Session G5:
Instrumentation for Current and Future Gravitational Wave Detectors

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

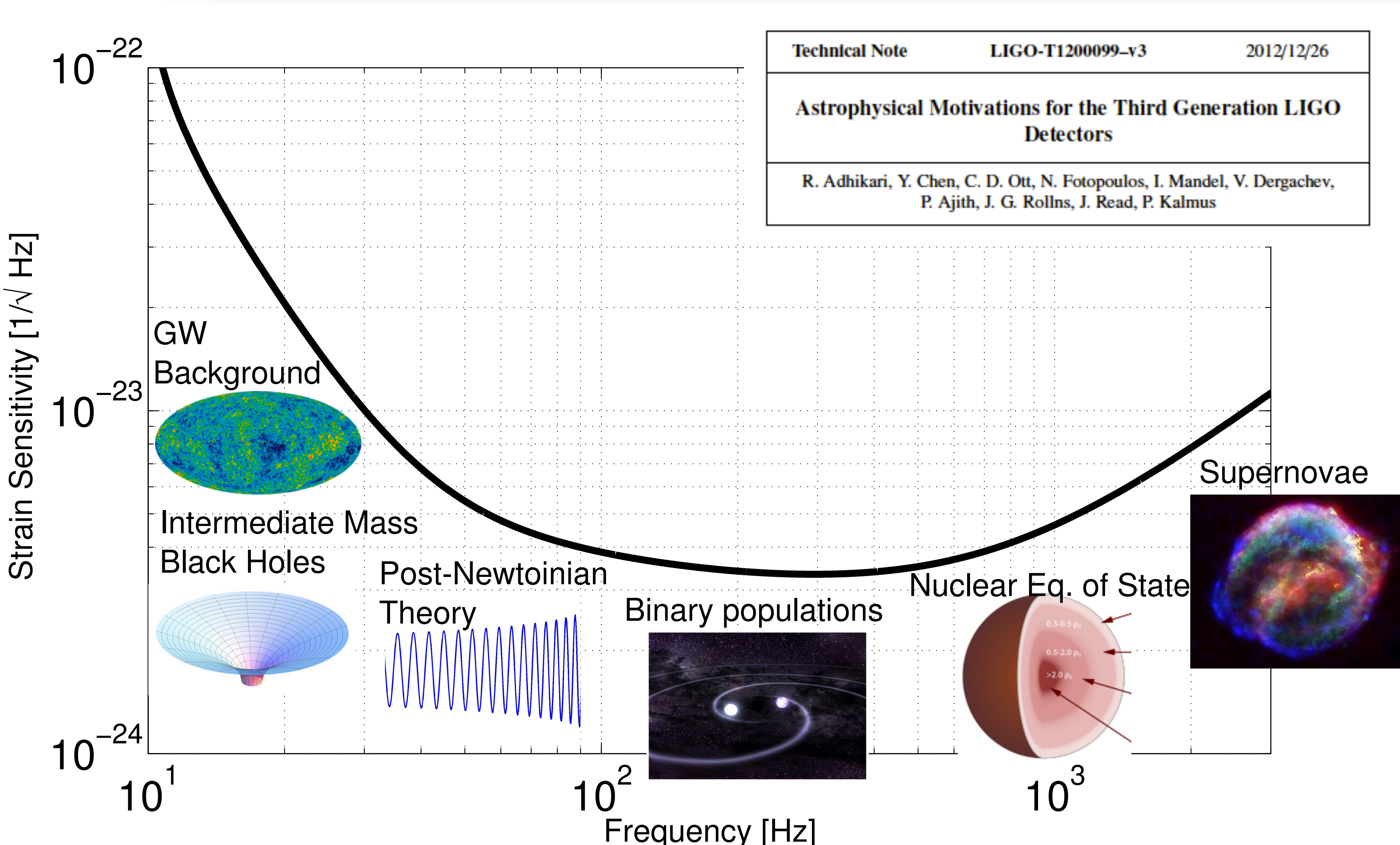
Lisa Barsotti

LIGO/MIT

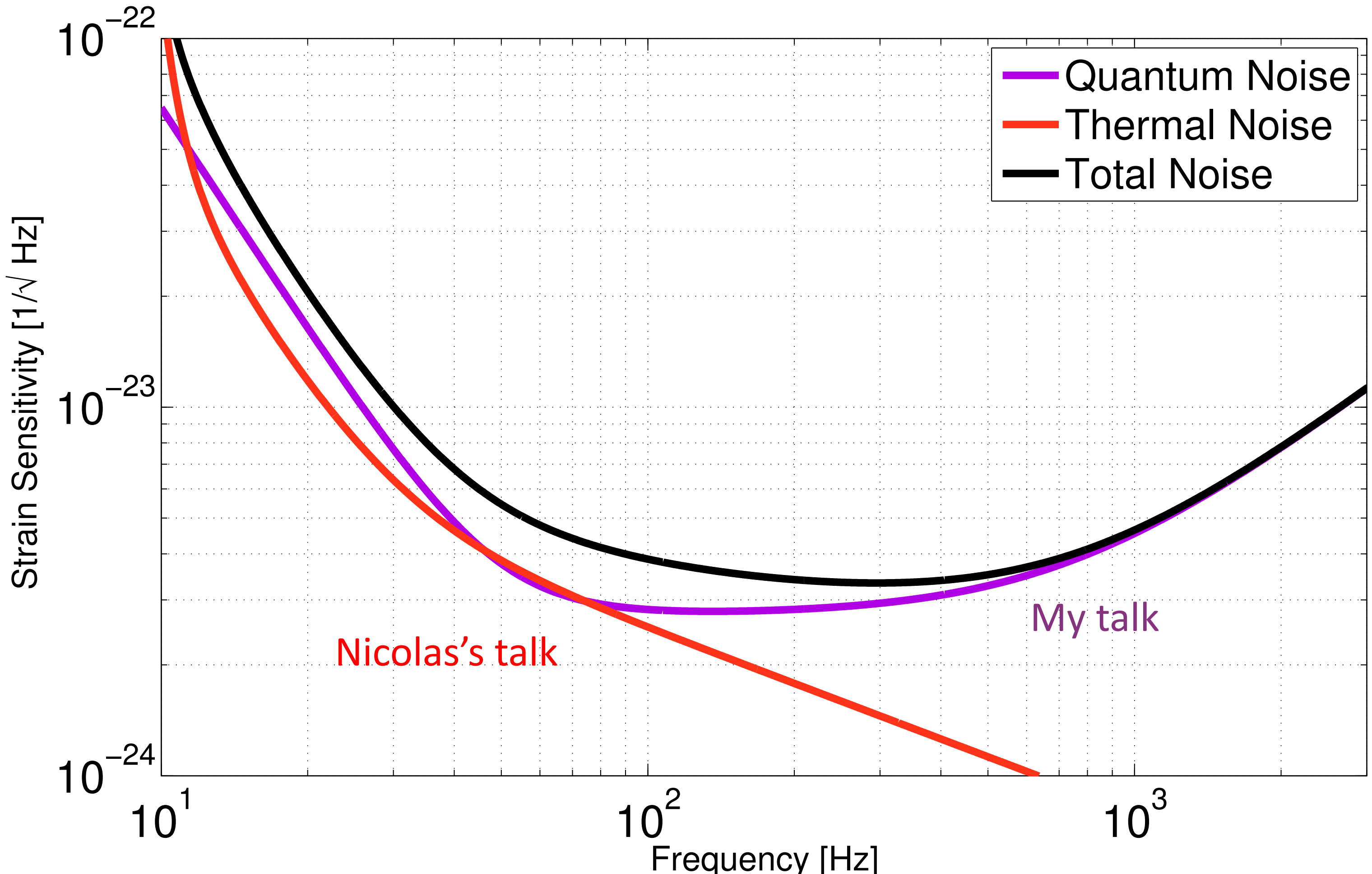
LIGO-G1300480-v2

Denver, Colorado - Apr 14, 2013

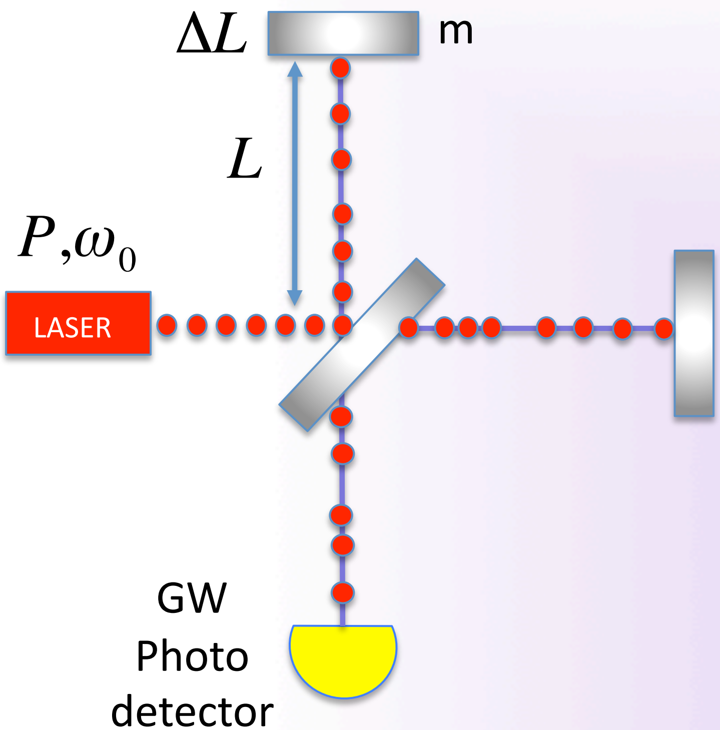
Astrophysical benefits beyond Advanced LIGO



Ideas for improving the astrophysical reach beyond advanced detectors



What is quantum noise?



✧ 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

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

Measurement frequency

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

"Standard Quantum Limit"

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

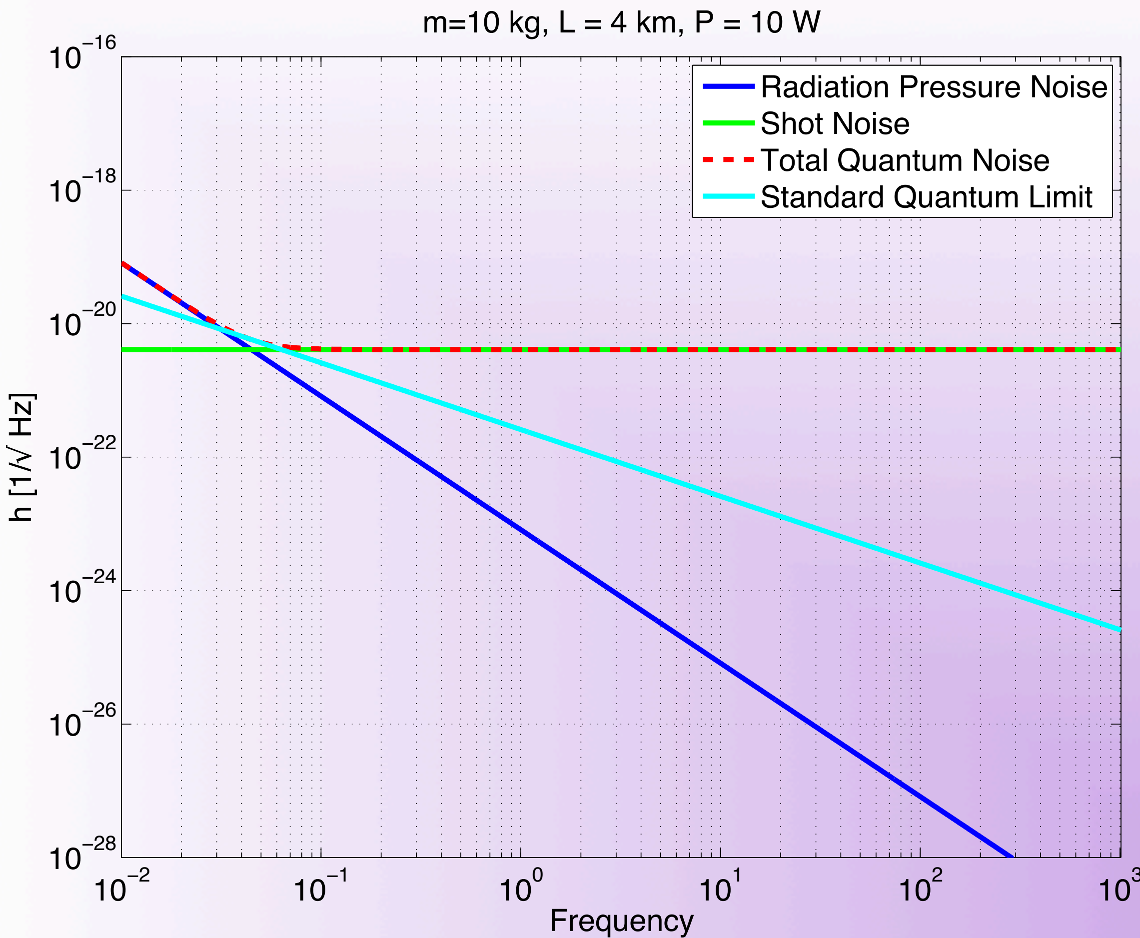
It doesn't depend on the optical parameters of the interferometer, just on the quantum mechanics of a harmonic oscillator mass

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

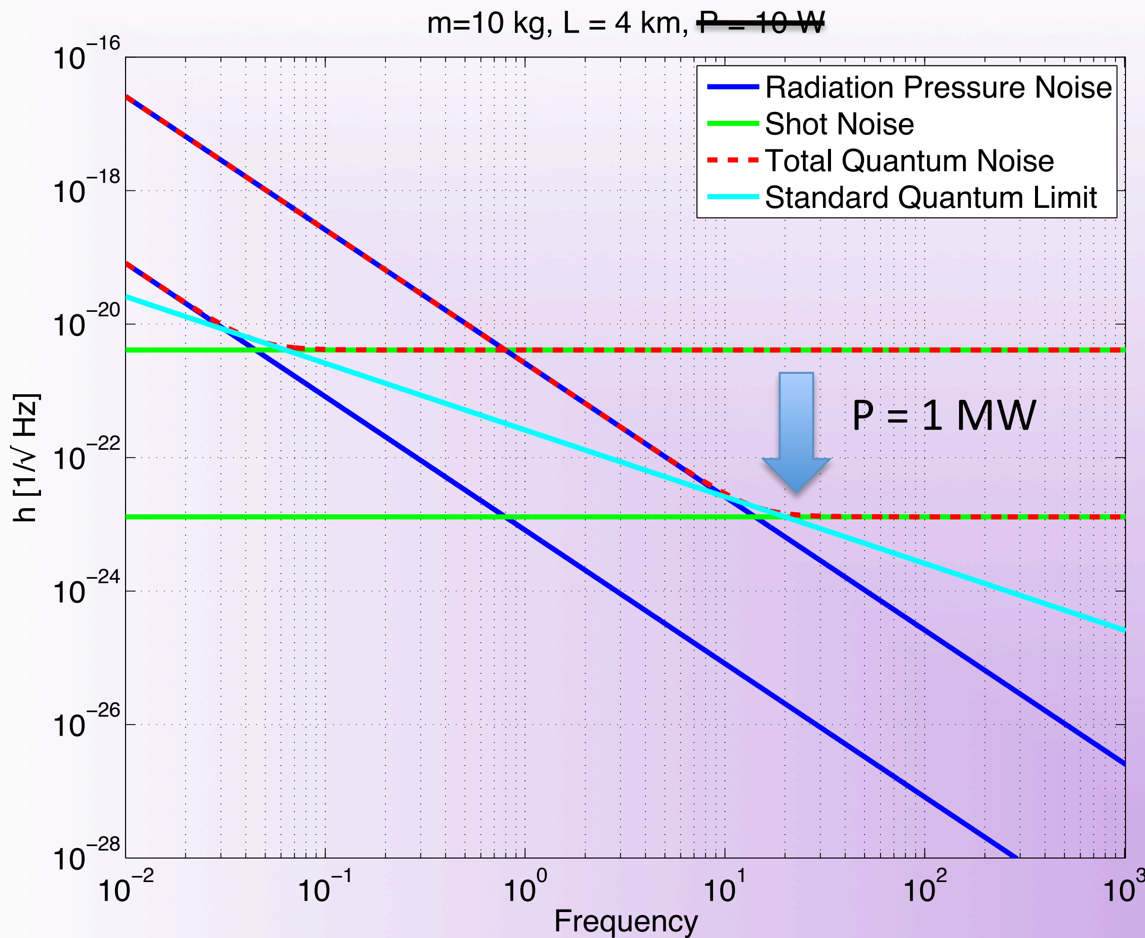
$$h_{Quantum} = \frac{\Delta L_{Quantum}}{L} = \sqrt{\frac{4\hbar}{m\Omega^2 L^2}}\sqrt{\frac{1}{2}\left(K + \frac{1}{K}\right)}$$

$$h_{SQL}$$

Simple Michelson, P = 10 W



Simple Michelson, P = 1 MW



“Easy” approaches to minimize quantum noise

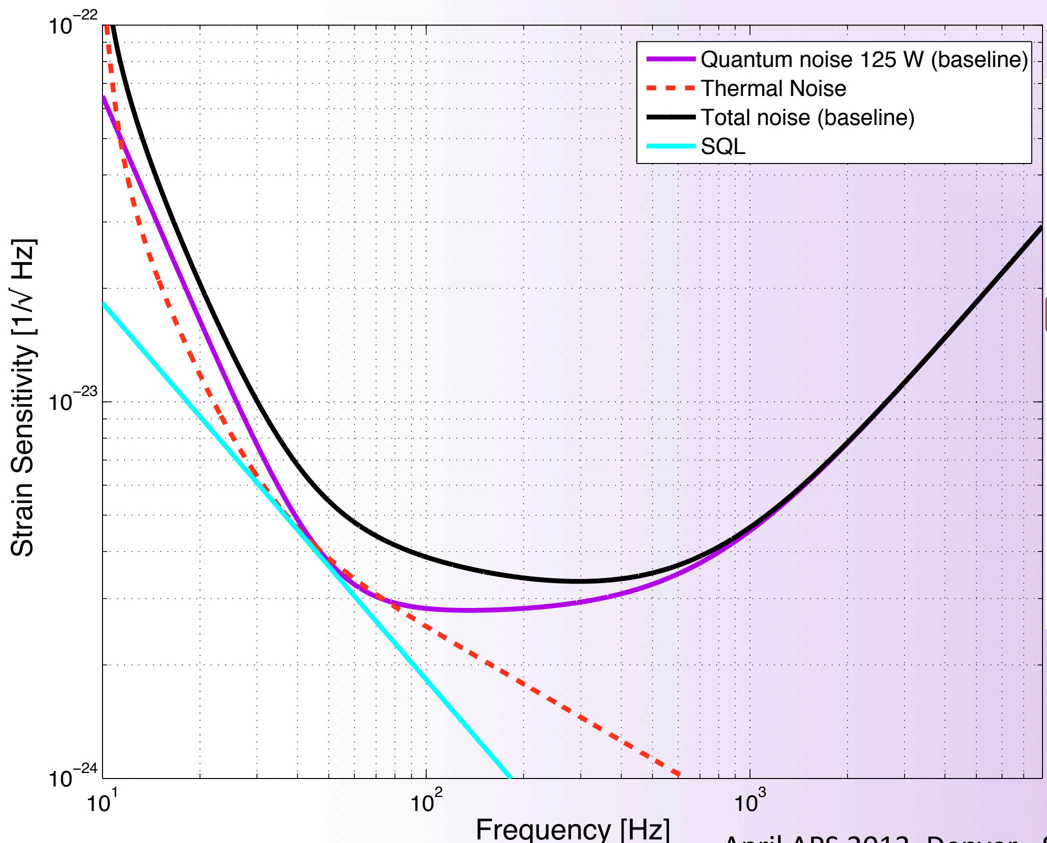
$$h_{Quantum} = \sqrt{\frac{1}{2}}\sqrt{\frac{4\hbar}{m\Omega^2 L^2}}\sqrt{\left(\mathrm{K}+\frac{1}{\mathrm{K}}\right)}, \qquad \mathrm{K} = \frac{4P\omega_0}{c^2 m\Omega^2}$$

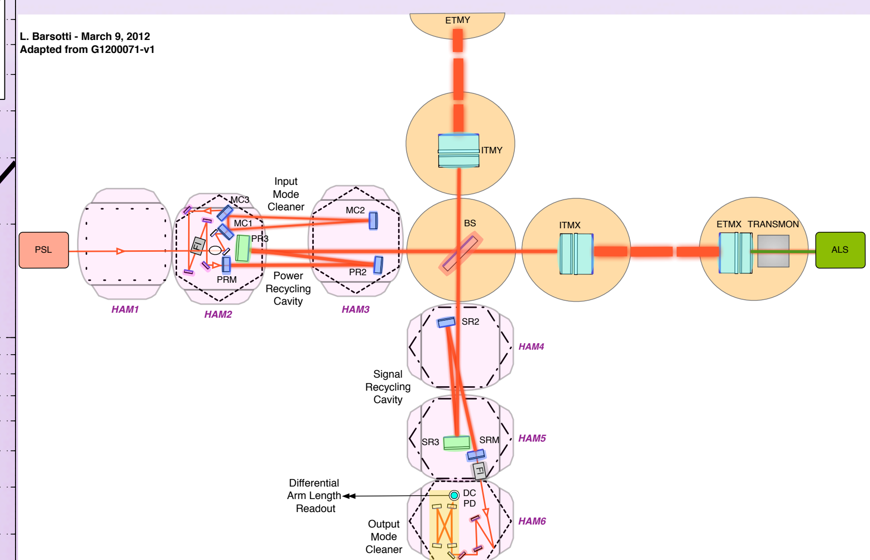
- ✧ Make your interferometer as long as possible
- ✧ Make your test masses as heavy as possible, and allow as much power in the arm until quantum noise is comparable to other noises

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

More Clever: Quantum Noise in aLIGO

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





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

How we go beyond advanced LIGO

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

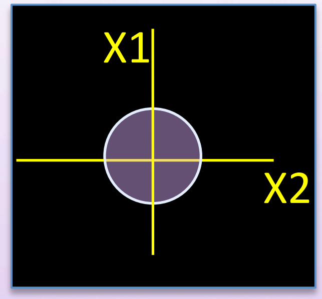
D. E. McClelland, N. Mavalvala, Y. Chen, and R. Schnabel, "Advanced interferometry, quantum optics and optomechanics in gravitational wave detectors", Laser and Photonics Rev.5, 677-696 (2011)

- ✧Injection of squeezed states of vacuum

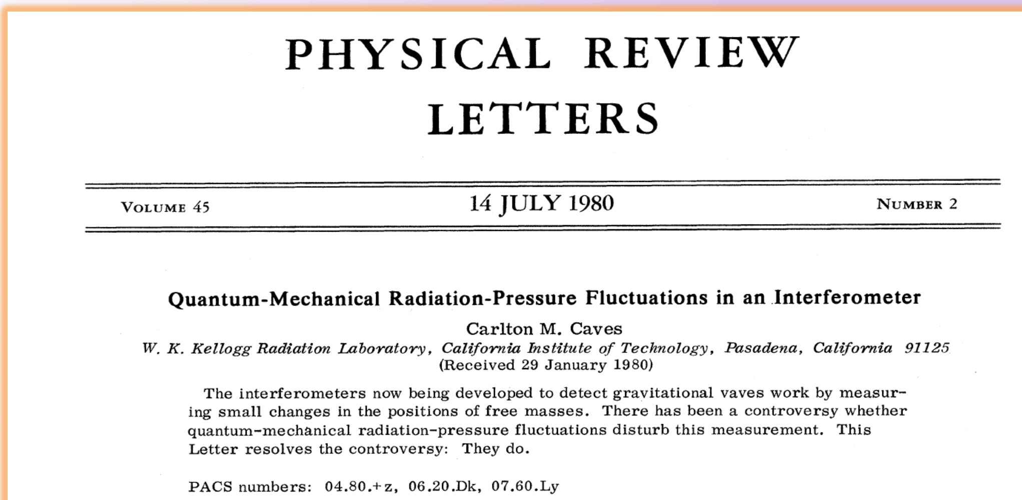
Where quantum noise REALLY comes from

Quantum noise comes from the quantization of the electro-magnetic field
→ Zero-point fluctuations

- ✧ When average amplitude is zero, the variance remains
- ✧ Heisenberg uncertainty principle, quadratures associated with **amplitude** and **phase**
- ✧ They enter the interferometer from all the open ports of the interferometer, but the ones which matter are the one **entering from the anti-symmetric port**!



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



PHYSICAL REVIEW LETTERS

VOLUME 45	14 JULY 1980	NUMBER 2

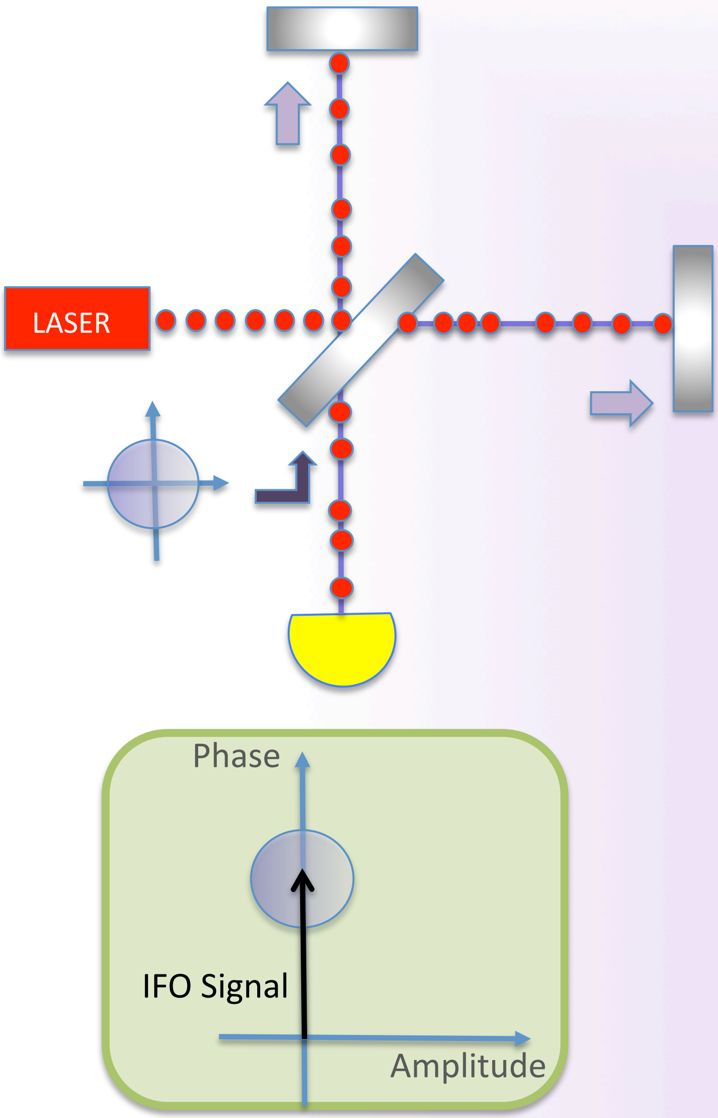
Quantum-Mechanical Radiation-Pressure Fluctuations in an Interferometer

Carlton M. Caves
W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125
(Received 29 January 1980)

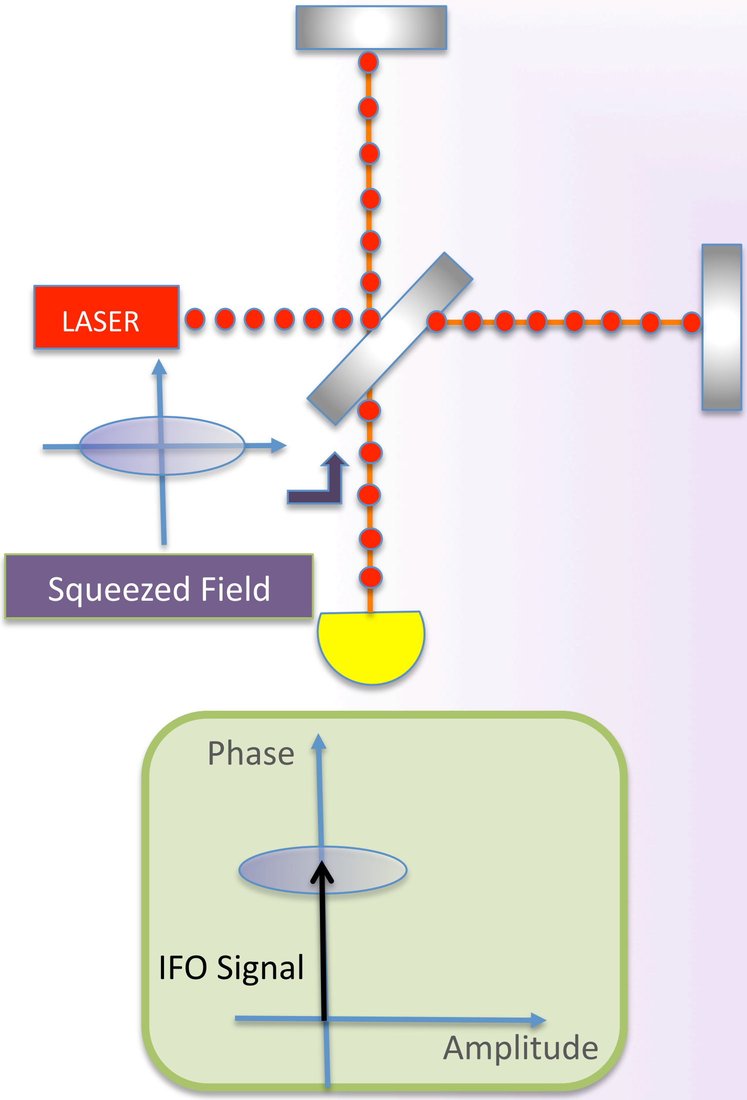
The interferometers now being developed to detect gravitational vaves work by measuring small changes in the positions of free masses. There has been a controversy whether quantum-mechanical radiation-pressure fluctuations disturb this measurement. This Letter resolves the controversy: They do.

PACS numbers: 04.80.+z, 06.20.Dk, 07.60.Ly

Vacuum Getting Squeezed



Vacuum Getting Squeezed



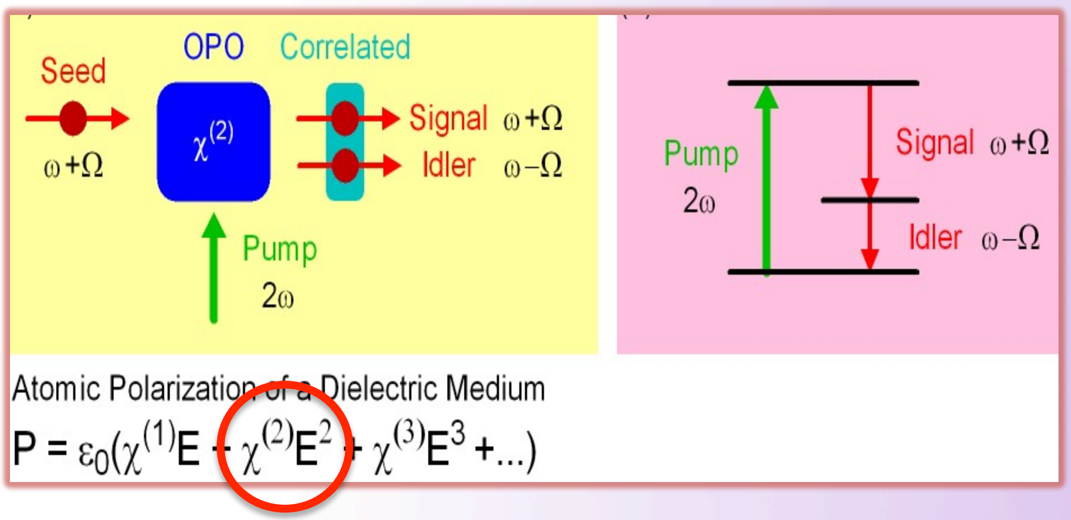
- Reduce quantum noise by injecting squeezed vacuum: less uncertainty in one of the two quadratures
- Heisenberg uncertainty principle: if the noise gets smaller in one quadrature, it gets bigger in the other one
- One can choose the relative orientation between the squeezed vacuum and the interferometer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

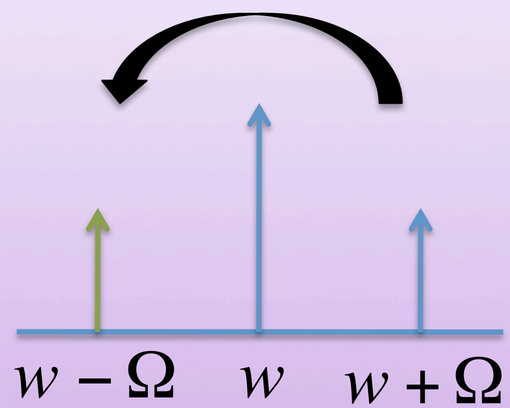
C. M. Caves, Phys. Rev. Lett. 45, 75 (1980).
C. M. Caves, Quantum-mechanical noise in an interferometer. Phys. Rev. D 23, p. 1693 (1981).

How to make squeezed fields…

…. in theory

- ✧ Non linear medium with a strong second order polarization component, pumped at 2w
- ✧ Refractive index depends on intensity of light illumination
- ✧ It creates correlation of upper and lower quantum sidebands

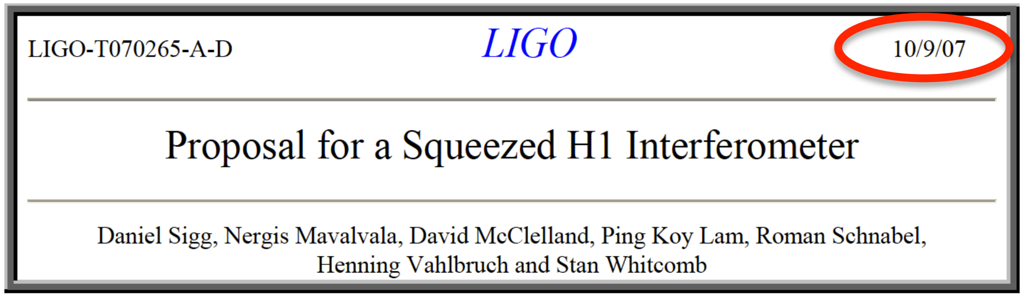




The OPO makes a "copy" of the quantum sideband, and it correlates the sidebands

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

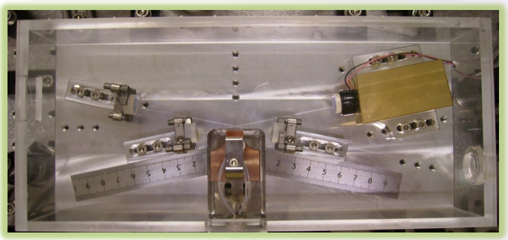
$$\Rightarrow Ee^{-i(w-\Omega)t}$$


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

Proposal for a Squeezed H1 Interferometer

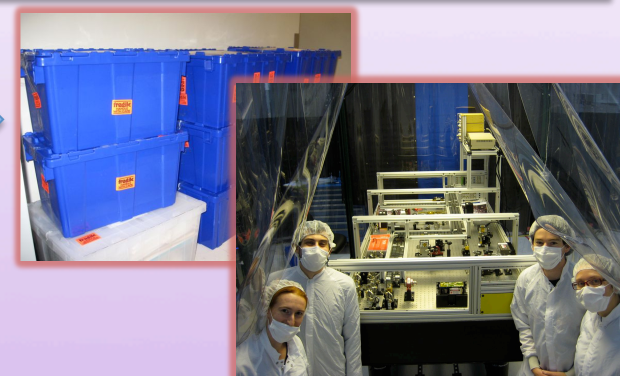
Daniel Sigg, Nergis Mavalvala, David McClelland, Ping Koy Lam, Roman Schnabel, Henning Vahlbruch and Stan Whitcomb

Bow-tie cavity OPO design at ANU (2008)

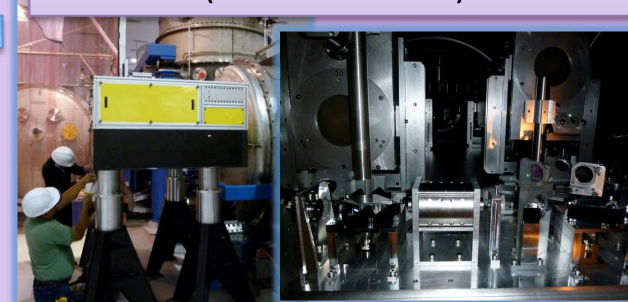


H1 Squeezer assembling at MIT (2009-2010)

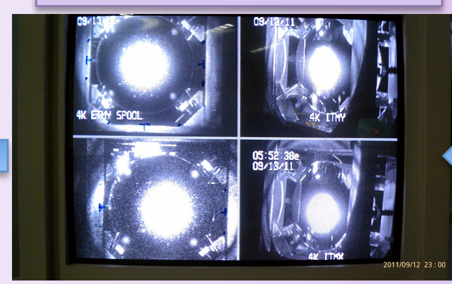
H1 Squeezer parts shipped to LHO (Oct 2010)



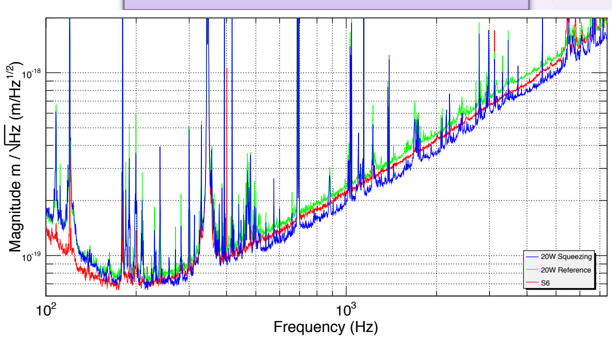
H1 Squeezer Installation (Summer 2011)



H1 Recovery (Sept 2011)



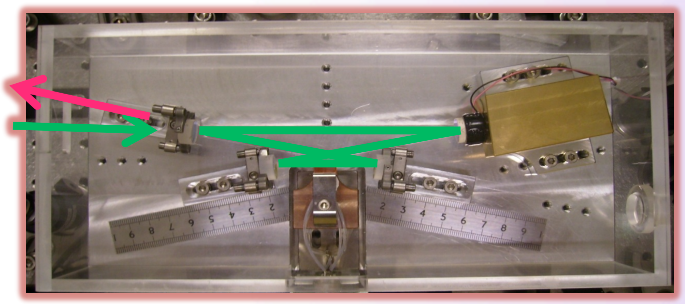
Squeezing in H1 (Oct 3 – Dec 4)

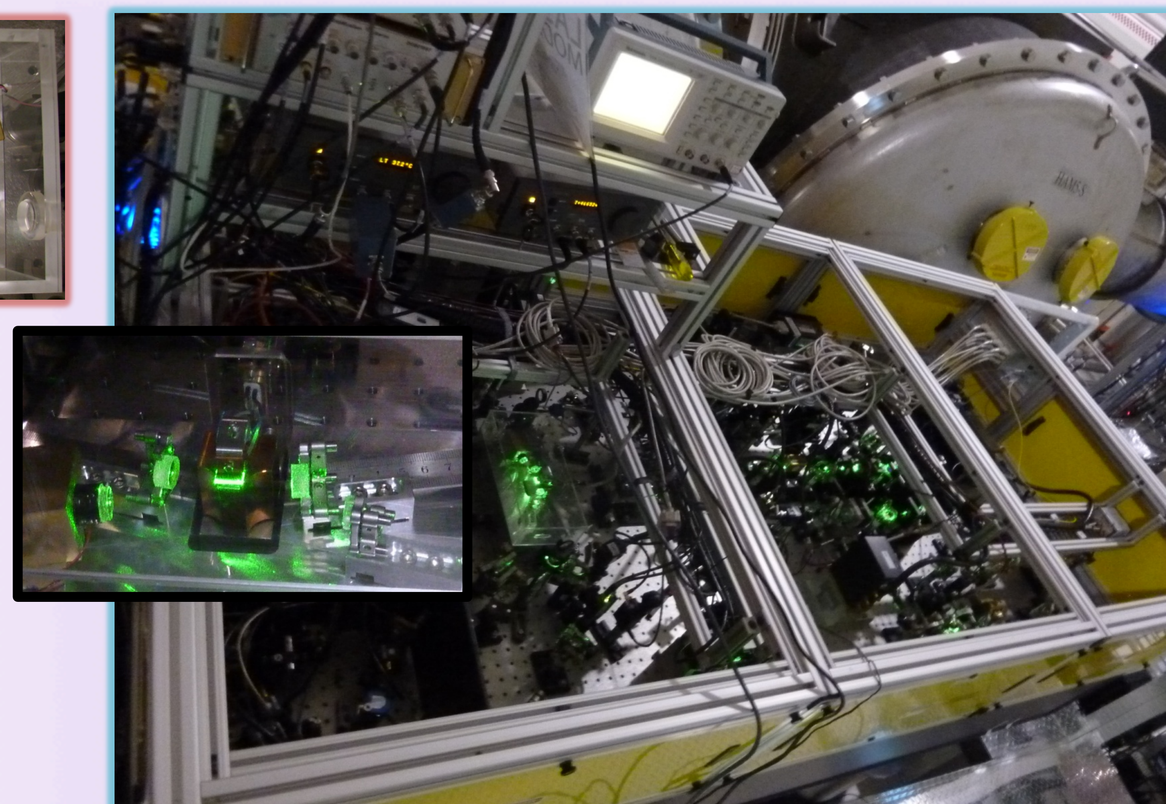


How to make squeezed fields..

.... in practice

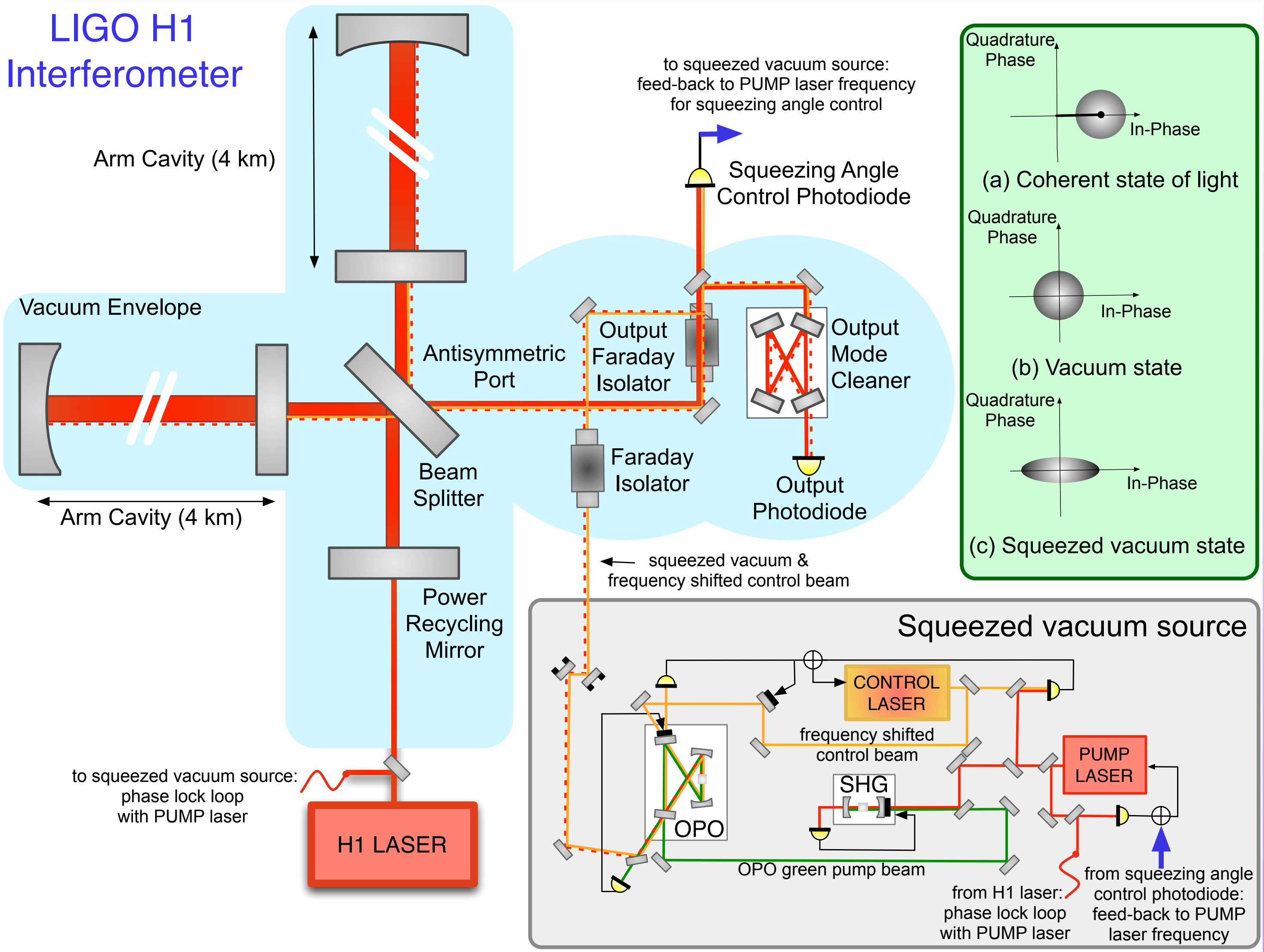
The LIGO H1 Squeezer



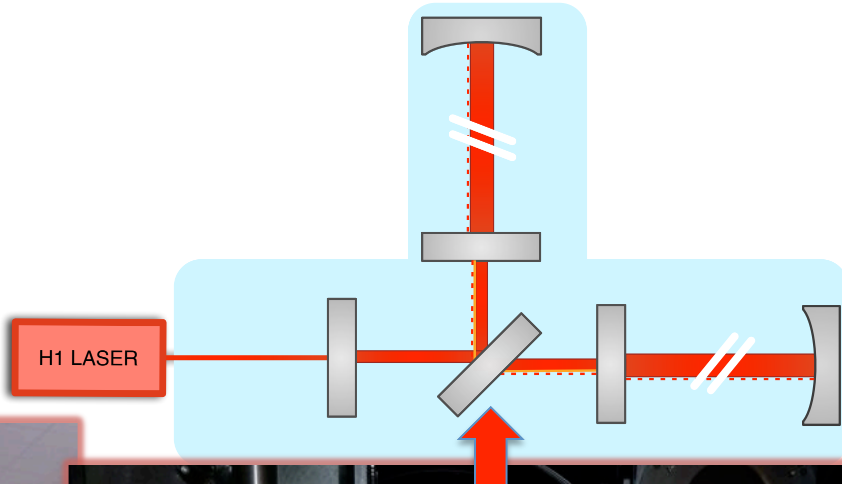


World-wide effort in the last 10 years to make squeezing in the audio-frequency band

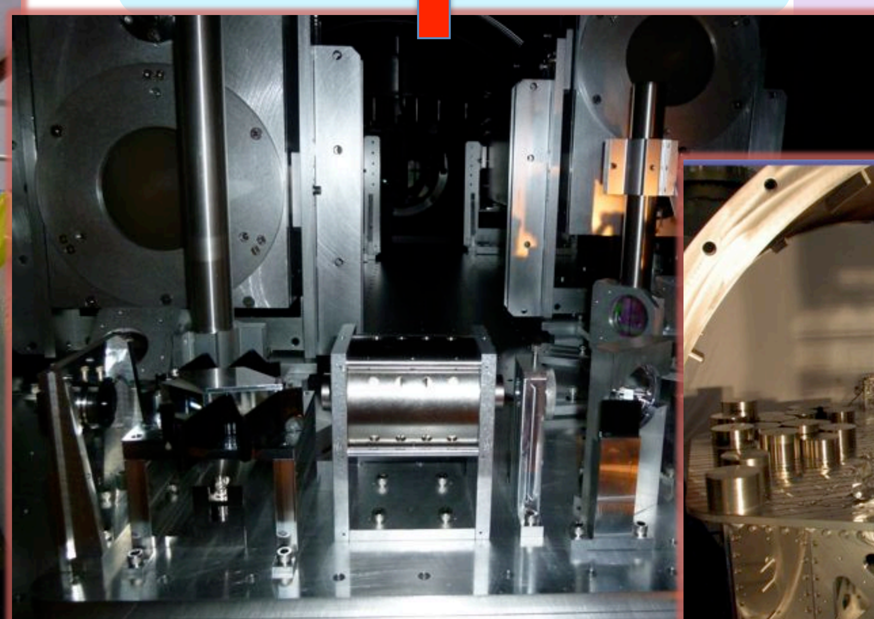
How to inject squeezed fields



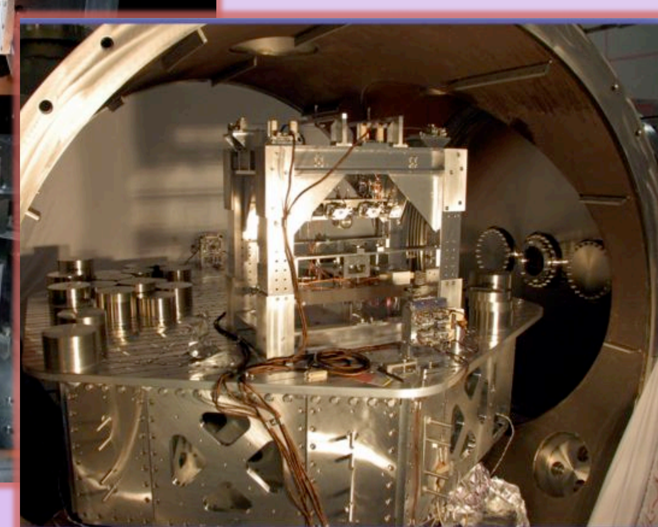
Squeezing injection into LIGO H1



Squeezer Table



Output Faraday

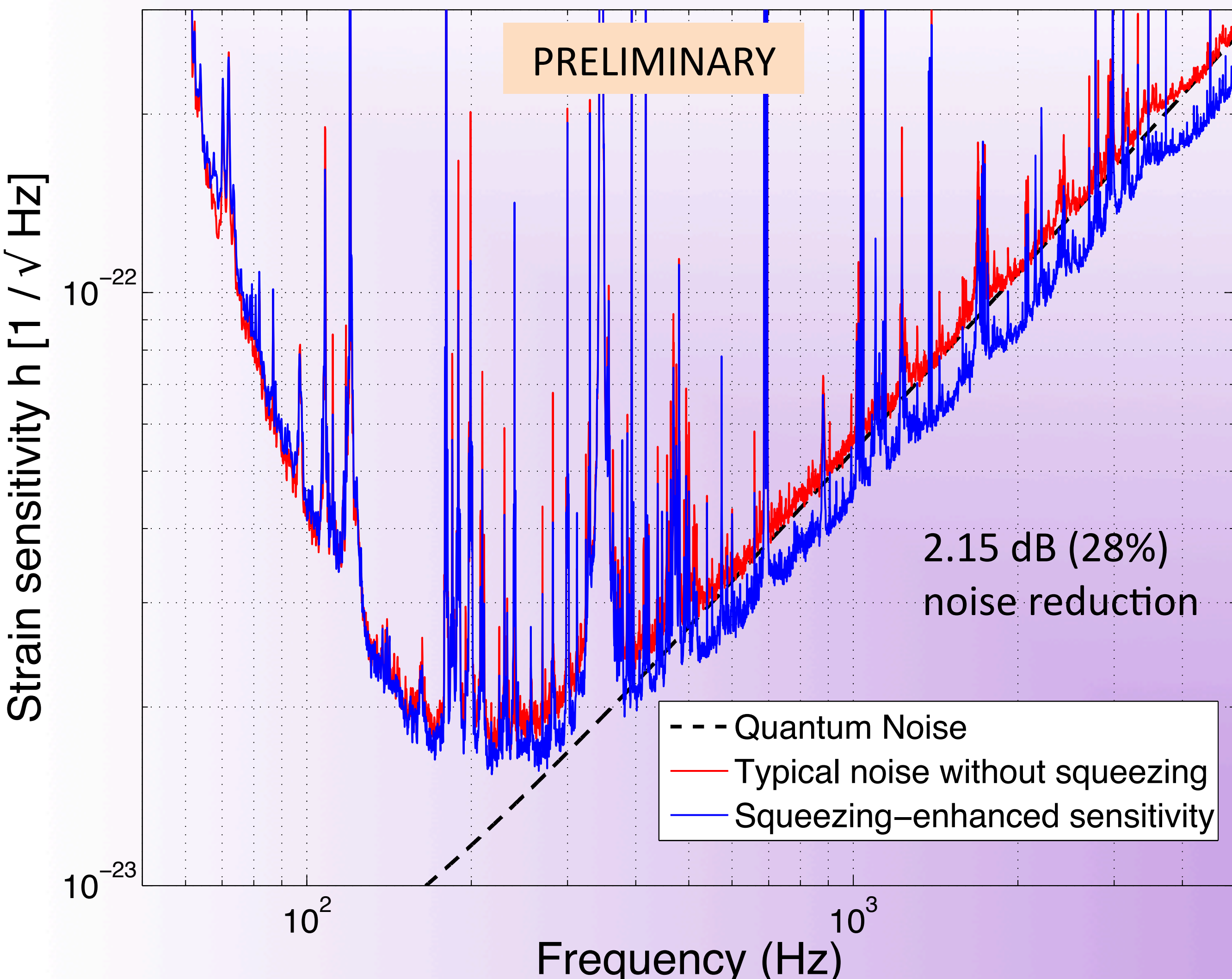


Output Mode Cleaner

LIGO H1 Squeezing Experiment Results

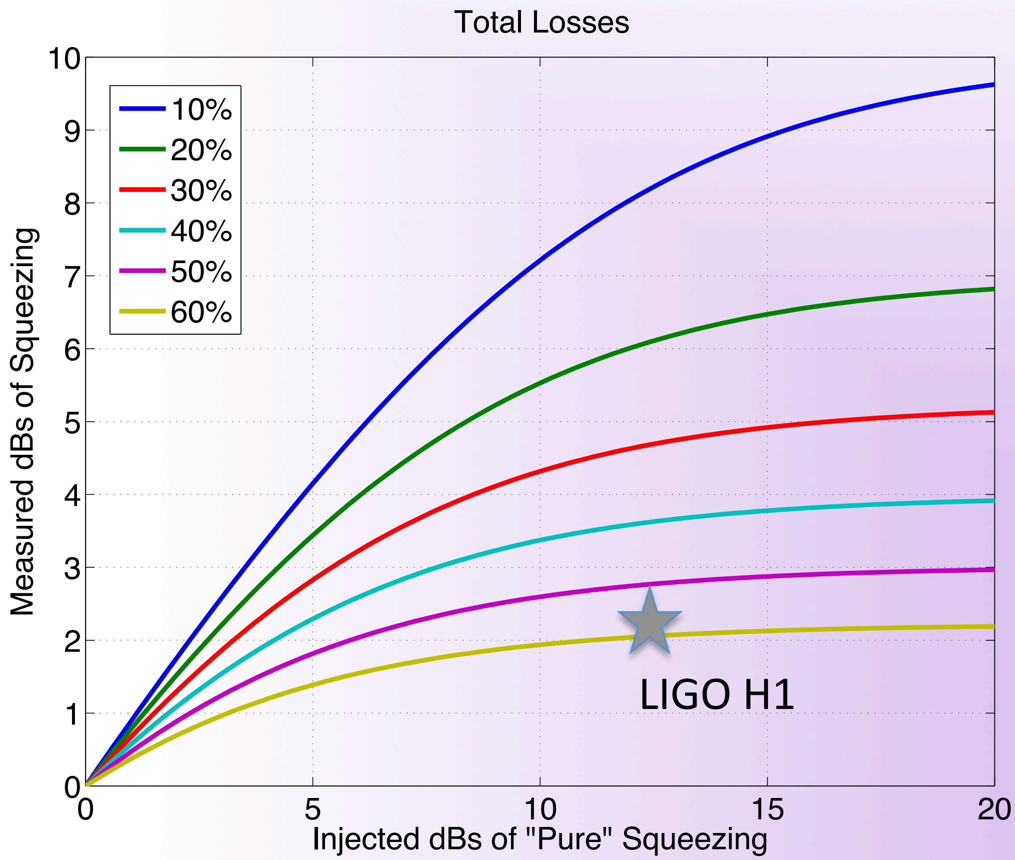
from the LIGO Scientific Collaboration

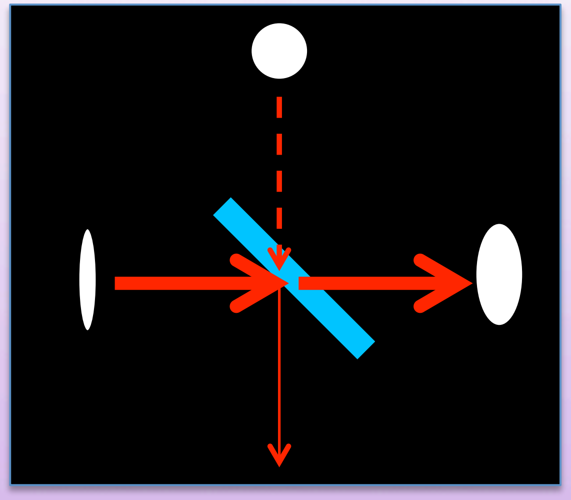
$$h = \frac{\Delta L}{L}$$



Limit to the amount of observed squeezing

✧ Losses are very unforgiving!





Total losses ~ 56%

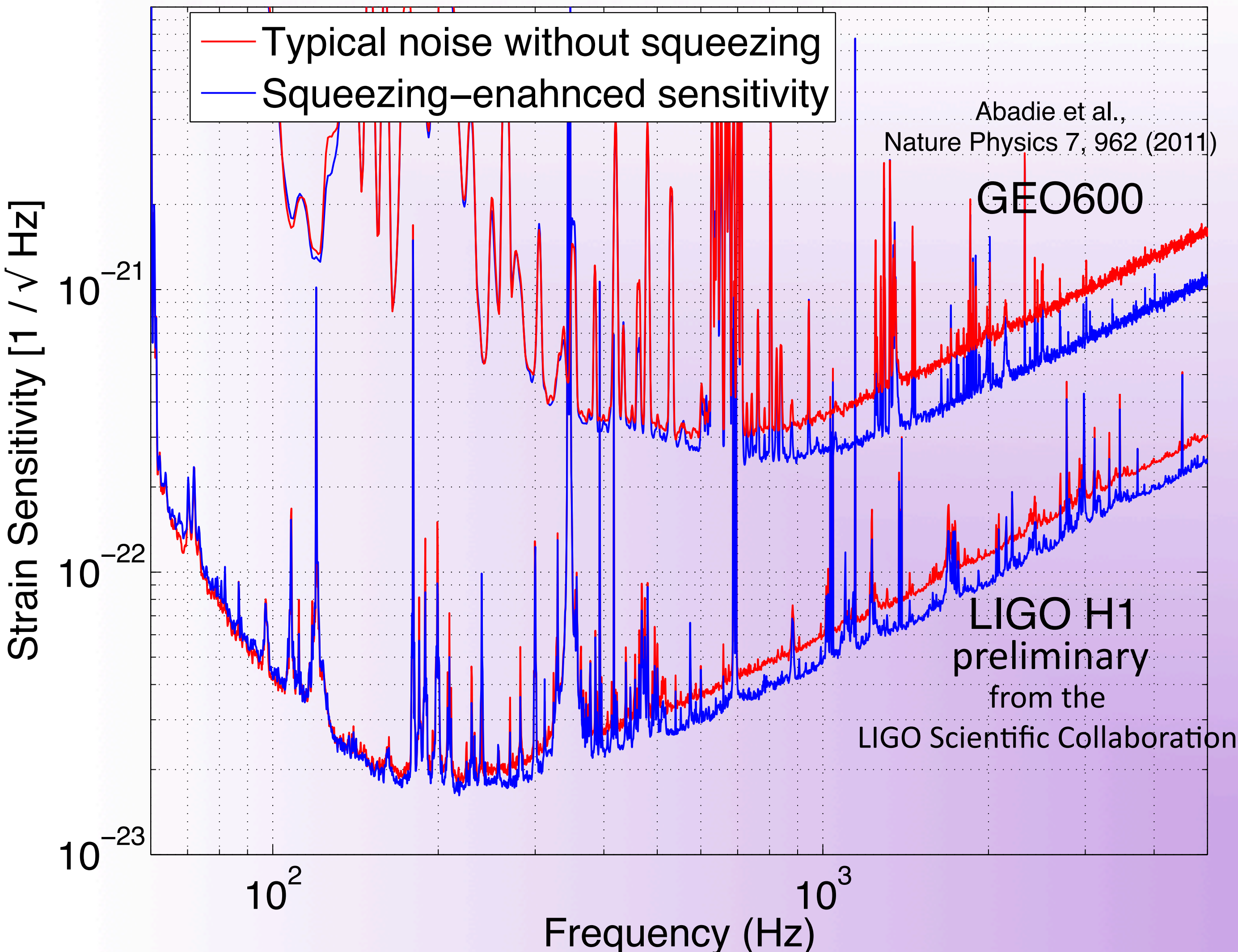
<u>Largest Losses Sources:</u>

✧Mode matching

✧ Faradays

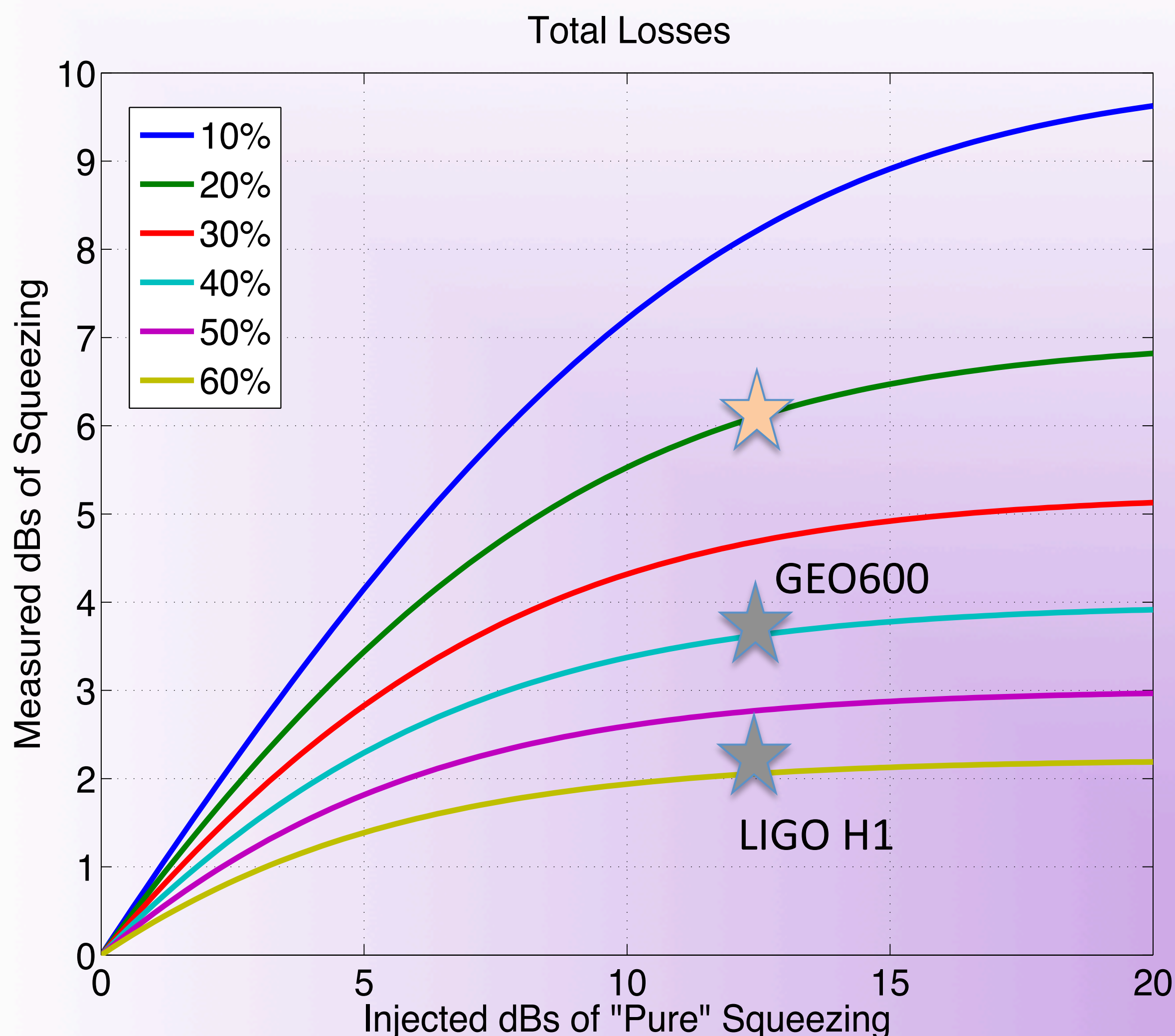
✧ Output mode cleaner

Squeezing in GEO600 and LIGO H1

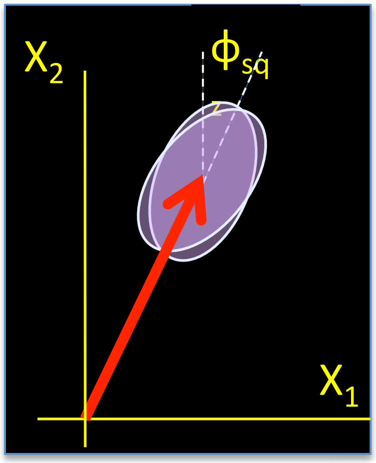


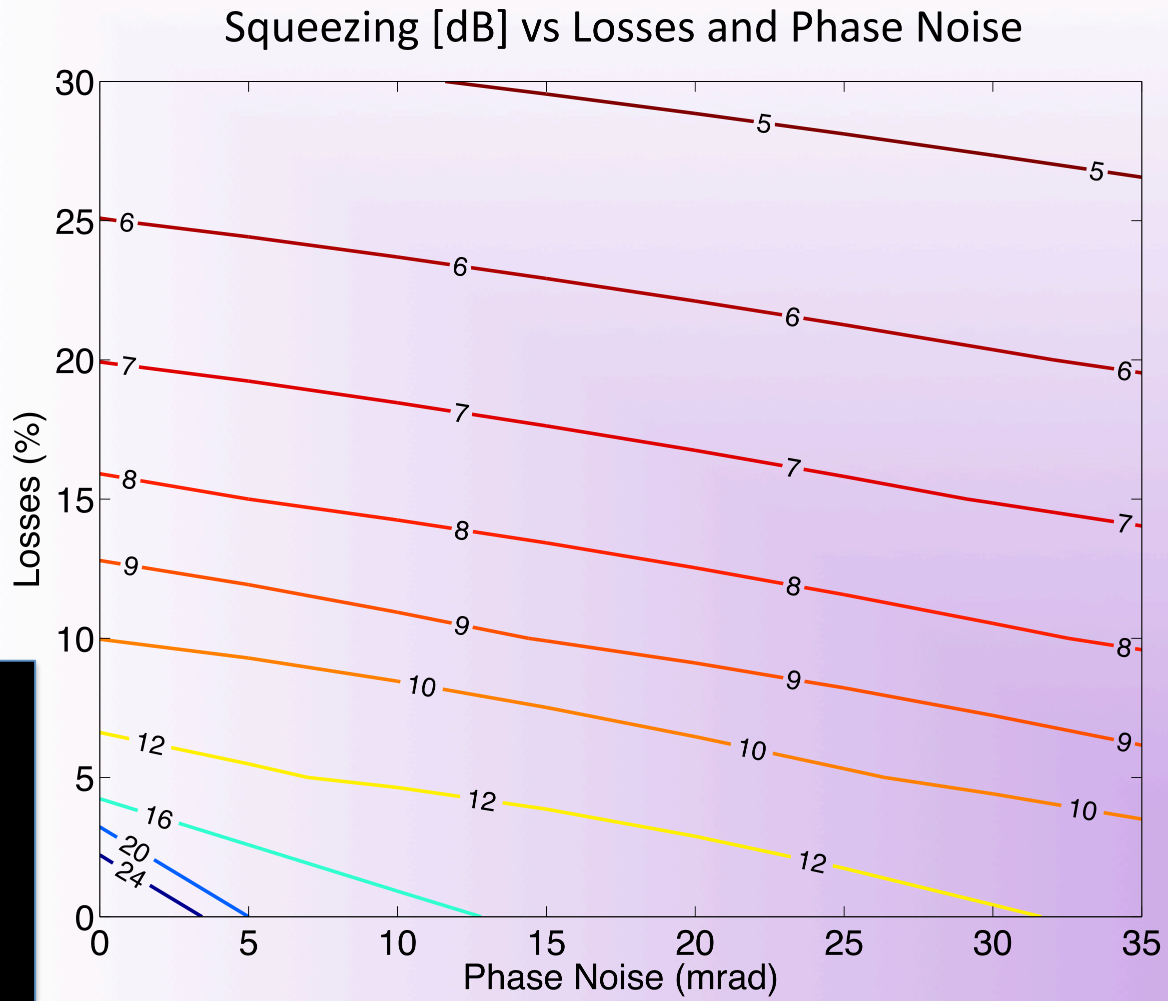
GEO data are courtesy of H. Grote

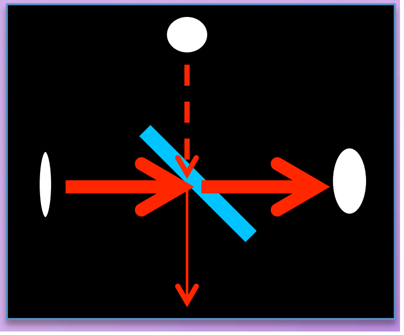
Projections for what we could do for Advanced LIGO



Not only losses, phase noise too

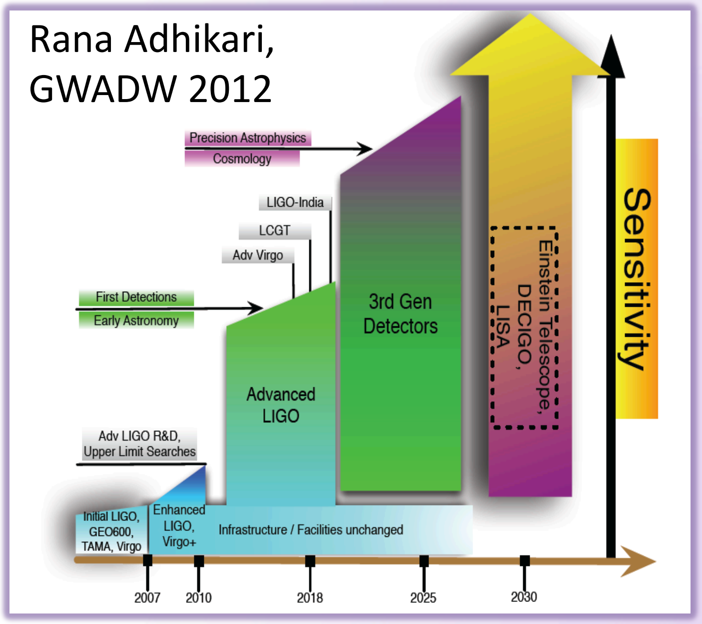






How about a “Quantum-Enhanced Advanced LIGO”?

✧ Do we want it? YES!

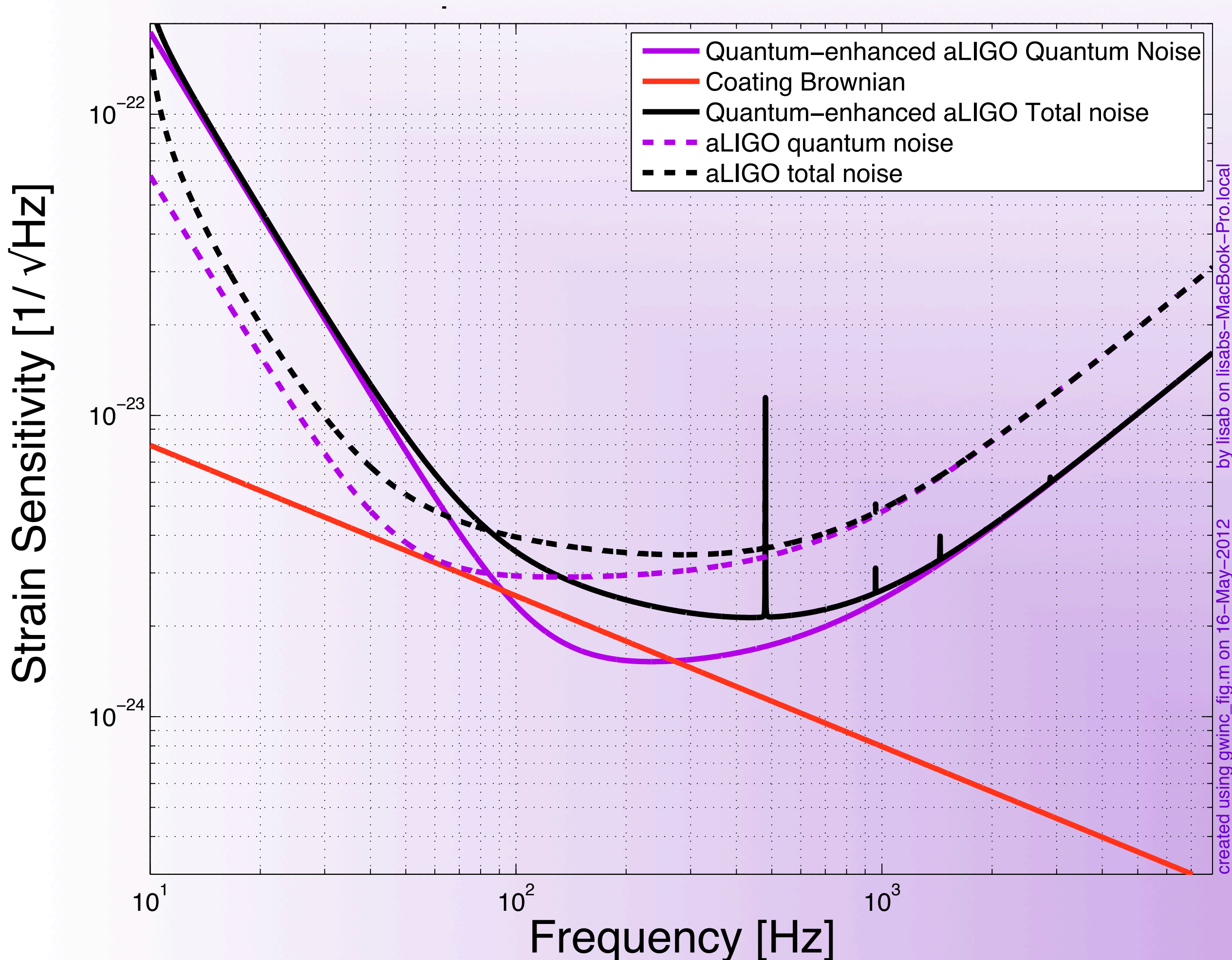


All current ideas for upgrading aLIGO include 10 dB of squeezing

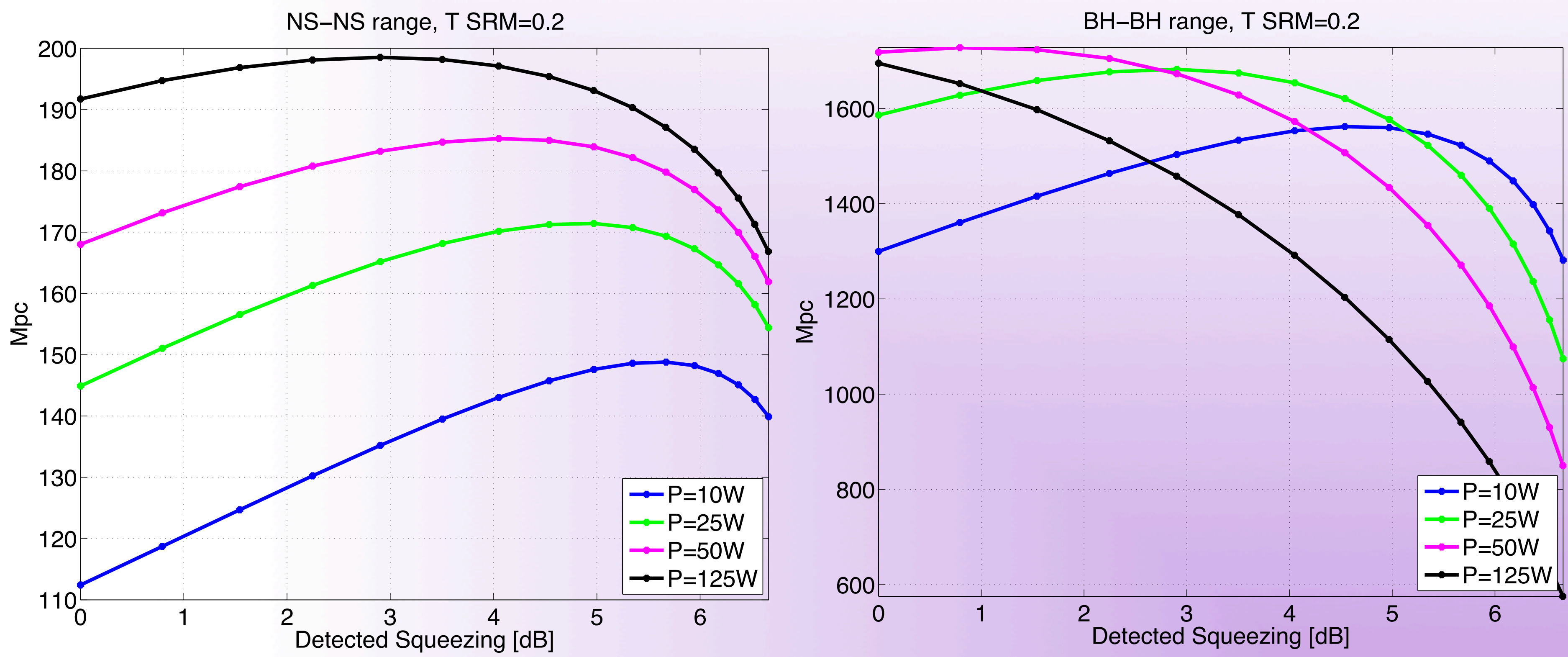
LIGO technical note T1200008-v3 Comparison of Quantum Noise in 3G Interferometer Configurations, Haixing Miao et al.

✧ Do we know how to make it? ALMOST!

Projections for a "Quantum-Enhanced Advanced LIGO"

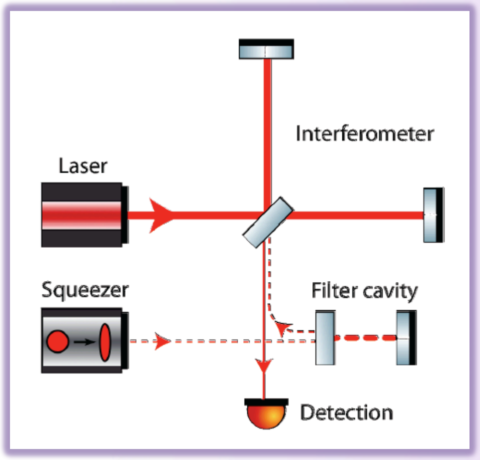


aLIGO + Squeezing: NS-NS and BH-BH Ranges



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)

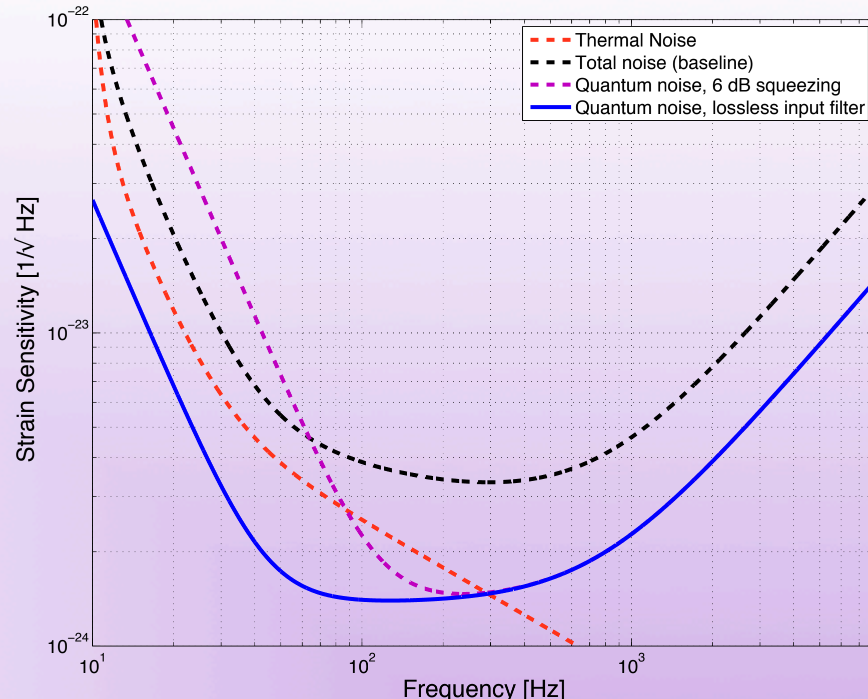
Squeezed-input, optical-spring, signal-recycled gravitational-wave detectors

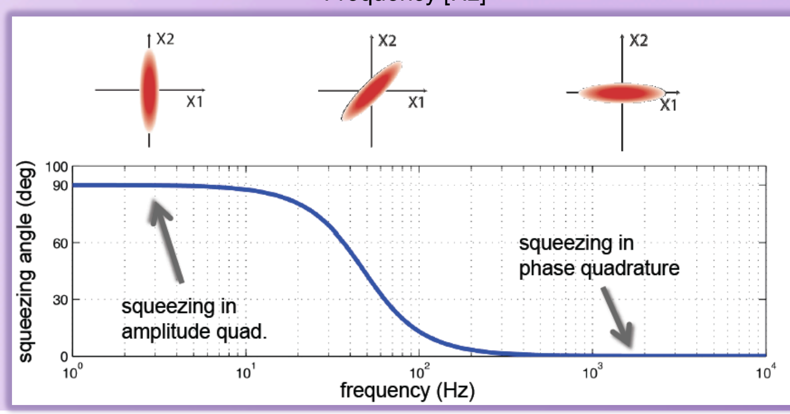
Jan Harms,[1] Yanbei Chen,[2] Simon Chelkowski,[1] Alexander Franzen,[1] Henning Vahlbruch,[1] Karsten Danzmann,[1] and Roman Schnabel[1]

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

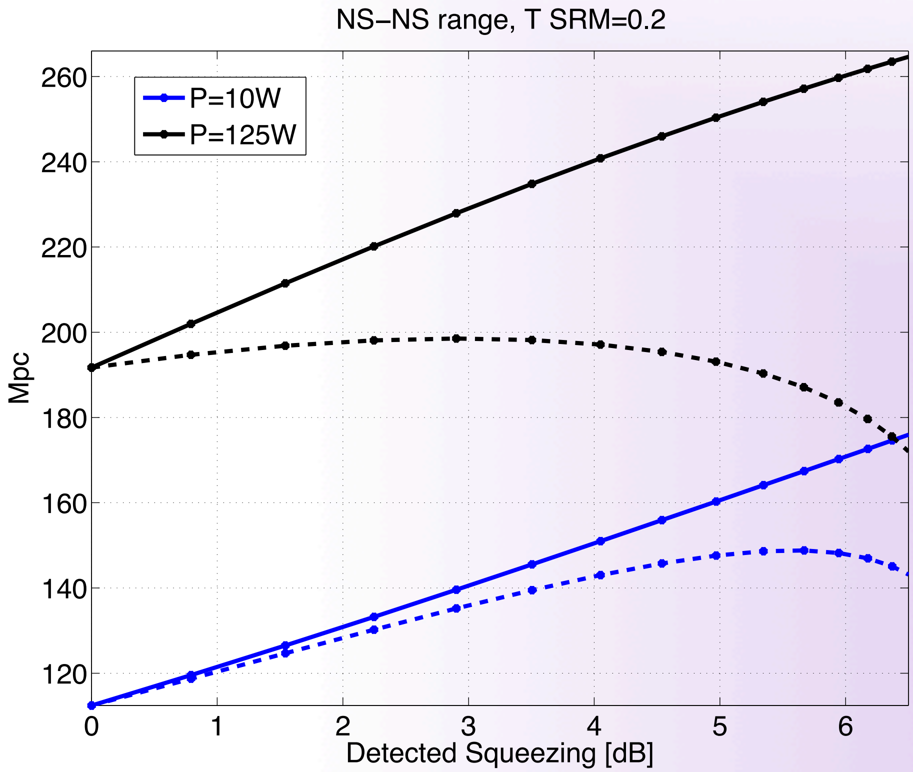
Experimental characterization of frequency-dependent squeezed light

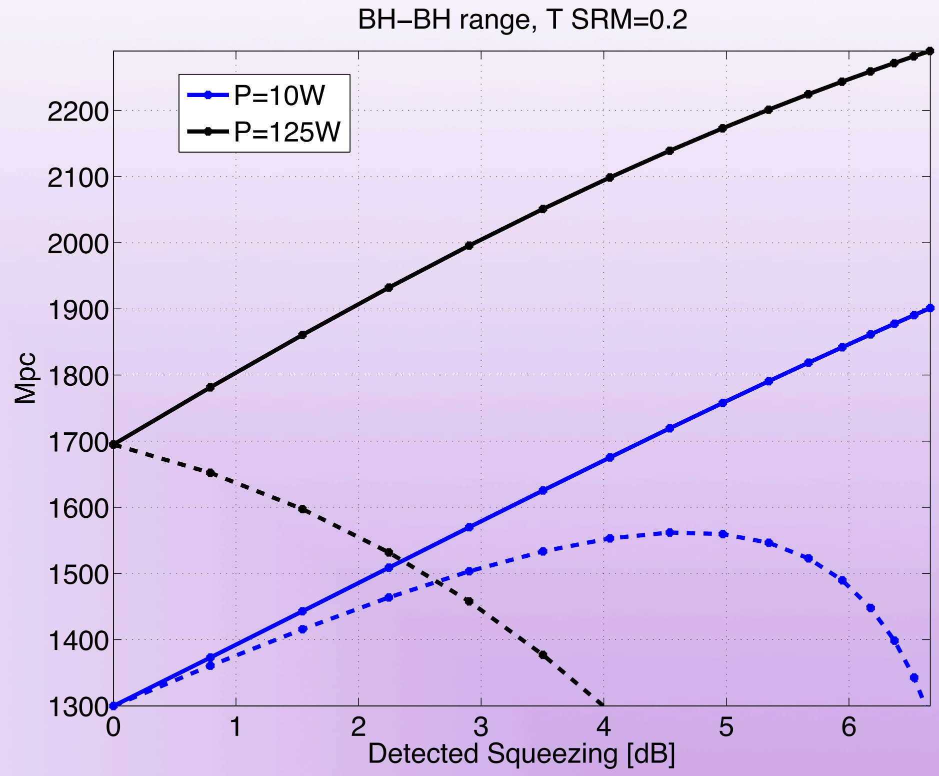
Simon Chelkowski, Henning Vahlbruch, Boris Hage, Alexander Franzen, Nico Lastzka, Karsten Danzmann, and Roman Schnabel





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



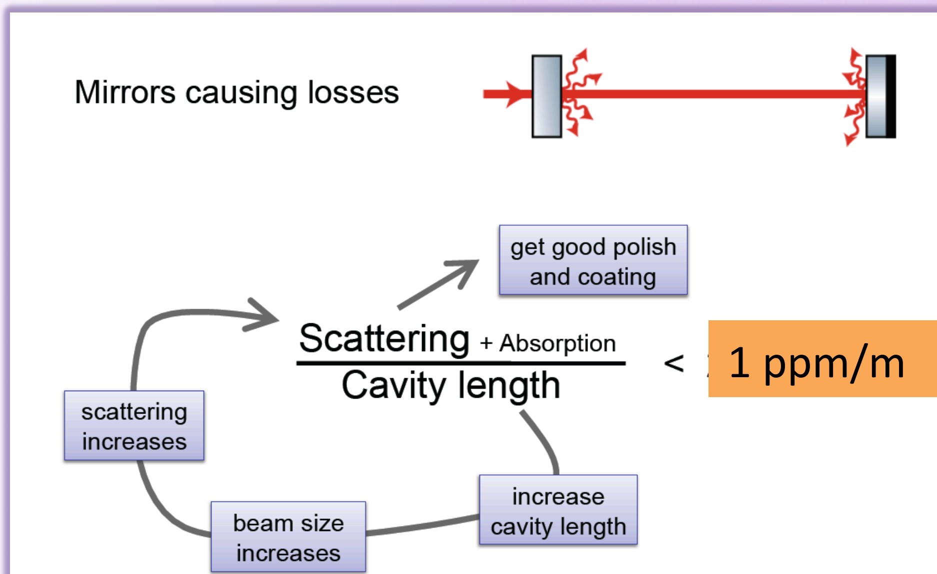


Nothing comes cheap: losses again..

Losses in a filter cavity, 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



Squeezing Experiments @ 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

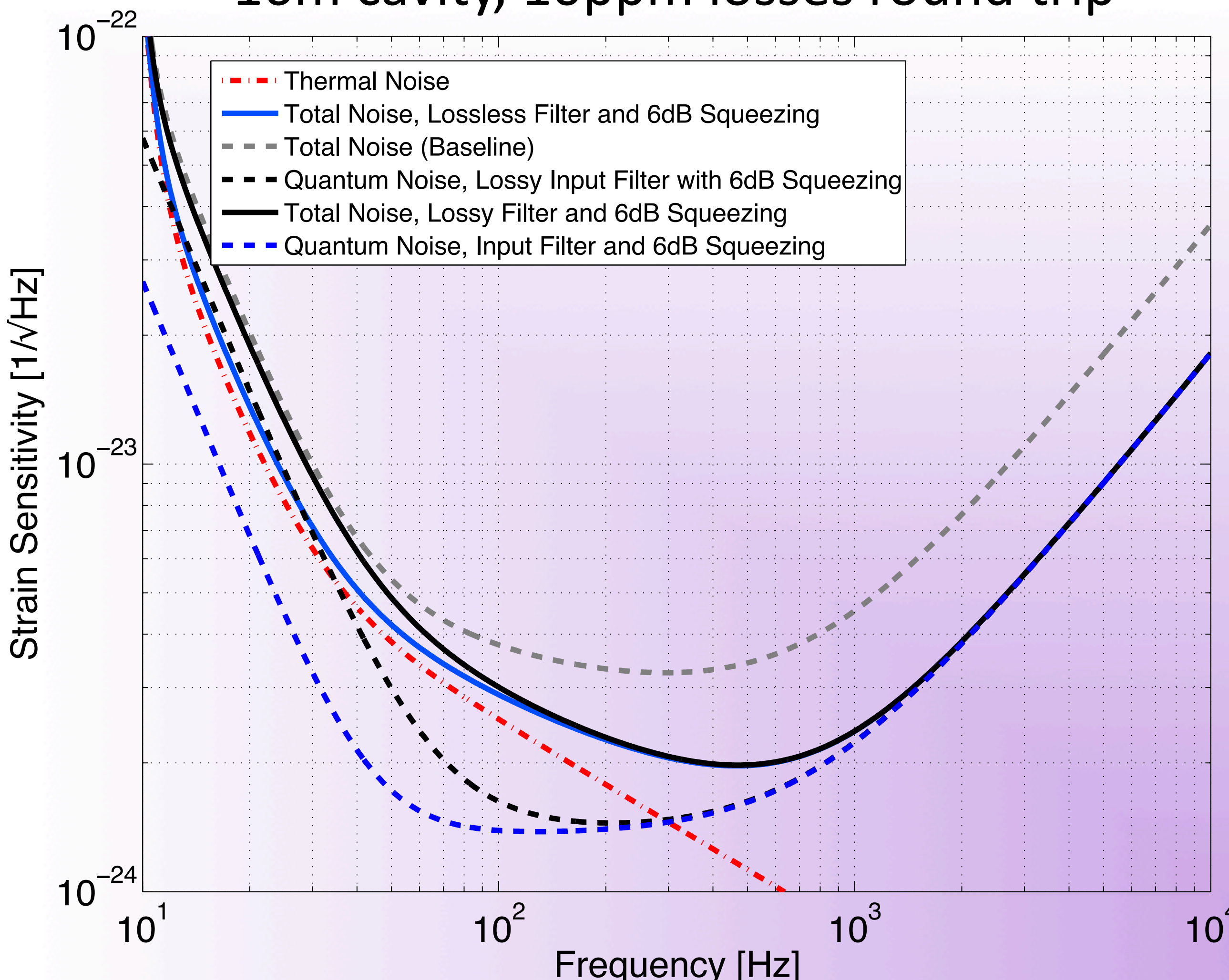
NEW aLIGO SQUEEZER SOURCE

✧ Working on a new design with an in-vacuum squeezer source cavity

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

For aLIGO, we could afford a “lossy” cavity

16m cavity, 10ppm losses round trip

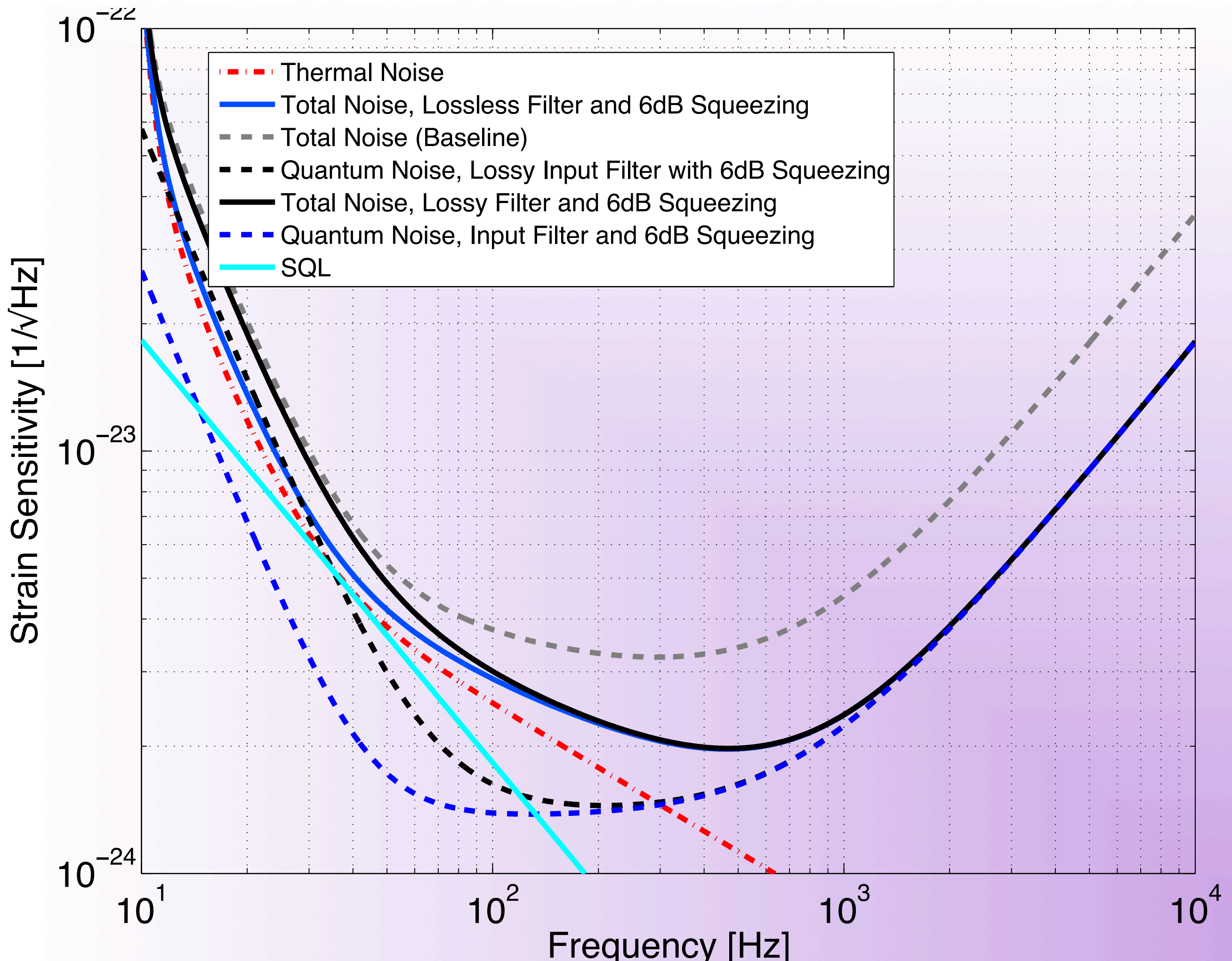


Realistic Filter Cavities for Advanced Gravitational Wave Detectors

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"



Ultimately, what we want is **10 dB** (possibly more!) of broadband squeezing

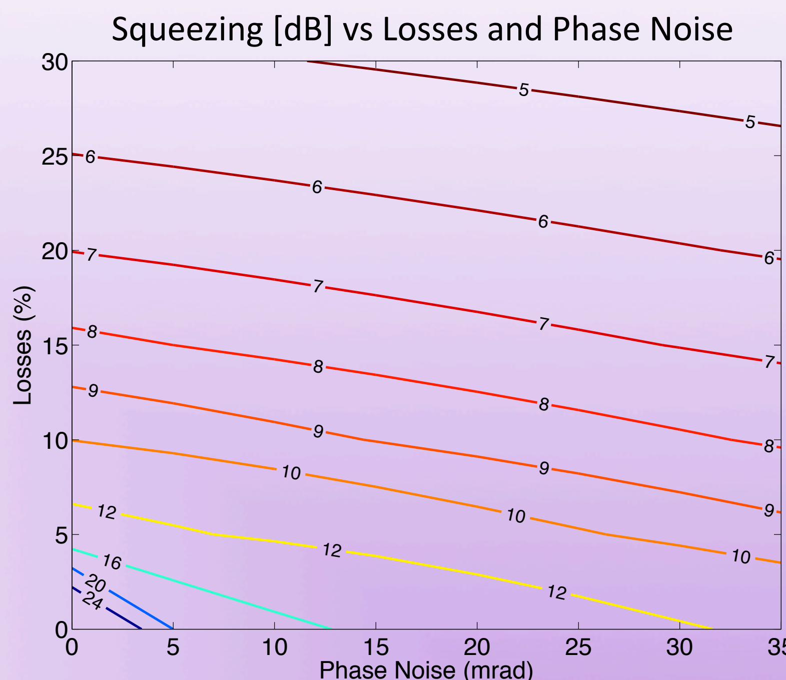
What do we need to do to make that happen?

✧Understand scattering losses for the filter cavity, and cavity control scheme

✧Work on low loss optical components in the squeezed beam path to reduce total losses below 10% (low loss Faradays, ..)

✧Move squeezer source in vacuum

✧Improve control strategy of squeezed beam relative to the interferometer beam



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

GEO600

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

We are doing it!

Conclusions

- Squeezing is not only a "promising" technique anymore…it works!
  - GEO600 reliably employing squeezing in normal operation
  - GEO600 and LIGO H1 squeezing experiment → informed design for aLIGO
- To realize the full potential of squeezing, more research is needed – in progress
  - informed design for a filter cavity in ~ 1 year
- Squeezing could potentially become a first upgrade to aLIGO
  - probably with squeezing at high frequency, "no harm" at low frequency
- Need to keep working on final goal: more squeezing, everywhere

LIGO H1 Squeezing Experiment

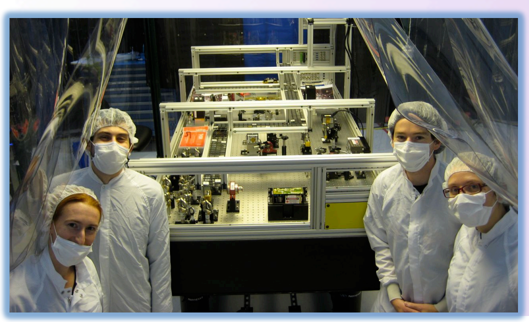
LIGO Hanford Observatory (US)
Massachusetts Institute of Technology (US)
Australian National University (Australia)
Albert Einstein Institute (Germany)

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

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

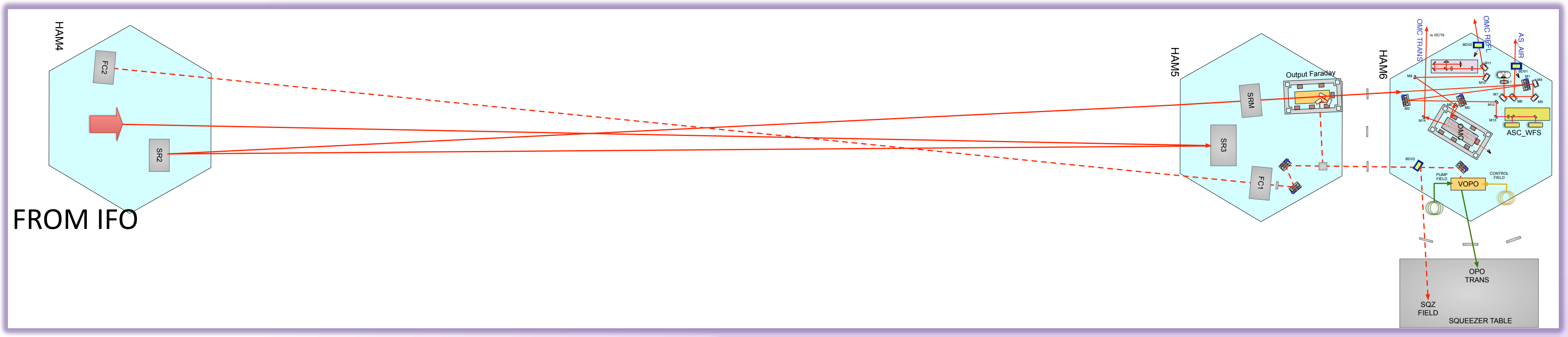
ANU: Sheon Chua, Michael Stefszky, Conor Mow-Lowry, Ping Koy Lam, Ben Buchler, David McClelland

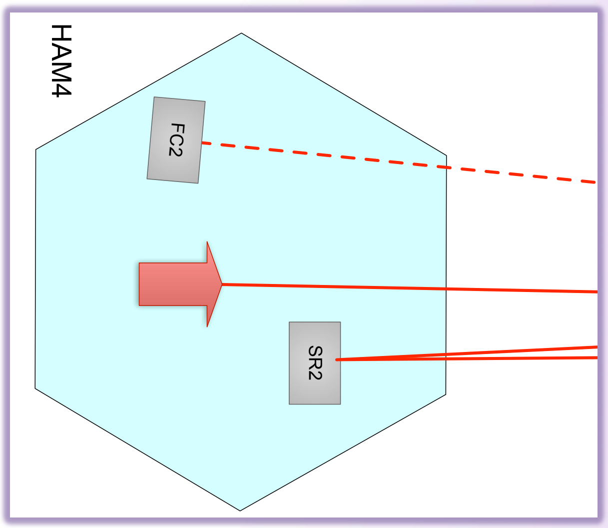
AEI: Alexander Khalaidovski, Roman Schnabel

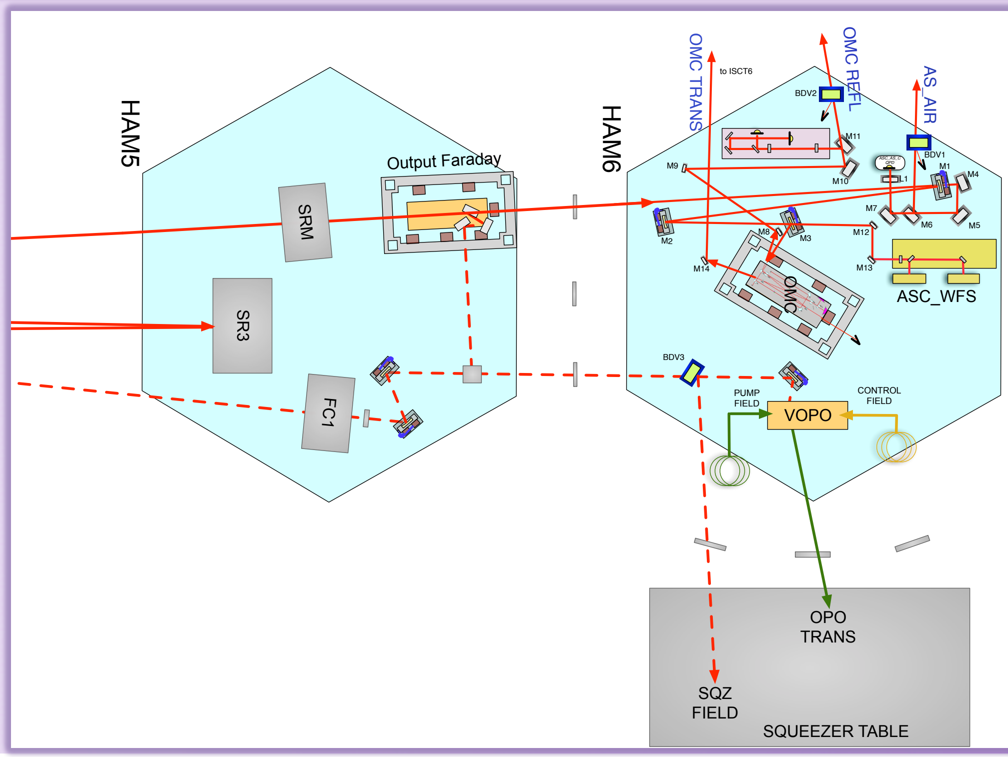


Spare slides

Something like this, maybe….



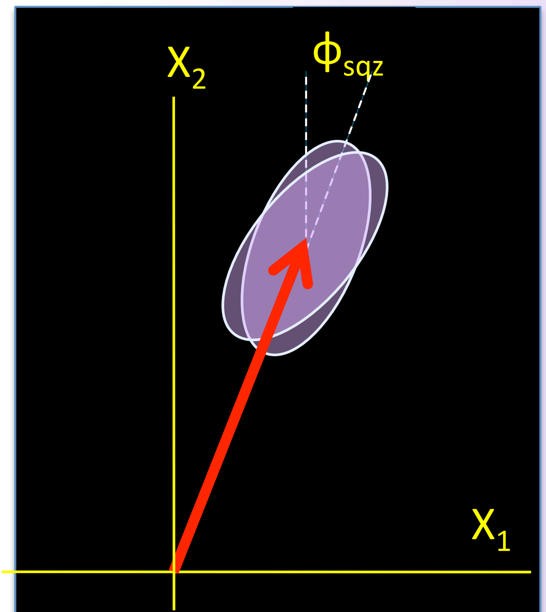


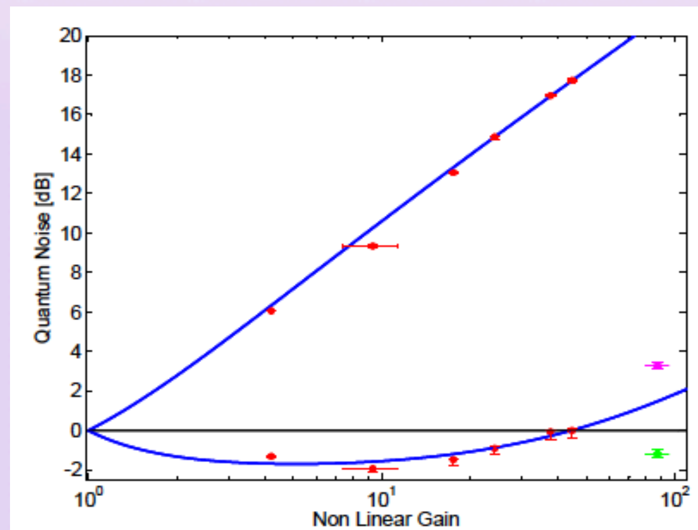


Just a cartoon!
Not a conceptual design yet!

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

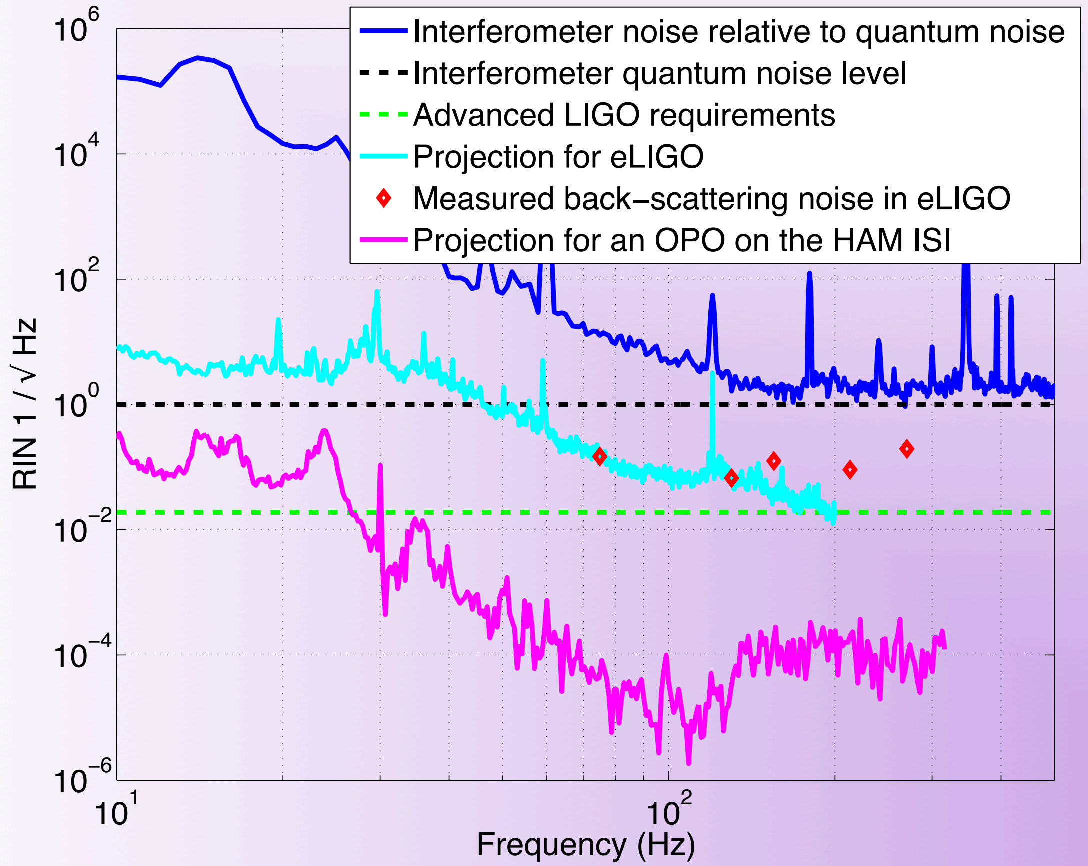
➔ at best ~40 mrad RMS,
only ~ 25mrad from squeezer source

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

Lessons Learned (III)

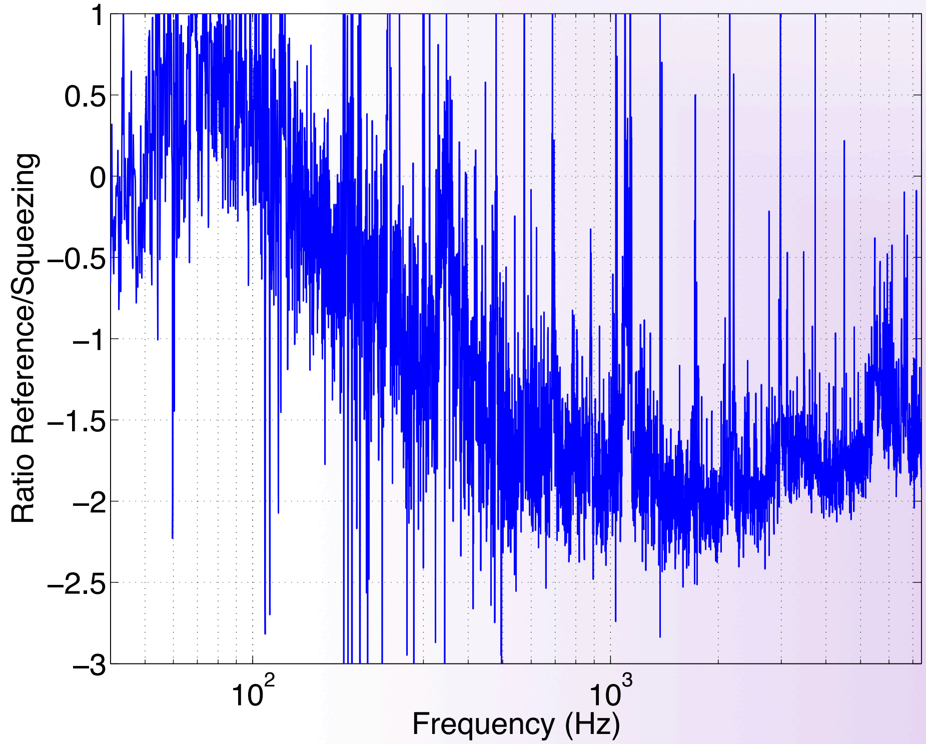
✧ Need better isolation from back scattering

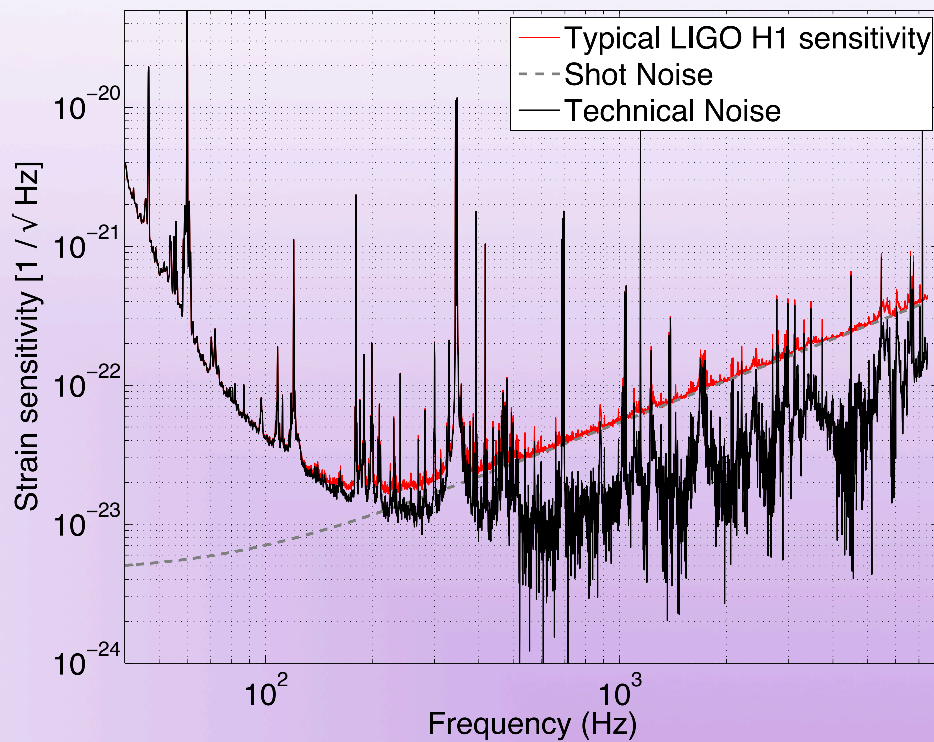
(it was ok for LIGO H1, it won't be enough for aLIGO)



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

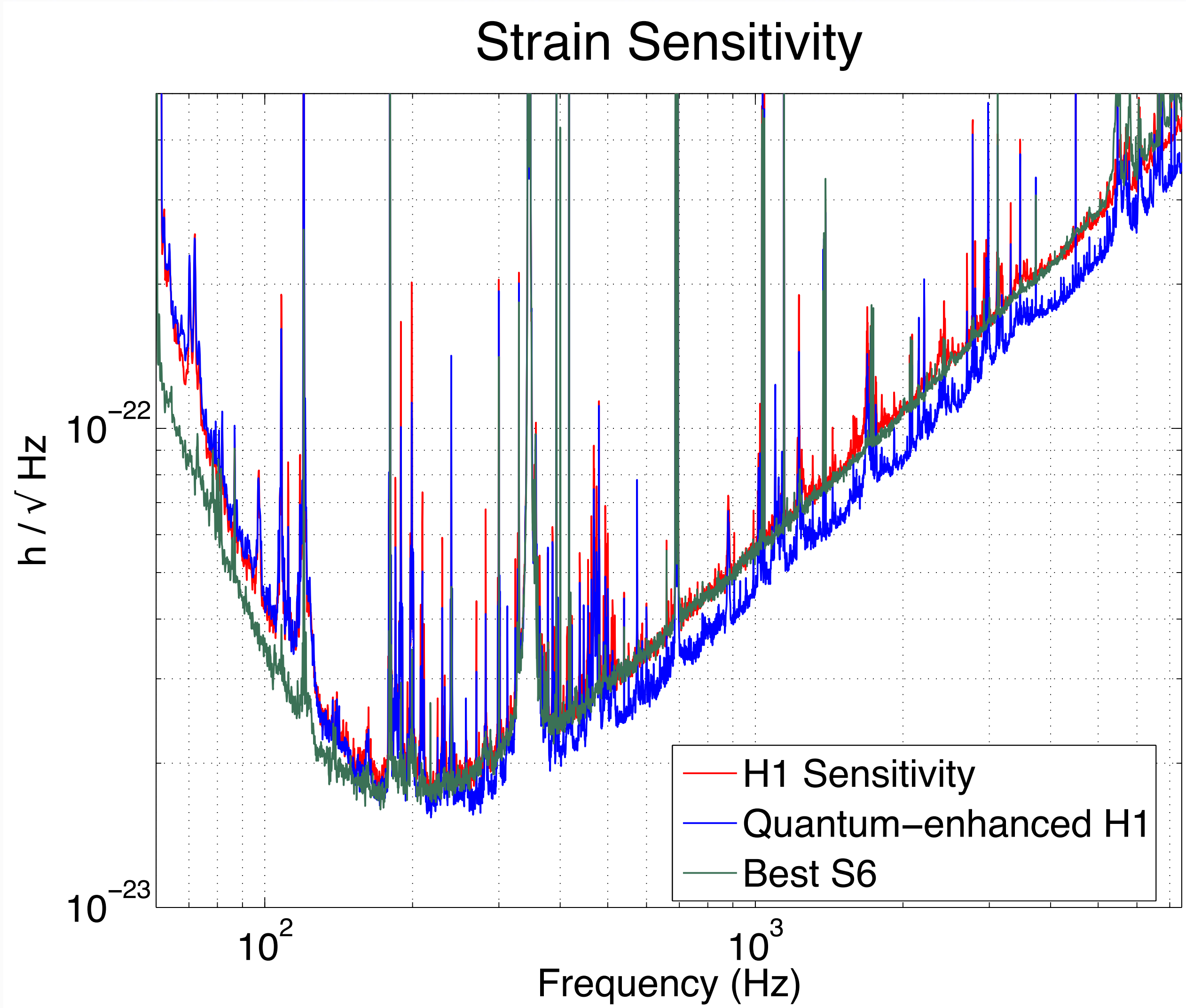
2.15 dB (28%) improvement over quantum noise



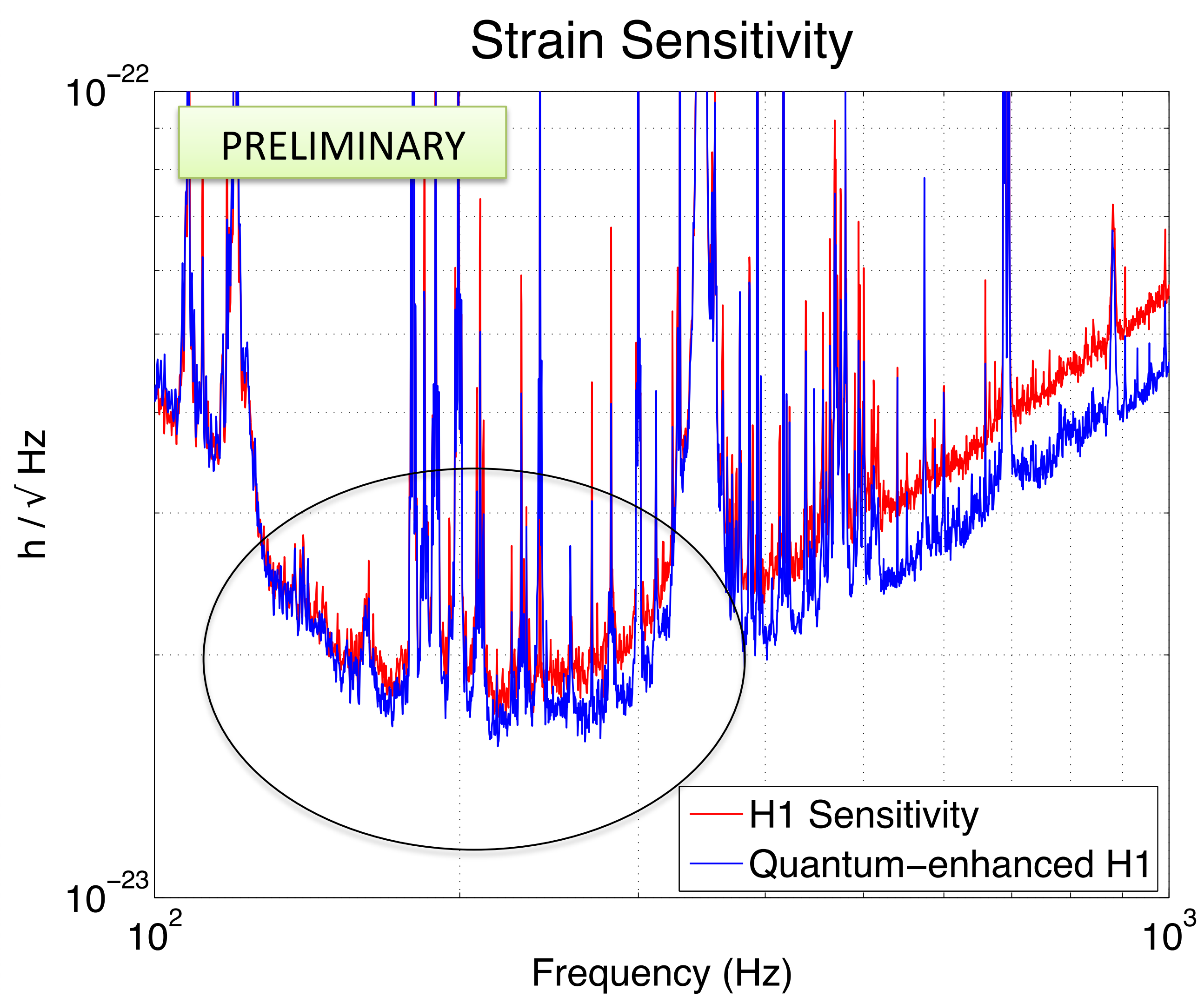


Squeezing improves only quantum noise, not other technical noises

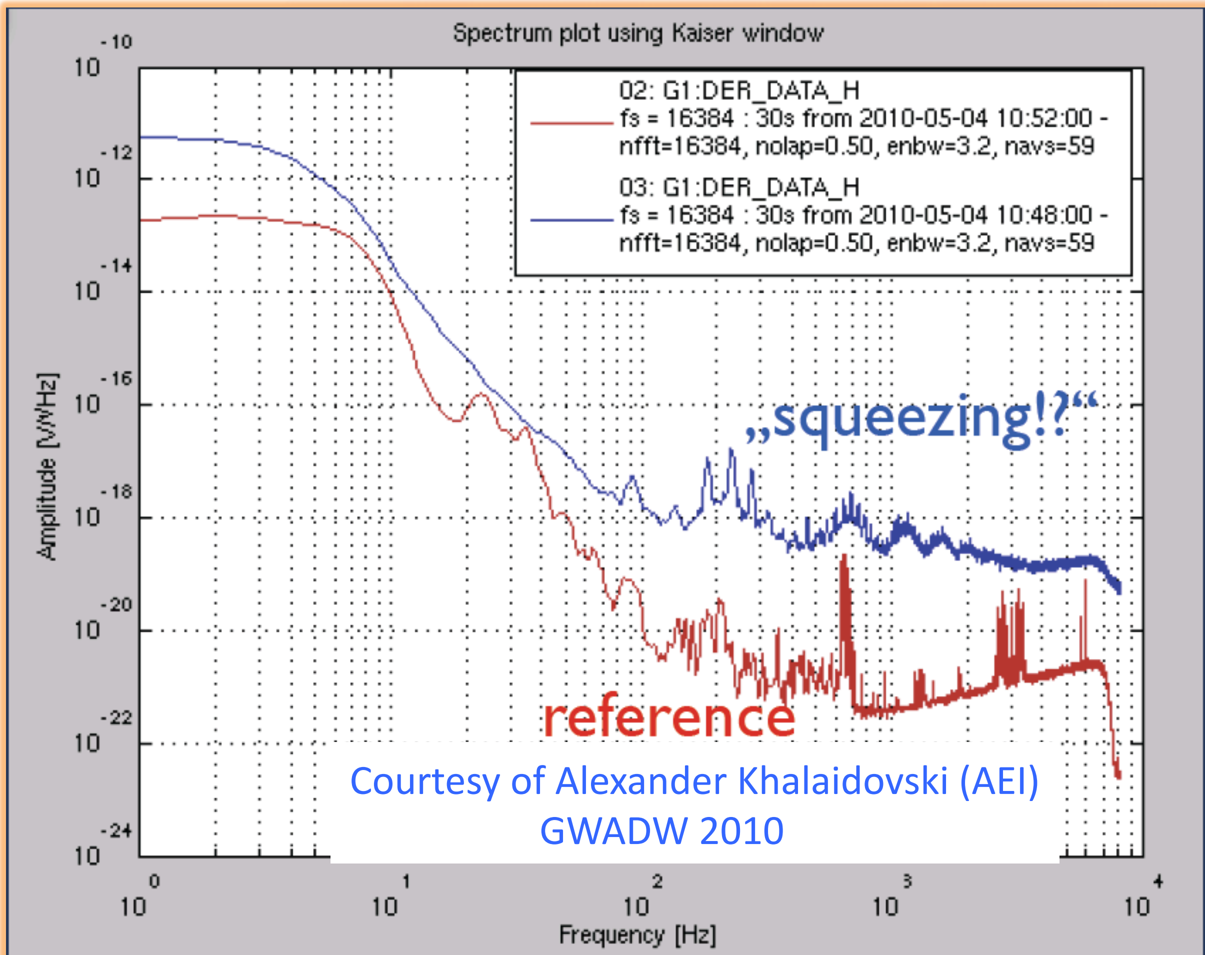
Best broadband sensitivity ever



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

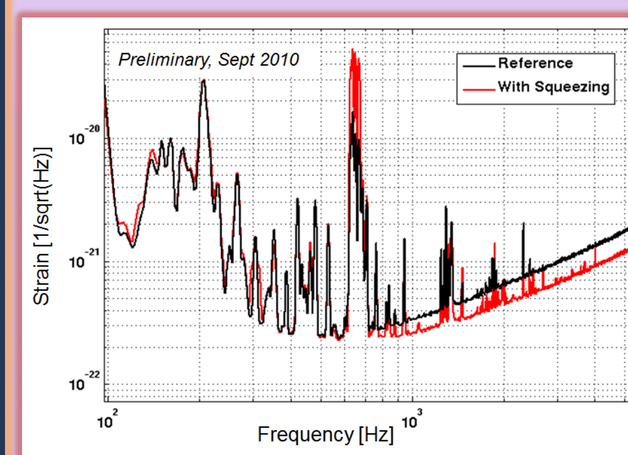


First try at squeezing in GEO



✧ 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)

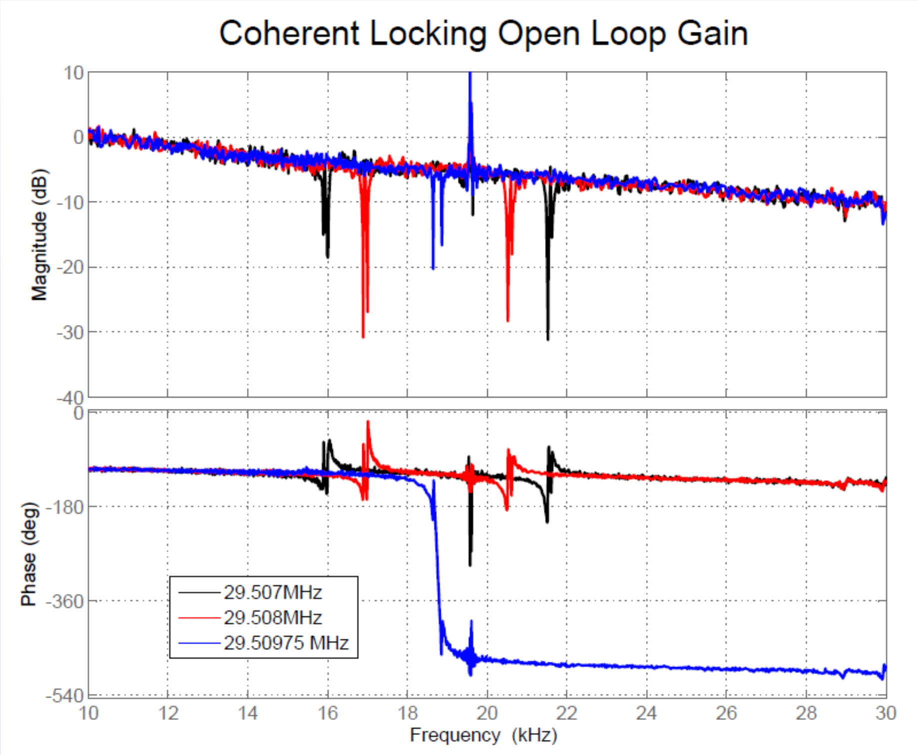
✧ Faradays (3 passes ~ 20% losses)

✧ OMC transmission (18% losses)

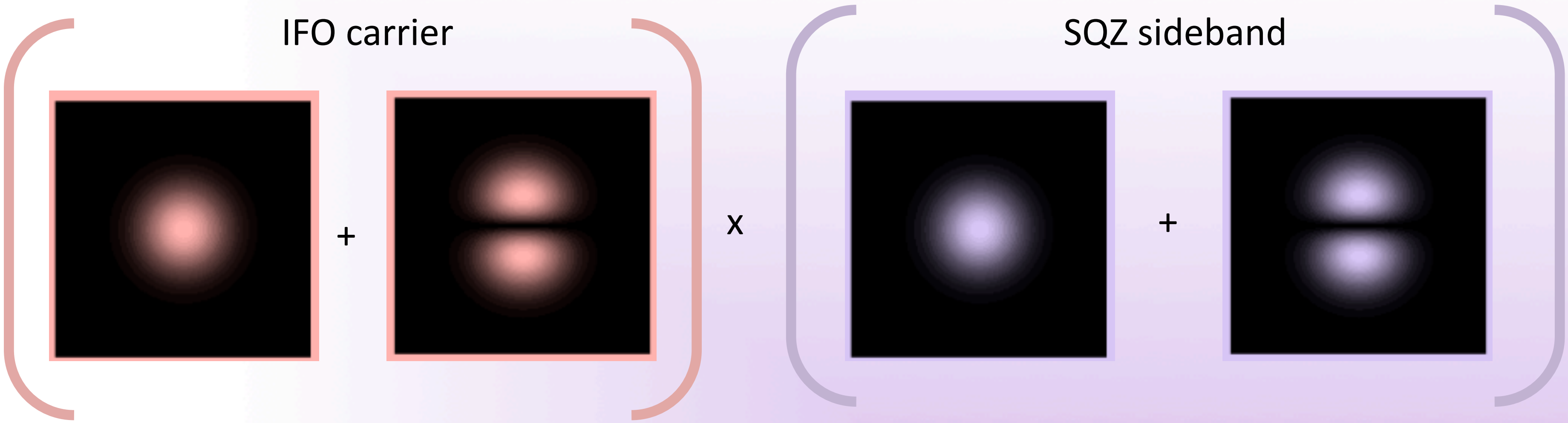
➔ “Technical” problems, total losses should be down to 10-15% in aLIGO

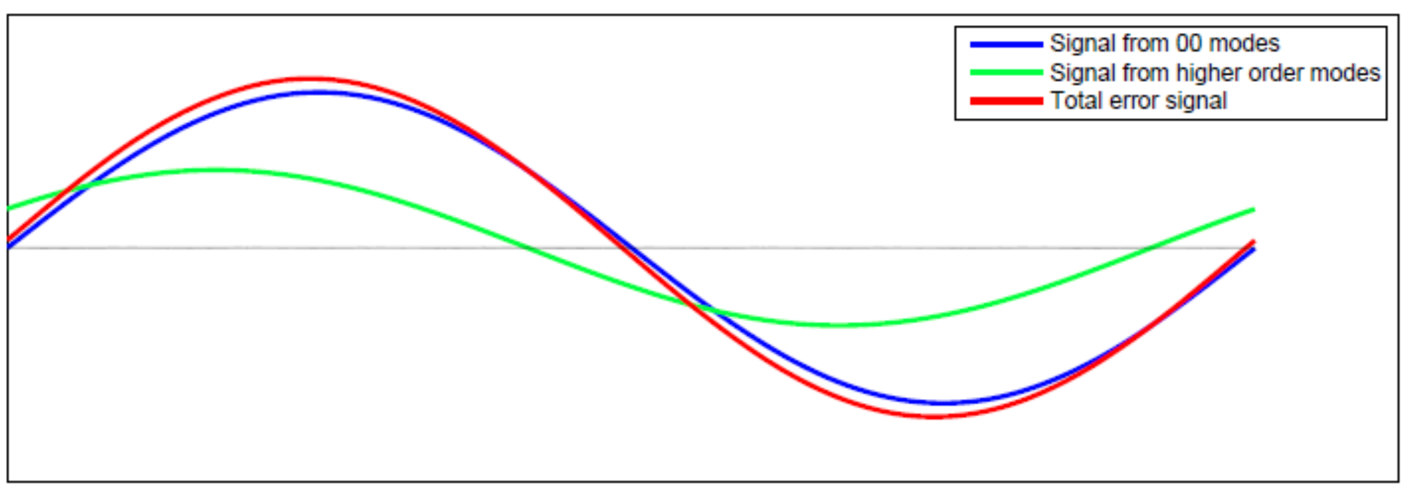
Phase noise control

- 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

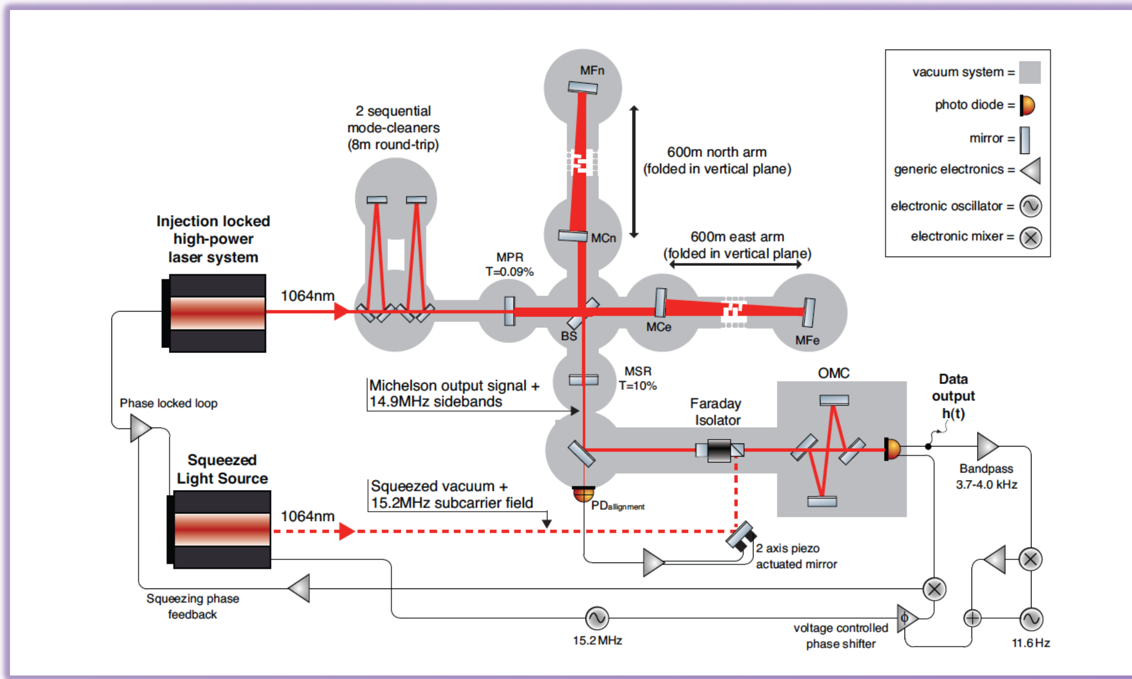




Lessons Learned (VI)

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

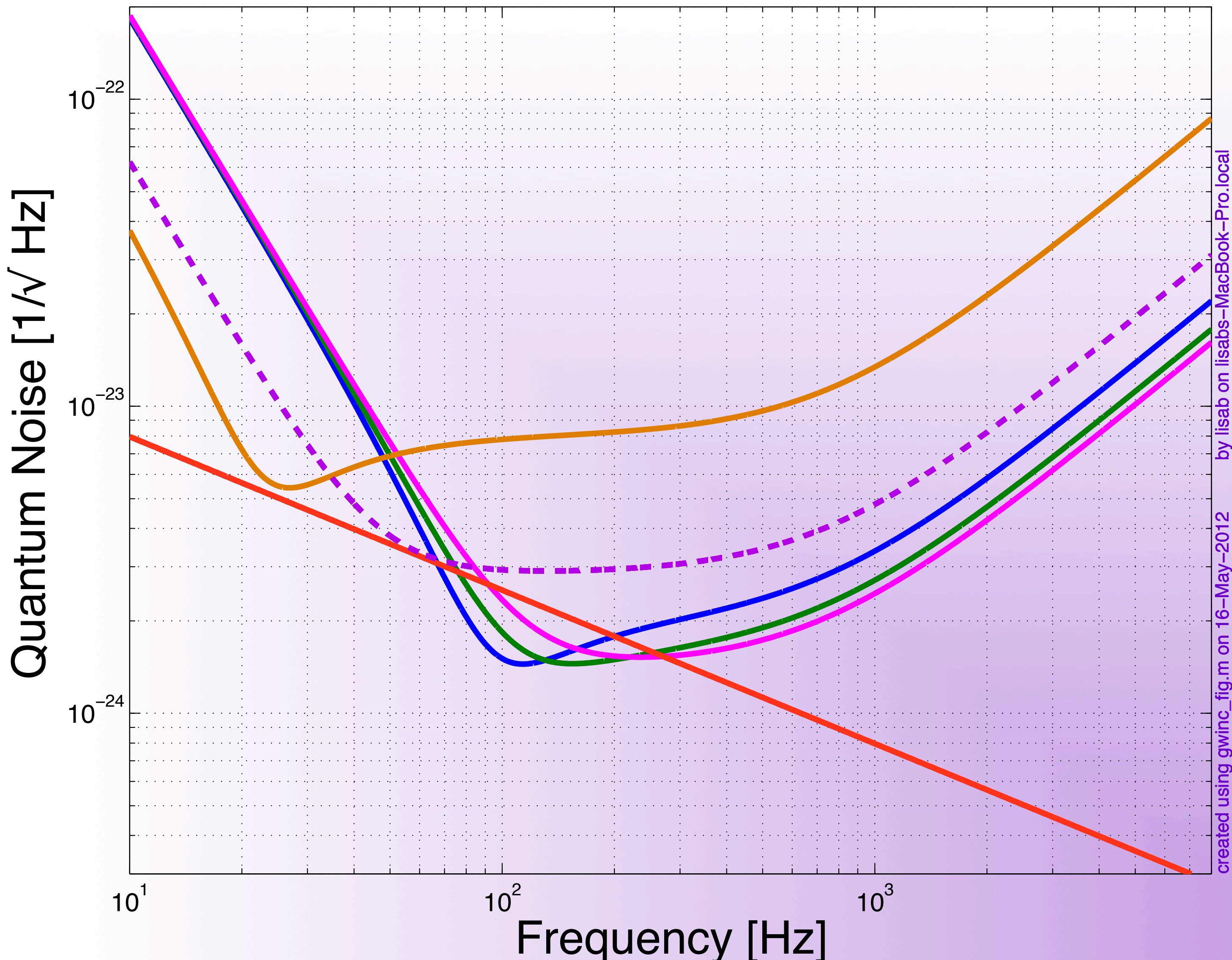
→ New "a-la-Hartmut" strategy (use transmission signals from the OMC)



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

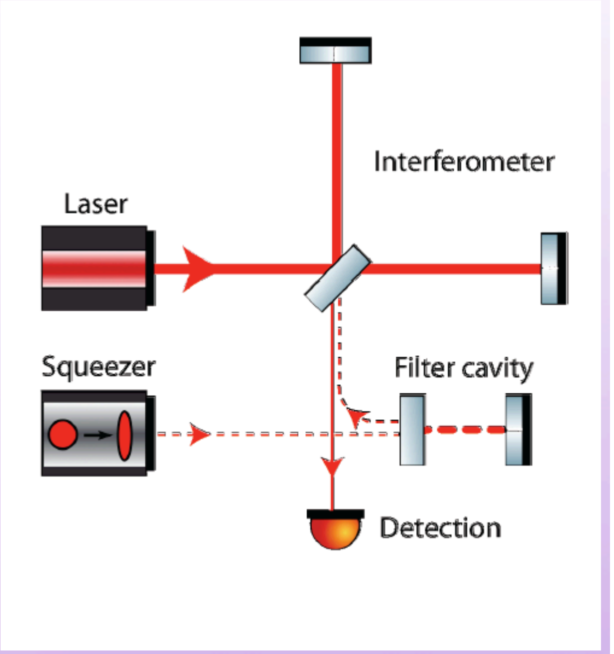
H. Grote,[1,*] K. Danzmann,[1] K.L. Dooley,[1] R. Schnabel,[1] J. Slutsky,[1] and H. Vahlbruch[1]

Quantum noise shaped by squeezed angle



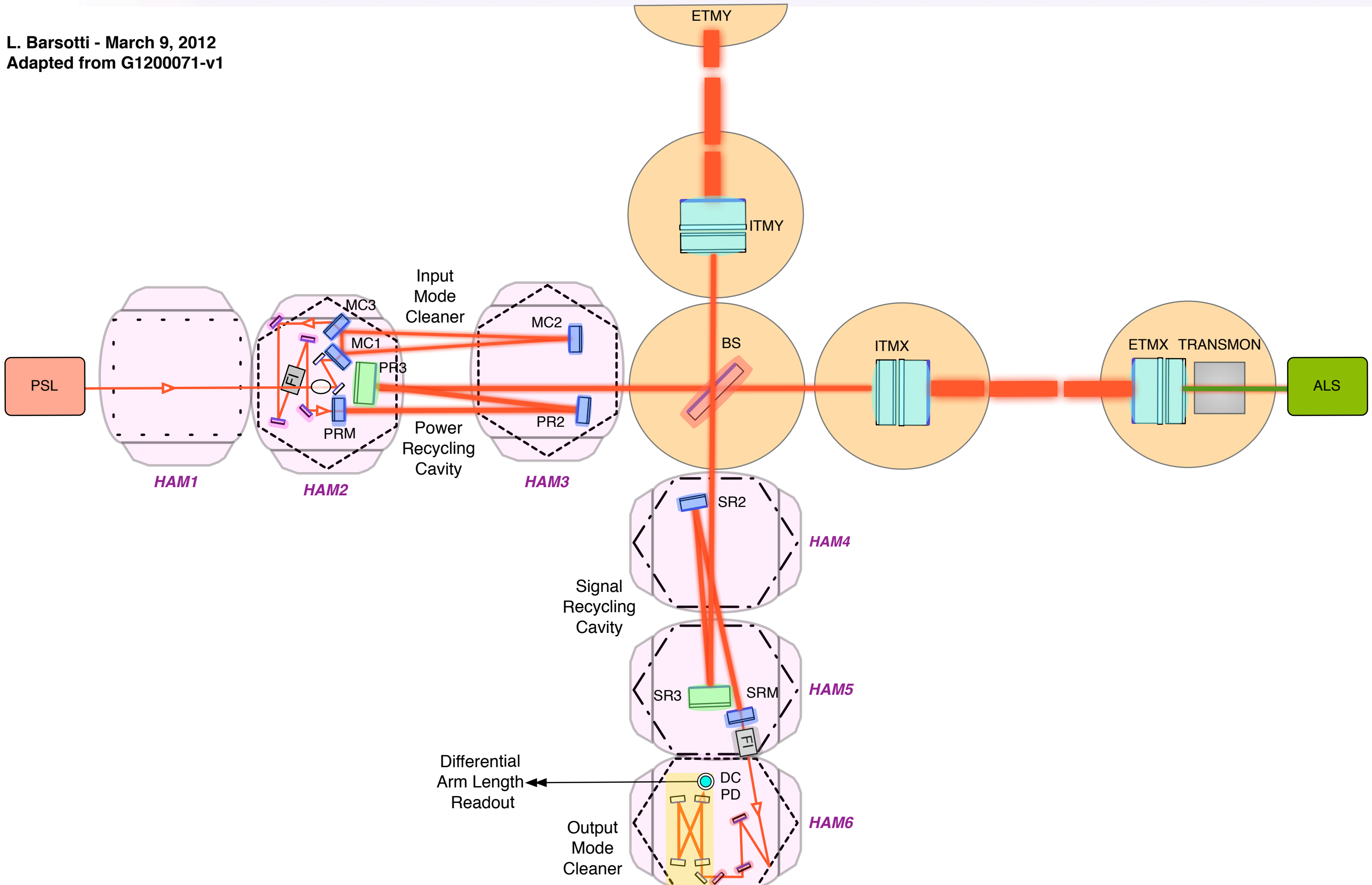
Frequency Dependent Squeezing

- ✧ 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).

Advanced LIGO configuration



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

Quantum States

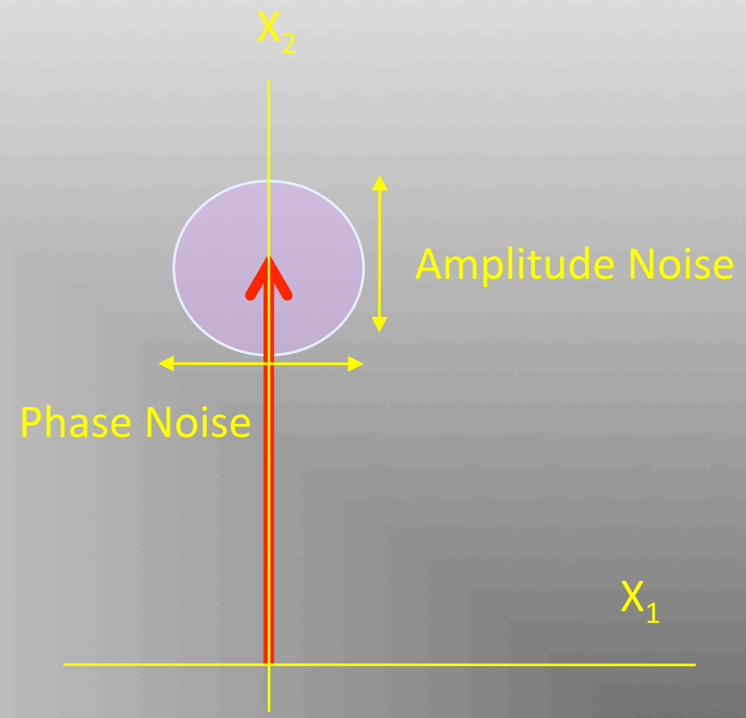
✧ Quantization of the electro-magnetic field

Quadrature Field Amplitudes

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

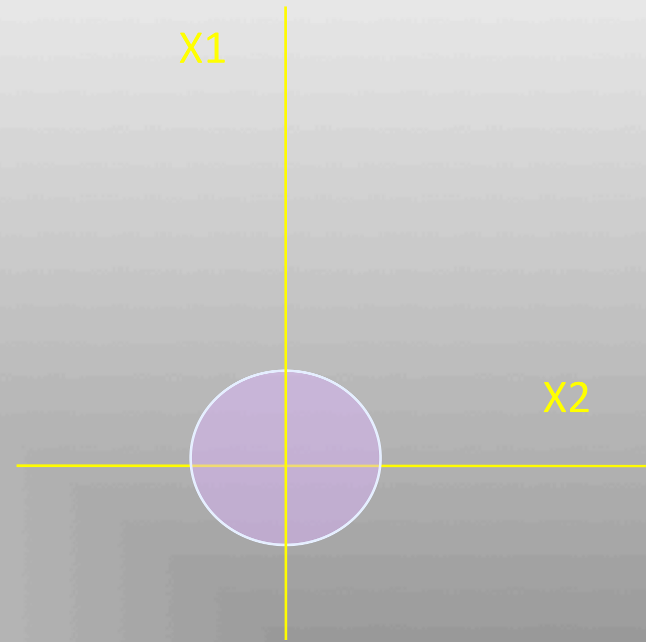
Heisenberg uncertainty principle:

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

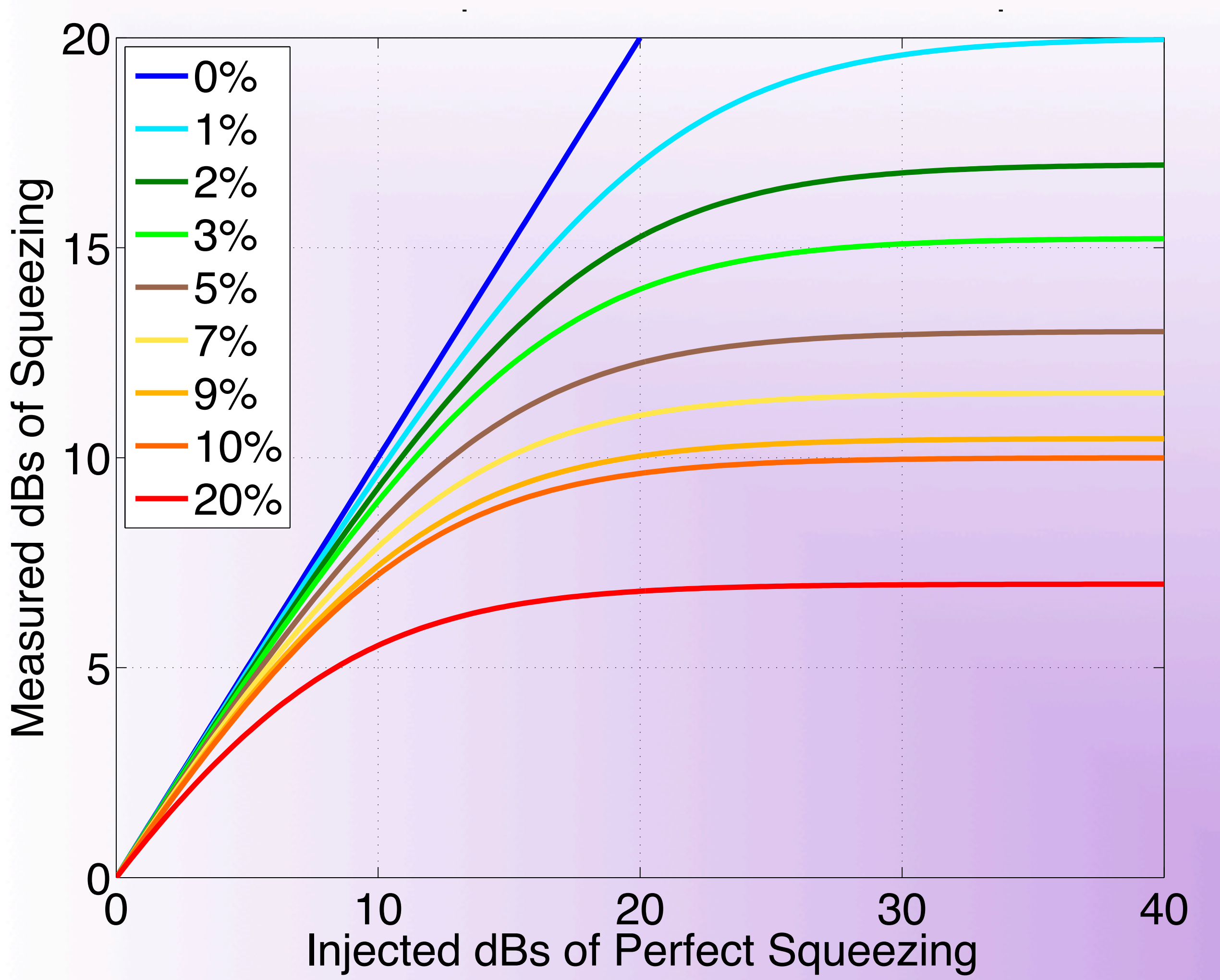


Vacuum Fluctuations

- 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!



Why not even more?



Have to consider phase noise too