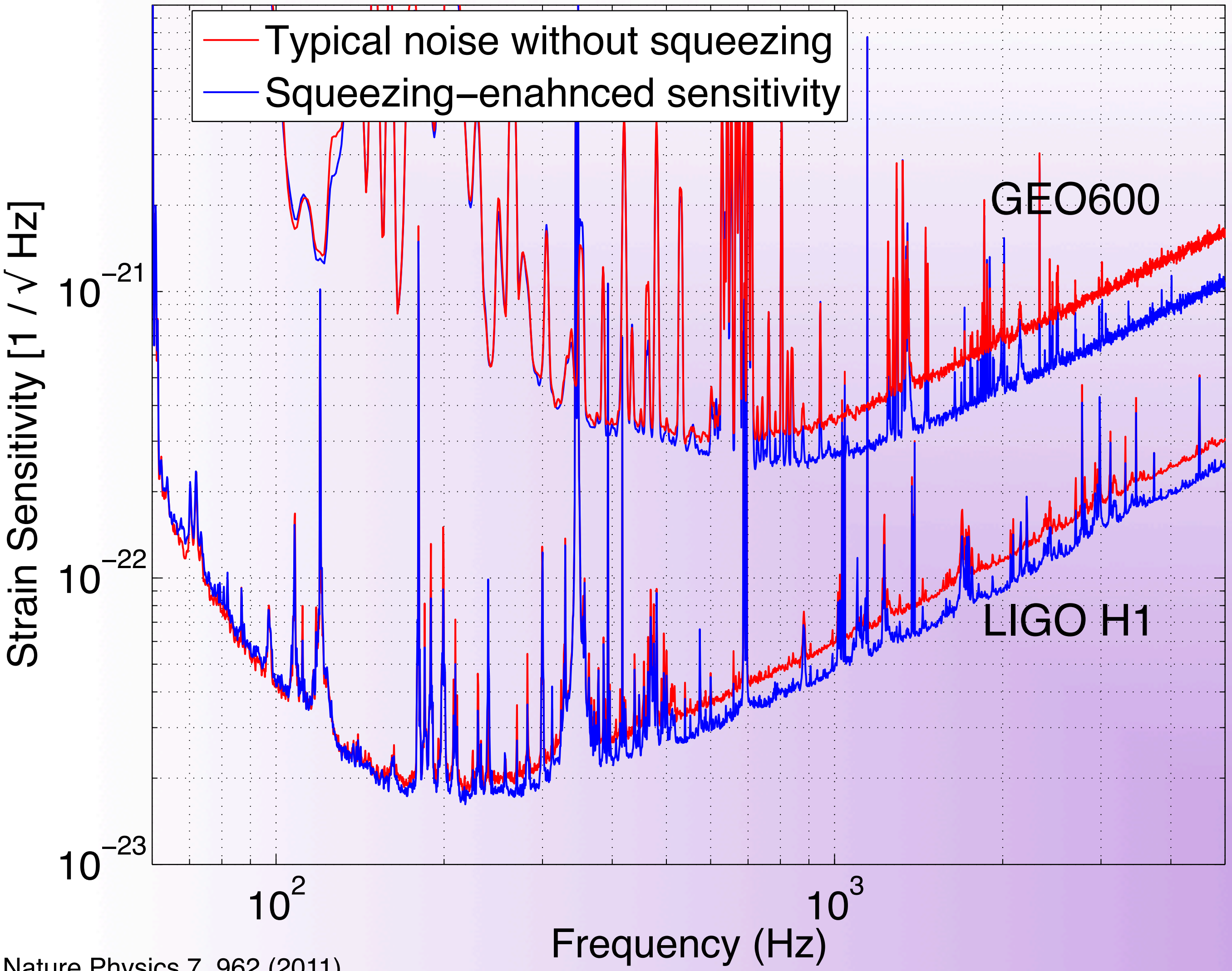
OPO

OPO green pump beam

from H1 laser:
phase lock loop
with PUMP laser

from squeezing angle
control photodiode:
feed-back to PUMP
laser frequency

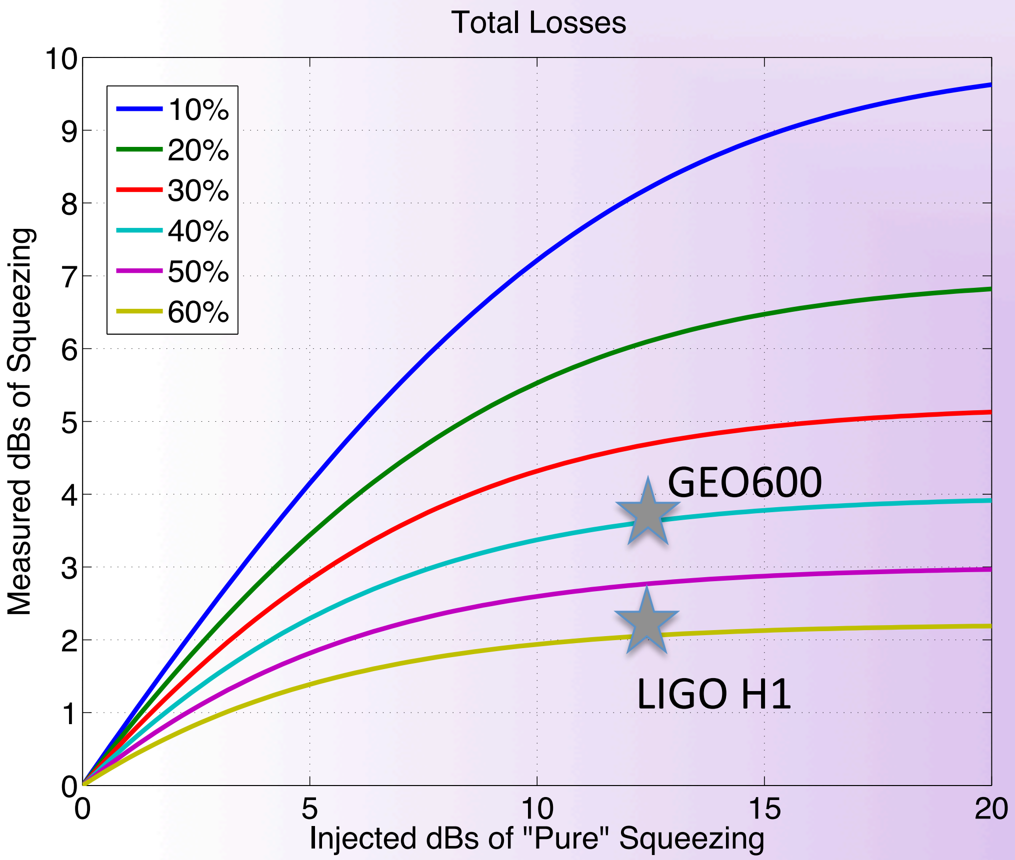
Squeezing in GEO600 and LIGO H1

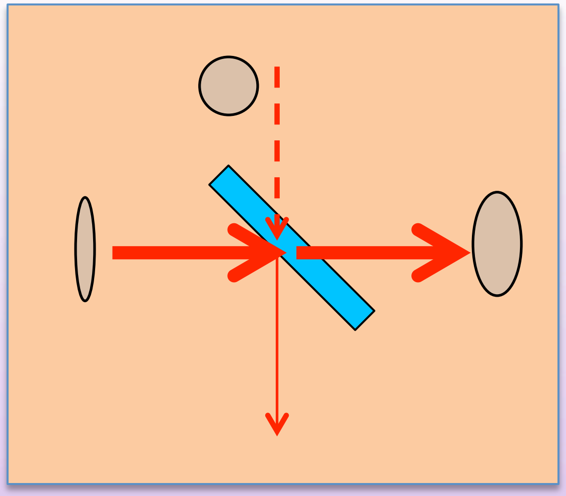


Abadie et al., Nature Physics 7, 962 (2011)
GEO data are courtesy of H. Grote

Lessons Learned (I)

- ✧ Losses are very unforgiving
  - ✧ GEO aimed for 6 dB → got 3.5 dB
  - ✧ LIGO aimed for 3 dB → got 2.15 dB

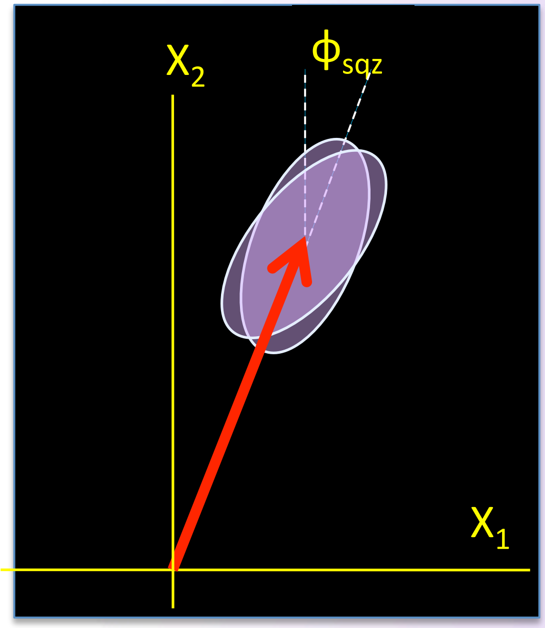


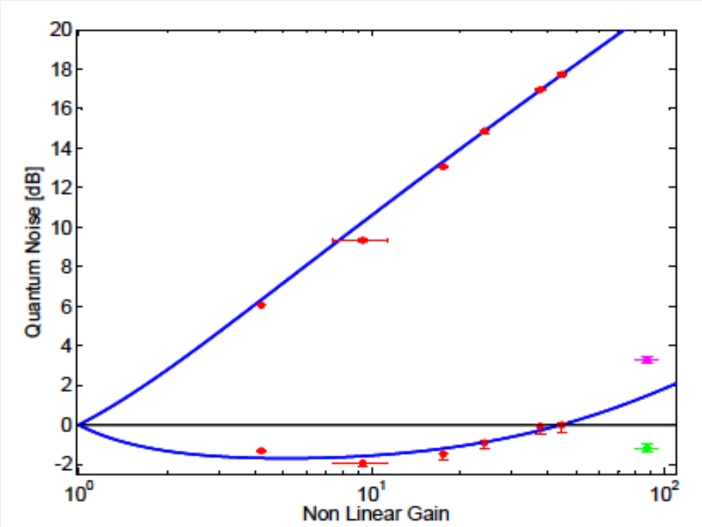


- ✧ Mode matching
- ✧ Faradays
- ✧ OMC transmission
- ✧ …

Lessons Learned (II)

- ✧ Phase noise between squeezed field and interferometer was dependent on interferometer alignment:
  - ✧ Static misalignments will cause a change in the demodulation phase needed to detect the maximum squeezing
  - ✧ Beam jitter will add phase noise when beating against a static misalignment.





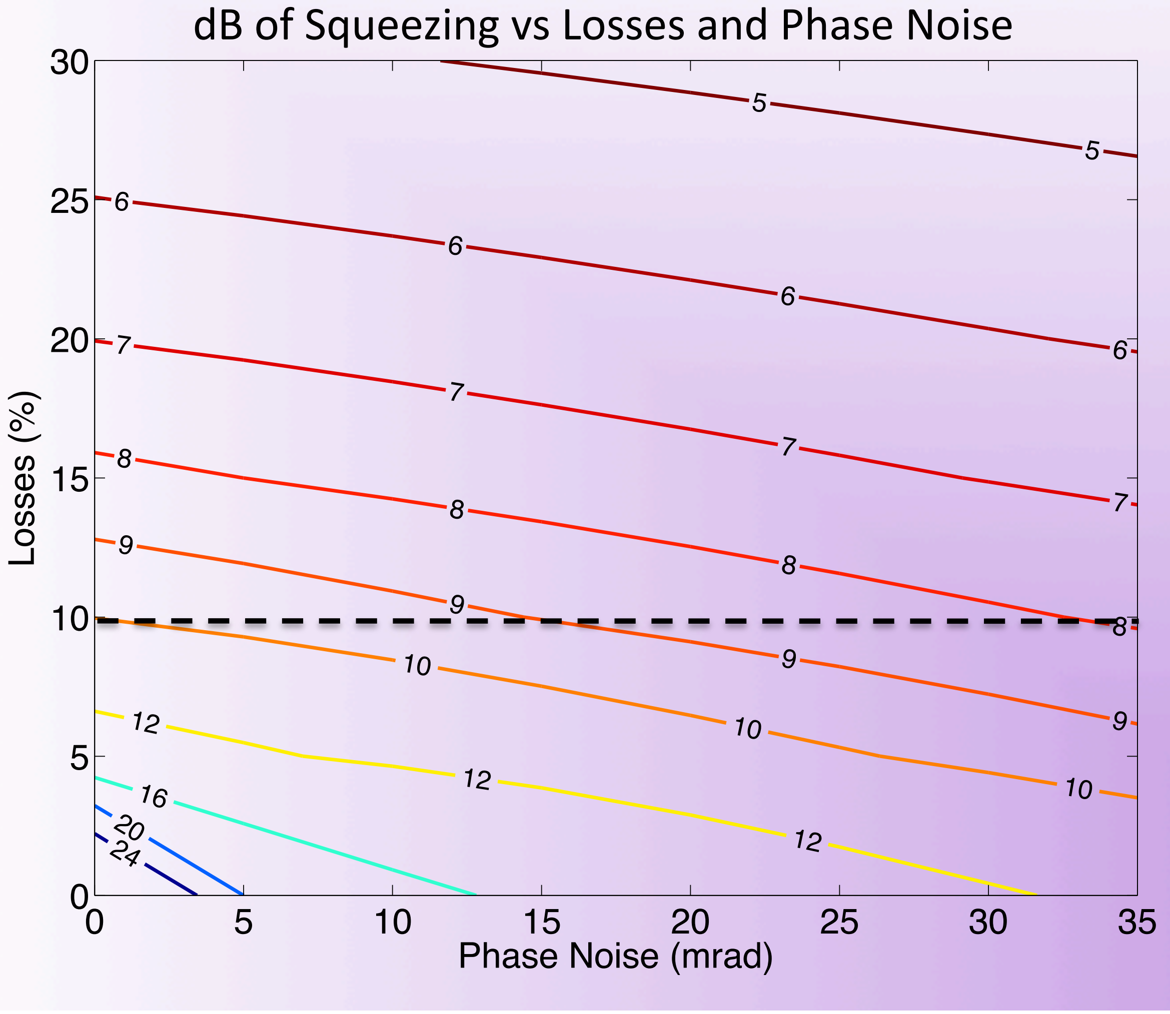
OPO squeezing level

➔ at best ~40 mrad RMS,
only ~ 25mrad from squeezer source

Fluctuations of the quantum quadrature in squeezed light application of a gravitational wave detector, S. Dwyer et al (in preparation)

To keep in mind for the future

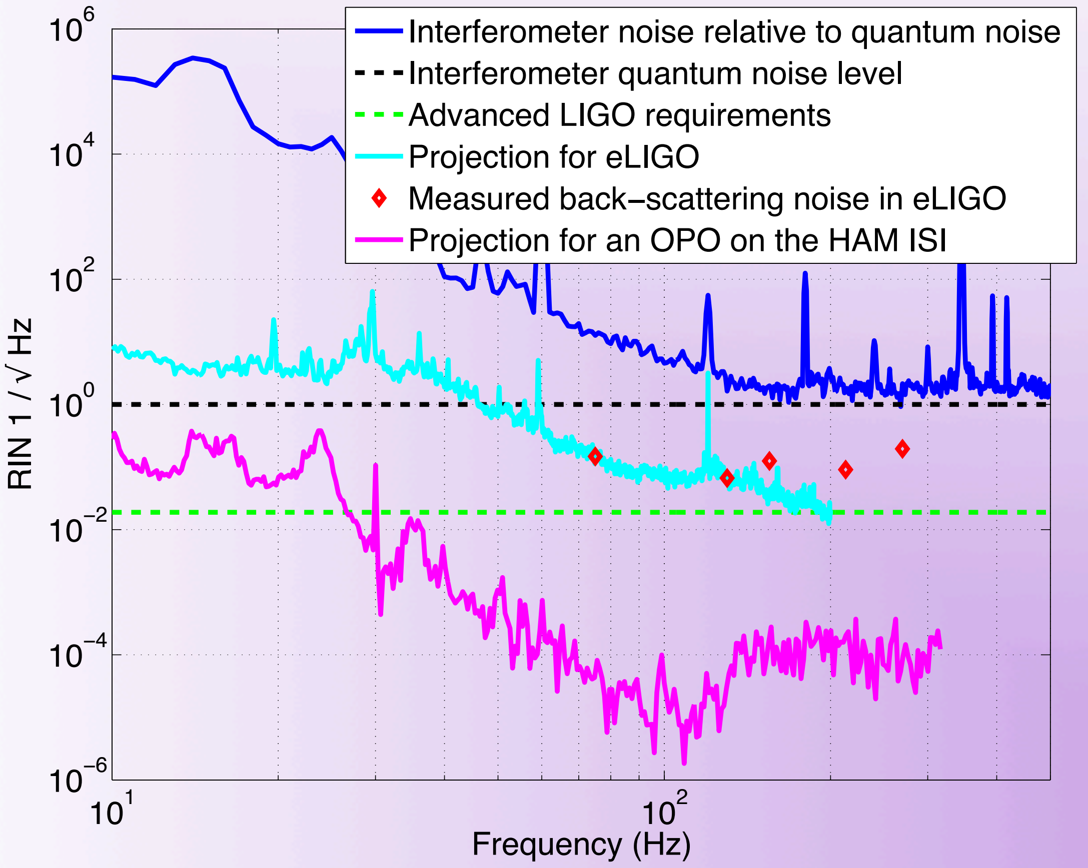
With 10% total losses, you can't afford any phase noise at all, if you want to measure 10dB of squeezing



Lessons Learned (III)

✧ Need better isolation from back scattering

(it was ok for LIGO H1, it won't be enough for aLIGO)

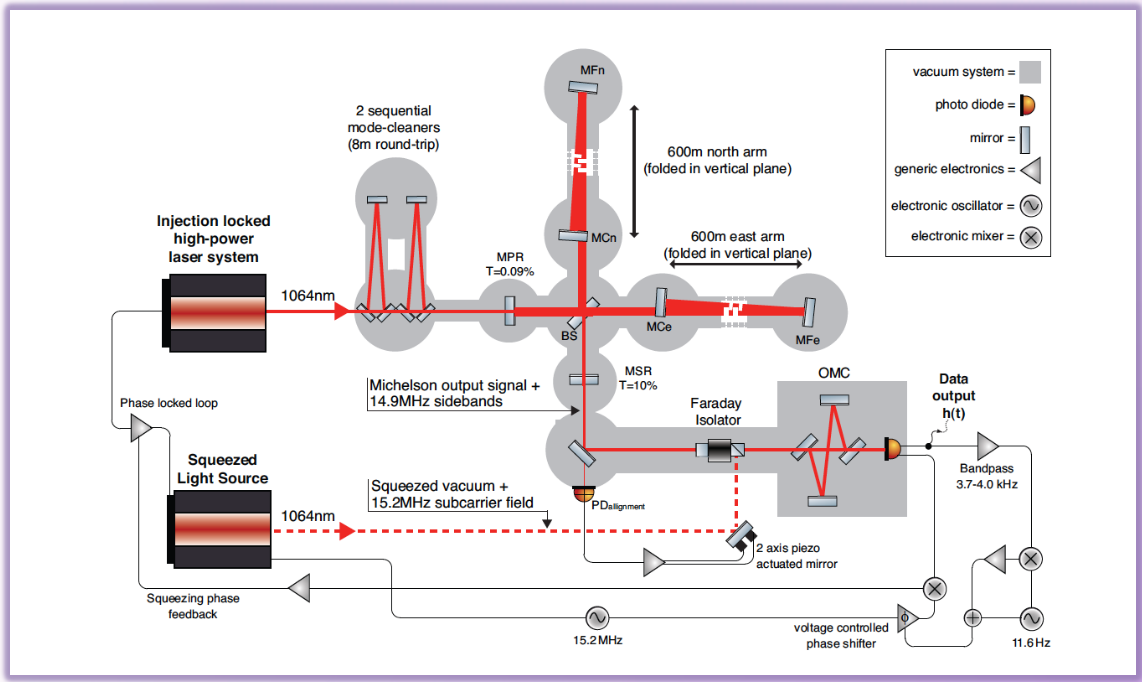


Impact of backscattered-light in a squeezing-enhanced interferometric gravitational-wave detector, S. Chua et al. (in preparation)

Lessons Learned (VI)

✧ From GEO600: Squeezing angle control signals from 1% pick-off are bad

→ New “a-la-Hartmut” strategy (use transmission signals from the OMC)

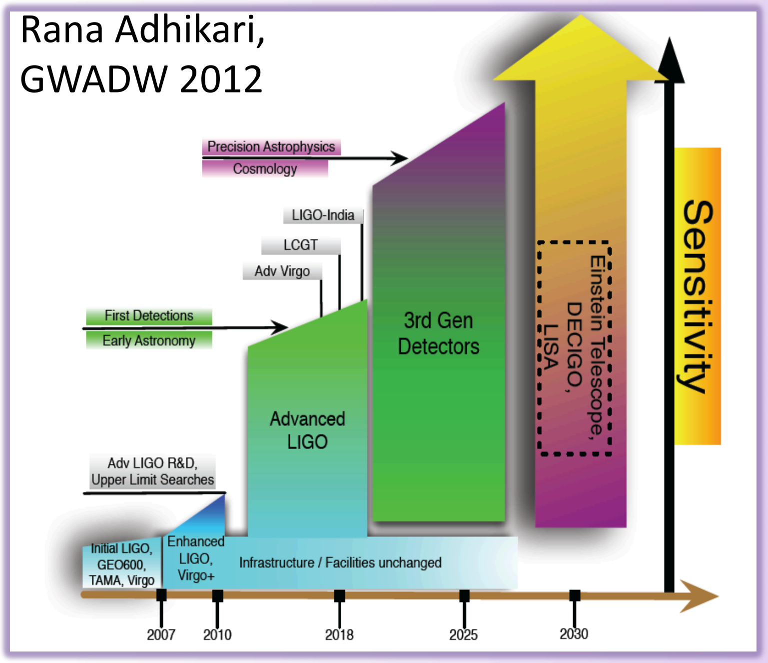


First Long-Term Application of Squeezed States of Light in a Gravitational-Wave Observatory

H. Grote,[1,*] K. Danzmann,[1] K.L. Dooley,[1] R. Schnabel,[1] J. Slutsky,[1] and H. Vahlbruch[1]

How about squeezing in aLIGO (and beyond)?

- ✧ Do we want it?
- ✧ Do we know how to make it? How do we incorporate all the "lessons learned" in the next generation of squeezers?



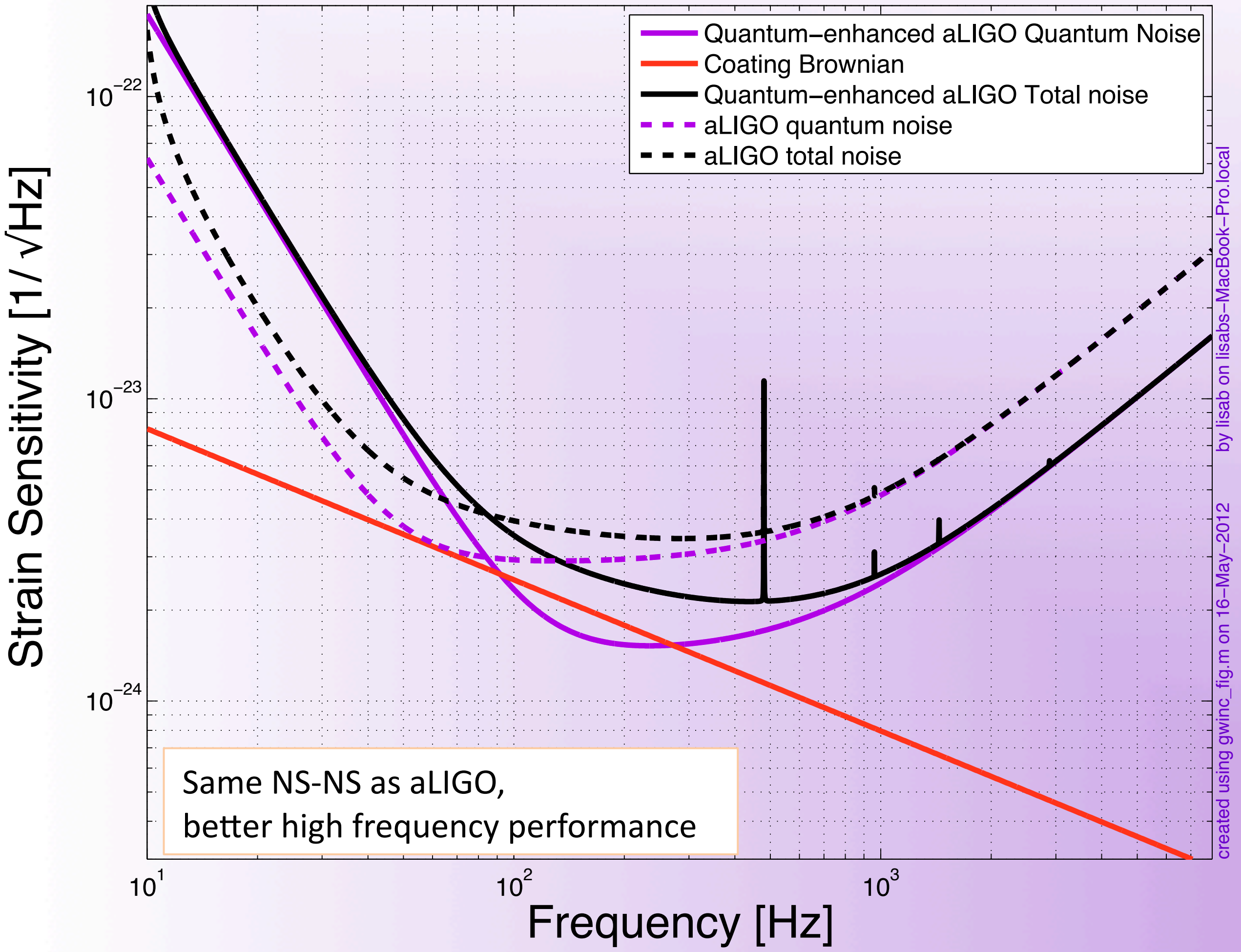
Rana Adhikari, GWADW 2012

LIGO technical note T1200008-v3
Comparison of Quantum Noise in 3G Interferometer Configurations,
Haixing Miao et al.

➔ 10 dB of squeezing needed for all future configurations..

How squeezing in aLIGO would look

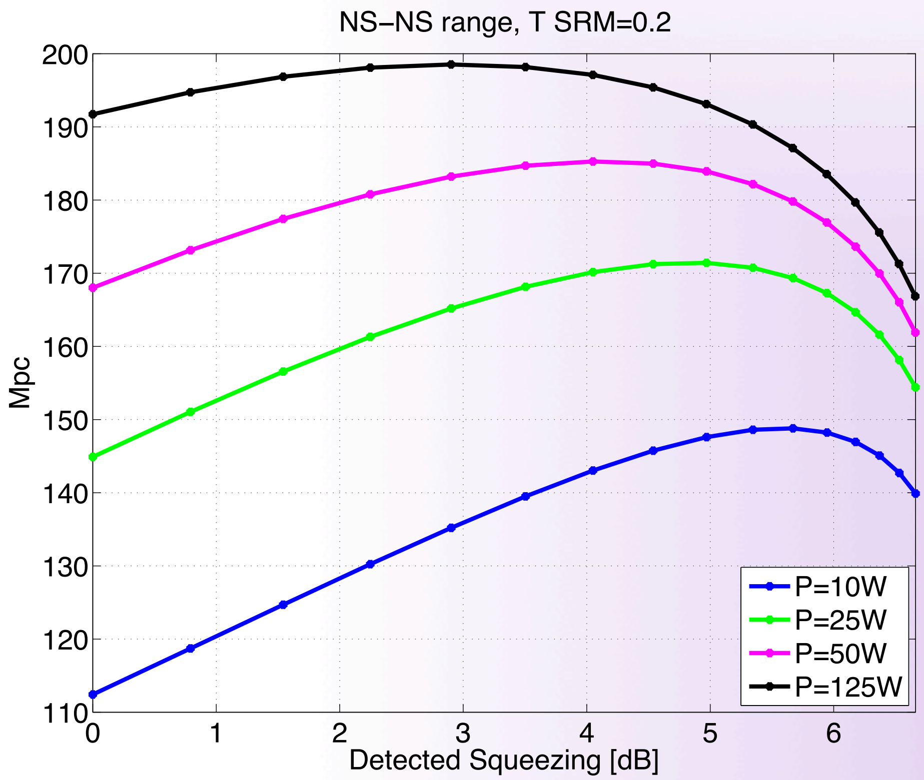
Projections for a “Quantum-Enhanced Advanced LIGO”

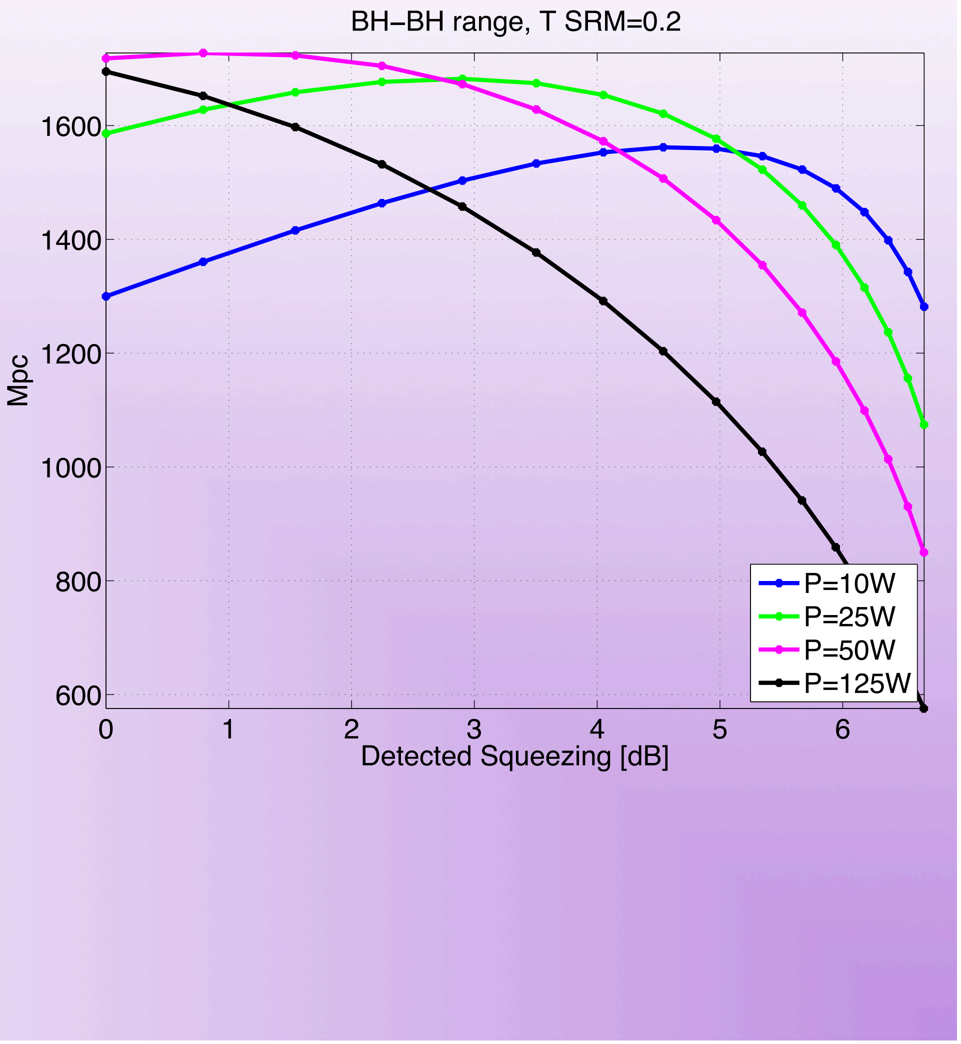


Same NS-NS as aLIGO,
better high frequency performance

created using gwinc_fig.m on 16−May−2012 by lisab on lisabs−MacBook−Pro.local

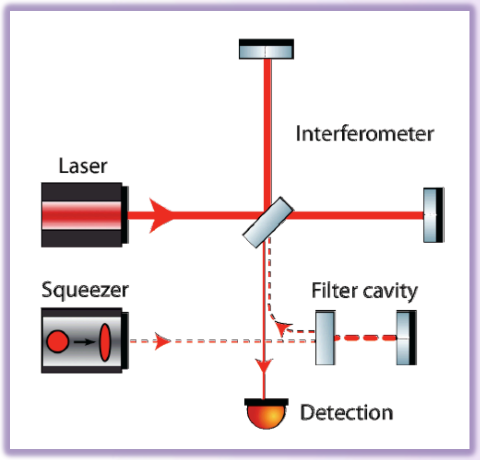
aLIGO + Squeezing: NS-NS and BH-BH Ranges





What we really want:
Frequency Dependent Squeezing

High finesse detuned cavity which rotates the squeezing angle as function of frequency




PHYSICAL REVIEW D, VOLUME 65, 022002

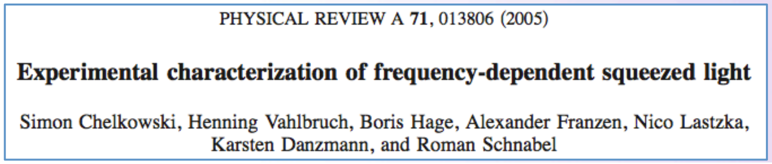
Conversion of conventional gravitational-wave interferometers into quantum nondemolition interferometers by modifying their input and/or output optics

H. J. Kimble,[1] Yuri Levin,[2,*] Andrey B. Matsko,[3] Kip S. Thorne,[2] and Sergey P. Vyatchanin[4]


PHYSICAL REVIEW D **68**, 042001 (2003)

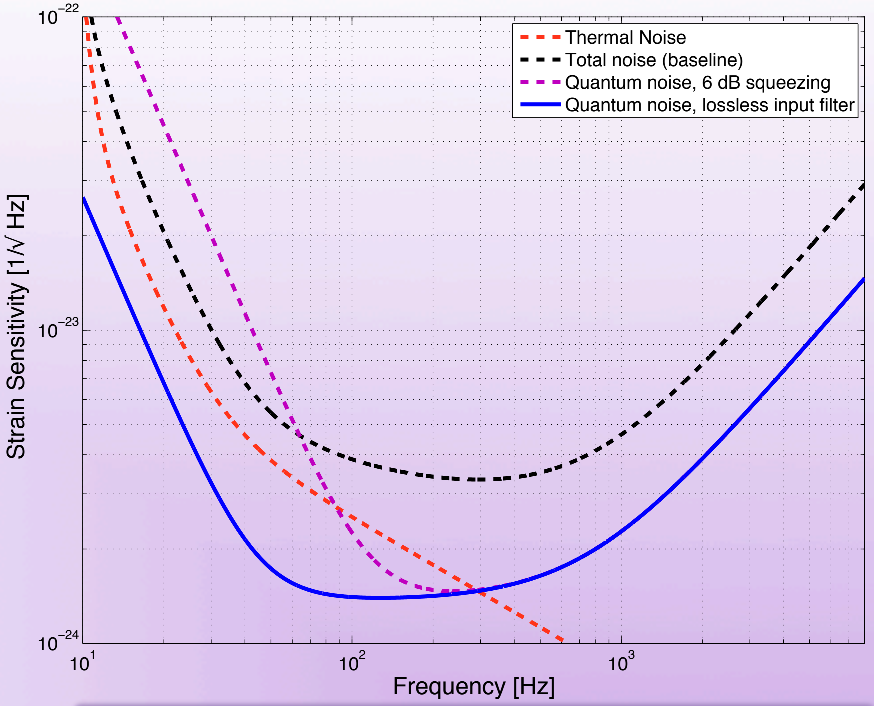
Squeezed-input, optical-spring, signal-recycled gravitational-wave detectors

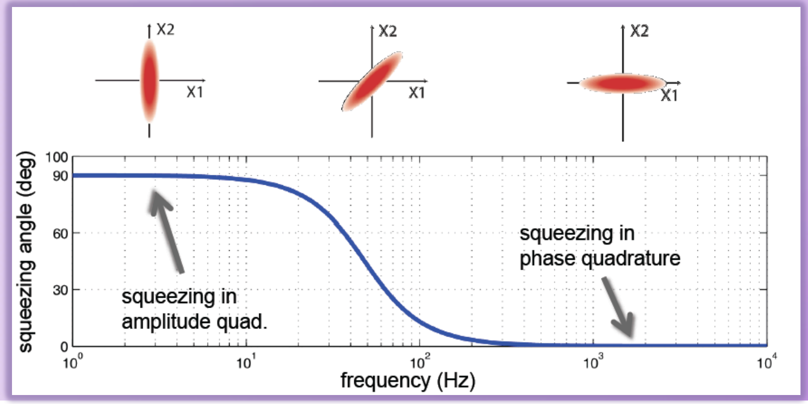
Jan Harms,[1] Yanbei Chen,[2] Simon Chelkowski,[1] Alexander Franzen,[1] Henning Vahlbruch,[1] Karsten Danzmann,[1] and Roman Schnabel[1]


PHYSICAL REVIEW A **71**, 013806 (2005)

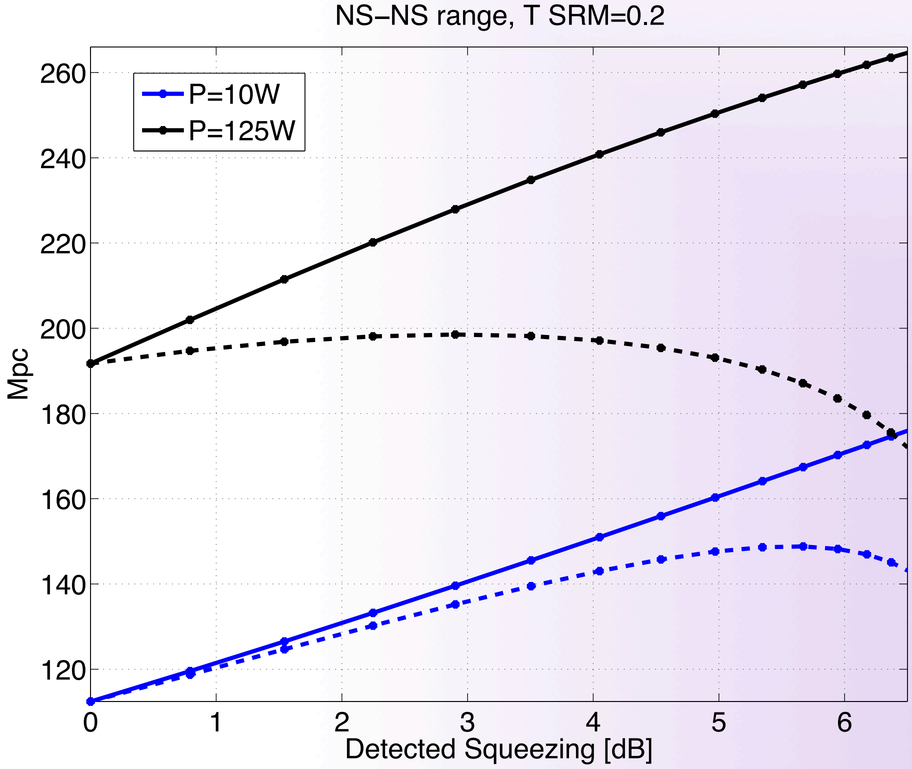
Experimental characterization of frequency-dependent squeezed light

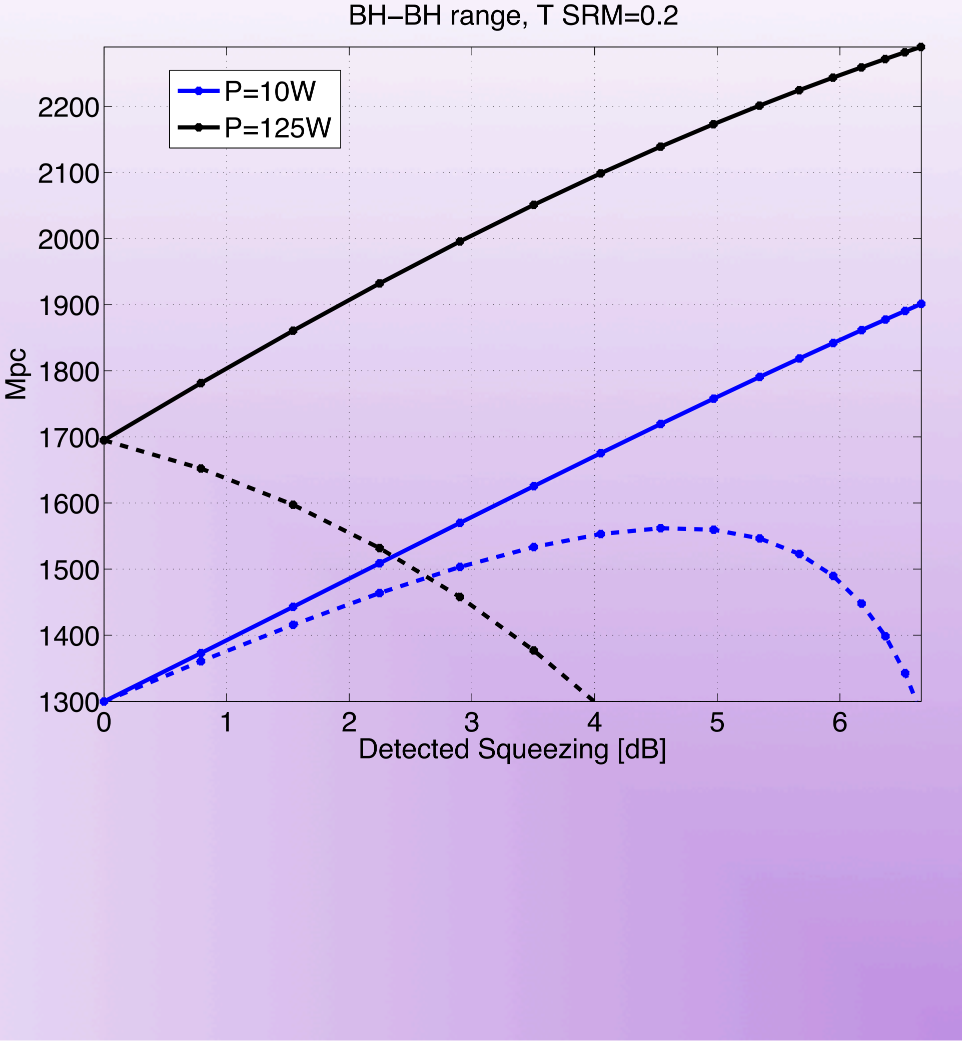
Simon Chelkowski, Henning Vahlbruch, Boris Hage, Alexander Franzen, Nico Lastzka, Karsten Danzmann, and Roman Schnabel





aLIGO + Frequency Dependent Squeezing: NS-NS and BH-BH Ranges



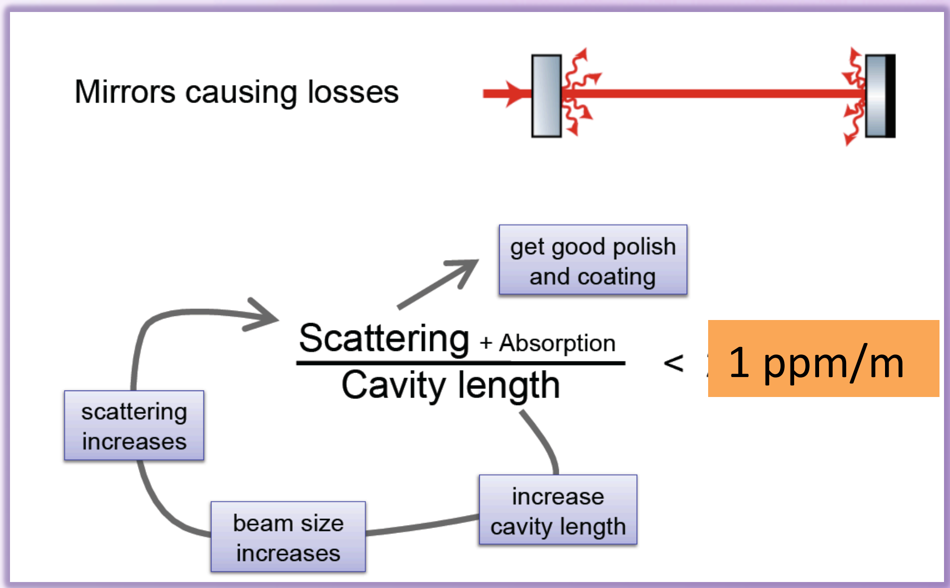


Nothing comes cheap: losses again..

Losses in a filter cavity deteriorate, if too high, make the filter cavity useless…

$$\text{Total Loss E} = \frac{4\varepsilon}{T} = \frac{\varepsilon}{L}\frac{c}{\gamma_{filter}}, \qquad \gamma_{filter} = \frac{Tc}{4L}$$

✧Per-round-trip loss depends on the beam spot size
(big beam size → higher scatter losses), which depends on L



Mirrors causing losses

$$\frac{\text{Scattering + Absorption}}{\text{Cavity length}} < 1\ \text{ppm/m}$$

get good polish and coating

scattering increases

beam size increases

increase cavity length

Squeezing @ MIT

FILTER CAVITY EXPERIMENT

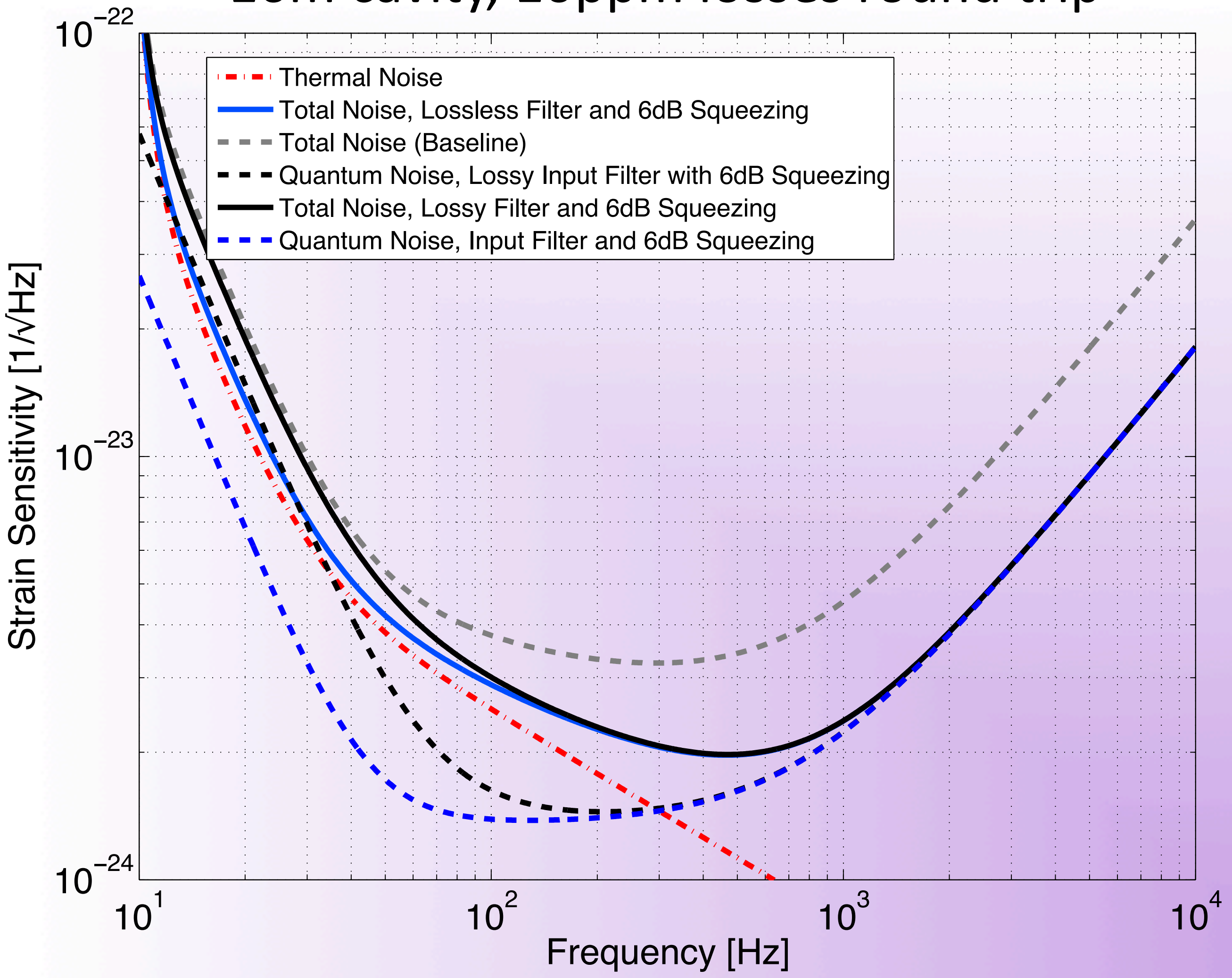
- ✧ Measuring optical losses to determine Advanced LIGO filter cavity design
- ✧ Implementing practical filter cavity control scheme
- ✧ Characterizing technical noises
- ✧ Preparing for demonstration of audio-band frequency dependent squeezing

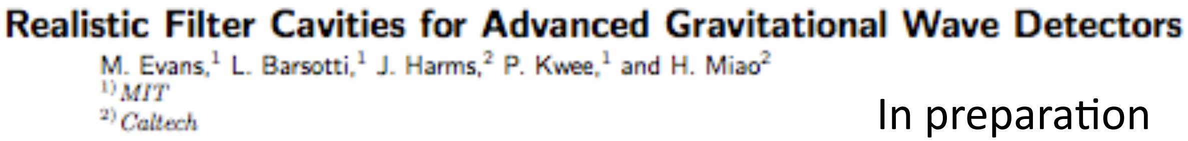
NEW SQUEEZER SOURCE compatible with aLIGO requirements

Tomoki Isogai, John Miller, Eric Oelker, (Patrick Kwee)

For aLIGO, we could afford a “lossy” cavity

16m cavity, 10ppm losses round trip





Realistic Filter Cavities for Advanced Gravitational Wave Detectors

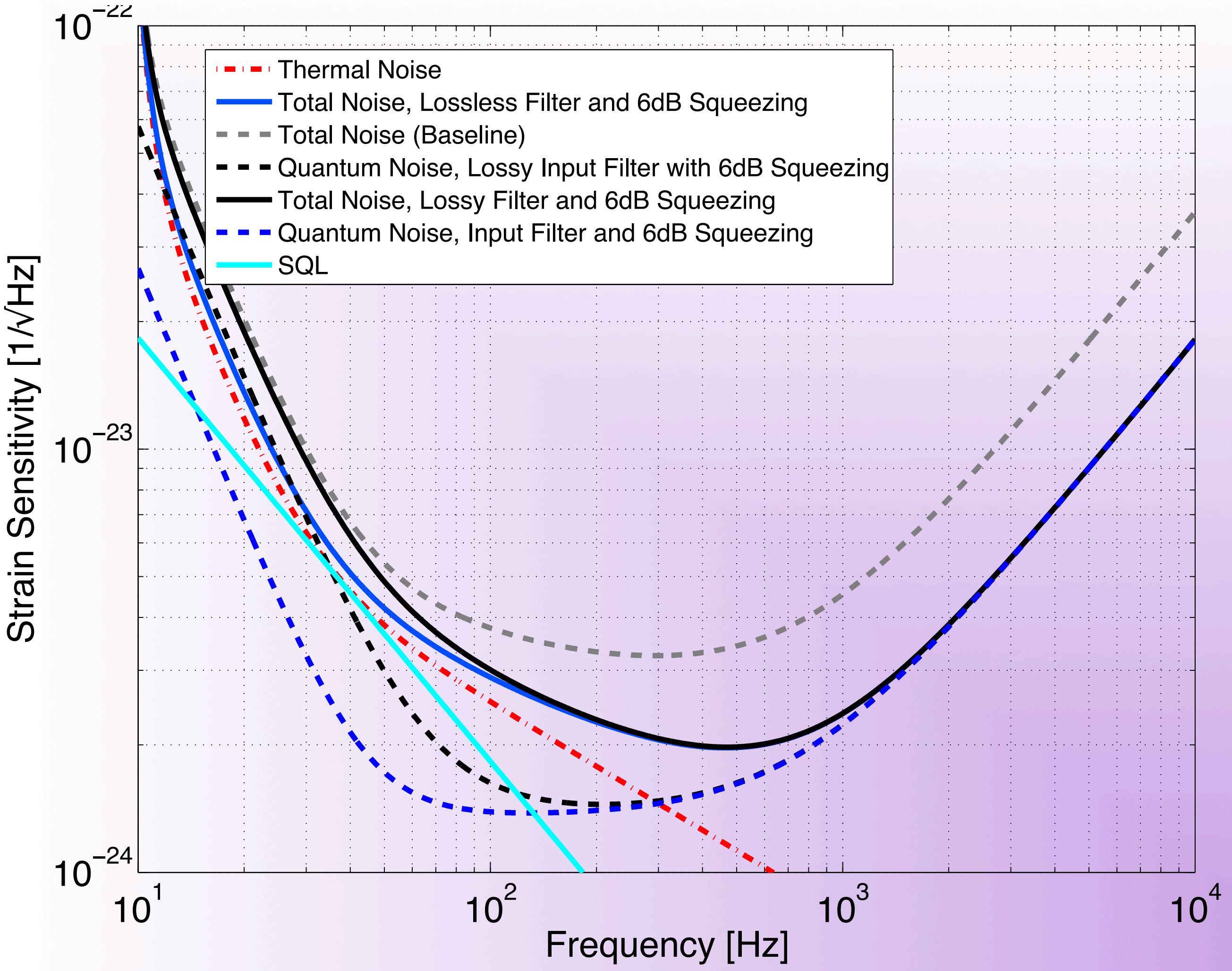
M. Evans,[1] L. Barsotti,[1] J. Harms,[2] P. Kwee,[1] and H. Miao[2]

[1] *MIT*

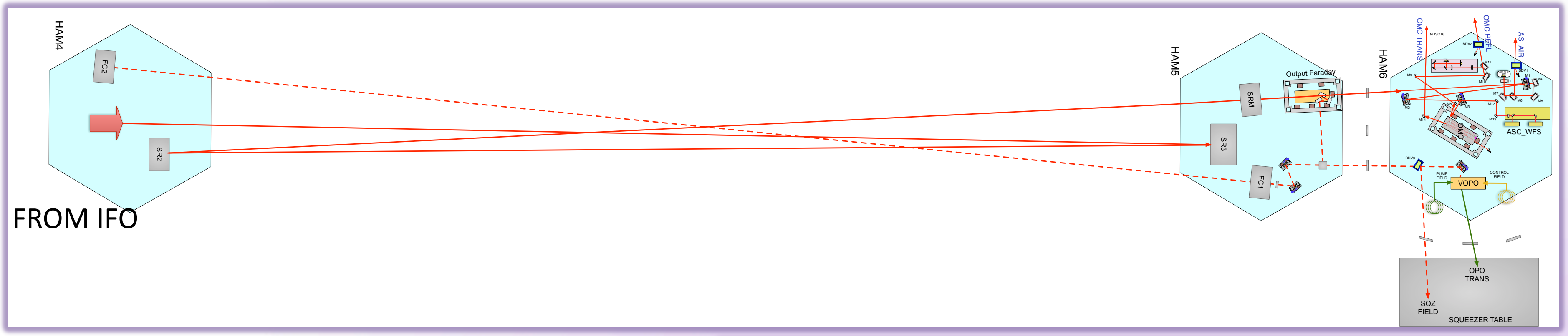
[2] *Caltech*

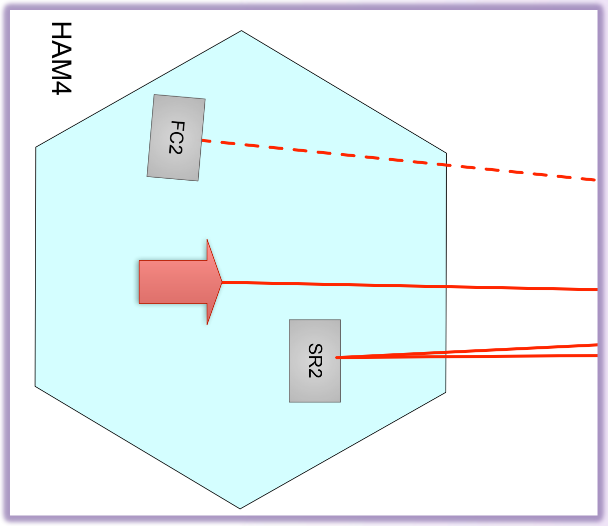
In preparation

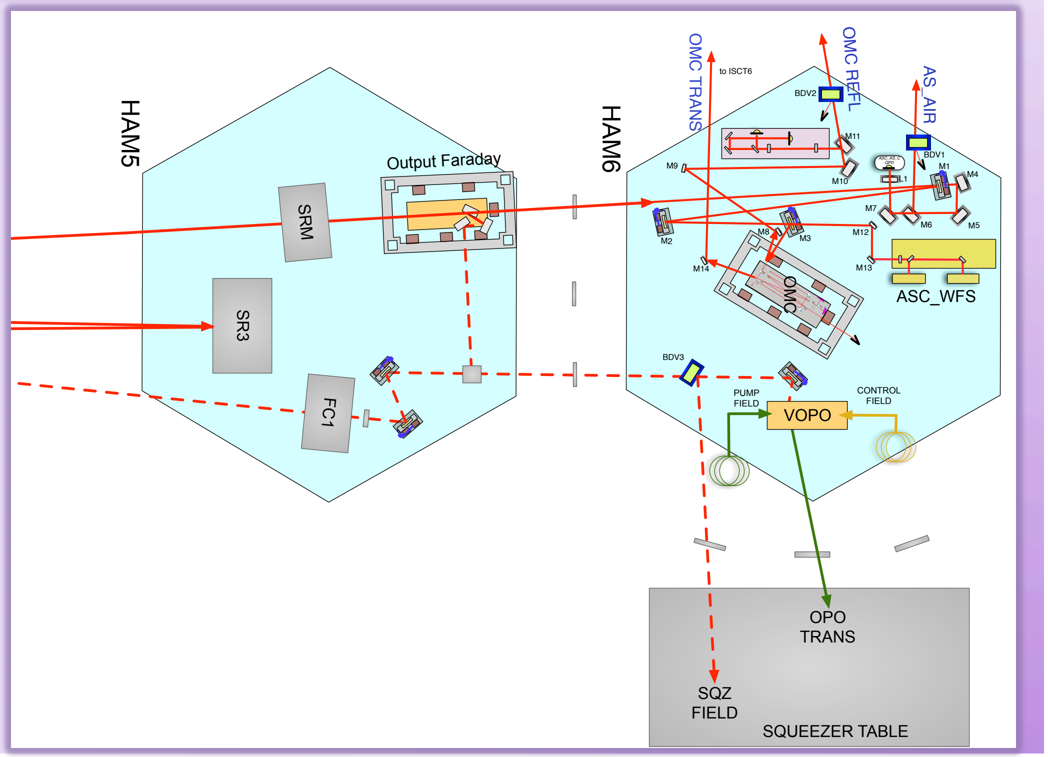
Beyond the “Standard Quantum Limit”



Something like this, maybe….







Just a cartoon!

Not a conceptual design yet!

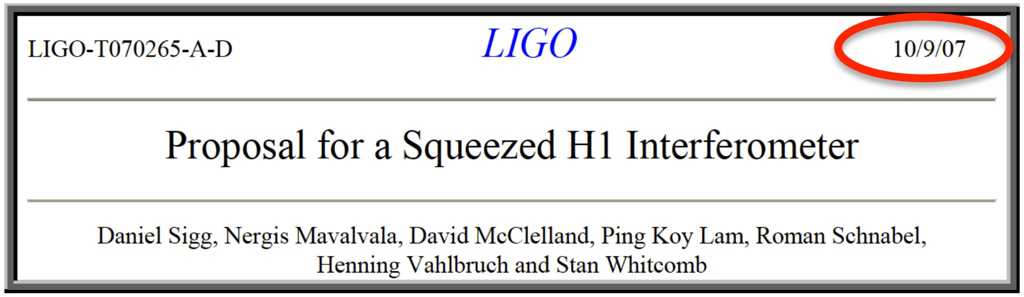
H1 Squeezing Experiment

LHO: Daniel Sigg, Keita Kawabe, Robert Schofield, Cheryl Vorvick, Dick Gustafson (Univ Mitchigan), Max Factourovich (Columbia), Grant Meadors (Univ Mitchigan), the LHO staff

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



LIGO-T070265-A-D

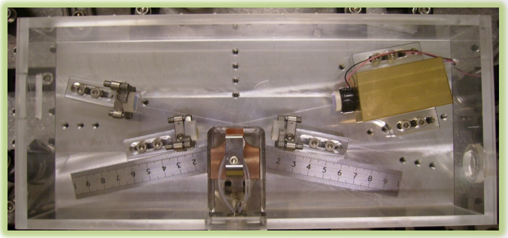
LIGO

10/9/07

Proposal for a Squeezed H1 Interferometer

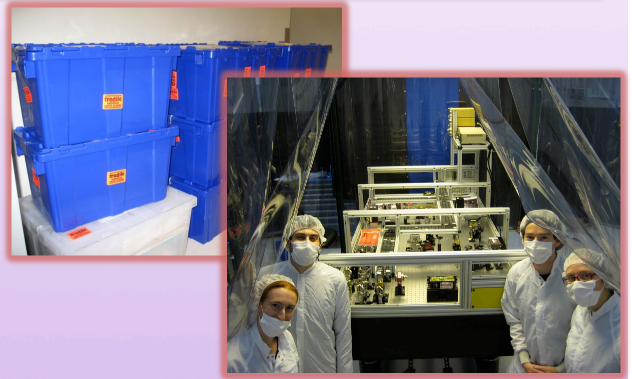
Daniel Sigg, Nergis Mavalvala, David McClelland, Ping Koy Lam, Roman Schnabel,
Henning Vahlbruch and Stan Whitcomb

Bow-tie cavity OPO design at ANU (2008)

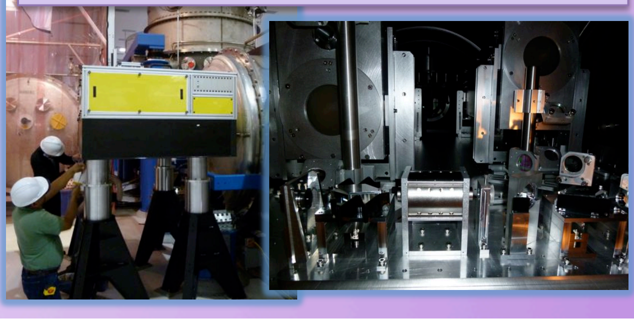


H1 Squeezer assembling at MIT (2009-2010)

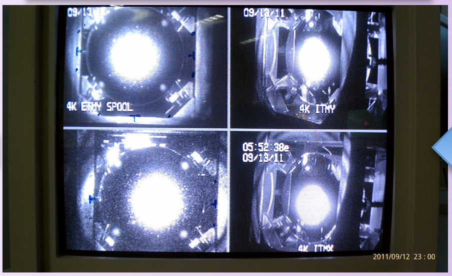
H1 Squeezer parts shipped to LHO (Oct 2010)



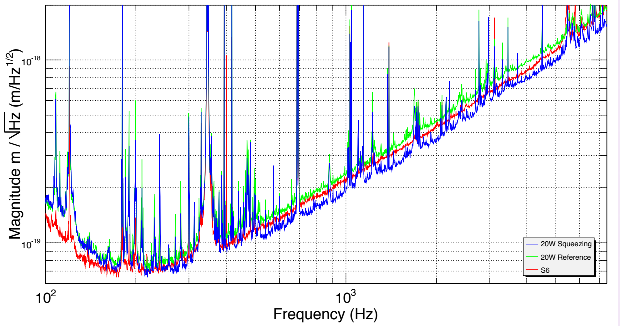
H1 Squeezer Installation (Summer 2011)



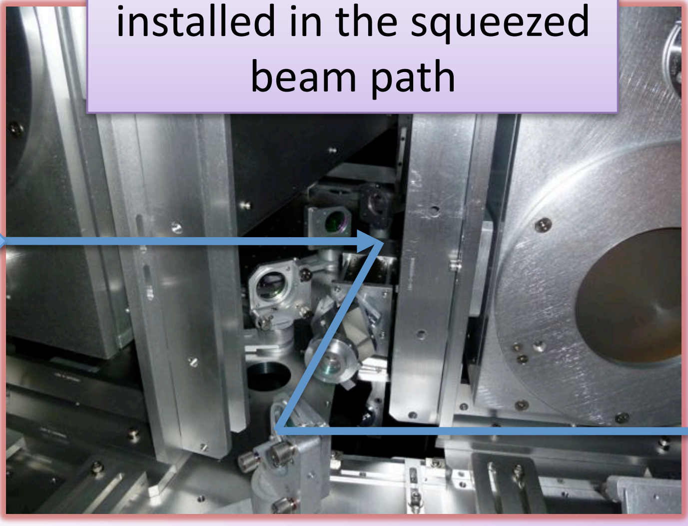
H1 Recovery (Sept 2011)



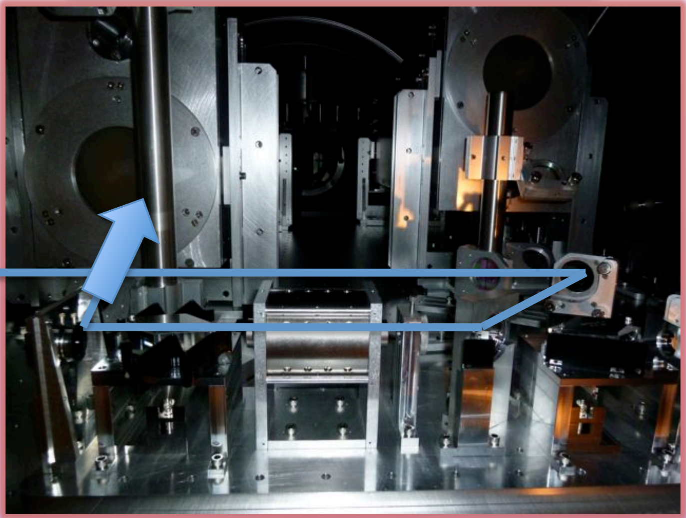
Squeezing in H1 (Oct 3 – Dec 4)



H1 Squeezing Experiment: Squeezer Installation



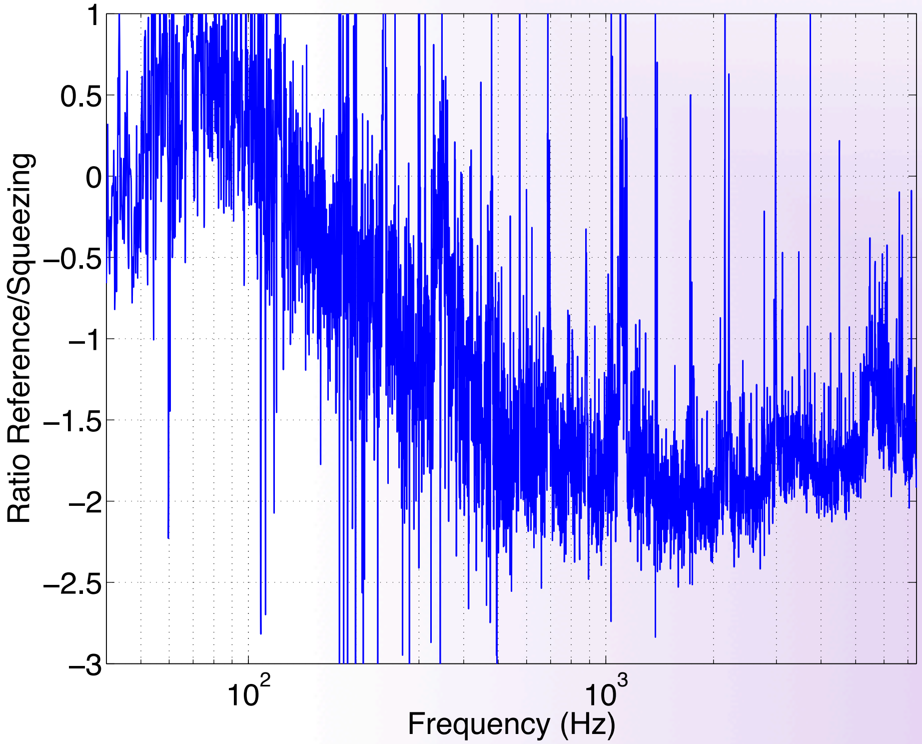
Additional Faraday installed in the squeezed beam path

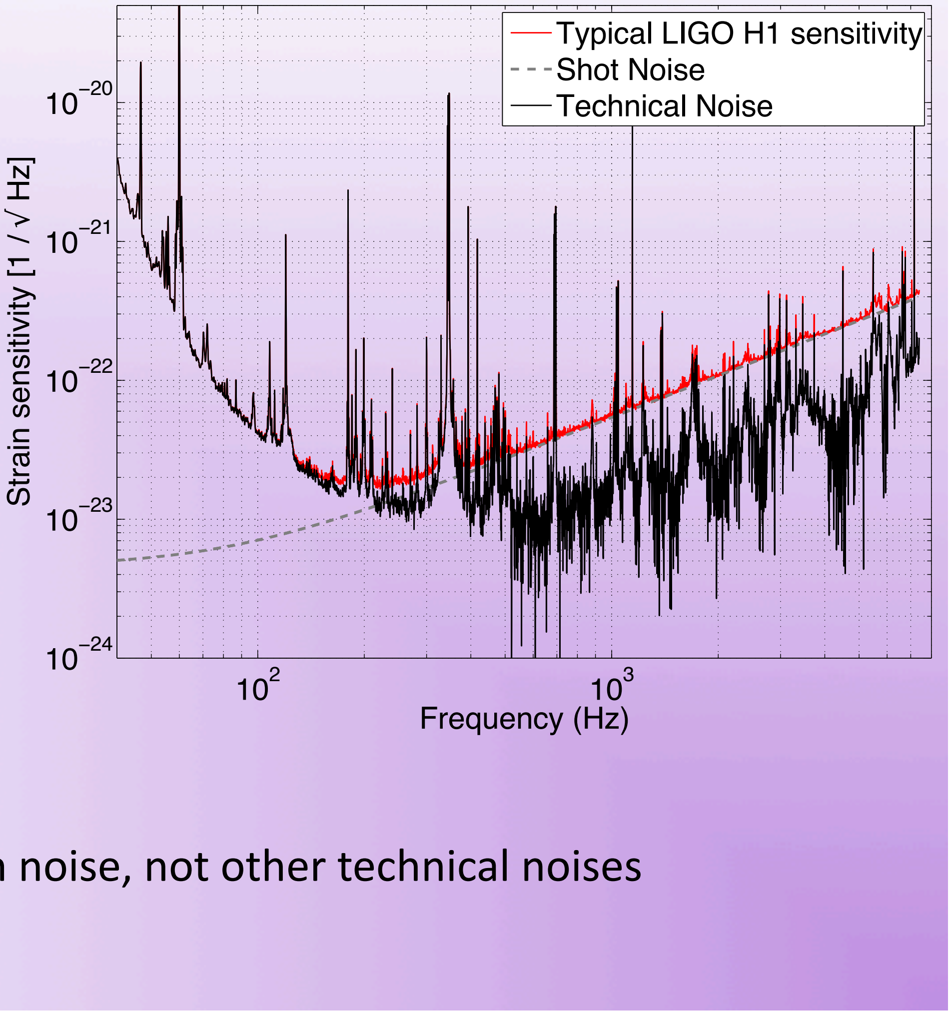


New H1 Output Faraday (first aLIGO unit)

Squeezer table craned to its final location

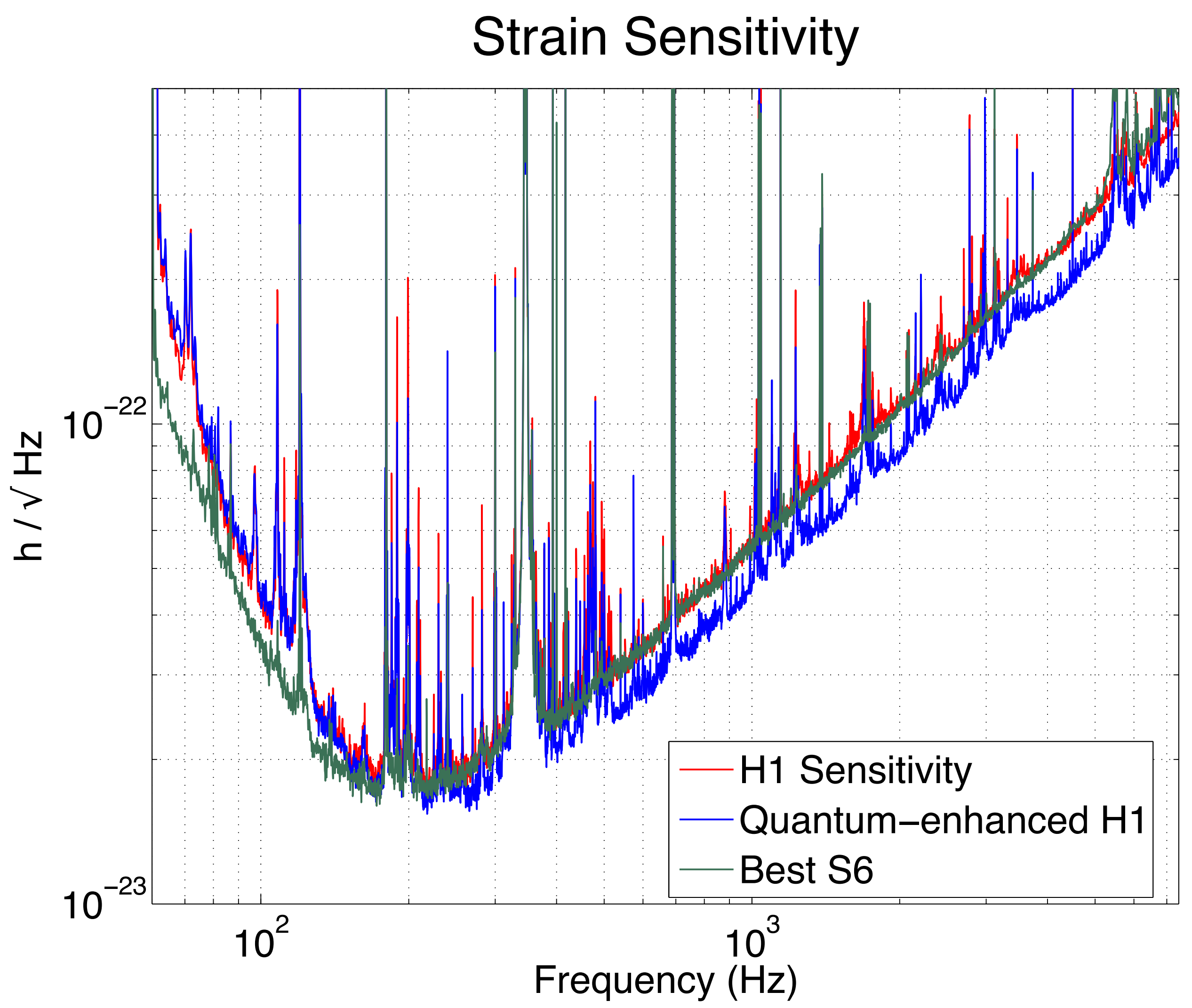
2.15 dB (28%) improvement over quantum noise



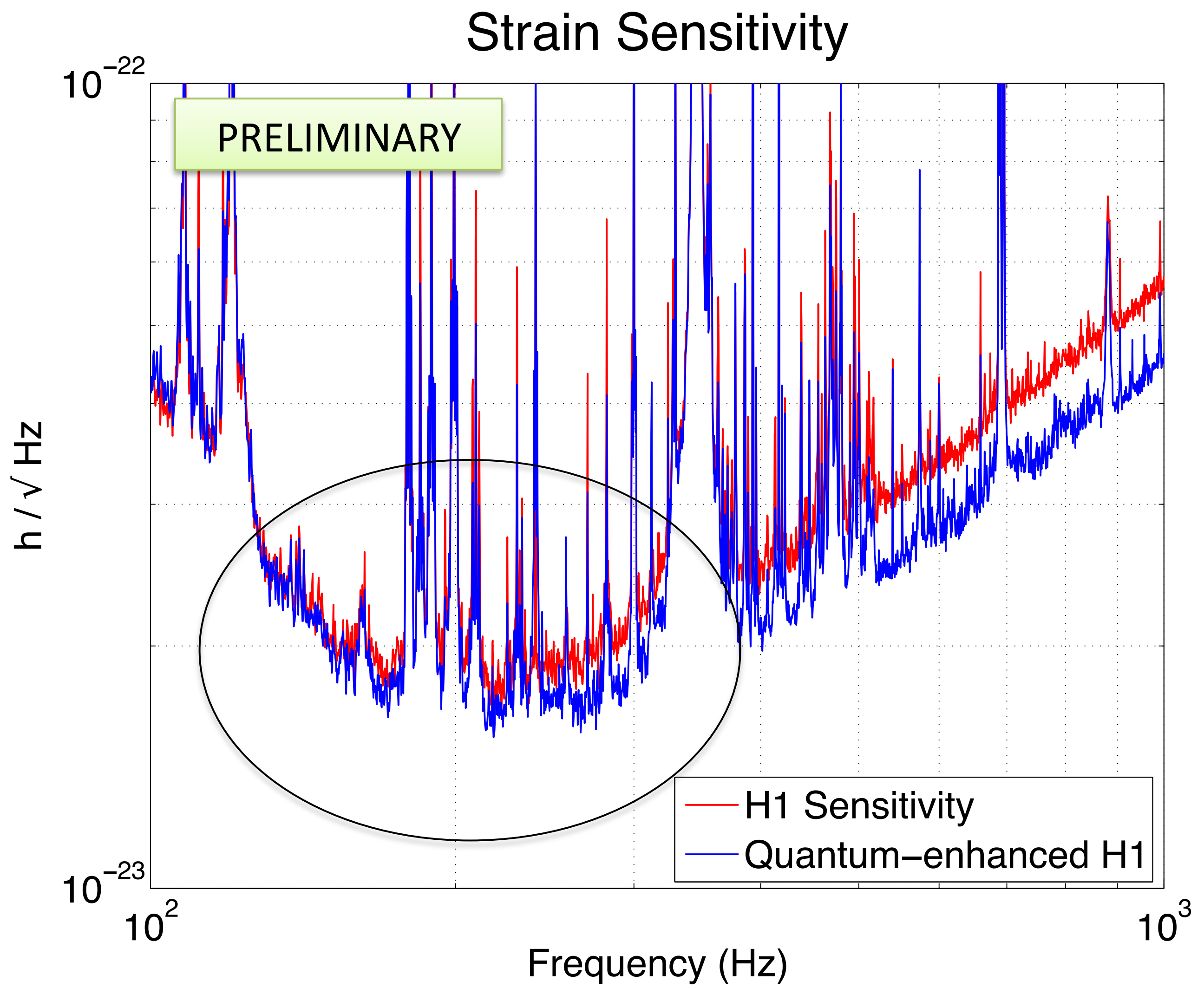


Squeezing improves only quantum noise, not other technical noises

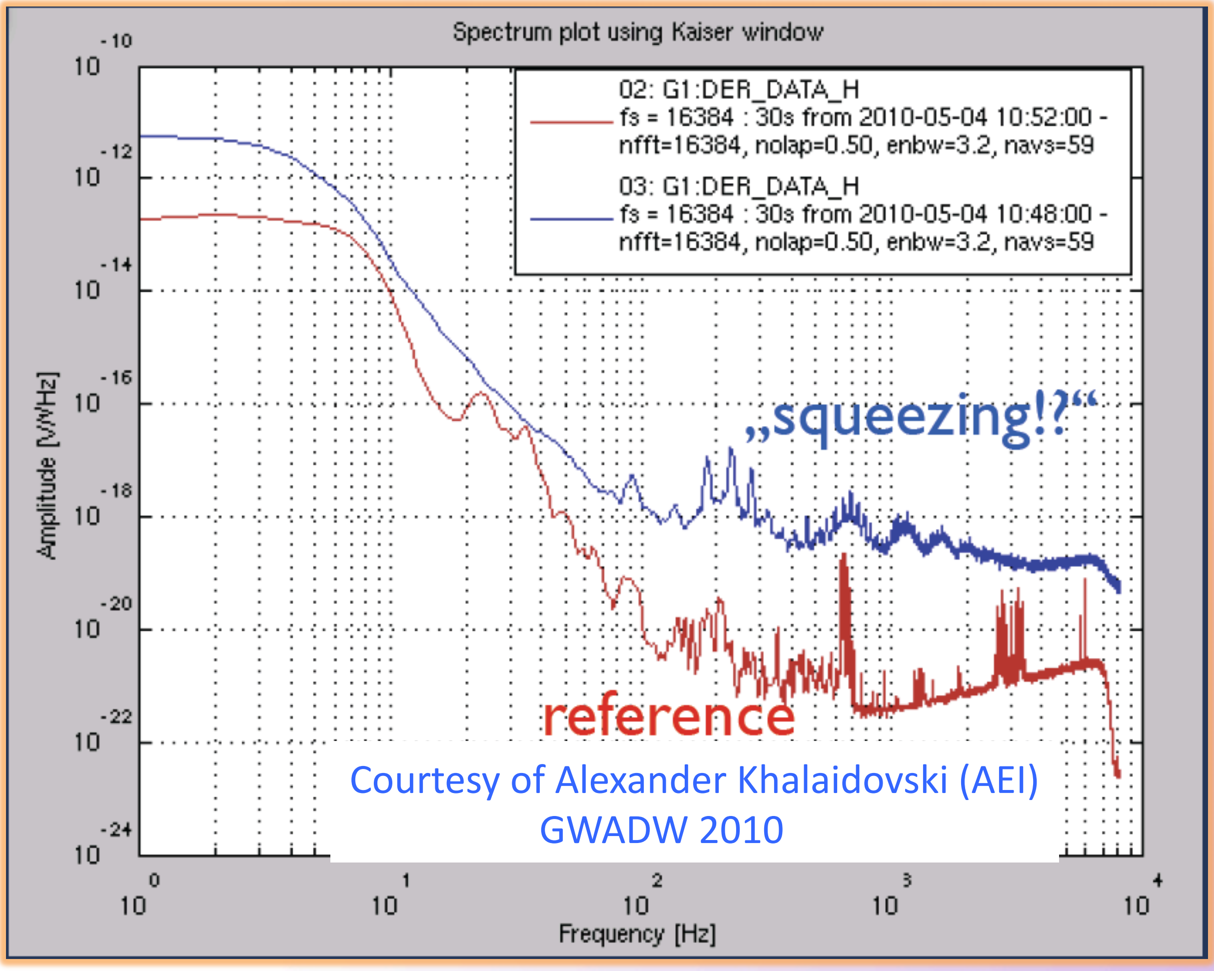
Best broadband sensitivity ever



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

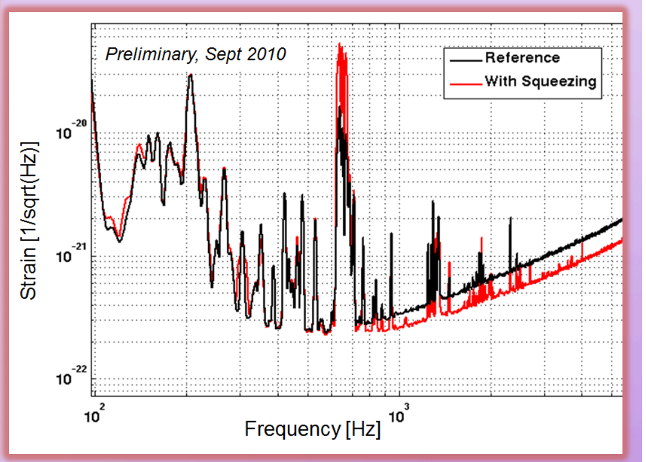


First try at squeezing in GEO



Courtesy of Alexander Khalaidovski (AEI)
GWADW 2010

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



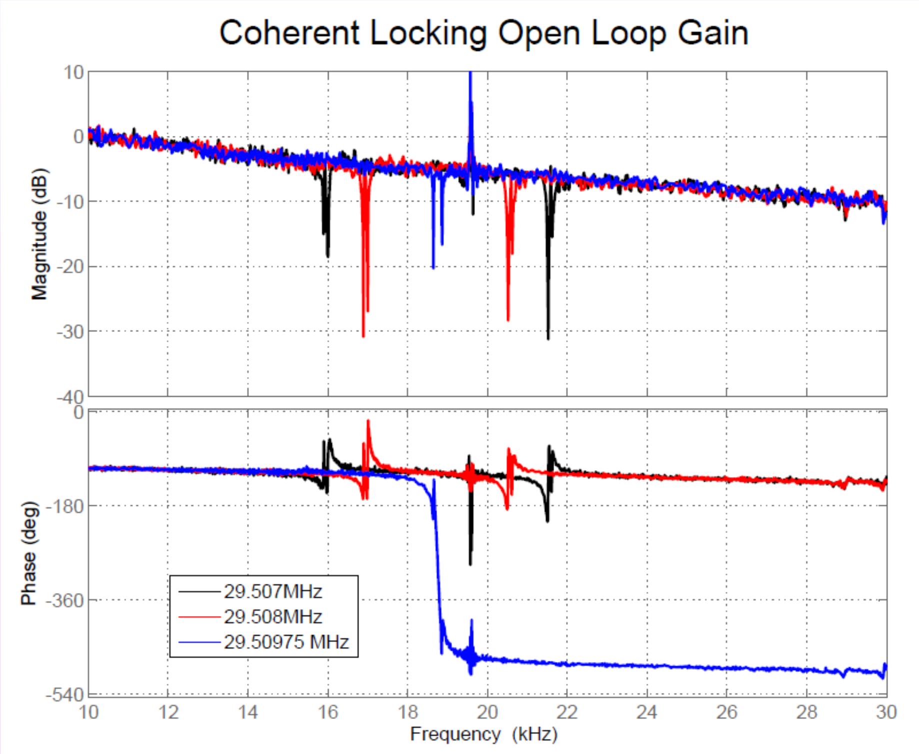
Where the main losses came from

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

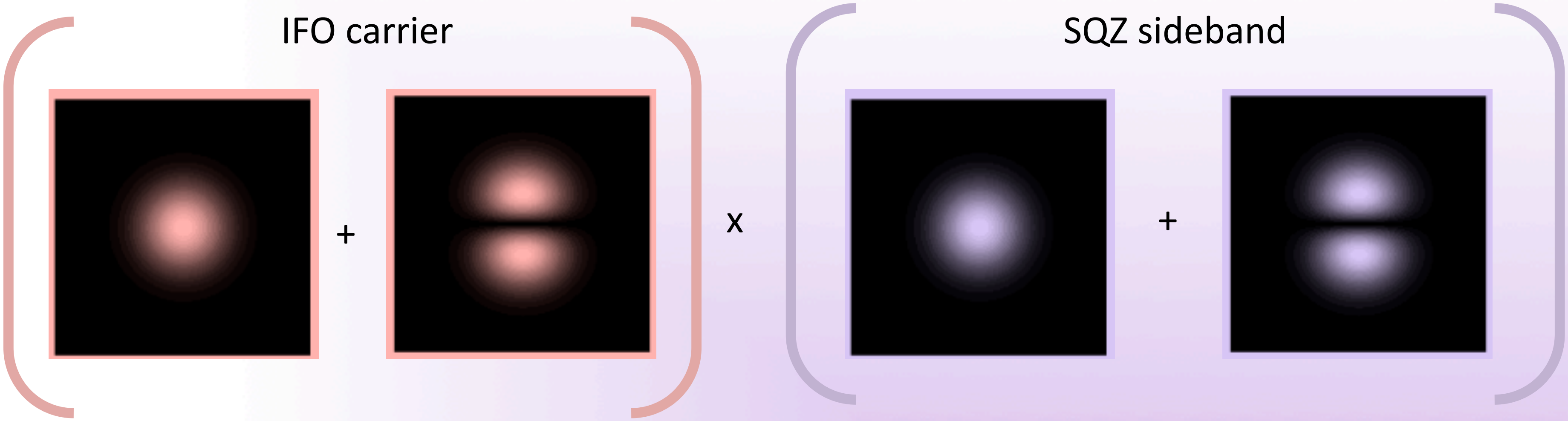
➔ “Technical” problems, total losses should be down to 10-15% in aLIGO

Phase noise control

- Bandwidth is limited to 10kHz by arm cavities
- Need to mitigate phase noise at the source
- Changes to control scheme and in vacuum OPO may be necessary for 10-15 dB of squeezing

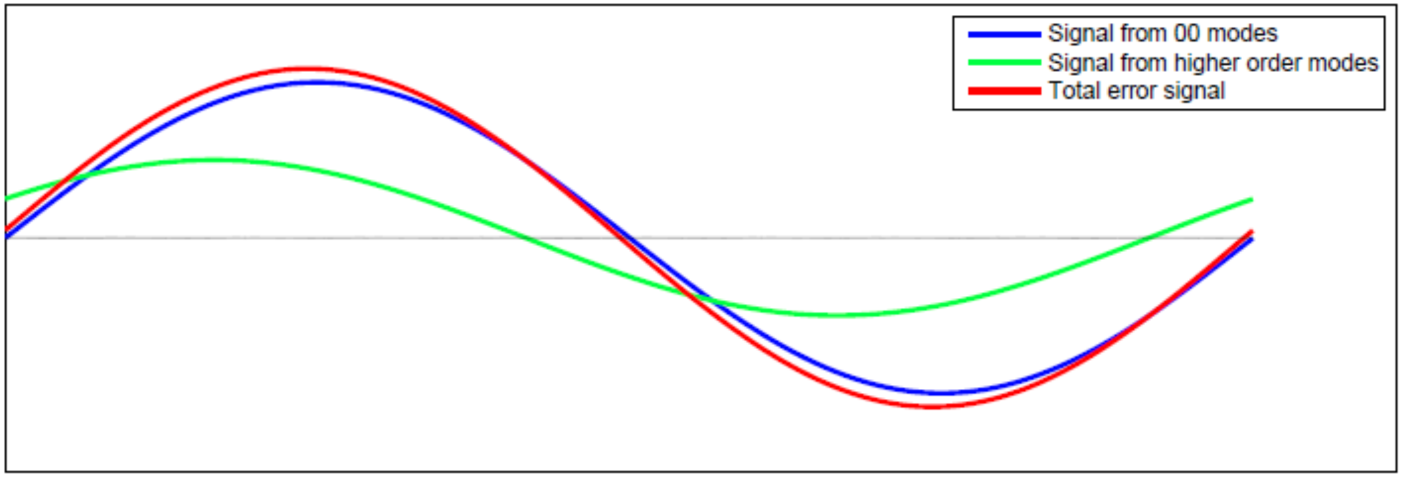


Squeezing angle error signal

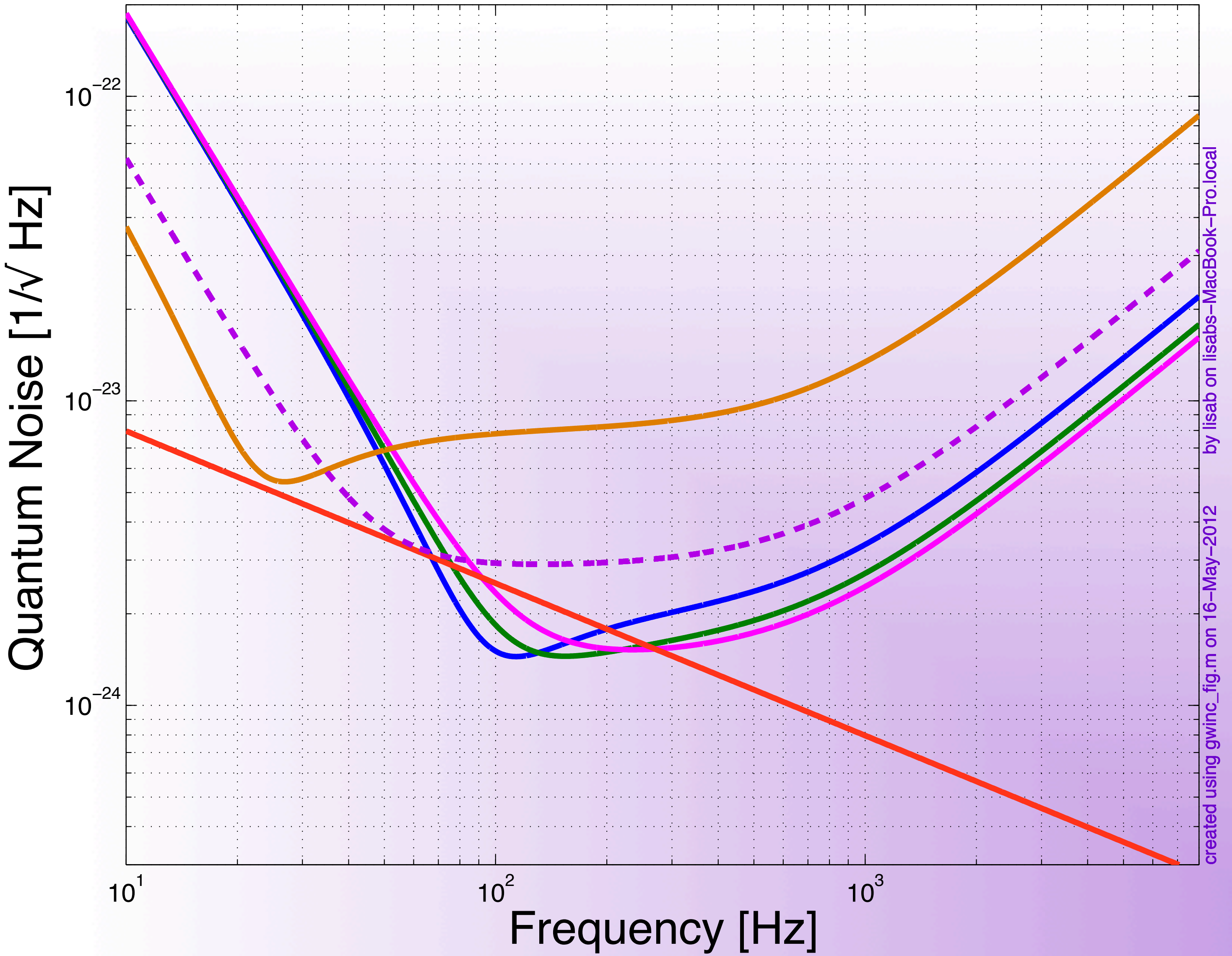


IFO carrier

SQZ sideband

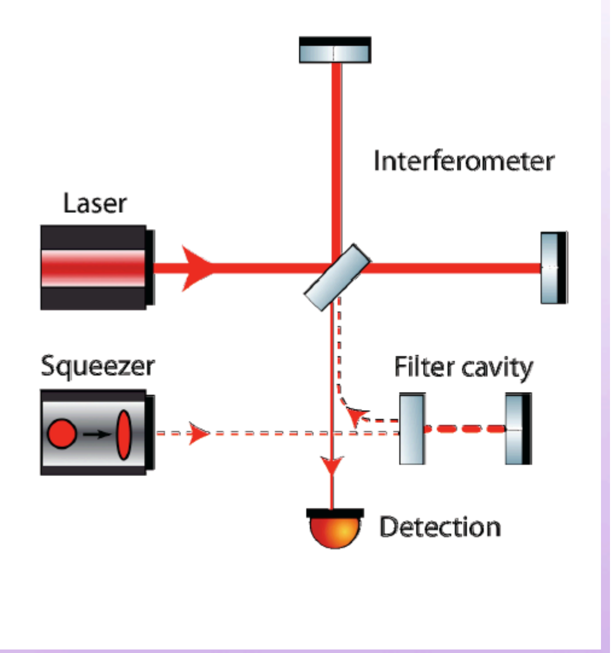


Quantum noise shaped by squeezed angle



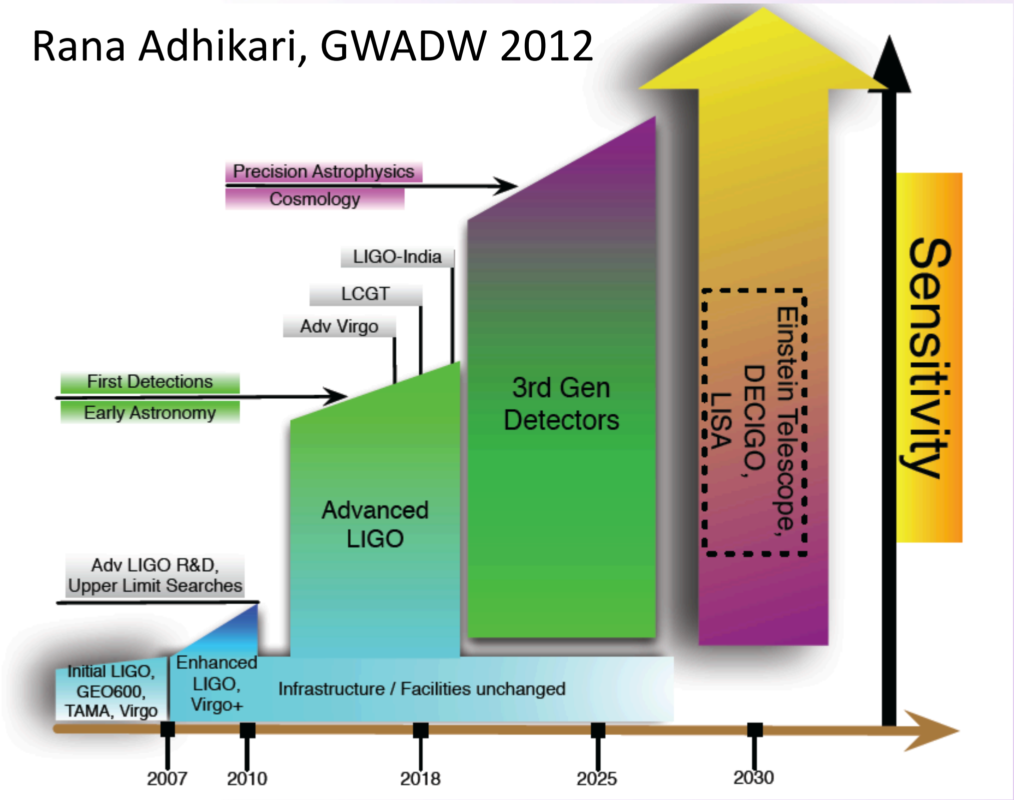
Frequency Dependent Squeezing

- ✧ 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

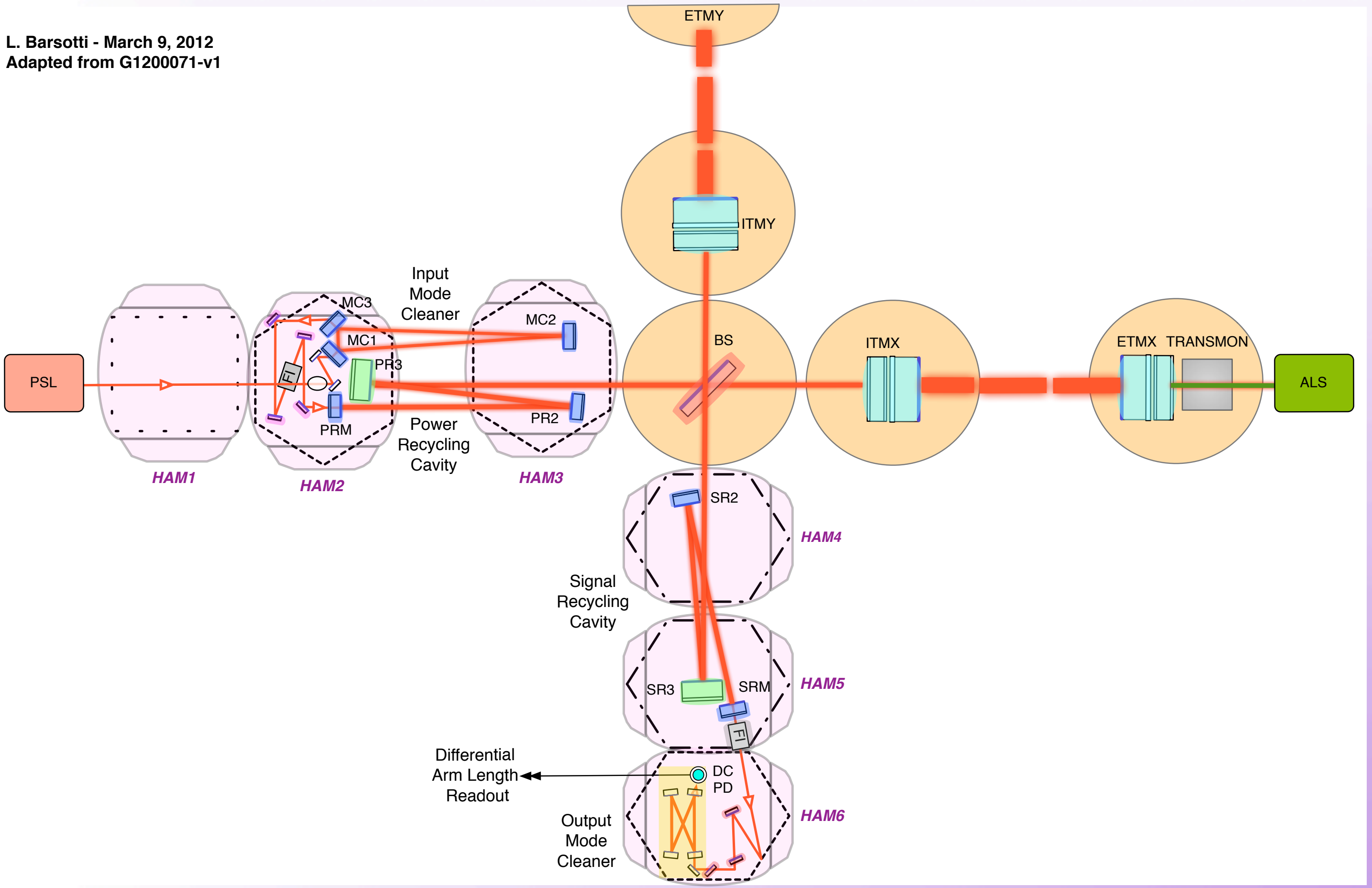
✧ Still work in progress, one thing already clear:

➔ 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

Advanced LIGO configuration



L. Barsotti - March 9, 2012
Adapted from G1200071-v1

✧Arm cavities, power and signal recycling cavity

✧Up to ~800 kW of light stored in the arms

Quantum States

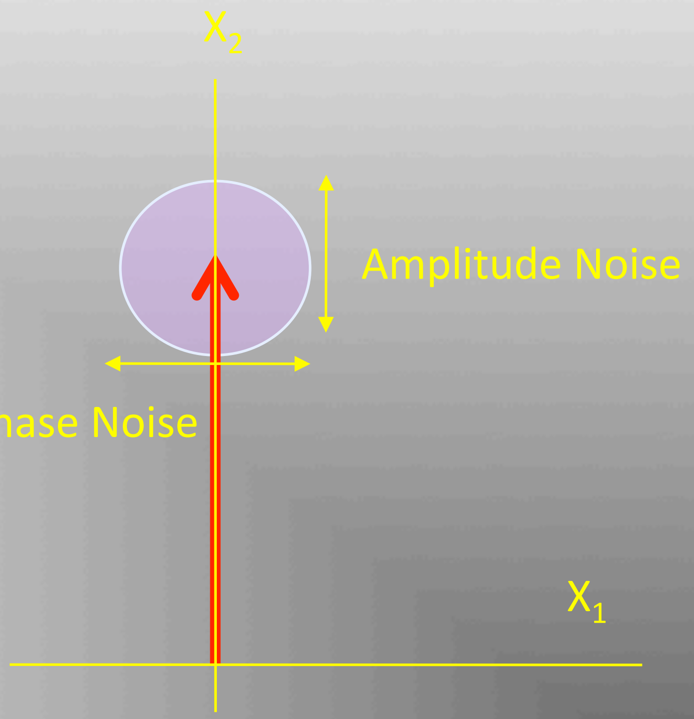
✧ Quantization of the electro-magnetic field

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!