Squeezed Light Techniques for Gravitational Wave Detection

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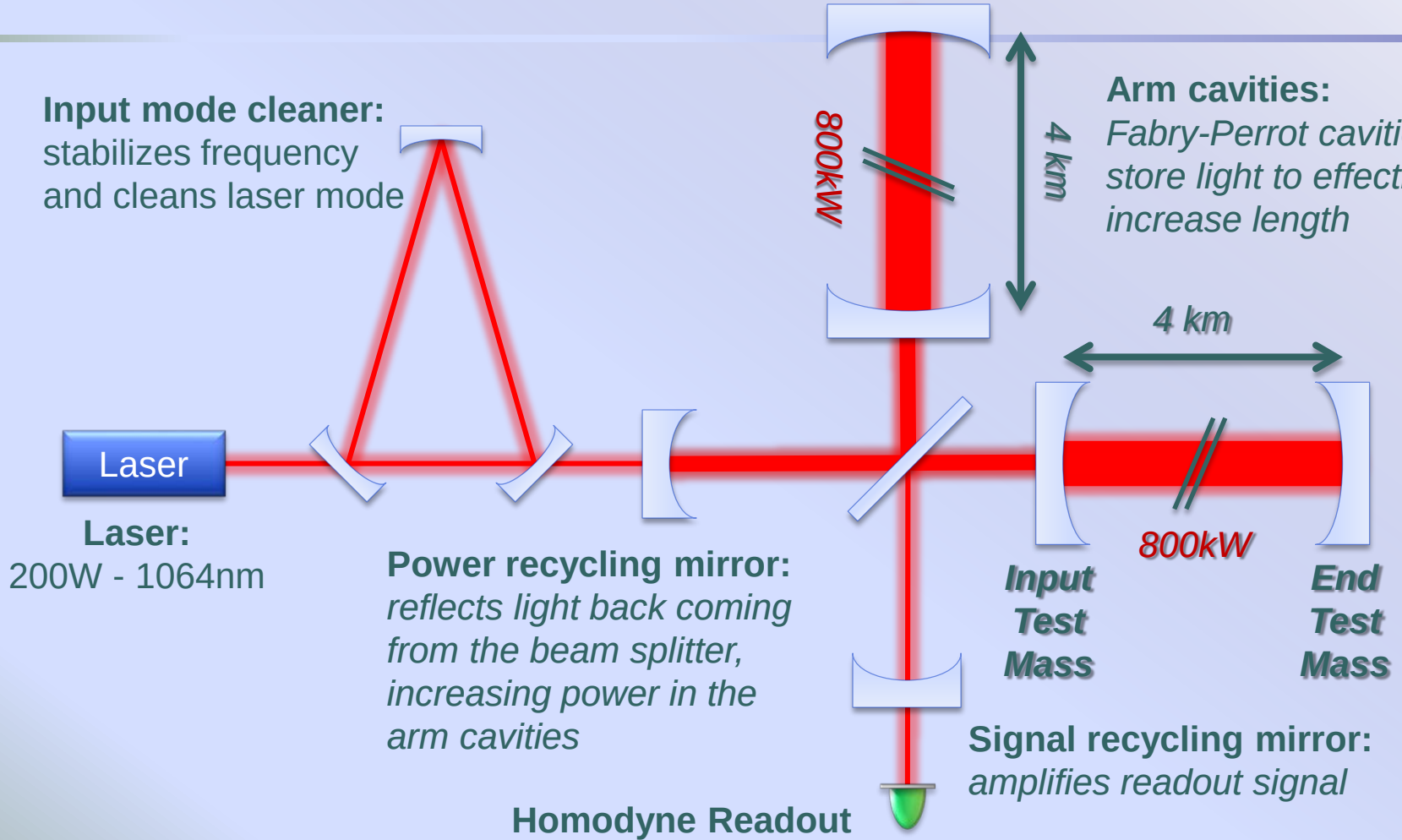
LIGO seminar at Caltech

LIGO

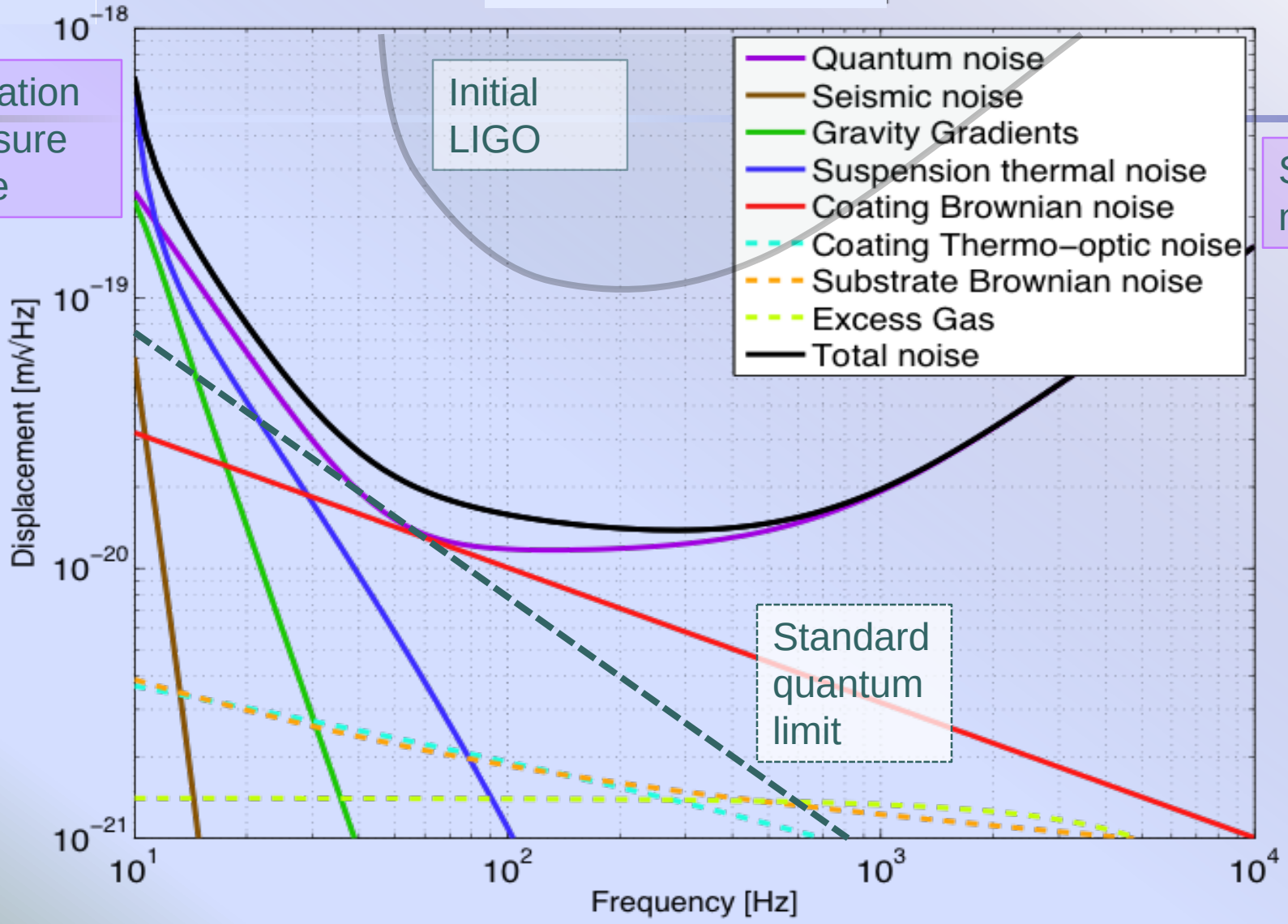
Abstract

Several kilometer long interferometers have been built over the past decade to search for gravitational waves of astrophysical origins. For the next generation detectors intra-cavity powers of several 100 kW are envisioned. The injection of squeezed light, a specially prepared quantum state, has the potential to further increase the sensitivity of these detectors. The technology behind squeezed light production has taken impressive steps forward in recent years. As a result a series of experiments is underway to prove the effectiveness of squeezed light and to make quantum technology a valid upgrade path for gravitational wave detectors.

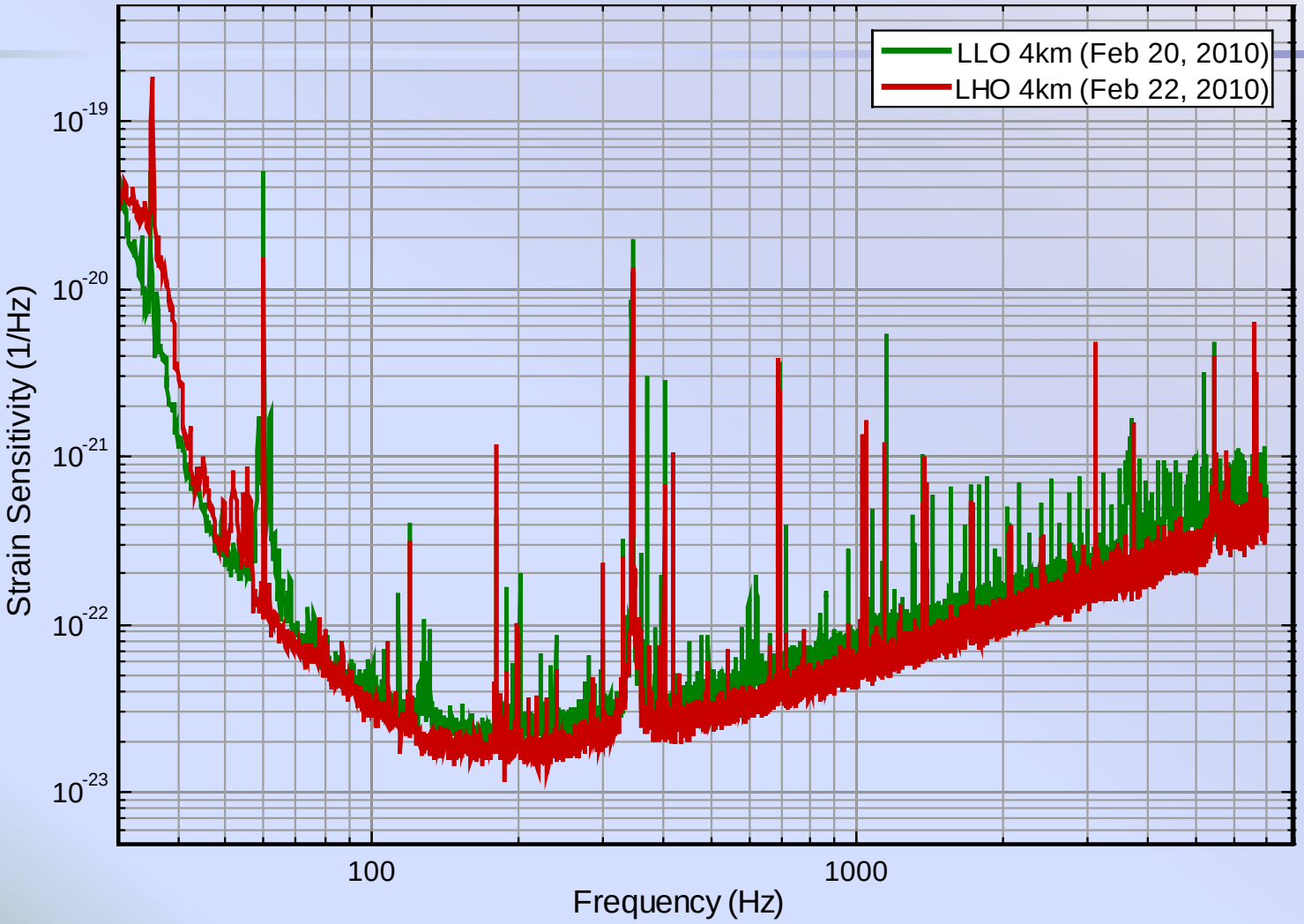
The Advanced LIGO Detector



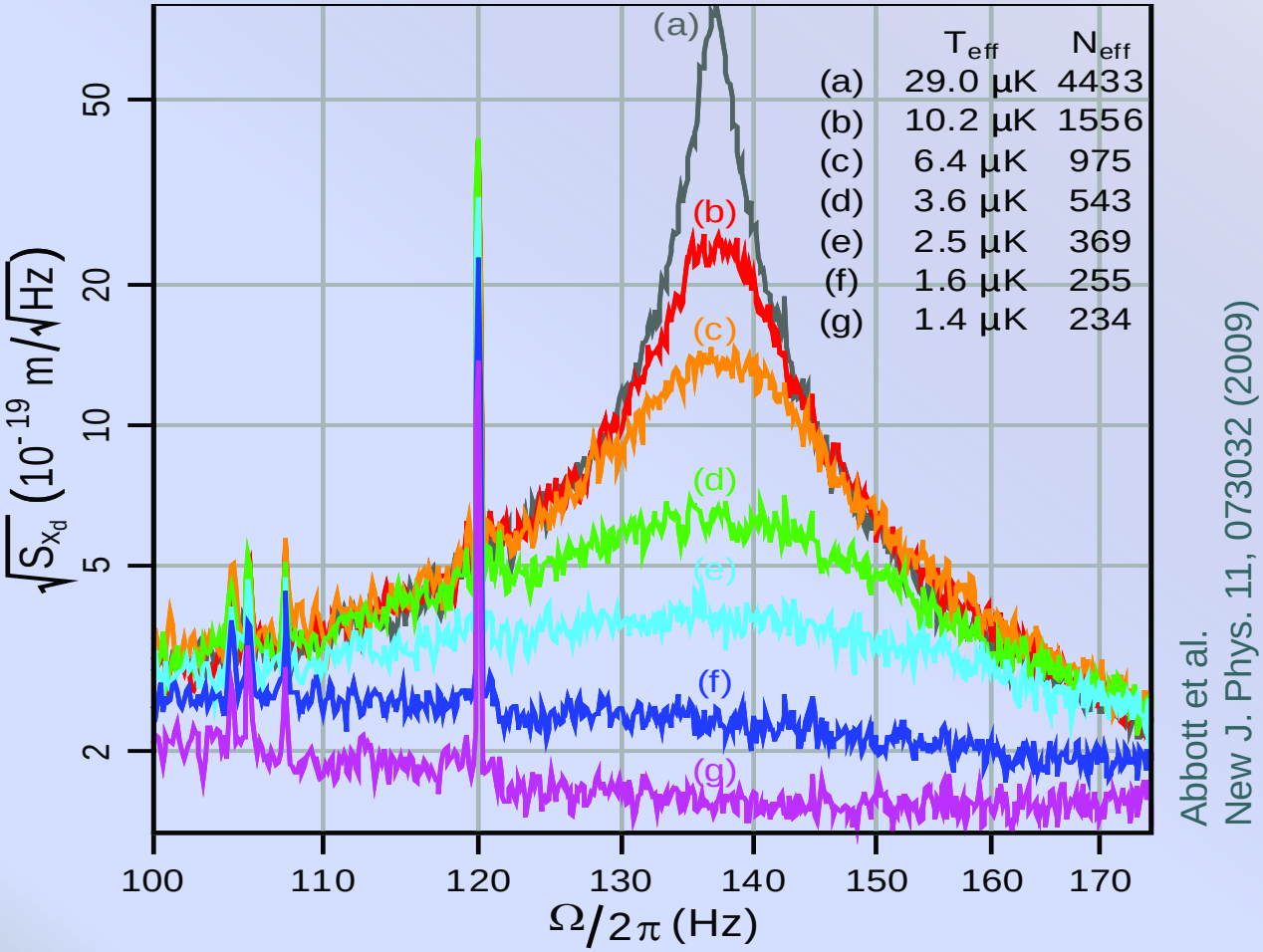
Advanced LIGO Sensitivity



Sensitivity Sixth Science Run

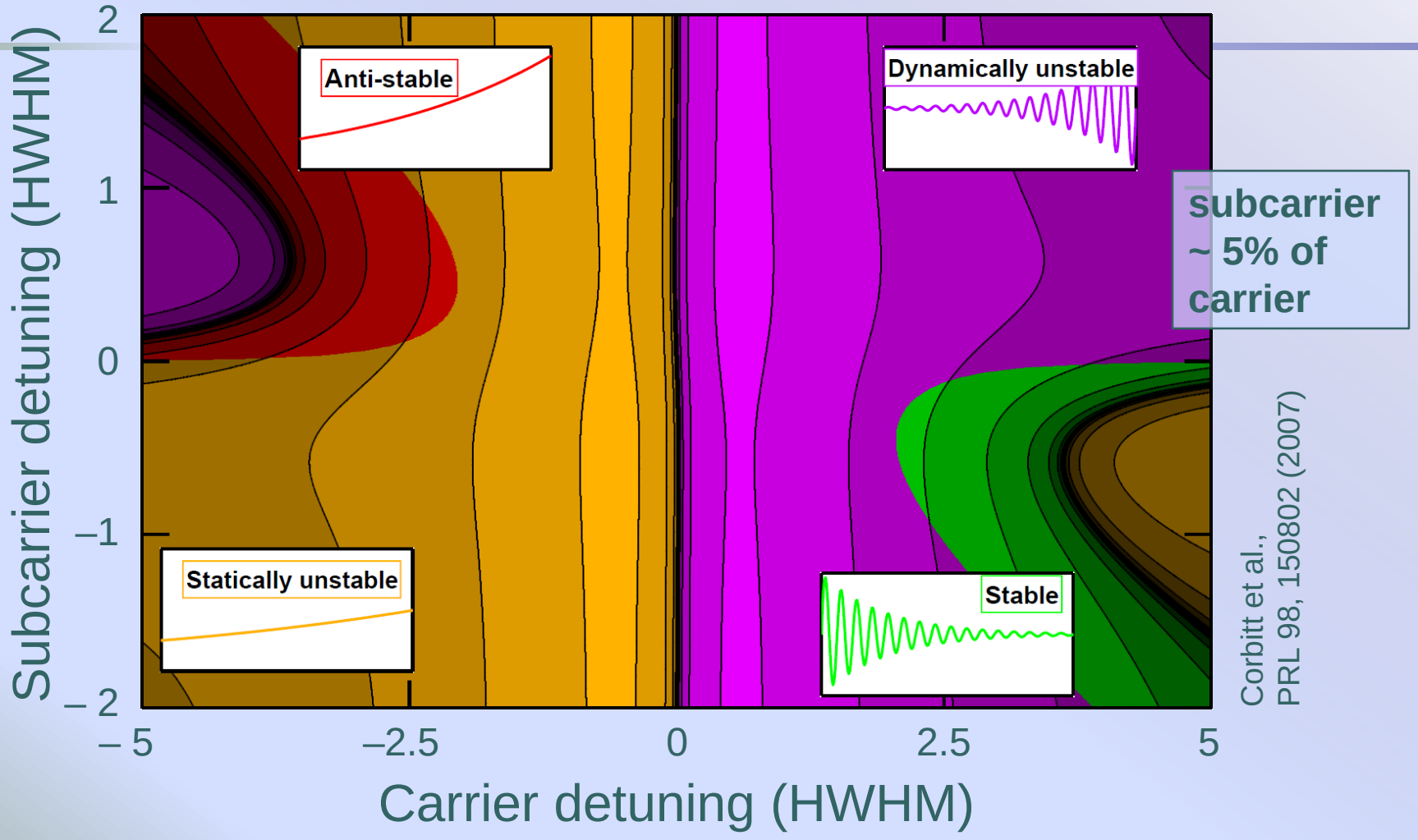


Towards the Quantum Ground State



Abbott et al.
New J. Phys. 11, 073032 (2009)

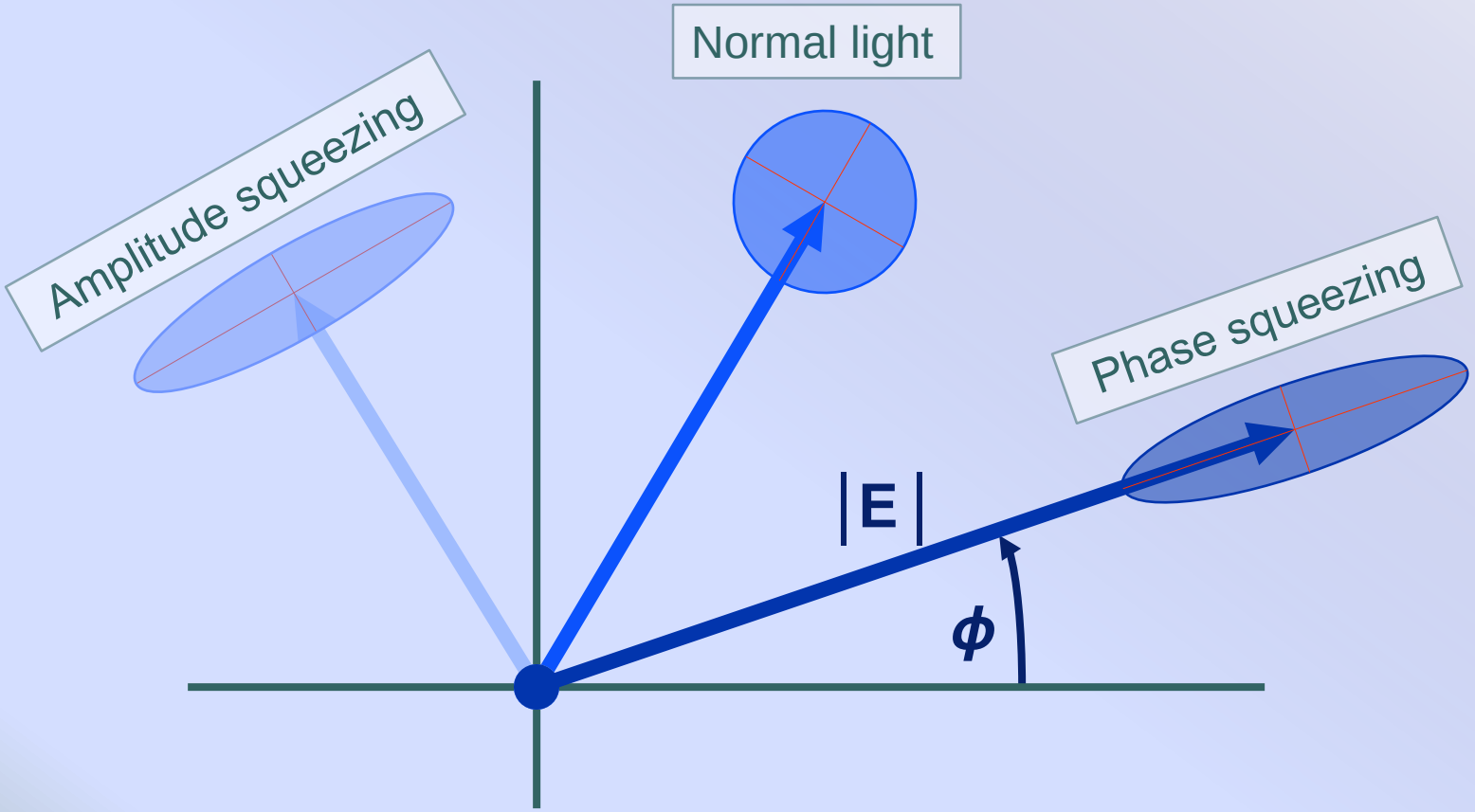
Optical Springs



subcarrier ~ 5% of carrier

Corbitt et al., PRL 98, 150802 (2007)

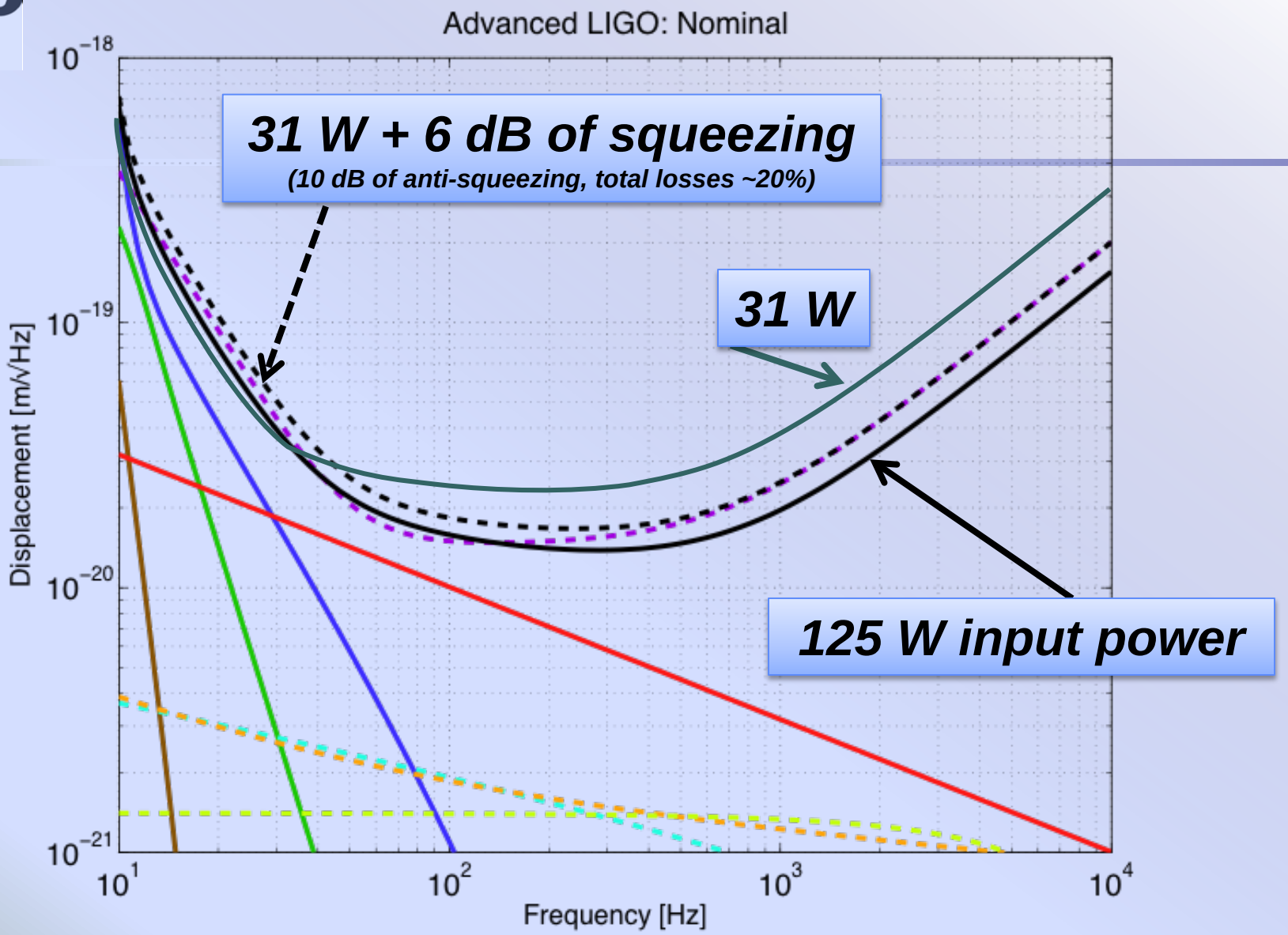
Squeezed Light

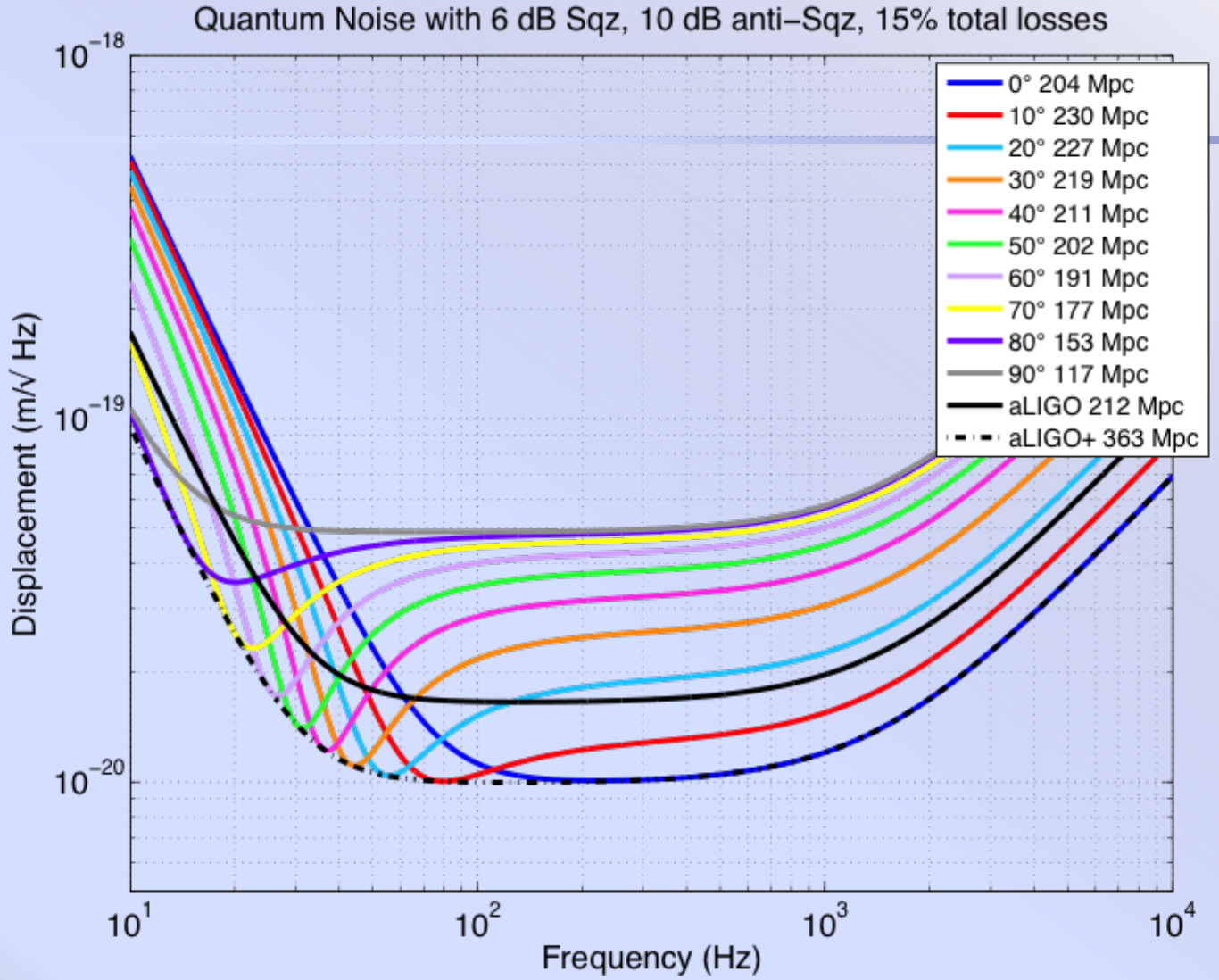


LIGO

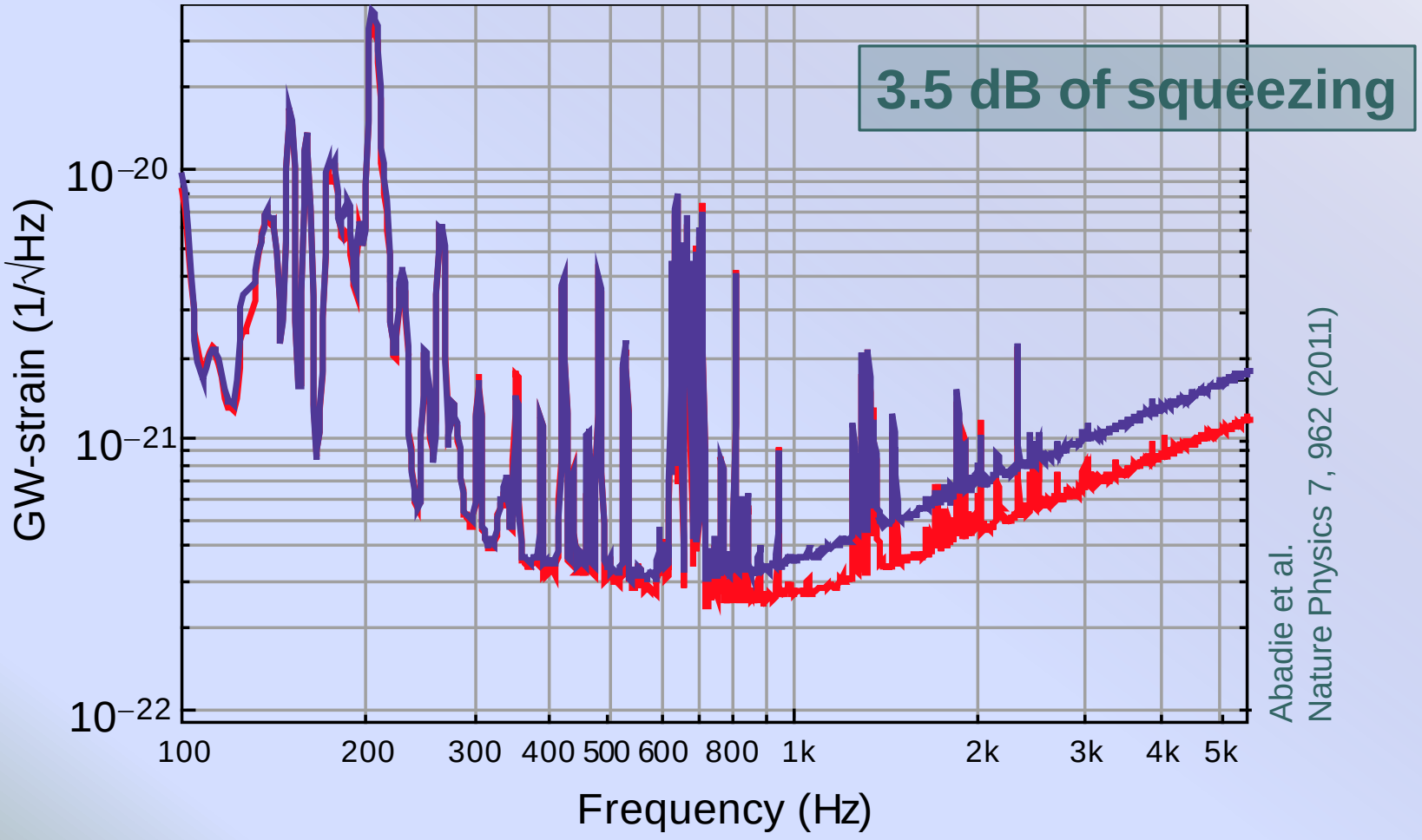
Key Insights

- Shot noise in a Michelson interferometer is due to vacuum fluctuations entering the dark port.
- Quantum noise also produces photon pressure noise.
- Injecting a specially prepared light state with reduced phase noise (relative to vacuum) into the dark port will improve the shot noise sensitivity.
- Similarly, injecting light with reduced amplitude noise will reduce the photon pressure noise.
- Non-linear optical effects can be used to generate a squeezed “vacuum” state.

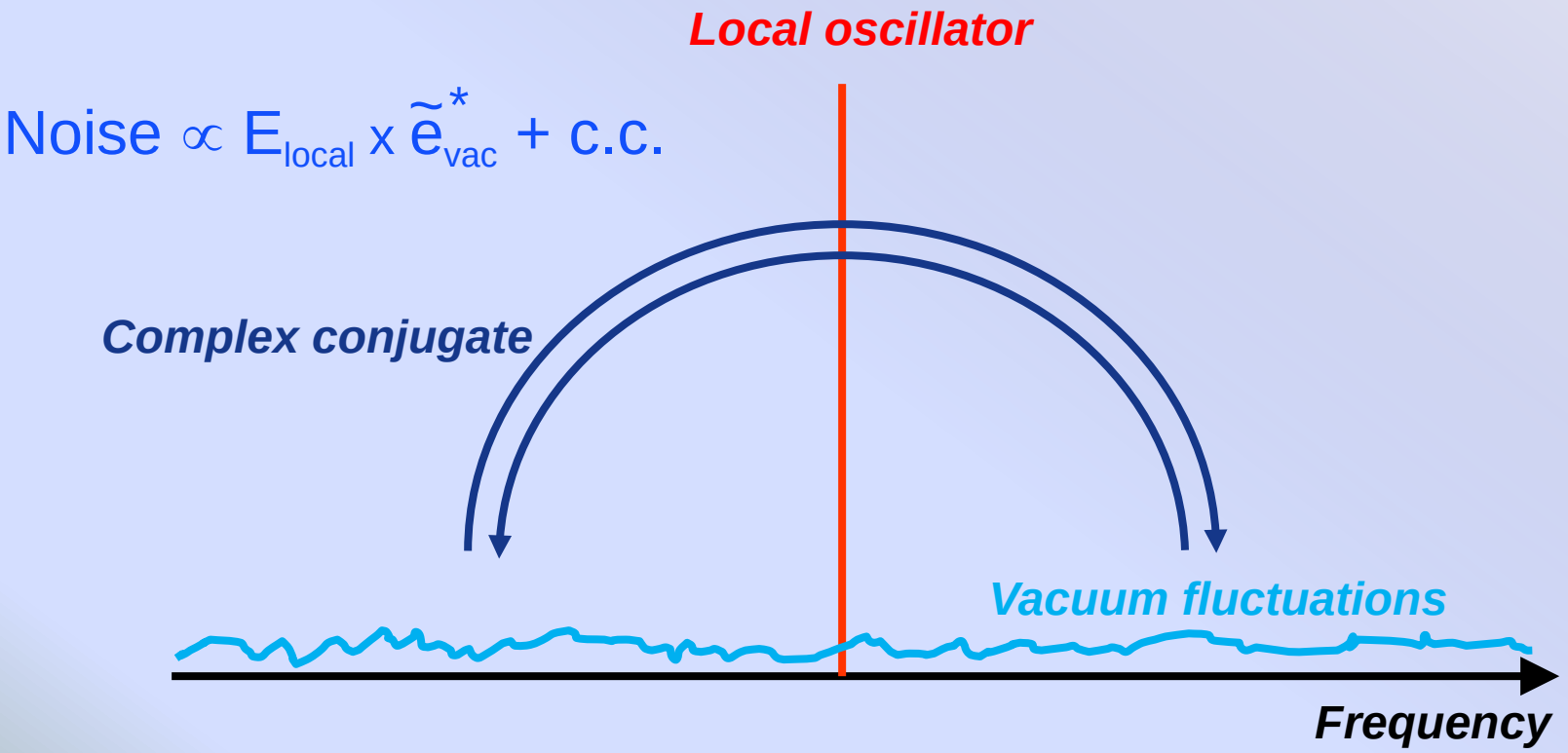

Advanced LIGO: Nominal
31 W + 6 dB of squeezing
(10 dB of anti-squeezing, total losses ~20%)
31 W
125 W input power
Displacement [m/√Hz]
Frequency [Hz]
10^-18
10^-19
10^-20
10^-21
10^1
10^2
10^3
10^4


Quantum Noise with 6 dB Sqz, 10 dB anti−Sqz, 15% total losses
Displacement (m/√ Hz)
Frequency (Hz)
10^{-18}
10^{-19}
10^{-20}
10^{1}
10^{2}
10^{3}
10^{4}
0° 204 Mpc
10° 230 Mpc
20° 227 Mpc
30° 219 Mpc
40° 211 Mpc
50° 202 Mpc
60° 191 Mpc
70° 177 Mpc
80° 153 Mpc
90° 117 Mpc
aLIGO 212 Mpc
aLIGO+ 363 Mpc

Experimental Confirmation at the GEO600 Detector



In Fourier Space



Generating Squeezed “Vacuum”

- Need an operation that applies

$$\tilde{e}_{vac} \rightarrow \tilde{e}_{vac} + e^{2i\varphi} \times \tilde{e}^{*}_{vac} \qquad \varphi\text{: squeezer angle}$$

$$\Rightarrow \text{Noise} \propto |E_{local}| \times |\tilde{e}_{vac}| \times \cos(\Phi_{local} - \varphi) \times \cos(\tilde{\Phi}_{vac} - \varphi)$$

- Optical parametric oscillator (OPO)

  Non-linear crystal that is pumped at double the frequency and below threshold.

Shot /Radiation Pressure Noise in the Quantum Picture

Phase fluctuations in the vacuum field entering the beamsplitter are responsible for the shot noise

- Phase squeezing reduces shot noise

Amplitude fluctuations in the vacuum field entering the beamsplitter are responsible for radiation pressure noise

- Amplitude squeezing reduced radiation pressure noise

The H1 Squeezer Experiment

Goals:

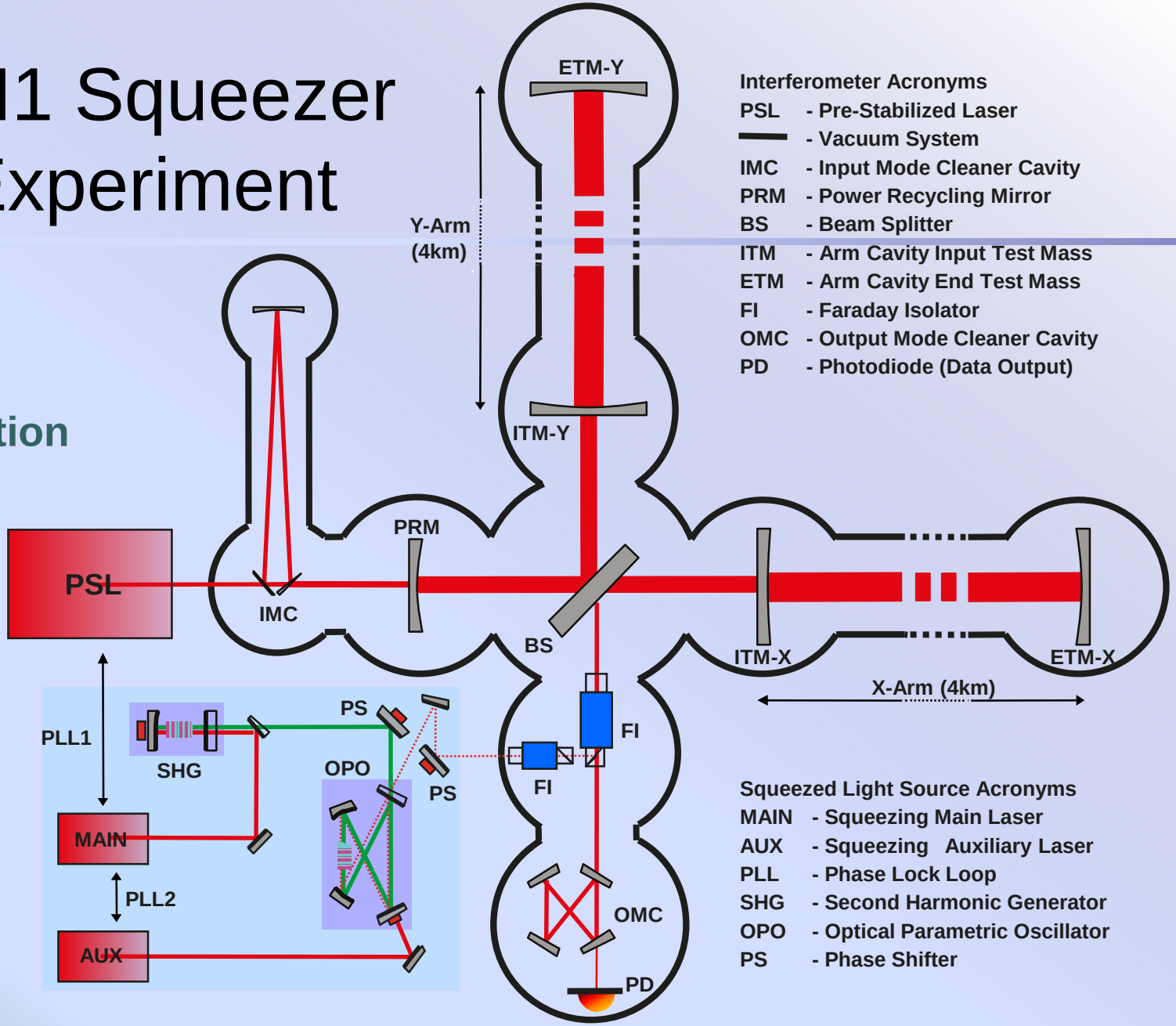
- Demonstrate 3dB of squeezing at the initial LIGO sensitivity
- Don't degrade low frequency sensitivity
- Risk mitigation for high power operations
- Pathfinder for advanced LIGO squeezer

Potential show stoppers:

- Back scattering
- Stray light
- Phase noise
- Optical losses
- Auxiliary servo noise
- Alignment jitter
- Stability

H1 Squeezer Experiment

ANU, AEI, MIT, LIGO collaboration



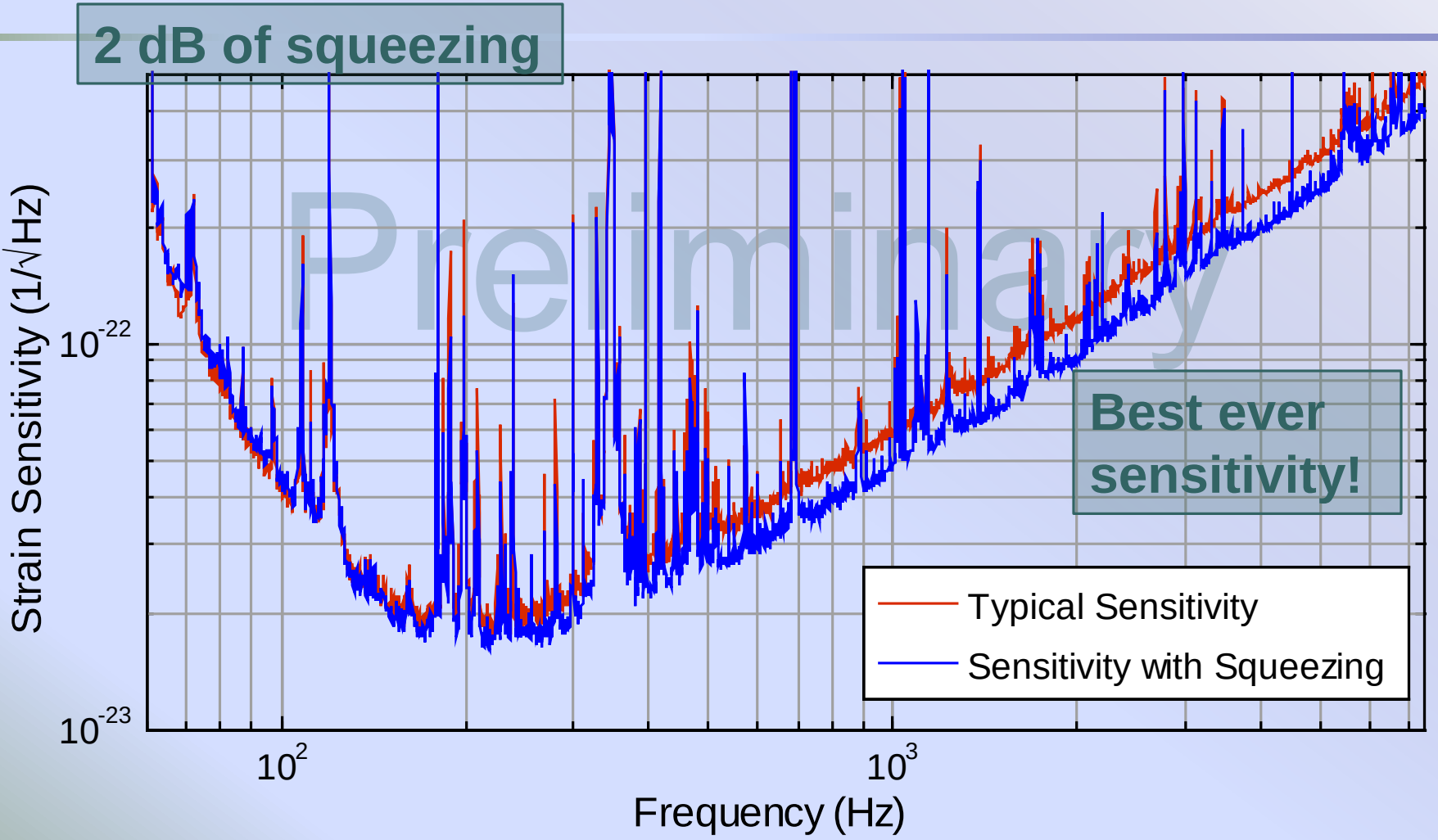
Interferometer Acronyms

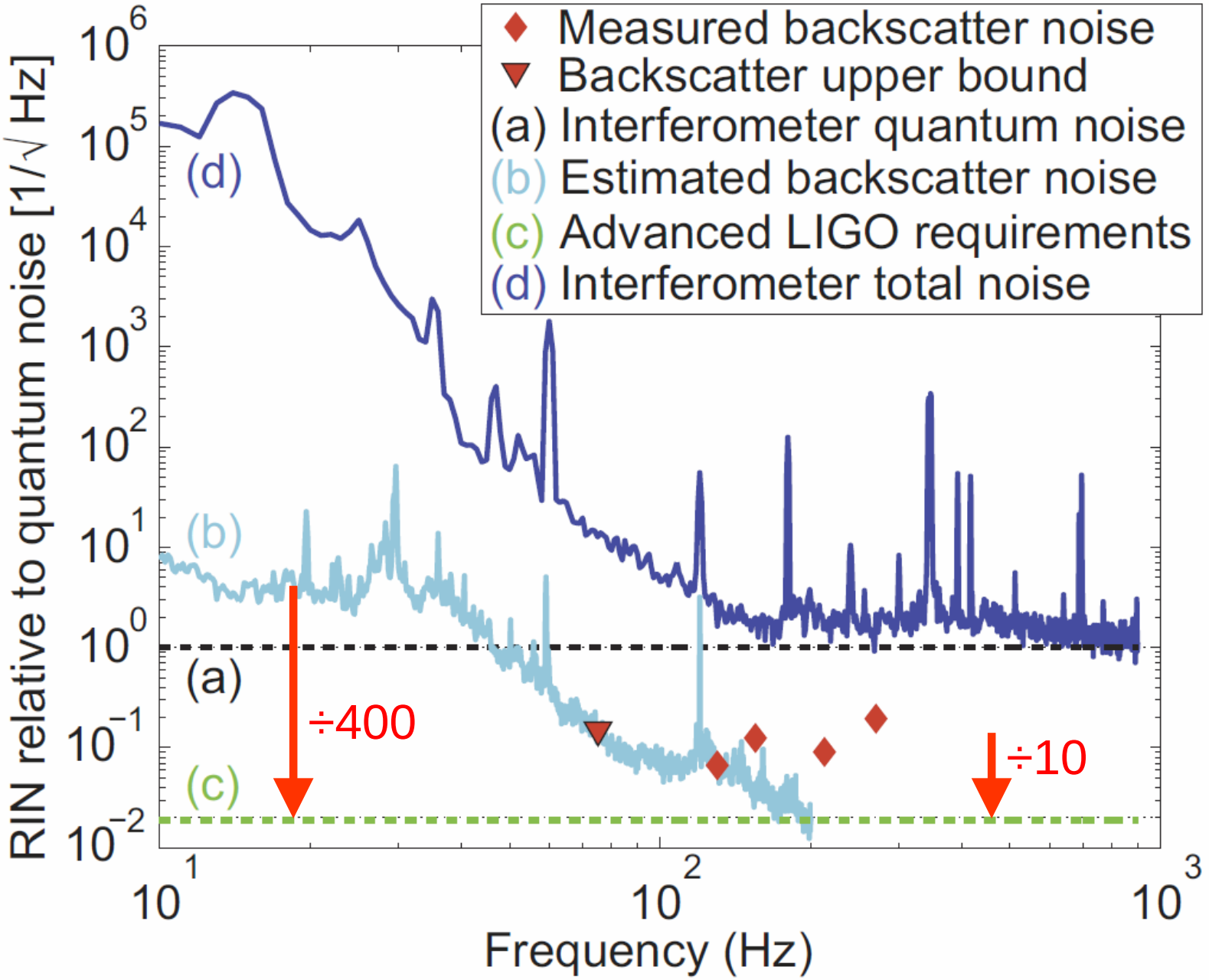
PSL	- Pre-Stabilized Laser
▬	- Vacuum System
IMC	- Input Mode Cleaner Cavity
PRM	- Power Recycling Mirror
BS	- Beam Splitter
ITM	- Arm Cavity Input Test Mass
ETM	- Arm Cavity End Test Mass
FI	- Faraday Isolator
OMC	- Output Mode Cleaner Cavity
PD	- Photodiode (Data Output)

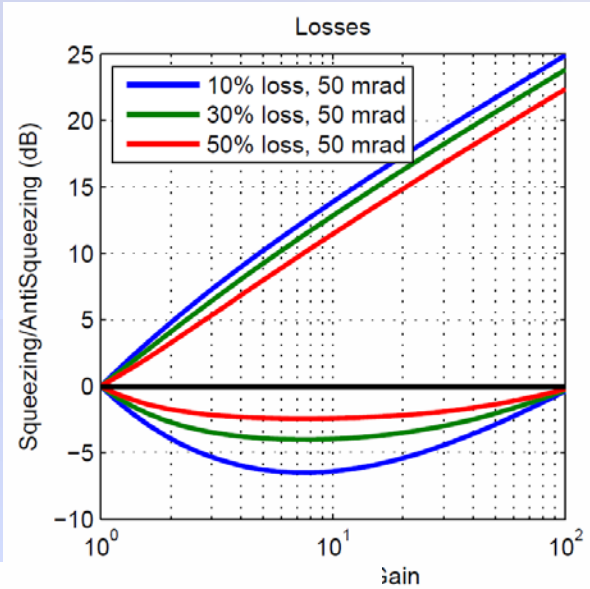
Squeezed Light Source Acronyms

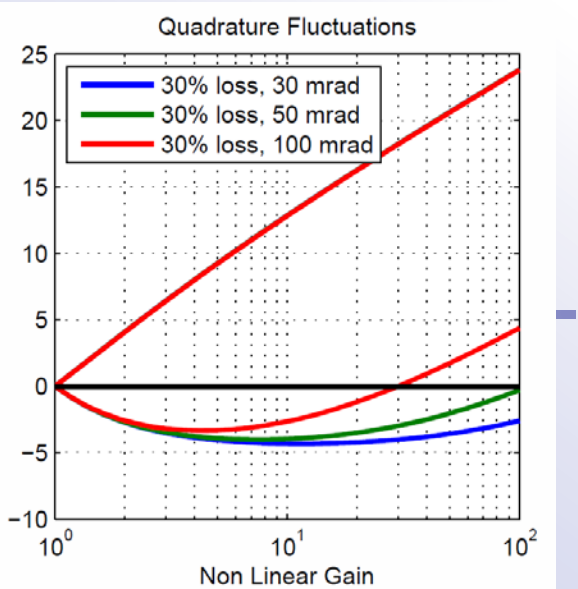
MAIN	- Squeezing Main Laser
AUX	- Squeezing Auxiliary Laser
PLL	- Phase Lock Loop
SHG	- Second Harmonic Generator
OPO	- Optical Parametric Oscillator
PS	- Phase Shifter

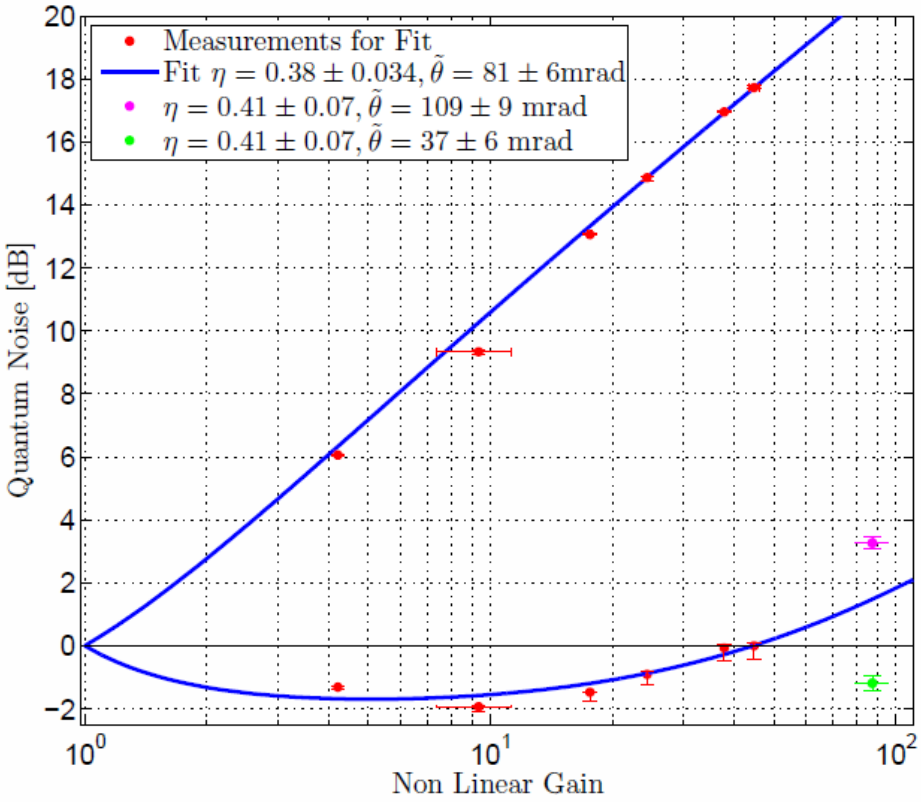
H1 Squeezed


2 dB of squeezing
Preliminary
Best ever sensitivity!
Typical Sensitivity
Sensitivity with Squeezing
Strain Sensitivity (1/√Hz)
10^-22
10^-23
10^2
10^3
Frequency (Hz)

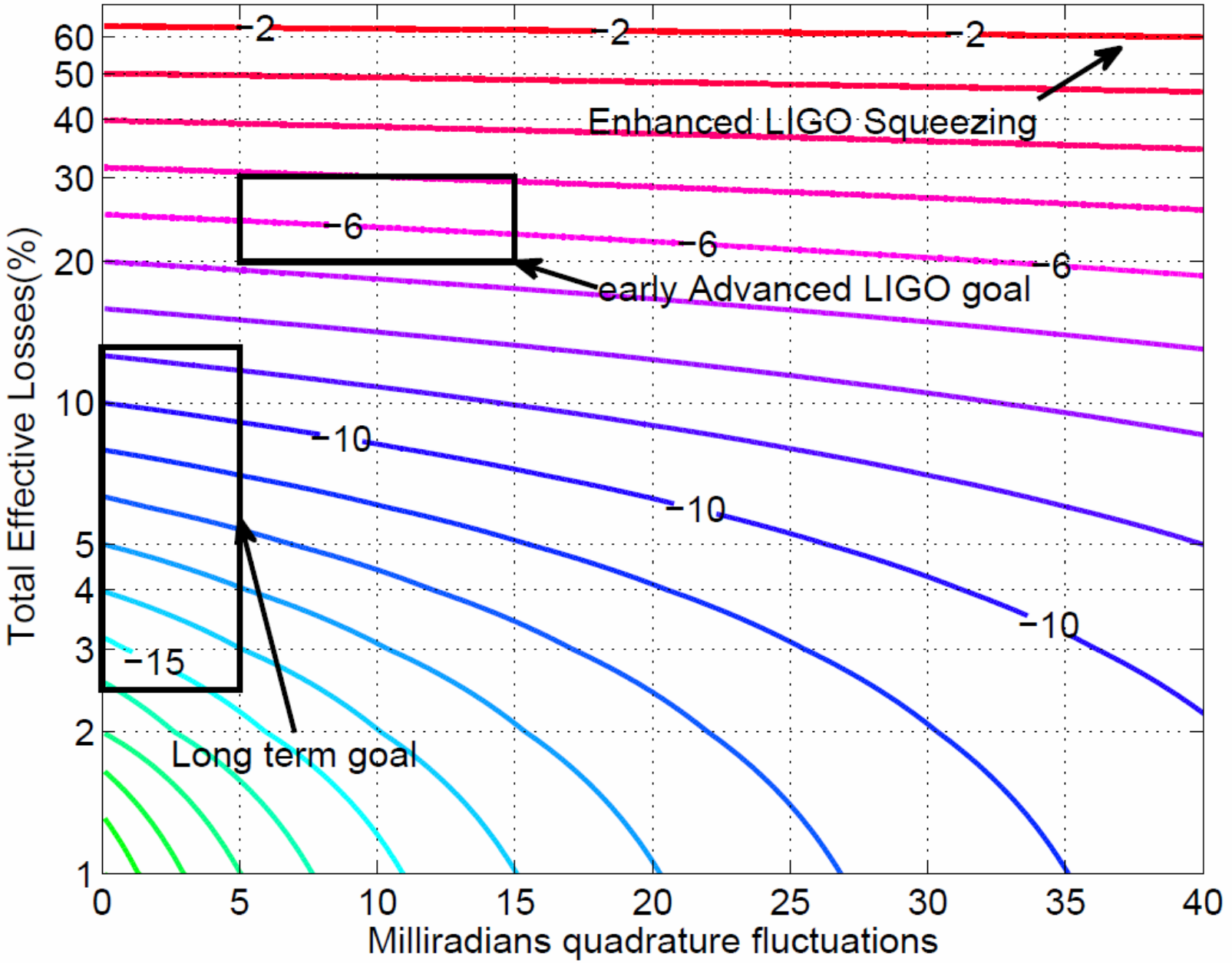

Measured backscatter noise
Backscatter upper bound
(a) Interferometer quantum noise
(b) Estimated backscatter noise
(c) Advanced LIGO requirements
(d) Interferometer total noise
RIN relative to quantum noise [1/√ Hz]
Frequency (Hz)
(d)
(b)
(a)
(c)
÷400
÷10


Losses
10% loss, 50 mrad
30% loss, 50 mrad
50% loss, 50 mrad
Squeezing/AntiSqueezing (dB)
25
20
15
10
5
0
−5
−10
10^0
10^1
10^2


Quadrature Fluctuations
30% loss, 30 mrad
30% loss, 50 mrad
30% loss, 100 mrad
25
20
15
10
5
0
−5
−10
10^0
10^1
10^2
Non Linear Gain


Measurements for Fit
Fit $\eta = 0.38 \pm 0.034, \tilde{\theta} = 81 \pm 6$mrad
$\eta = 0.41 \pm 0.07, \tilde{\theta} = 109 \pm 9$ mrad
$\eta = 0.41 \pm 0.07, \tilde{\theta} = 37 \pm 6$ mrad
Quantum Noise [dB]
20
18
16
14
12
10
8
6
4
2
0
−2
10^0
10^1
10^2
Non Linear Gain

LI


Total Effective Losses(%)
Milliradians quadrature fluctuations
60
50
40
30
20
10
5
4
3
2
1
0
5
10
15
20
25
30
35
40
−2
−2
−2
Enhanced LIGO Squeezing
−6
−6
−6
early Advanced LIGO goal
−10
−10
−10
−15
Long term goal

Optical Losses and Phase Noise

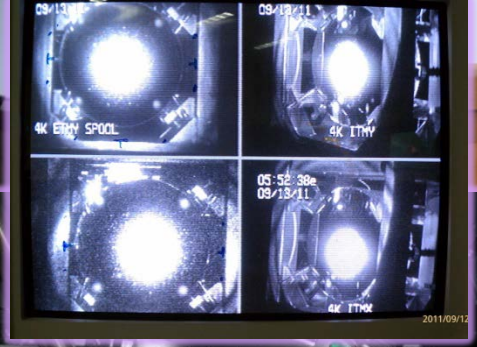
Measured mode mismatch squeezer/OMC	25%	5%
Measured scatter and absorption loss in OMC	18%	2%
Measured Faraday losses	20%	2%
Measured total optical losses	56%	2%

	Source	Estimate	Measurement
Squeezer	OPO length noise	24.6 ± 2	
	Coherent locking field(CLF) sensor noise	1.8 ± 0.5	
	OPO and SHG length control sidebands	< 1	
	Crystal temperature fluctuations	unknown	
	Total intrinsic to squeezer	24.7 ± 2	21 ± 6
IFO	Interferometer (IFO) sidebands	3.1 ± 0.4	
	Alignment jitter coupling (inferred from total)	35-100 mrad	
	Squeezer + IFO total (good alignment)		37 ± 6

Summary and Outlook

- Advanced LIGO squeezer needs in-vacuum OPO
  - Planned R&D programs at ANU and MIT for VOPO
- Need a low loss readout chain
- GEO is developing an auto-alignment system
- R&D program at MIT to work on filter cavities

Squeezed light sources will be the first upgrade to advanced gravitational-wave interferometers


HAM4-S

4K ETMY SPOOL
4K ITMY
05:52:38e
09/13/11
4K ITMX
2011/09/12

2011/06/07 11:4