Detecting gravitational waves with Advanced LIGO: how, when, and what will come next

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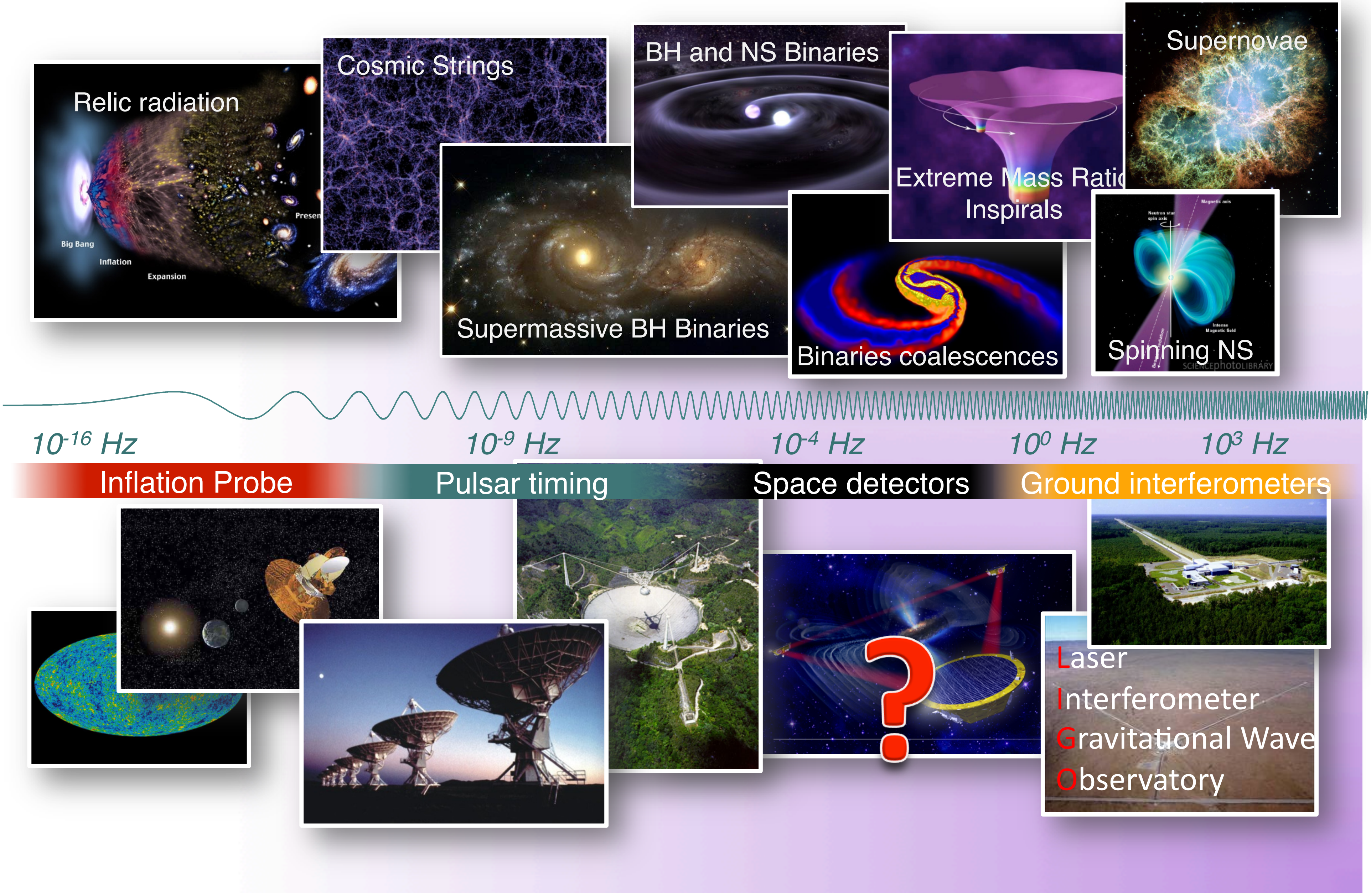
MIT-LIGO Laboratory

LIGO-G1300500-v1

University of Massachusetts Amherst - Apr 26, 2013

Gravitational Waves



Relic radiation

Cosmic Strings

Supermassive BH Binaries

BH and NS Binaries

Binaries coalescences

Extreme Mass Rati
Inspirals

Supernovae

Spinning NS

10^{-16} Hz

10^{-9} Hz

10^{-4} Hz

10^{0} Hz

10^{3} Hz

Inflation Probe

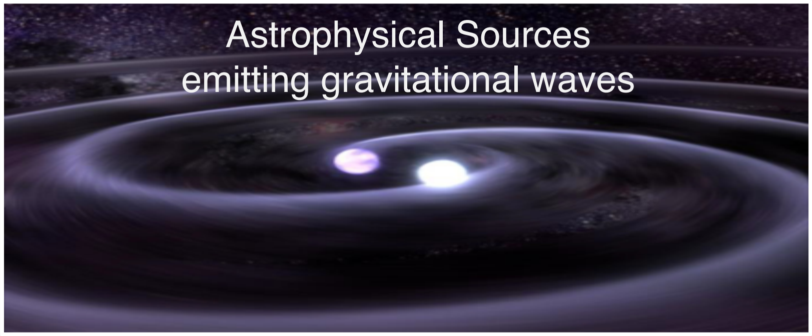
Pulsar timing

Space detectors

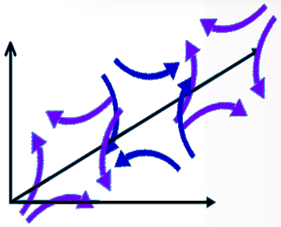
Ground interferometers

Laser
Interferometer
Gravitational Wave
Observatory

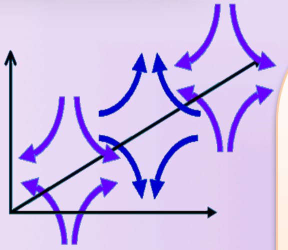
Gravitational Waves Detection: How

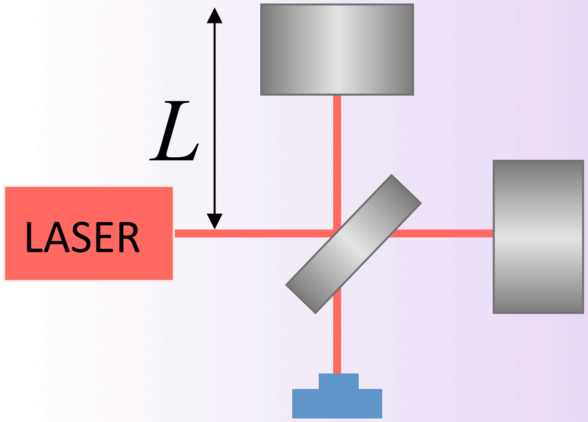

Astrophysical Sources emitting gravitational waves

h is amplitude of gravitational waves, and it is expected to be SMALL



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





Michelson Interferometer

Difference in arm lengths ↓

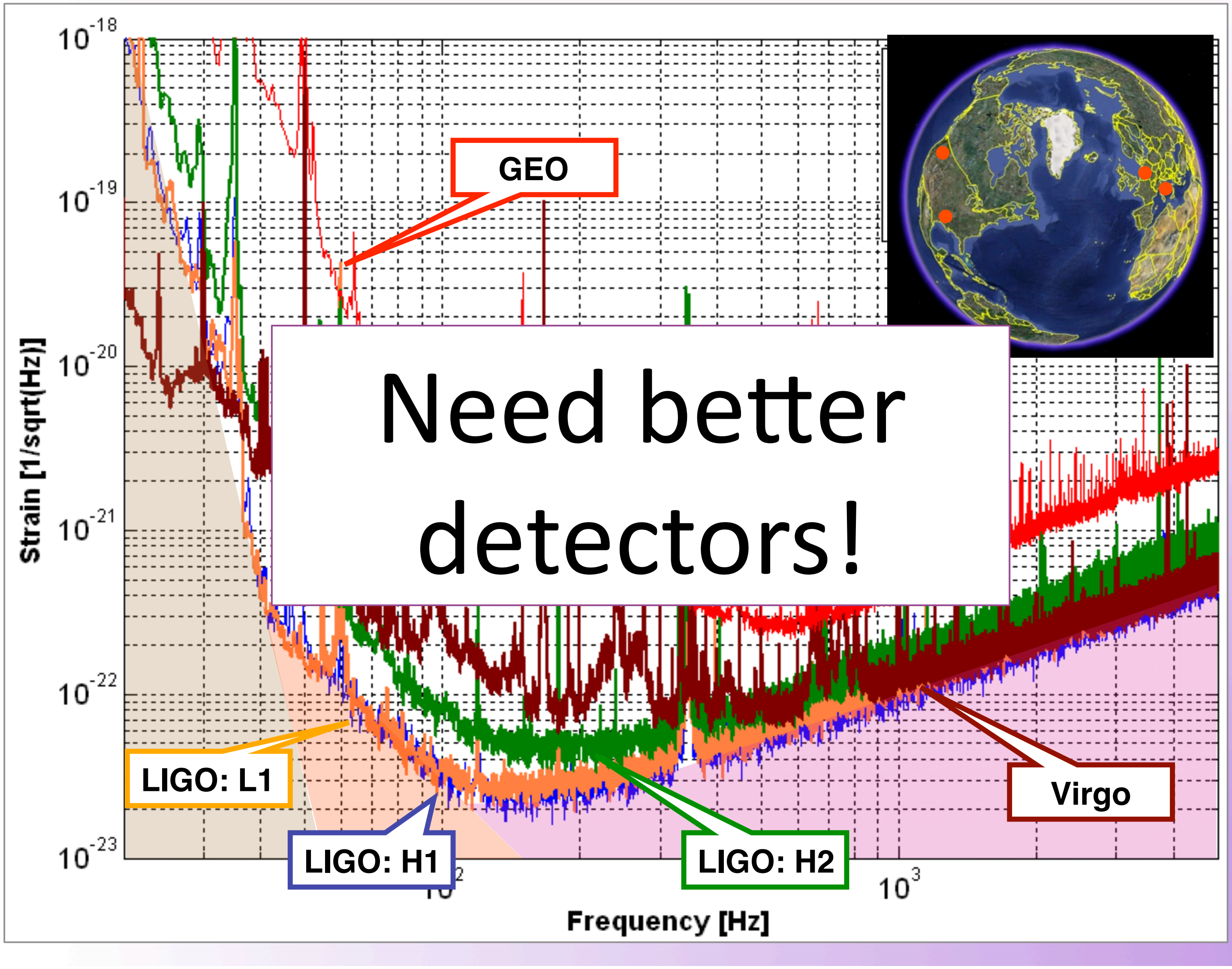
GW Amplitude ↙

$$\Delta L = Lh$$

$$\sim 10^{-22} \times 4\ km$$

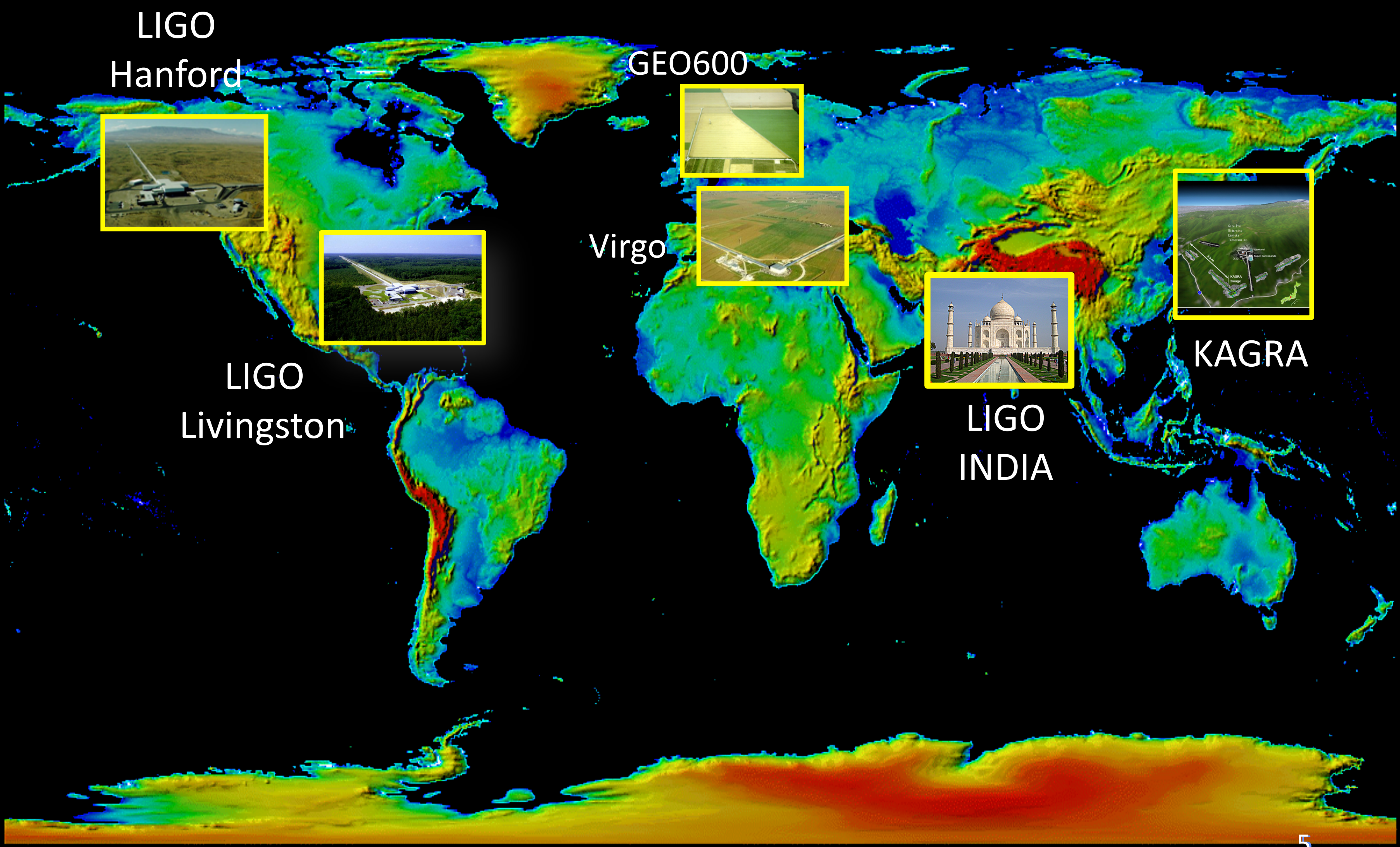
$$\sim 10^{-18}$$

“First Generation” GW Detectors… …NO DETECTION ☹

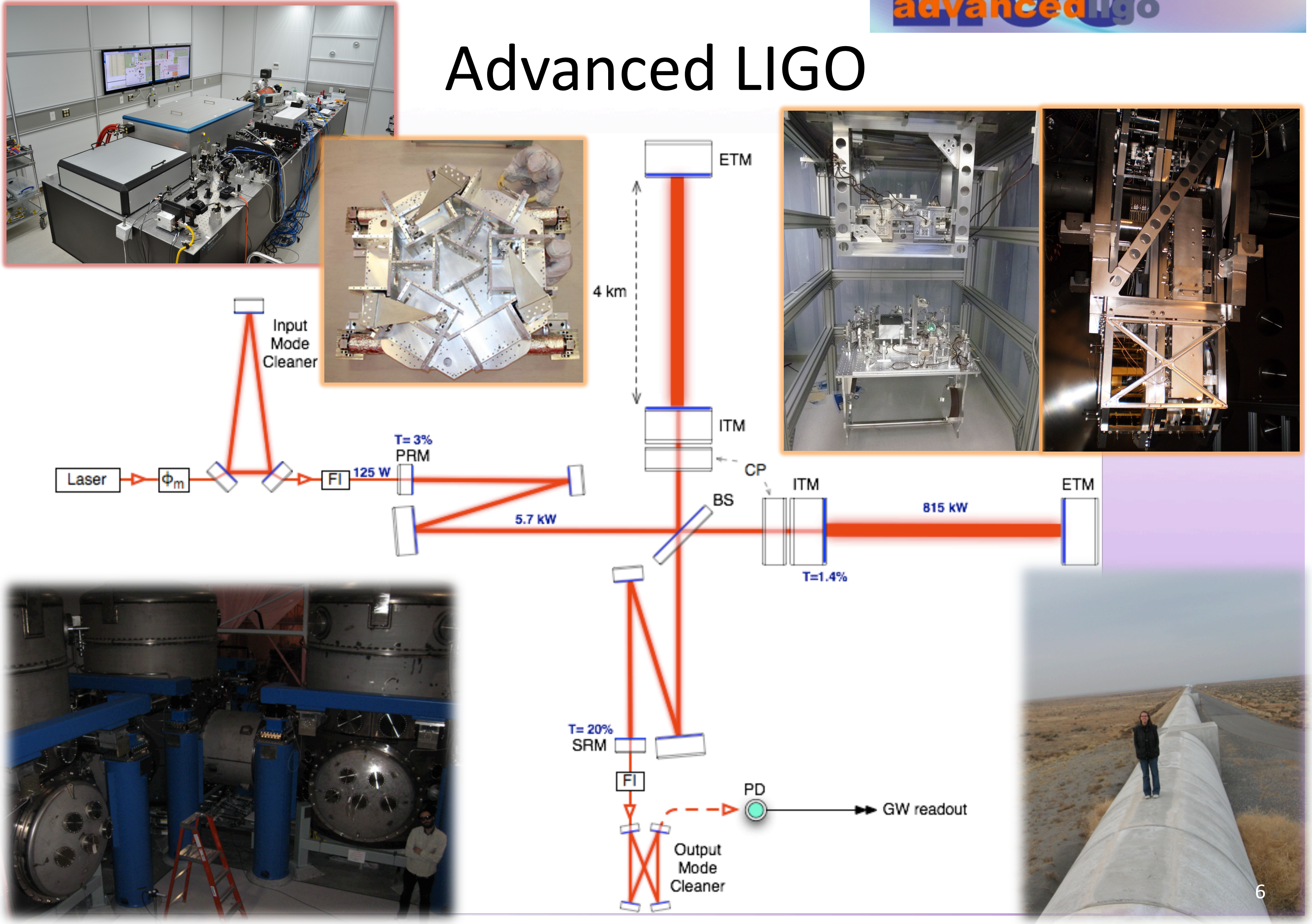


Need better detectors!

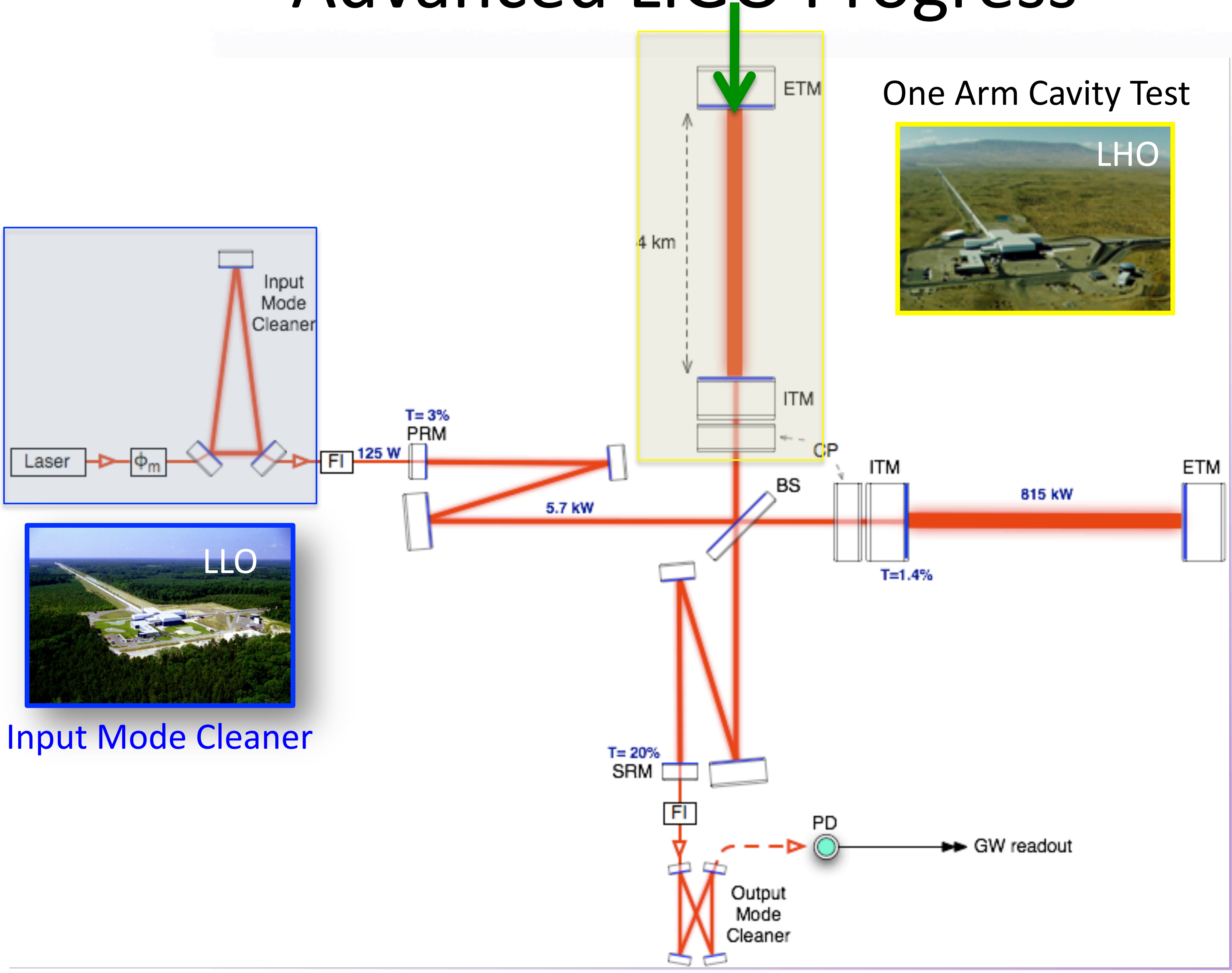
The Upcoming Gravitational Wave Network



Advanced LIGO



Advanced LIGO Progress

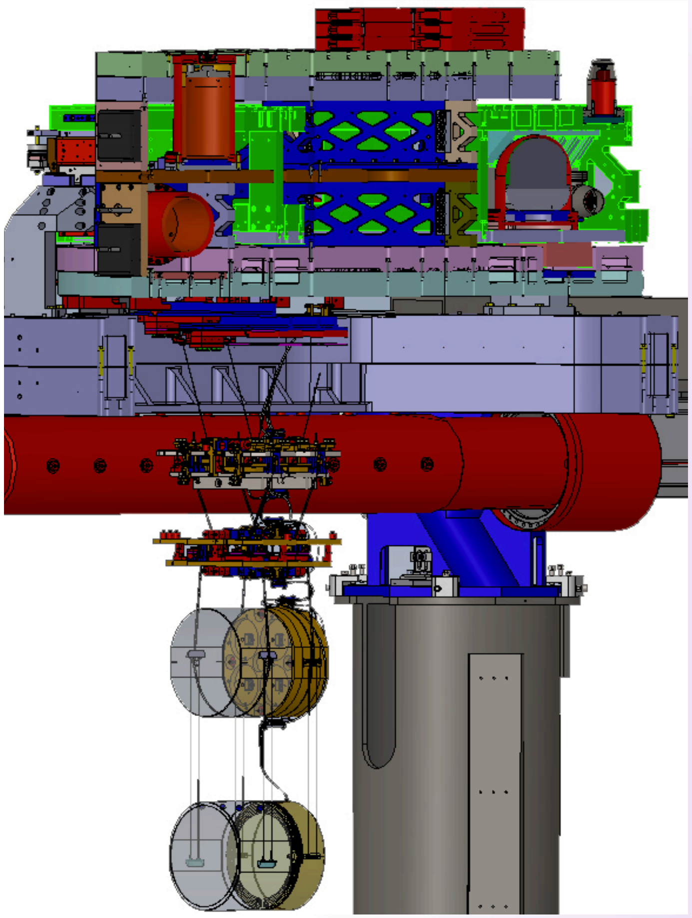


One Arm Cavity Test

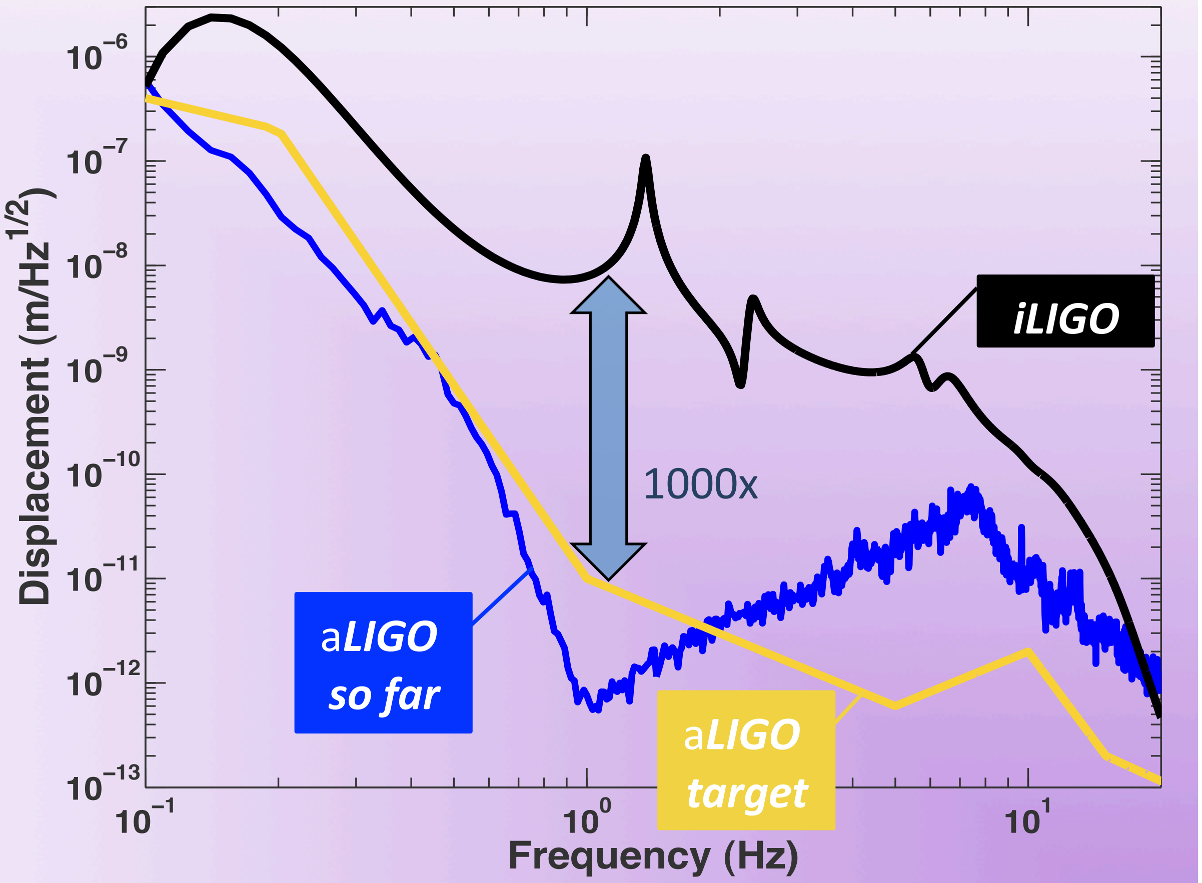
Input Mode Cleaner

Highlights from Hanford:

Seismic noise transferred to the arm cavity suspensions



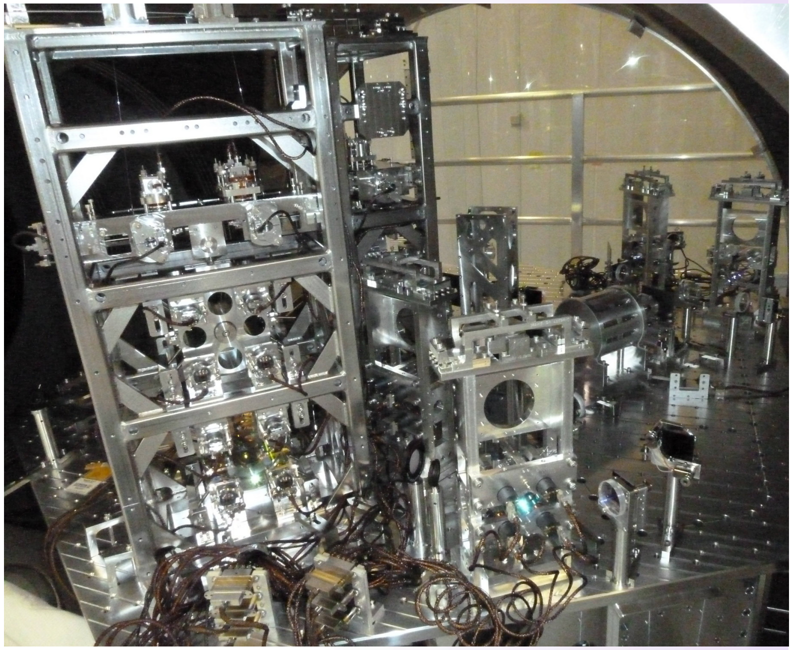
Seismic noise transferred to the suspensions

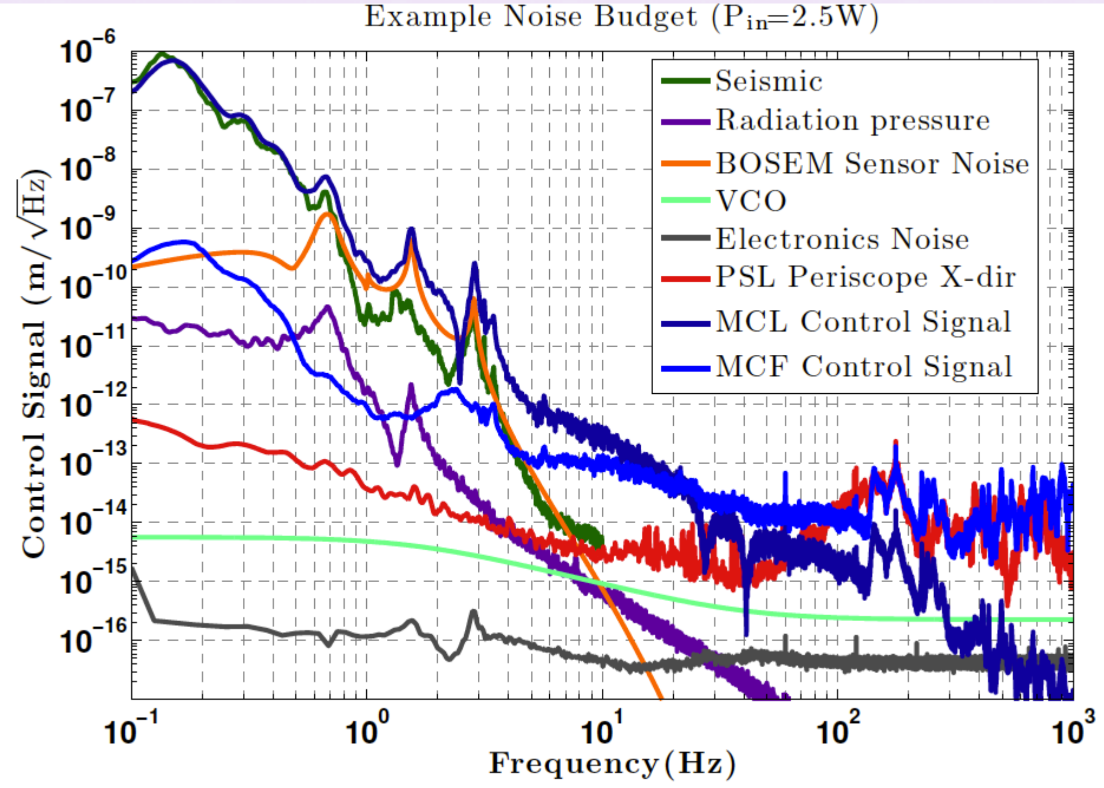


Highlights from Livingston:

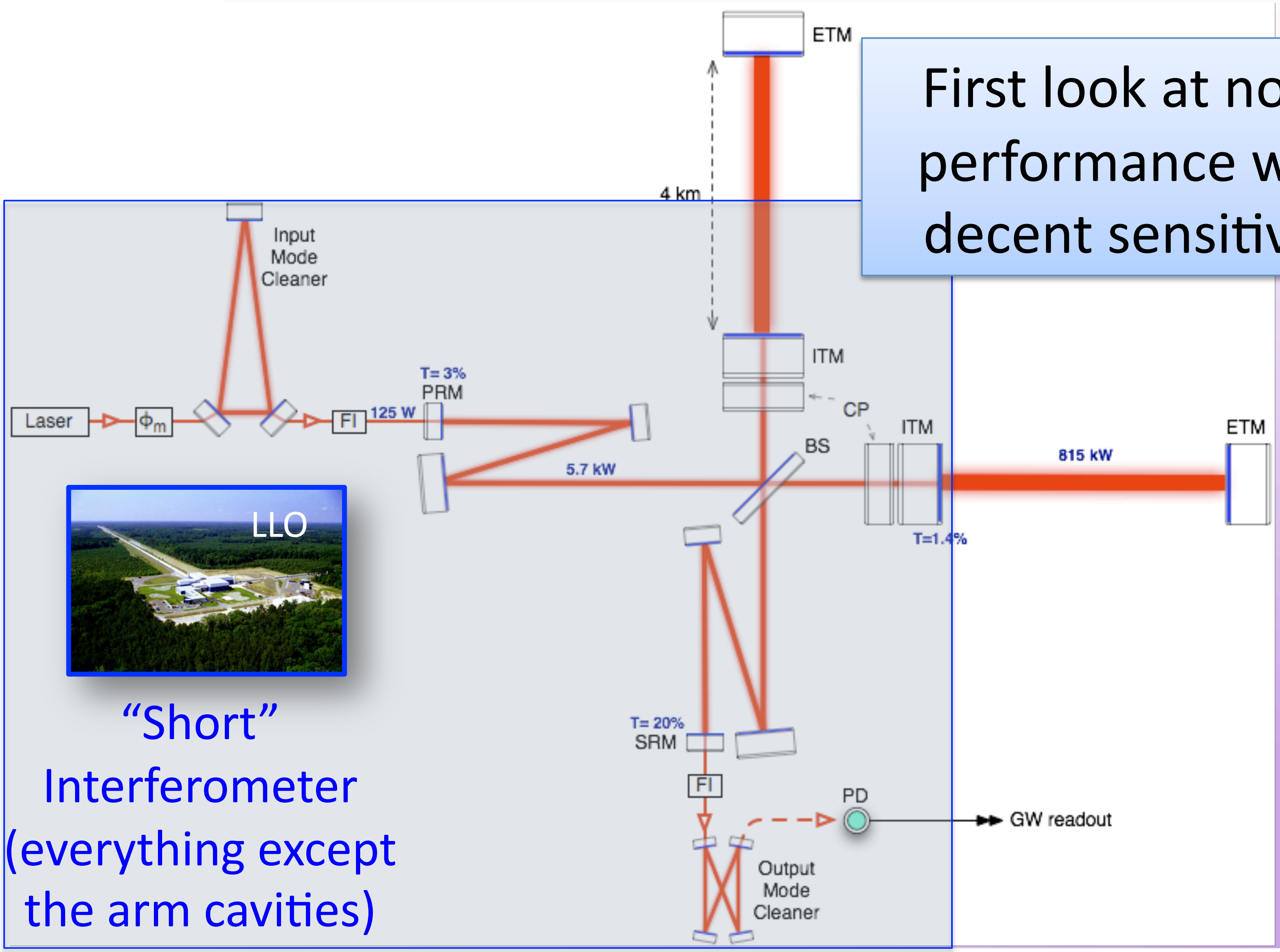
the Input Mode Cleaner

NOISE PERFORMANCE (MOSTLY) UNDERSTOOD





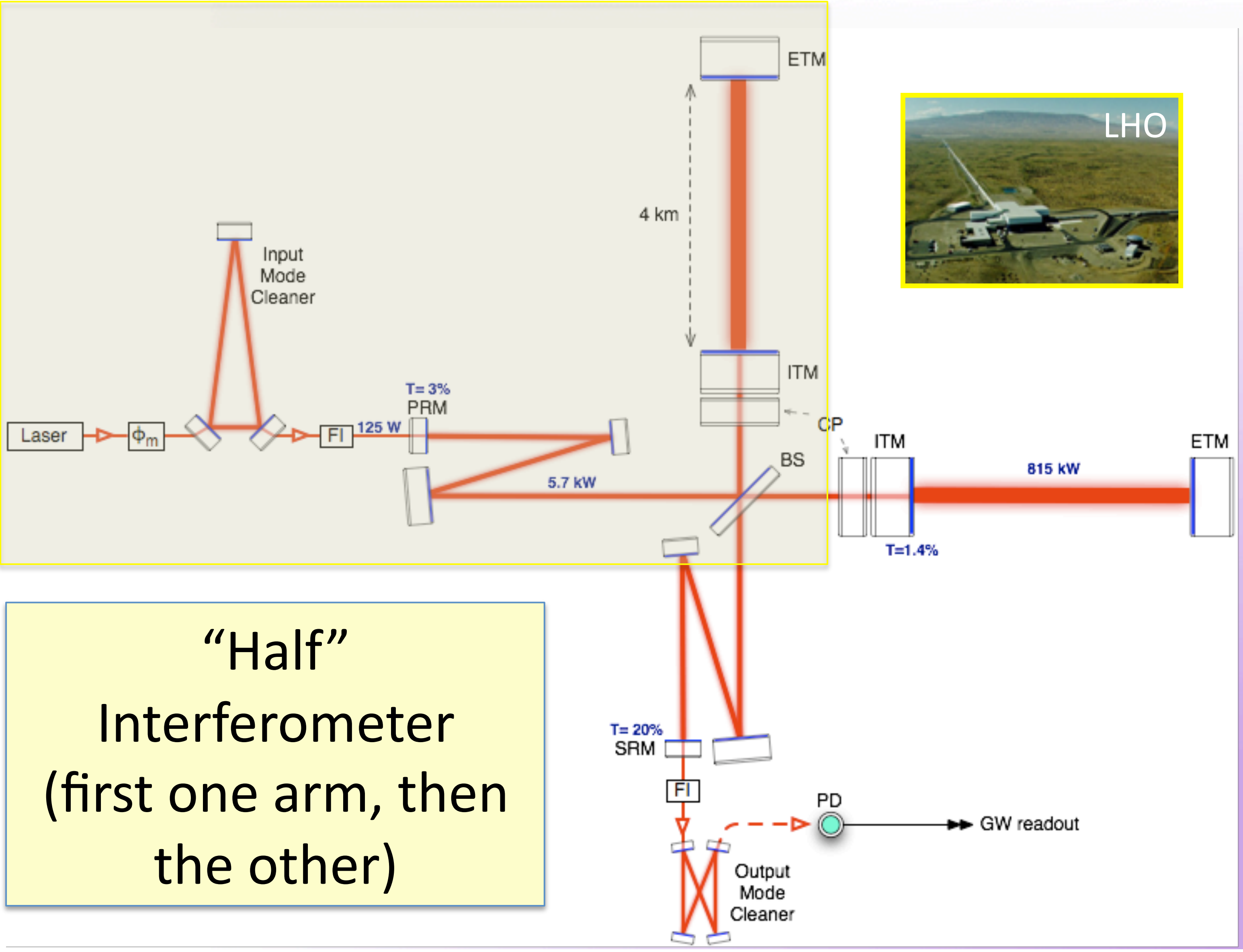
Advanced LIGO Livingston: Coming next



First look at noise performance with decent sensitivity

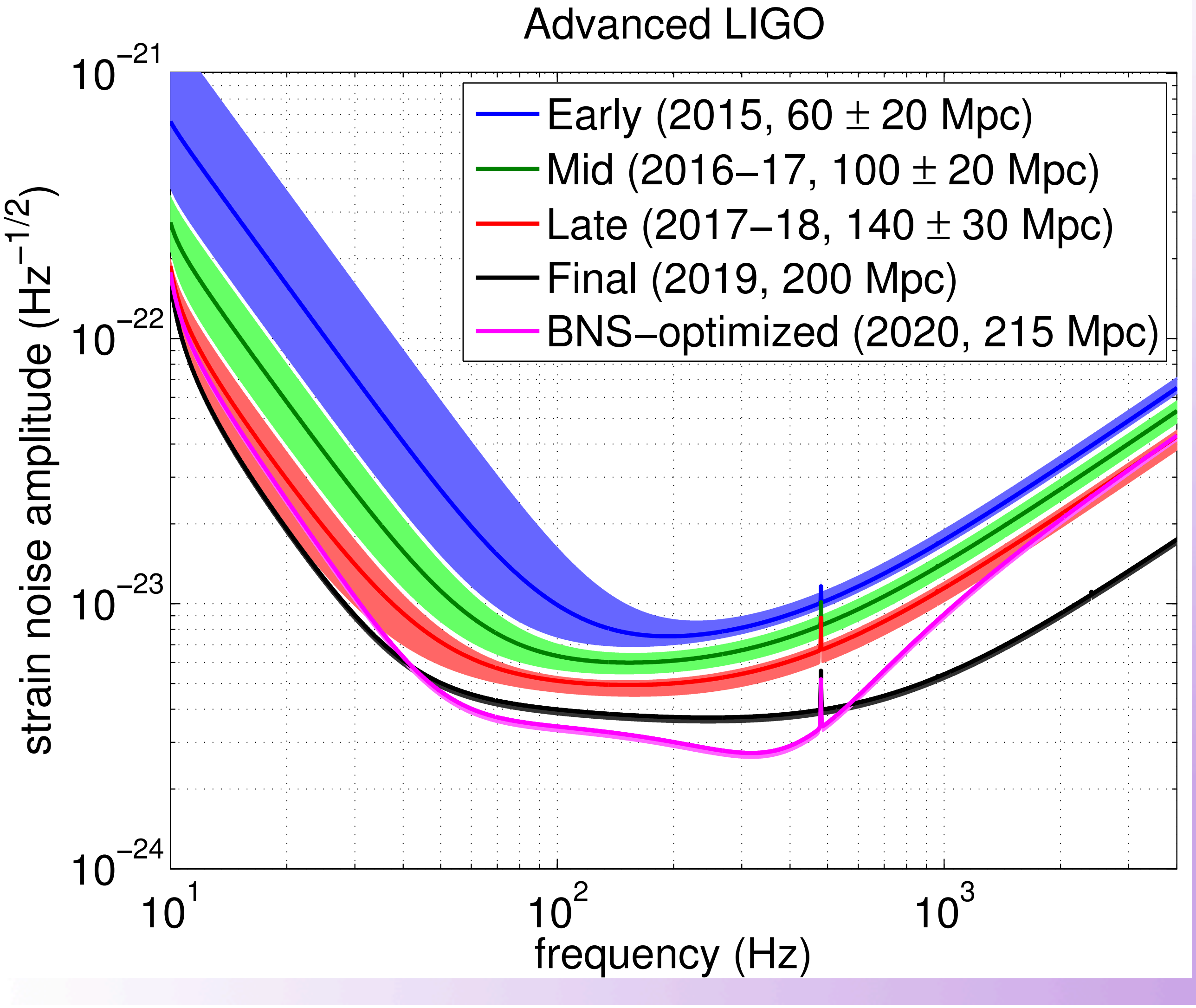
"Short" Interferometer (everything except the arm cavities)

Advanced LIGO Hanford: Coming next



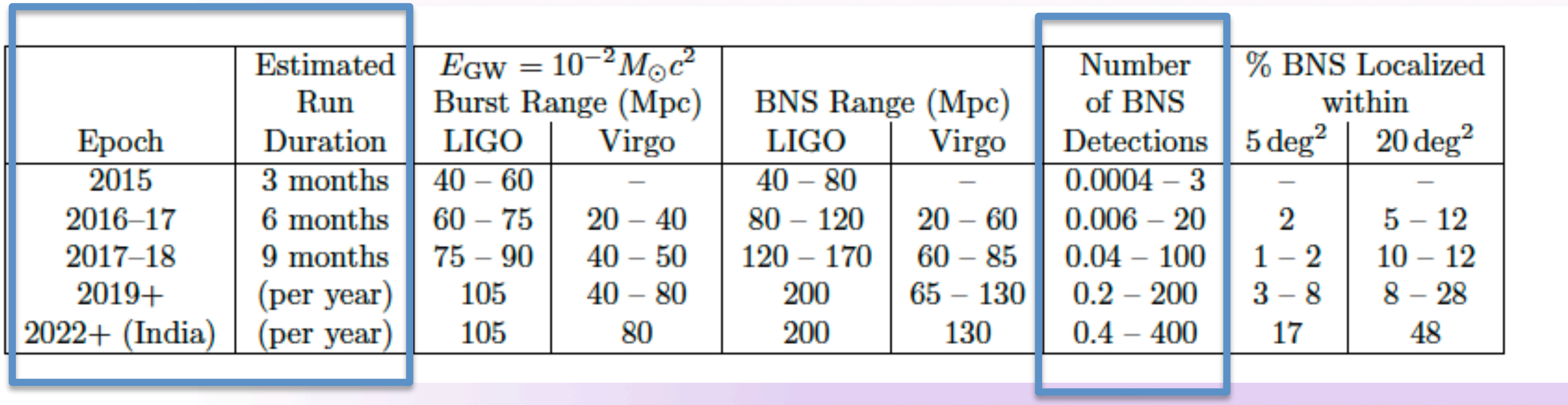
"Half"
Interferometer
(first one arm, then
the other)

Goal: Reach a scientifically interesting sensitivity as soon as possible



Advanced LIGO Detection Rates

http://arxiv.org/abs/1304.067



Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_\odot c^2$ Burst Range (Mpc)		BNS Range (Mpc)		Number of BNS Detections	% BNS Localized within	
		LIGO	Virgo	LIGO	Virgo		5 deg^2	20 deg^2
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48

Neutron Star Binaries:

Initial LIGO: ~15 Mpc → rate ~1/50yrs

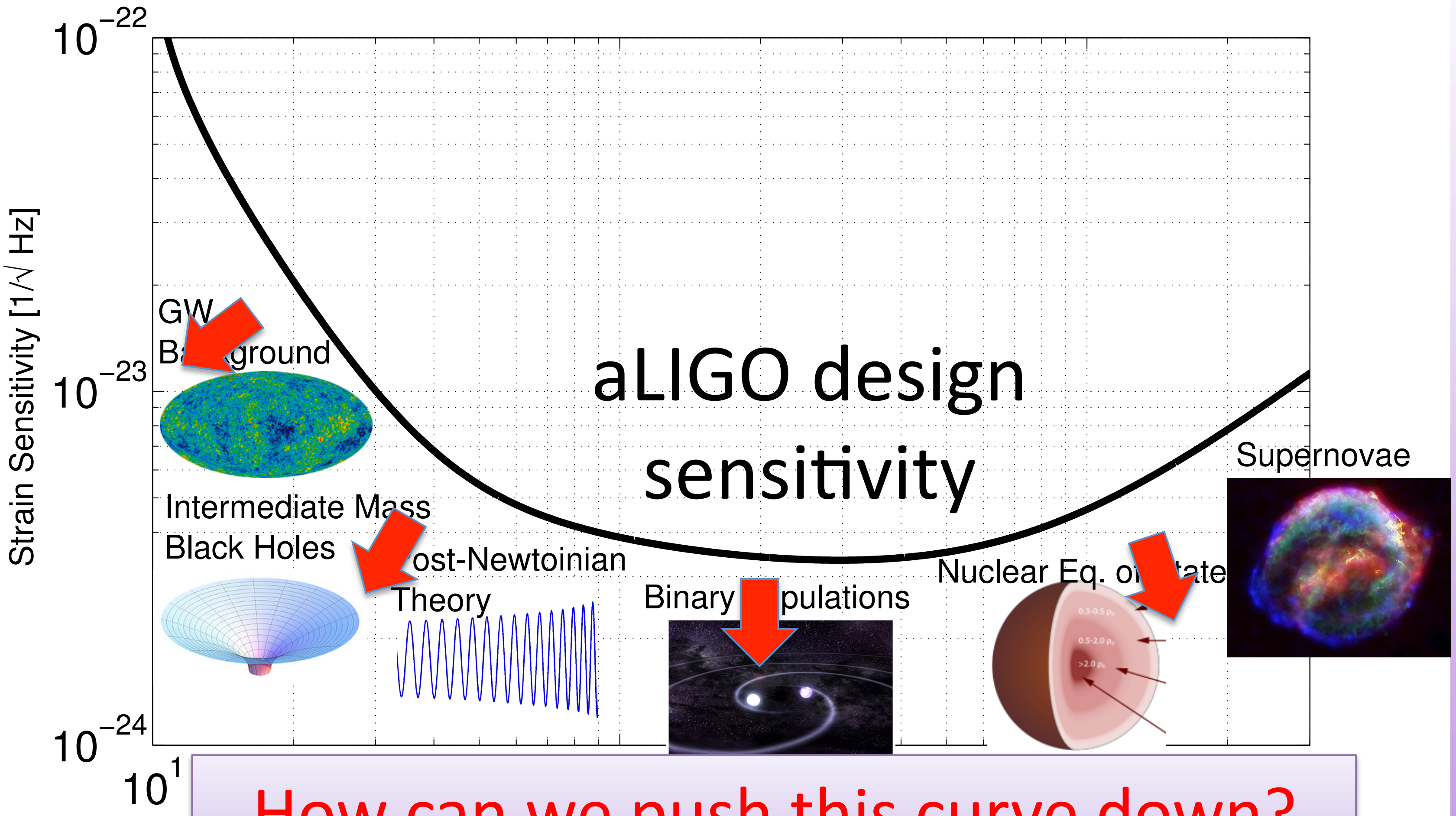
Advanced LIGO: ~ 200 Mpc

"Realistic rate" ~ 40/year

Class. Quant. Grav. **27**, 173001 (2010)

In 2016 we should see something!

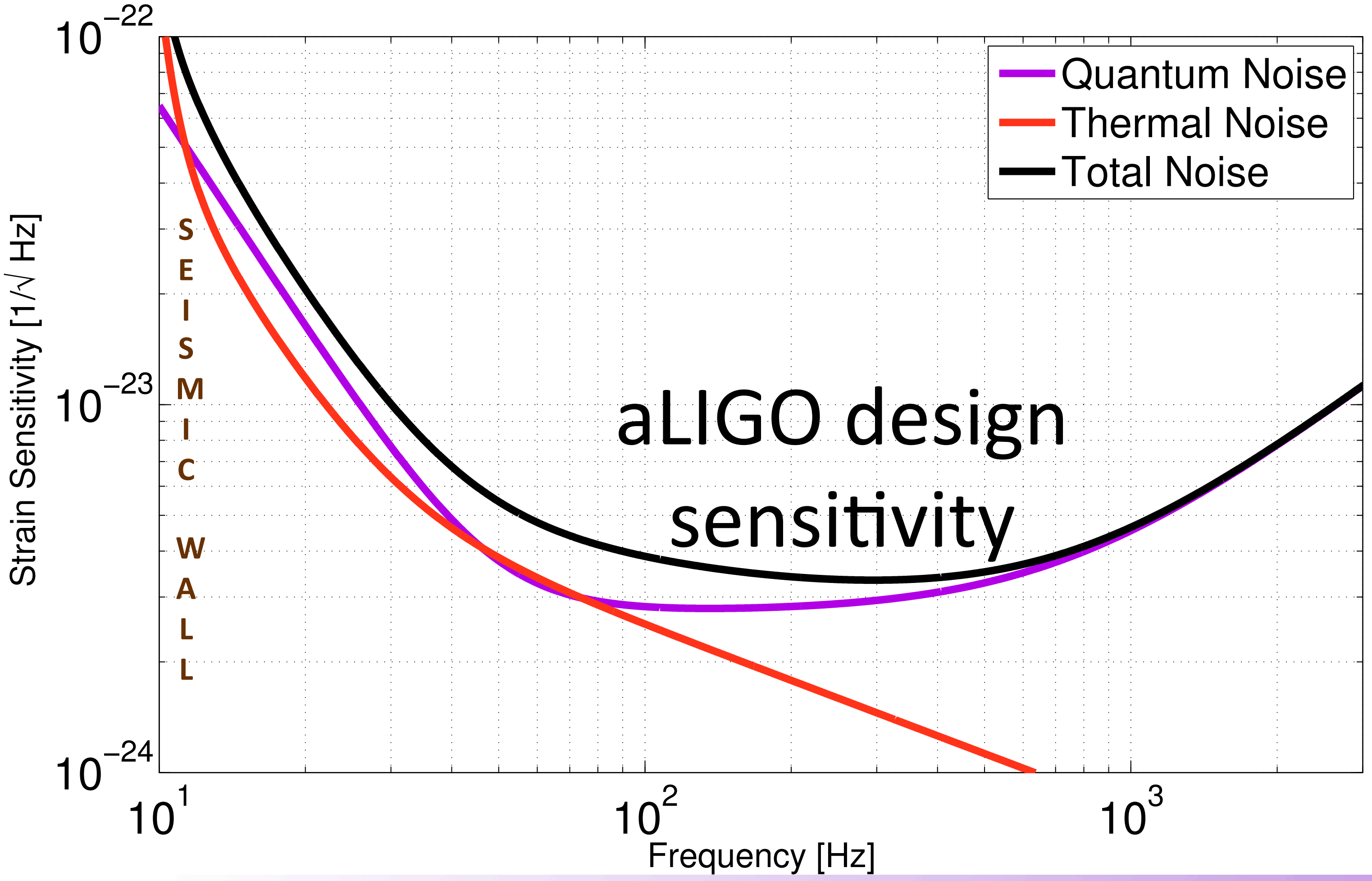
“More” and “New” science beyond Advanced LIGO



aLIGO design sensitivity

How can we push this curve down?

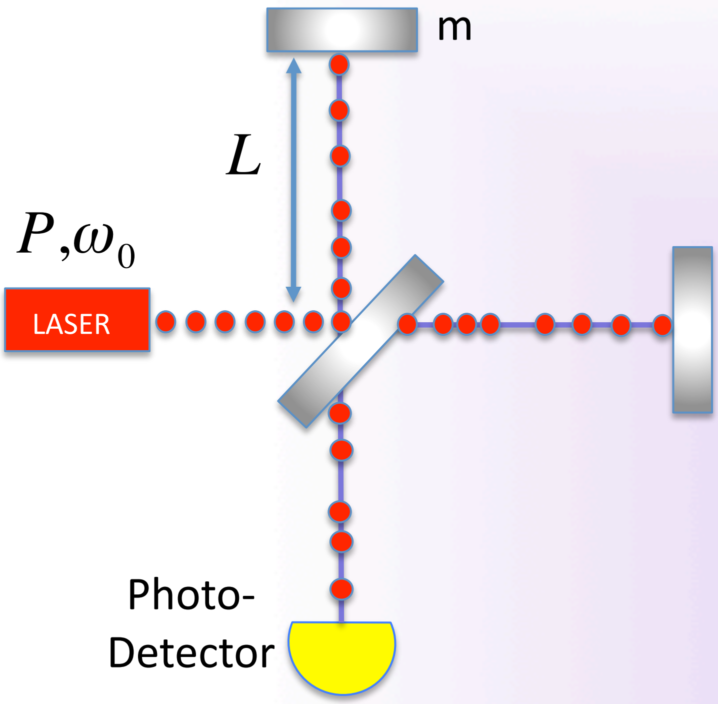
How can we go beyond aLIGO?
Reduce the noises!



SEISMIC WALL

aLIGO design sensitivity

What is quantum noise?



$$h_{quantum} = \sqrt{h_{rad}^{\;2} + h_{shot}^{\;2}}$$

✧ SHOT NOISE:

Photon counting noise

$$h_{shot} \propto \frac{1}{L}\sqrt{\frac{1}{P}}$$

✧ RADIATION PRESSURE NOISE:

Back-action noise caused by random motion of the mirrors

$$h_{rad} \propto \frac{1}{f^{2}L}\,\frac{\sqrt{P}}{\mathrm{m}}$$

Measurement frequency

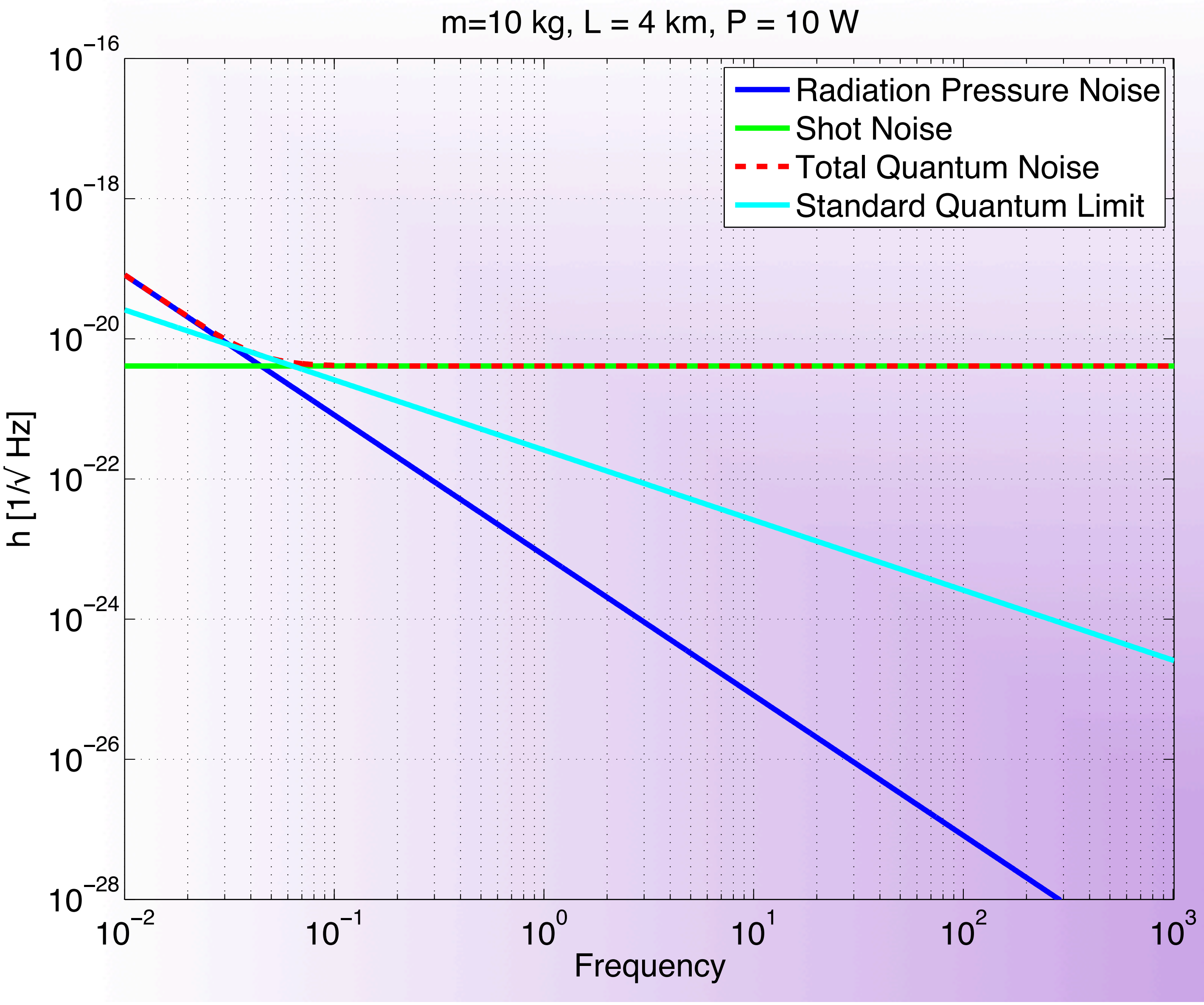
“Standard Quantum Limit”

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

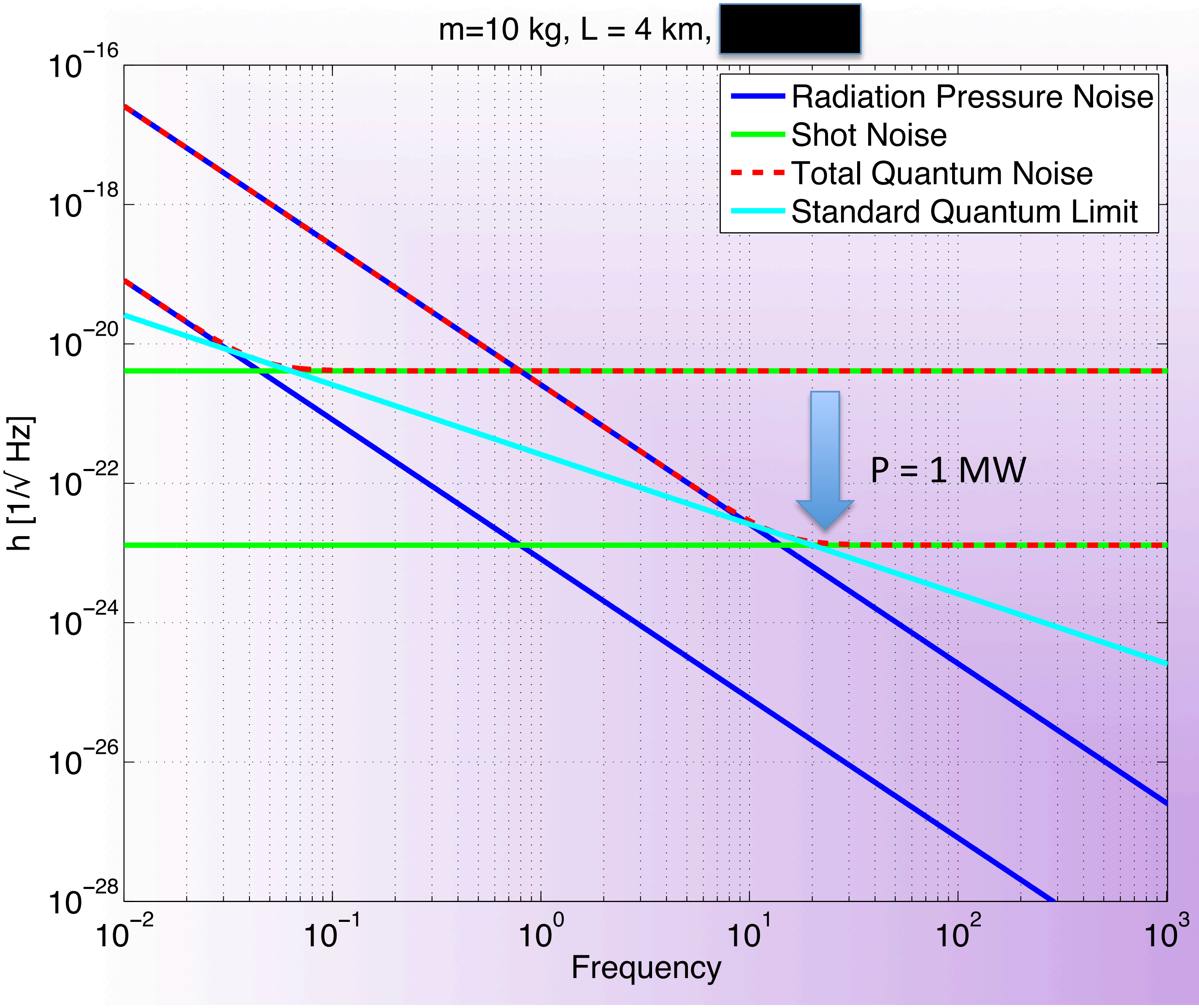
$$h_{Quantum} \geq \sqrt{\frac{4\hbar}{m\Omega^2L^2}} \qquad h_{SQL}$$

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

Simple Michelson, P = 10 W



Simple Michelson, P = 1 MW



“Easy” approaches to minimize quantum noise

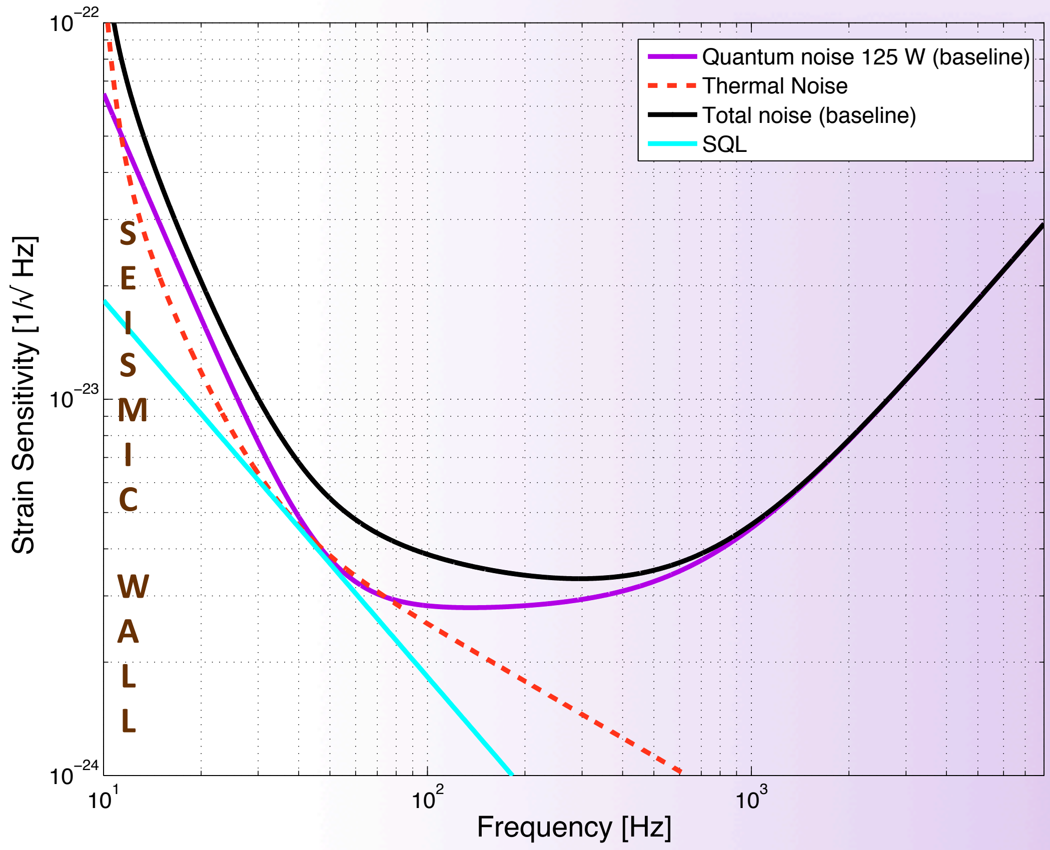
$$h_{quantum} = \sqrt{h_{rad}{}^2 + h_{shot}{}^2}$$

$$h_{shot} \propto \frac{1}{L}\sqrt{\frac{1}{P}} \qquad h_{rad} \propto \frac{1}{f^2 L}\frac{\sqrt{P}}{\mathrm{m}}$$

- ✧ 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

More Clever: Quantum Noise in aLIGO

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



More complex optical configuration than a simple Michelson

~ 800 kW of light stored in the arm cavities

How we go beyond advanced LIGO

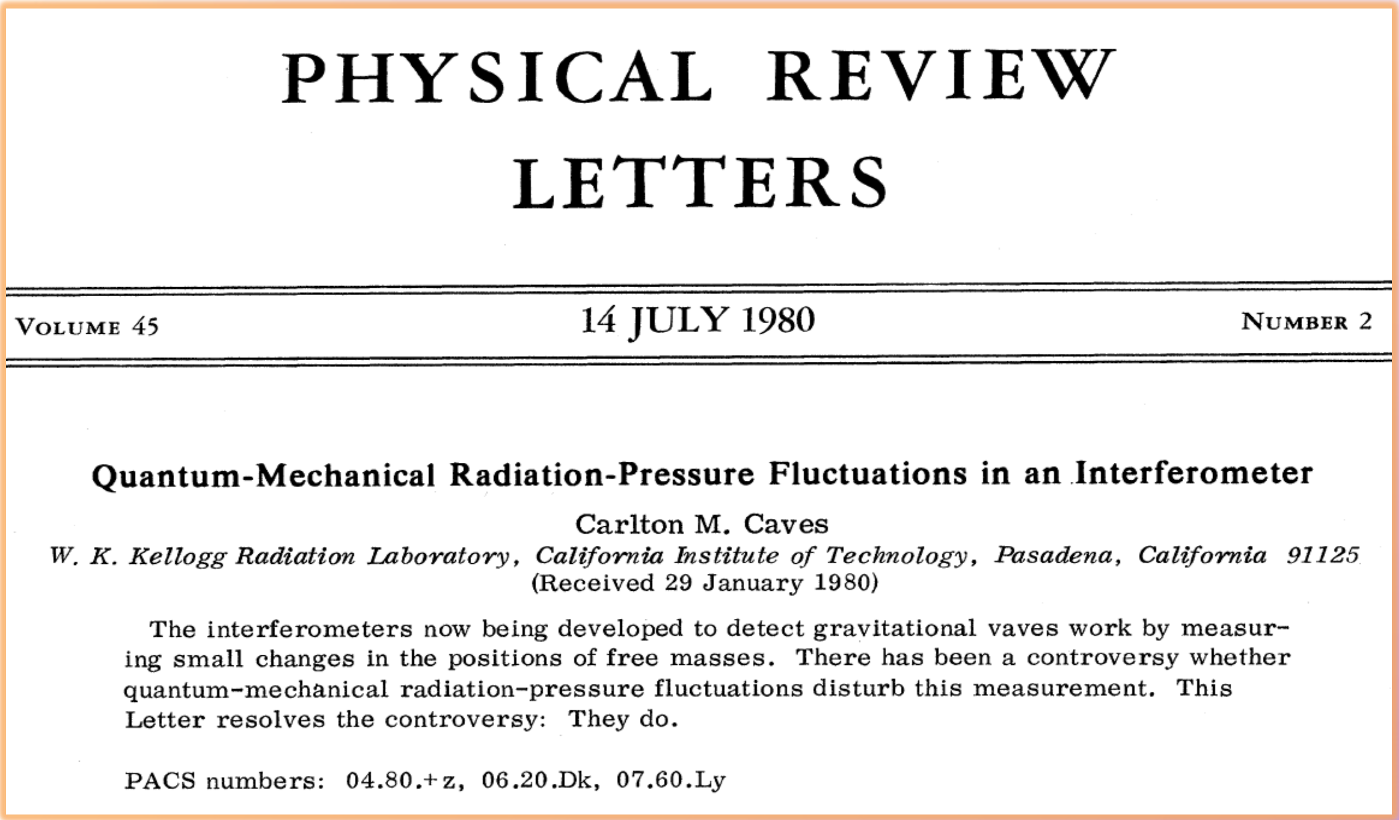
- ✧Make your interferometer longer!
  - ✧ It is already 4 km, Ultra High Vacuum is not cheap
- ✧Heavier test masses, more power
  - ✧Already ~1 MW in the arm cavities, need to compensate for thermal effects and instabilities
- ✧(Even) more complex optical configuration which shapes the interferometer 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 electromagnetic field → Zero-point fluctuations



PHYSICAL REVIEW LETTERS

VOLUME 45 14 JULY 1980 NUMBER 2

Quantum-Mechanical Radiation-Pressure Fluctuations in an Interferometer

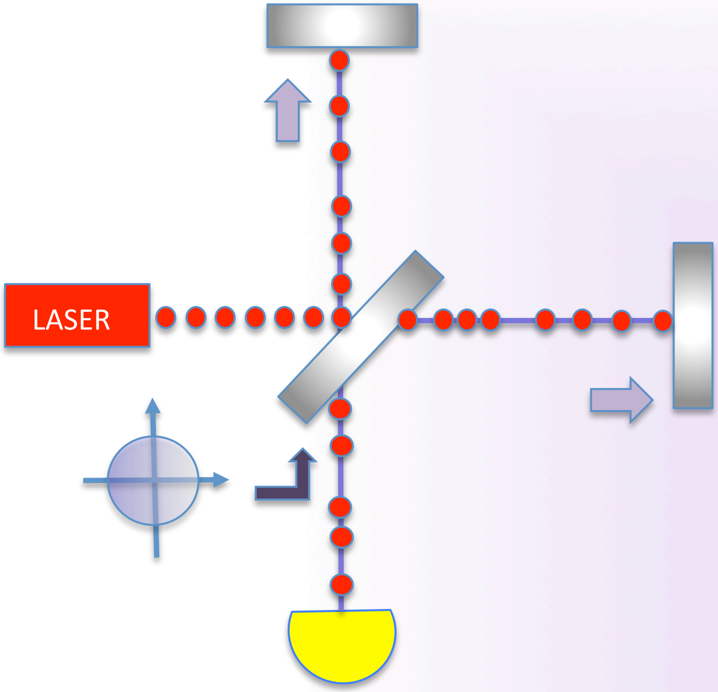
Carlton M. Caves
W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125

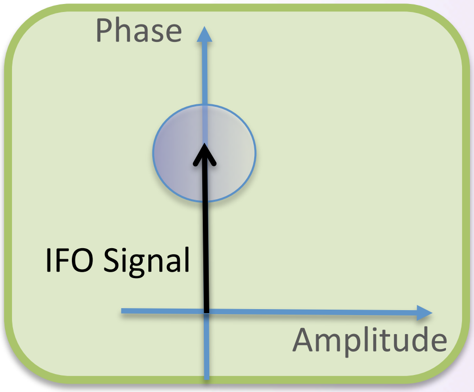
(Received 29 January 1980)

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.

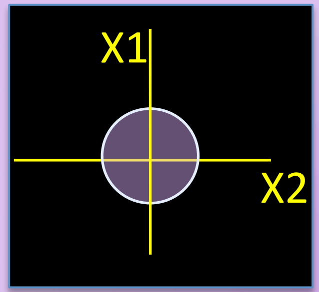
PACS numbers: 04.80.+z, 06.20.Dk, 07.60.Ly

Vacuum Getting Squeezed



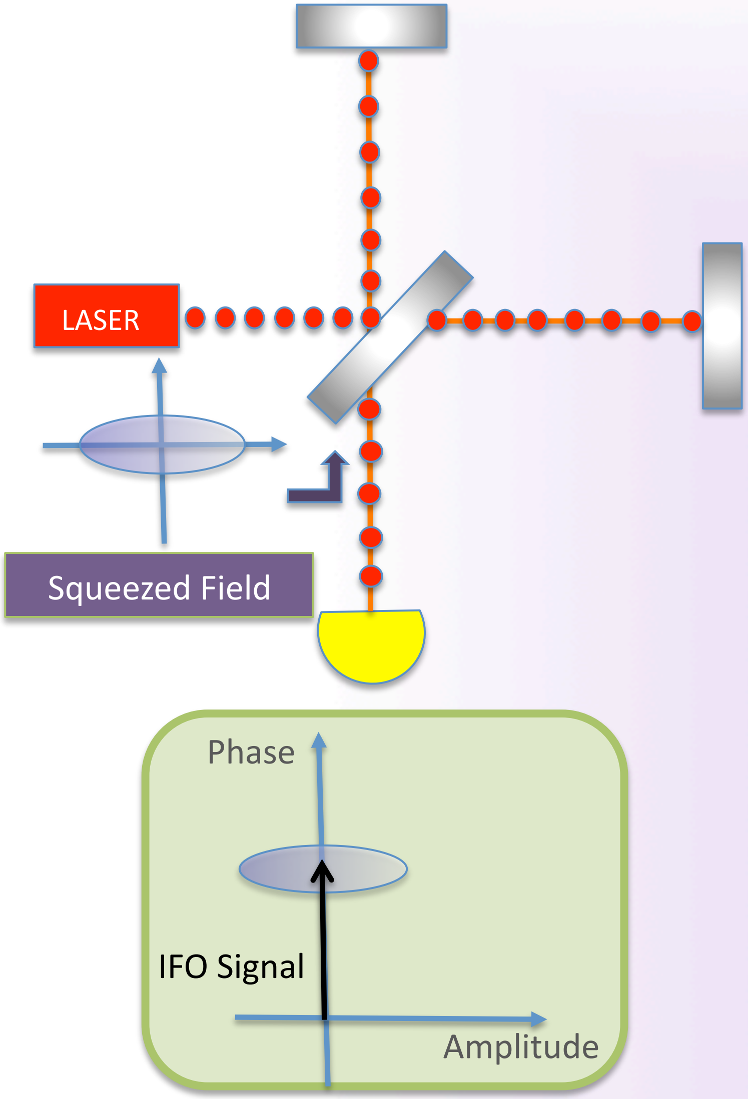


- When average amplitude of electromagnetic field is zero, the variance remains
- Heisenberg uncertainty principle, quadratures associated with **amplitude** and **phase**



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

Vacuum Getting Squeezed



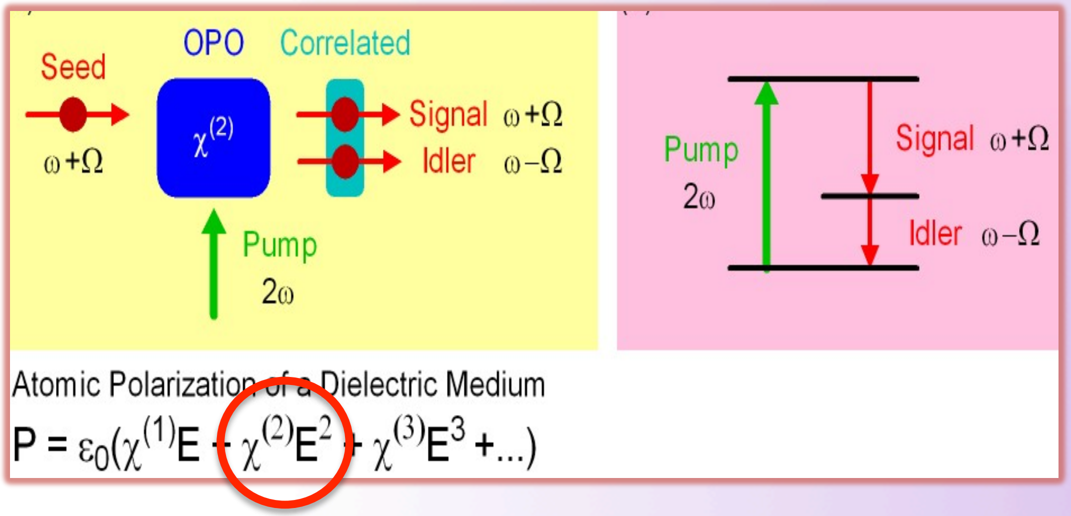
✧ Squeezed vacuum: less uncertainty in one of the two quadratures
✧ Heisenberg uncertainty principle still holds
✧ One can choose the relative orientation between the squeezed vacuum and the interferometer signal (squeeze angle)

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…

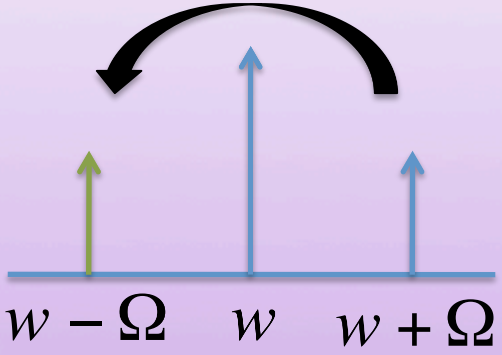
…. in theory

- 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



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

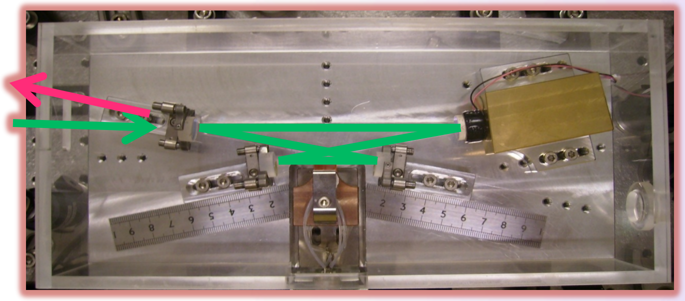
$$\Rightarrow Ee^{-i(w-\Omega)t}$$



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

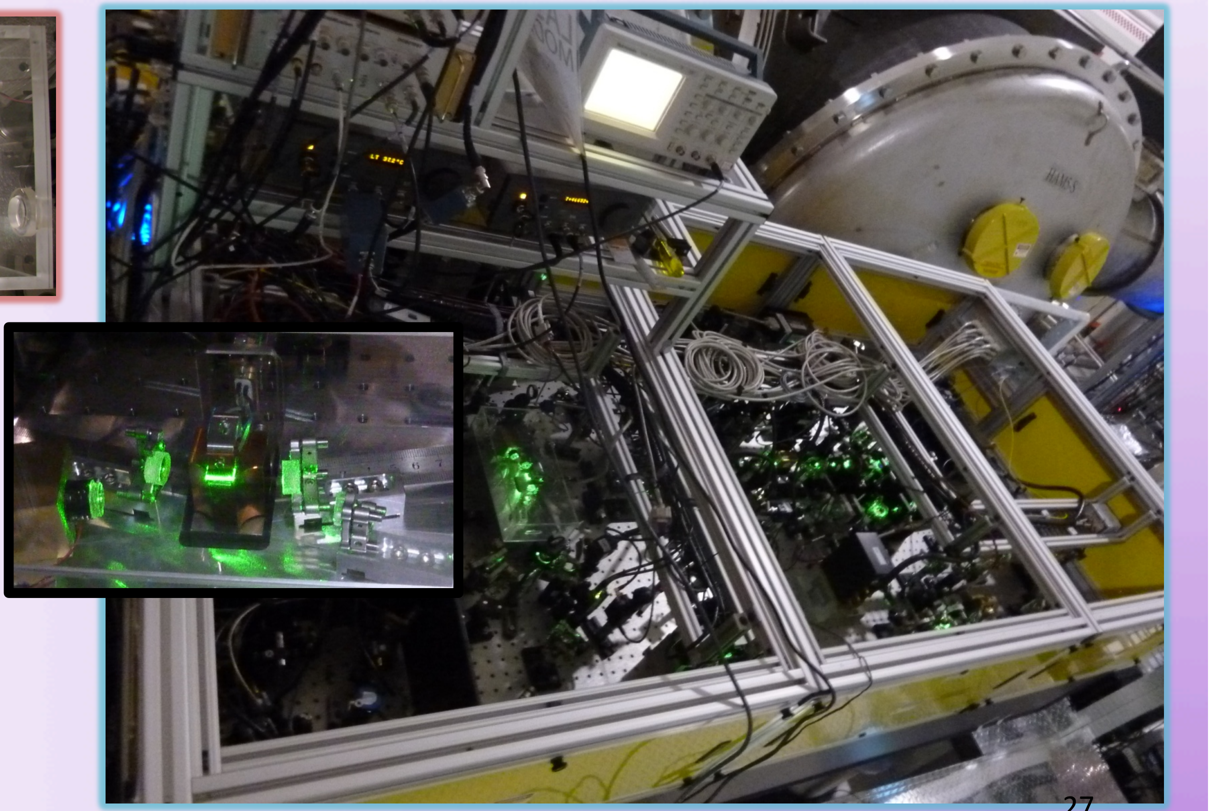
How to make squeezed fields..

…. in practice

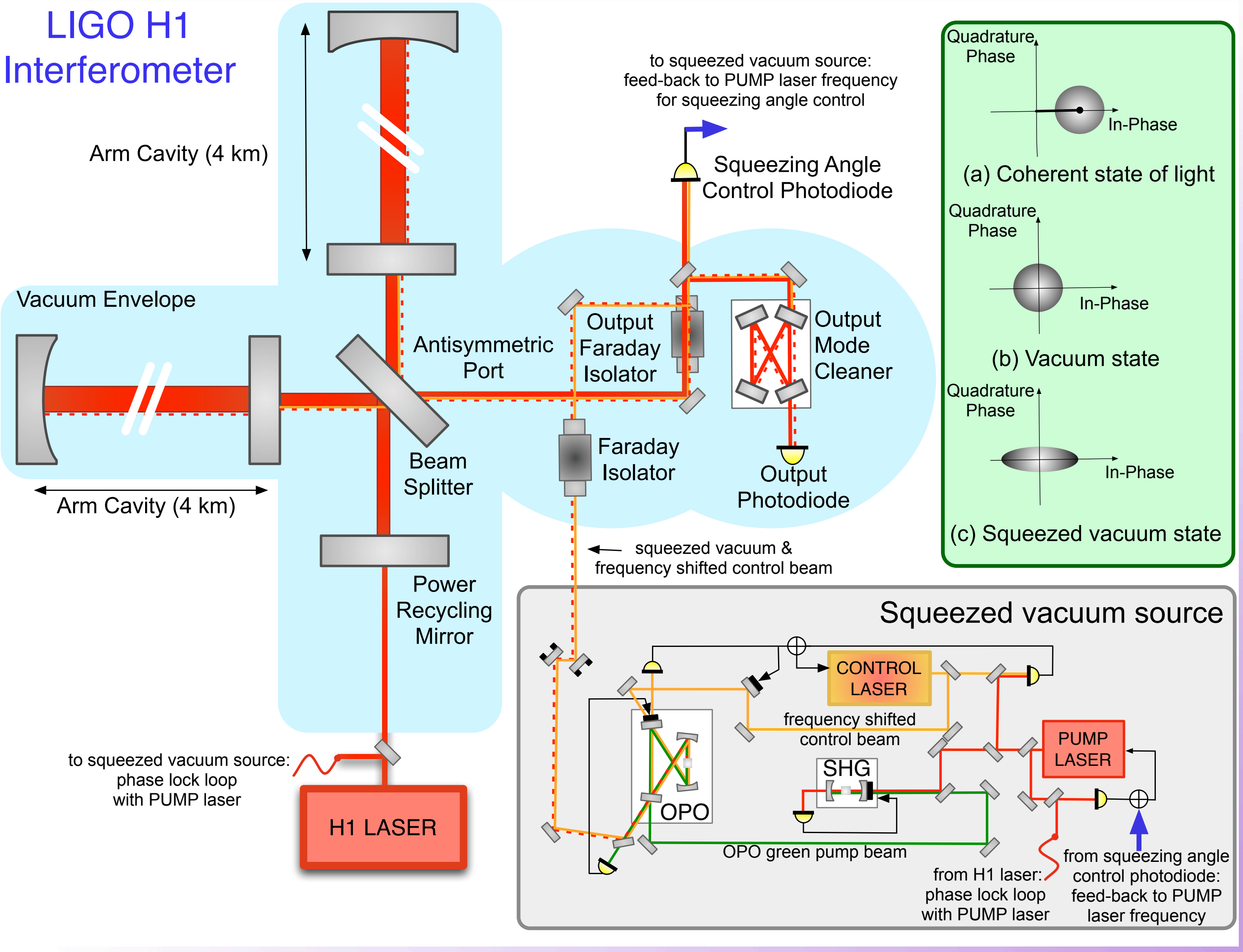


World-wide effort in the last 10 years to make squeezing in the audio-frequency band

The LIGO H1 Squeezer



How to inject squeezed fields



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

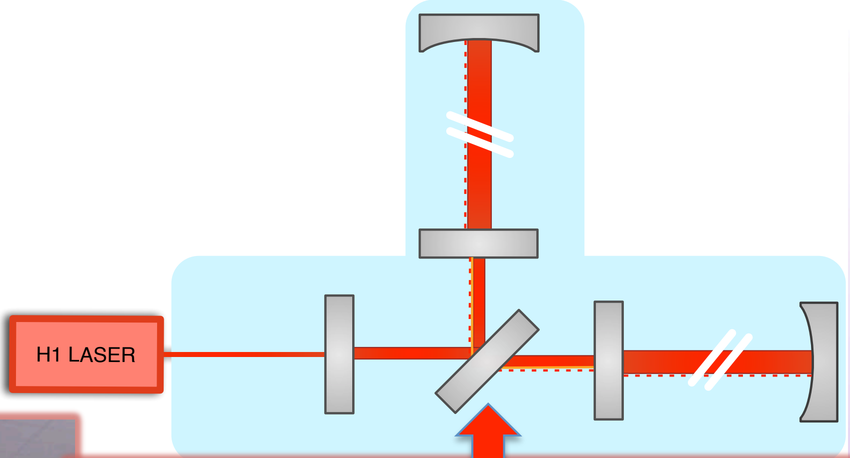
squeezed vacuum &
frequency shifted control beam

to squeezed vacuum source:
phase lock loop
with PUMP laser

from H1 laser:
phase lock loop
with PUMP laser

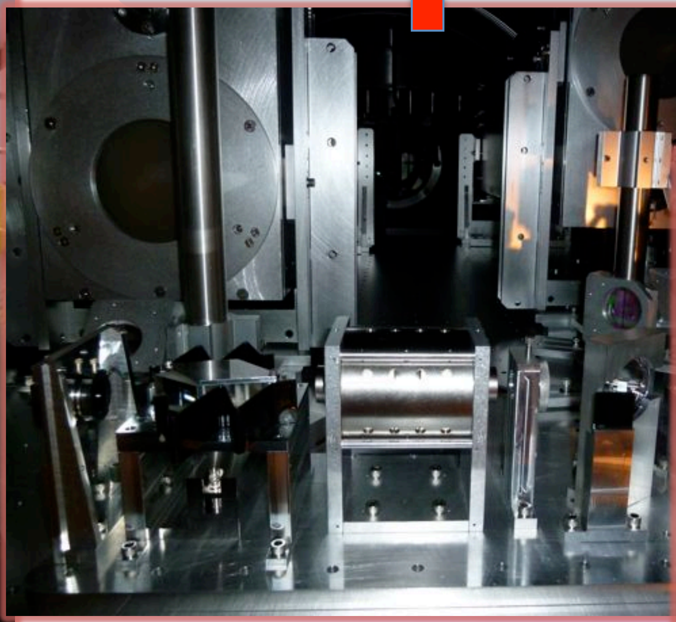
from squeezing angle
control photodiode:
feed-back to PUMP
laser frequency

Squeezing injection into LIGO H1

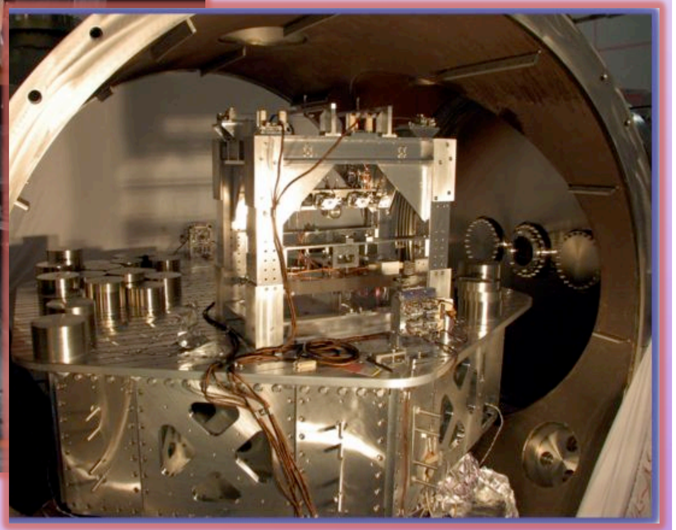


End of 2011
right before aLIGO
installation started

Squeezer Table



Output Faraday

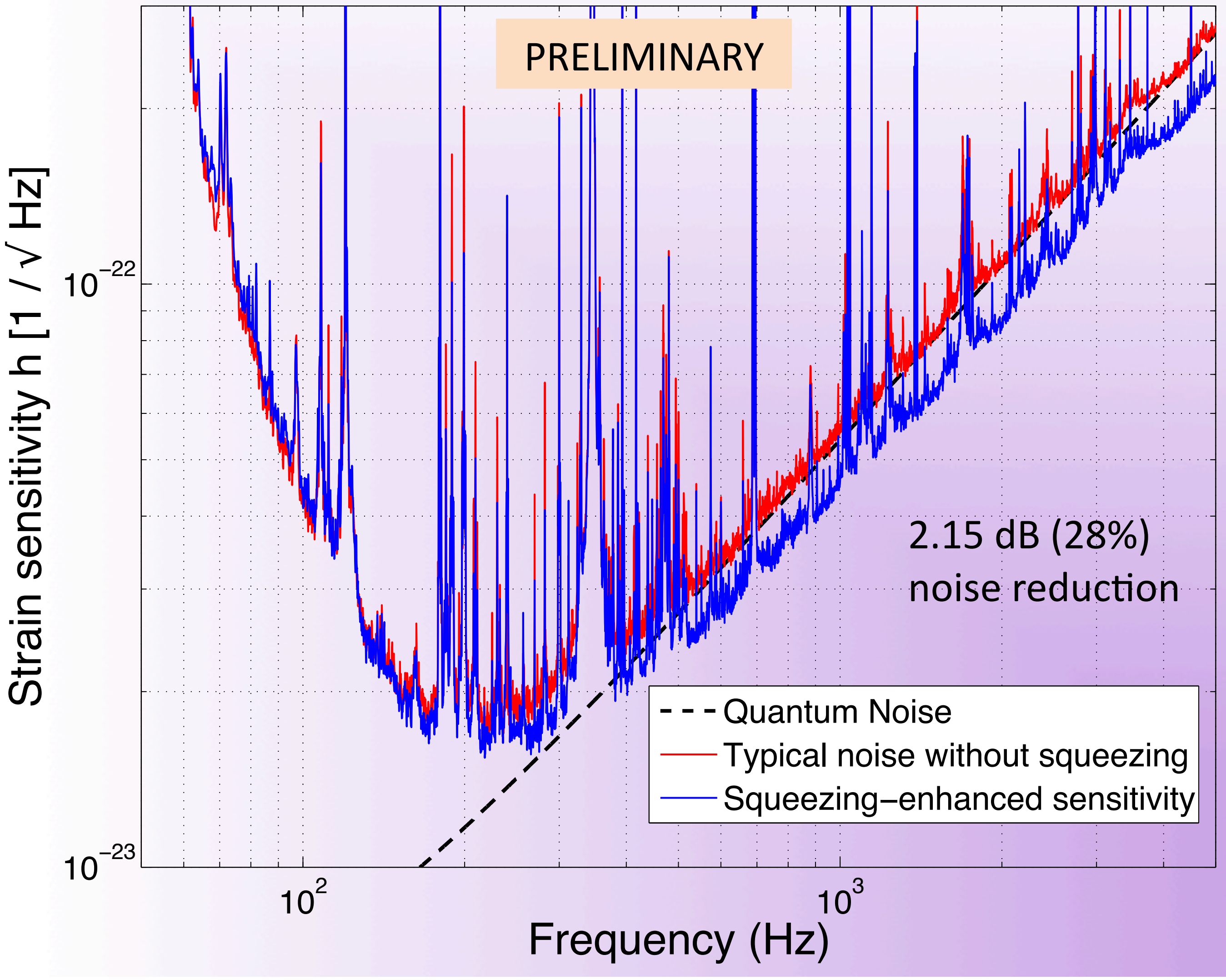


Output Mode Cleaner

LIGO H1 Squeezing Experiment Results

from the LIGO Scientific Collaboration

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



2.15 dB (28%)
noise reduction

LIGO H1 Squeezing Experiment

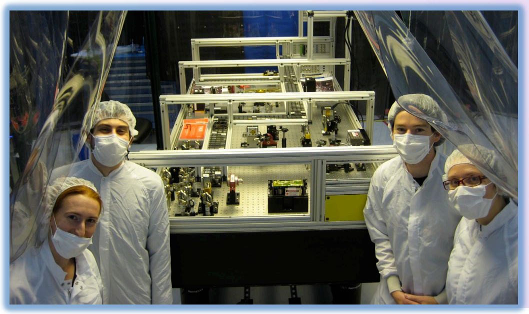
LIGO Hanford Observatory (US)
Massachusetts Institute of Technology (US)
Australian National University (Australia)
Albert Einstein Institute (Germany)

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

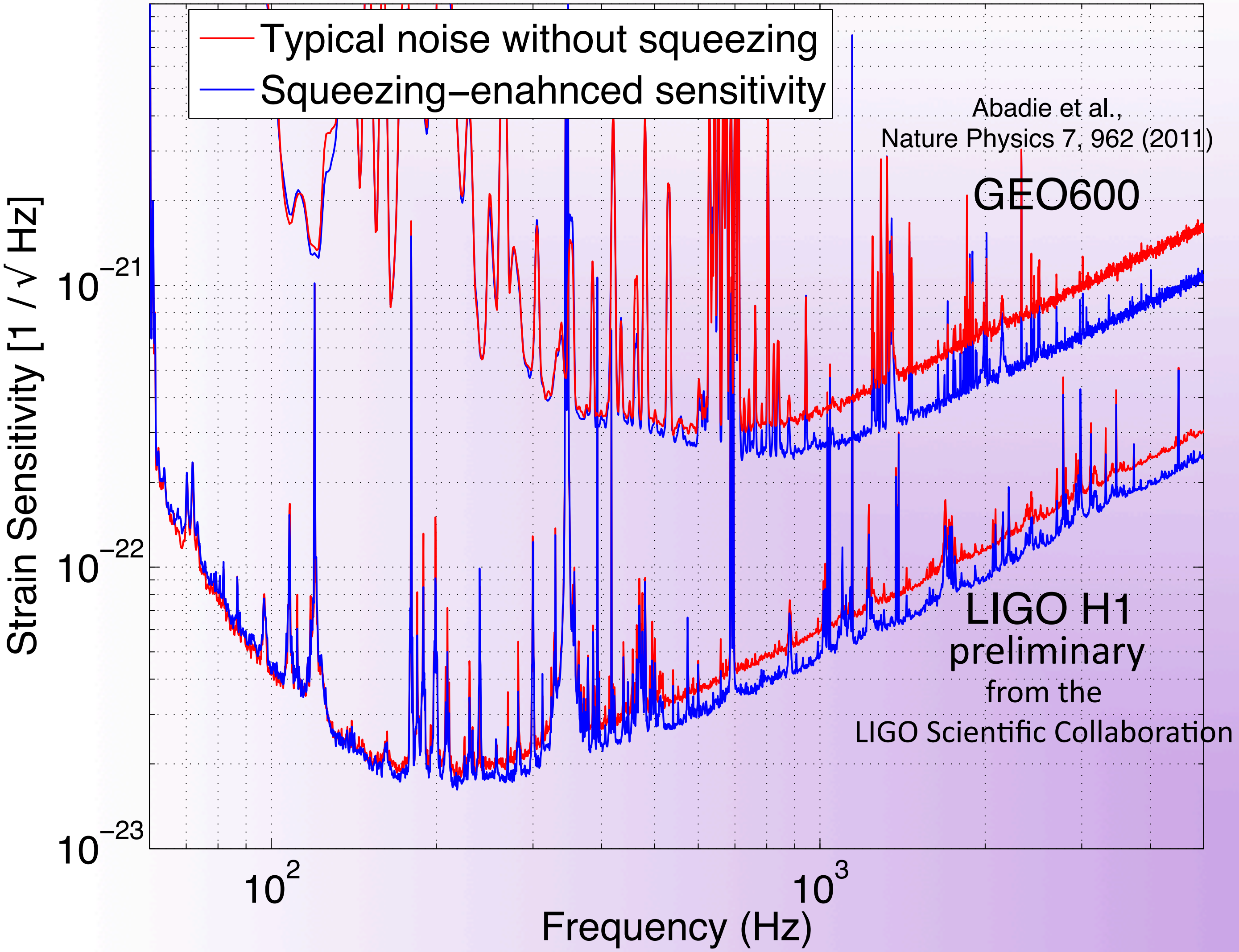
LHO: Daniel Sigg, Keita Kawabe, Robert Schofield (Univ. Oregon), Cheryl Vorvick, Dick Gustafson (Univ Mitchigan), Max Factourovich (Columbia), Grant Meadors (Univ Mitchigan), M. Landry and the LHO staff

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

AEI: Alexander Khalaidovski, Roman Schnabel



Squeezing in GEO600 and LIGO H1

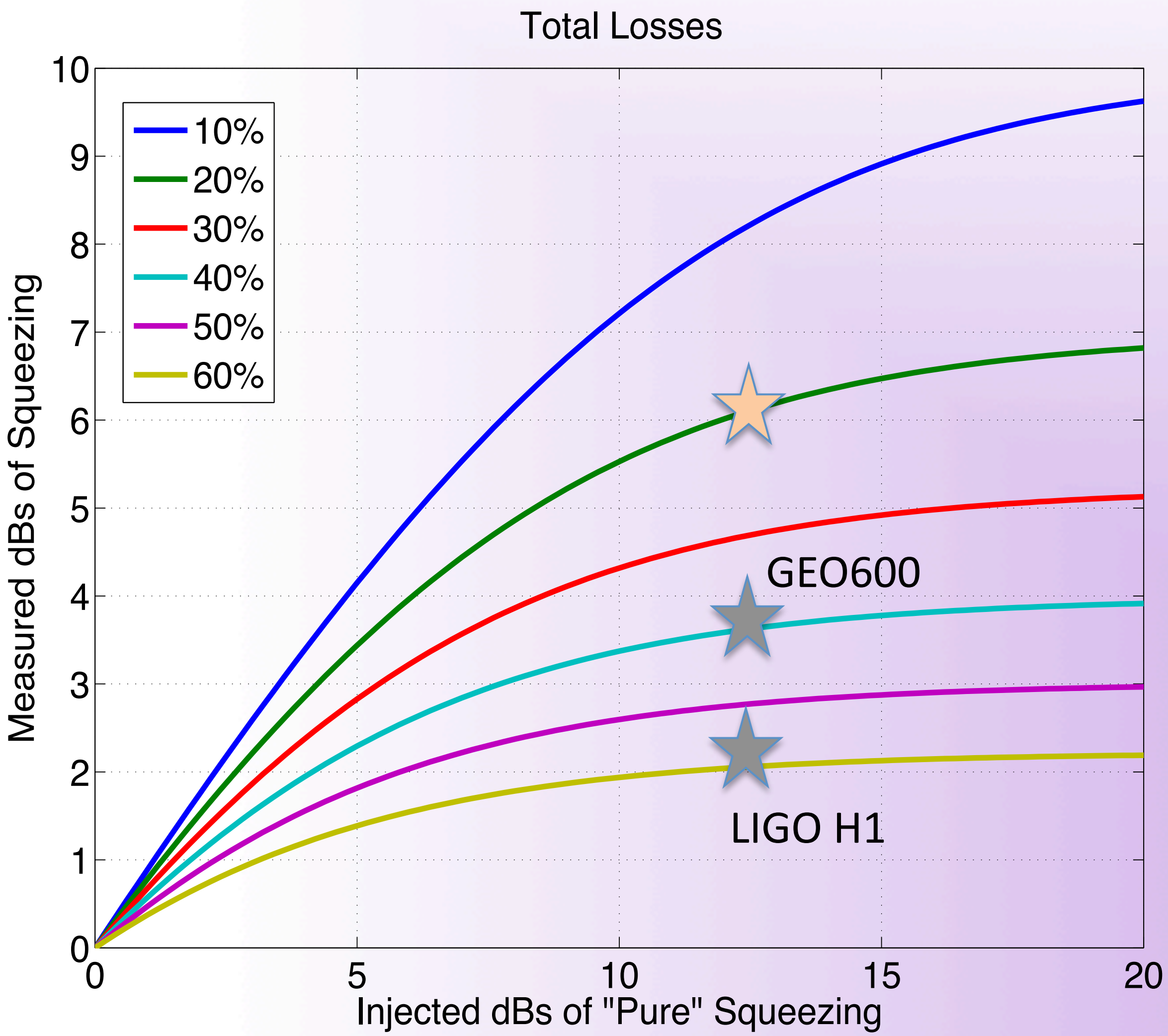


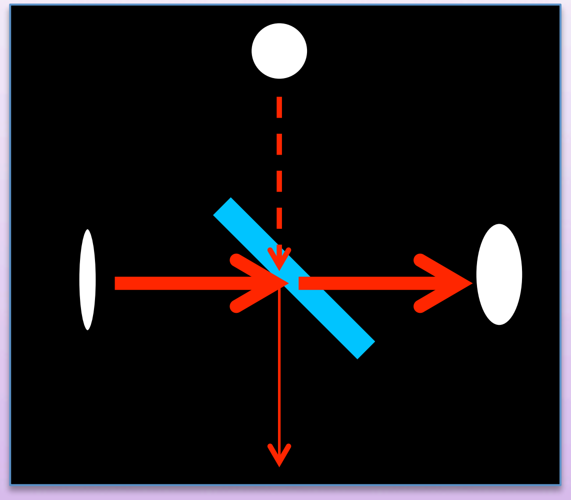
Abadie et al.,
Nature Physics 7, 962 (2011)

GEO data are courtesy of H. Grote

Limit to the amount of observed squeezing

✧ Losses are very unforgiving!





Largest Losses Sources:

✧Mode matching

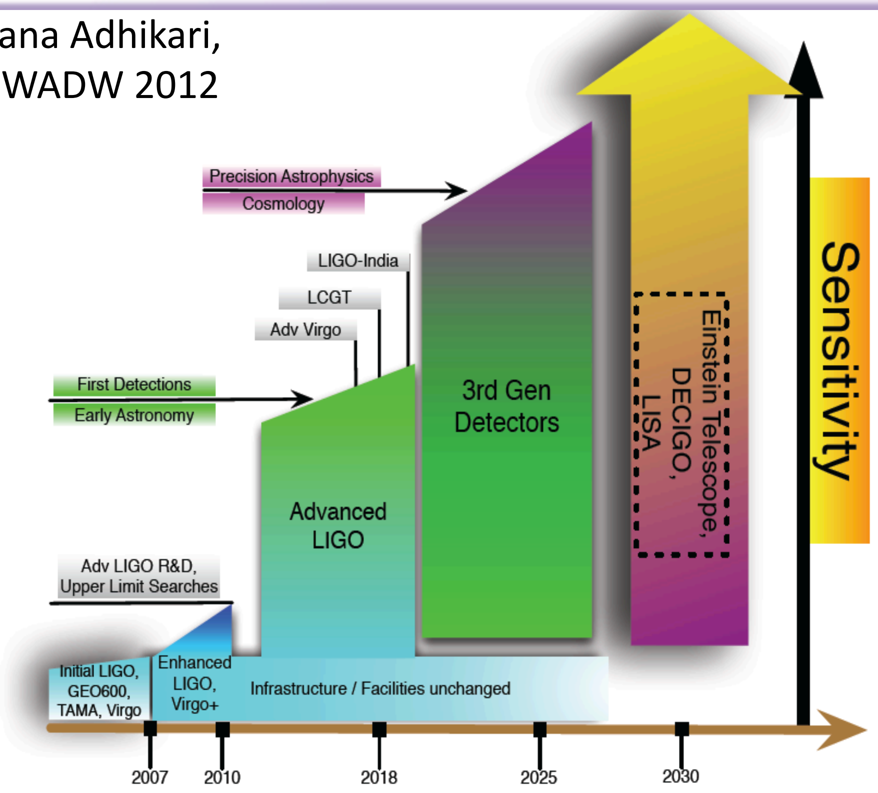
✧ Faradays

✧ Output mode cleaner

How about a
"Quantum-Enhanced Advanced LIGO"?

✧ Do we want it? YES!

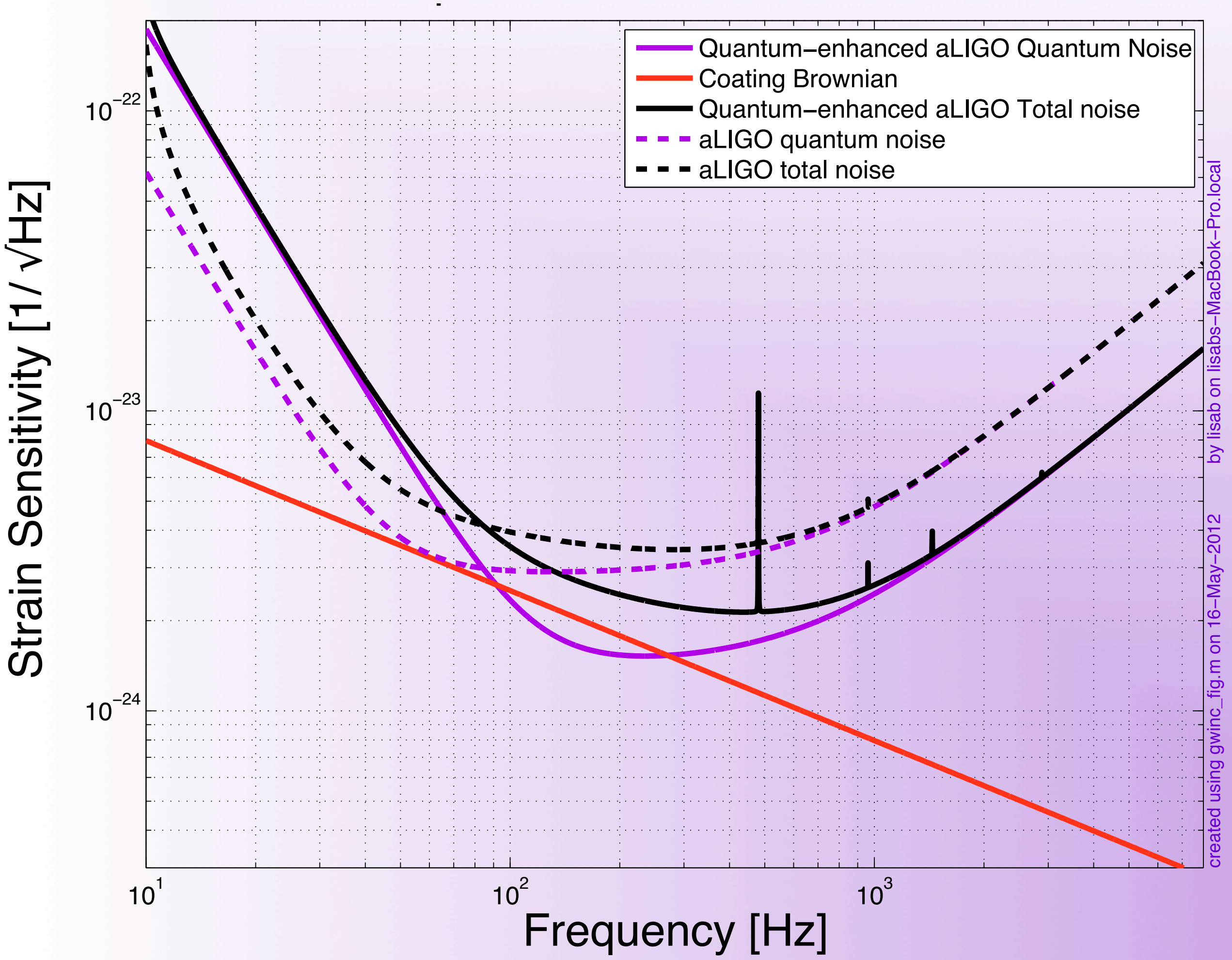
Rana Adhikari,
GWADW 2012



All current ideas for upgrading aLIGO include 10 dB of squeezing

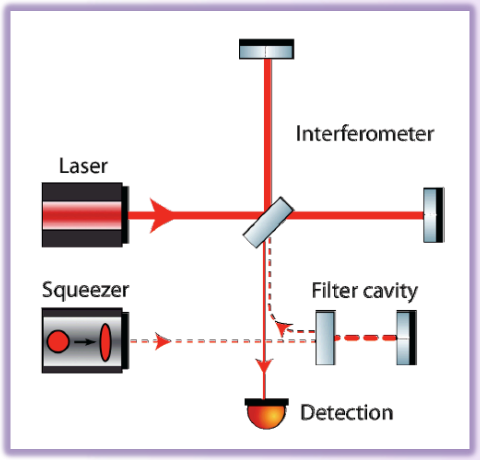
✧ Do we know how to make it? ALMOST!

Projections for a "Quantum-Enhanced Advanced LIGO"



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

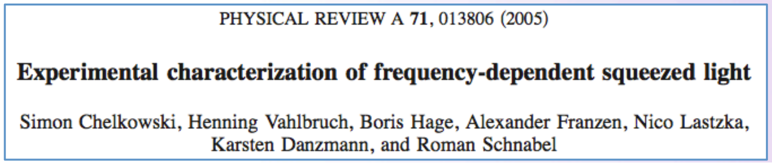
Conversion of conventional gravitational-wave interferometers into quantum nondemolition interferometers by modifying their input and/or output optics

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)

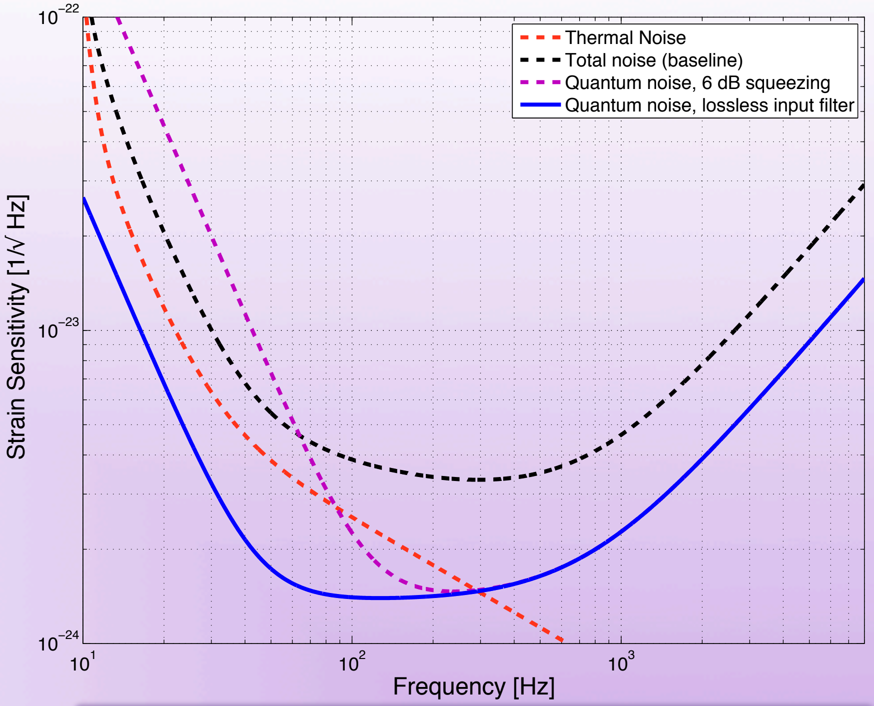
Squeezed-input, optical-spring, signal-recycled gravitational-wave detectors

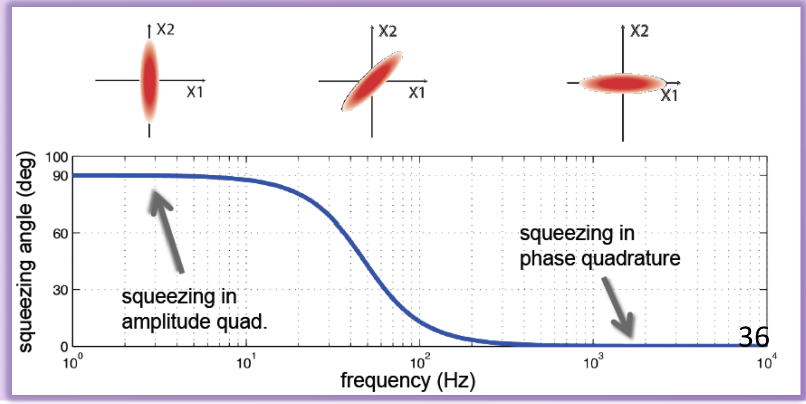
Jan Harms,[1] Yanbei Chen,[2] Simon Chelkowski,[1] Alexander Franzen,[1] Henning Vahlbruch,[1] Karsten Danzmann,[1] and Roman Schnabel[1]


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





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

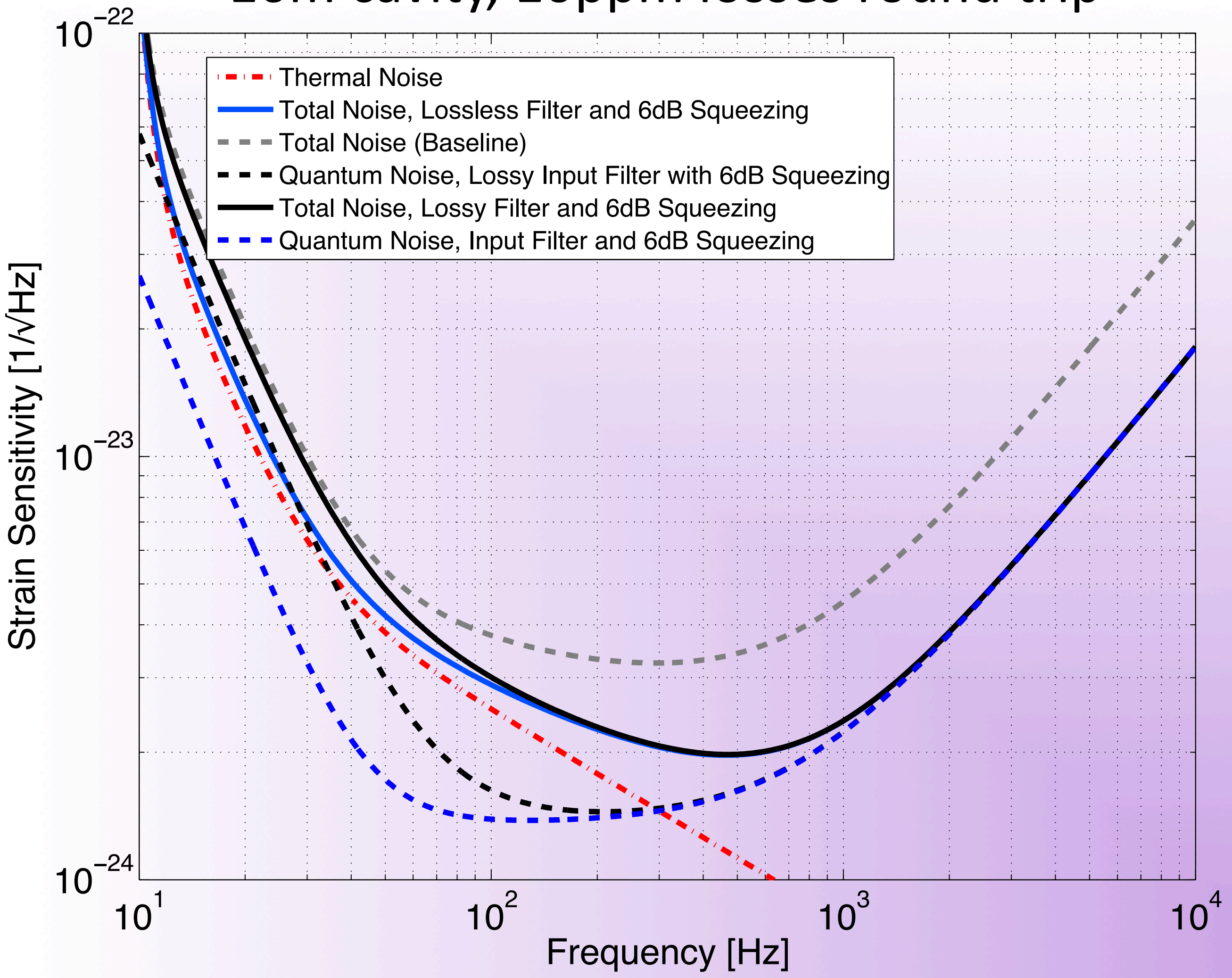
NEW aLIGO SQUEEZER SOURCE

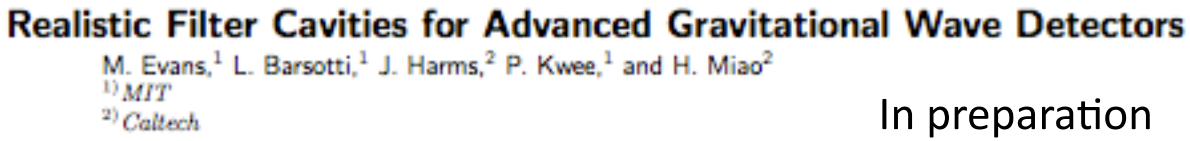
- ✧ Working on a new design with an in-vacuum squeezer source cavity

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

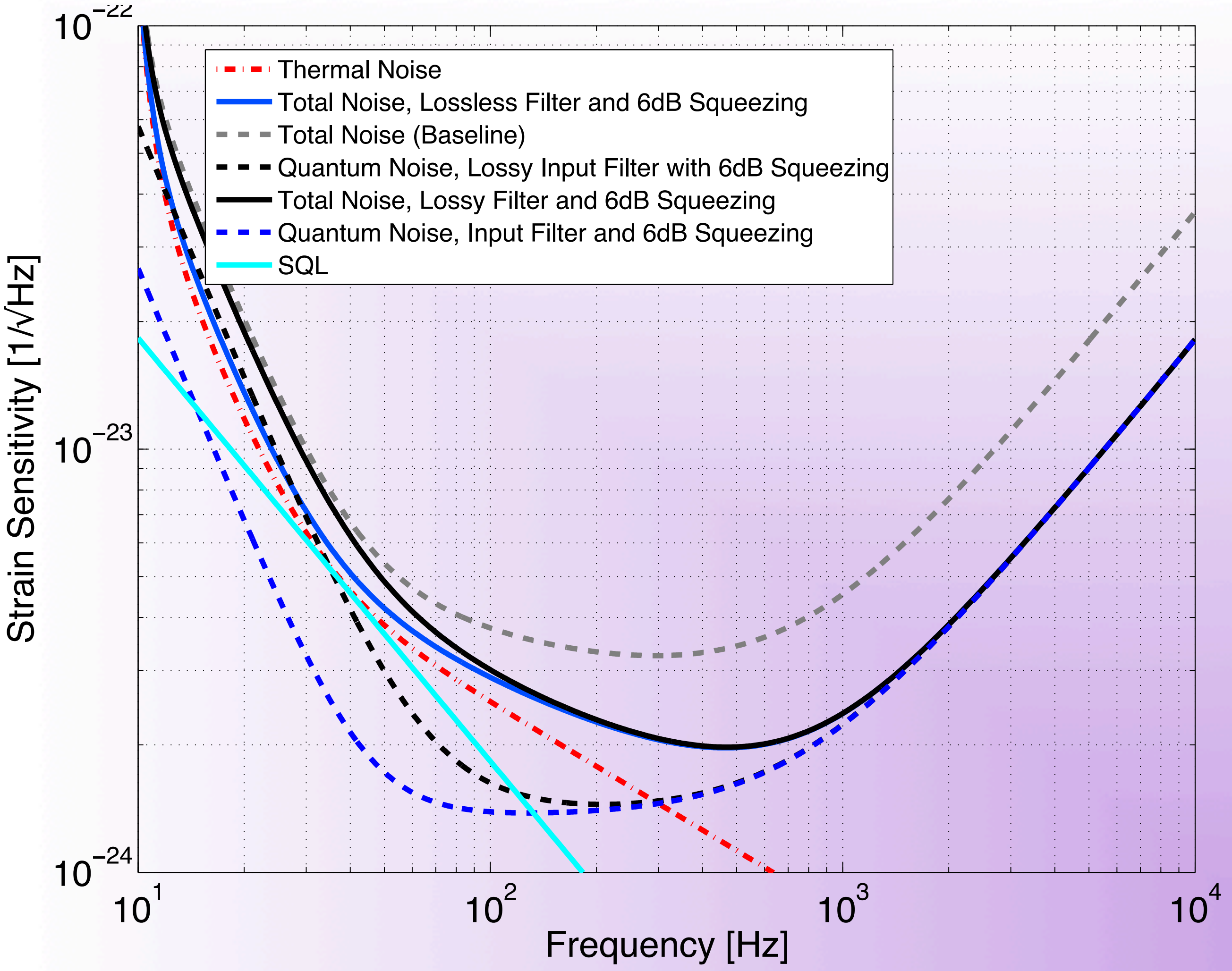
M. Evans,[1] L. Barsotti,[1] J. Harms,[2] P. Kwee,[1] and H. Miao[2]

[1] *MIT*

[2] *Caltech*

In preparation

Beyond the “Standard Quantum Limit”



Squeezing Future

✧Near future goal: develop technology to achieve a factor of 2 (**6 dB**) broadband reduction in quantum noise

→ **possible** “first” major upgrade to aLIGO

✧Ultimately, what we want is a factor of 3 (**10 dB**), possibly more!, of broadband squeezing:

✧Reduce total losses below 10% (low loss Faradays, adaptive mode matching, ..)

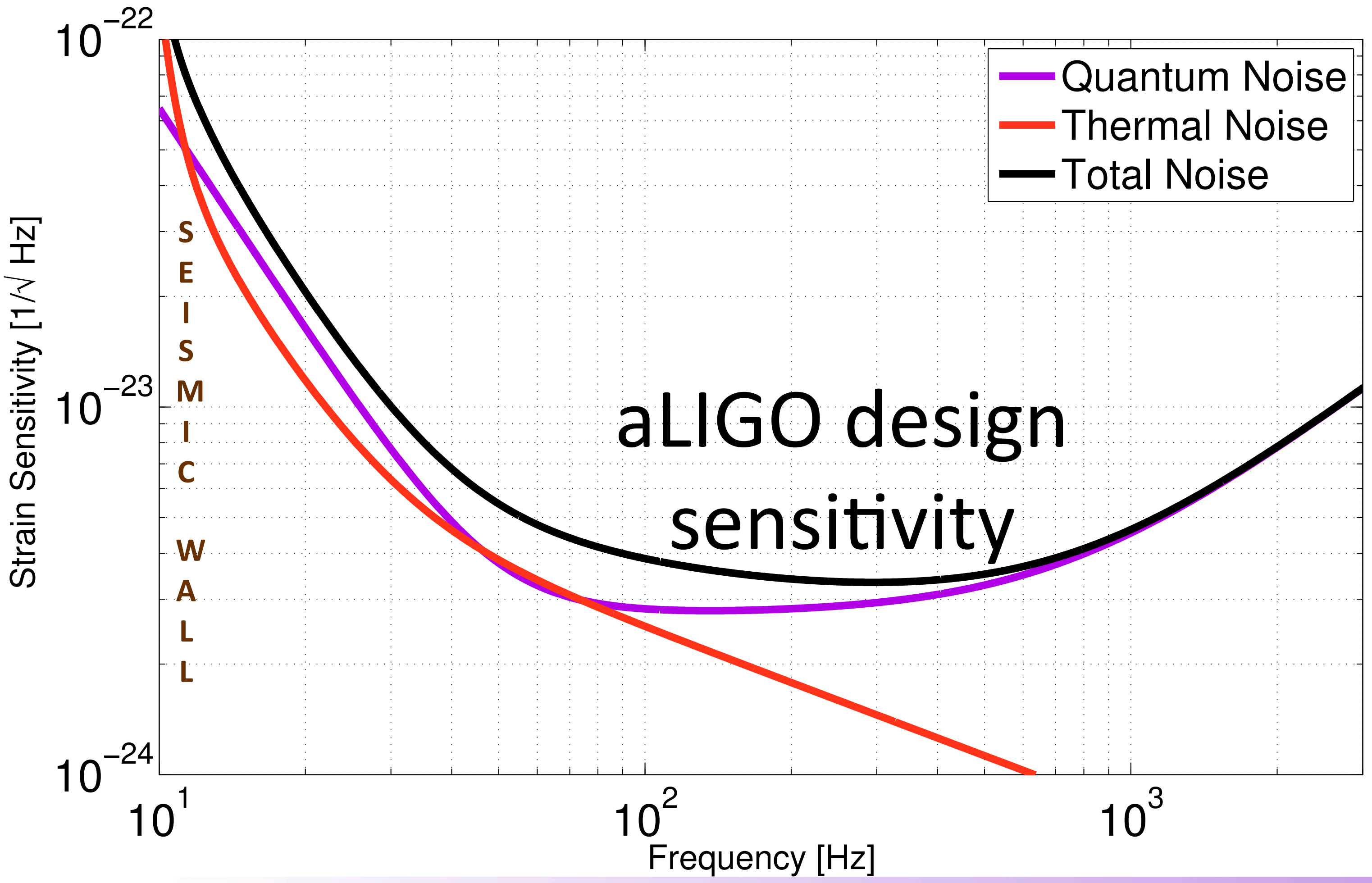
✧ improve control strategy of squeezed beam relative to the interferometer beam

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

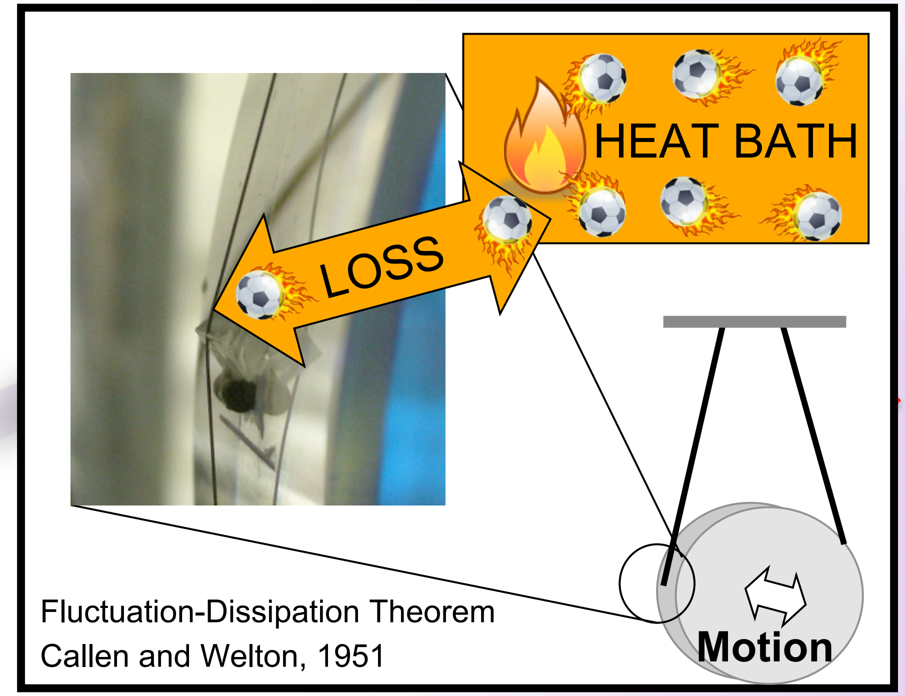
H. Grote,[1,*] K. Danzmann,[1] K.L. Dooley,[1] R. Schnabel,[1] J. Slutsky,[1] and H. Vahlbruch[1]

GEO600, in preparation

How can we go beyond aLIGO?
Reduce the noises!



Fluctuation-dissipation theorem to interpret thermal noise



Fluctuation-Dissipation Theorem
Callen and Welton, 1951

Thermal fluctuations are closely related to mechanical loss (friction)

TEMPERATURE

$$\left\langle x_{\mathrm{th}}^{2} \right\rangle \propto \frac{T}{Q}$$

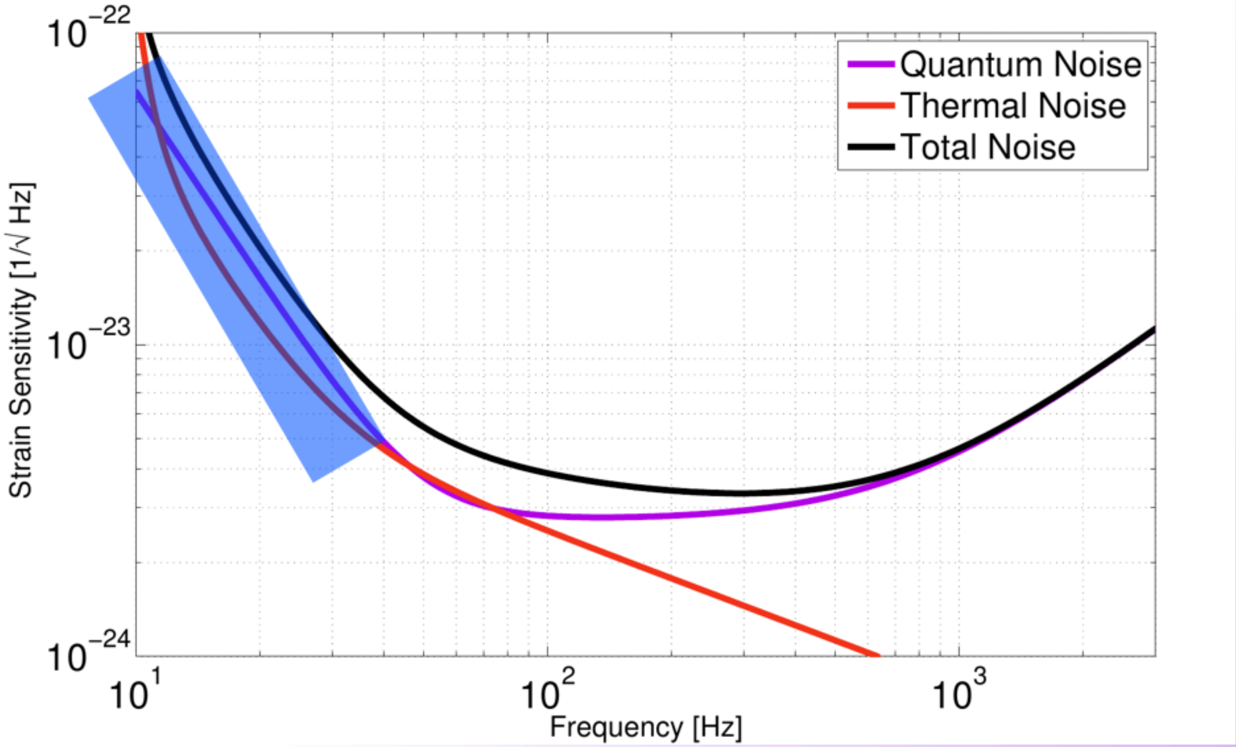
QUALITY FACTOR

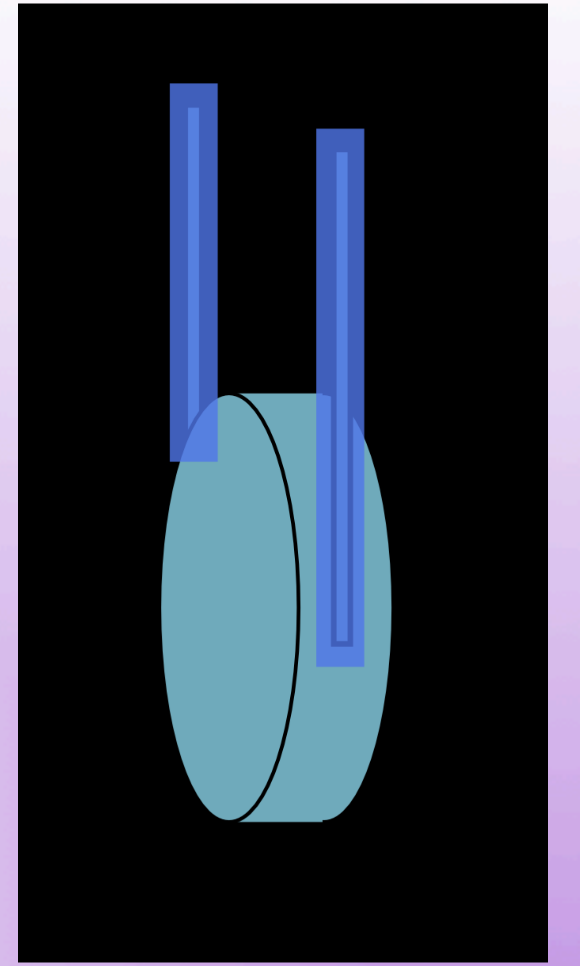
inverse of fractional energy lost after one oscillation

Just reducing T is not enough, T and Q are not independent..for fused silica Q gets worse for lower T..

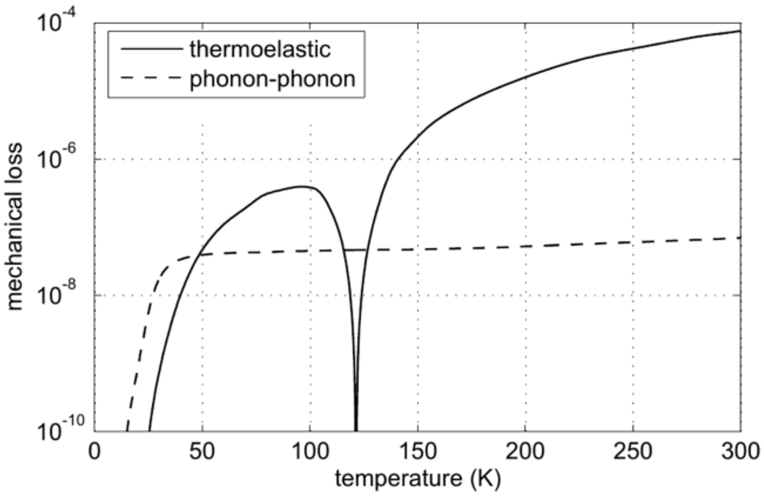
Where thermal noise comes from

SUSPENSION THERMAL NOISE





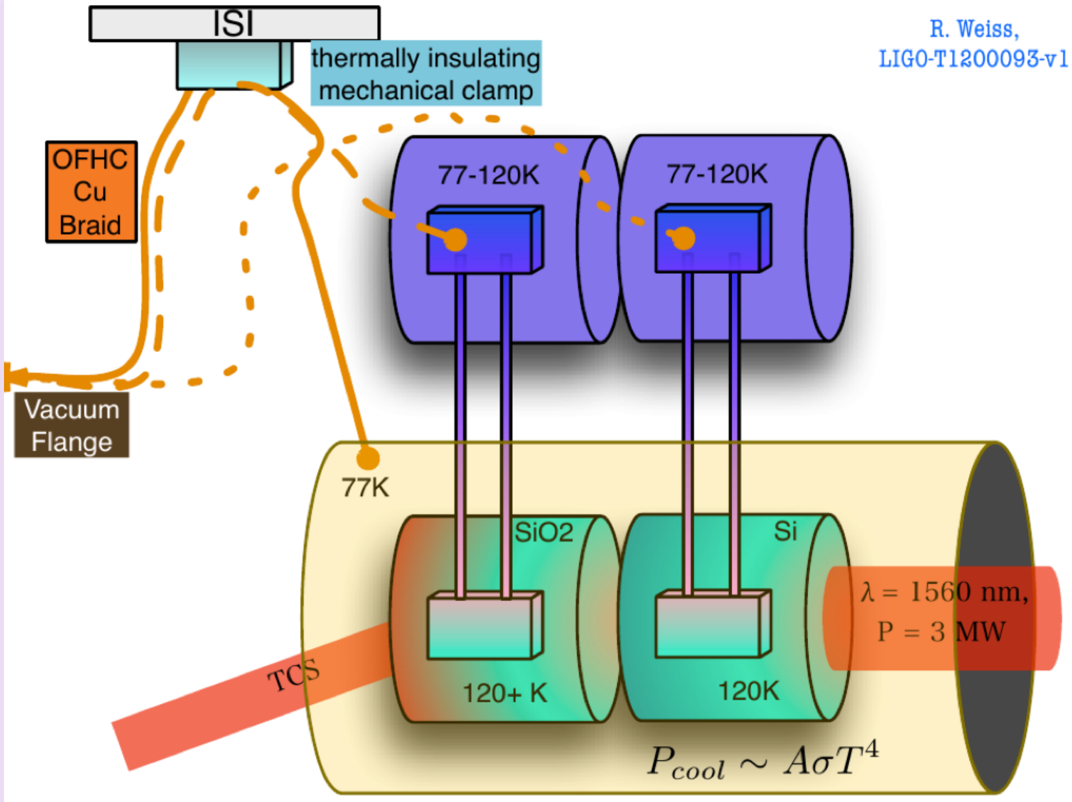
Long story short: Silicon test masses @ 120K



R. Nawrodt et al arXiv:1003.2893

Zero crossing of thermal expansion coefficient, very low intrinsic loss at 124K

We don't really know how to do this yet, a lot of R&D needed

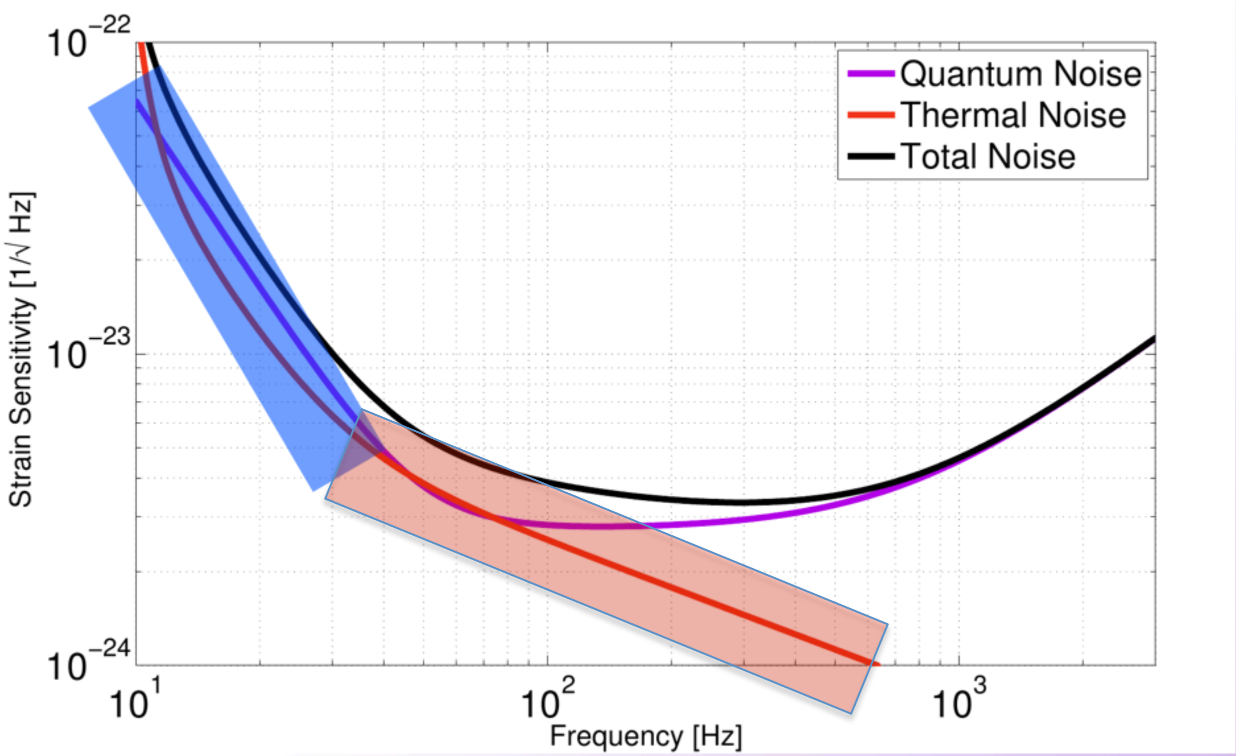


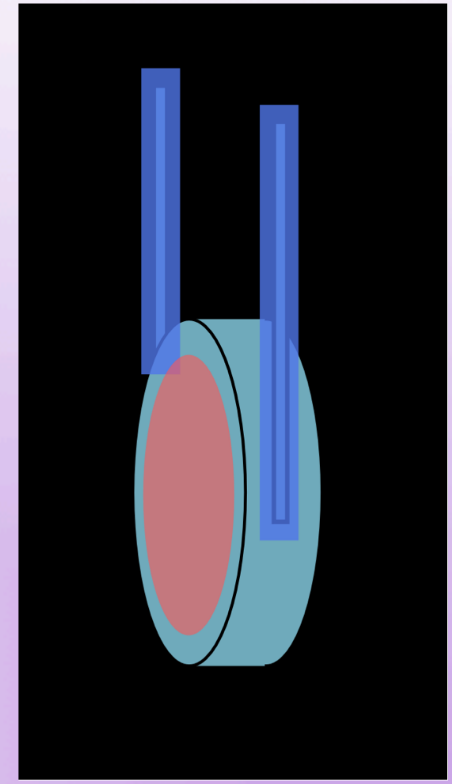
R. Weiss,
LIGO-T1200093-v1

Nicolas Smith, Rana Adhikari
(Caltech)
Rai Weiss (MIT)

Where thermal noise comes from

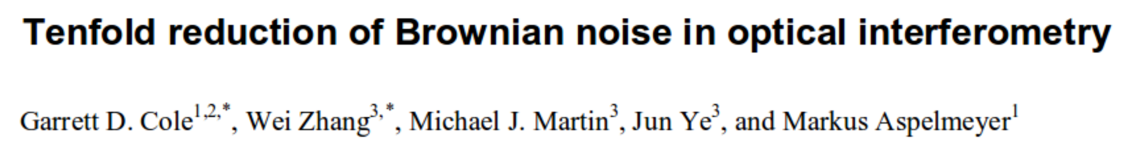
COATING THERMAL NOISE





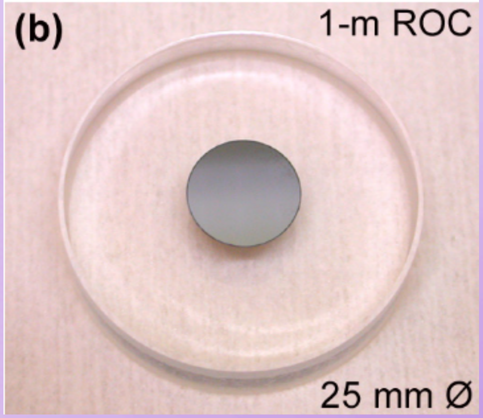
Optical Coating Research

- Traditional materials (amorphous Silica/Tantala) used for optical coatings have relatively low Q ~ few 10^4
- High Q optical coatings has been a major research subject for many years, small improvement
- Recent results on new crystalline materials show order of magnitude higher Q



Tenfold reduction of Brownian noise in optical interferometry

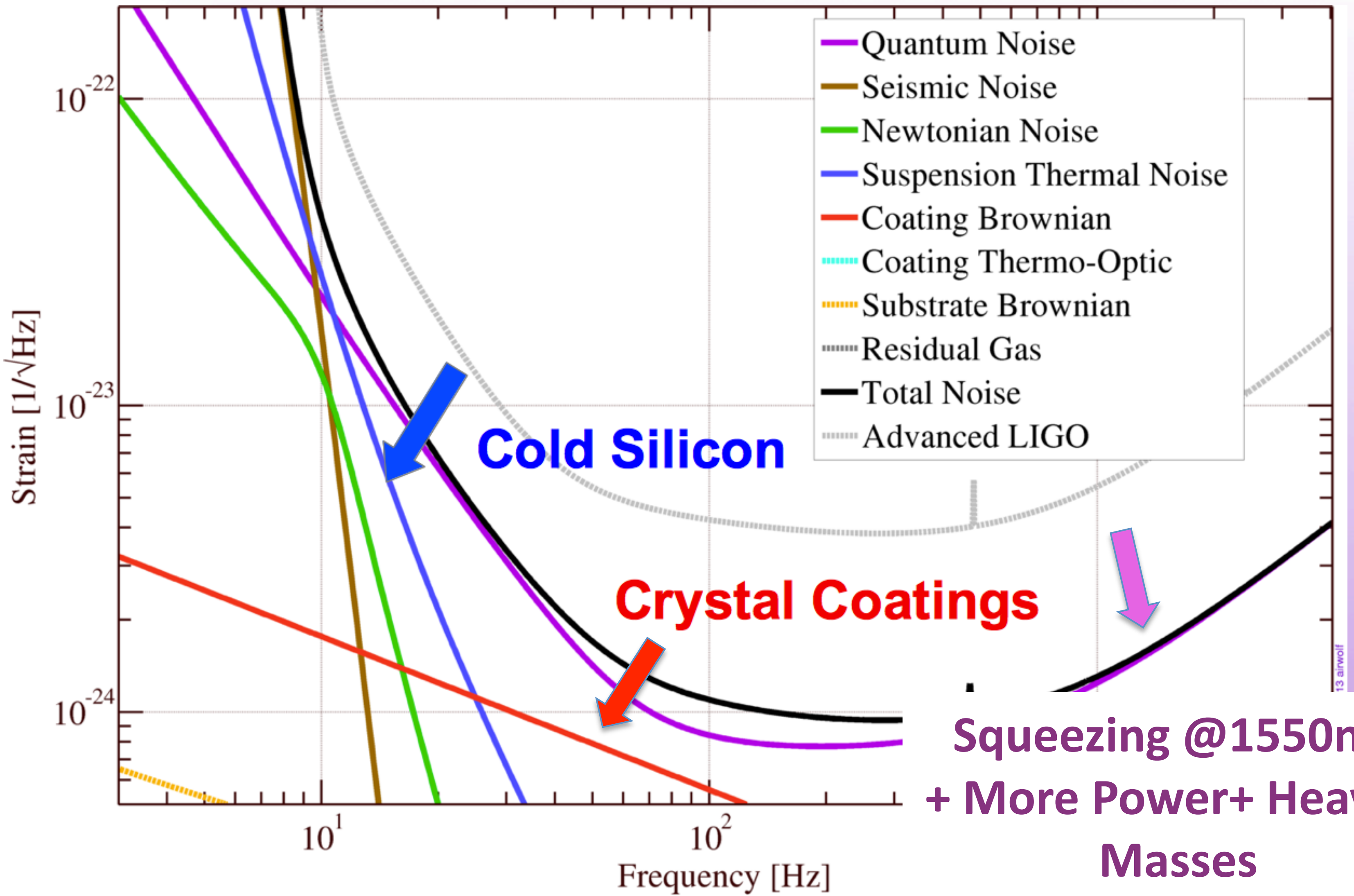
Garrett D. Cole[1,2,*], Wei Zhang[3,*], Michael J. Martin[3], Jun Ye[3], and Markus Aspelmeyer[1]



AlGaAs Coatings, grown on GaAs substrate, lifted and bonded onto optic (any material)

→ Need to scale it to a BIG test mass

One Possible Target for “third” generation detectors (@1550nm)



Cold Silicon

Crystal Coatings

Squeezing @1550nm + More Power+ Heavier Masses

Conclusions

- ✧Advanced LIGO is happening!
- ✧Installation & commissioning progressing well, great effort to go on-line as soon as possible
- ✧Scientific data in 2015, first detection (hopefully) in 2016
- ✧We think we can make even a better detector in a few years…
- ✧… but critical instrument science R&D needs to happen now to make that possible!

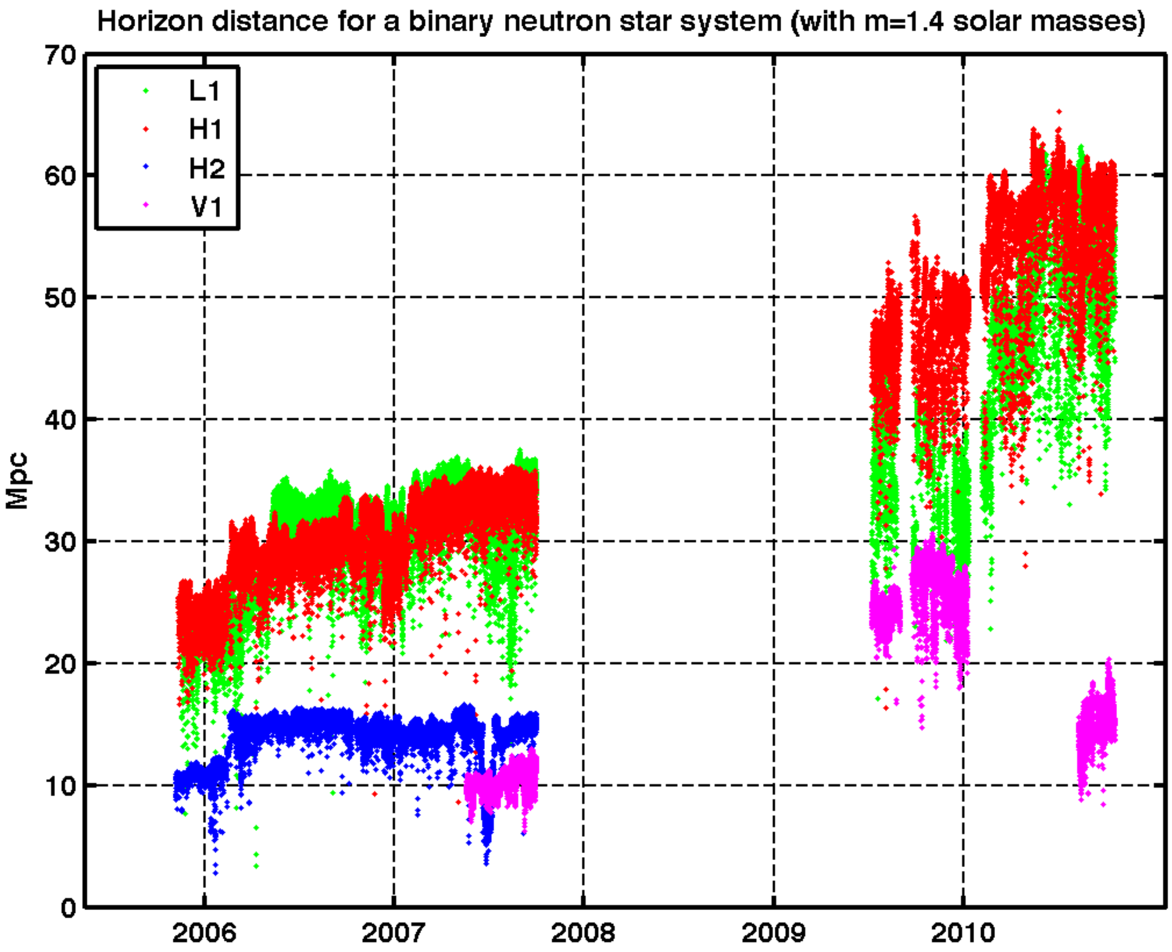
Thank you!

- ✧ Slide Credits:

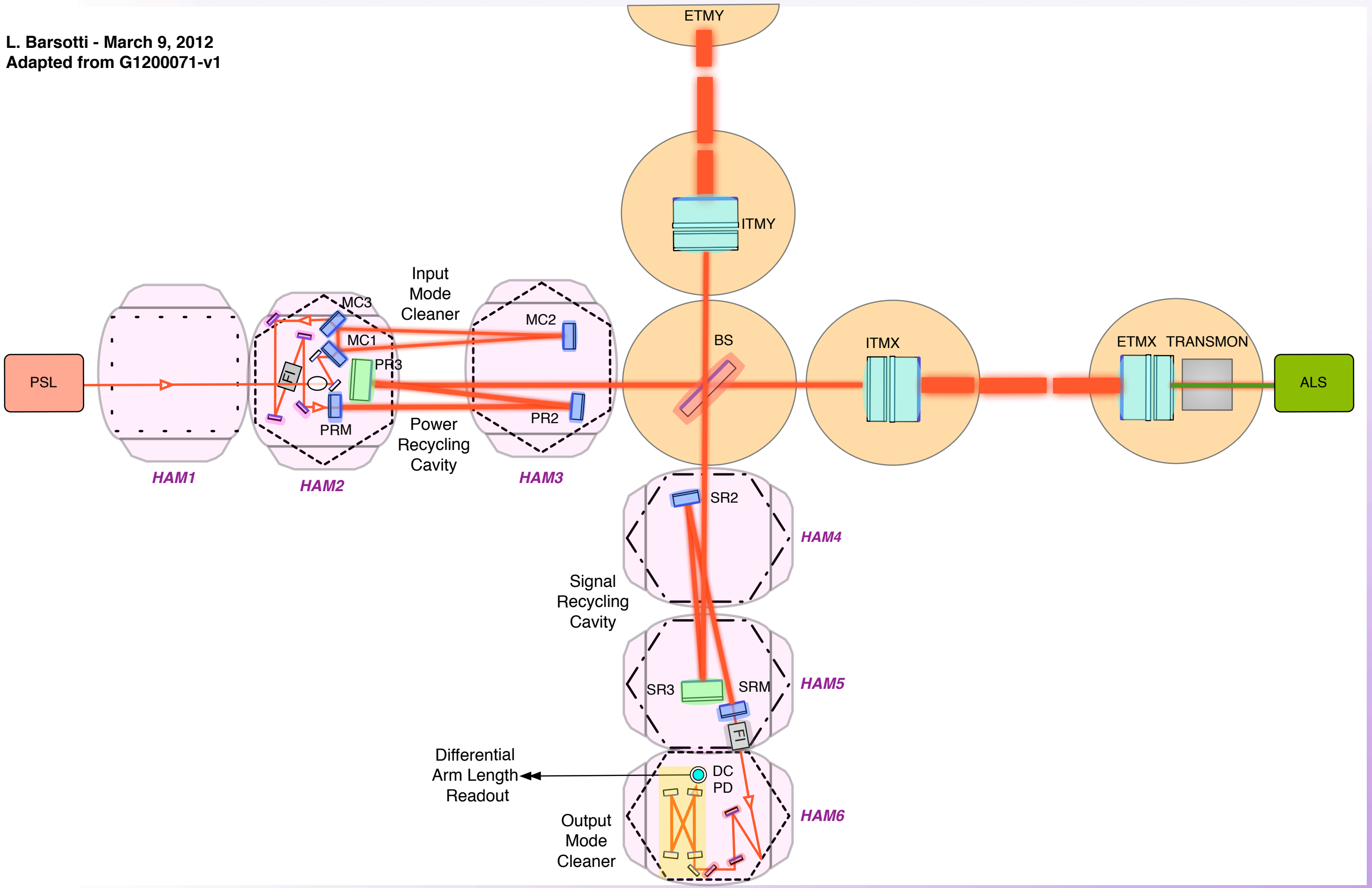
  Nicolas Smith, Peter Fritschel, Jeff Kissel, Anamaria Effler, Matthew Evans, Gabriela Gonzales, Sheila Dwyer

Spare slides

2005-2010 Scientific Data Taking



Advanced LIGO configuration



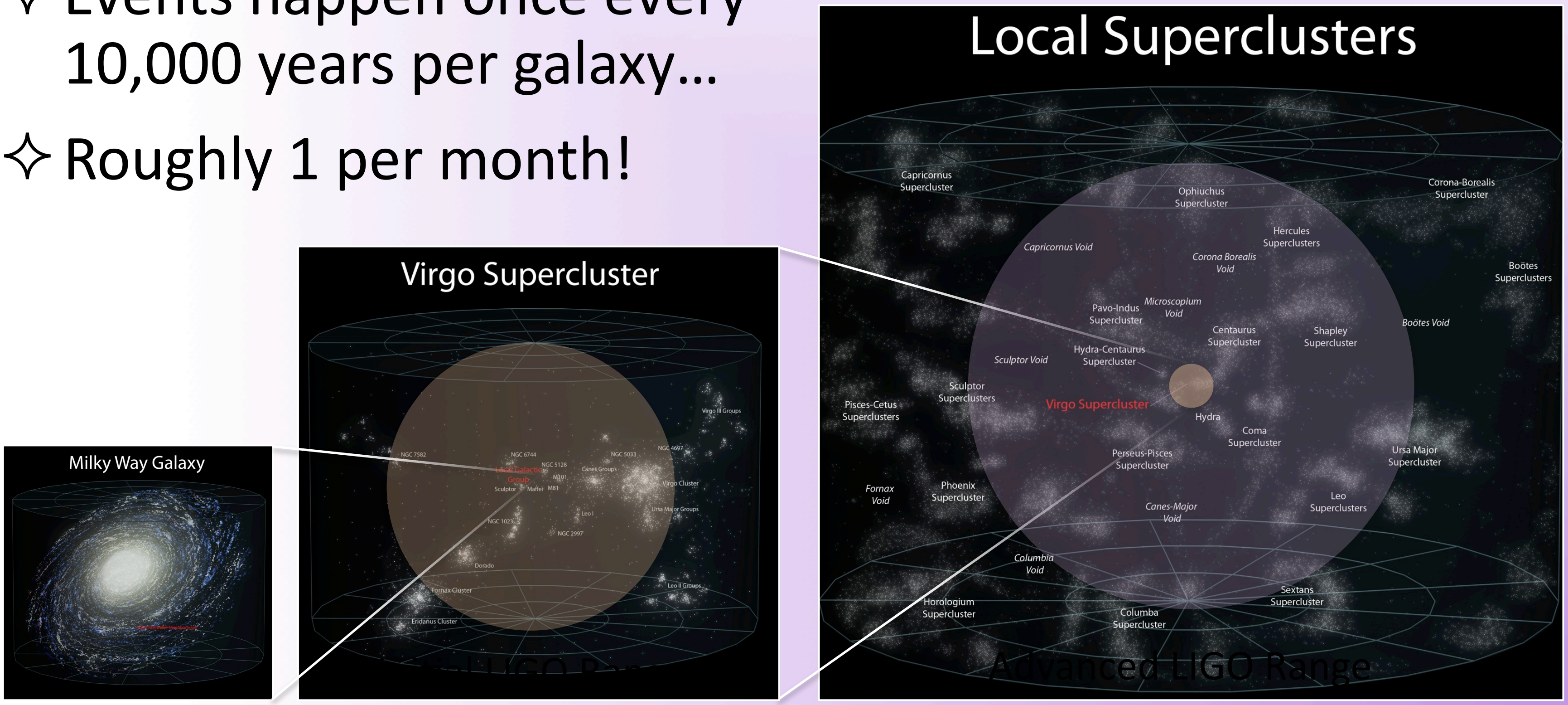
✧Arm cavities, power and signal recycling cavity

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

Need more sensitive detectors.. ”Advanced” Detectors, 10x more range

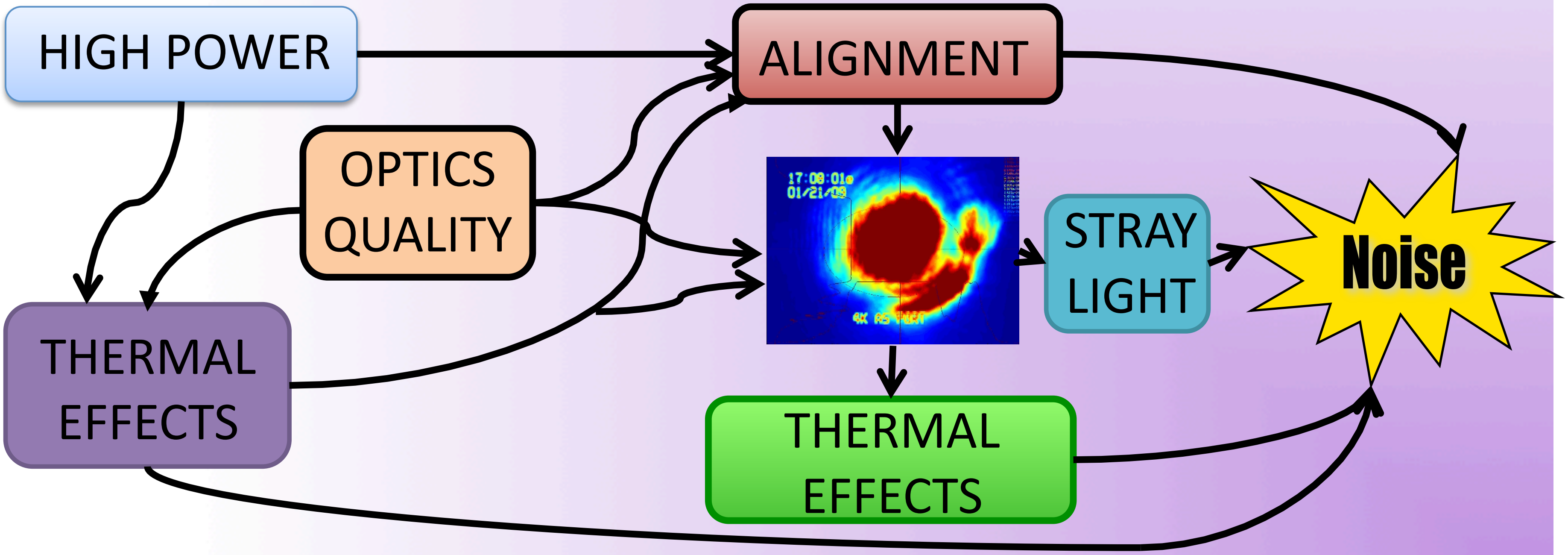
- ✧ Advanced detectors will reach about 100,000 galaxies
- ✧ Events happen once every 10,000 years per galaxy…
- ✧ Roughly 1 per month!

(considering only NS-NS mergers)



What we call “commissioning”: from installation to science data

Understand and fix an entanglement of noise coupling mechanisms



HIGH POWER

ALIGNMENT

OPTICS QUALITY

STRAY LIGHT

Noise

THERMAL EFFECTS

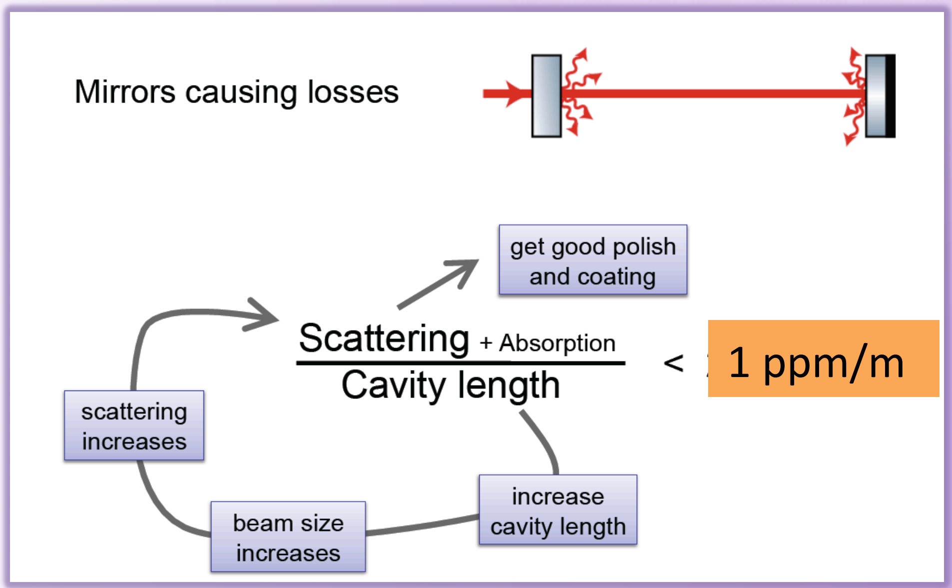
THERMAL EFFECTS

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



Mirrors causing losses

get good polish and coating

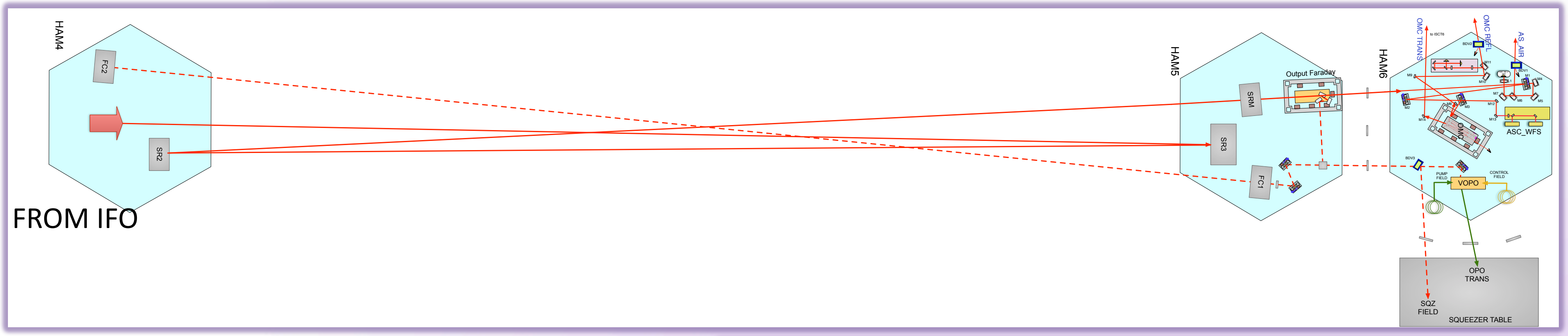
$$\frac{\text{Scattering + Absorption}}{\text{Cavity length}} < 1\ \text{ppm/m}$$

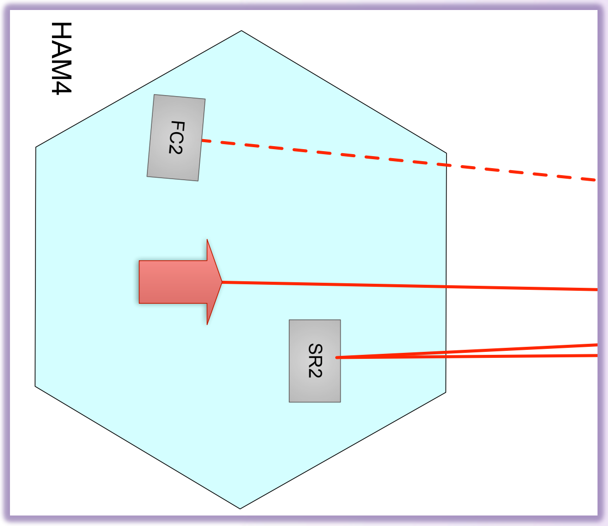
scattering increases

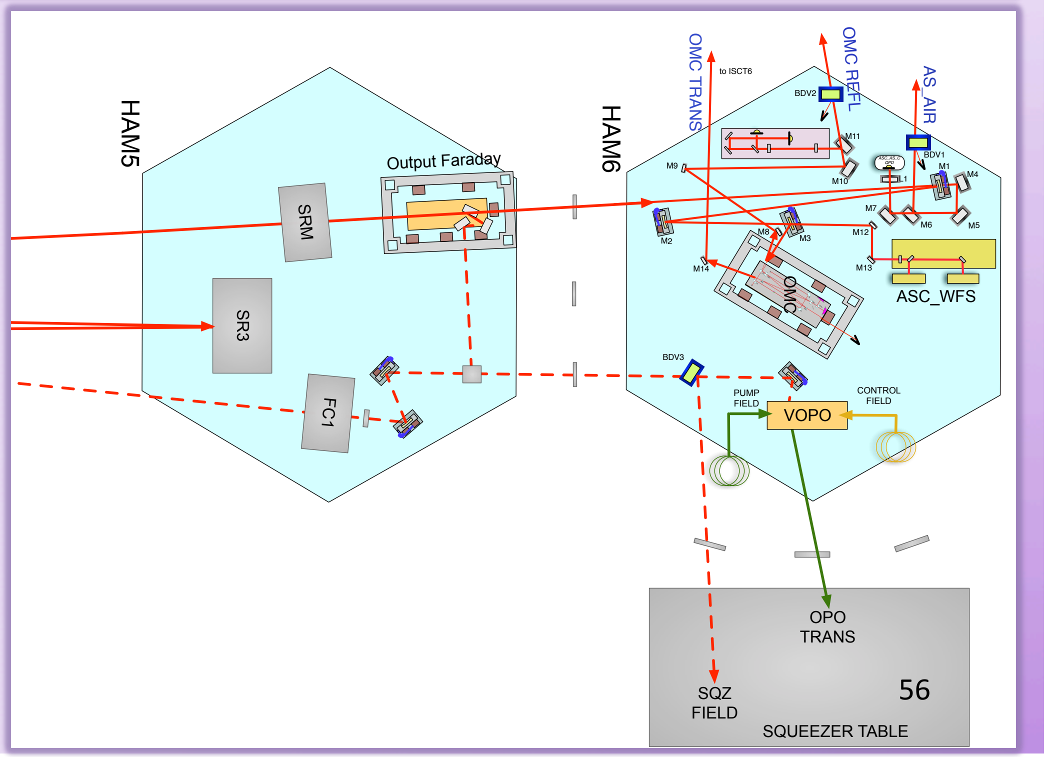
beam size increases

increase cavity length

Something like this, maybe....

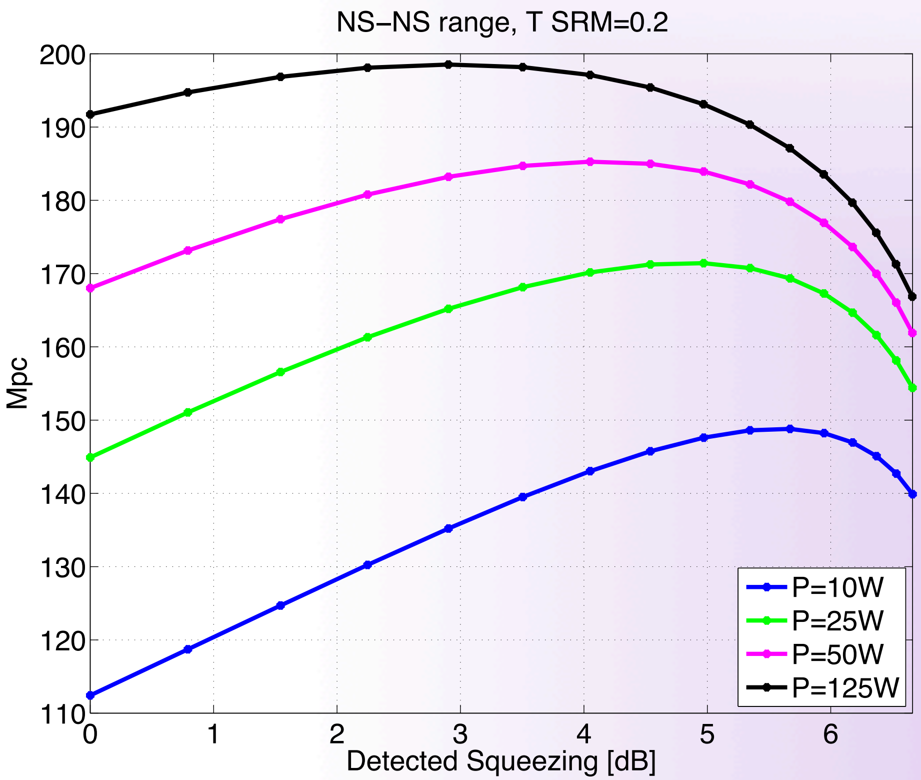


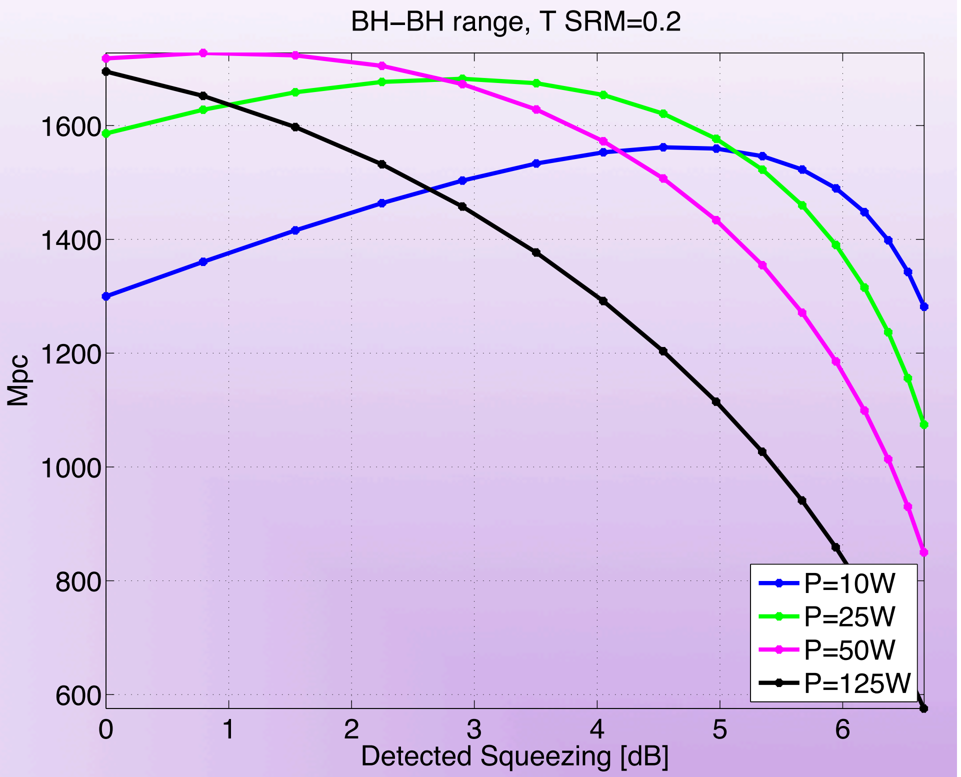




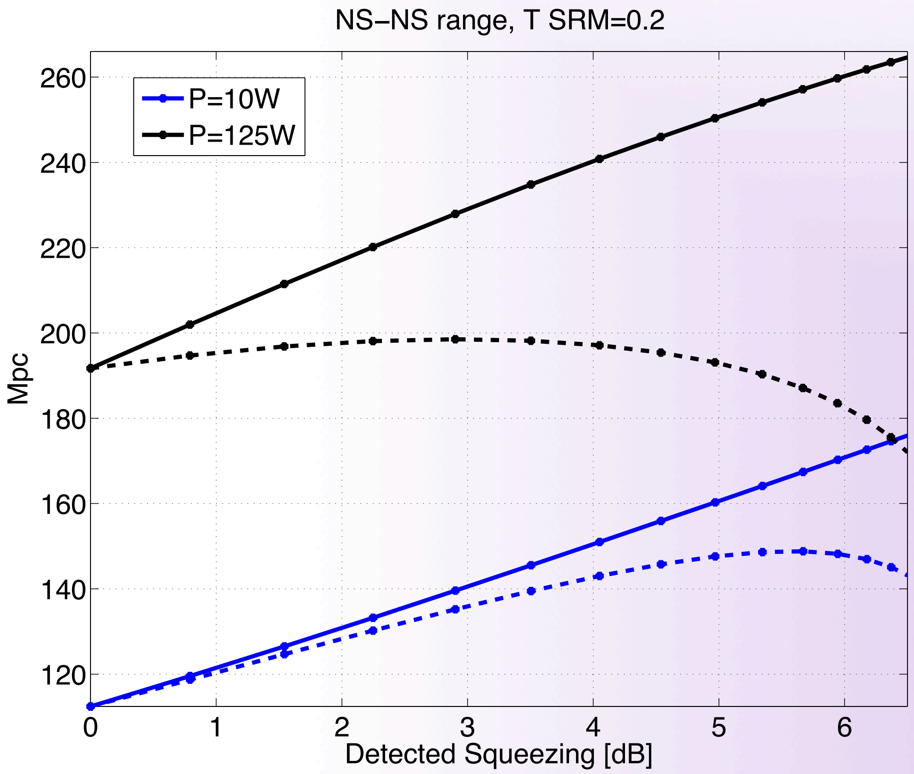
Just a cartoon!
Not a conceptual design yet!

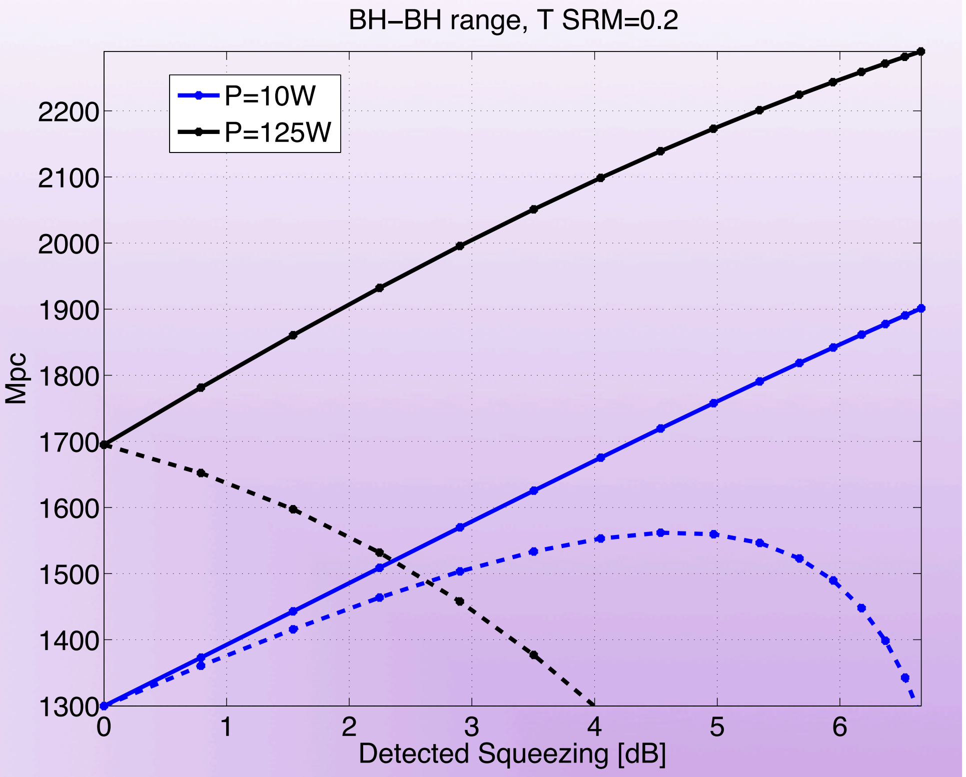
aLIGO + Squeezing: NS-NS and BH-BH Ranges

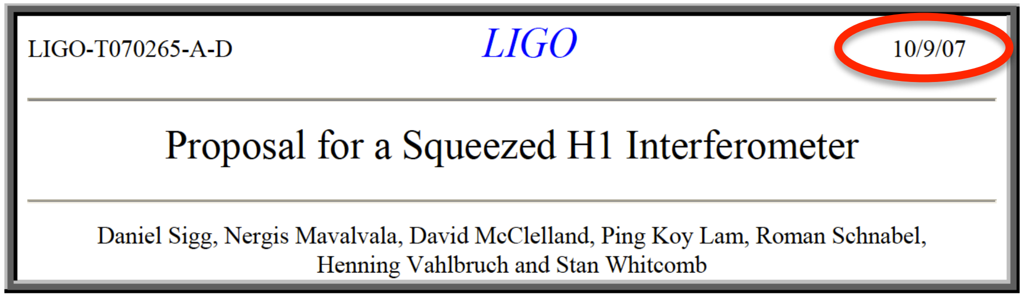

NS−NS range, T SRM=0.2


BH−BH range, T SRM=0.2

aLIGO + Frequency Dependent Squeezing: Predicted Ranges


NS−NS range, T SRM=0.2


BH−BH range, T SRM=0.2



LIGO-T070265-A-D

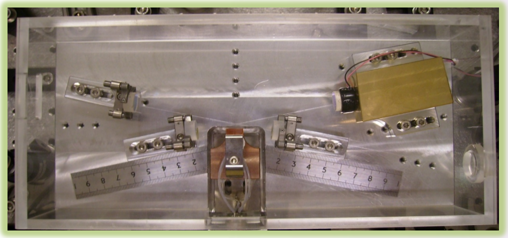
LIGO

10/9/07

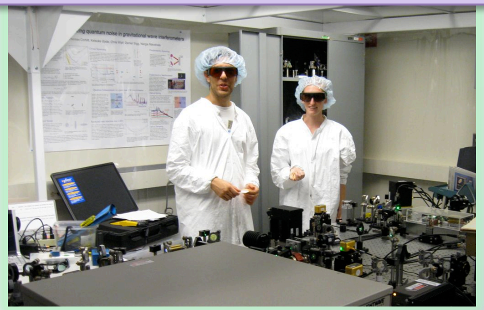
Proposal for a Squeezed H1 Interferometer

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

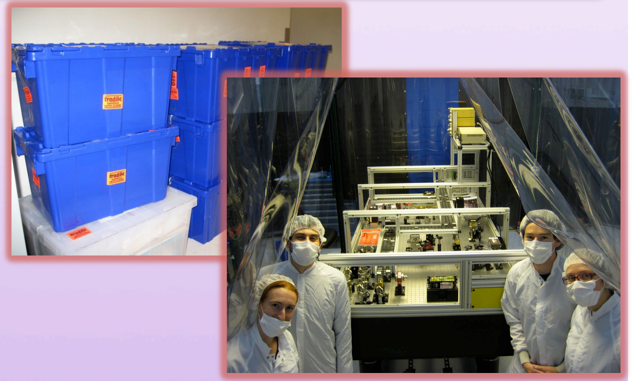
Bow-tie cavity OPO design at ANU (2008)



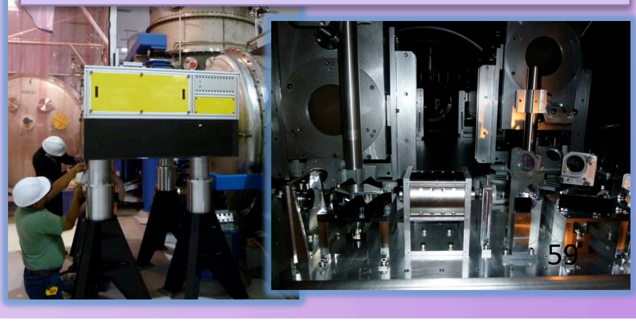
H1 Squeezer assembling at MIT (2009-2010)



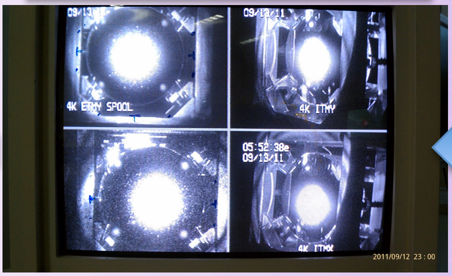
H1 Squeezer parts shipped to LHO (Oct 2010)



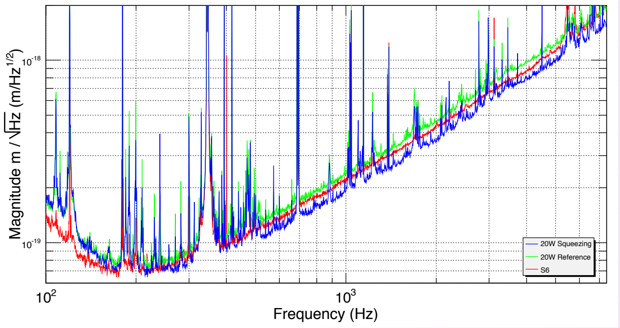
H1 Squeezer Installation (Summer 2011)



H1 Recovery (Sept 2011)



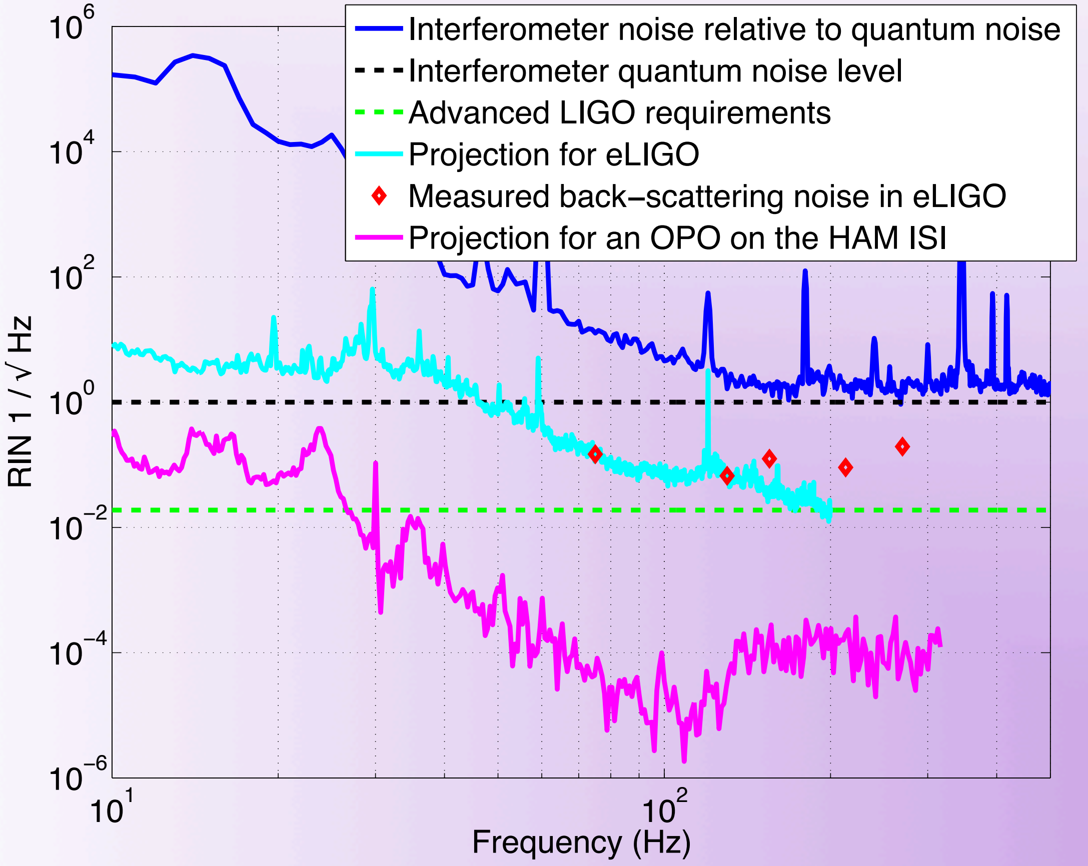
Squeezing in H1 (Oct 3 – Dec 4)



Lessons Learned (III)

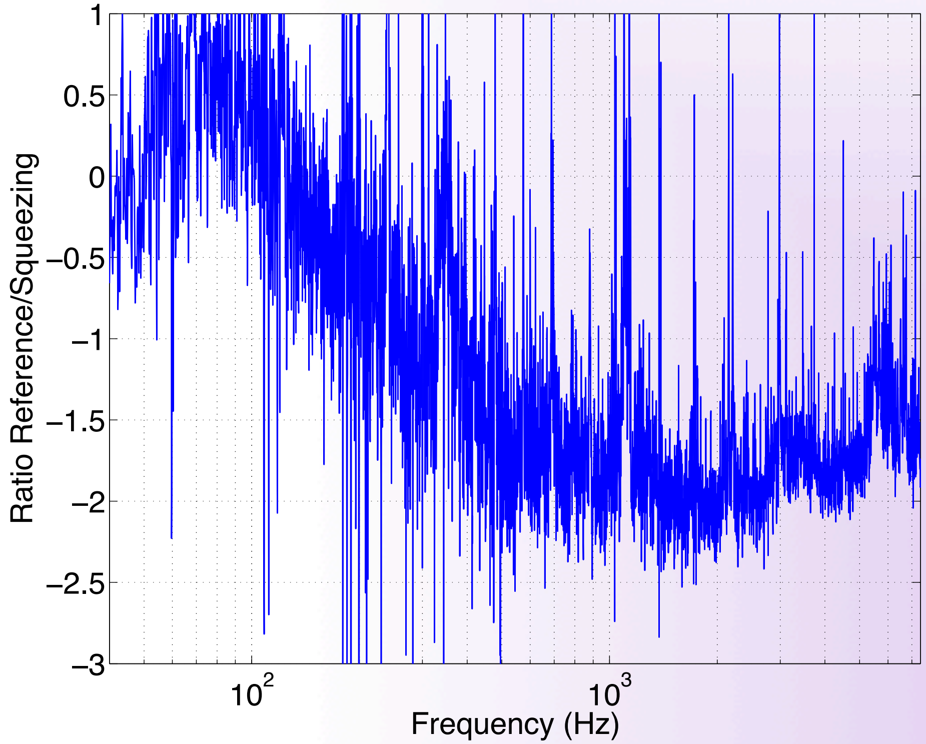
✧ Need better isolation from back scattering

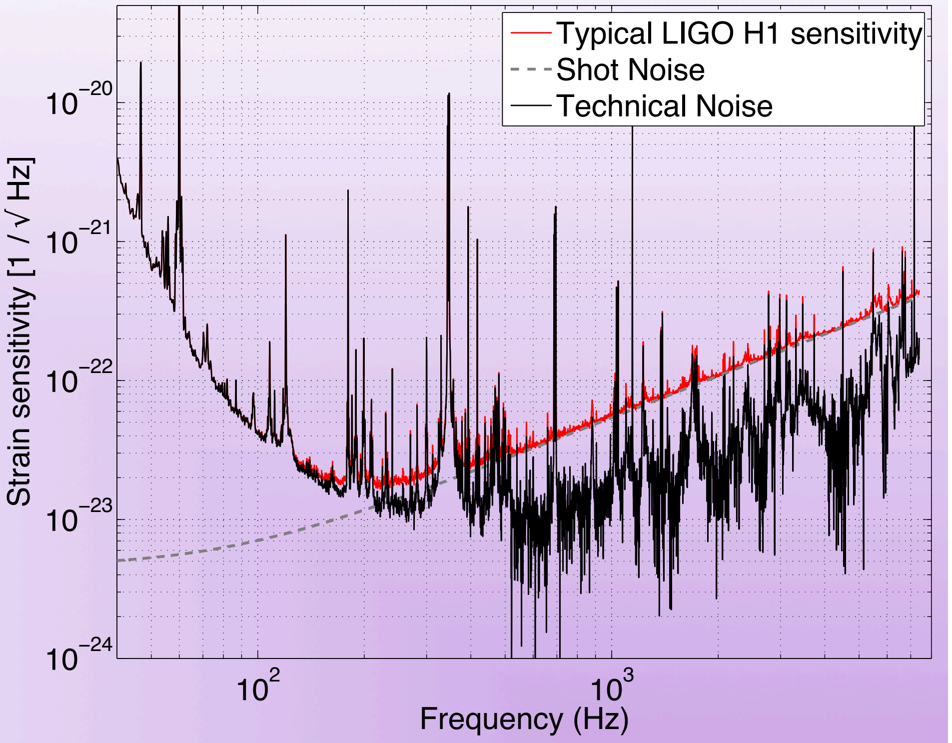
(it was ok for LIGO H1, it won't be enough for aLIGO)



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

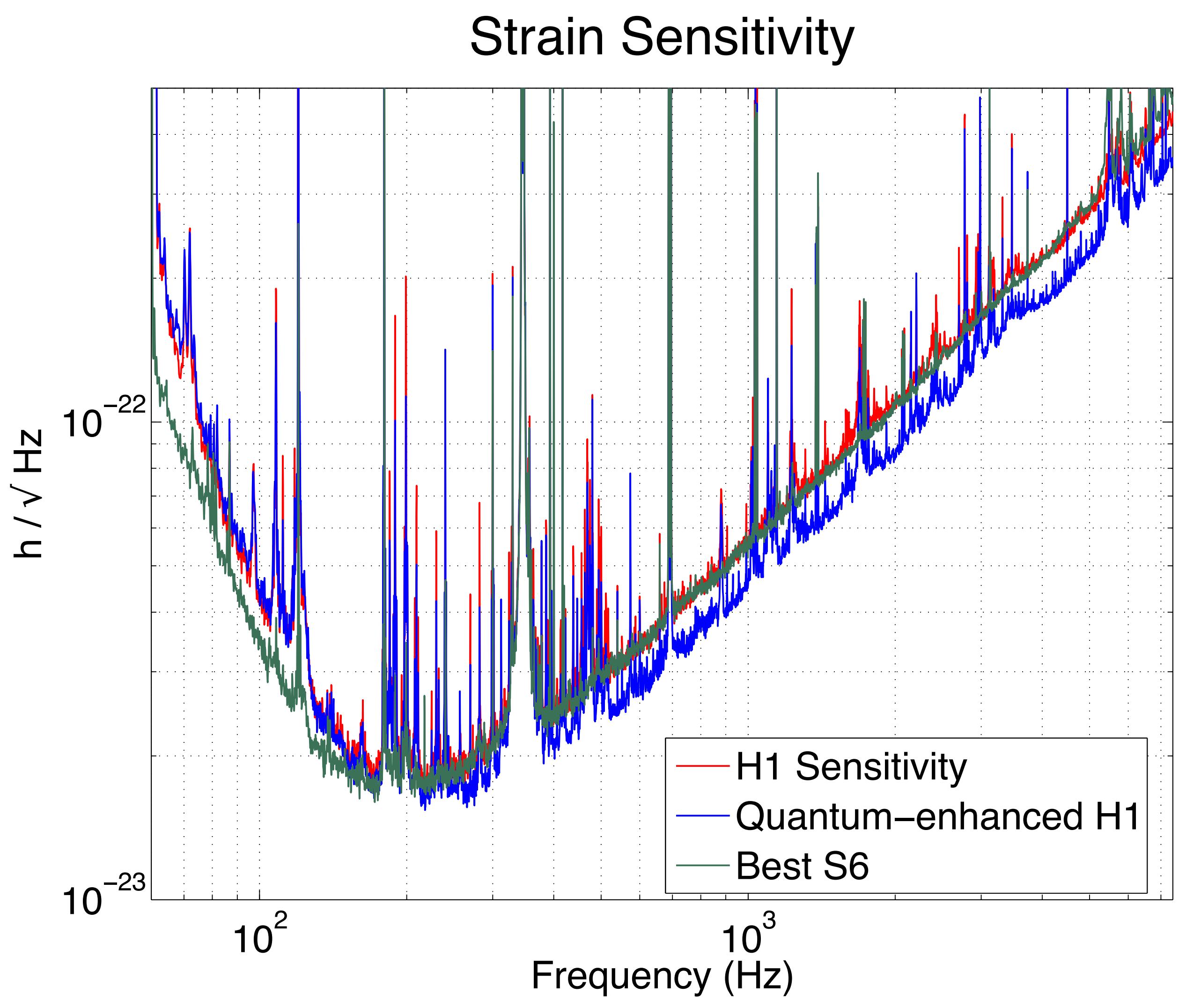
2.15 dB (28%) improvement over quantum noise



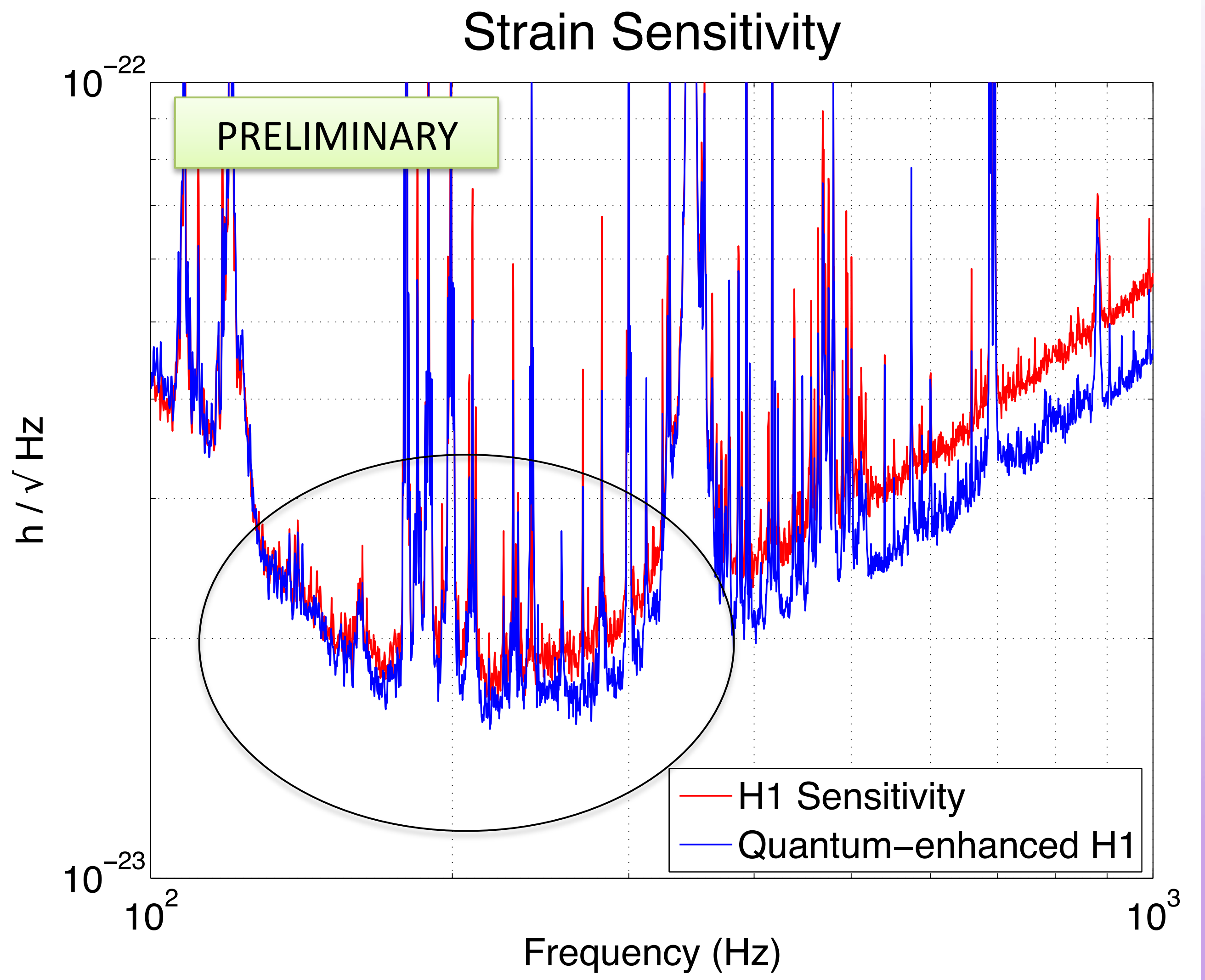


Squeezing improves only quantum noise, not other technical noises

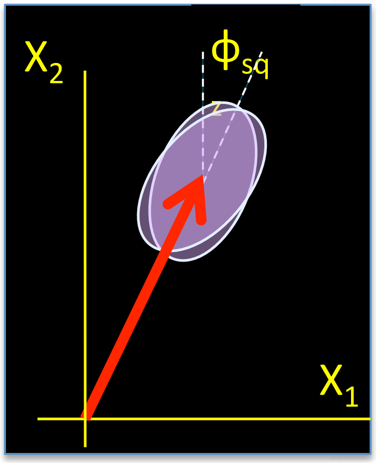
Best broadband sensitivity ever



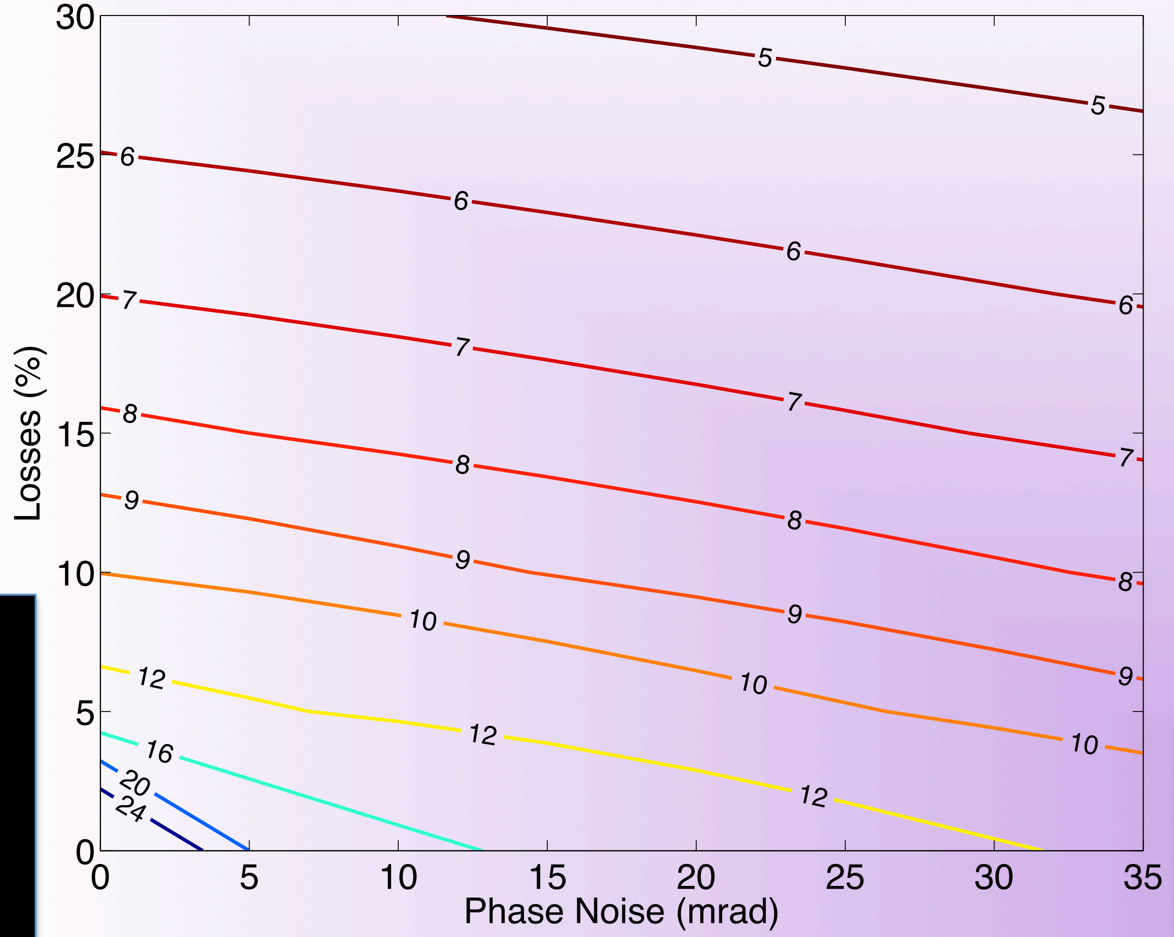
Improving H1 by 2 dB (28%) with squeezing ..without spoiling the sensitivity at 200 Hz

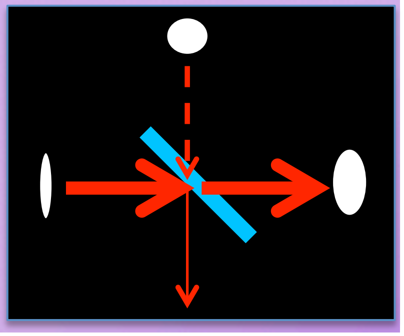


Not only losses, phase noise too



Squeezing [dB] vs Losses and Phase Noise





Where the main losses came from

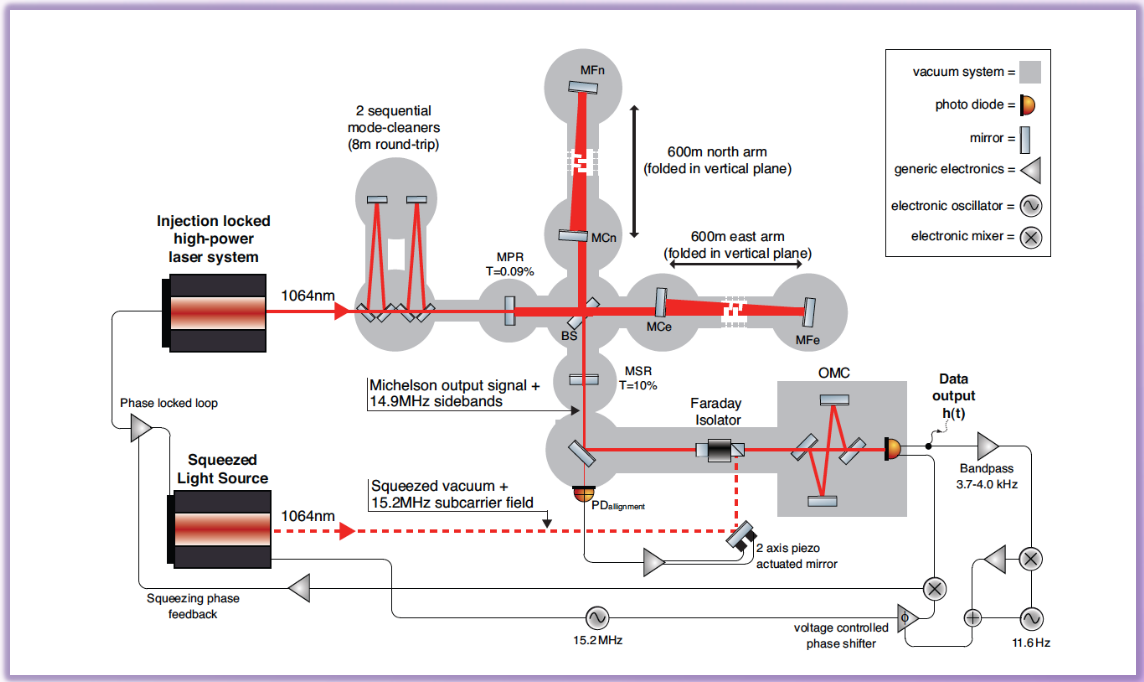
- ✧ Mode matching (~30% losses)
- ✧ Faradays (3 passes ~ 20% losses)
- ✧ OMC transmission (18% losses)

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

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)



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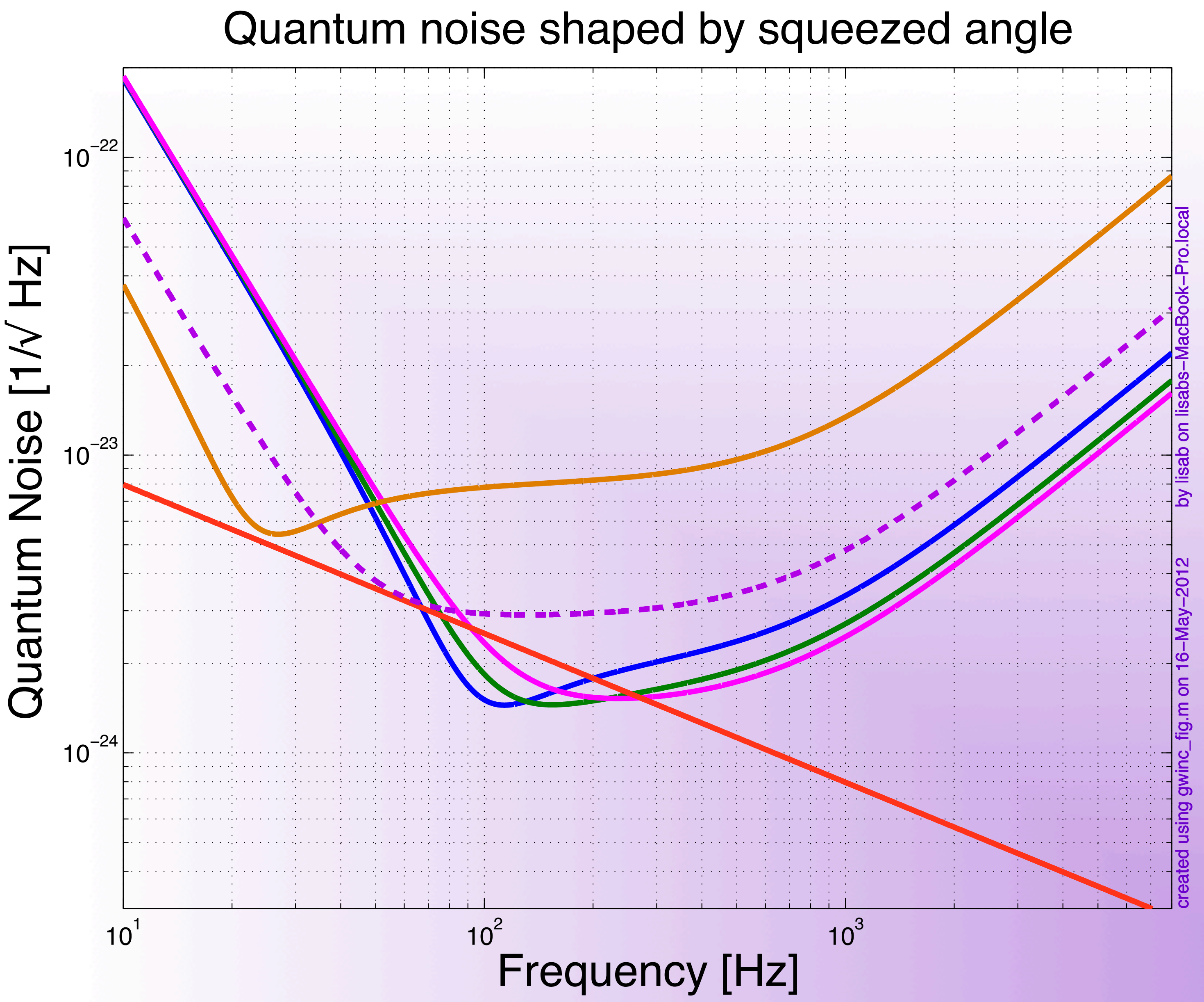
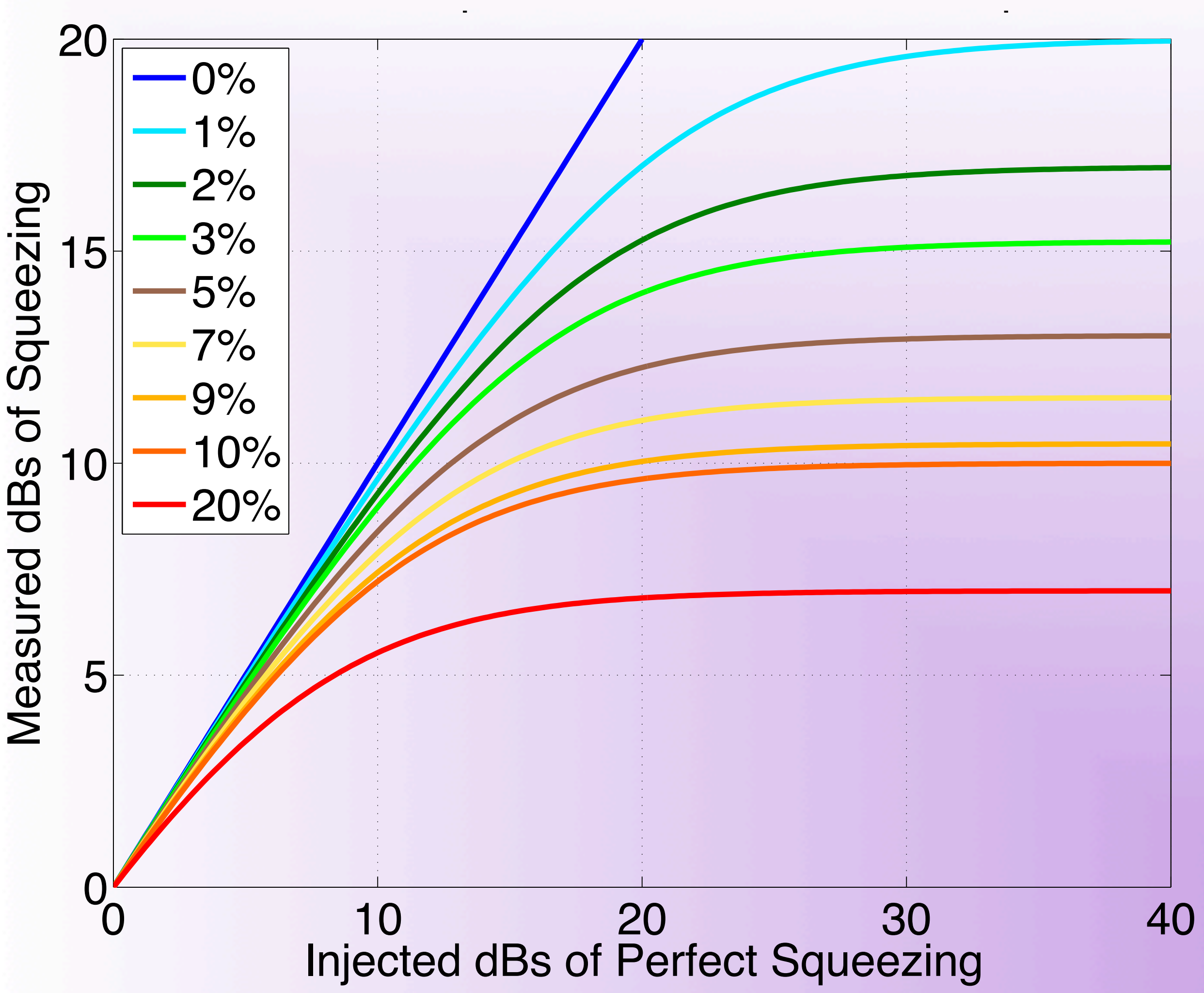

Quantum noise shaped by squeezed angle
Quantum Noise [1/√ Hz]
Frequency [Hz]
10^{-22}
10^{-23}
10^{-24}
10^{1}
10^{2}
10^{3}
created using gwinc_fig.m on 16−May−2012
by lisab on lisabs−MacBook−Pro.local

Why not even more?



Have to consider phase noise too