LIGO

Squeezed Light Techniques for Gravitational Wave Detection

February 27, 2012

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Colloquium at Columbia University, NY

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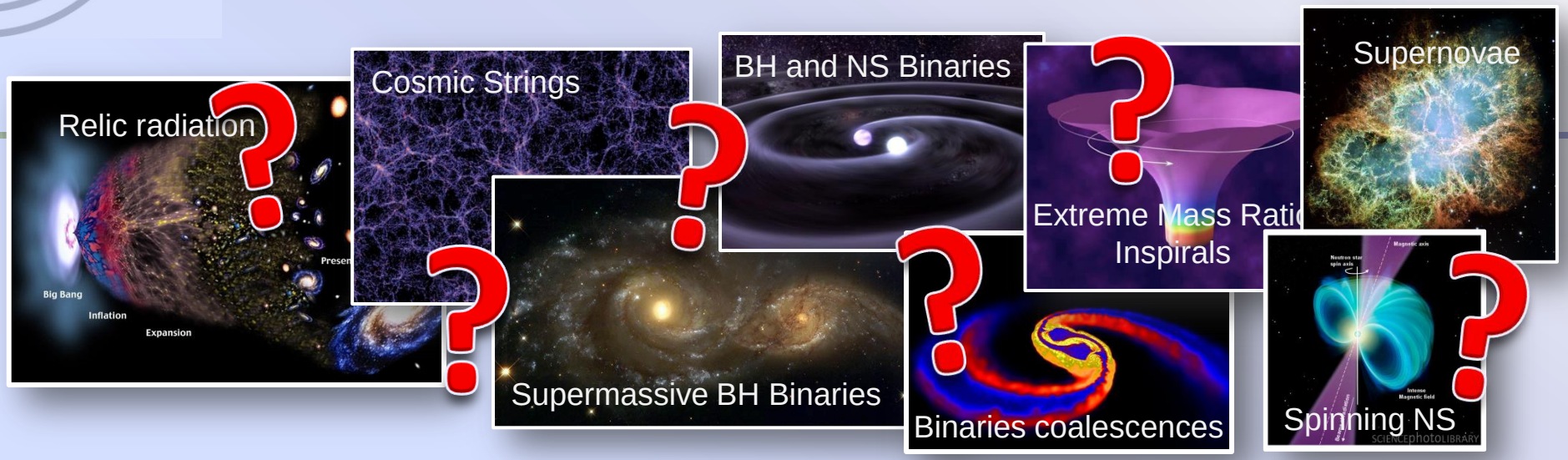
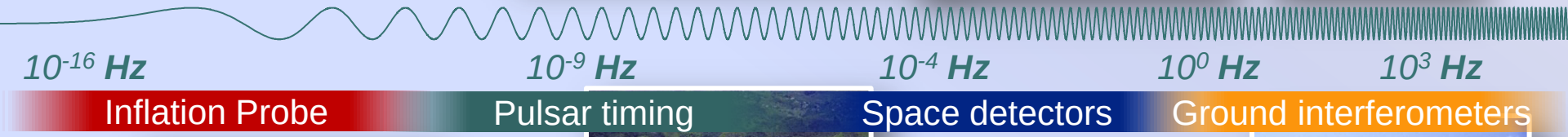
Abstract

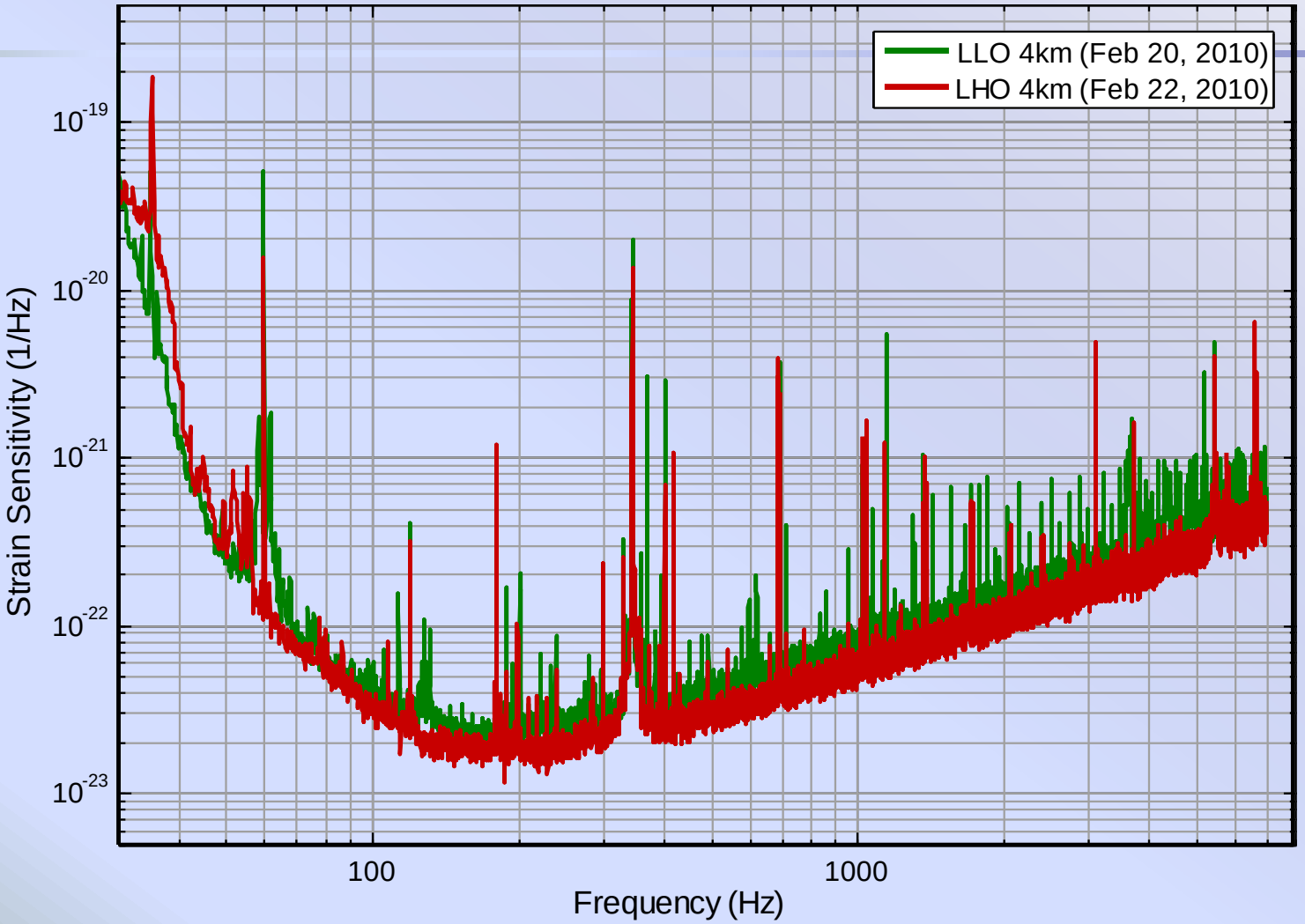
Several kilometer long interferometers have been built over the past decade to search for gravitational waves of astrophysical origins. For the next generation detectors intra-cavity powers of several 100 kW are envisioned. The injection of squeezed light, a specially prepared quantum state, has the 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.

Gravitational Waves

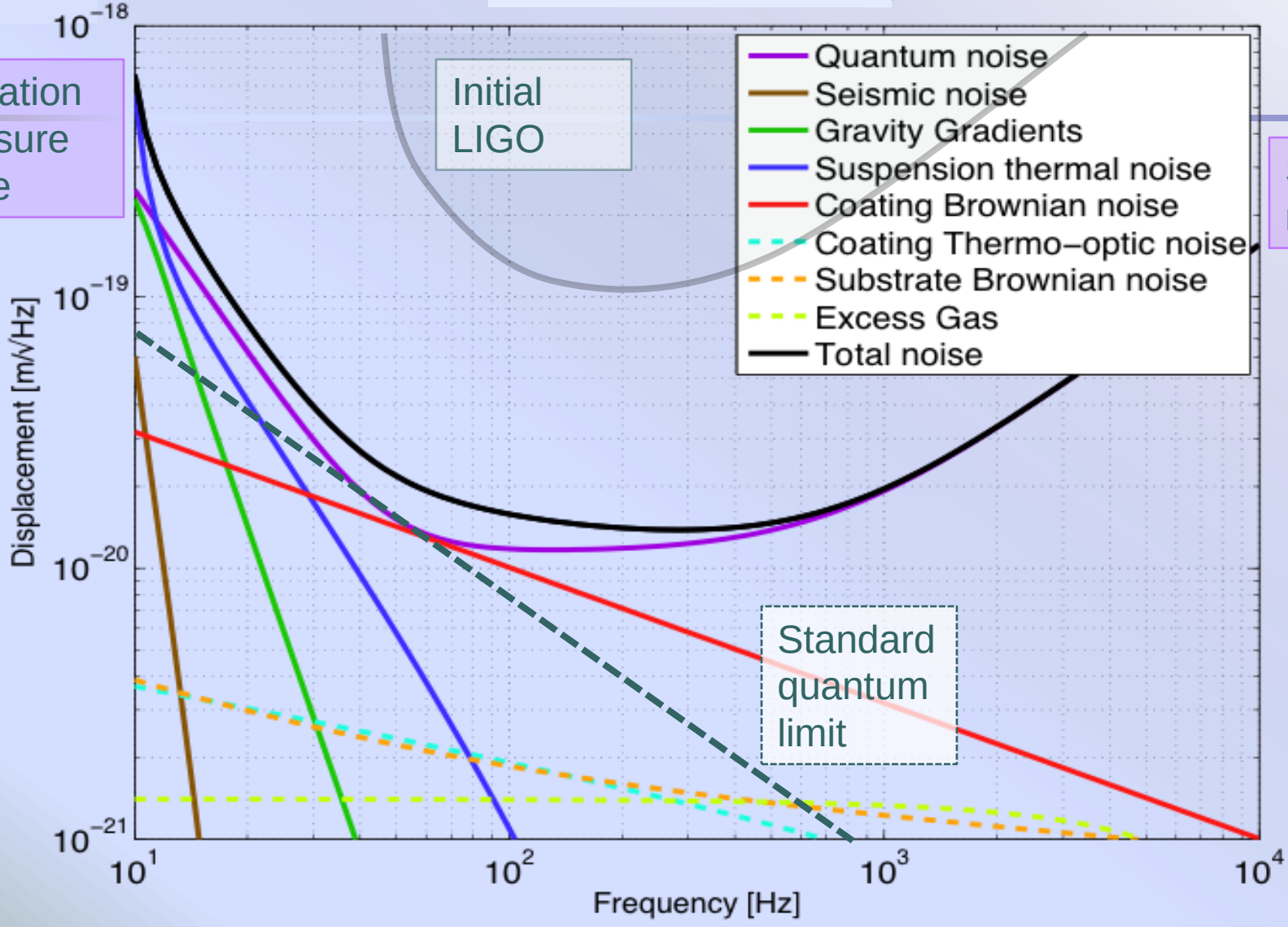




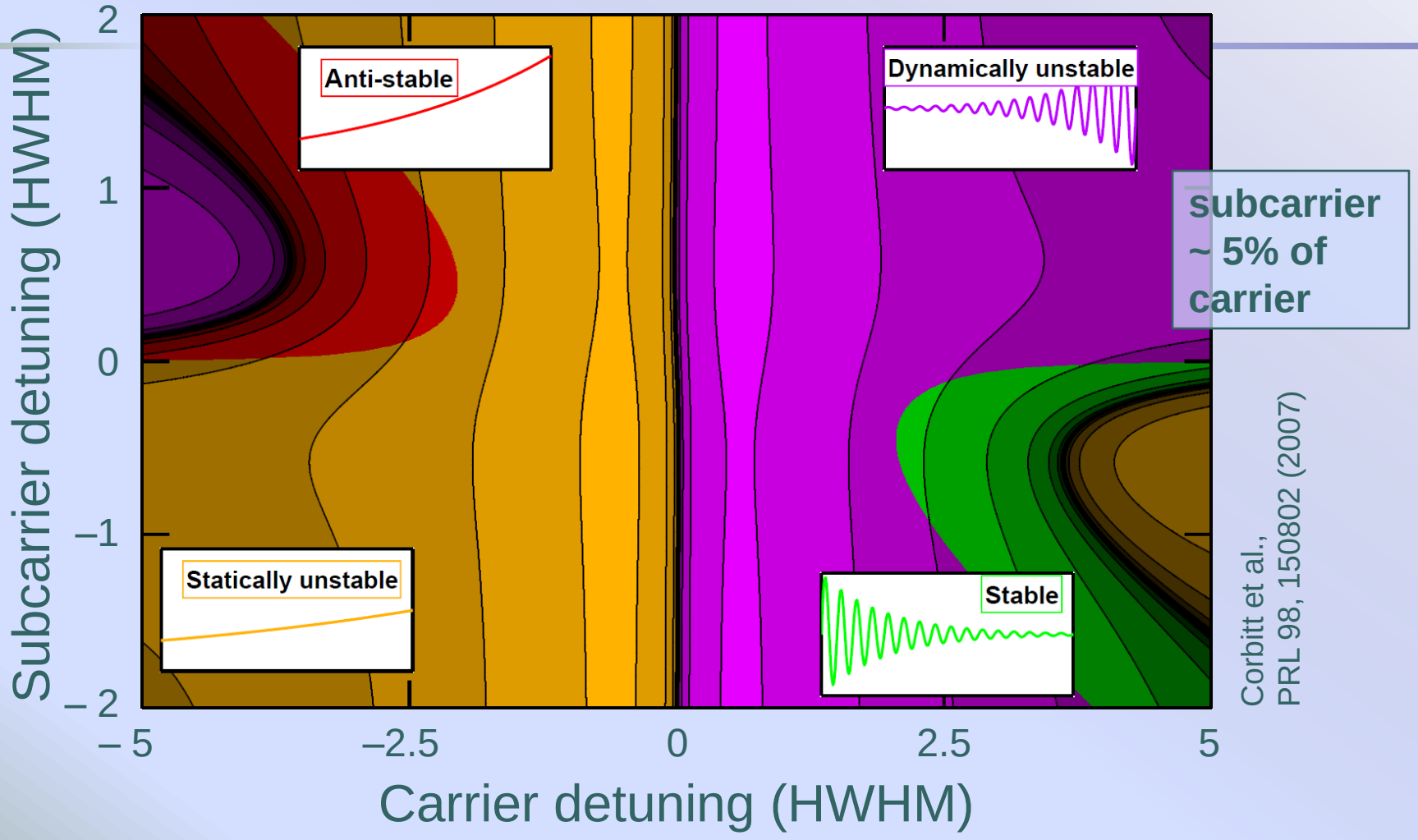
Sensitivity Sixth Science Run



Advanced LIGO Sensitivity



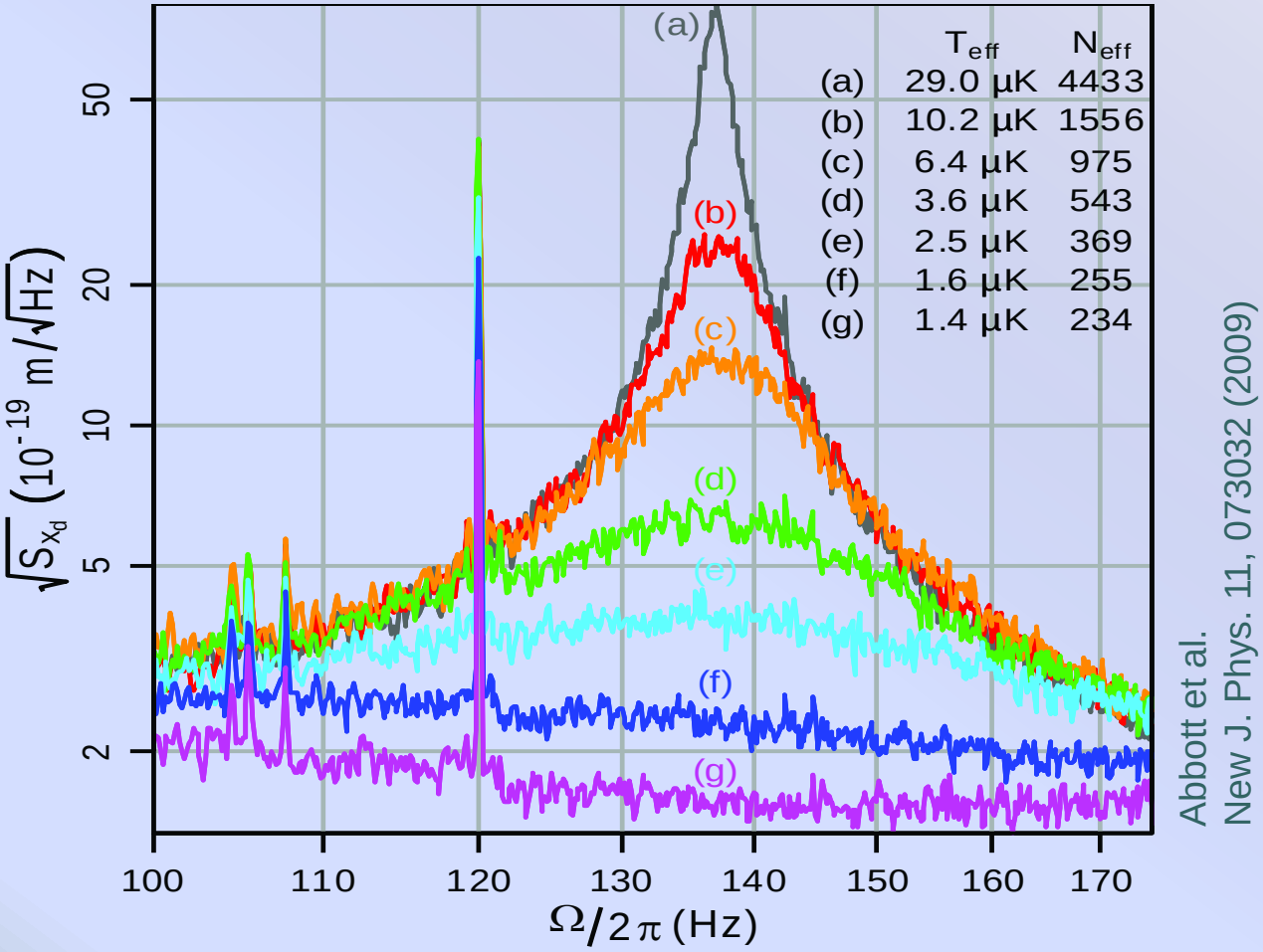
Optical Springs



subcarrier ~ 5% of carrier

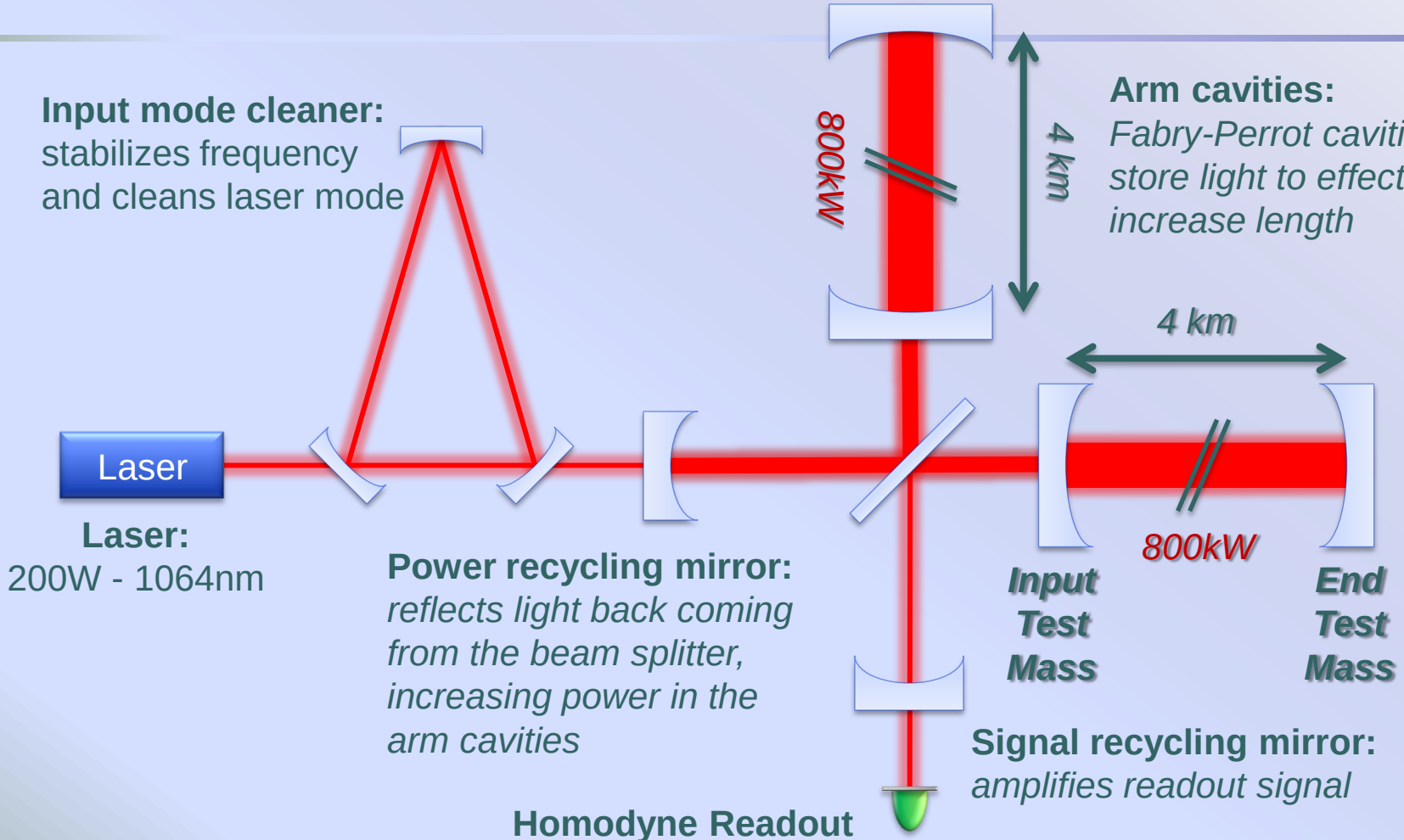
Corbitt et al., PRL 98, 150802 (2007)

Towards the Quantum Ground State



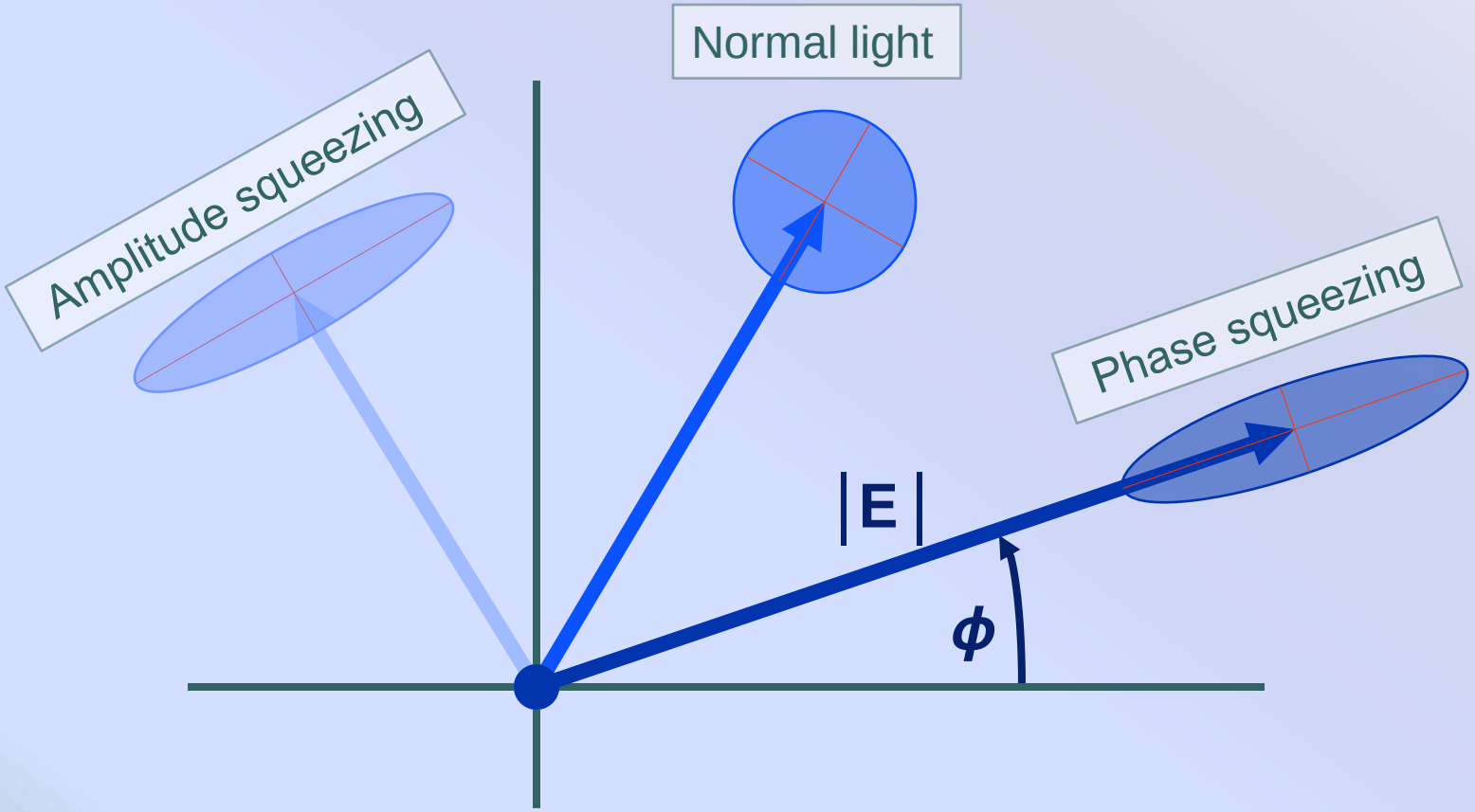
Abbott et al.
New J. Phys. 11, 073032 (2009)

The Advanced LIGO Detector



LIGO

Squeezed Light



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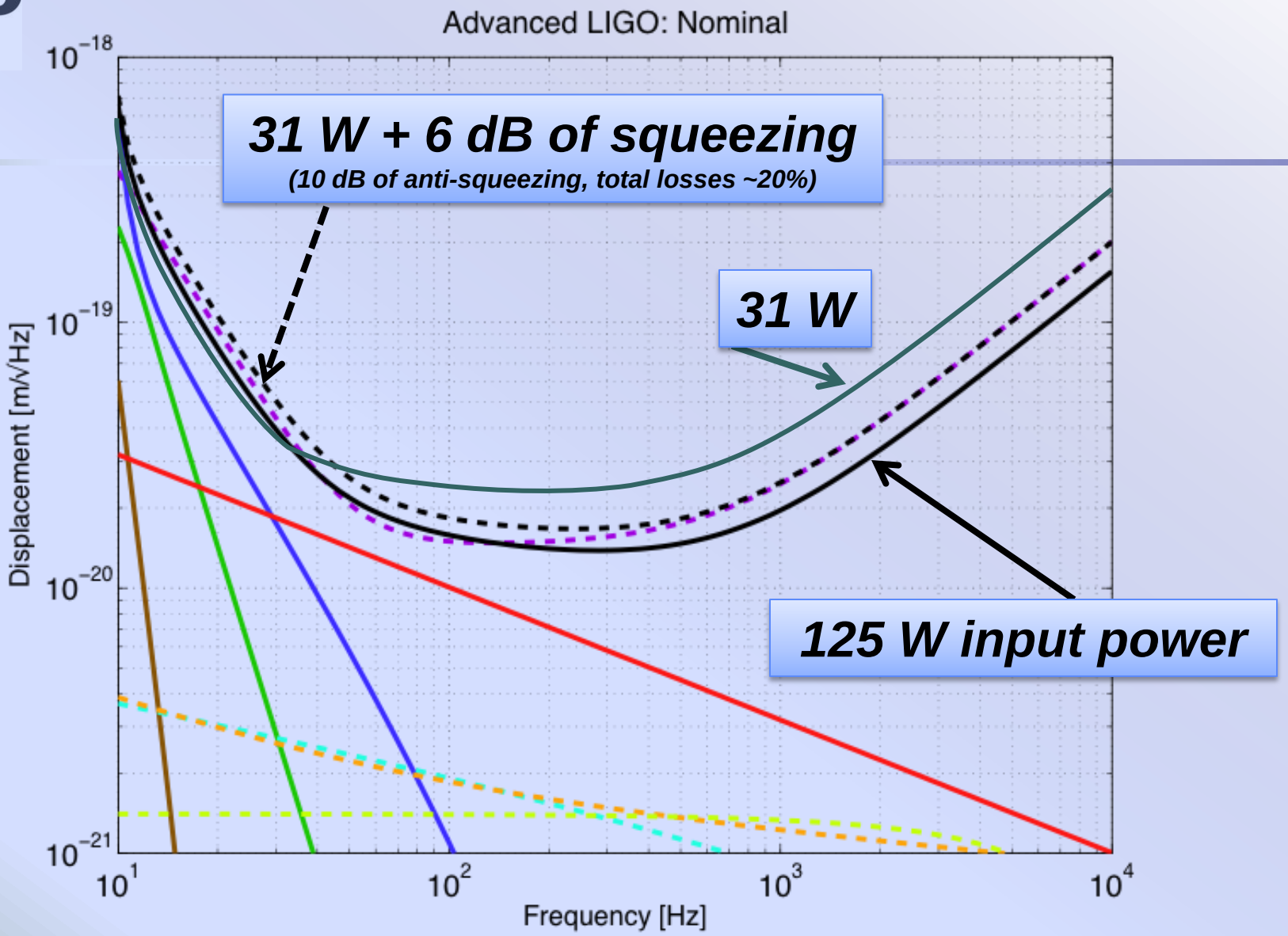
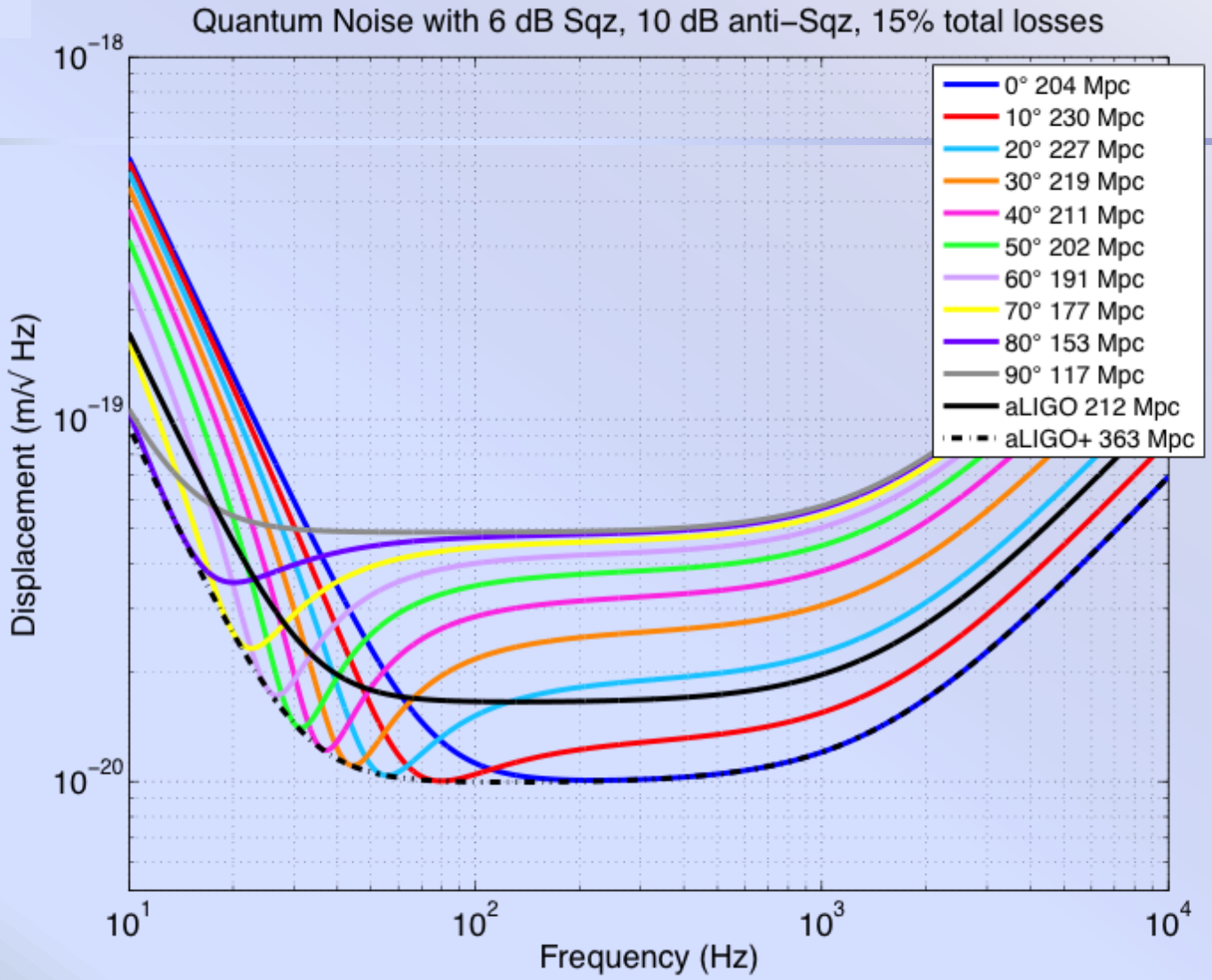
Key Insights

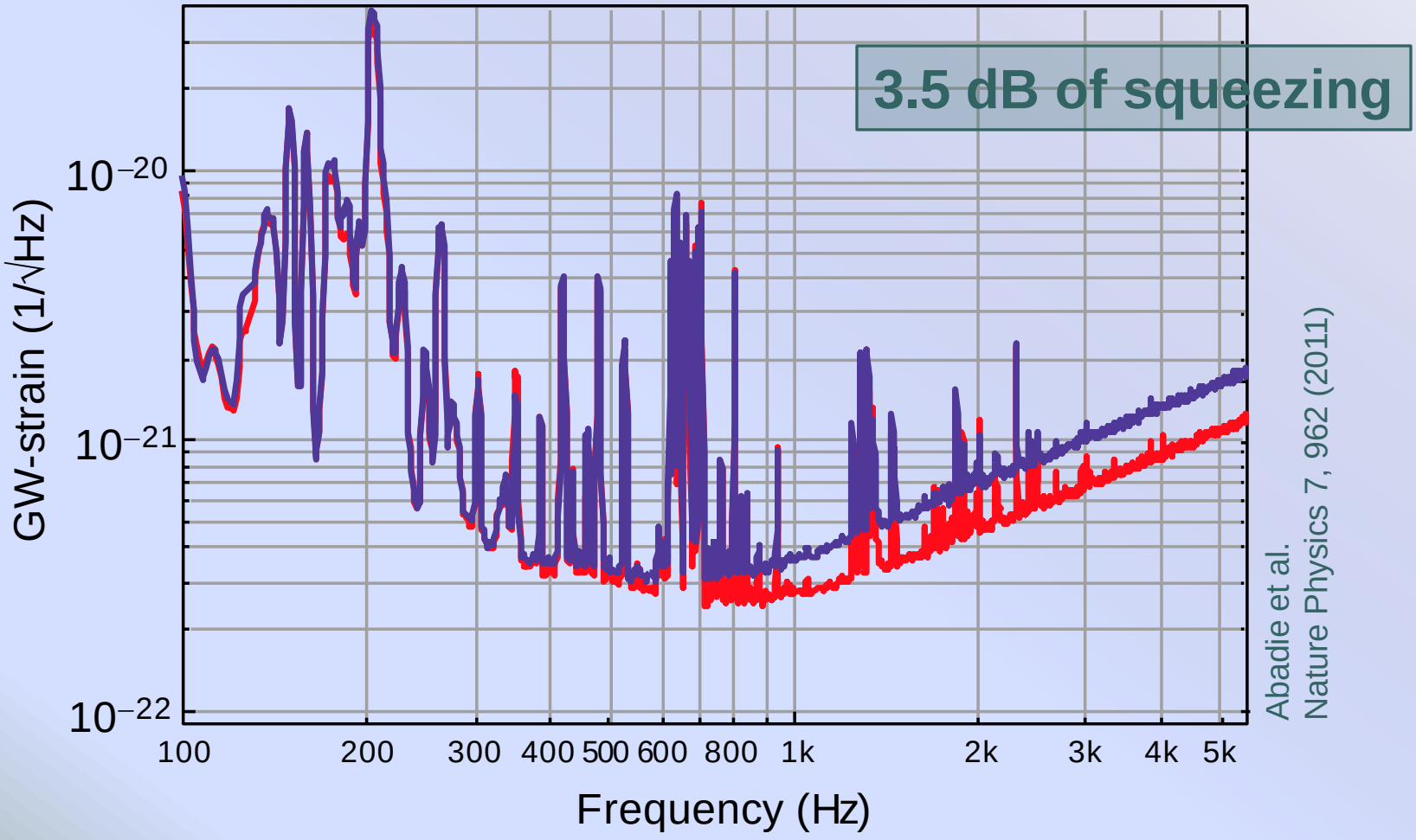
- Shot noise in a Michelson interferometer is due to vacuum fluctuations entering the dark port.
- Quantum noise also produces photon pressure noise.
- Injecting a specially prepared light state with reduced phase noise (relative to vacuum) into the dark port will improve the shot noise sensitivity.
- 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.

LIGO

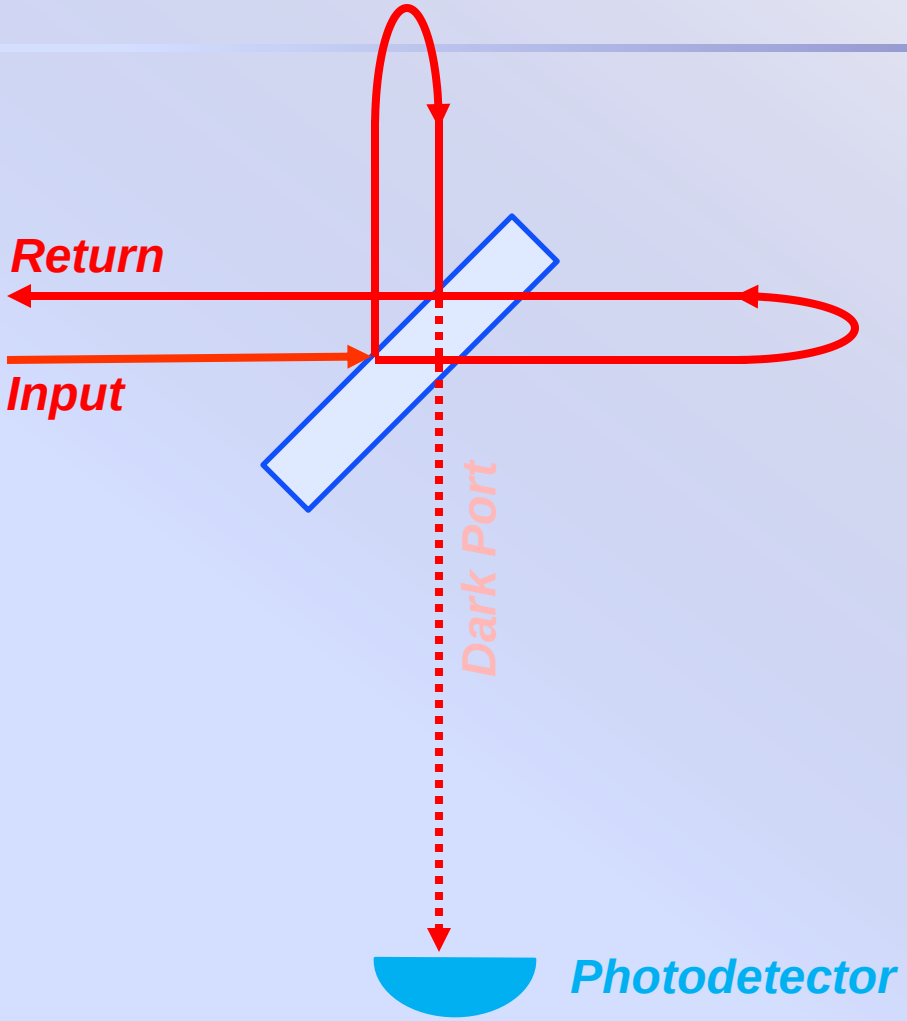

Advanced LIGO: Nominal
31 W + 6 dB of squeezing
(10 dB of anti-squeezing, total losses ~20%)
31 W
125 W input power
Displacement [m/√Hz]
Frequency [Hz]
10^-18
10^-19
10^-20
10^-21
10^1
10^2
10^3
10^4


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



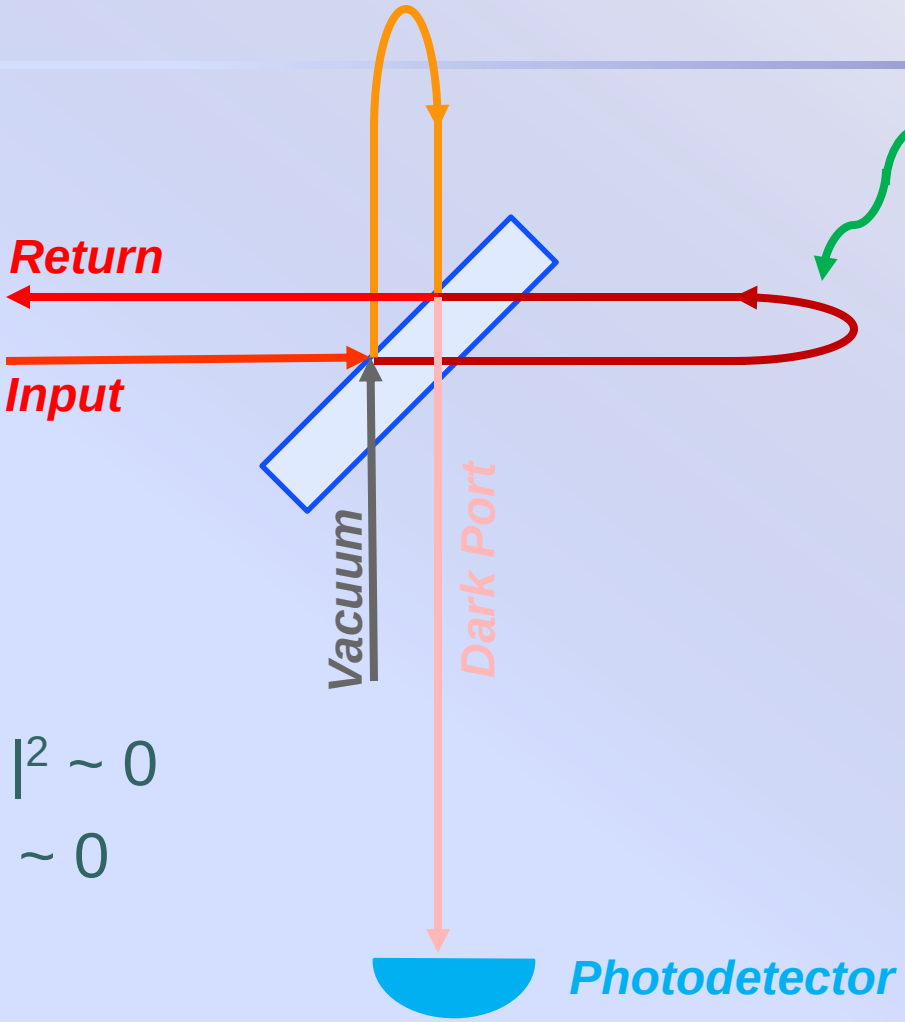
The Beamsplitter



Signal $\propto |E_{in} - E_{in}|^2 = 0$

Noise = 0

The Beamsplitter

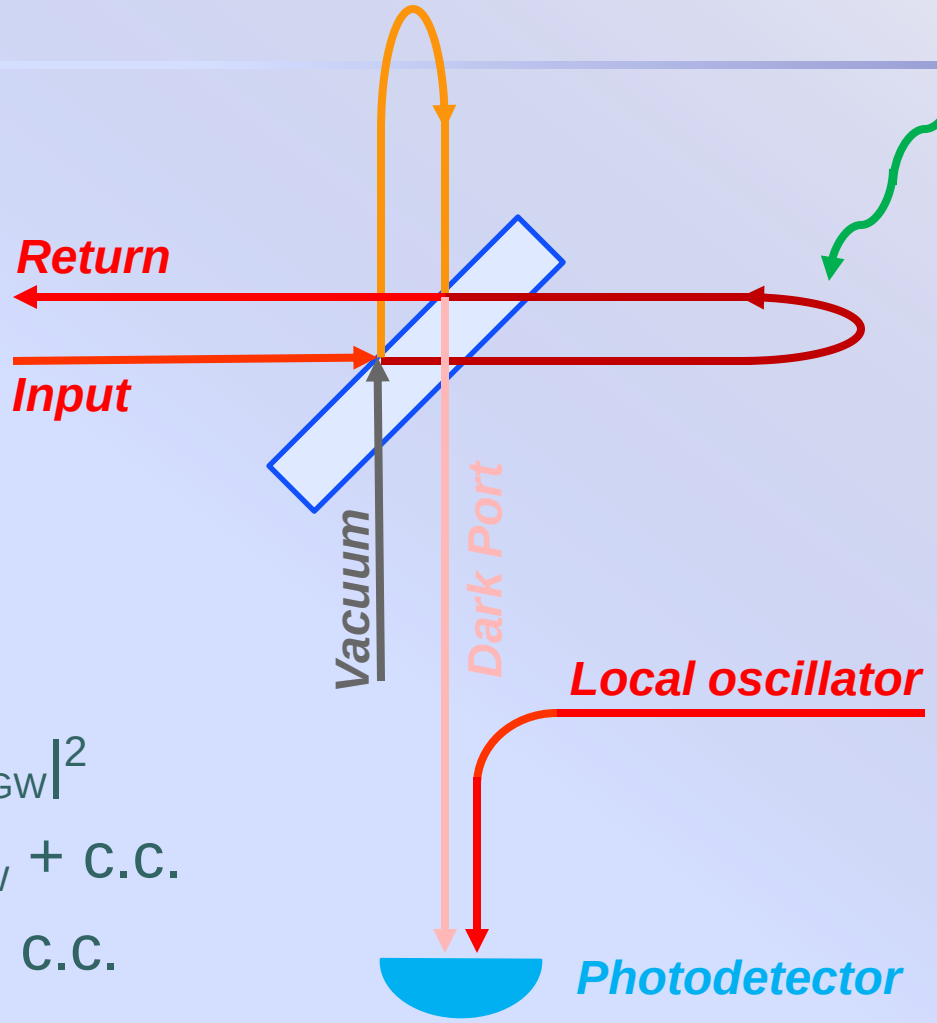


$E_{vac} = 0 + \tilde{e}_{vac}$

Signal $\propto |\tilde{e}_{vac} + \Delta E_{GW}|^2 \sim 0$

Noise $\propto |\tilde{e}_{vac} \times \Delta E_{GW}| \sim 0$

The Beamsplitter



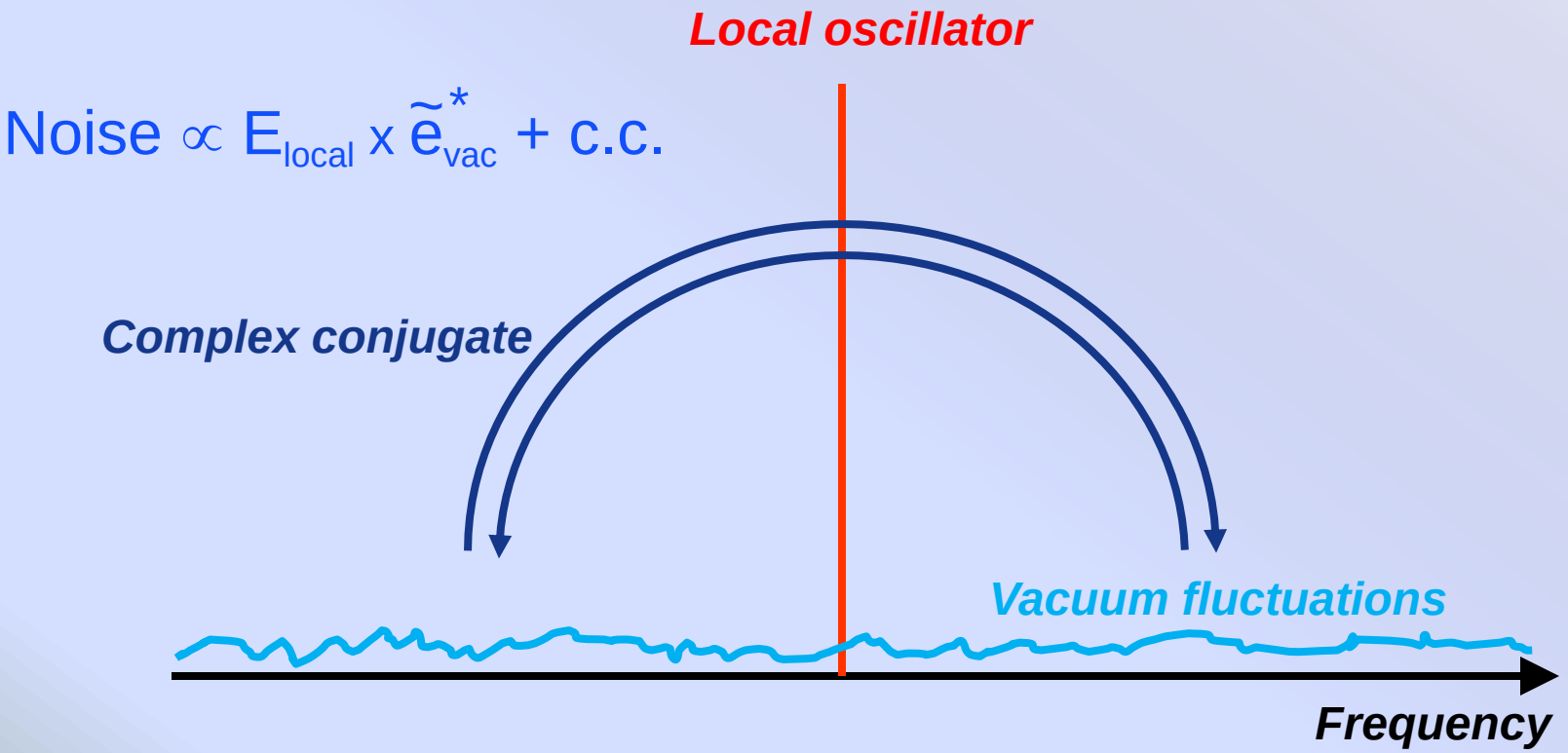
$E_{vac} = 0 + \tilde{e}_{vac}$

Signal $\propto |E_{local} + \Delta E_{GW}|^2$

$\sim E_{local} \times \Delta E^*_{GW} + c.c.$

Noise $\propto E_{local} \times \tilde{e}^*_{vac} + c.c.$

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:

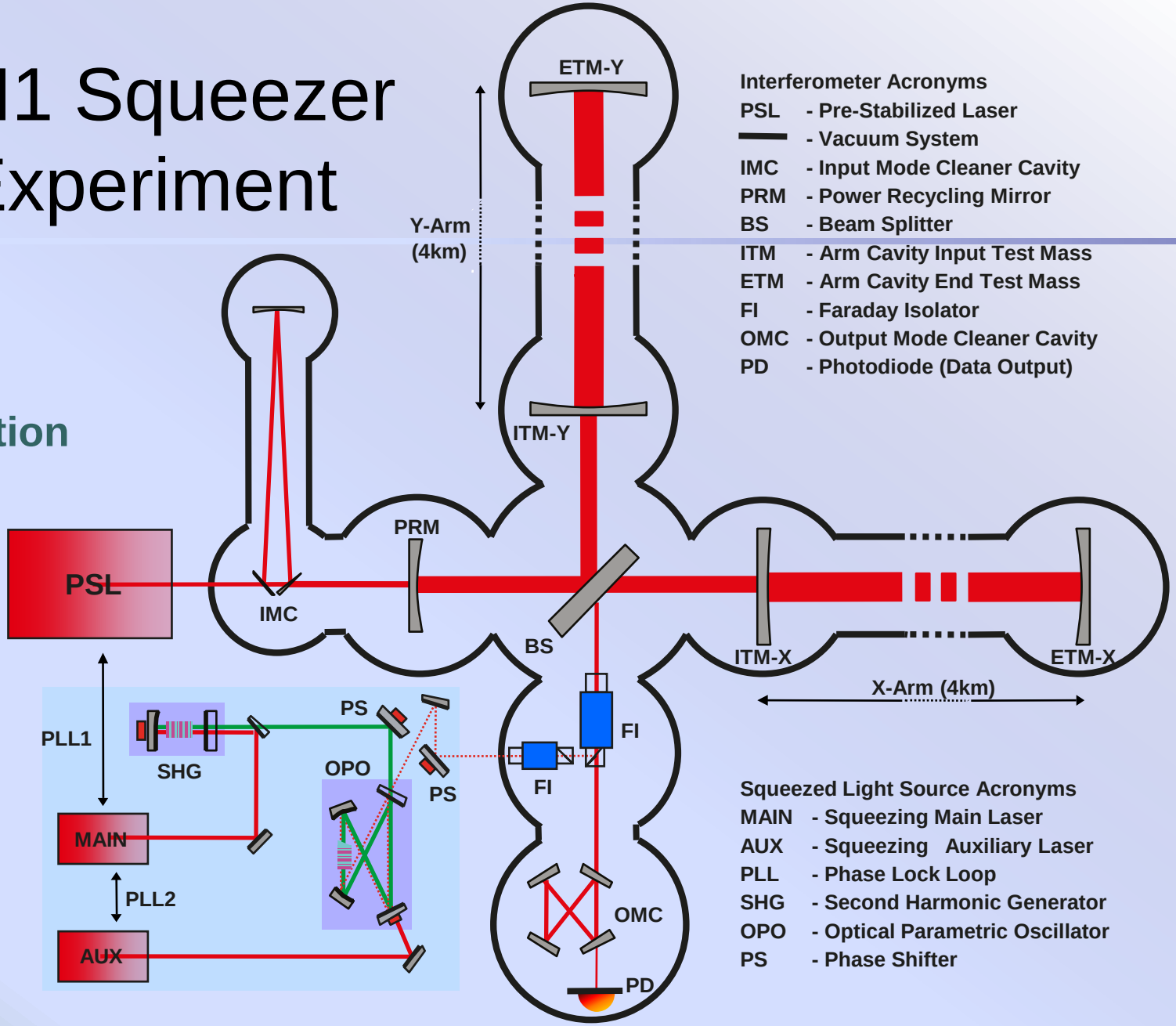
- Demonstrate 3dB of squeezing at the initial LIGO sensitivity
- Don't degrade low frequency sensitivity
- Risk mitigation for high power operations
- Pathfinder for advanced LIGO squeezer

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



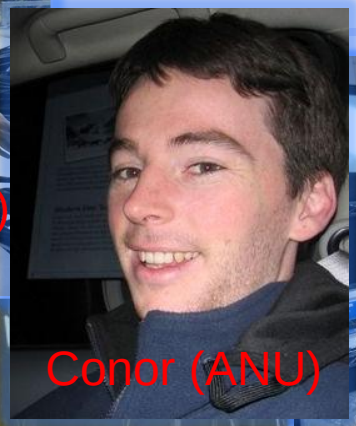
Interferometer Acronyms

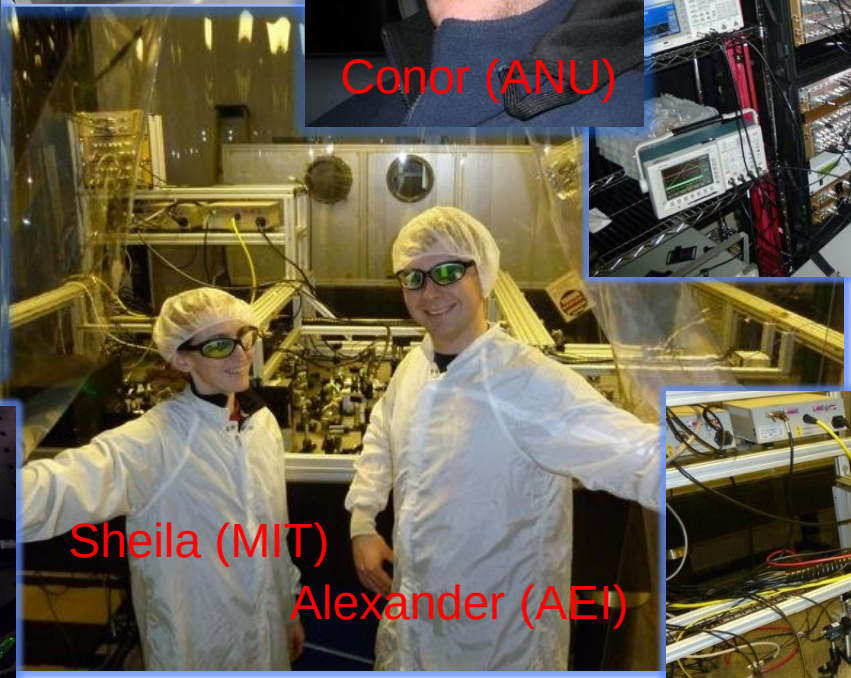
PSL	- Pre-Stabilized Laser
▬	- Vacuum System
IMC	- Input Mode Cleaner Cavity
PRM	- Power Recycling Mirror
BS	- Beam Splitter
ITM	- Arm Cavity Input Test Mass
ETM	- Arm Cavity End Test Mass
FI	- Faraday Isolator
OMC	- Output Mode Cleaner Cavity
PD	- Photodiode (Data Output)

Squeezed Light Source Acronyms

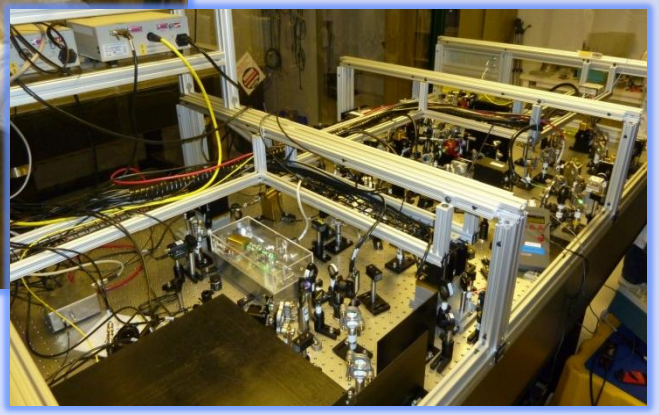
MAIN	- Squeezing Main Laser
AUX	- Squeezing Auxiliary Laser
PLL	- Phase Lock Loop
SHG	- Second Harmonic Generator
OPO	- Optical Parametric Oscillator
PS	- Phase Shifter

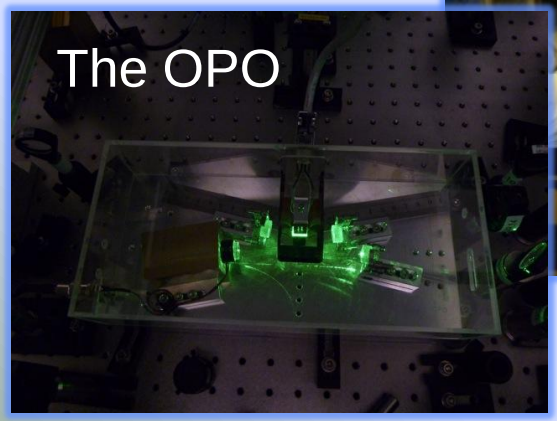
Squeezer at Hanford





Optics Table

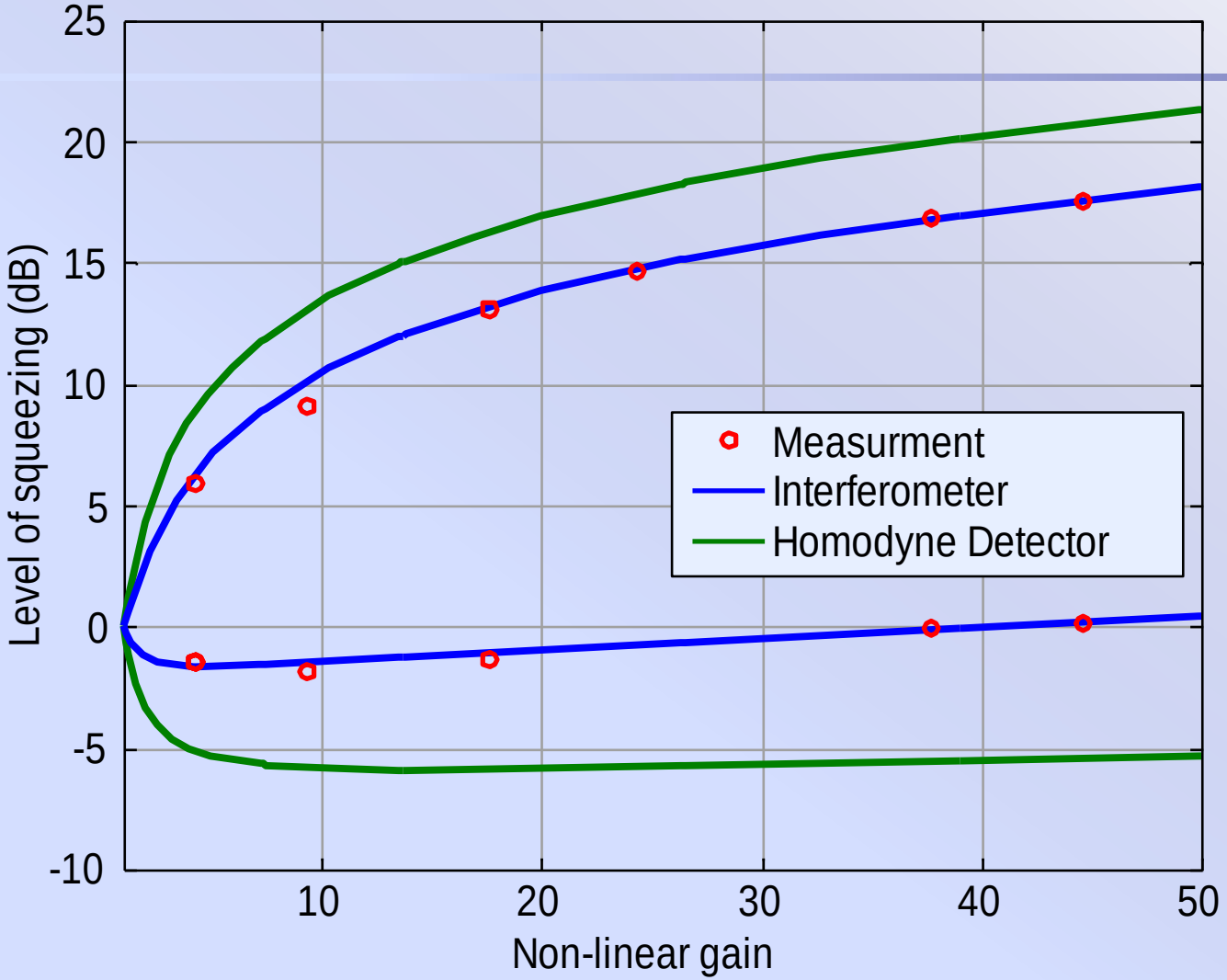




Non-Linear Gain

61% loss
5º phase noise

19% loss
1.3º phase noise



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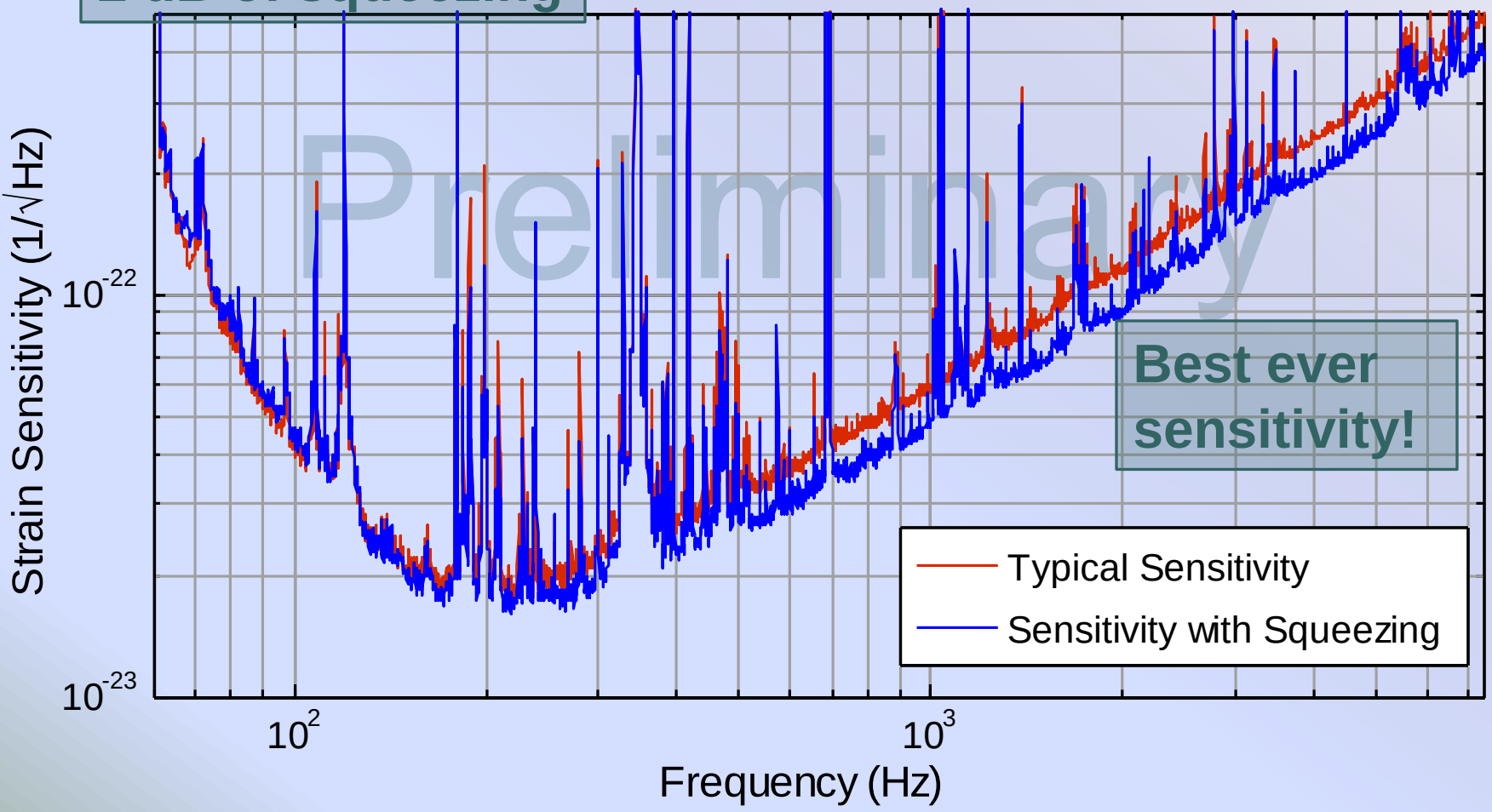
H1 Squeezed

2 dB of squeezing



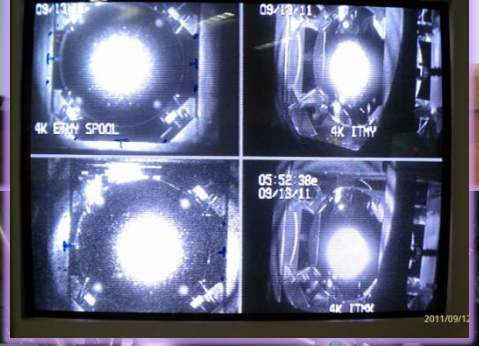
Best ever sensitivity!

LIGO

Outlook

- GEO600/AEI will work on high performance squeezing and long term stability
- ANU continues to optimize the ring-cavity OPO
- R&D program at MIT to work on filter cavities and a low loss readout chain
- Start a design for an advanced LIGO squeezer

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


HAM4-S

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

2011/06/07 11:4