Squeezed Light Techniques for Gravitational Wave Detection

July 6, 2012

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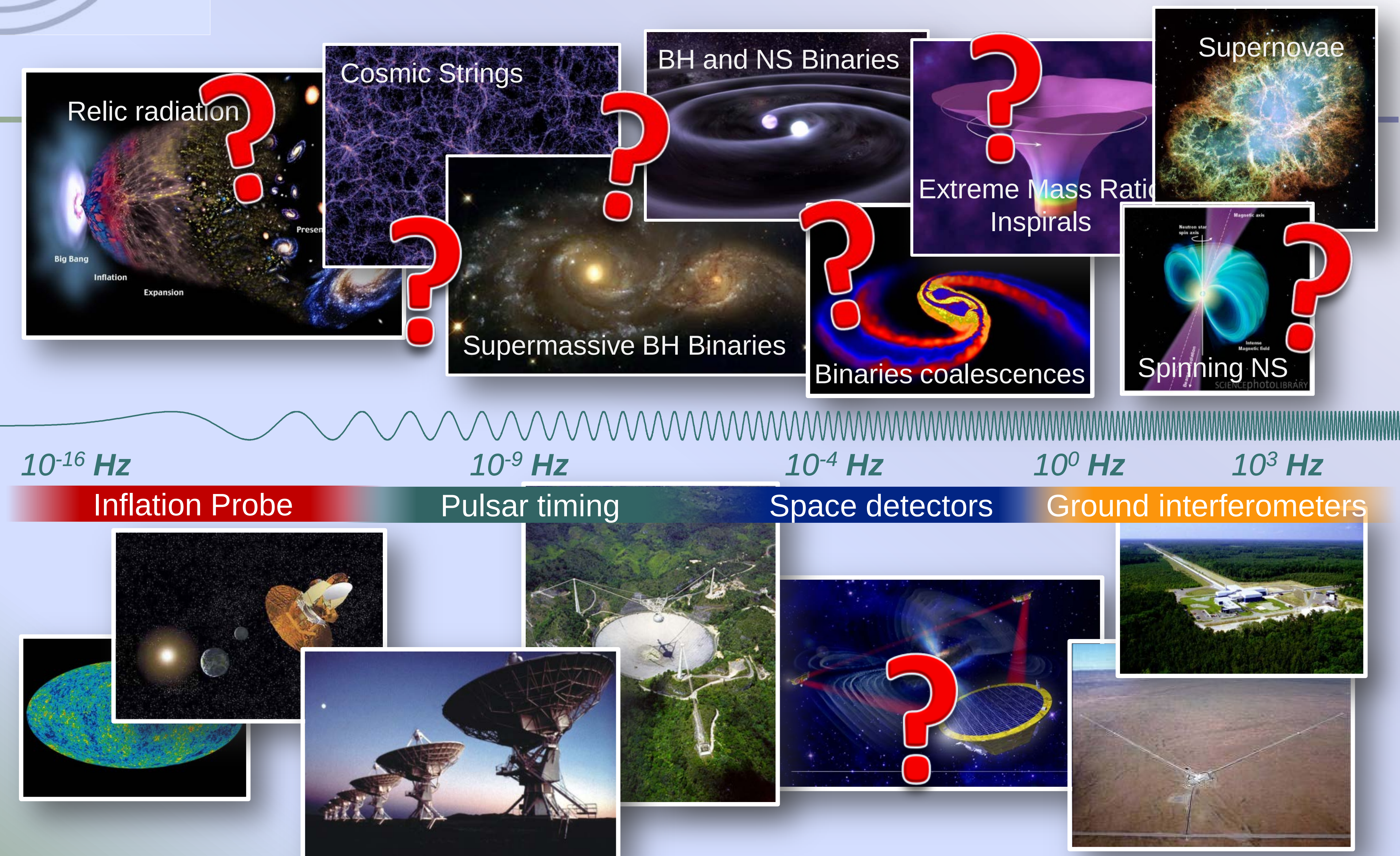
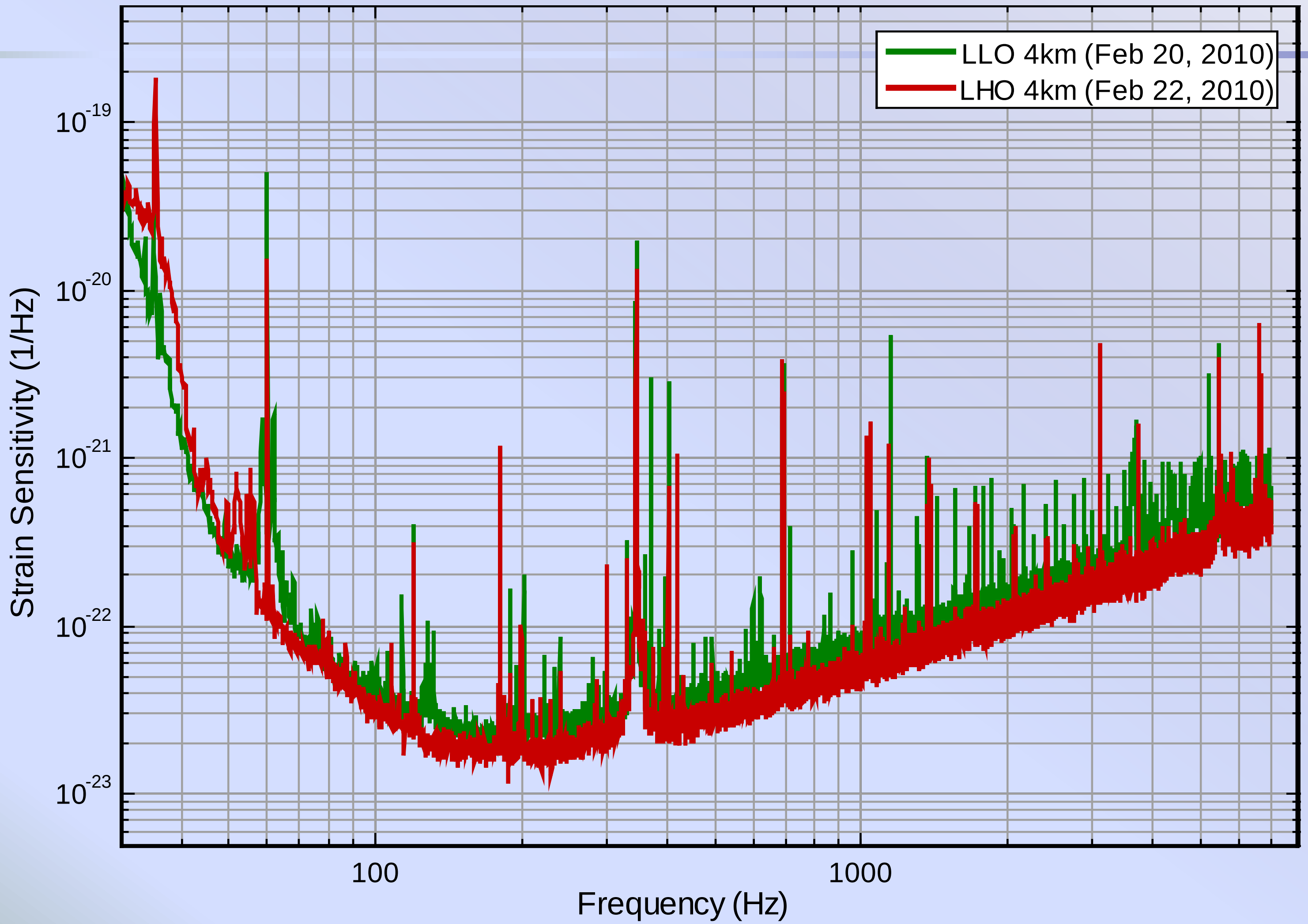
Abstract

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.

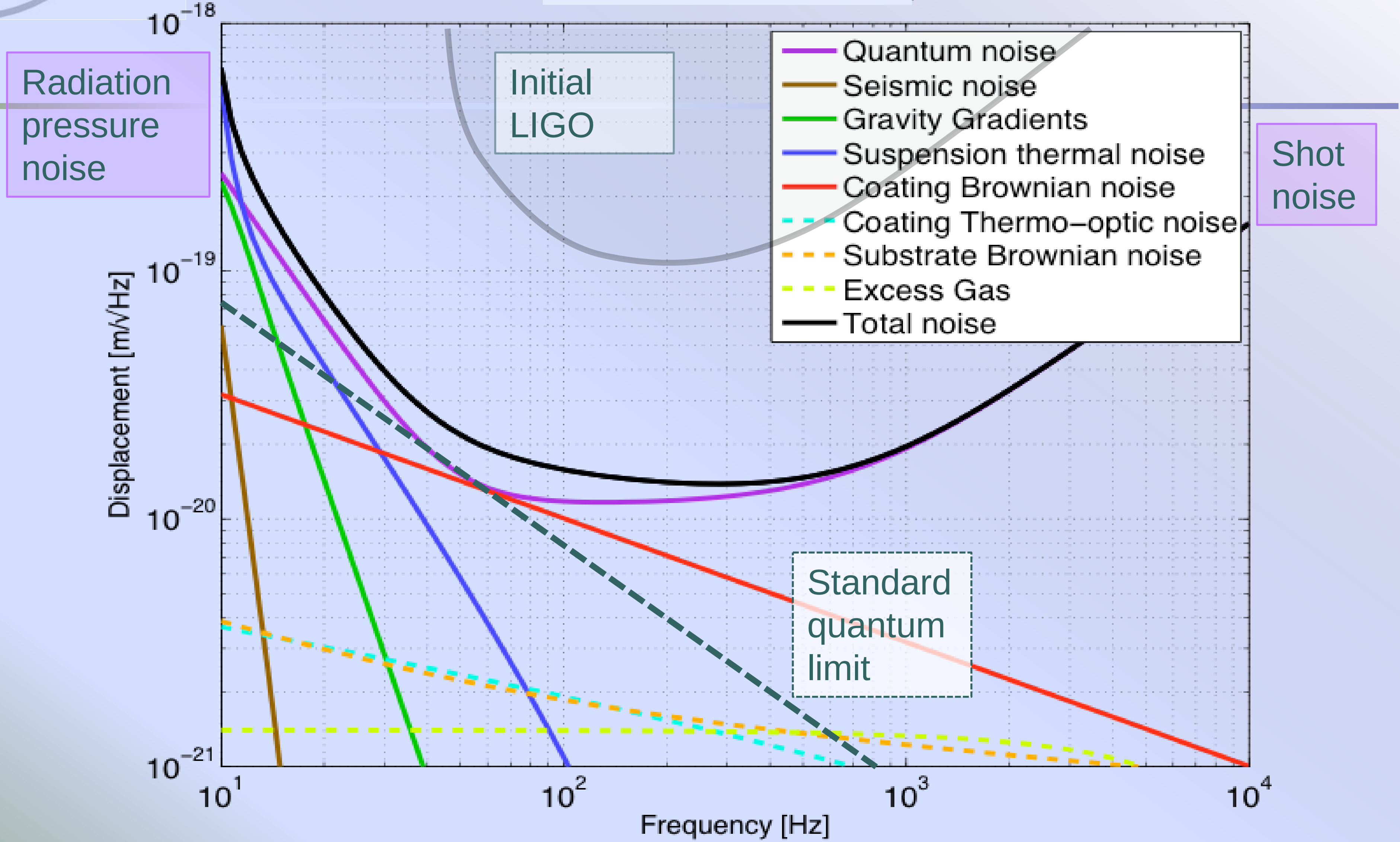
Gravitational Waves



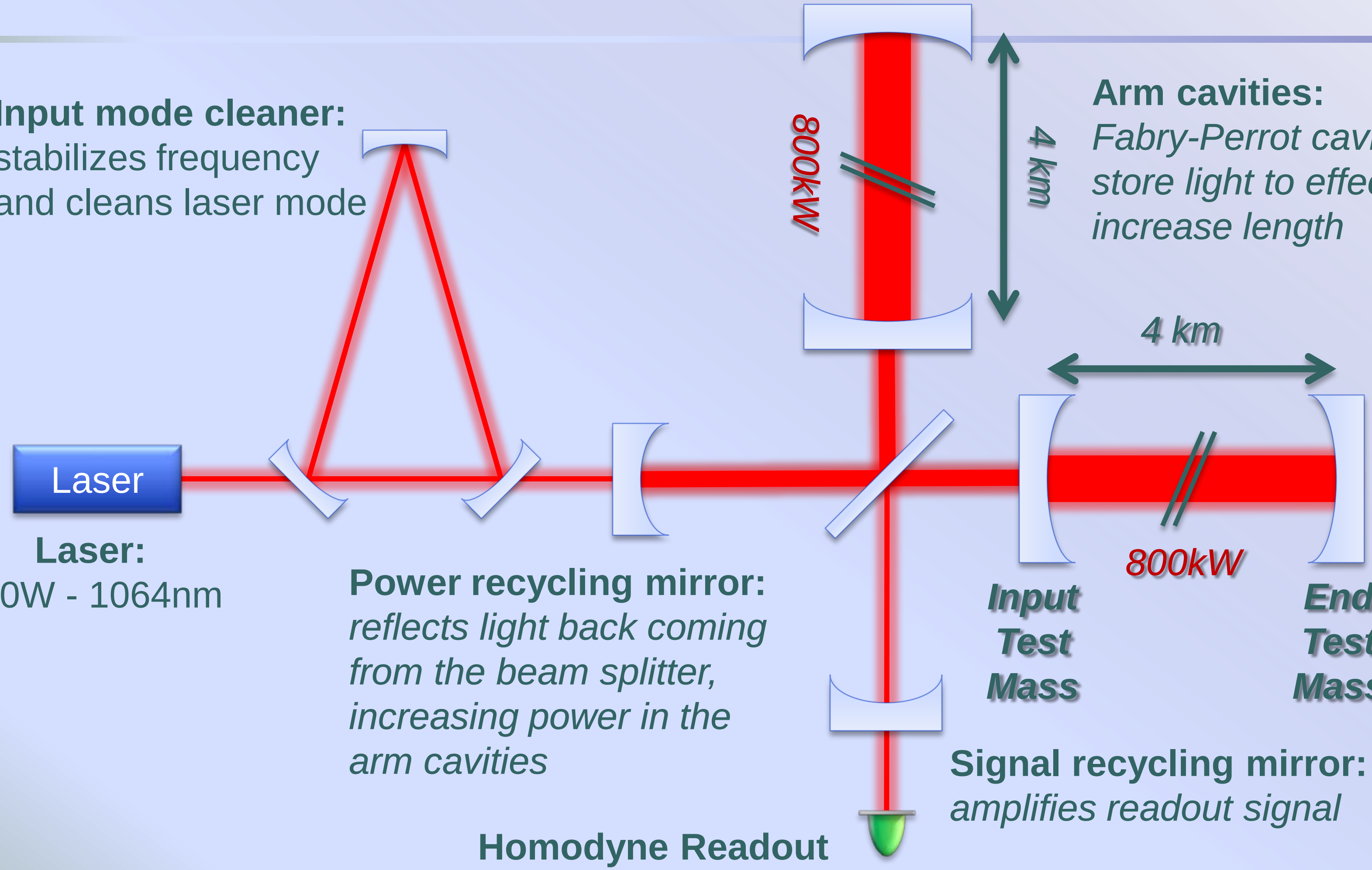
Sensitivity Sixth Science Run



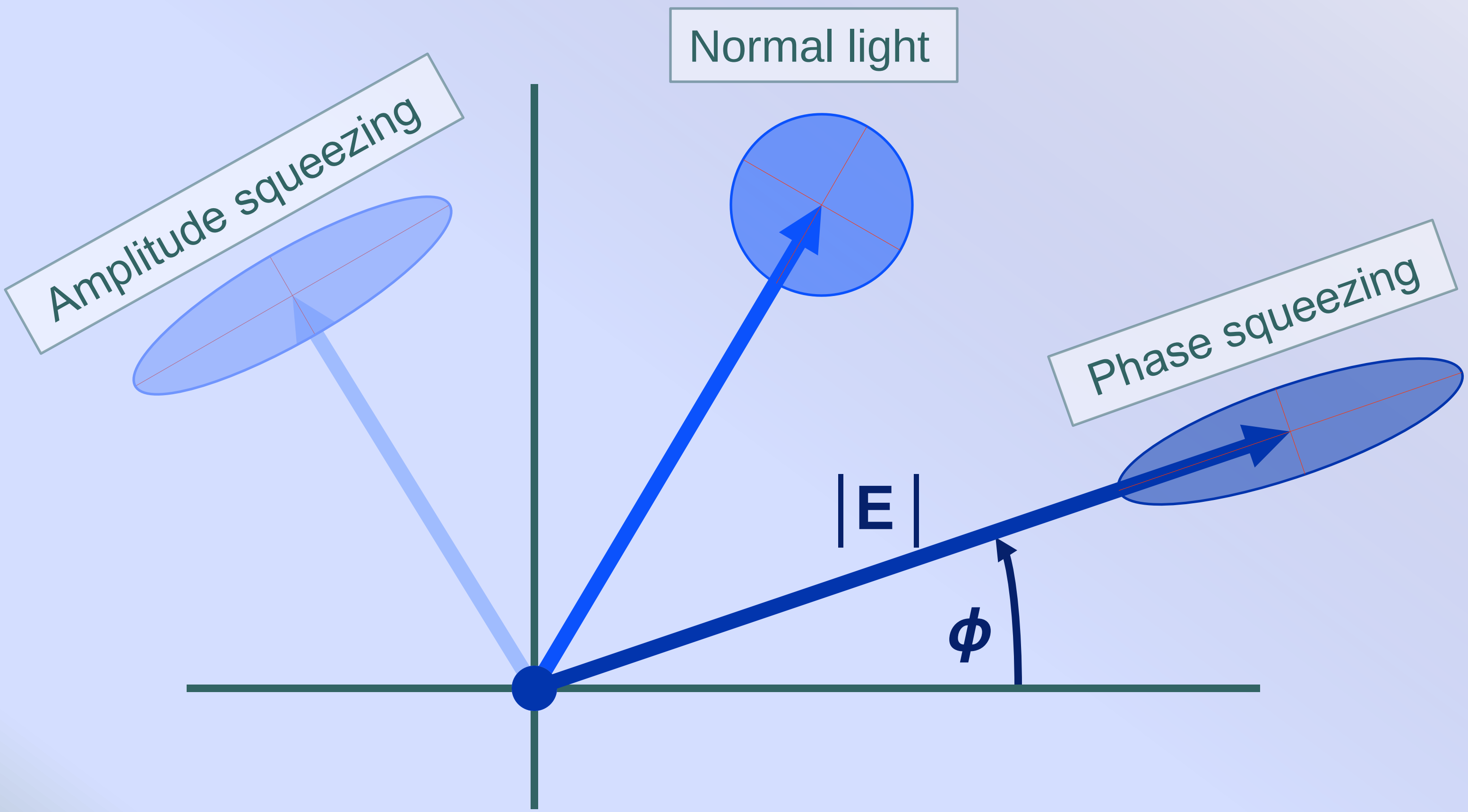
Advanced LIGO Sensitivity



The Advanced LIGO Detector

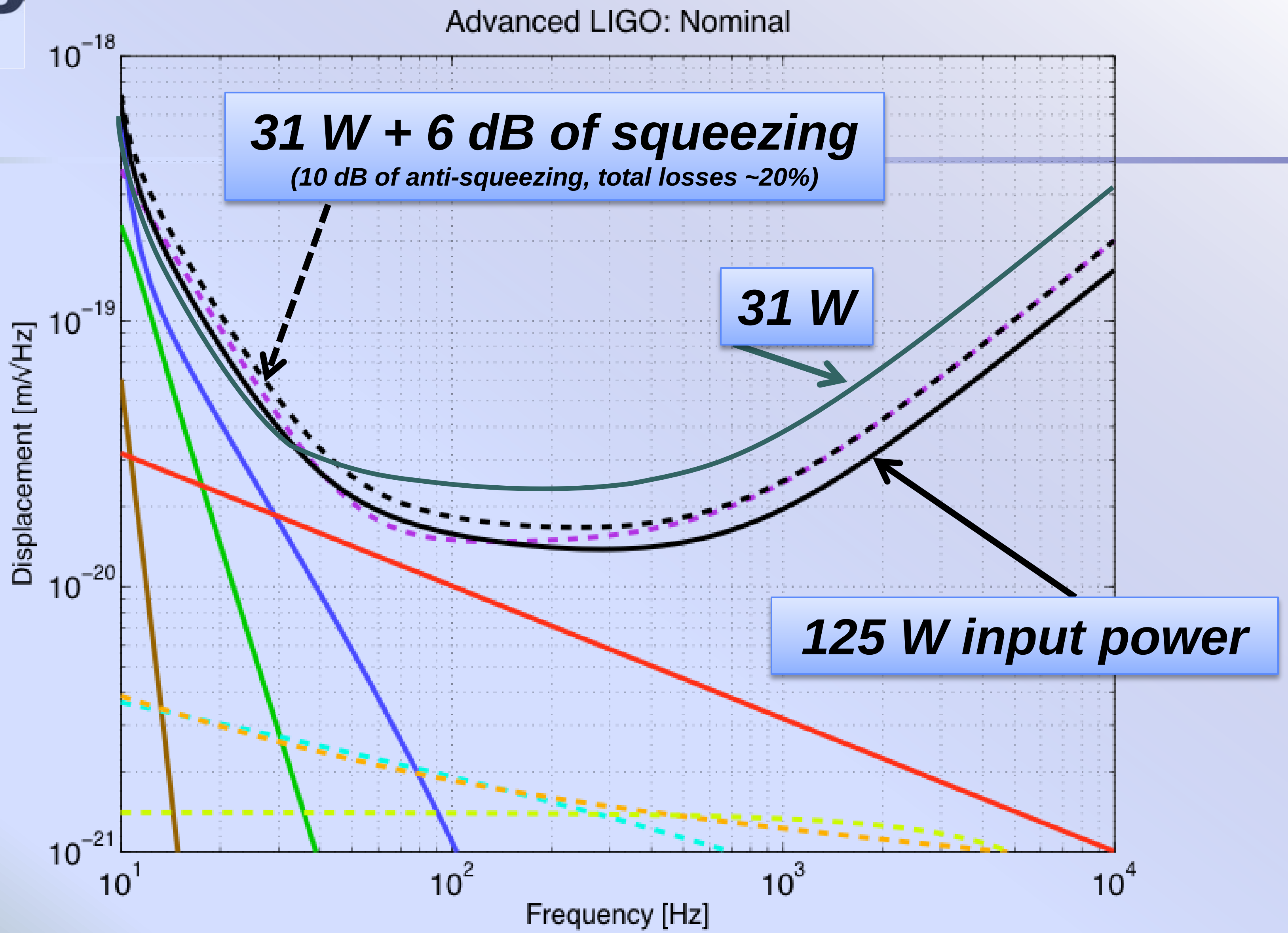


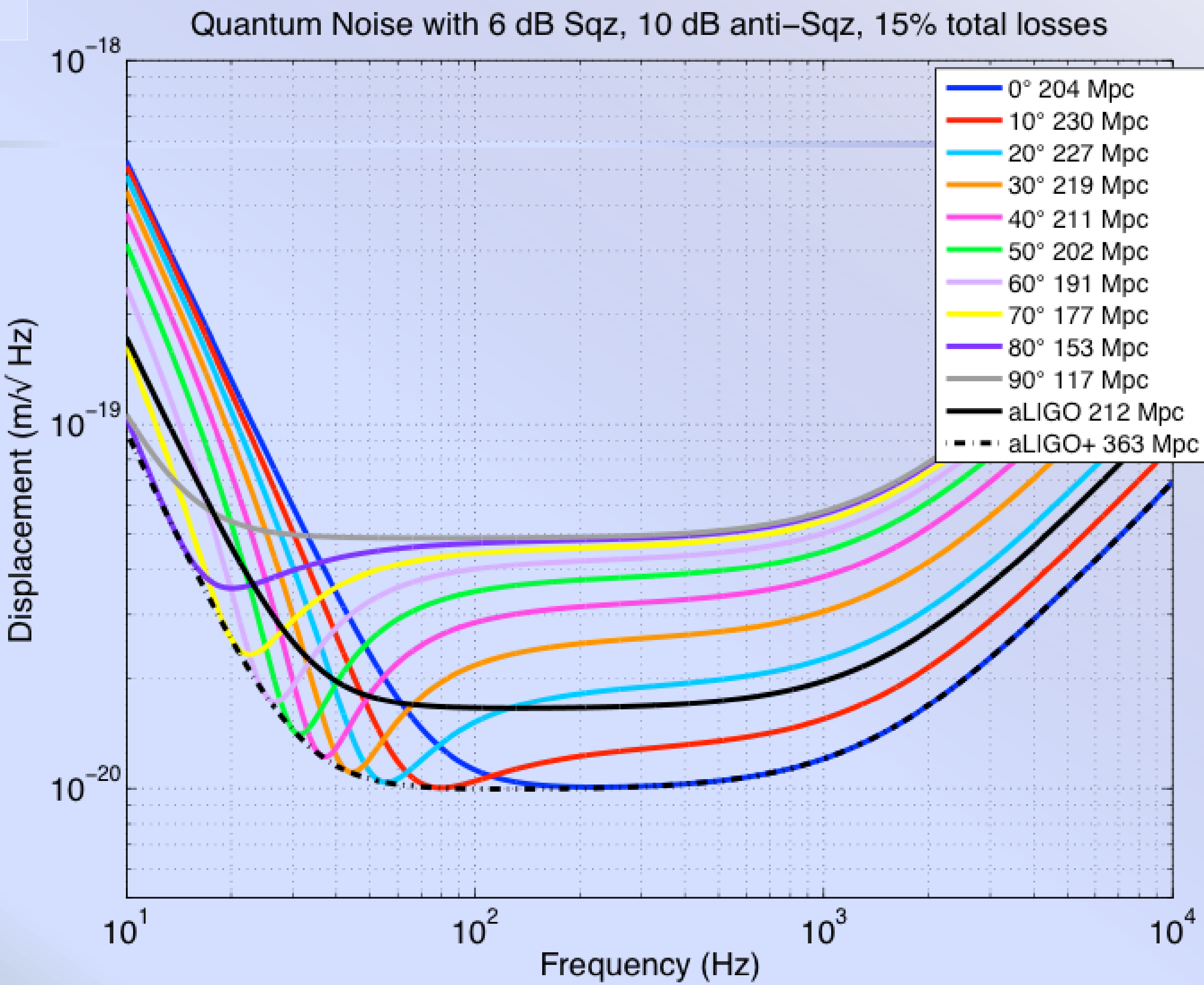
Squeezed Light



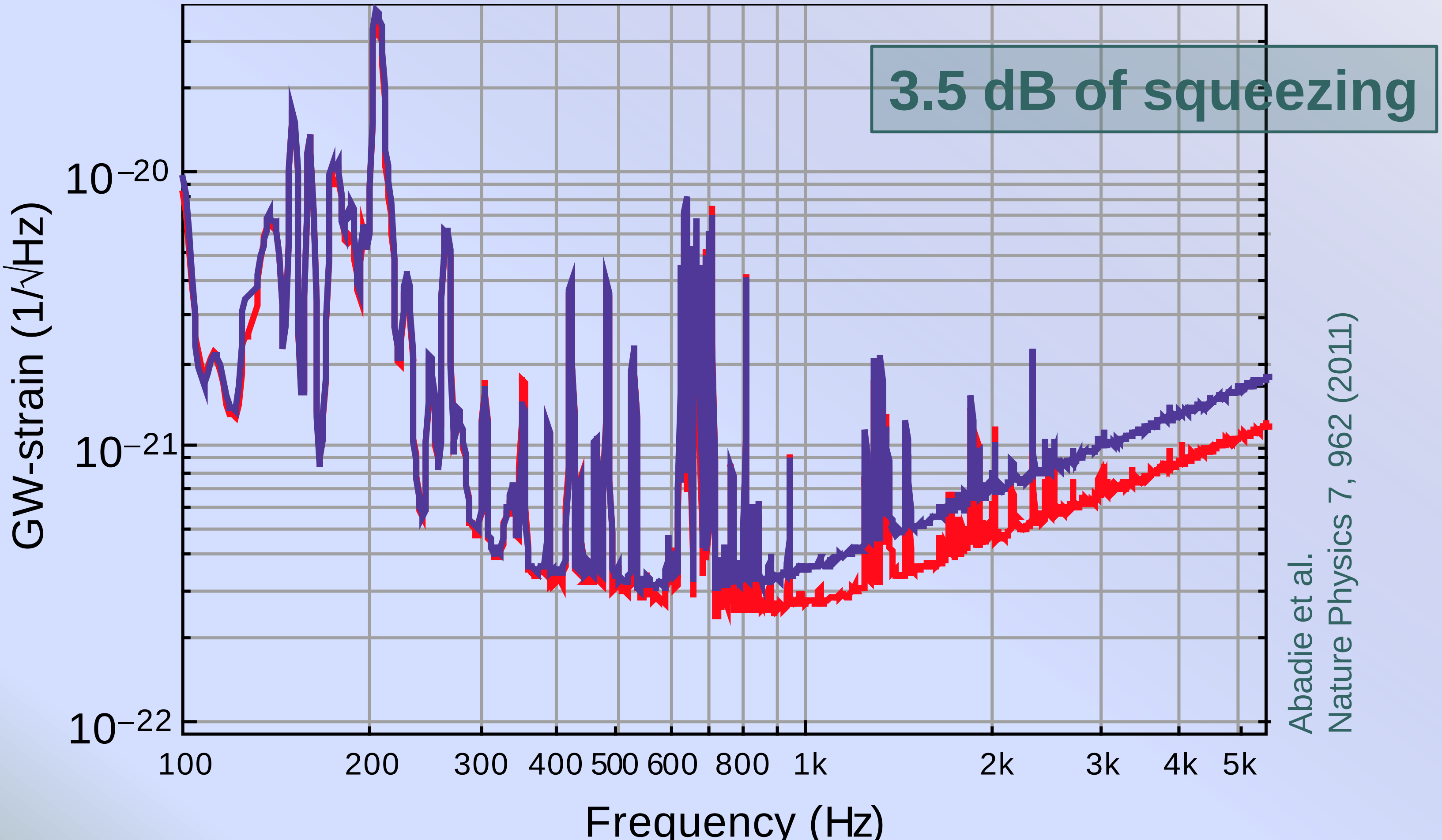
Key Insights

- 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.

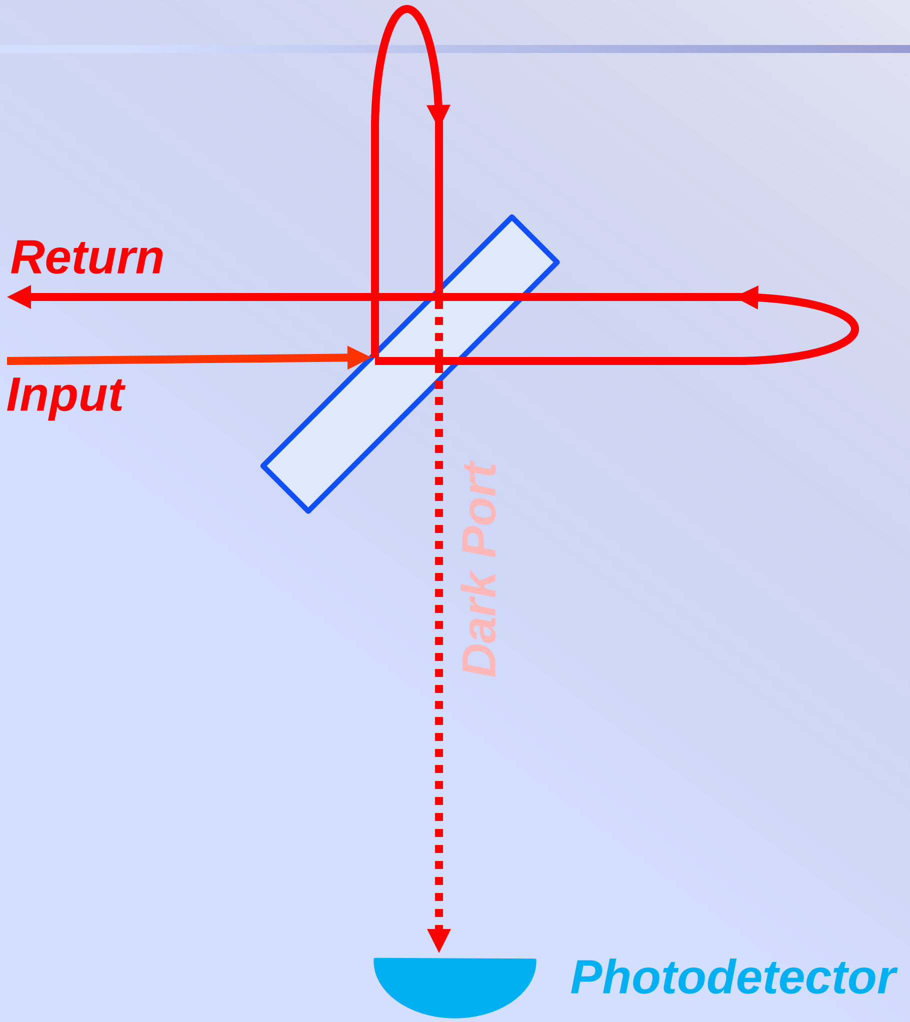

Advanced LIGO: Nominal
31 W + 6 dB of squeezing
(10 dB of anti-squeezing, total losses ~20%)
31 W
125 W input power
Displacement [m/√Hz]
Frequency [Hz]
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{1}
10^{2}
10^{3}
10^{4}


Quantum Noise with 6 dB Sqz, 10 dB anti–Sqz, 15% total losses
Displacement (m/√ Hz)
Frequency (Hz)
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



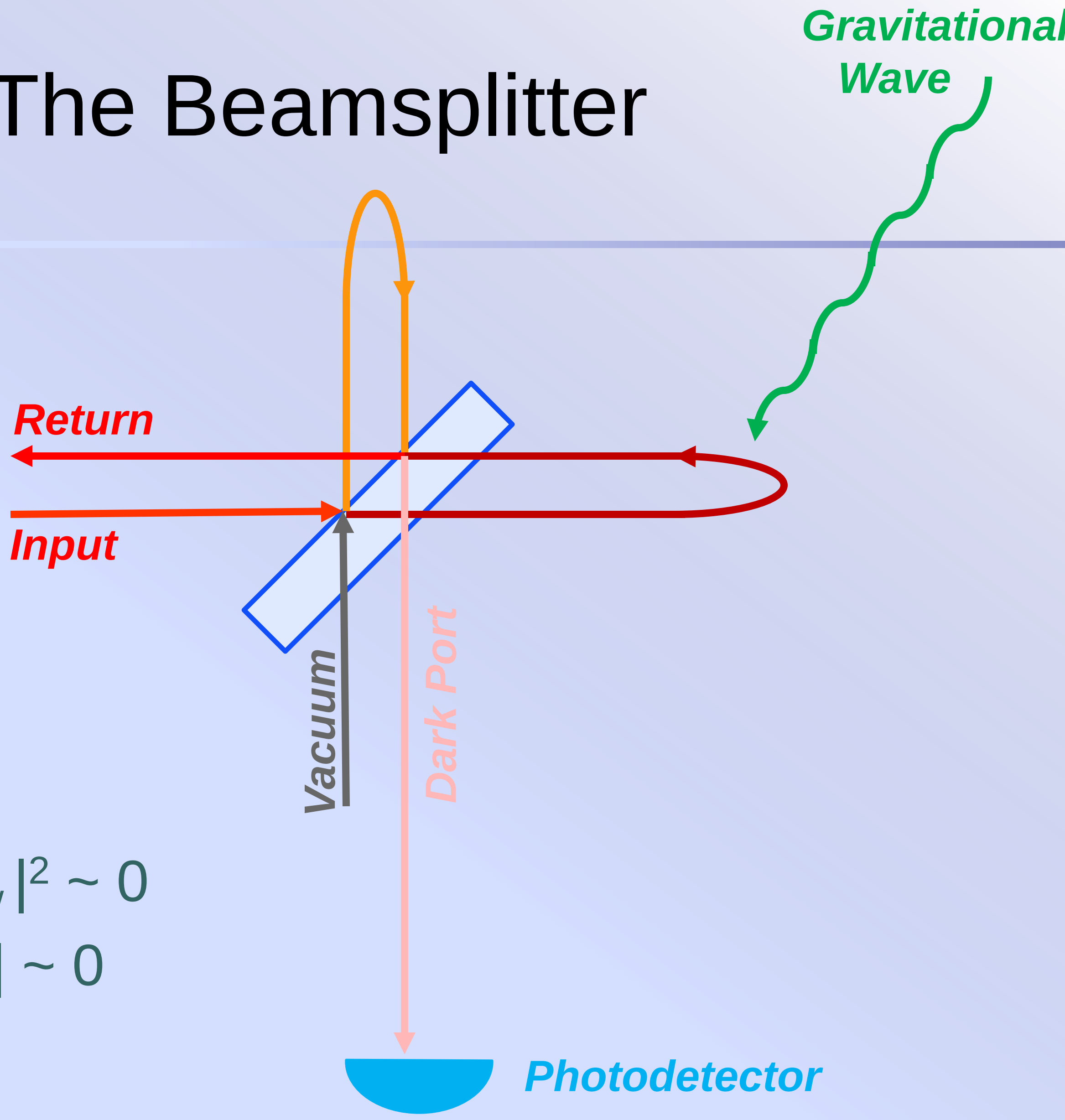
The Beamsplitter



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

Noise = 0

The Beamsplitter

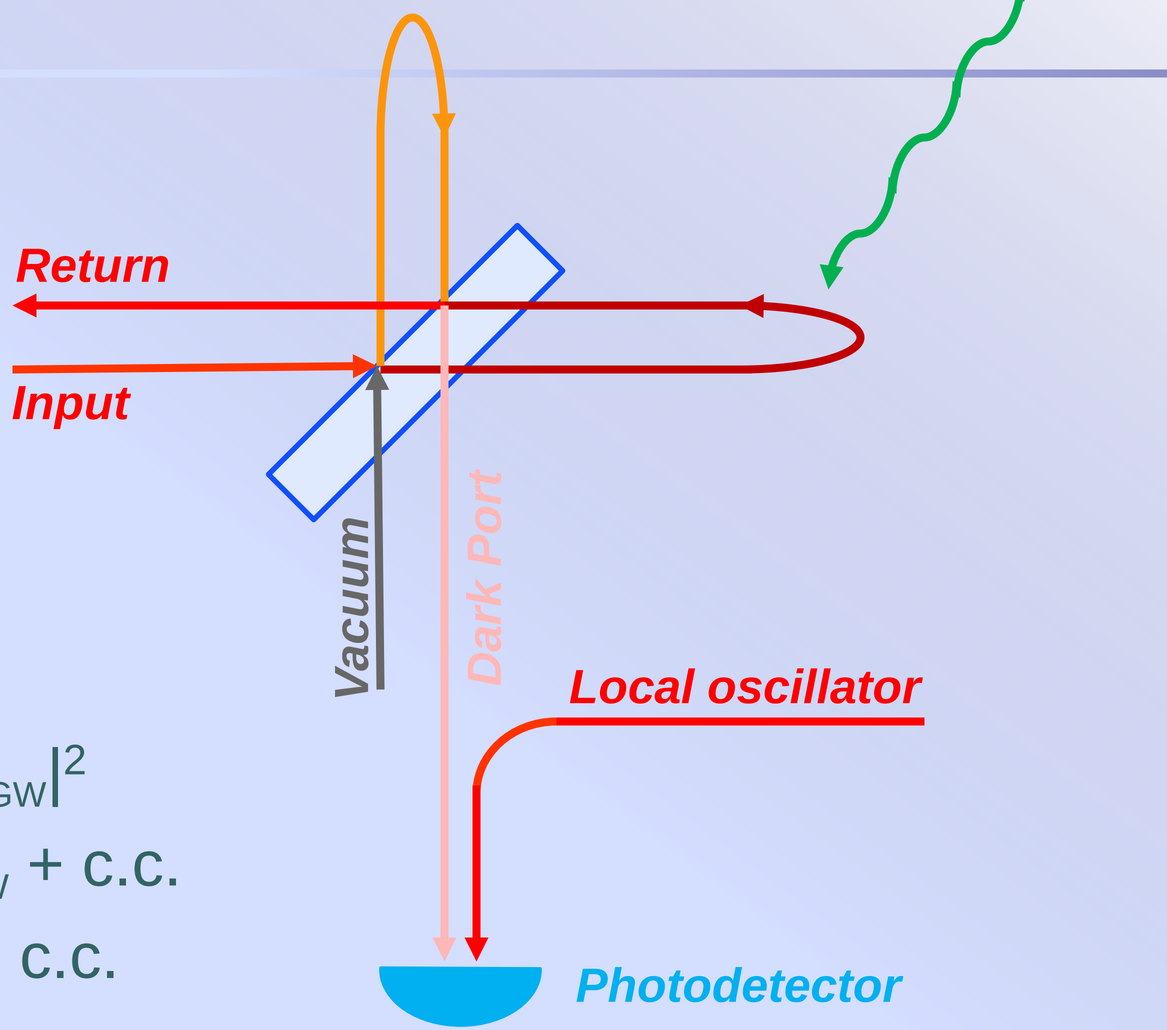


$E_{vac} = 0 + \tilde{e}_{vac}$

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

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

The Beamsplitter



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

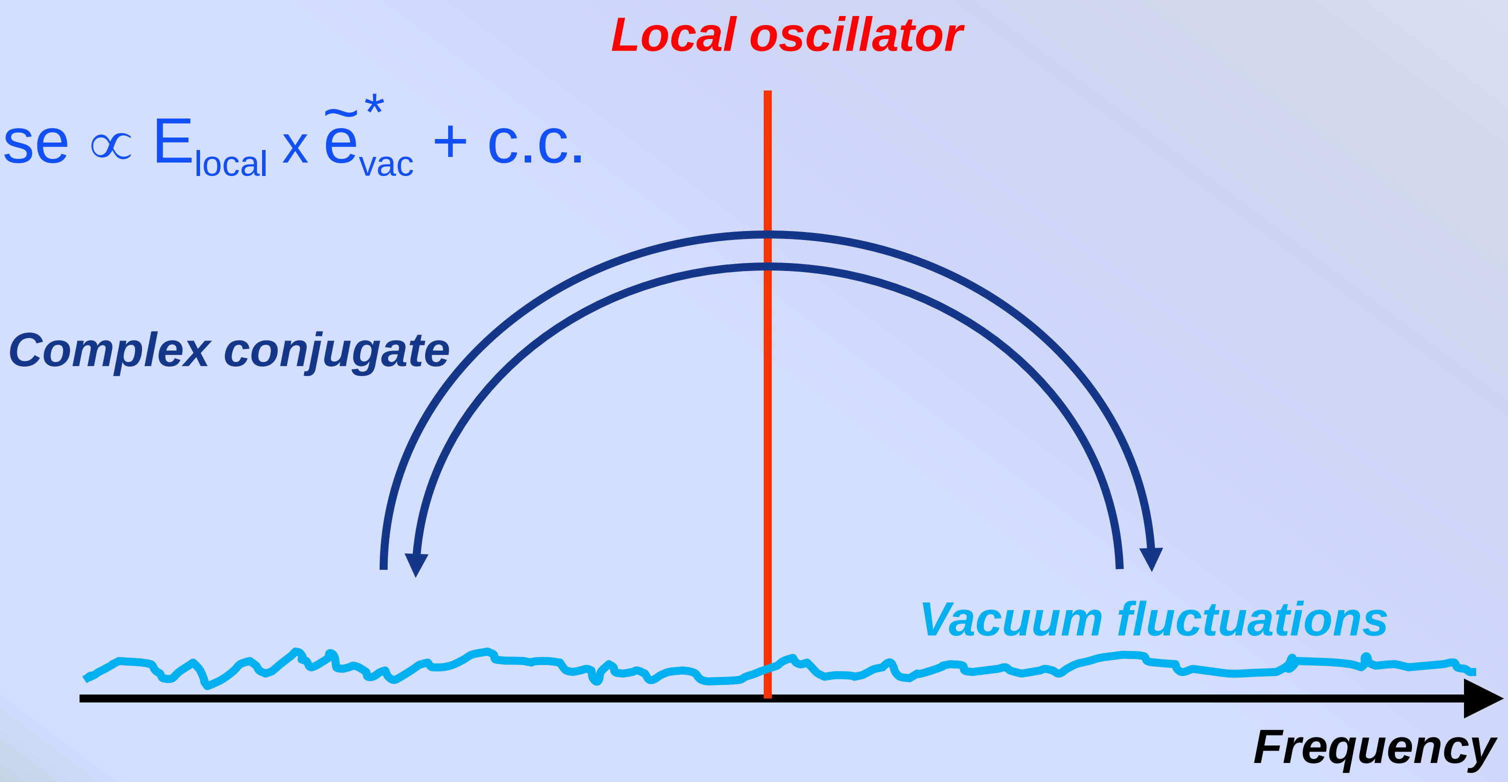
$$\text{Signal} \propto |E_{local} + \Delta E_{GW}|^2$$

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

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

In Fourier Space

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



Generating Squeezed "Vacuum"

- Need an operation that applies

$$\tilde{e}_{vac} \rightarrow \tilde{e}_{vac} + e^{2i\varphi} \times \tilde{e}^{*}_{vac}$$

φ: 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:

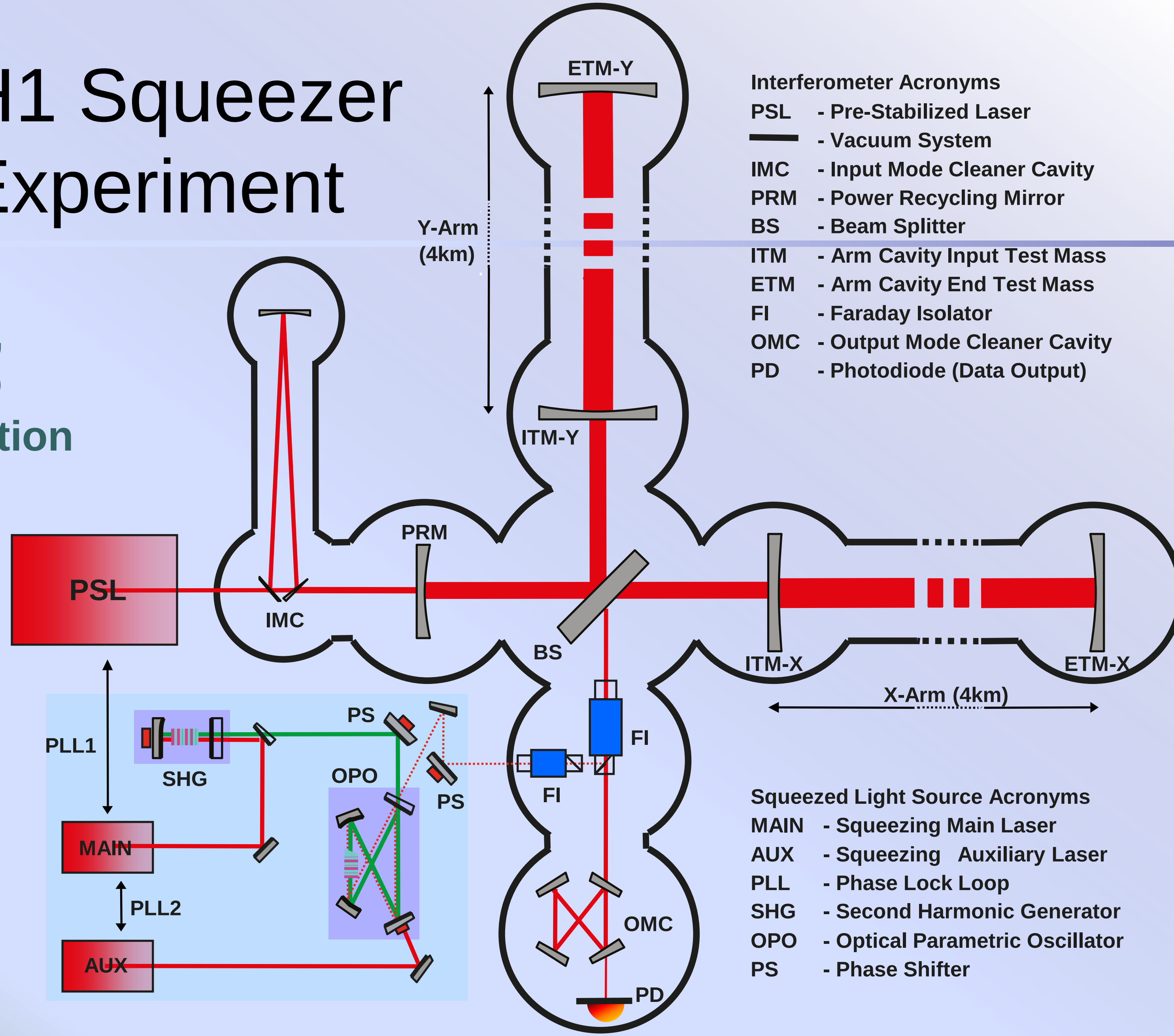
- Demonstrate 3dB of squeezing at the initial LIGO sensitivity
- Don’t degrade low frequency sensitivity
- Risk mitigation for high power operations
- Pathfinder for advanced LIGO squeezer

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



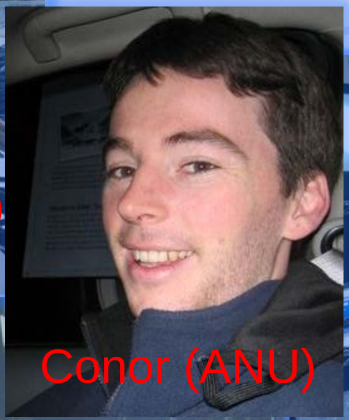
Interferometer Acronyms

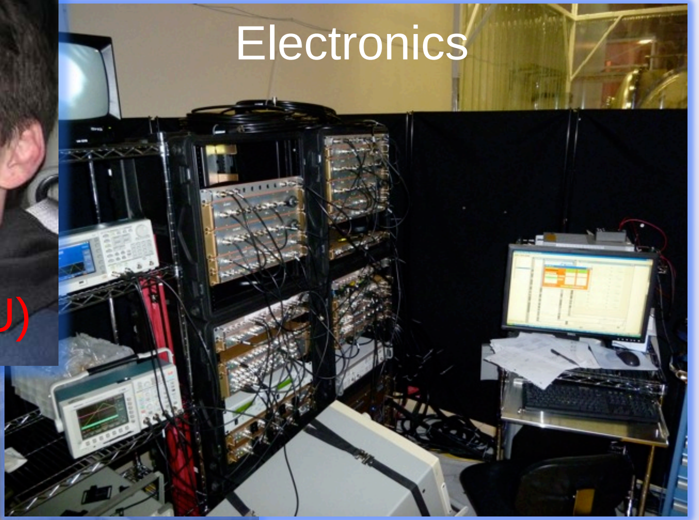
- PSL - Pre-Stabilized Laser
- (black line) - Vacuum System
- IMC - Input Mode Cleaner Cavity
- PRM - Power Recycling Mirror
- BS - Beam Splitter
- ITM - Arm Cavity Input Test Mass
- ETM - Arm Cavity End Test Mass
- FI - Faraday Isolator
- OMC - Output Mode Cleaner Cavity
- PD - Photodiode (Data Output)

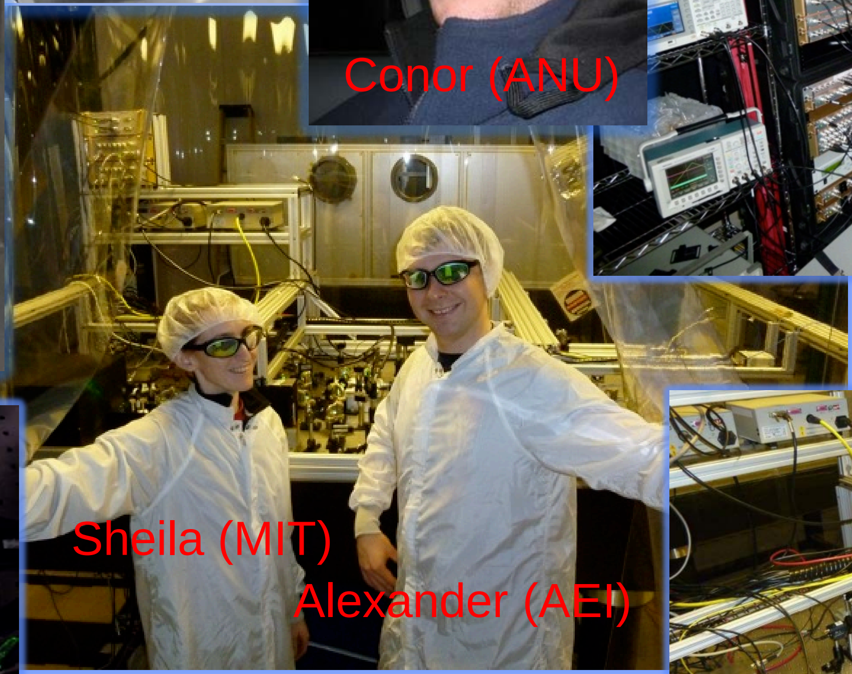
Squeezed Light Source Acronyms

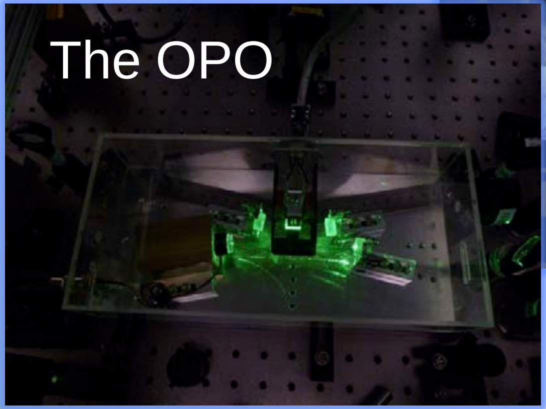
- MAIN - Squeezing Main Laser
- AUX - Squeezing Auxiliary Laser
- PLL - Phase Lock Loop
- SHG - Second Harmonic Generator
- OPO - Optical Parametric Oscillator
- PS - Phase Shifter

Squeezer at Hanford

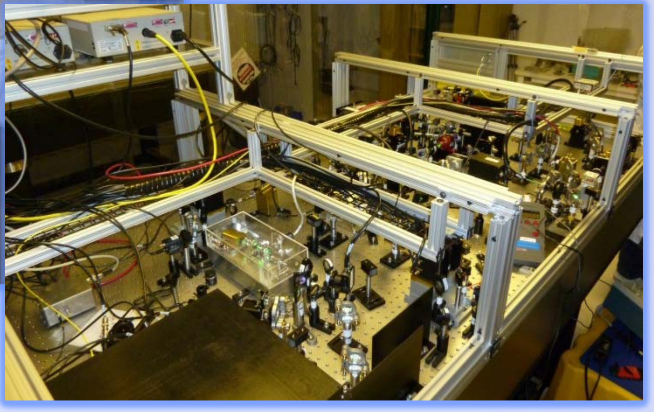




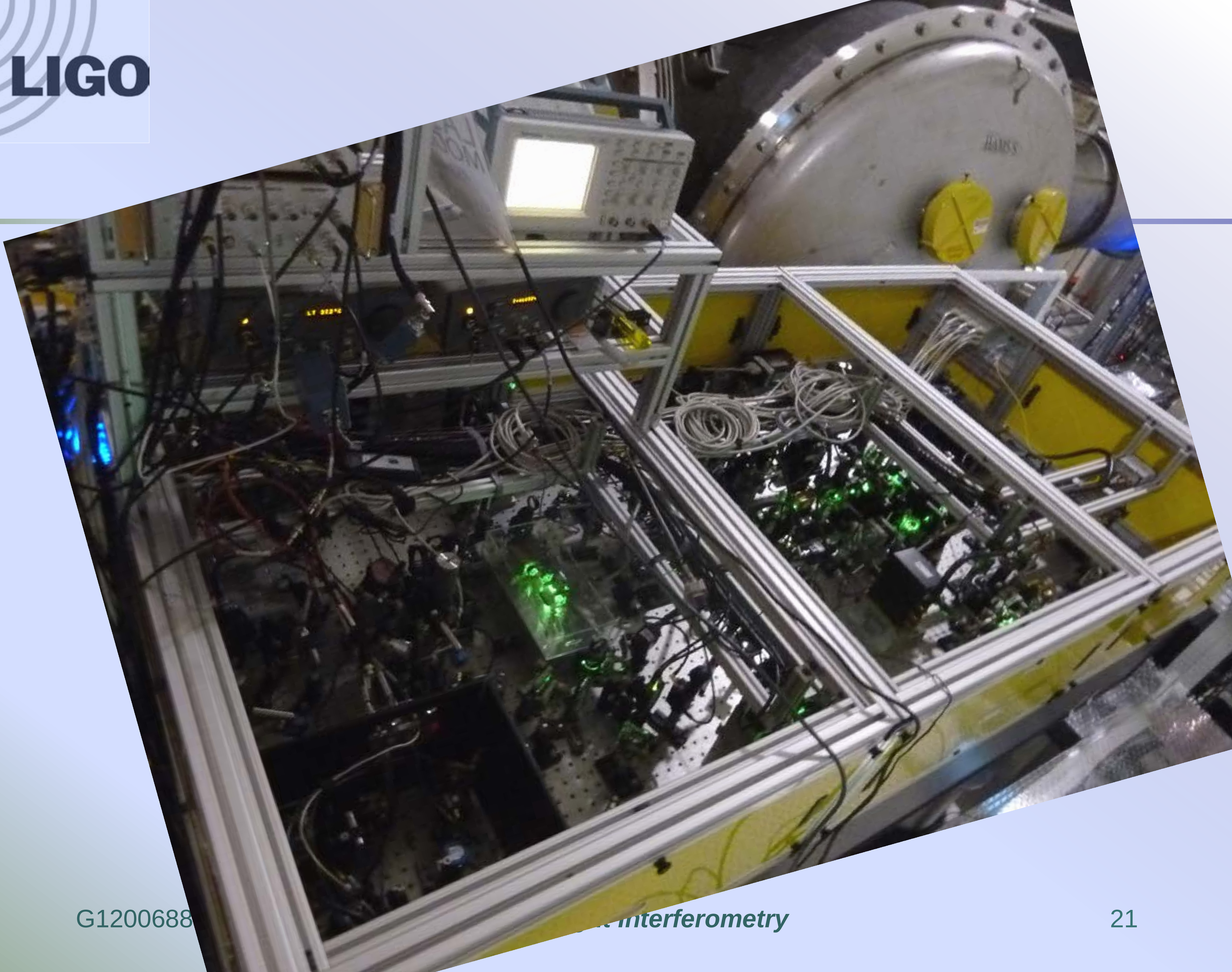


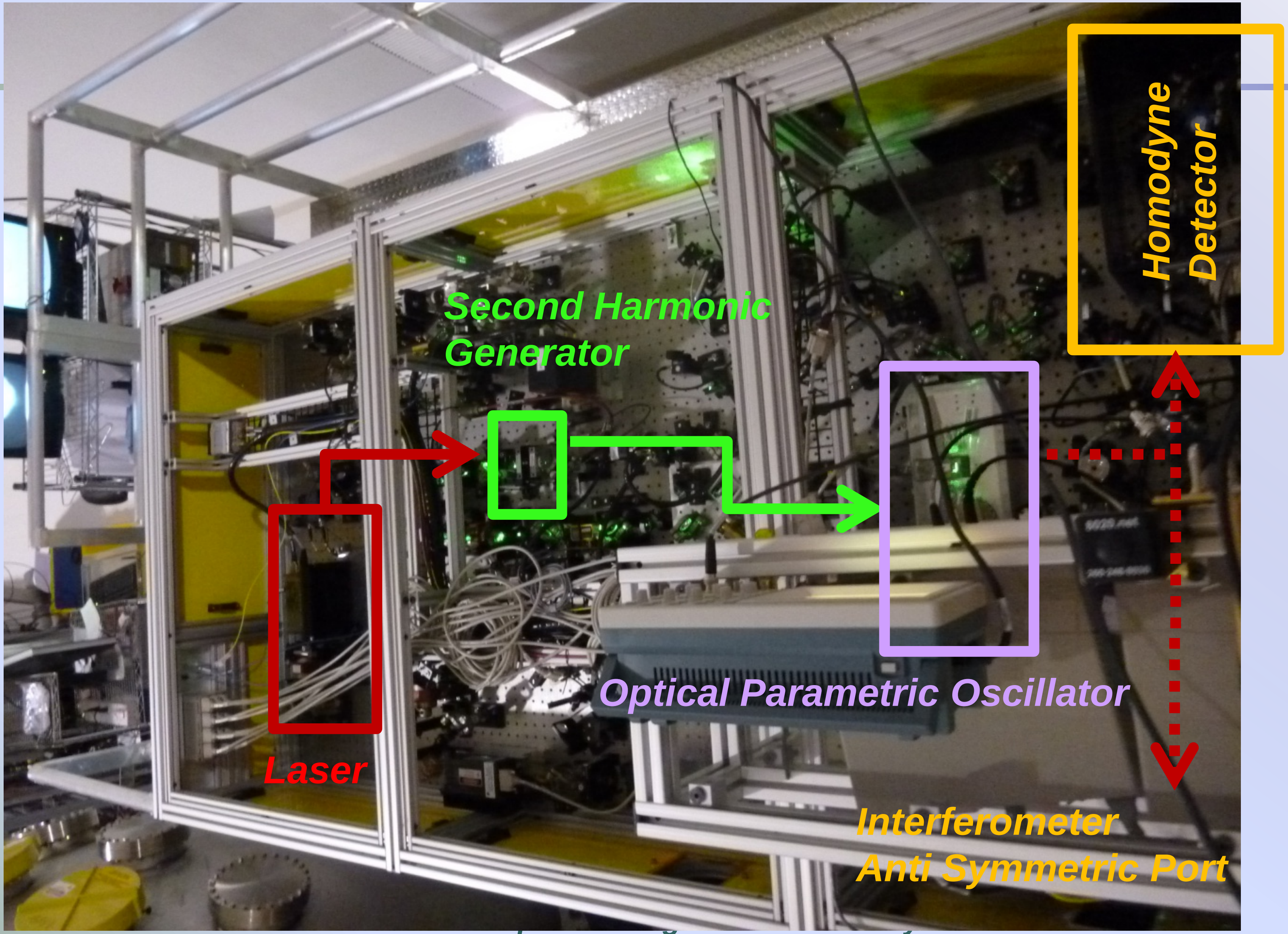


Optics Table



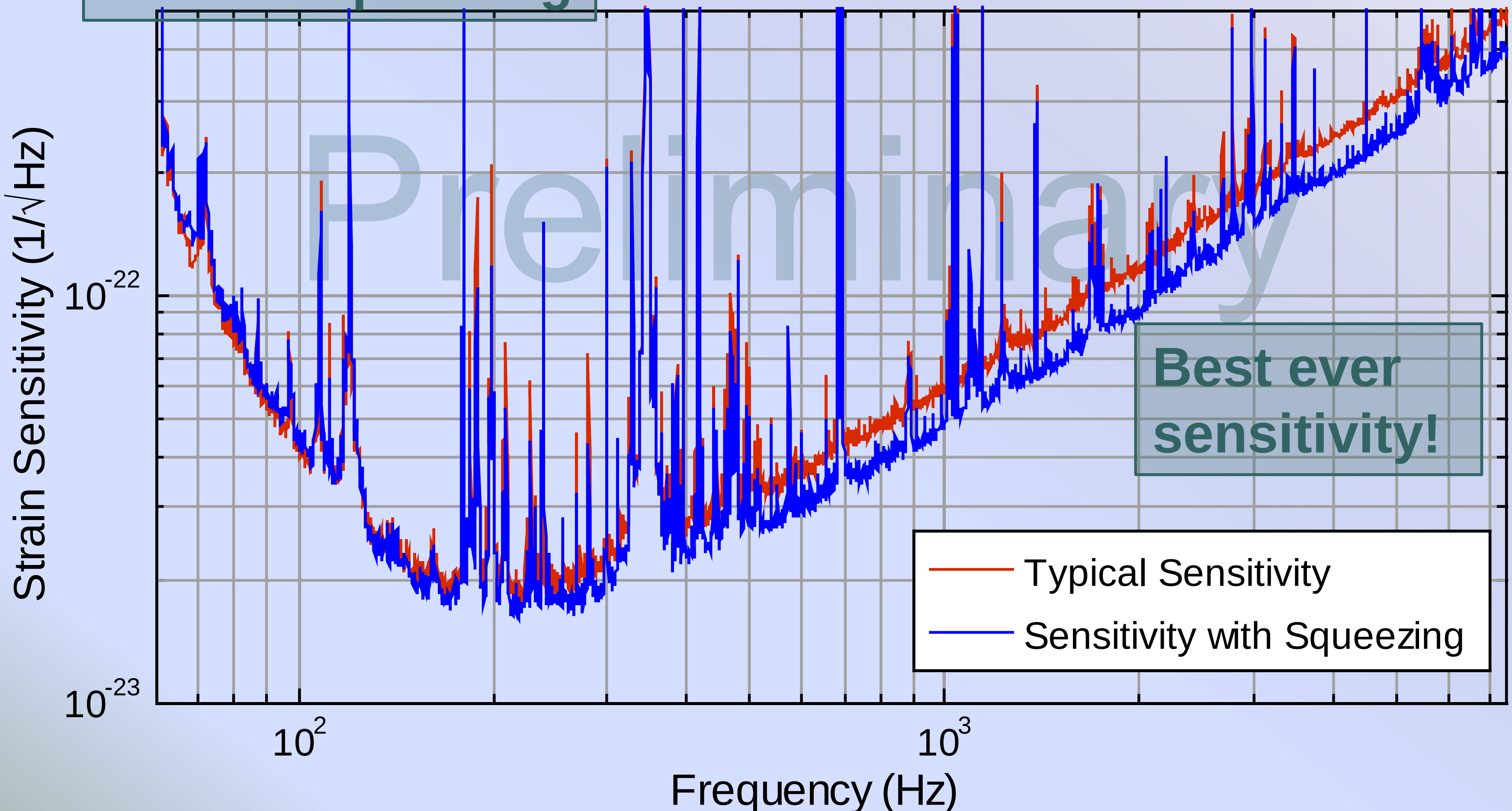
LIGO




Homodyne Detector
Second Harmonic Generator
Optical Parametric Oscillator
Laser
Interferometer Anti Symmetric Port

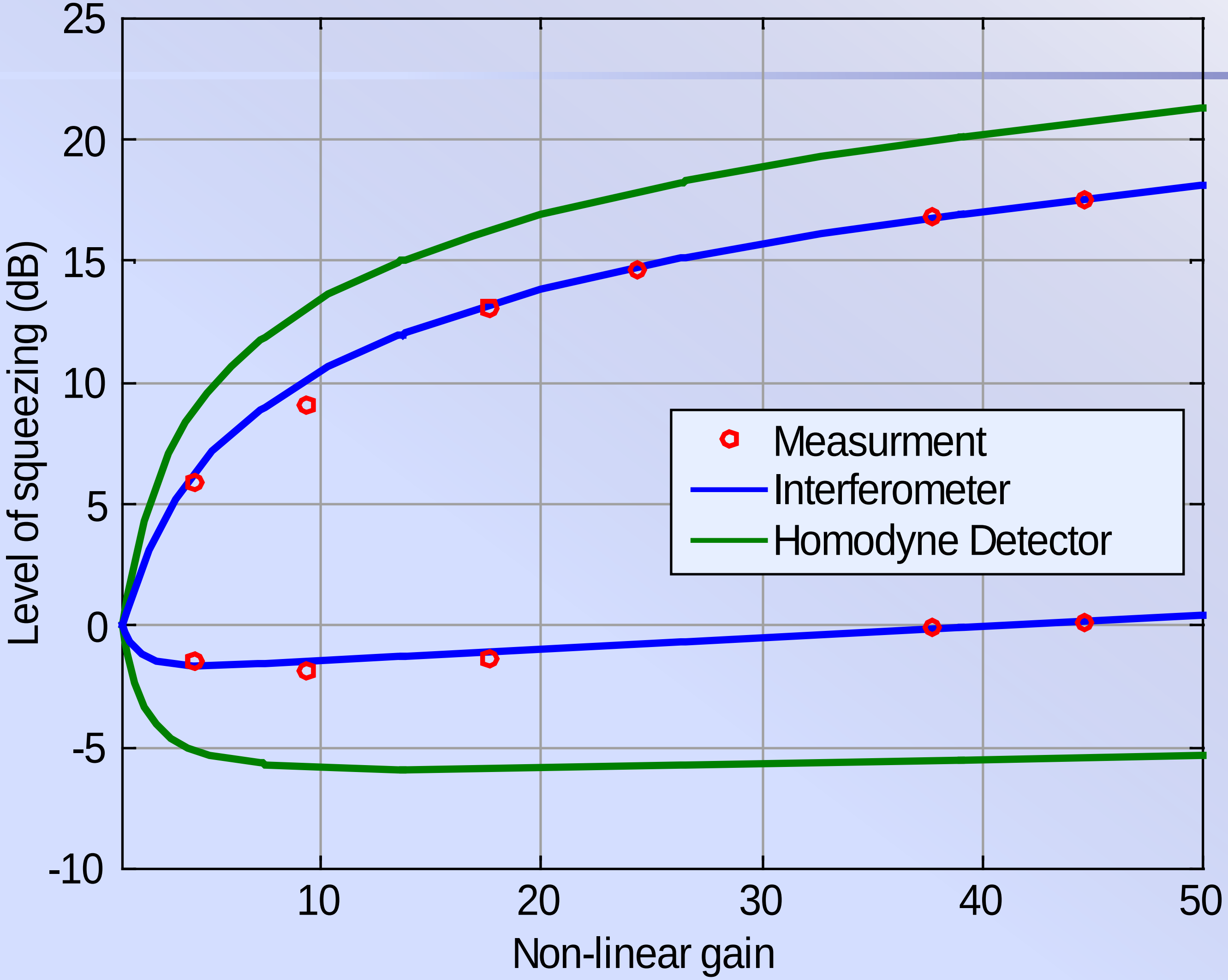
H1 Squeezed

2 dB of squeezing



Best ever sensitivity!

Non-Linear Gain



61% loss
5º phase noise

19% loss
1.3º phase noise

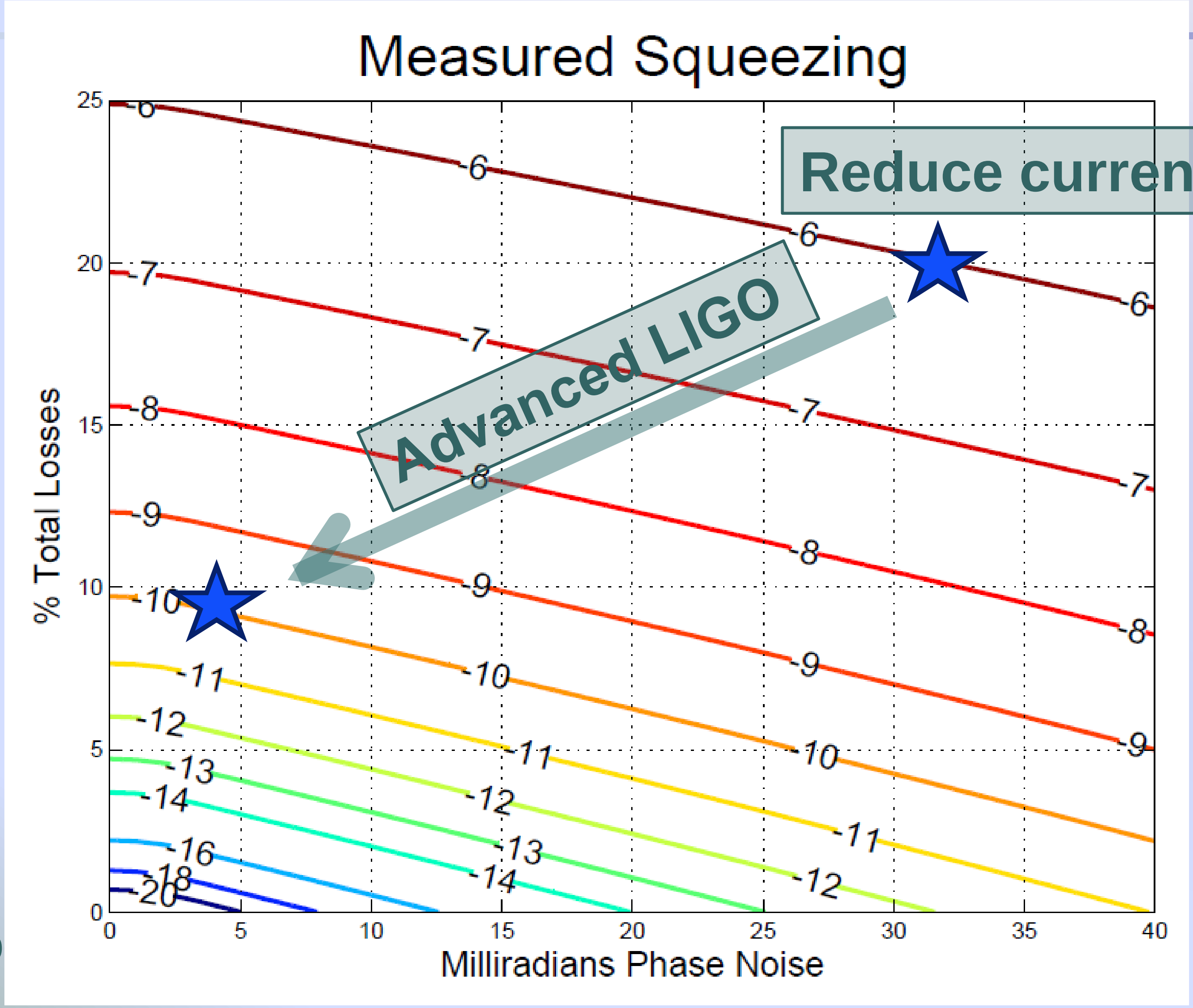
	Now	Near future	Advanced LIGO
3 Faraday passes	5% each	3% each	Aim for less than 10% total
Signal recycling cavity@100 Hz		2.5% (T=35%)	
Squeezer mode matching to OMC	30%	4%	
OMC transmission	19%	1%	
Total losses	55-60%	20%	
Detected Squeezing	2+dB	6dB	10-15dB

Losses

Phase Noise

	Now	Near future	Advanced LIGO
RF sidebands	1.3 mrad	same	Reduce to less than 2 mrad total
Sources on squeezer table	≤22 mrad		
Beam jitter	30 mrad		
Total phase noise	37mrad		
Detected squeezing	2+dB	6dB	10-15dB

Future Phase Noise and Loses



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 ITMY
4K ITMX
09/13/11
2011/09/12