Squeezed Light Techniques for Gravitational Wave Detection

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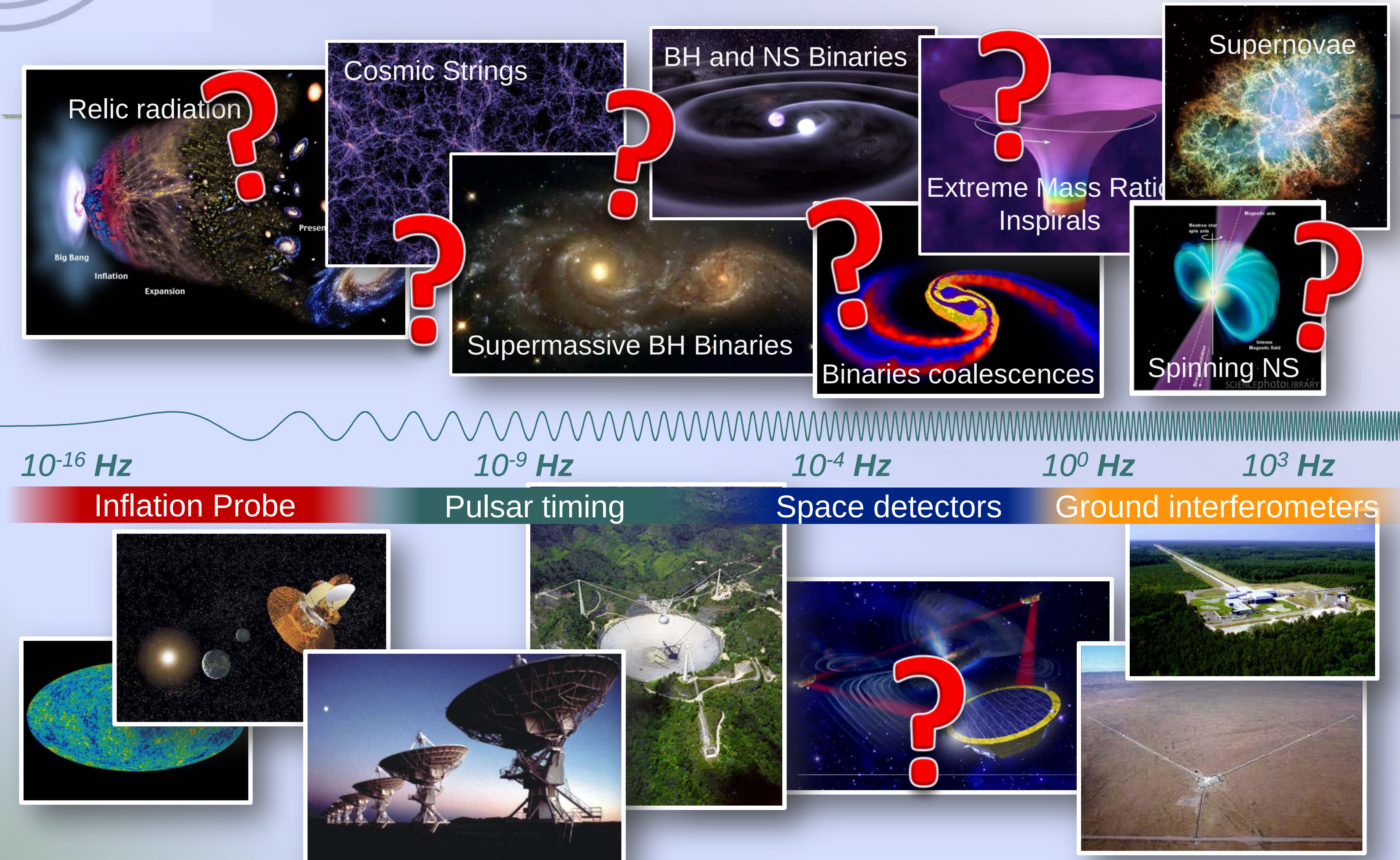
Seminar at RRCAT, Indore, India

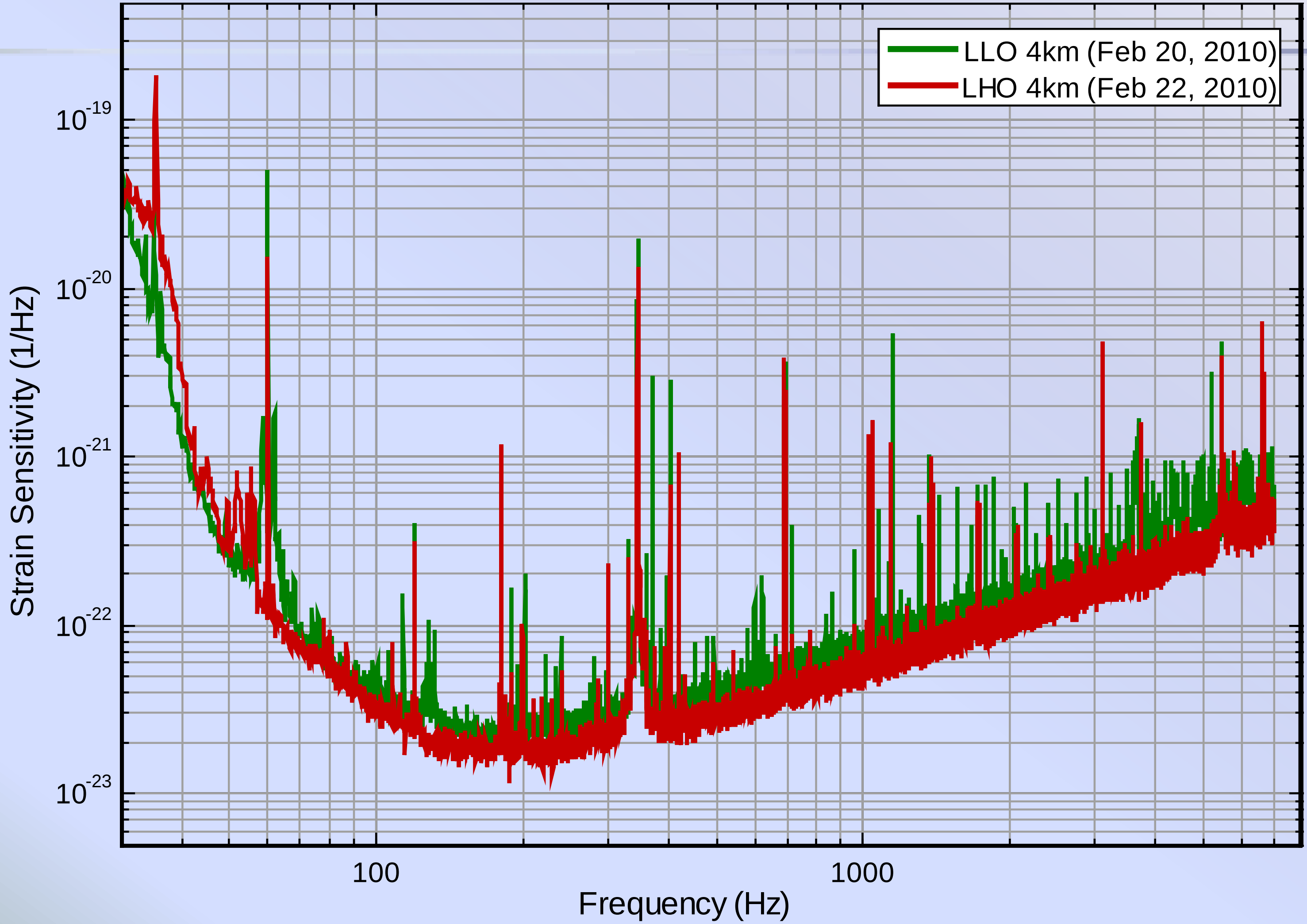
Abstract

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.

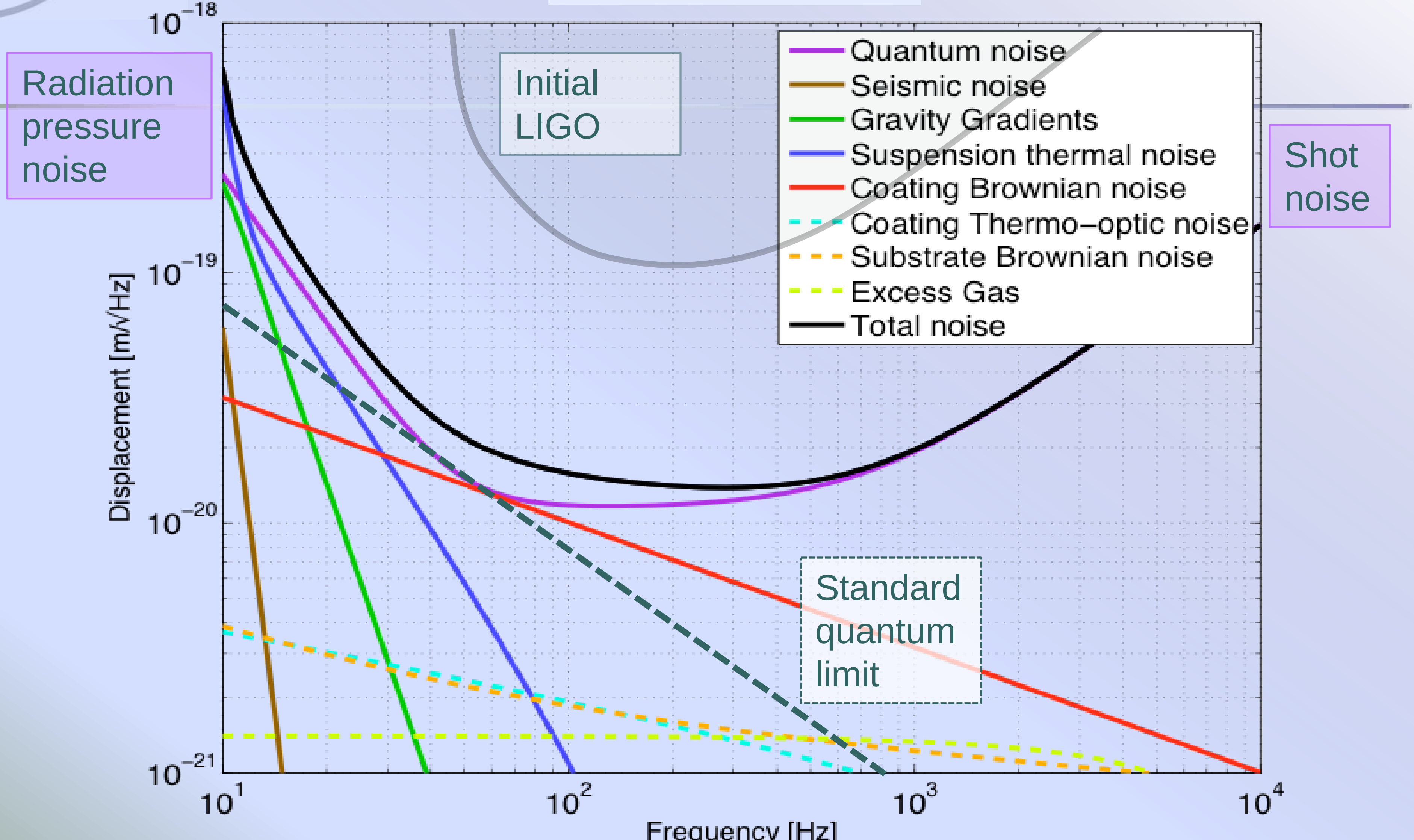
Gravitational Waves



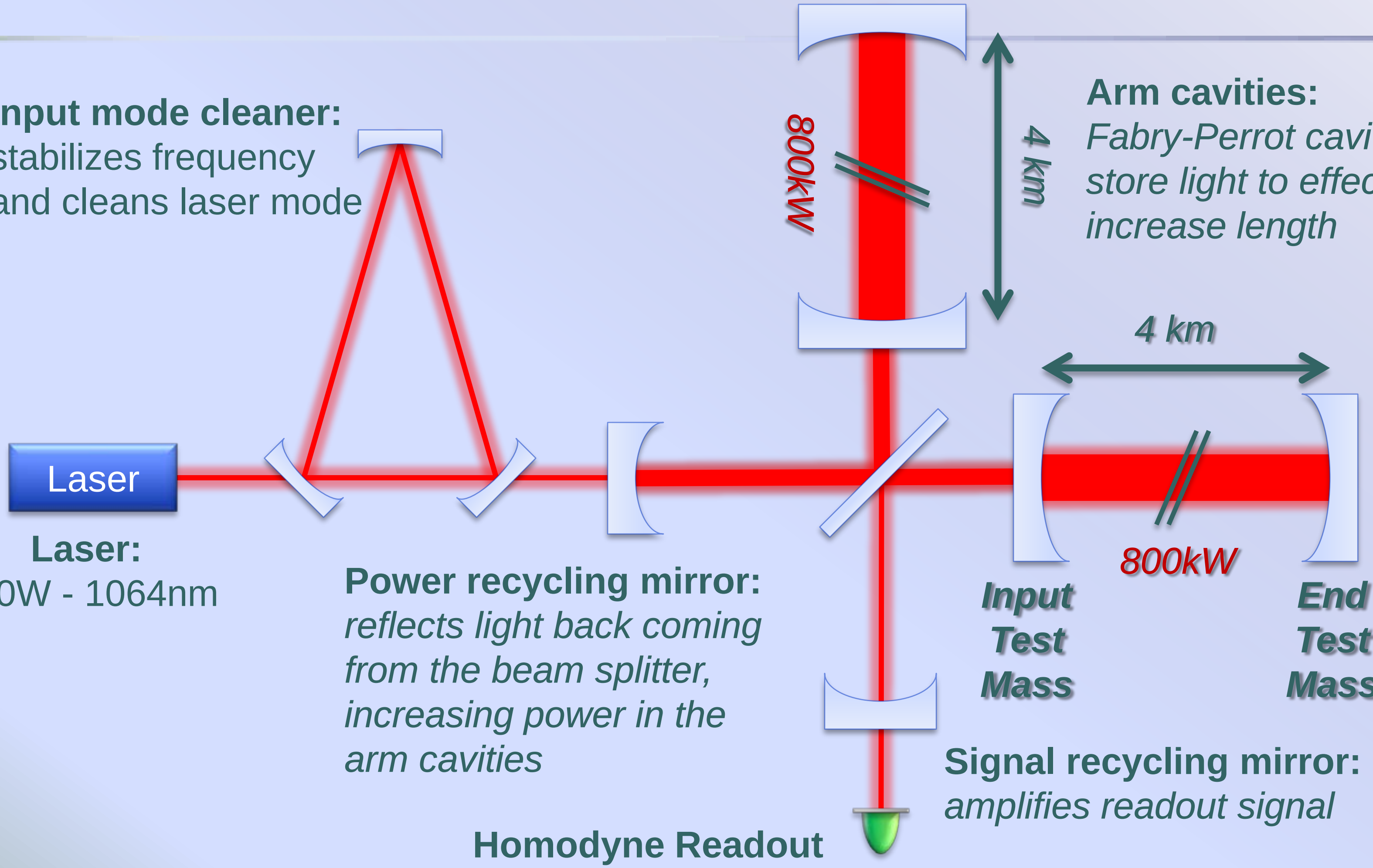
Sensitivity Sixth Science Run



Advanced LIGO Sensitivity



The Advanced LIGO Detector



Input mode cleaner: stabilizes frequency and cleans laser mode

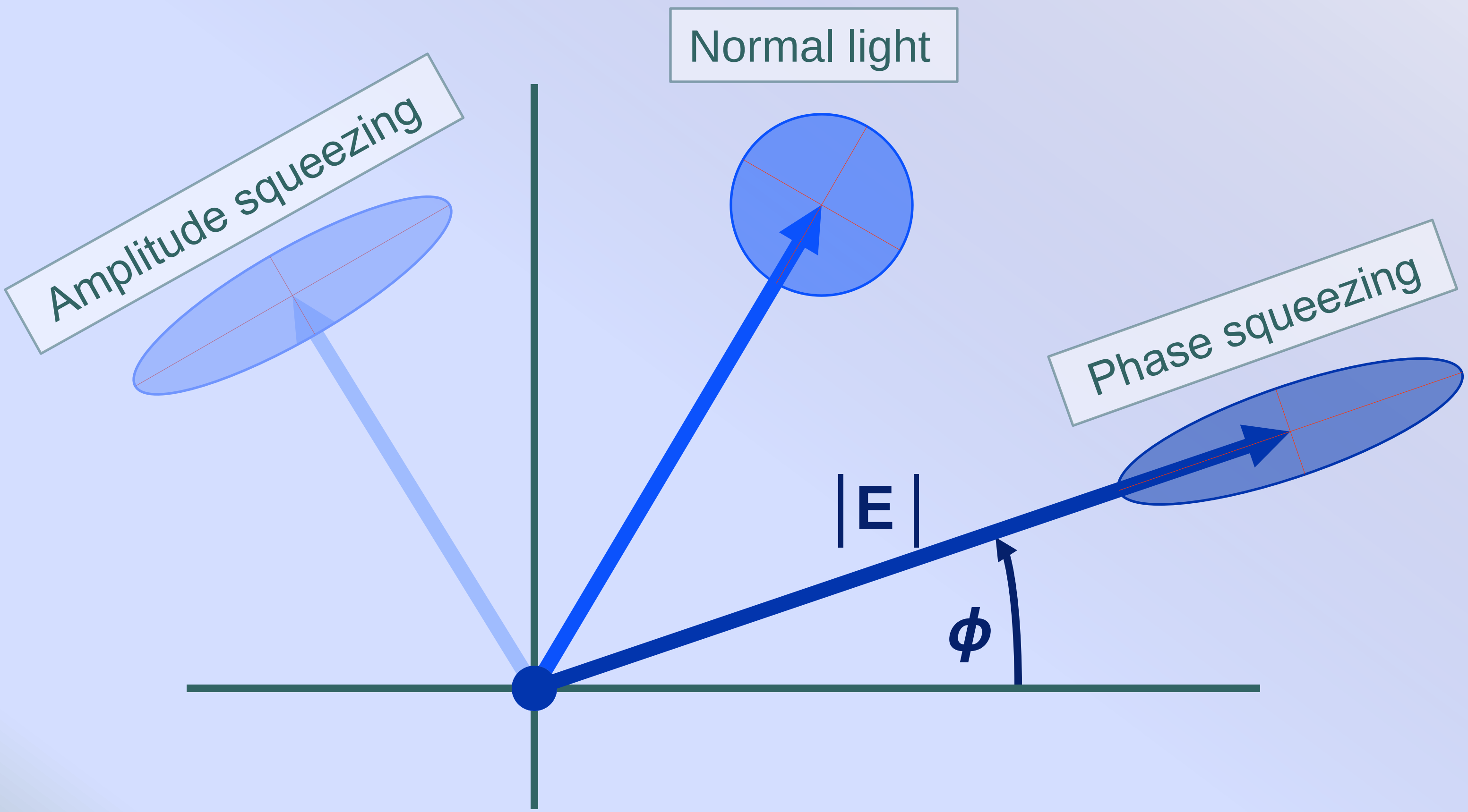
Arm cavities: *Fabry-Perrot cavities store light to effectively increase length*

Laser: 200W - 1064nm

Power recycling mirror: *reflects light back coming from the beam splitter, increasing power in the arm cavities*

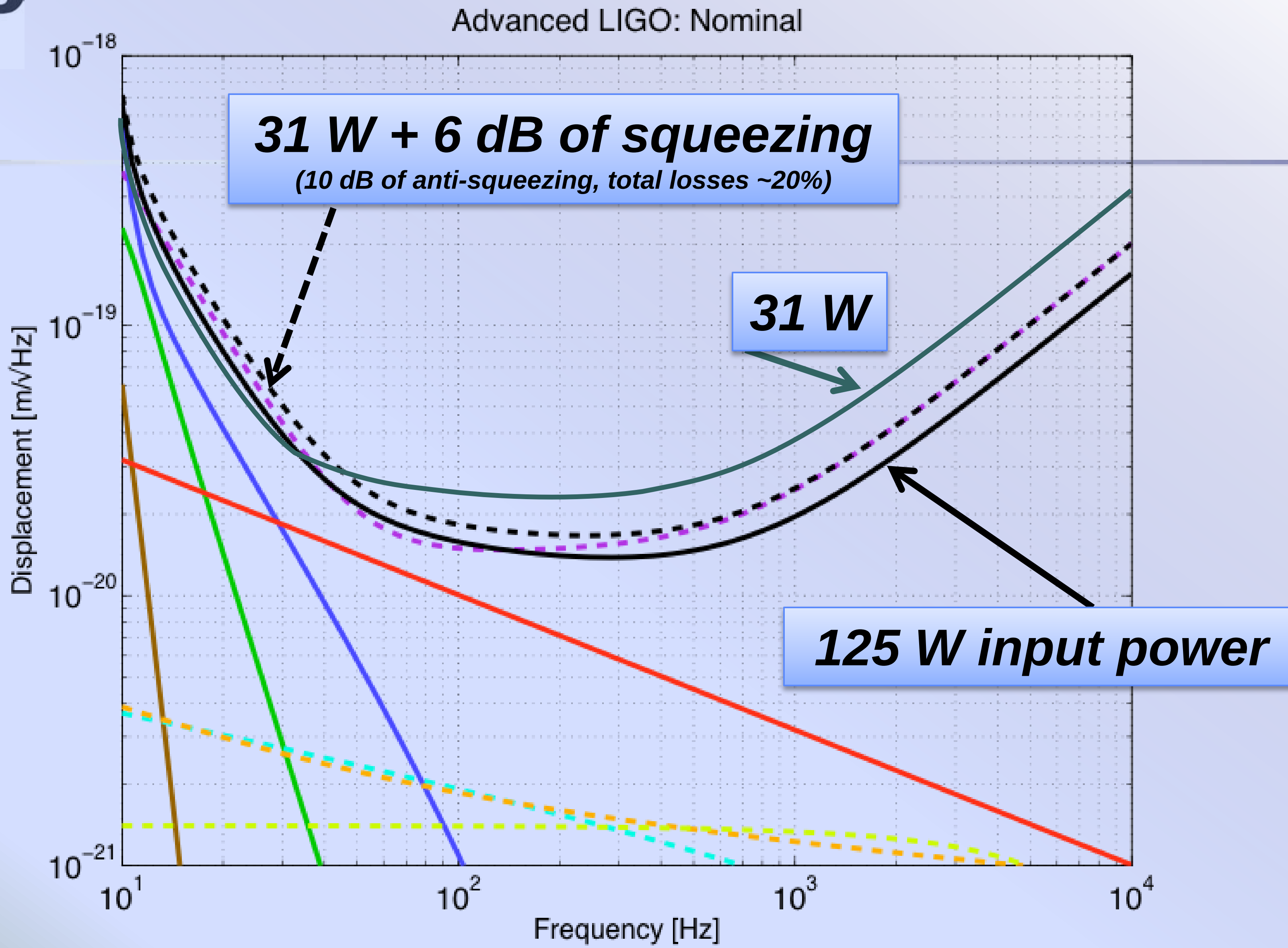
Signal recycling mirror: *amplifies readout signal*

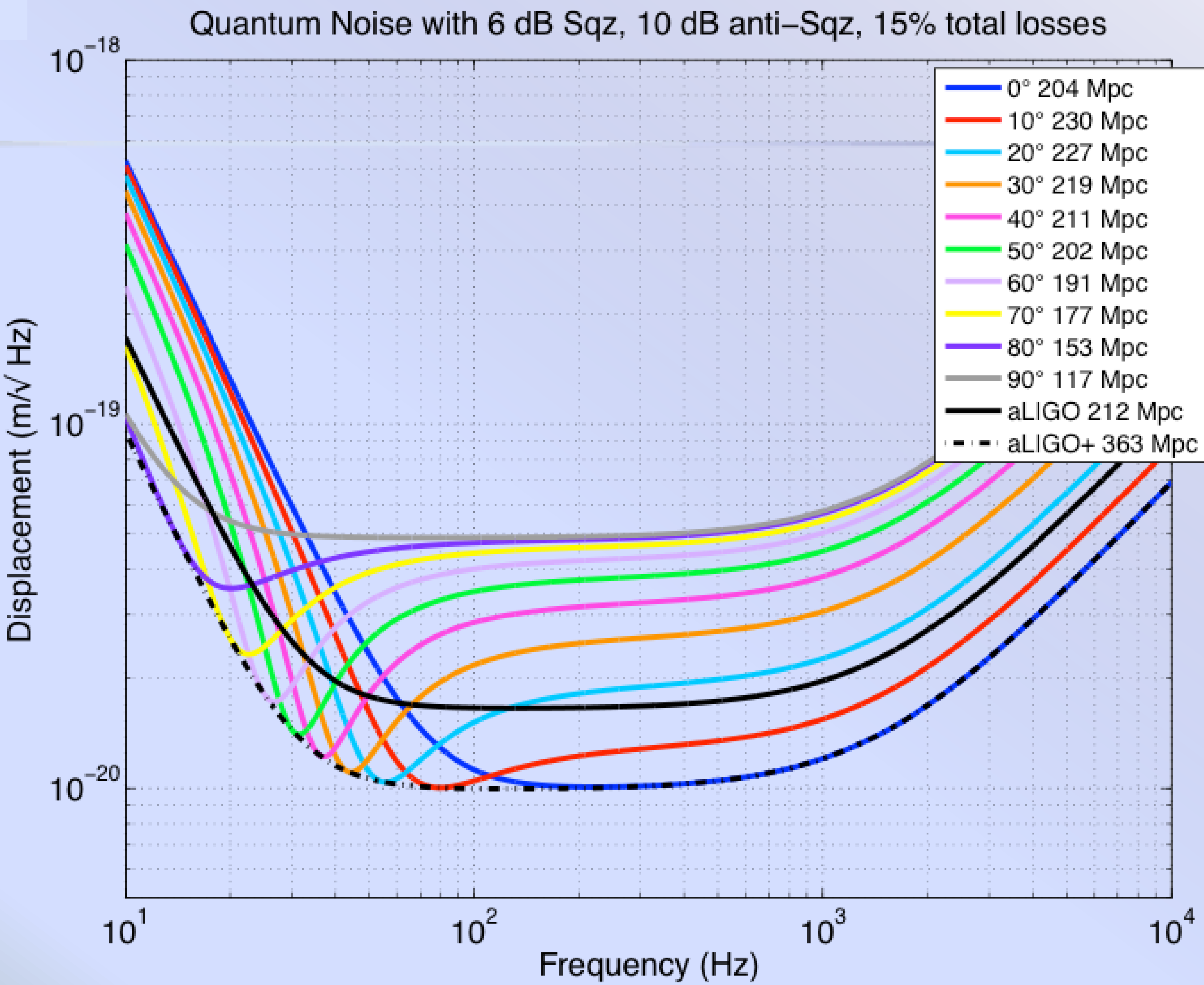
Squeezed Light



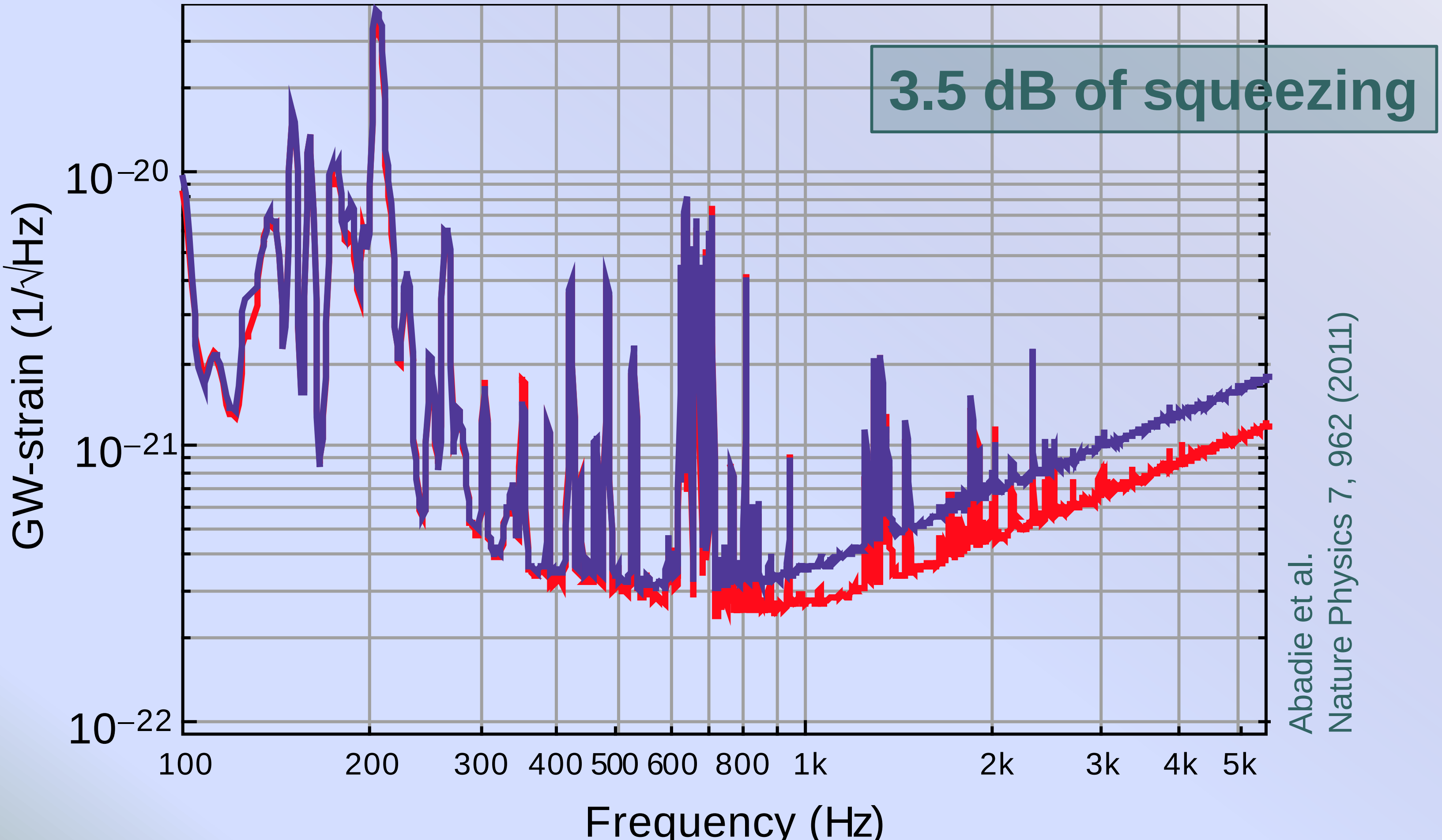
Key Insights

- 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}

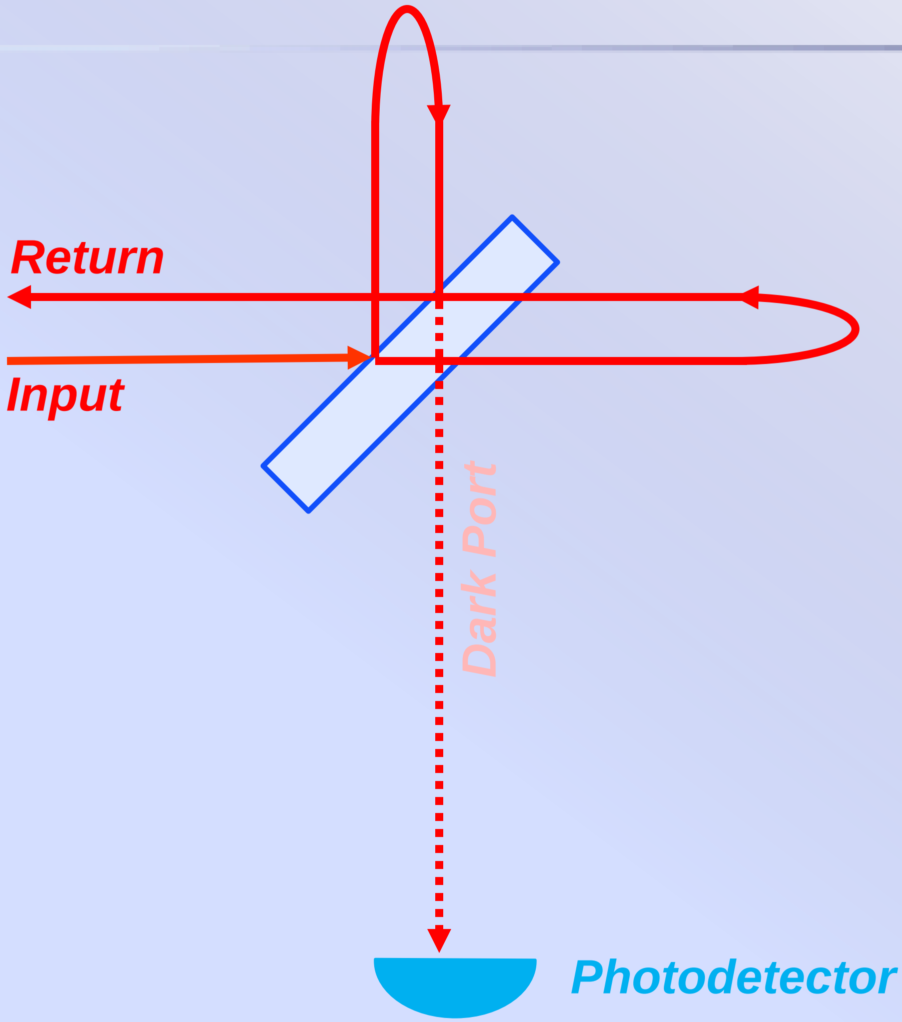

Quantum Noise with 6 dB Sqz, 10 dB anti–Sqz, 15% total losses
Displacement (m/√ Hz)
Frequency (Hz)
10^{-18}
10^{-19}
10^{-20}
10^{1}
10^{2}
10^{3}
10^{4}
0° 204 Mpc
10° 230 Mpc
20° 227 Mpc
30° 219 Mpc
40° 211 Mpc
50° 202 Mpc
60° 191 Mpc
70° 177 Mpc
80° 153 Mpc
90° 117 Mpc
aLIGO 212 Mpc
aLIGO+ 363 Mpc

Experimental Confirmation at the GEO600 Detector



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

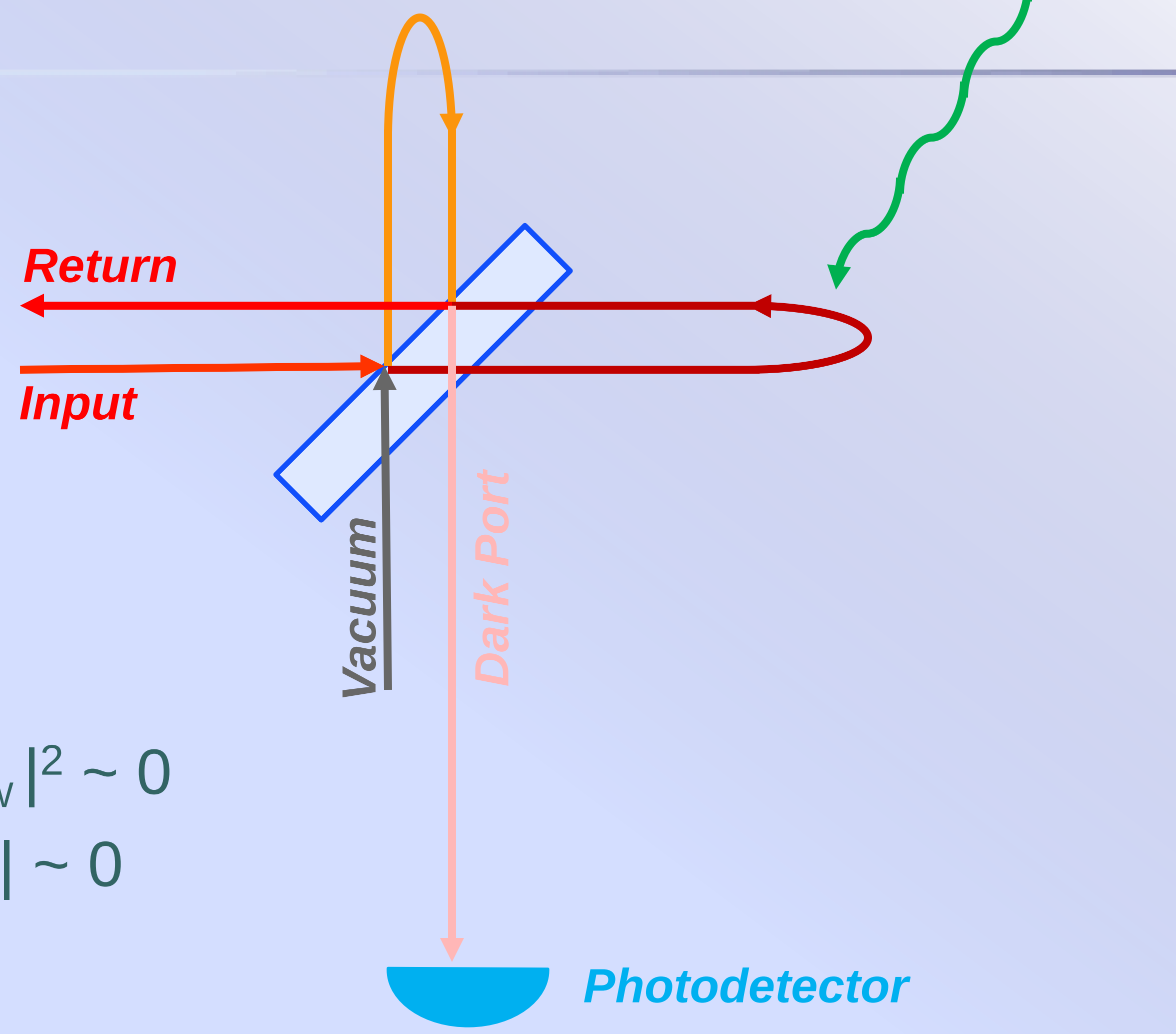
The Beamsplitter



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

Noise = 0

The Beamsplitter

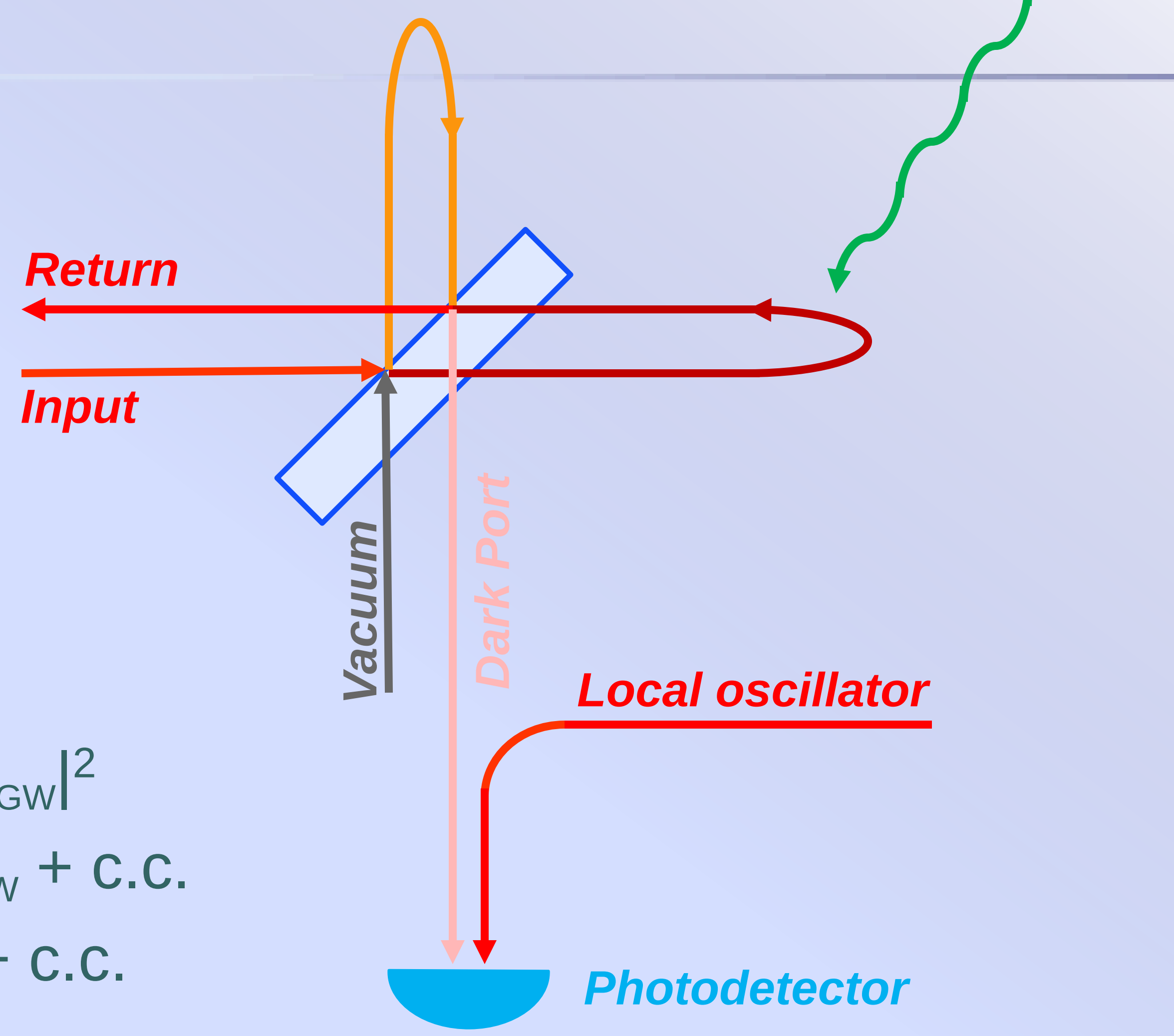


$E_{vac} = 0 + \tilde{e}_{vac}$

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

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

The Beamsplitter



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

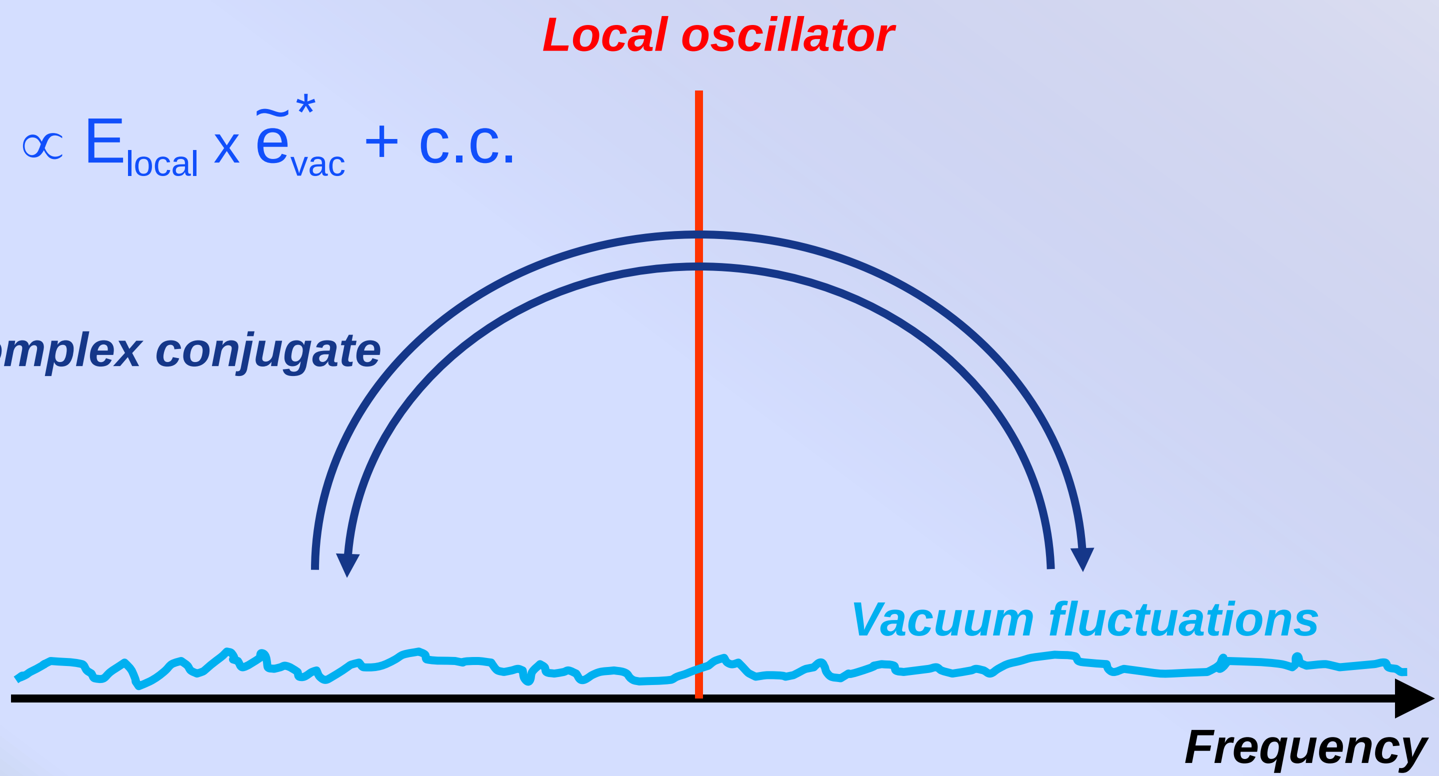
$\text{Signal} \propto |E_{local} + \Delta E_{GW}|^2$

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

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

In Fourier Space

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



Generating Squeezed "Vacuum"

- Need an operation that applies

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

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

- 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:

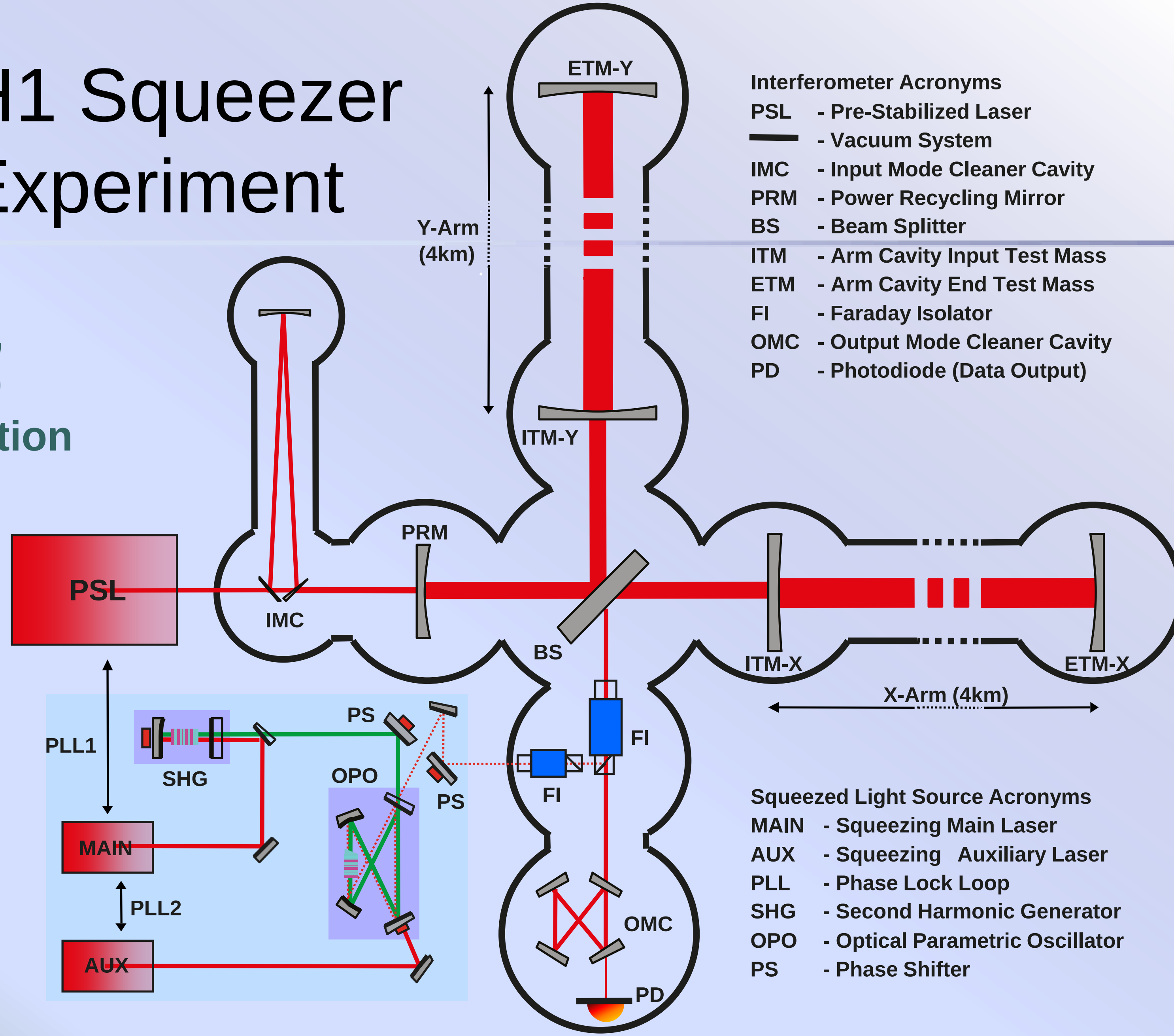
- Demonstrate 3dB of squeezing at the initial LIGO sensitivity
- Don't degrade low frequency sensitivity
- Risk mitigation for high power operations
- Pathfinder for advanced LIGO squeezer

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

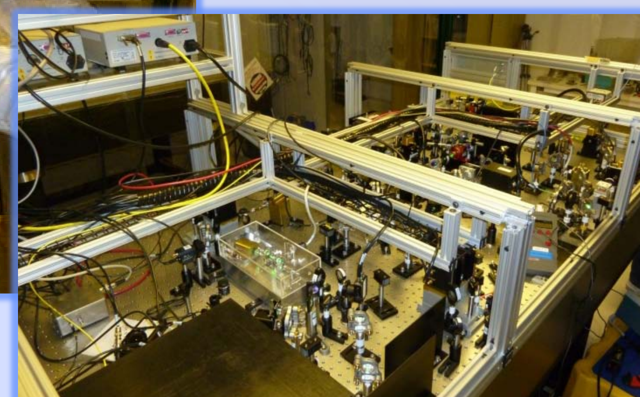
- PSL - Pre-Stabilized Laser
- (thick line) - Vacuum System
- IMC - Input Mode Cleaner Cavity
- PRM - Power Recycling Mirror
- BS - Beam Splitter
- ITM - Arm Cavity Input Test Mass
- ETM - Arm Cavity End Test Mass
- FI - Faraday Isolator
- OMC - Output Mode Cleaner Cavity
- PD - Photodiode (Data Output)

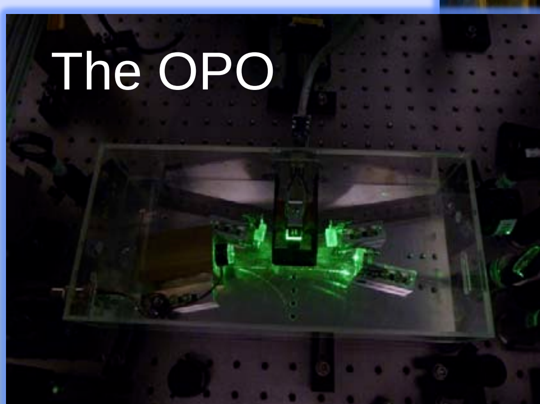
Squeezed Light Source Acronyms

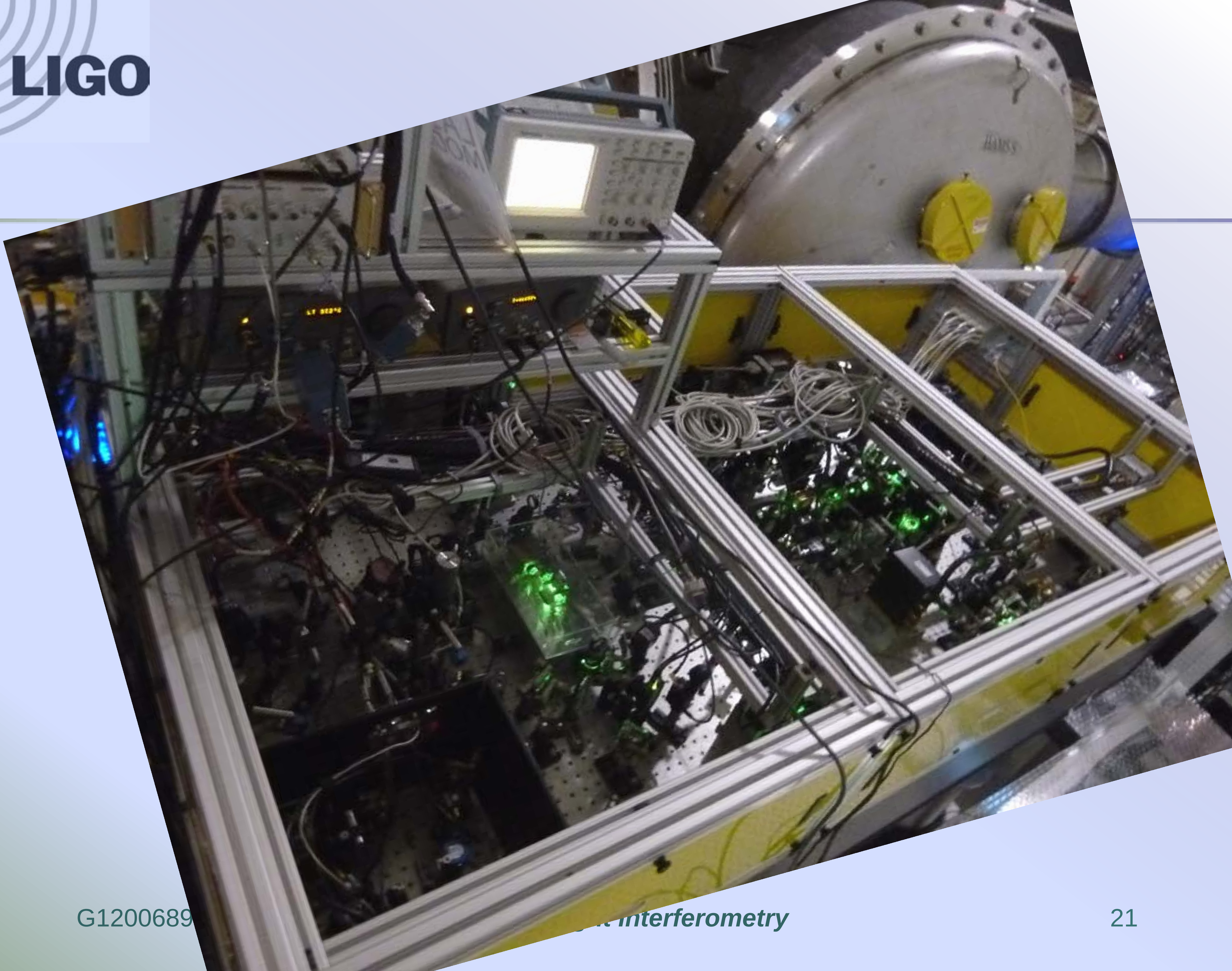
- MAIN - Squeezing Main Laser
- AUX - Squeezing Auxiliary Laser
- PLL - Phase Lock Loop
- SHG - Second Harmonic Generator
- OPO - Optical Parametric Oscillator
- PS - Phase Shifter

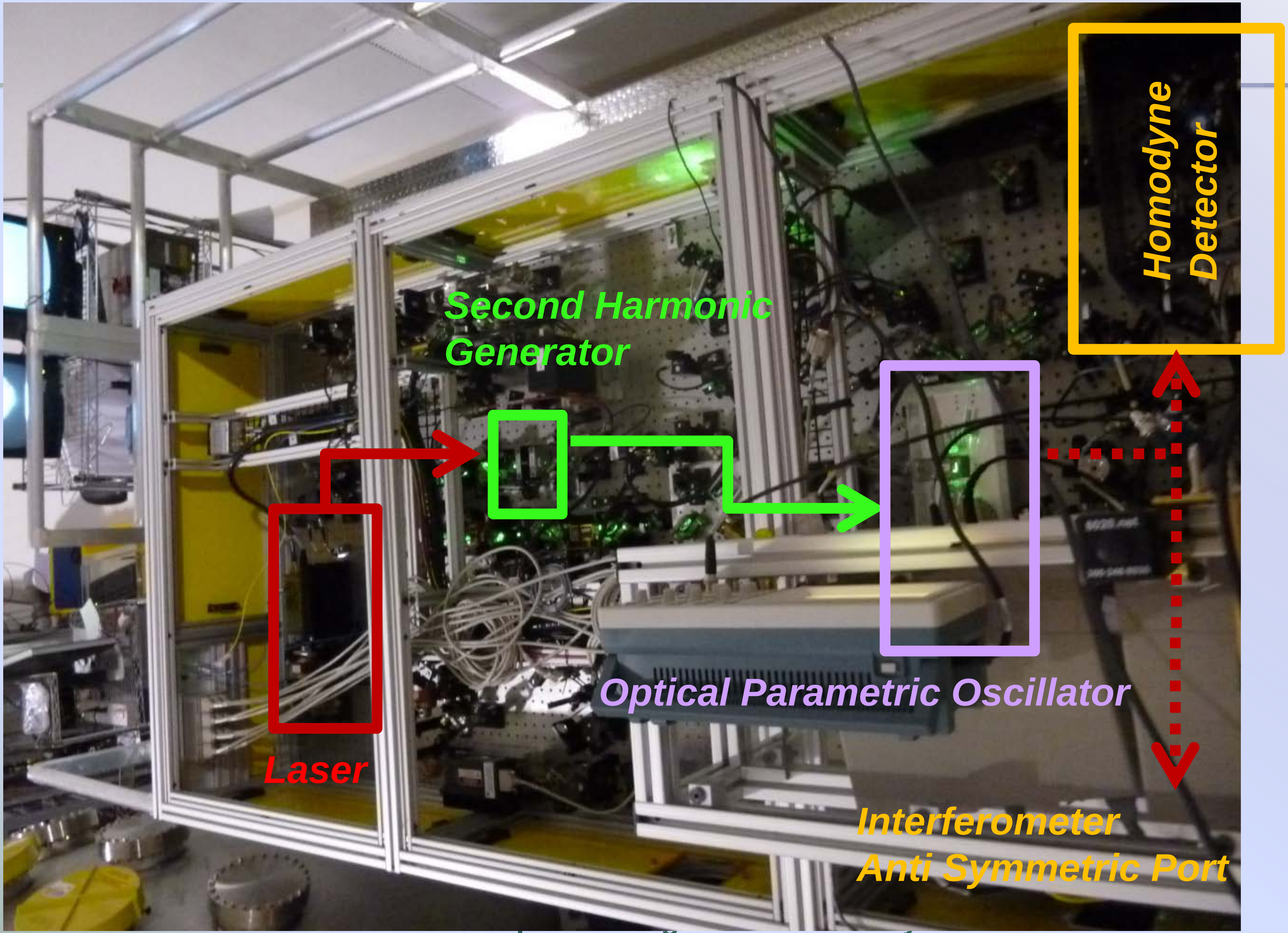
Squeezer at Hanford

Optics Table

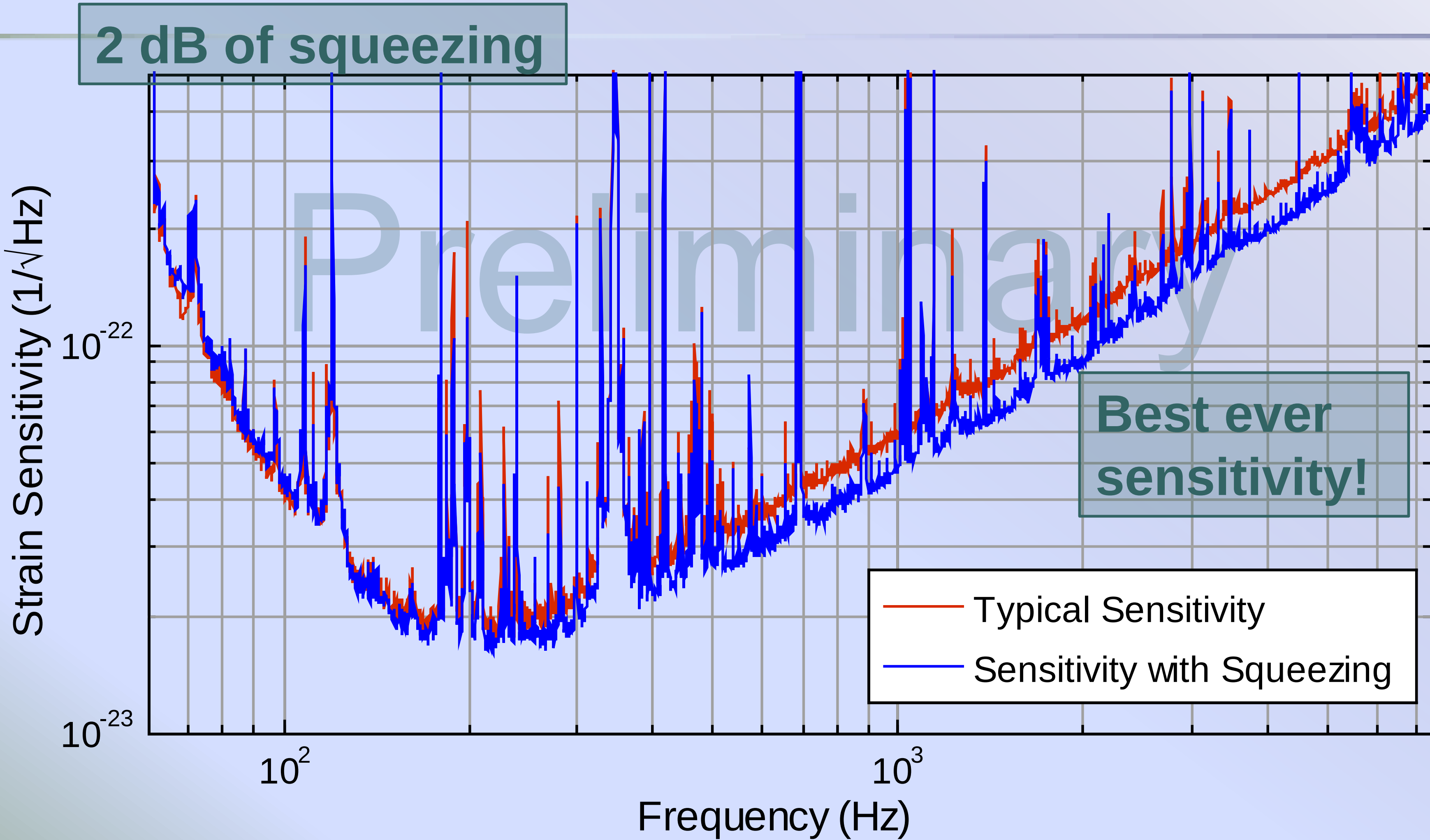






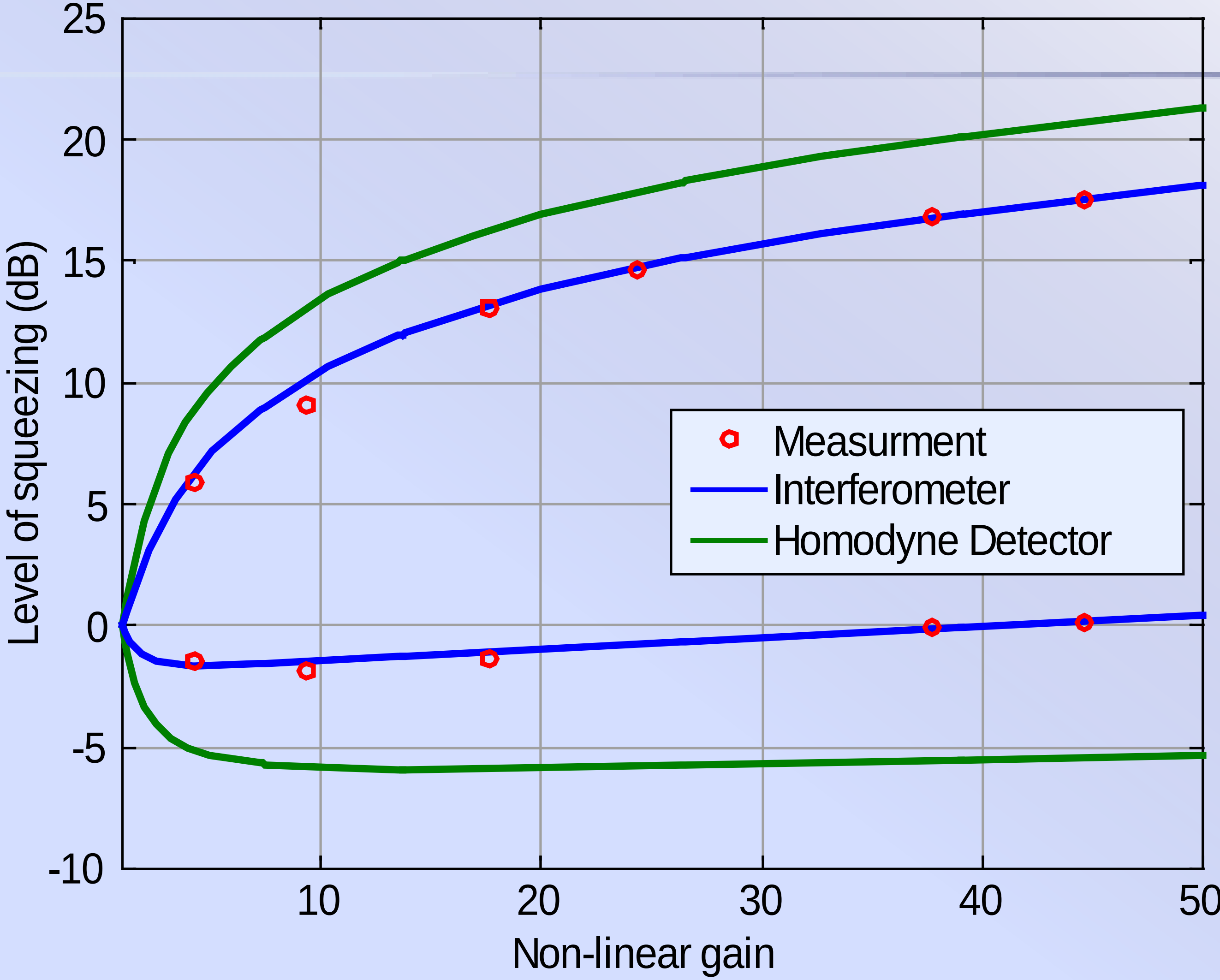

Homodyne
Detector
Second Harmonic
Generator
Laser
Optical Parametric Oscillator
Interferometer
Anti Symmetric Port

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)

Non-Linear Gain



61% loss
5º phase noise

19% loss
1.3º phase noise

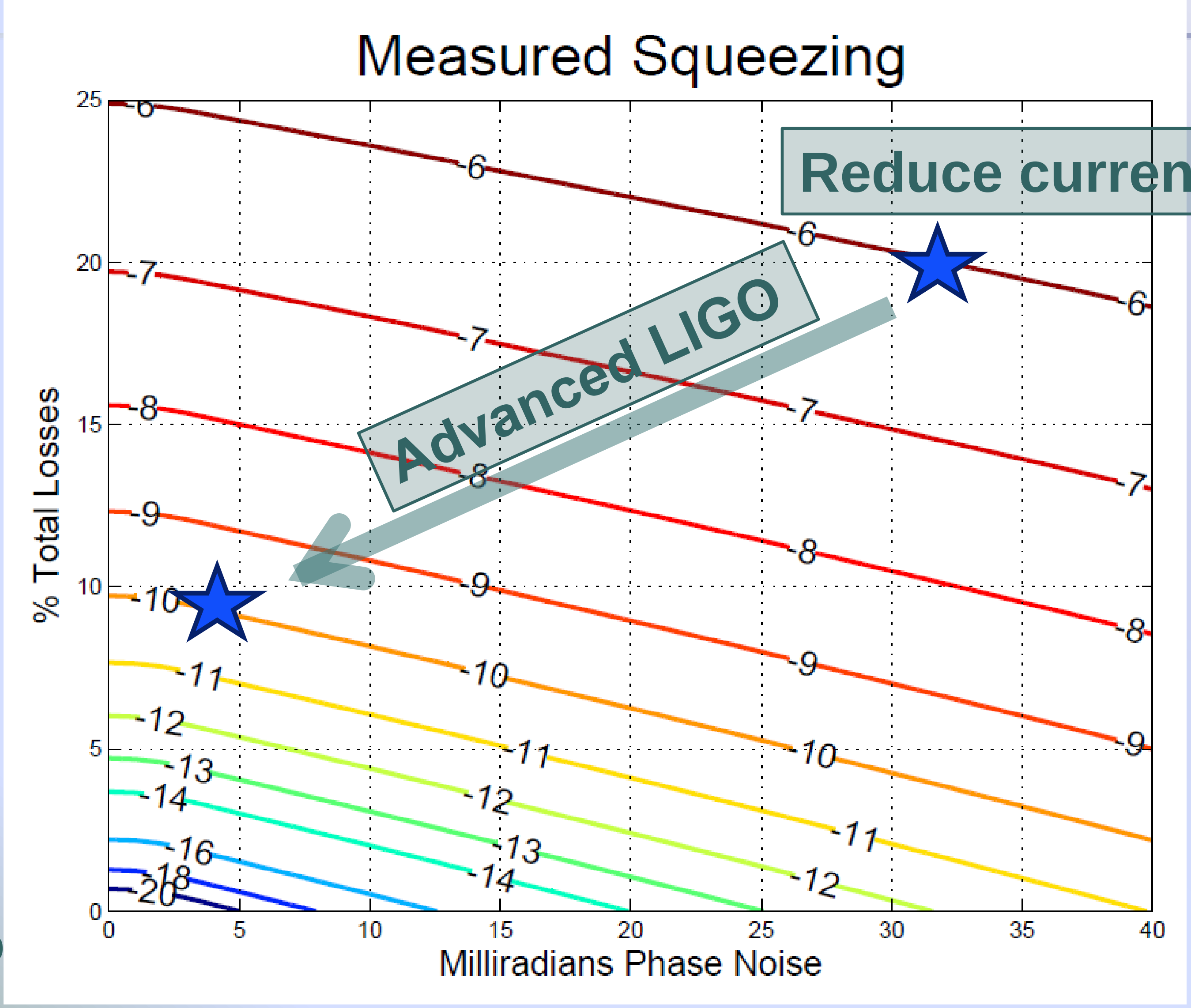
	Now	Near future	Advanced LIGO
3 Faraday passes	5% each	3% each	Aim for less than 10% total
Signal recycling cavity@100 Hz		2.5% (T=35%)	
Squeezer mode matching to OMC	30%	4%	
OMC transmission	19%	1%	
Total losses	55-60%	20%	
Detected Squeezing	2+dB	6dB	10-15dB

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 ETMY SPOOL
4K ITMY
05:52:38e
09/13/11
4K ITMX
2011/09/12
2011/06/07 11:4