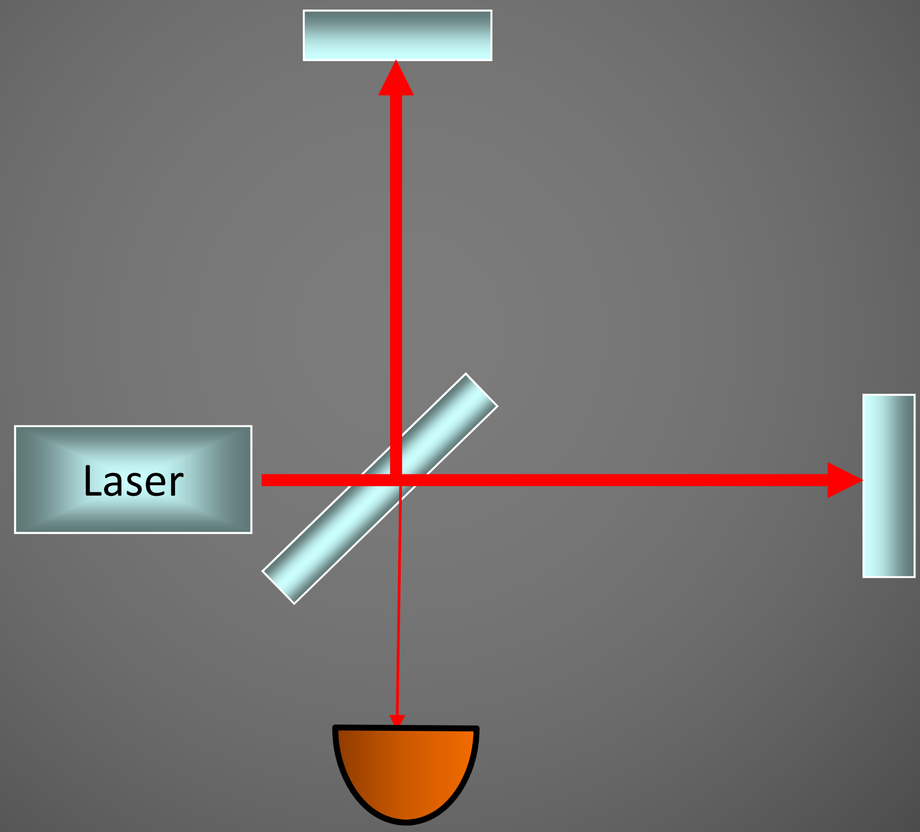
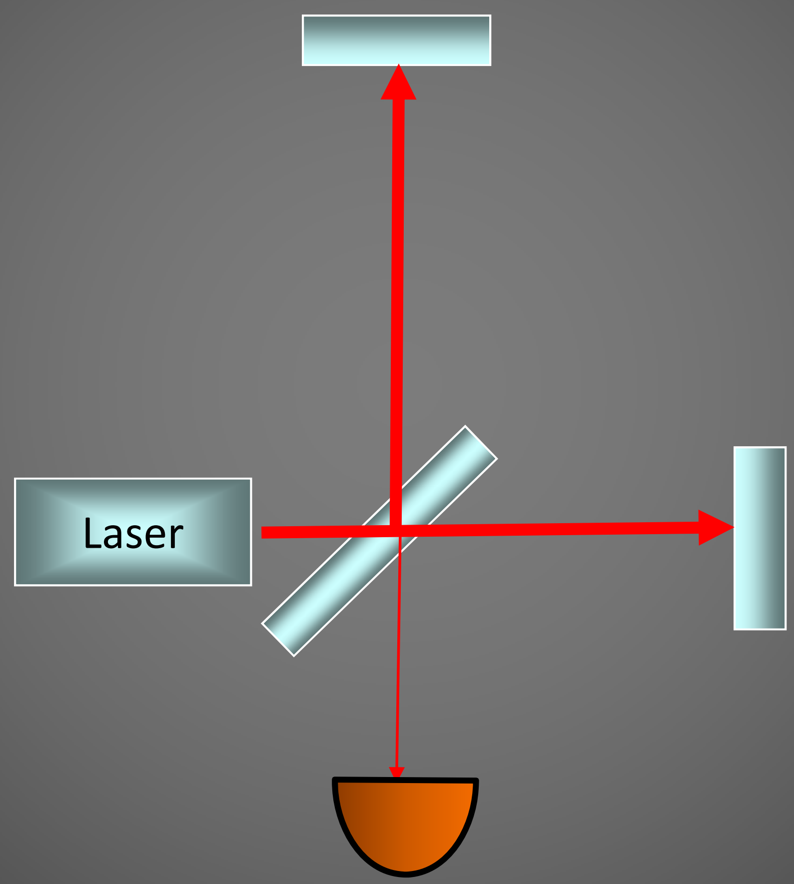
Quantum noise reduction using squeezed states in LIGO

- LIGO interferometers, quantum light and quantum noise
- Generation and detection of squeezing
- Squeezing in Enhanced LIGO
- Environmental noise couplings
- Limits to the level of squeezing
  - Losses
  - Squeezing angle fluctuations
- Potential benefit for Advanced LIGO and beyond

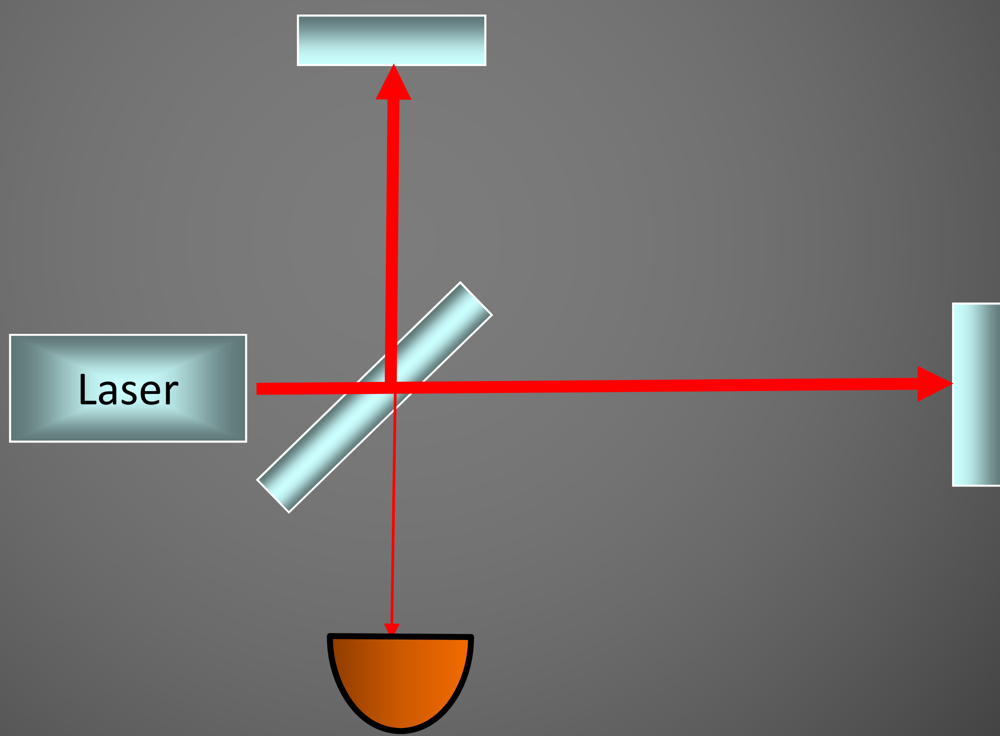
Michelson interferometer



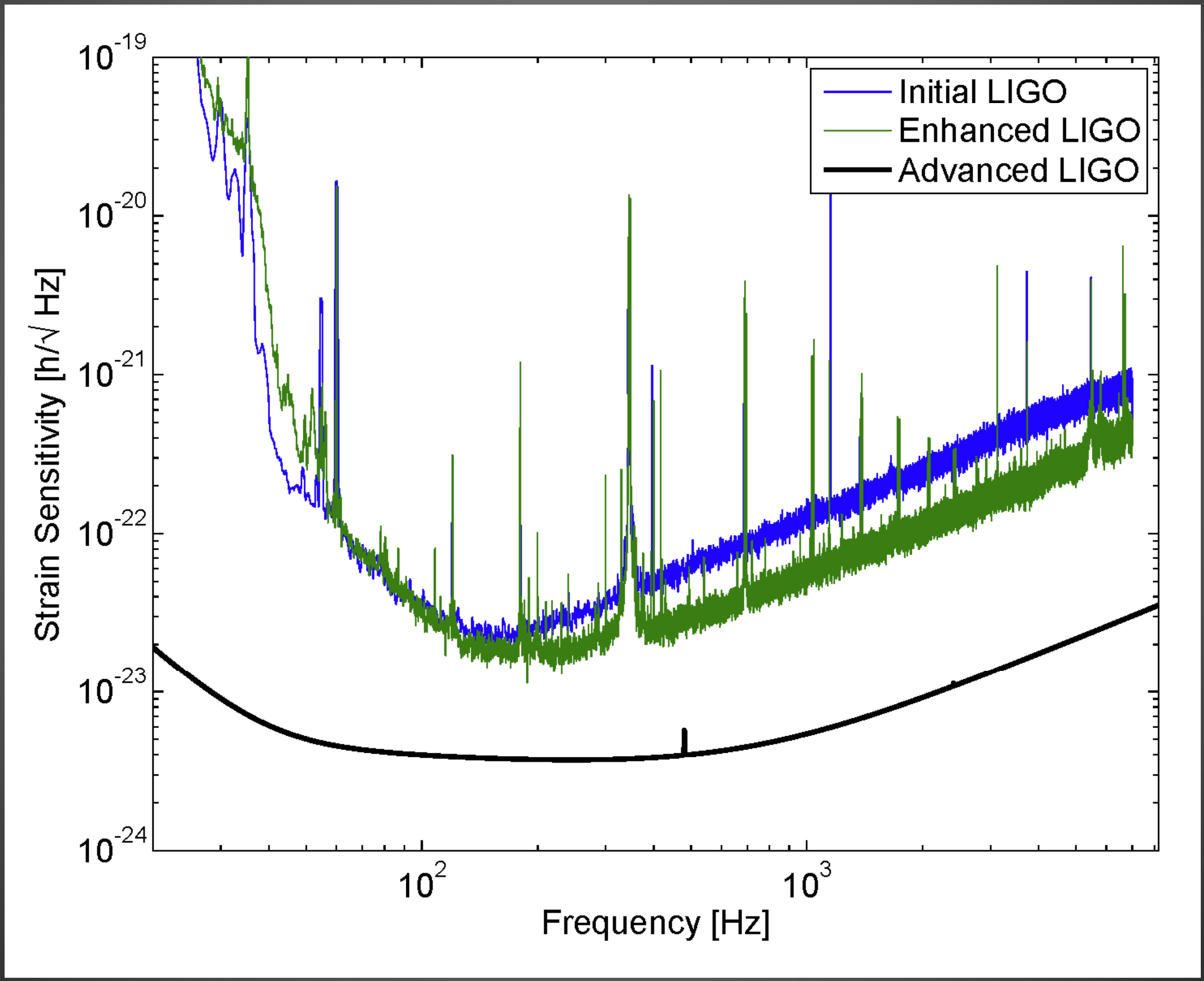
Michelson interferometer



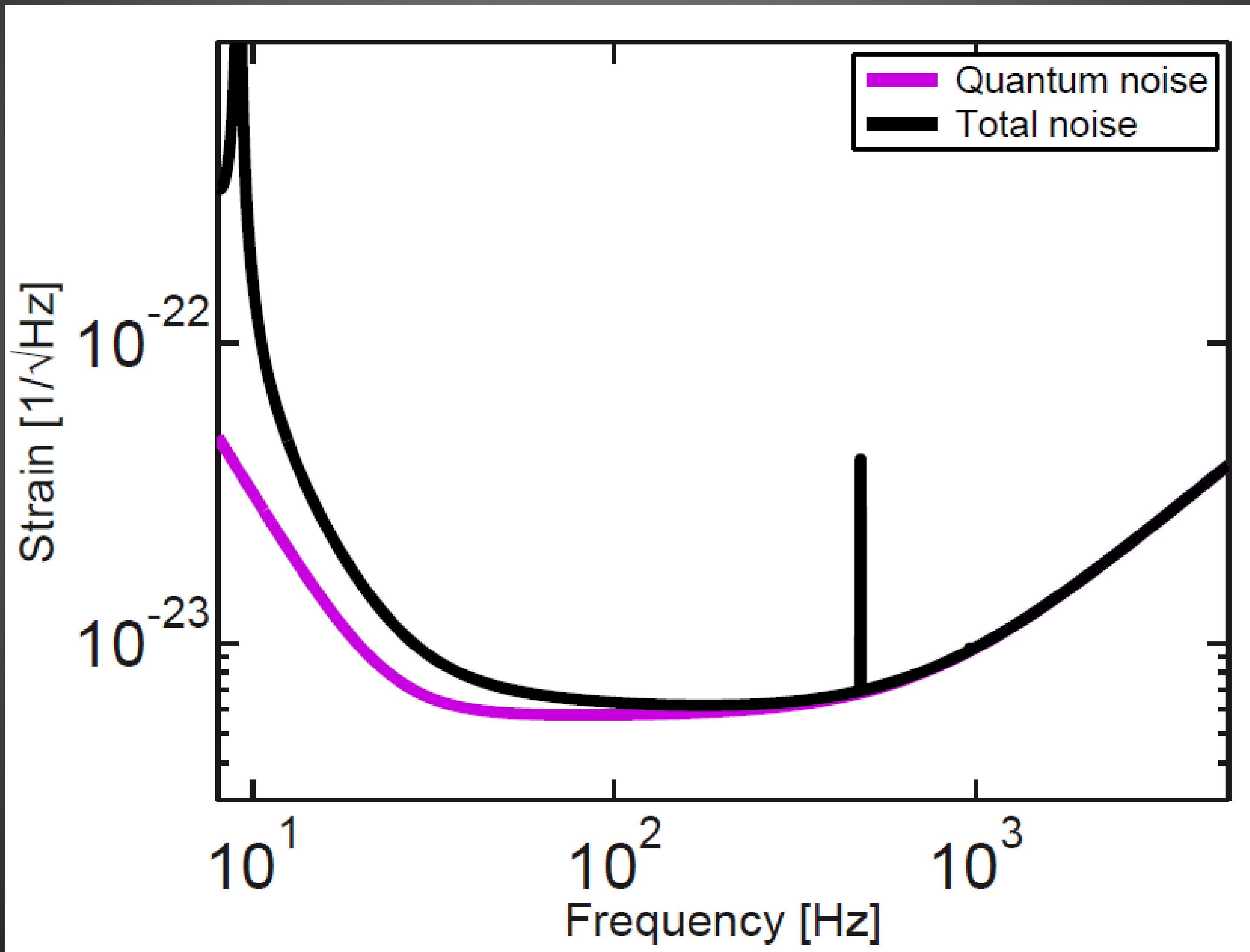
Michelson interferometer



LIGO interferometers



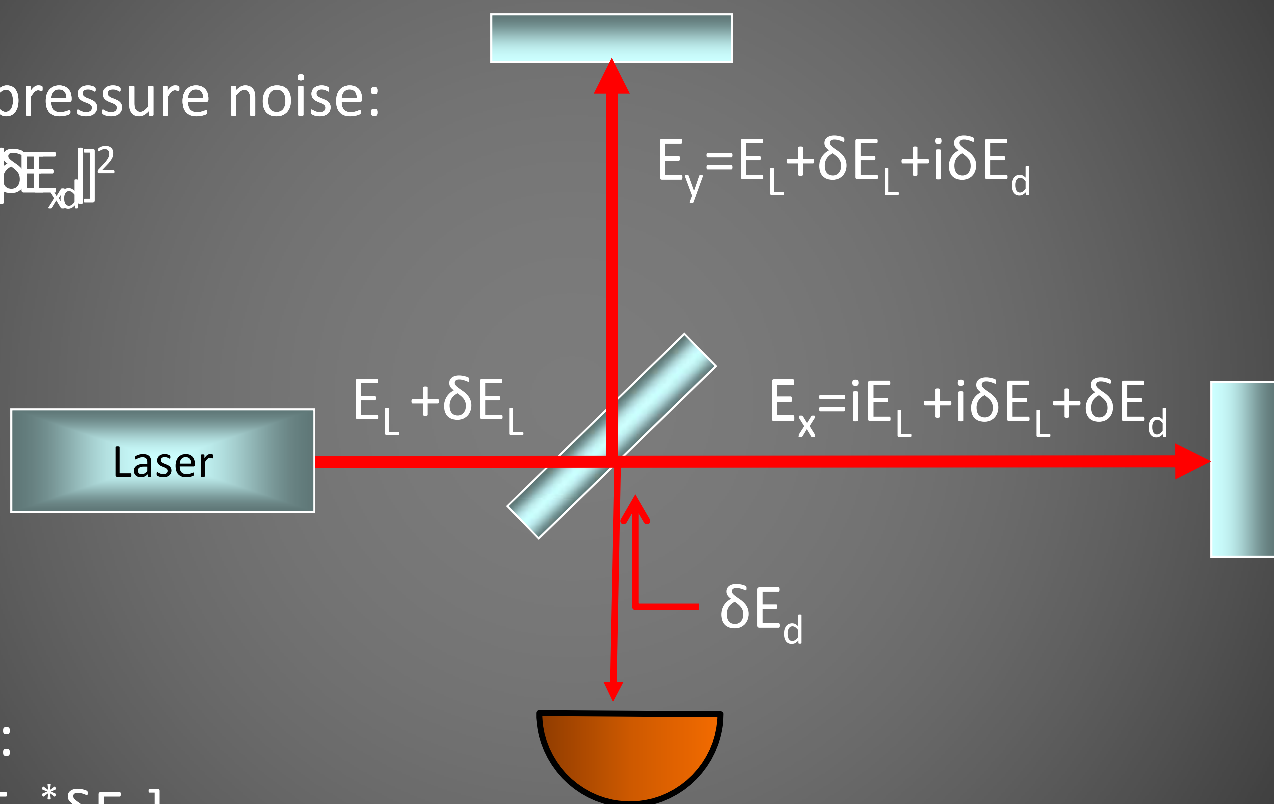
Need to reduce quantum noise



Quantum noise in an interferometer

Radiation pressure noise:

$\Delta F \, \alpha \, |E_y|^2 - |E_x|^2$ $\text{Im}[E_L^* \delta E_d]$



Shot noise:

$\delta I_{PD} \, \alpha \, \text{Re}[E_L^* \delta E_d]$

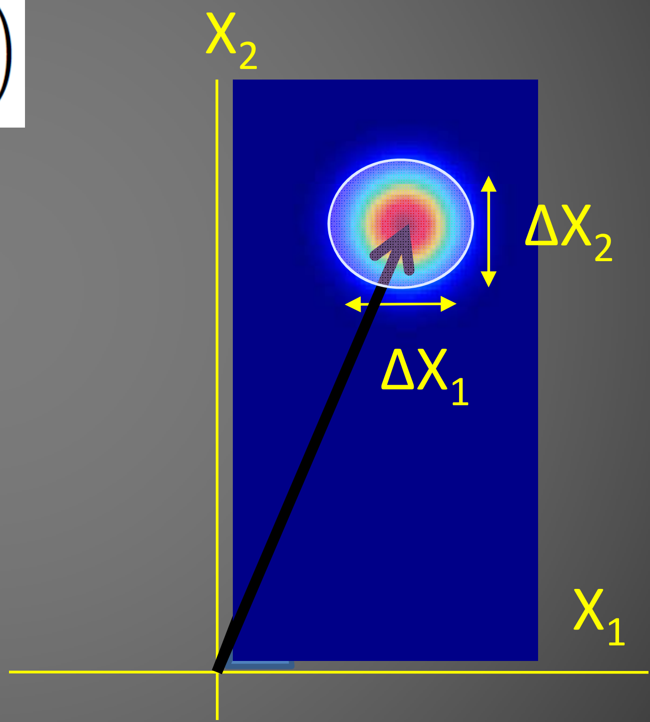
Shot noise limited sensitivity α $\text{Re}[\delta E_d]/E_L$

Quantum Light

$$\hat{E} = \varepsilon\left(\hat{X}_1 \cos\omega t + \hat{X}_2 \sin\omega t\right)$$

The uncertainty principle

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



Quantum Light

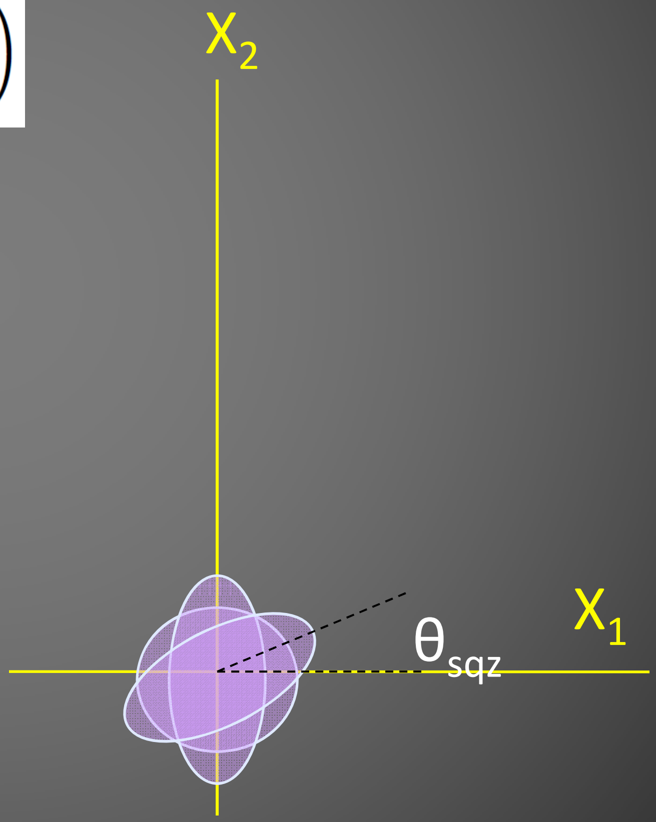
$$\hat{E} = \varepsilon \left(\hat{X}_1 \cos \omega t + \hat{X}_2 \sin \omega t \right)$$

The uncertainty principle

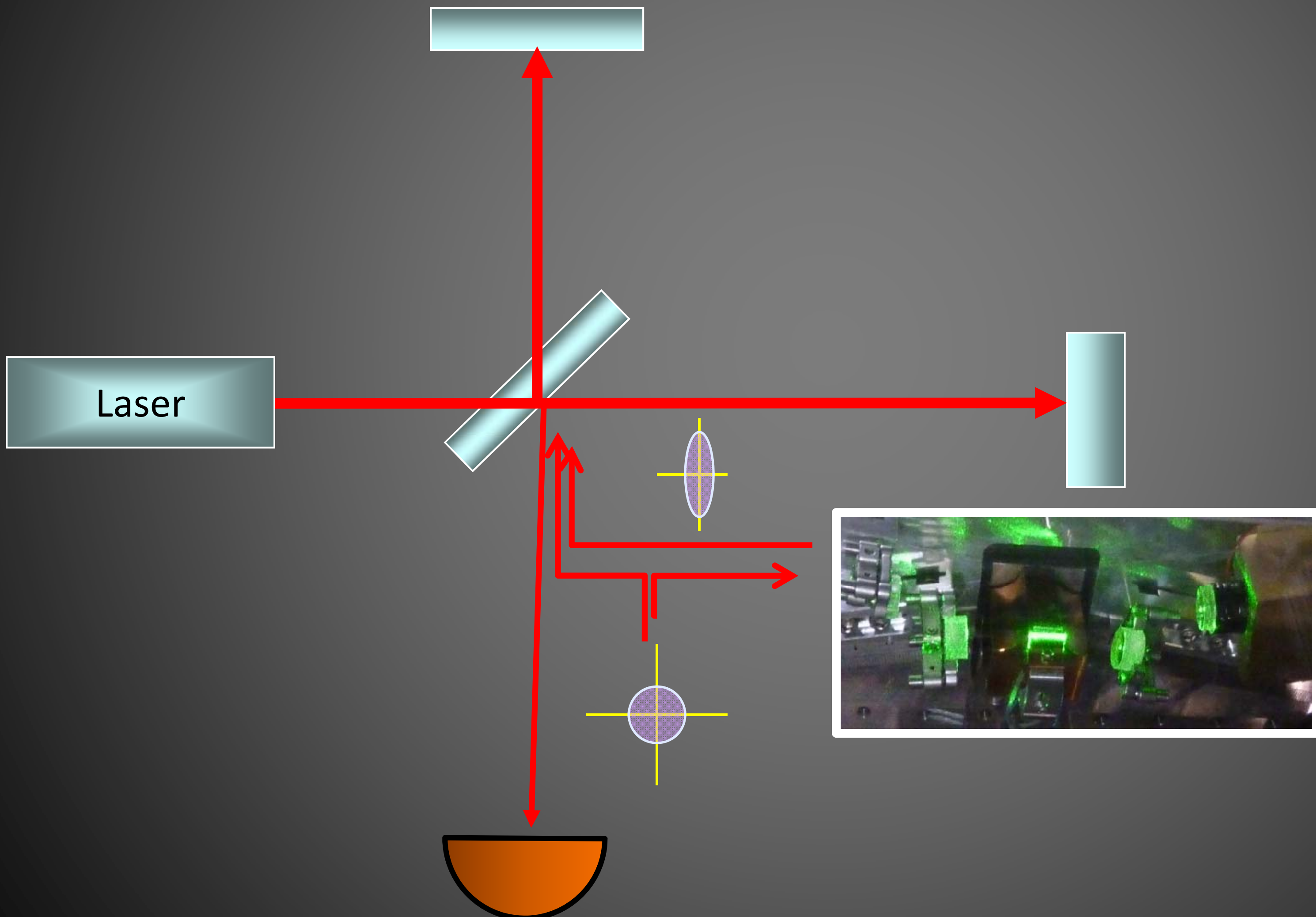
$$\Delta X_1 \, \Delta X_2 \geq 1$$

Vacuum fluctuations

Squeezed vacuum



Squeezing in an interferometer



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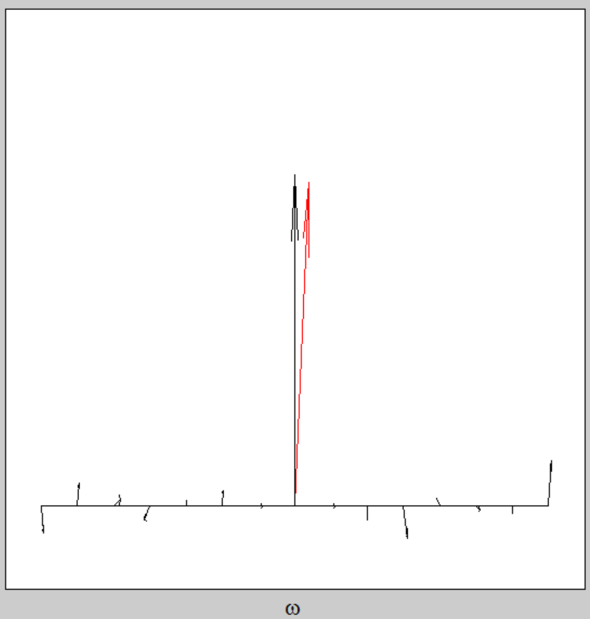
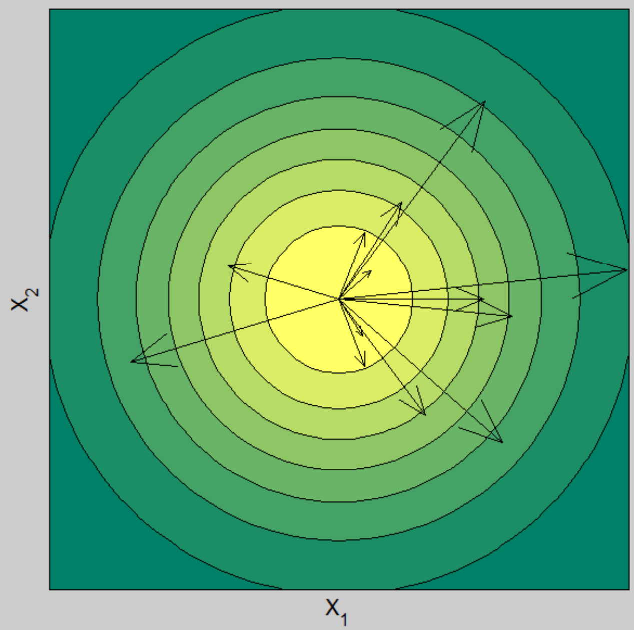
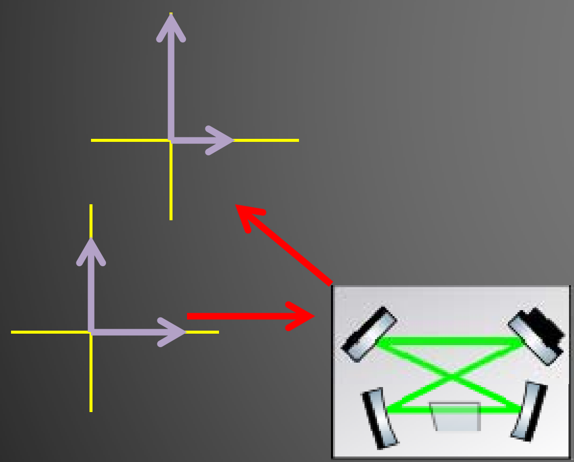
Vacuum and coherent states are sums of uncorrelated sidebands



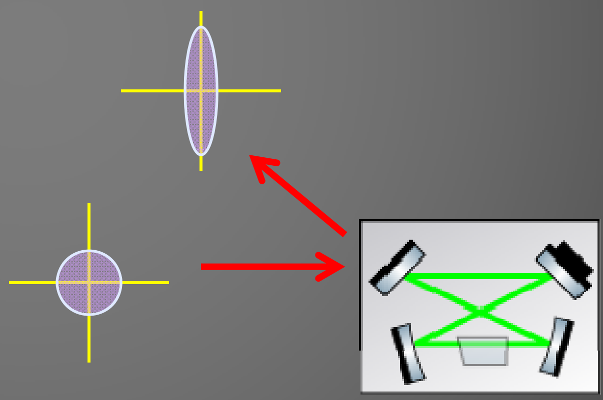


Squeezer: Optical parametric oscillator

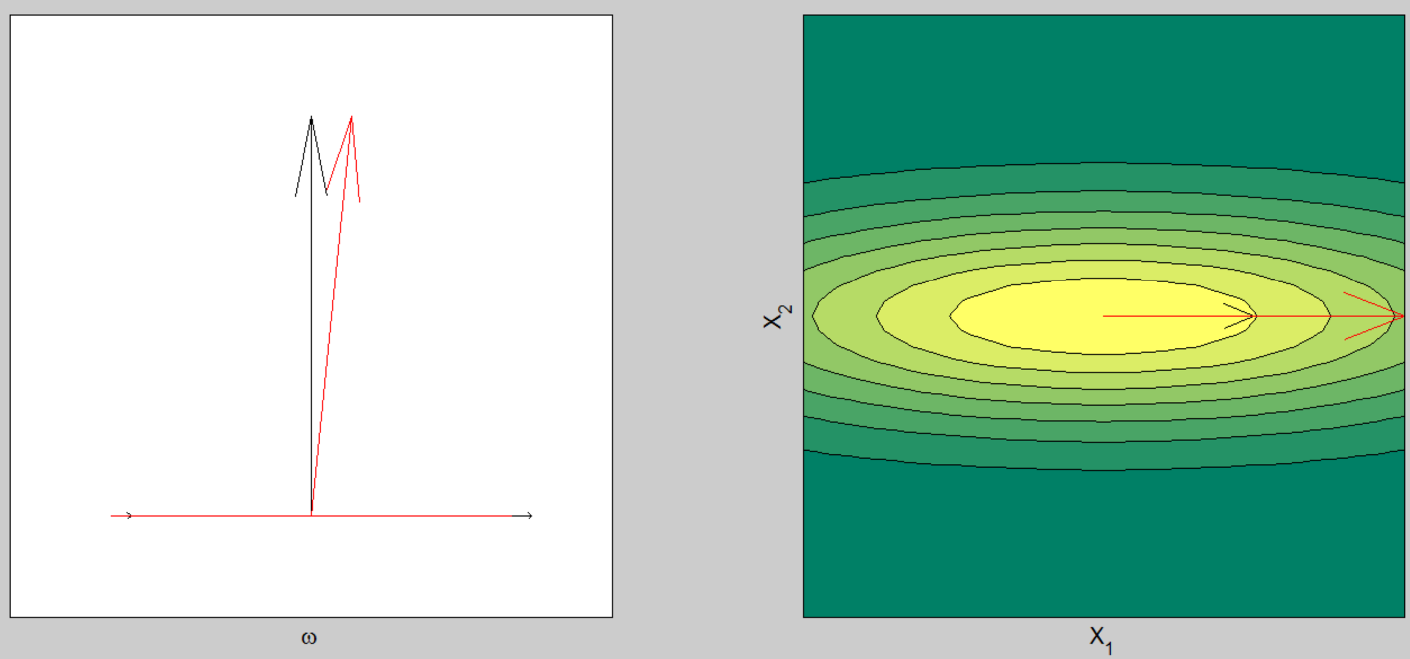
Classical OPO:
Phase sensitive amplifier



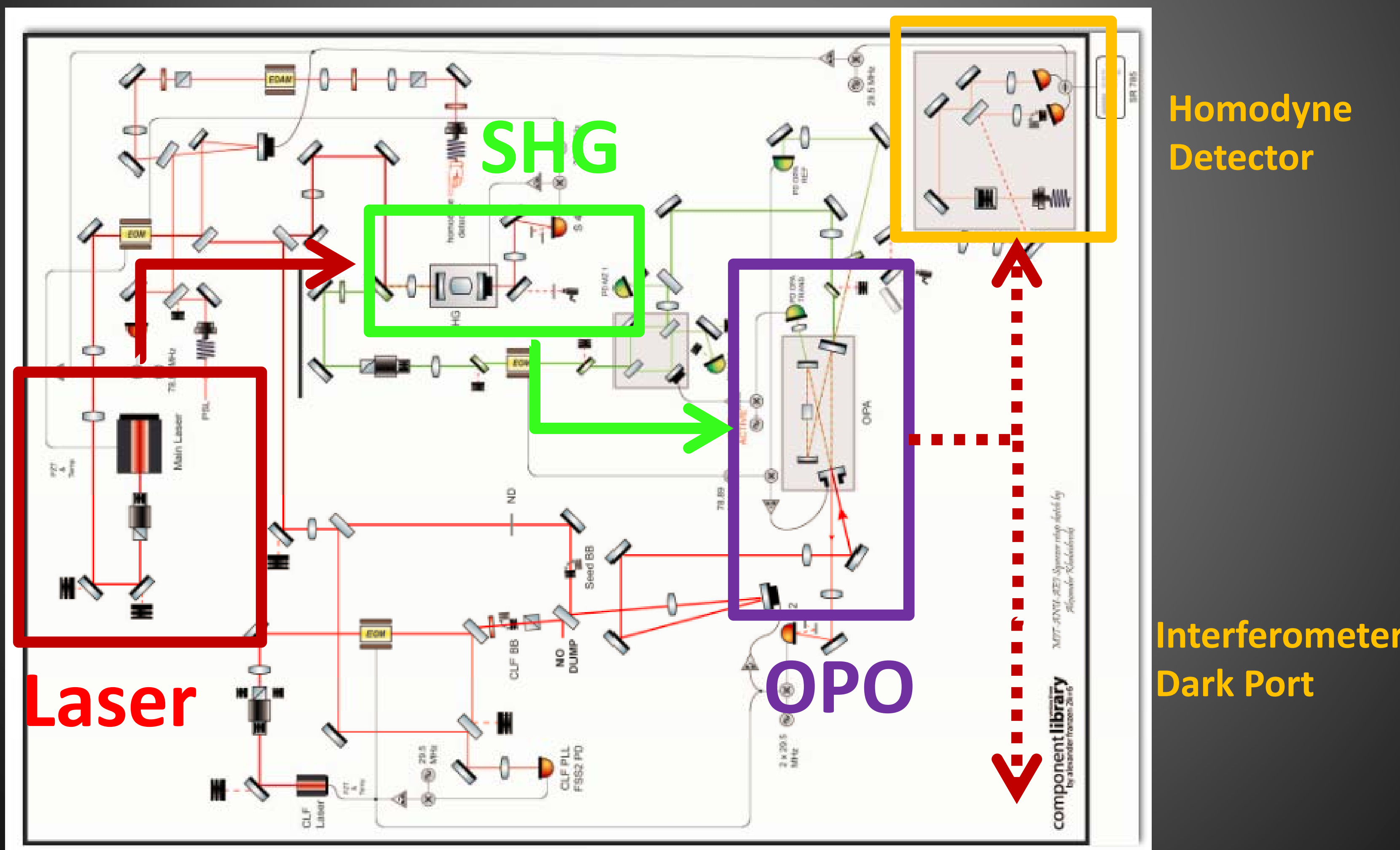
Quantum OPO:
Turns a vacuum state into
squeezed vacuum



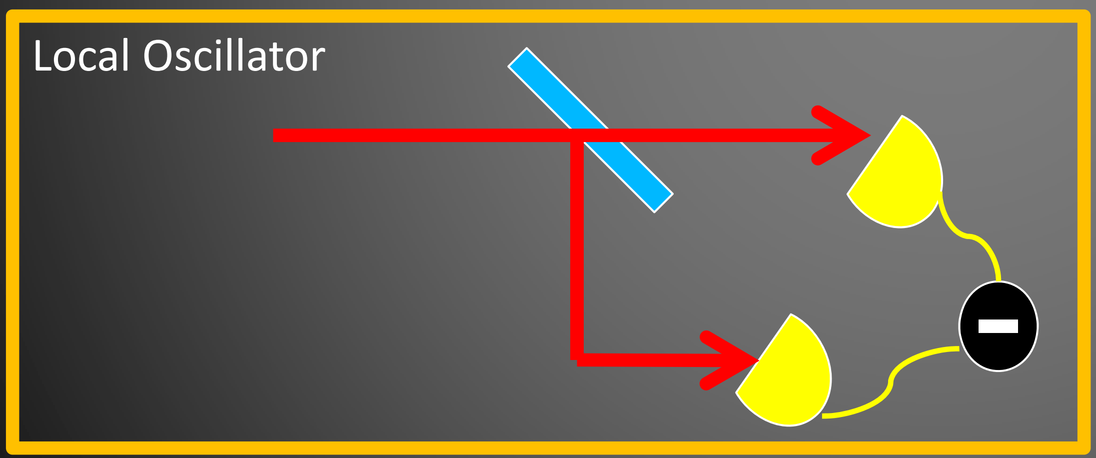
A squeezed state is a sum of correlated sidebands



A squeezer table



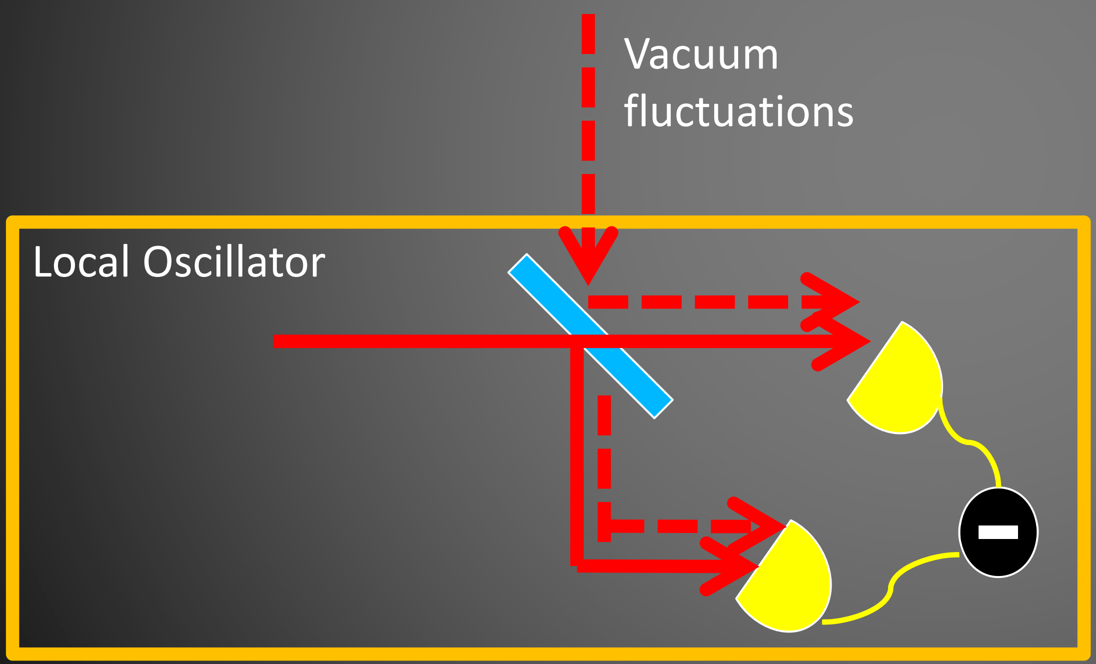
Balanced Homodyne Detection

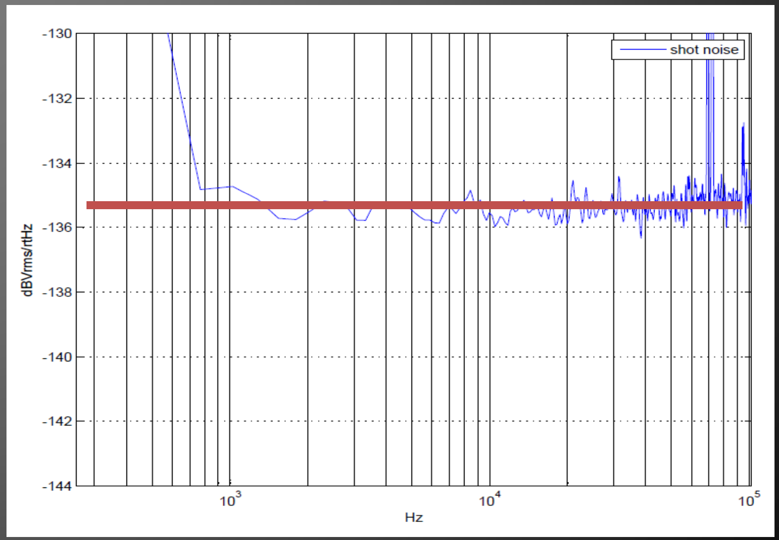


- Noise of local oscillator is subtracted

Balanced Homodyne Detection

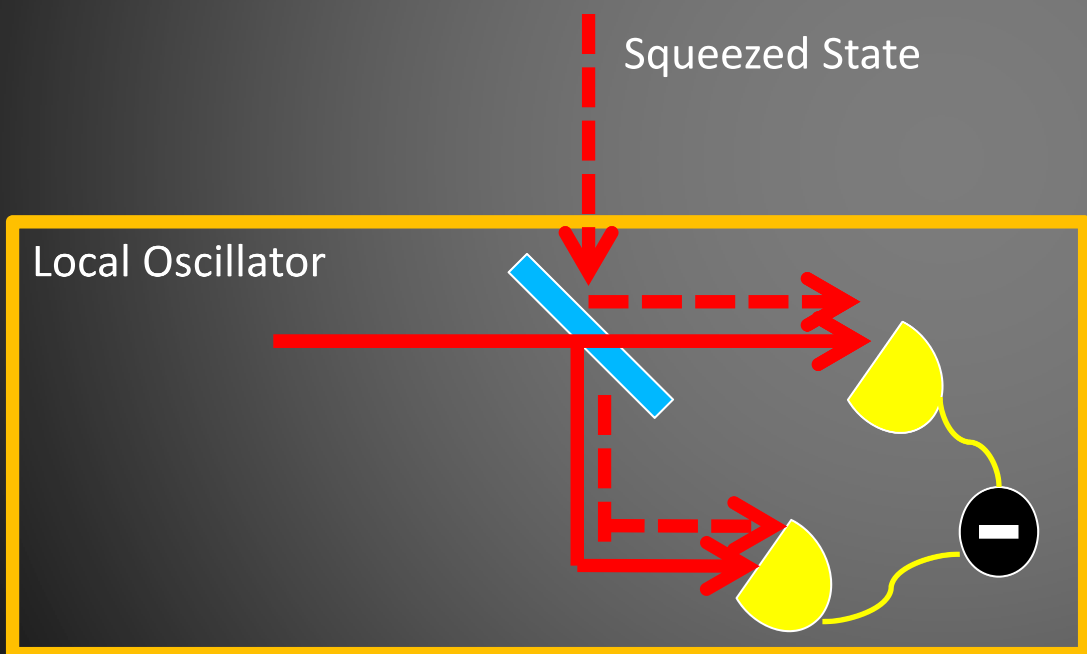
- Local Oscillator amplifies noise on the squeezed field

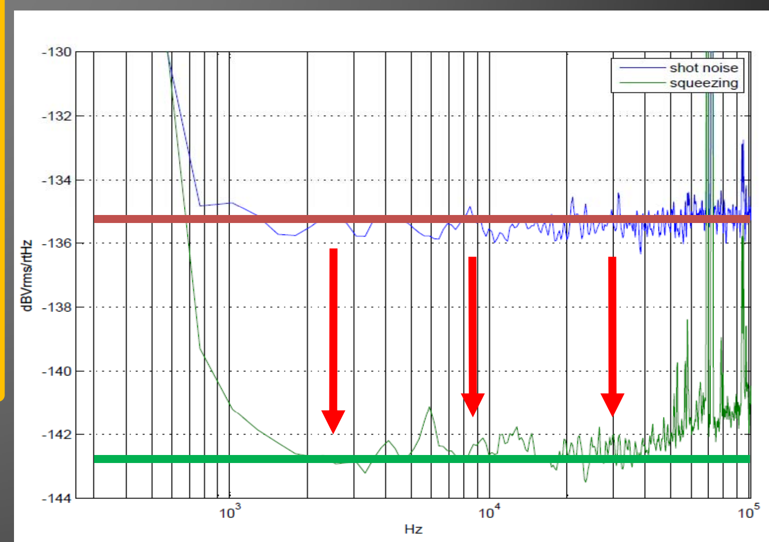




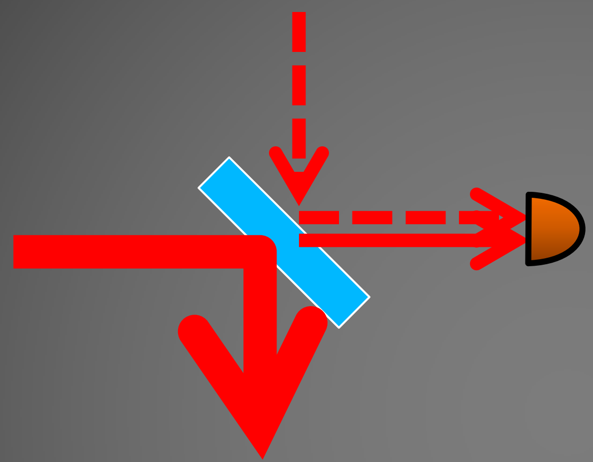
Balanced Homodyne Detection

- Local Oscillator amplifies noise on the squeezed field
- Local Oscillator noise is subtracted



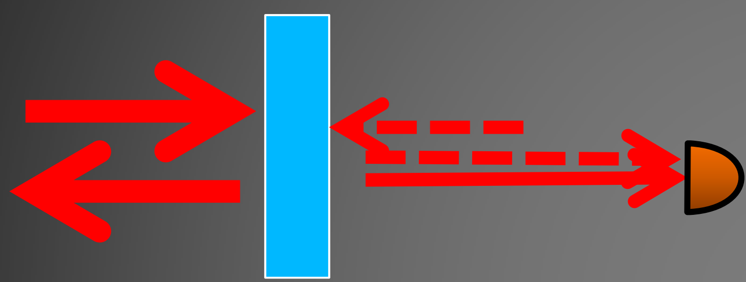


Unbalanced Homodyne Detection



- High reflectivity beam splitter
- Requires low noise local oscillator

Unbalanced Homodyne Detection



- High reflectivity beam splitter
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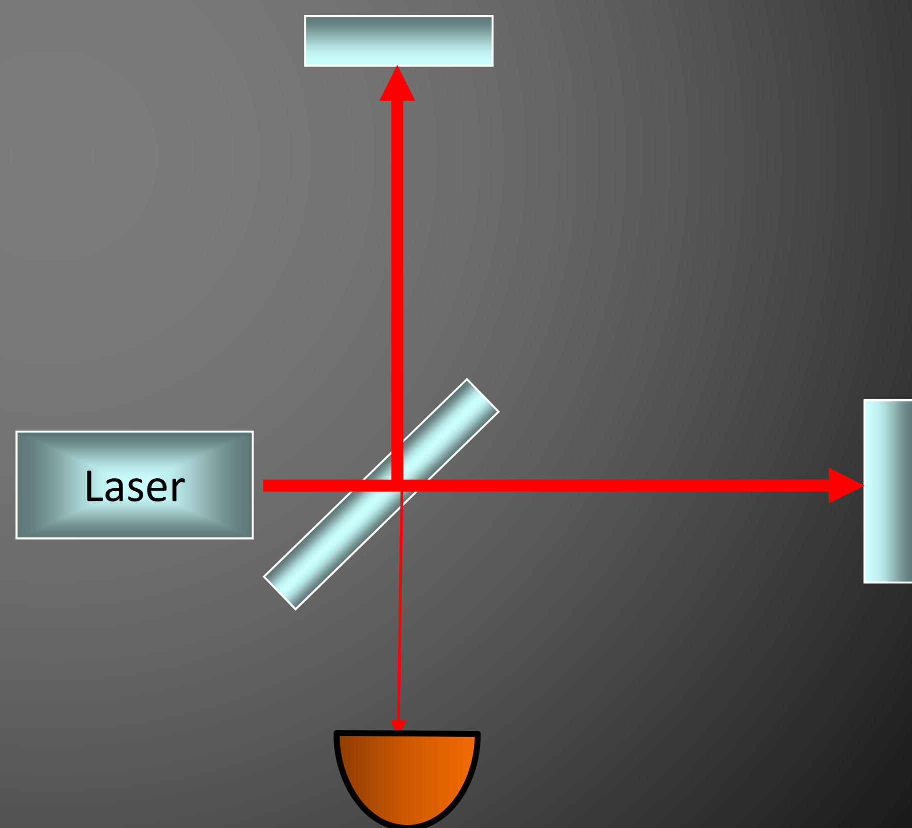

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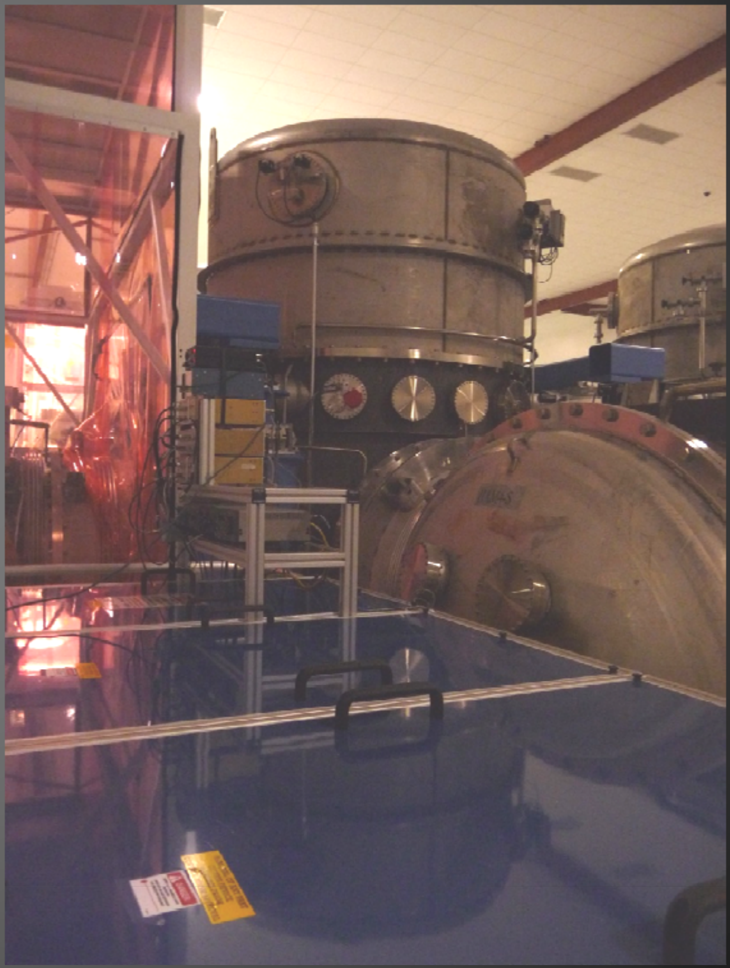
H1 squeezing experiment

- Demonstrate that squeezing does not add noise in the LIGO band
- Study environmental noise couplings
- Understand limits to measured squeezing in order to plan for aLIGO+ squeezing

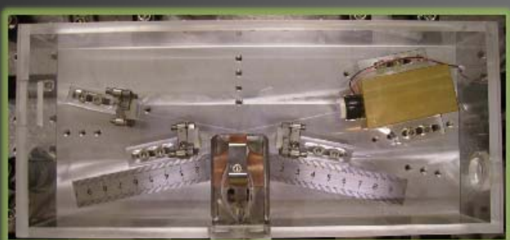


LIGO-T070265-A-D *LIGO* 10/9/07

Proposal for a Squeezed H1 Interferometer

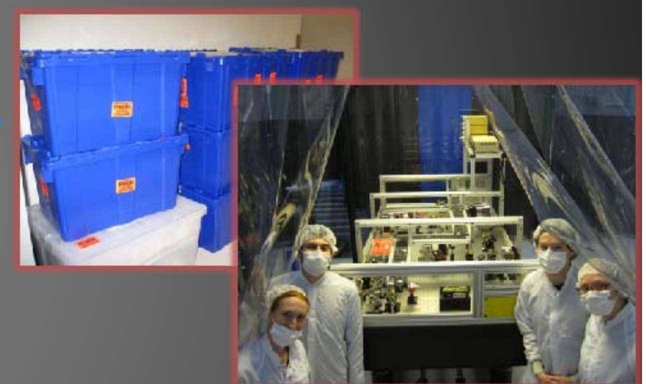
Daniel Sigg, Nergis Mavalvala, David McClelland, Ping Koy Lam, Roman Schnabel, Henning Vahlbruch and Stan Whitcomb

Bow-tie cavity OPO design from ANU (2008)



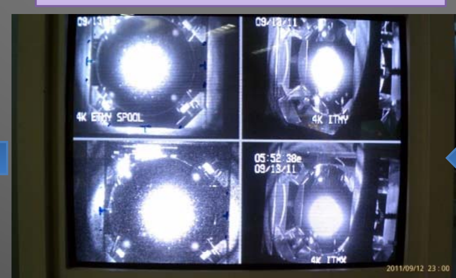
H1 Squeezer built at MIT (2009-2010)

H1 Squeezer shipped to LHO (Oct 2010)

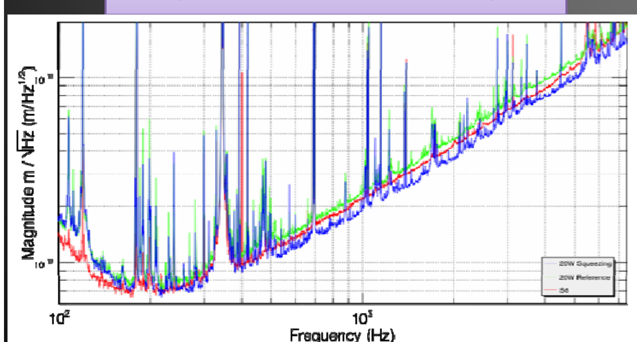


H1 Squeezer Installation (Summer 2011)

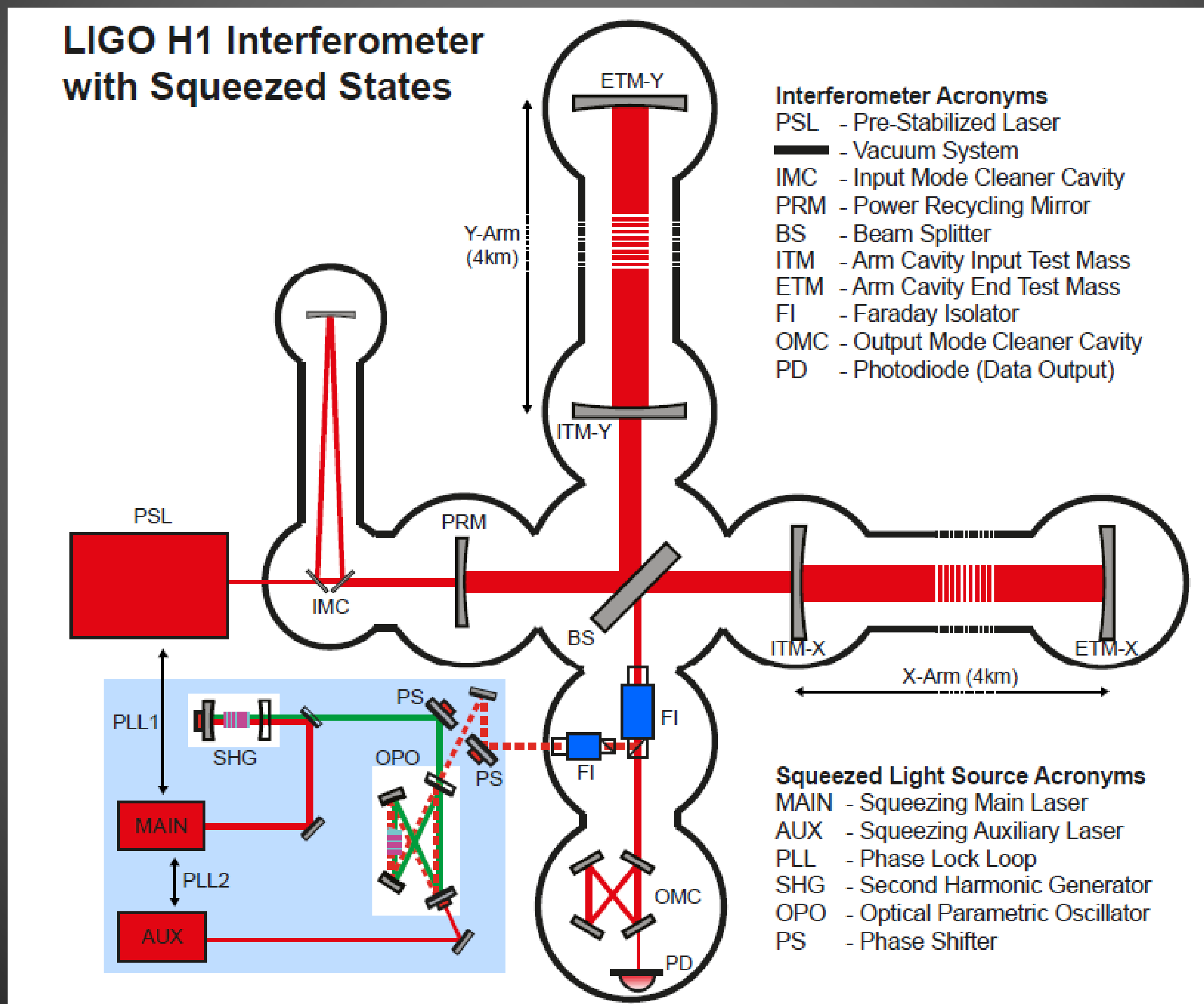
H1 Recovery (Sept 2011)



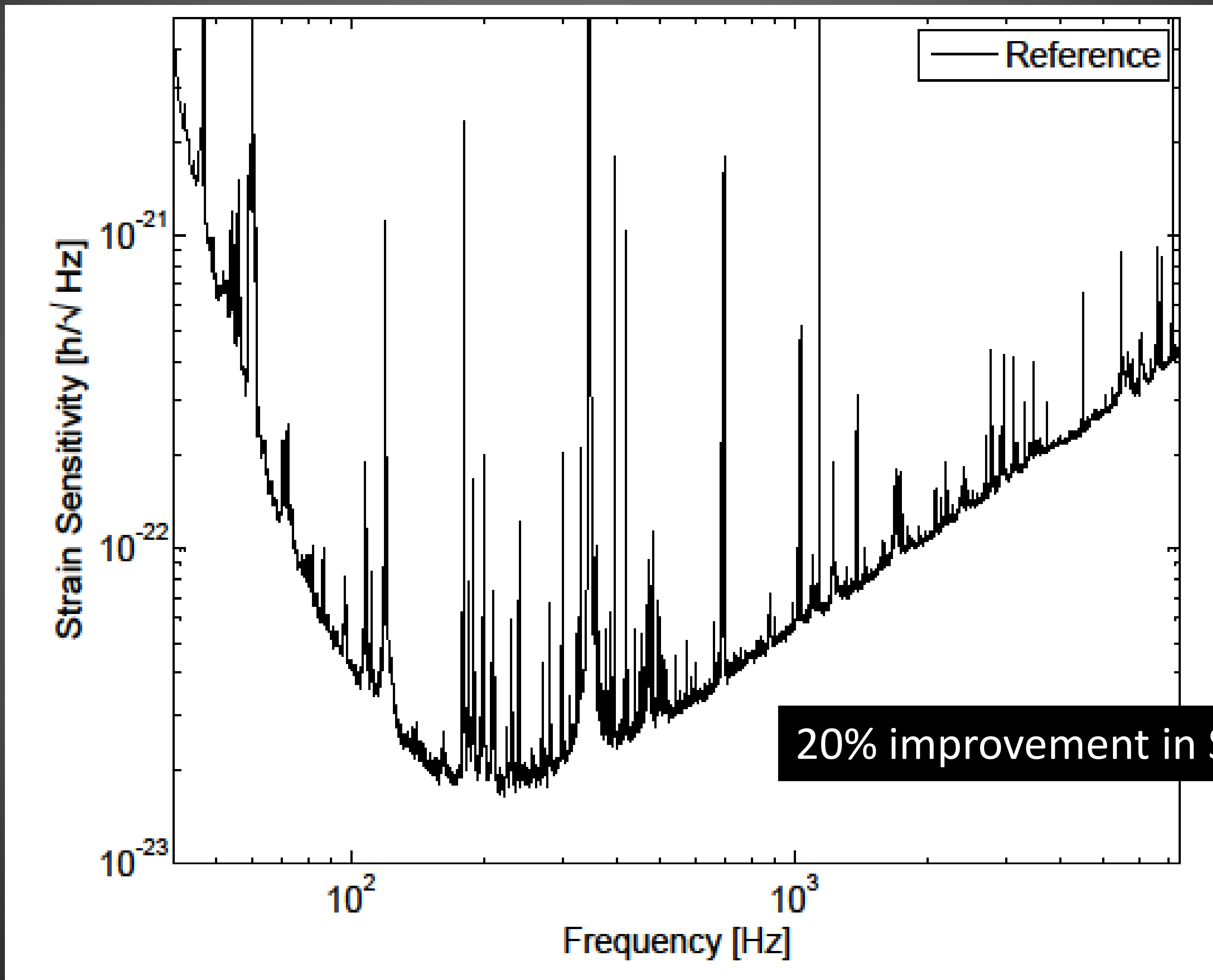
Squeeze injection in H1 (Nov – Dec 4 2011)



Experiment Layout

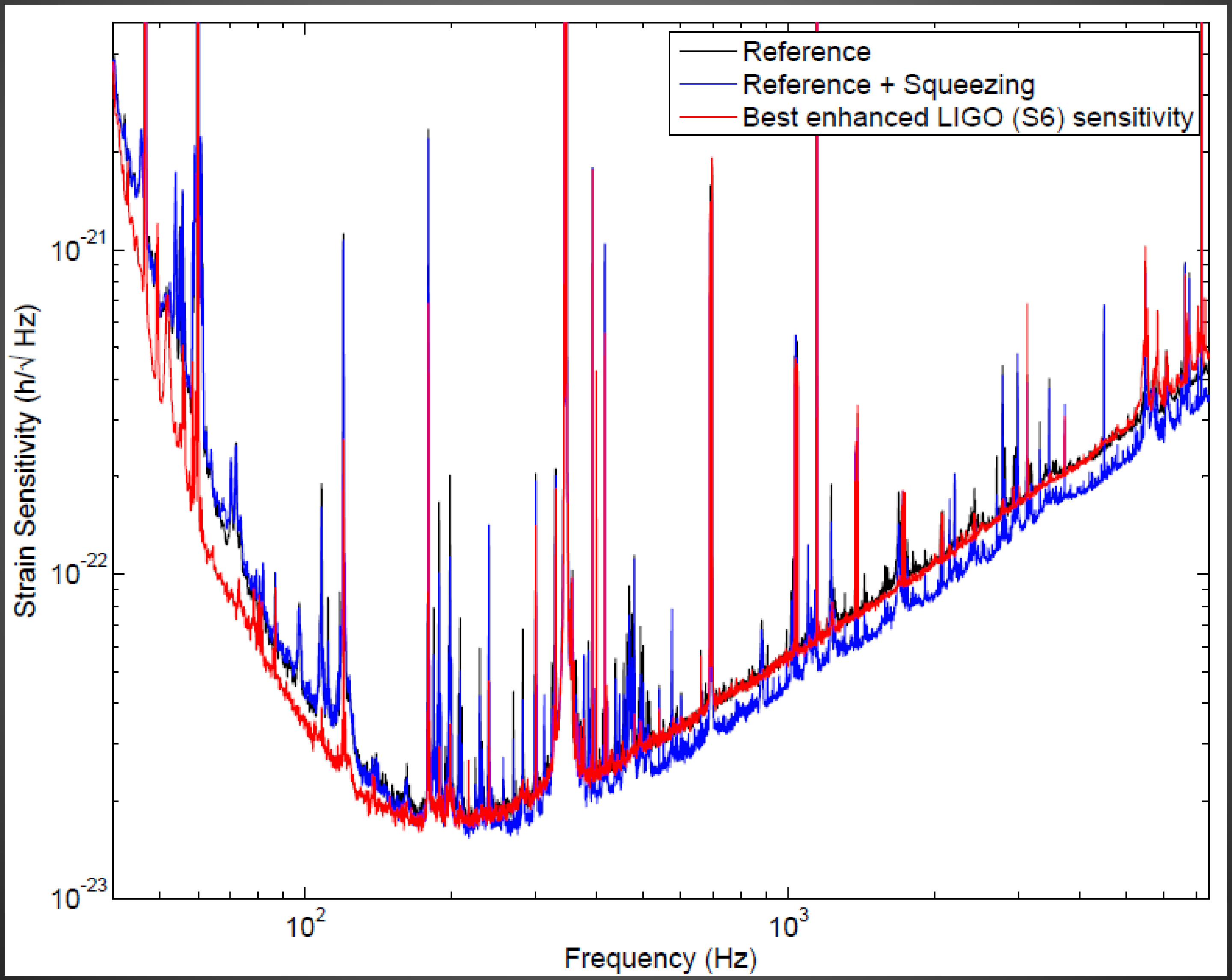


Squeezing in Enhanced LIGO

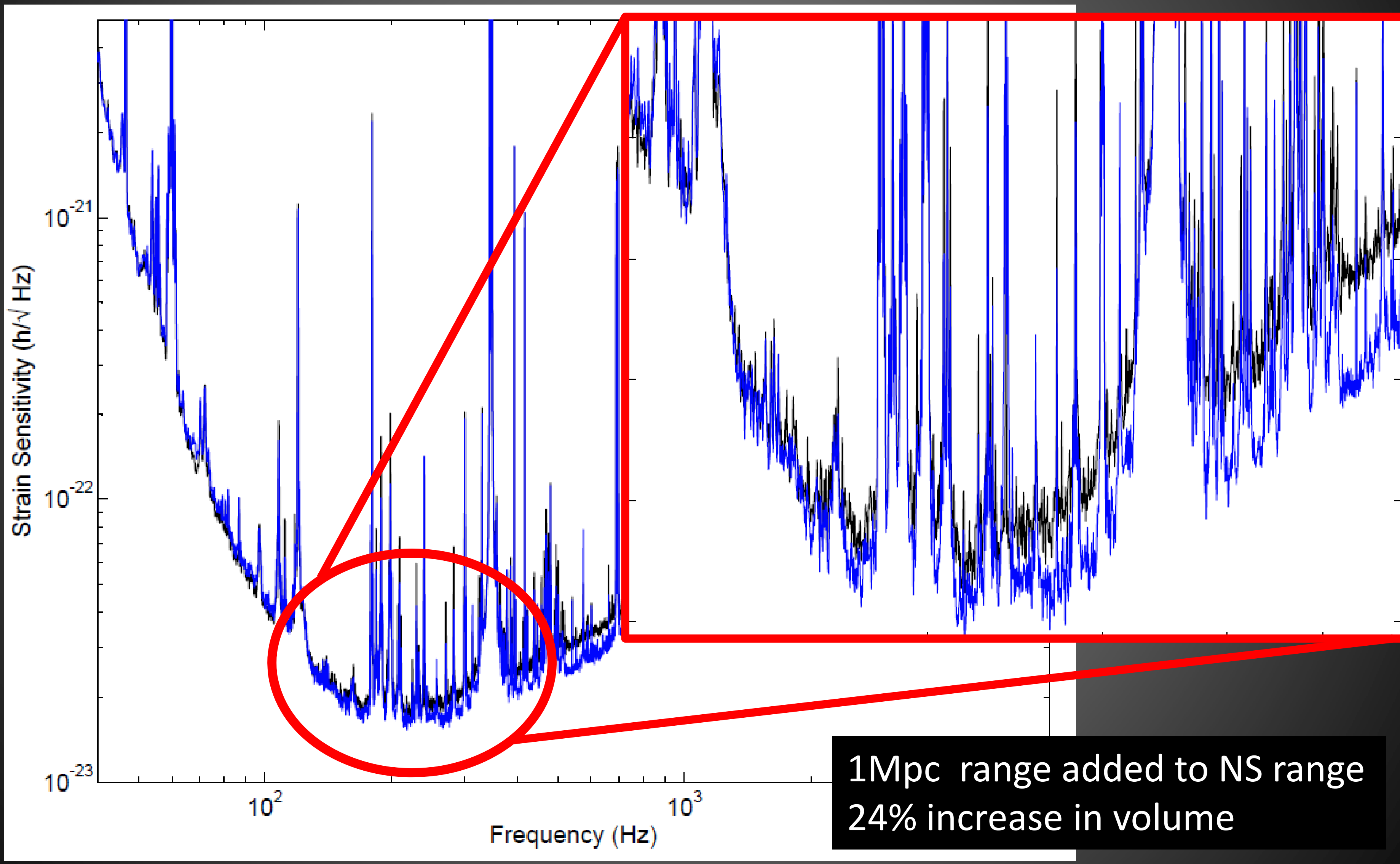


20% improvement in SNR

Best broadband sensitivity to date



Squeezing in Enhanced LIGO



1Mpc range added to NS range
24% increase in volume

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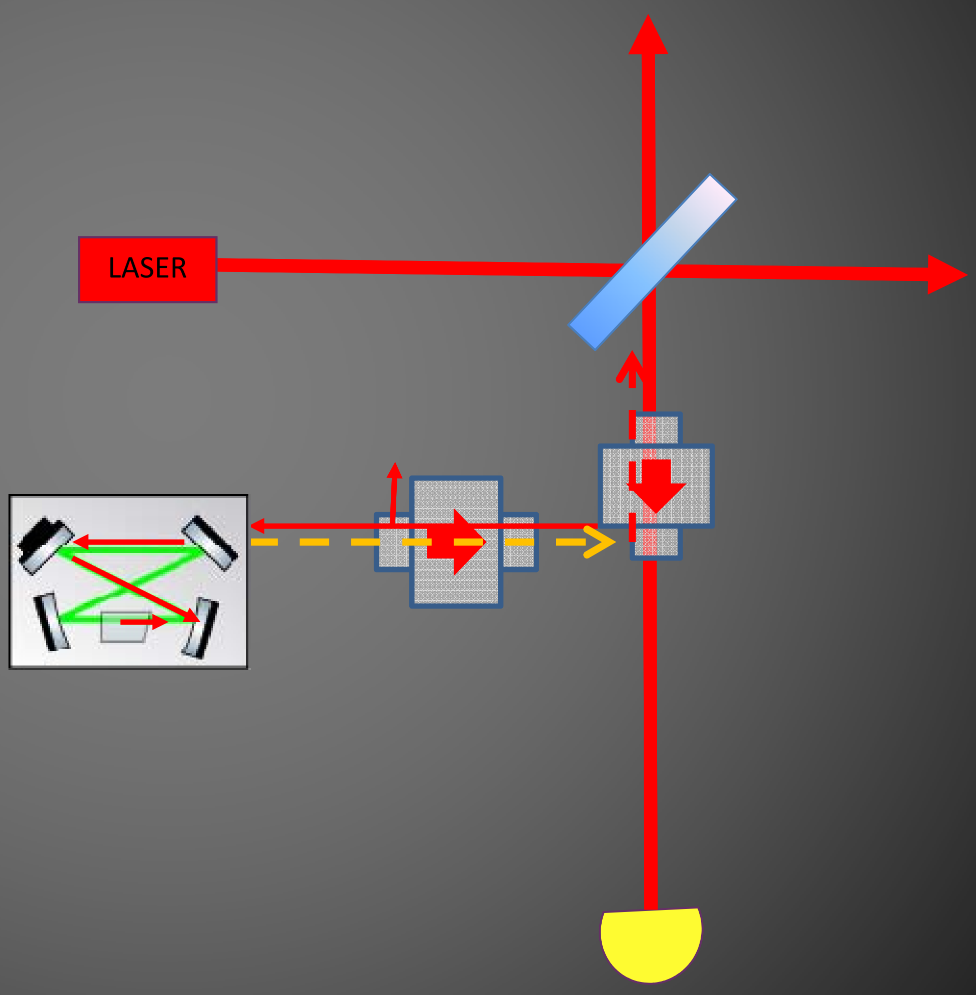
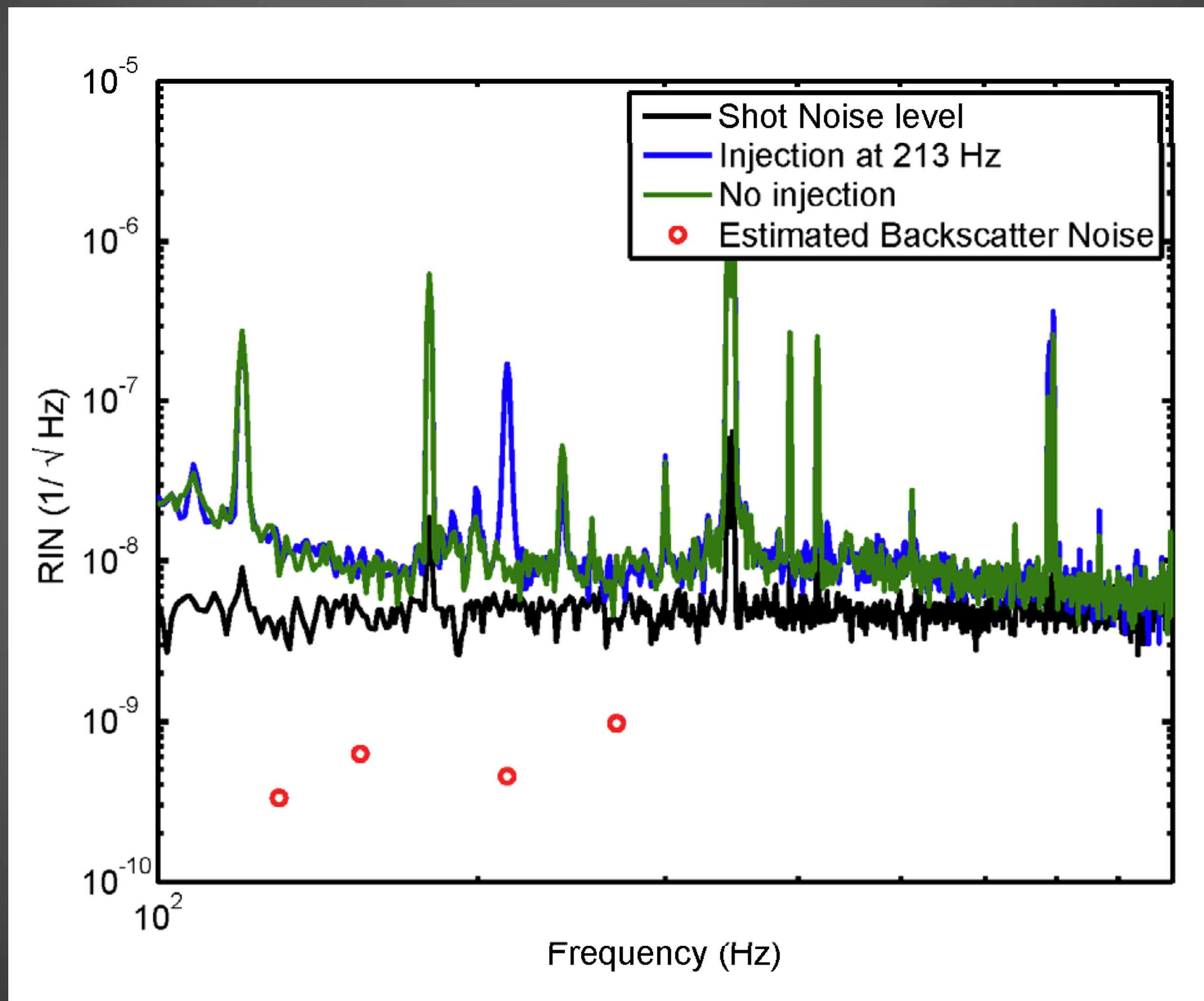
Backscatter noise

- Light from interferometer is sent towards OPO
- A second scattering event in OPO sends light back towards IFO
- Spurious interferometer adds noise



Noise Coupling



Around 100 fW of backscattered power at detector

Backscatter in Advanced LIGO

<u>Better</u>

- Acoustic enclosure (factor of 10 above 100 Hz)
- Lower OPO finesse (needed anyway)
- Good Faraday performance in vacuum

<u>Worse</u>

- More power
- 6 dB of squeezing
- Better detection efficiency
- Possibly better matching of scattered beam into OPO

Backscatter noise 40-80x below shot noise above 100 Hz.

Out of vacuum OPO is compatible with Advanced LIGO sensitivity, in vacuum OPO probably needed for a third generation interferometer.

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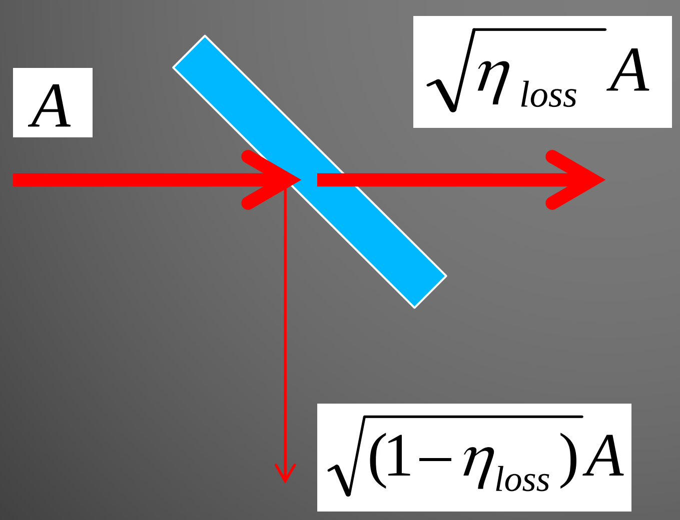
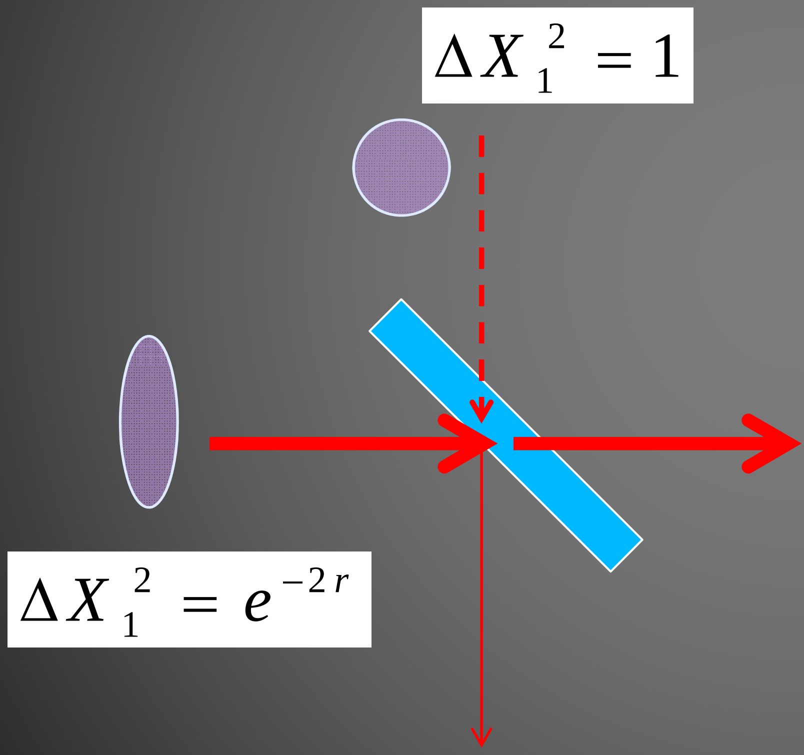
Losses destroy squeezing

- Every loss can be seen as a beamsplitter with power transmission η_{loss}

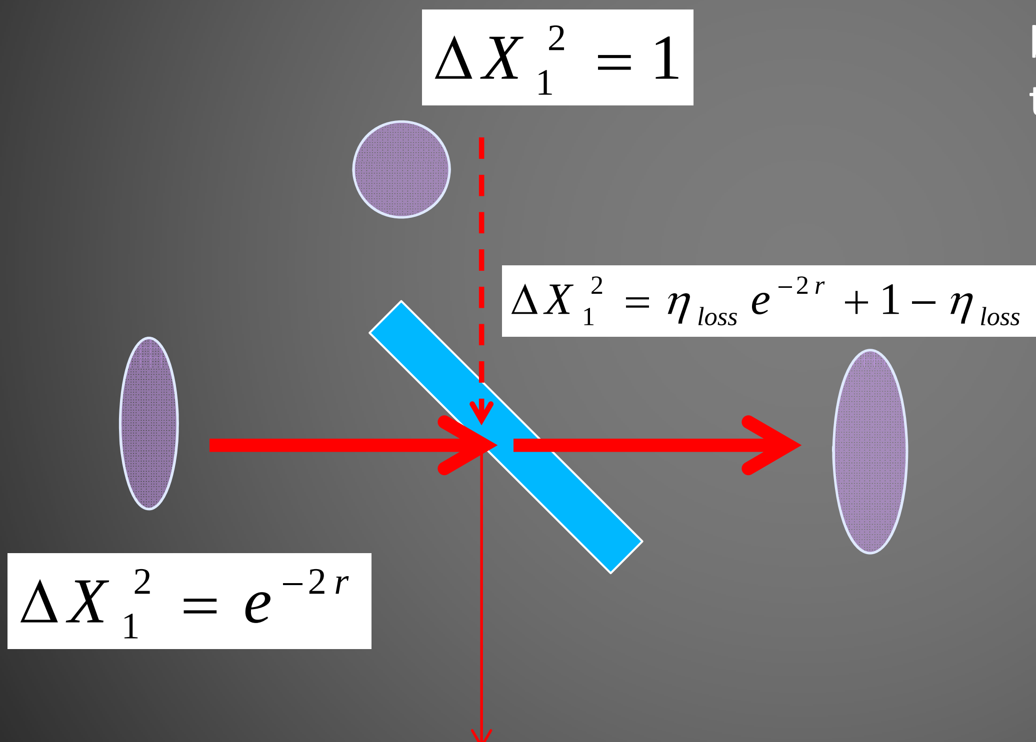


Losses destroy squeezing



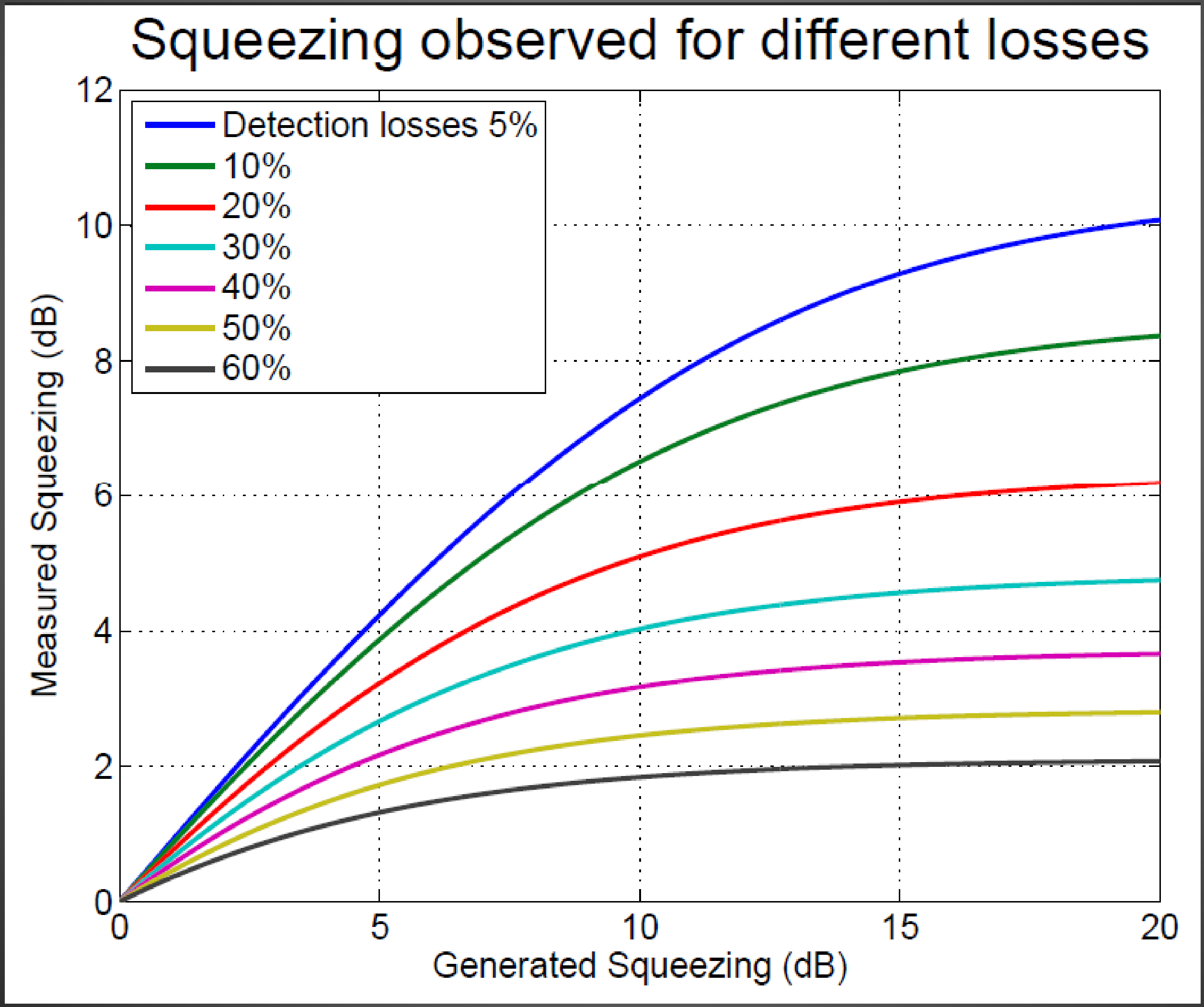
- Every loss can be seen as a beamsplitter with power transmission η_{loss}
- A loss allows vacuum state to "leak" into the beam

Losses destroy squeezing



- Every loss can be seen as a beamsplitter with power transmission η_{loss}
- Beamsplitter mixes the squeezed state with vacuum state
- Resulting state has higher noise in squeezed quadrature

Losses limit squeezing

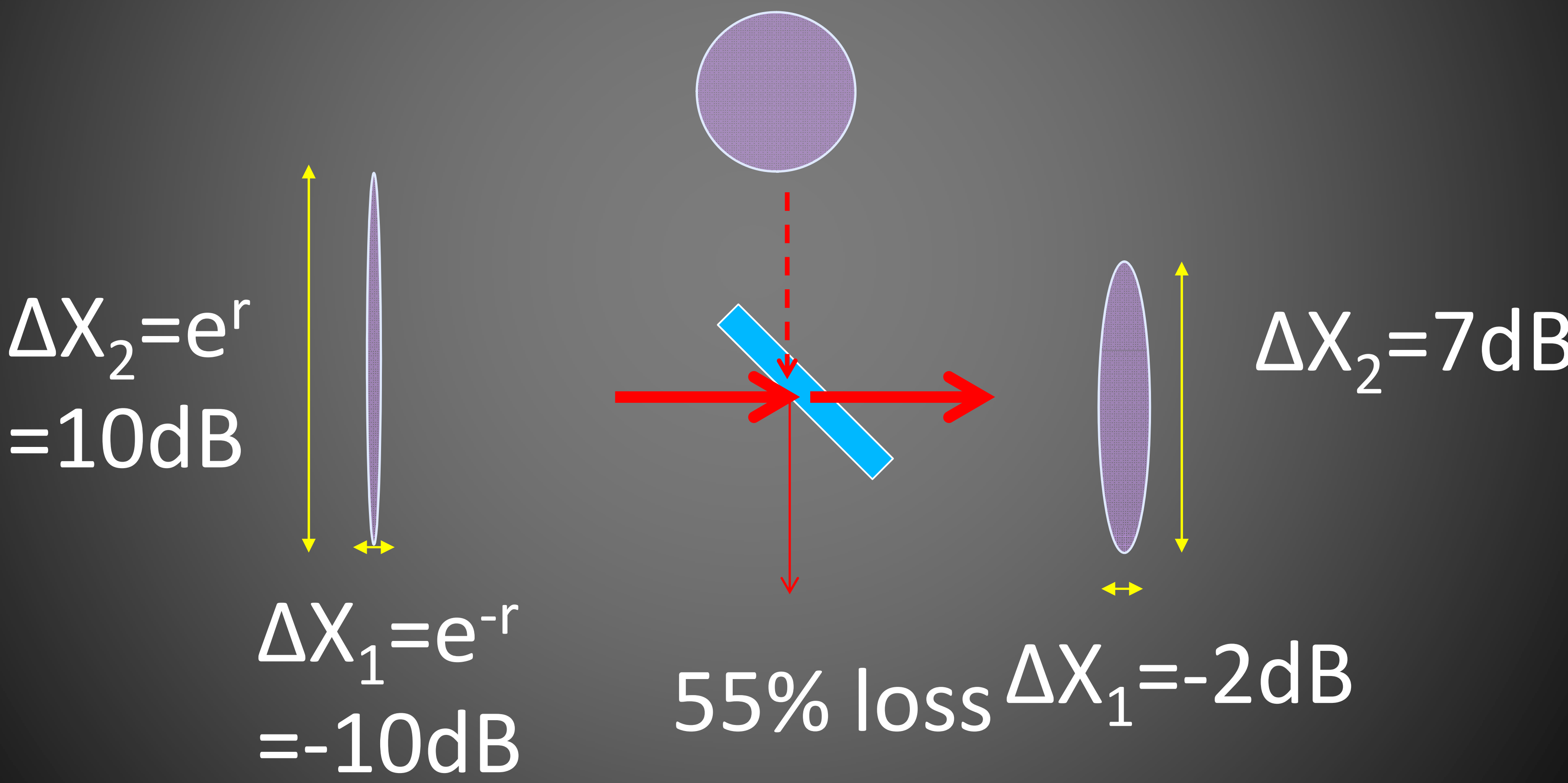


Loss budget and goals

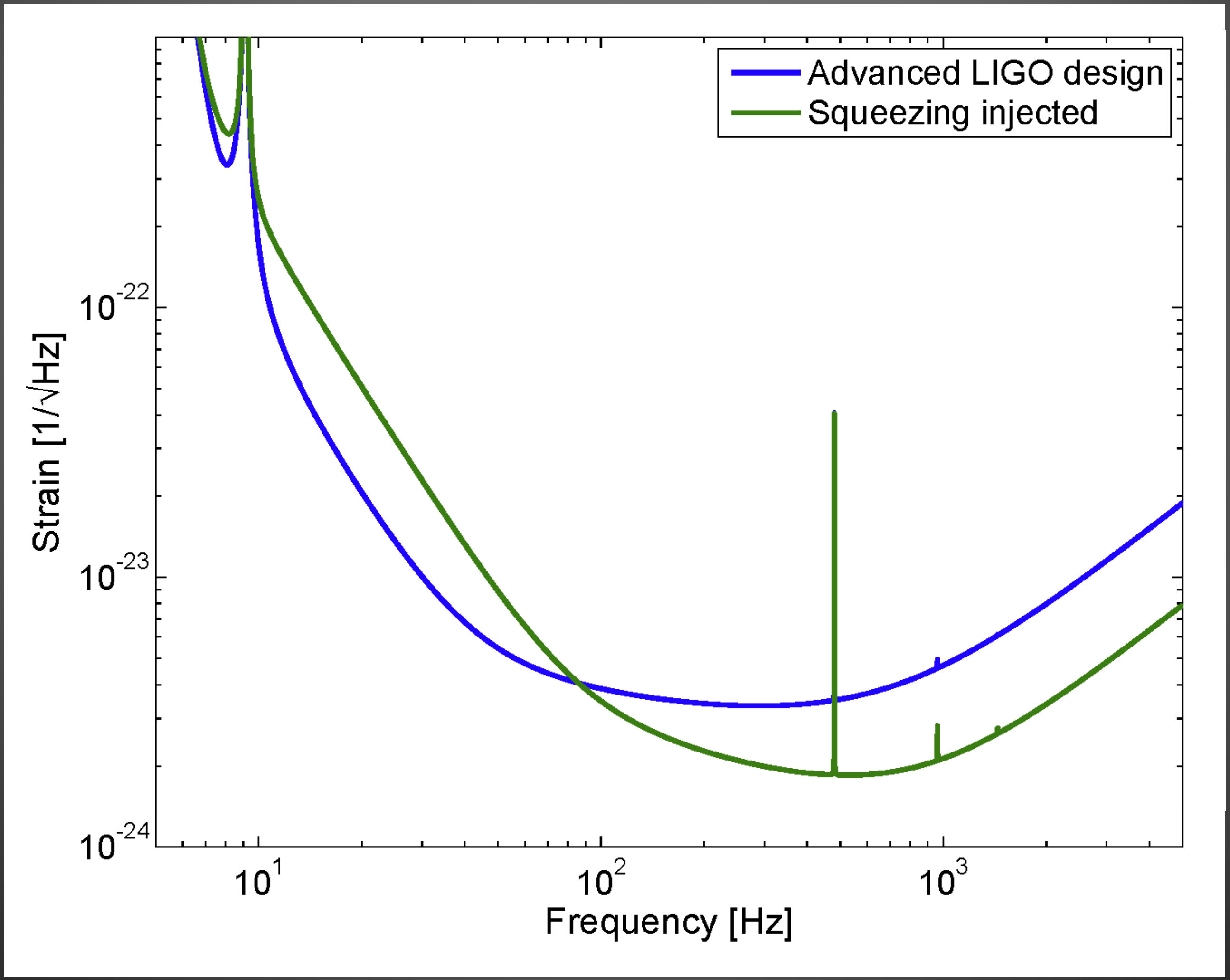
	Enhanced LIGO squeezing	Advanced LIGO assumptions
3 faraday passes	5% each	3% each
Mode matching	30%	4%
Output mode cleaner	19%	3%
Total losses	55-60%	20-25%

Based on a tally of 11 different loss sources

Losses degrade the purity of the squeezed state



Squeezing with a radiation pressure limited interferometer



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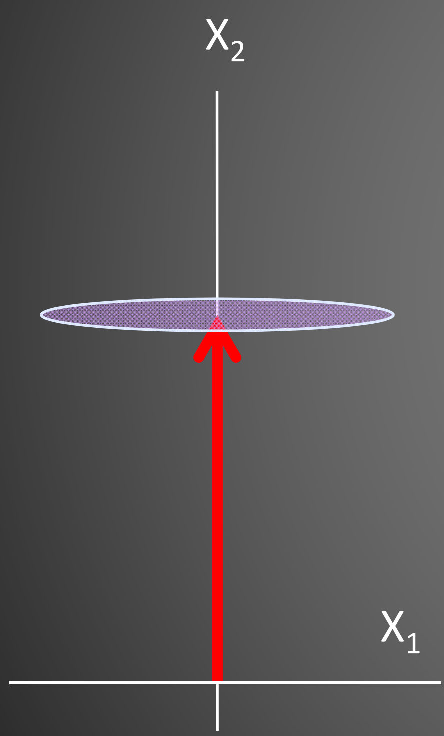
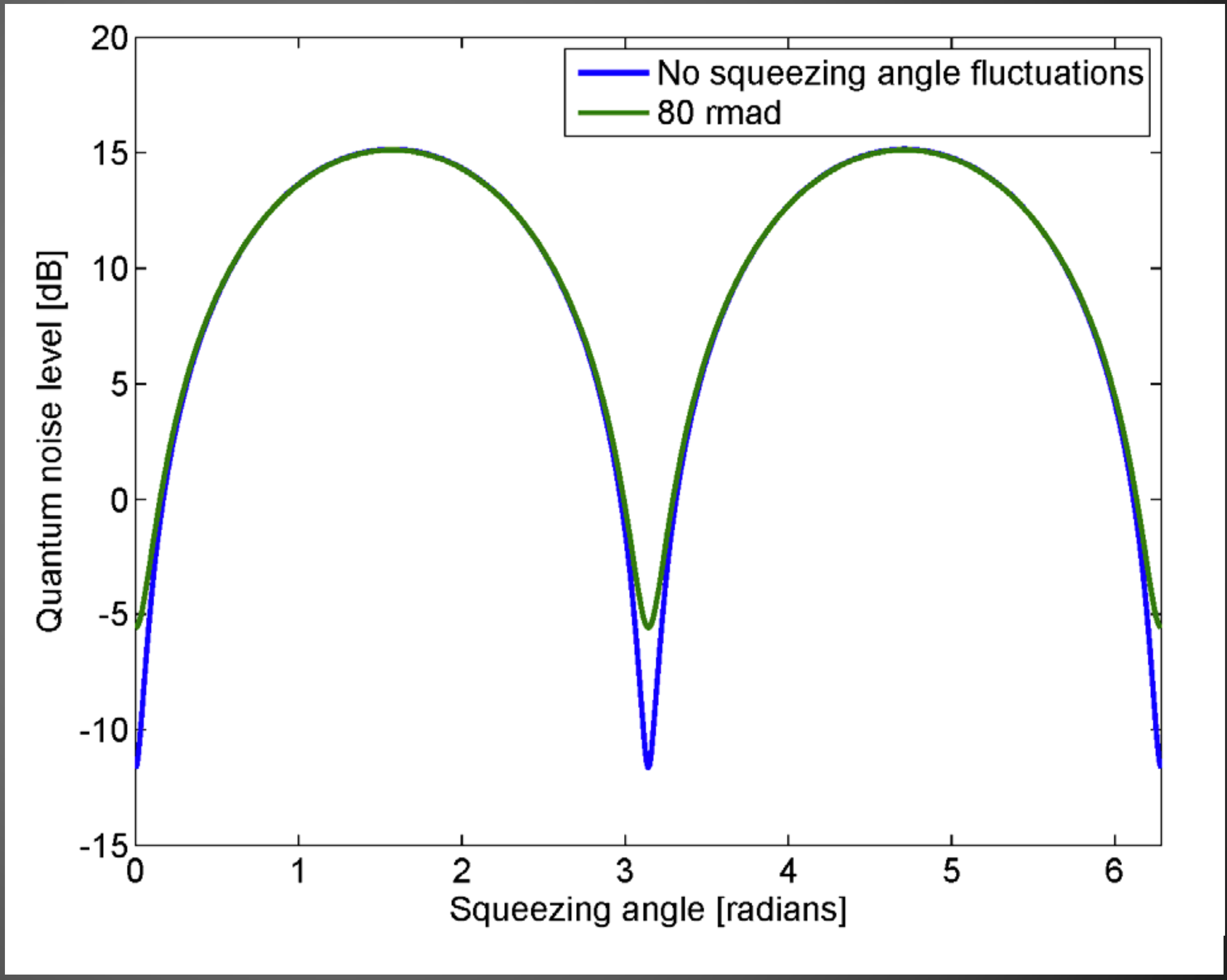
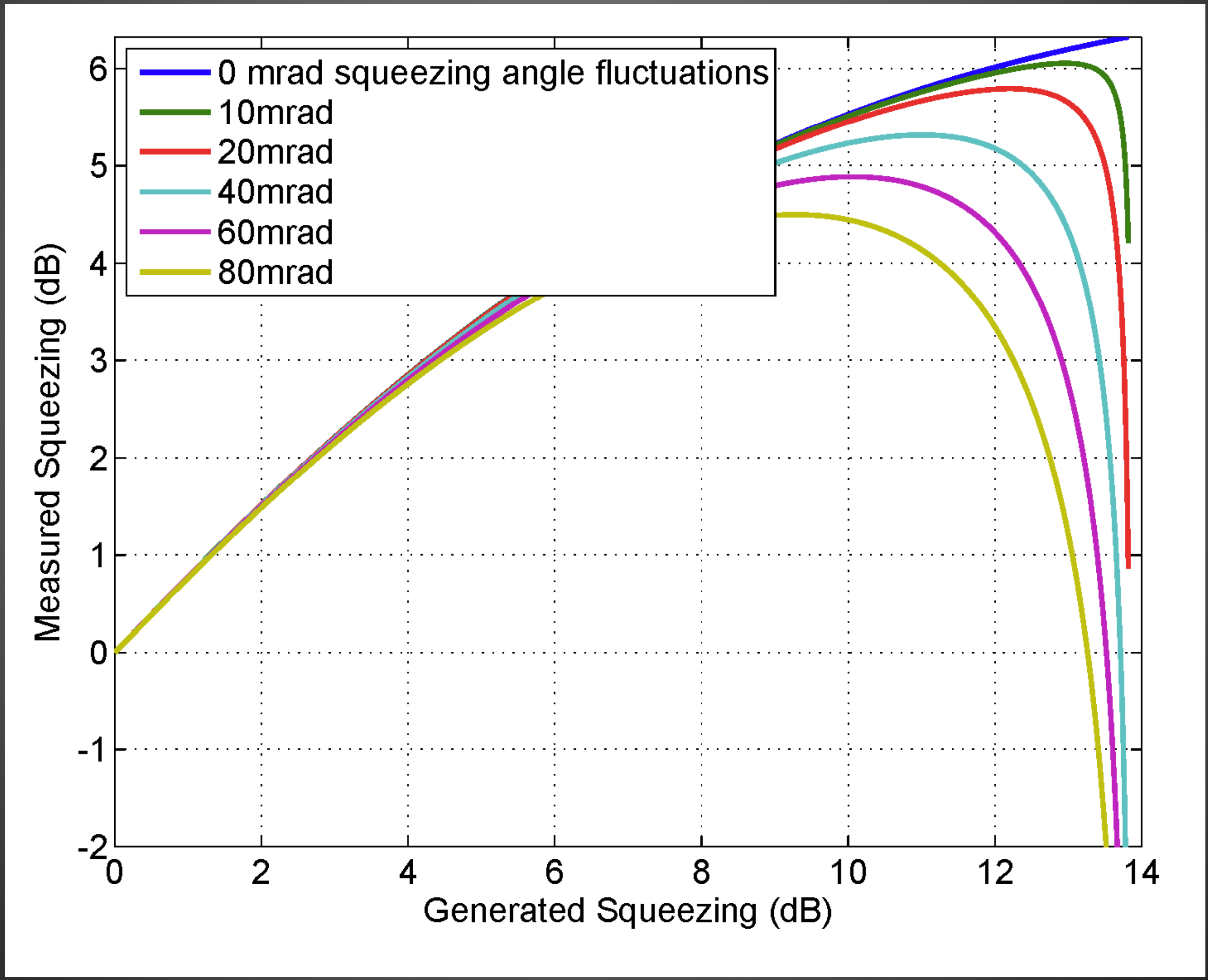
Squeezing Angle Fluctuations

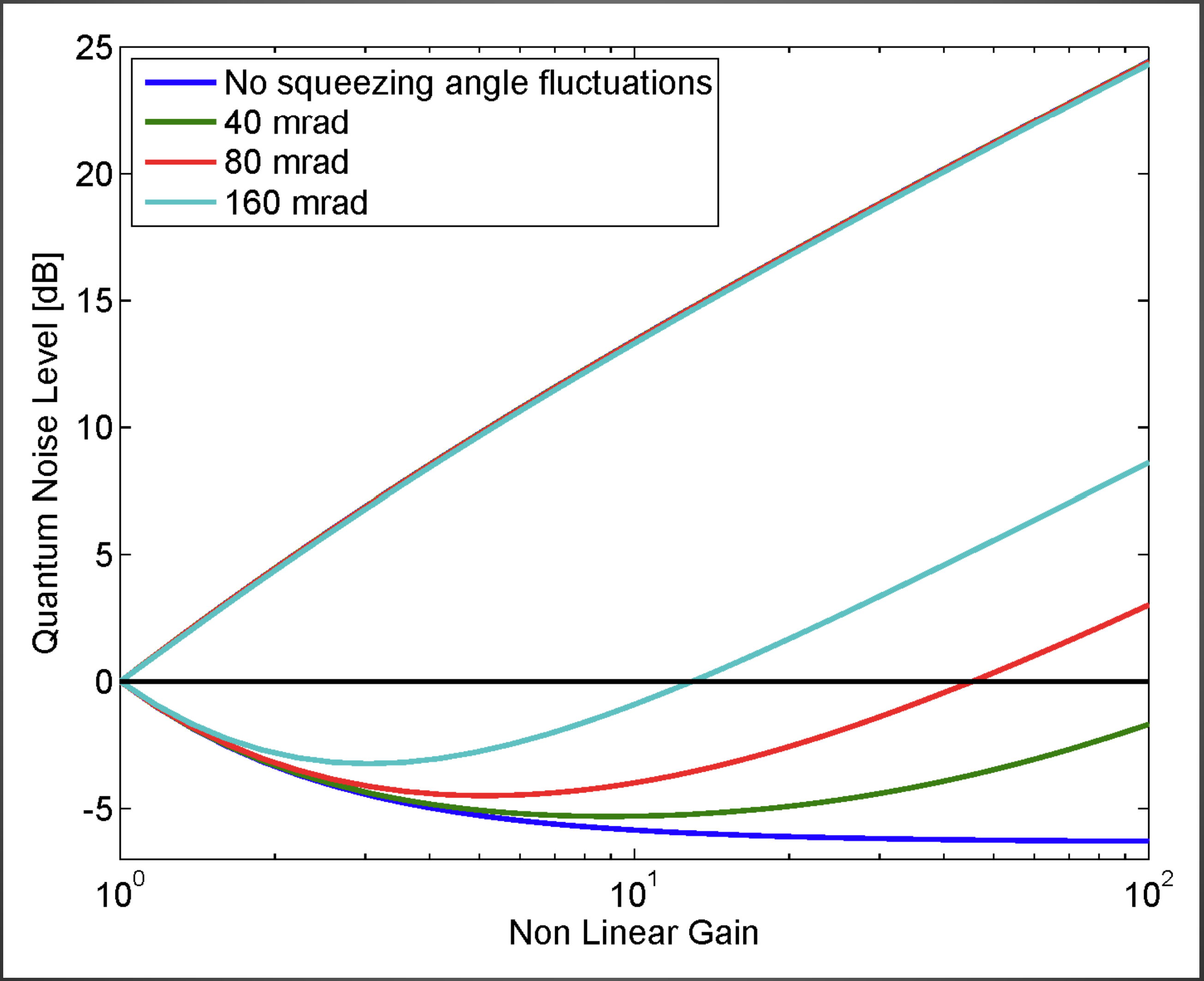




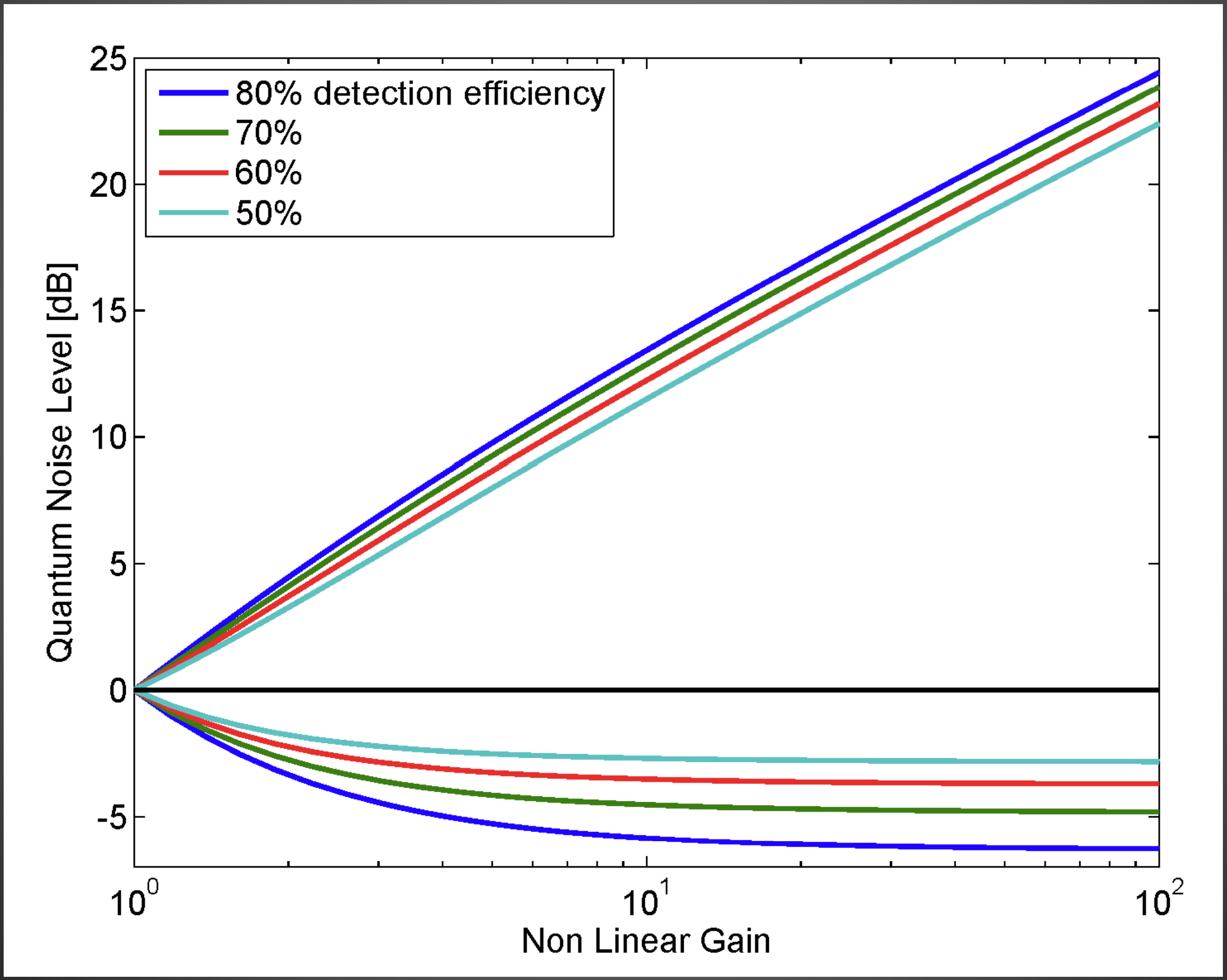
Squeezing Angle Fluctuations



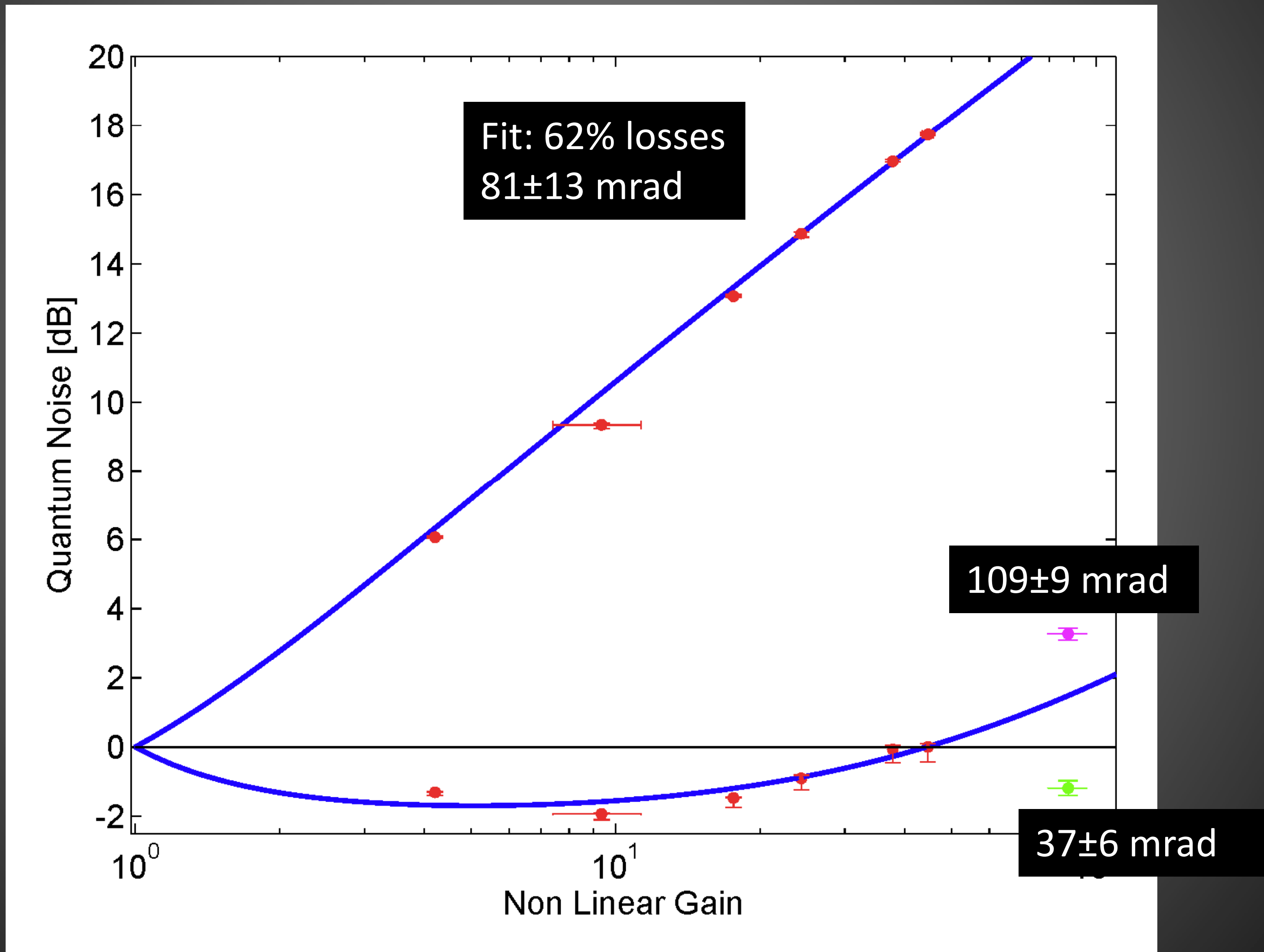
Squeezing angle fluctuations



Measurement of squeezing angle fluctuations and losses



Squeezing angle fluctuations



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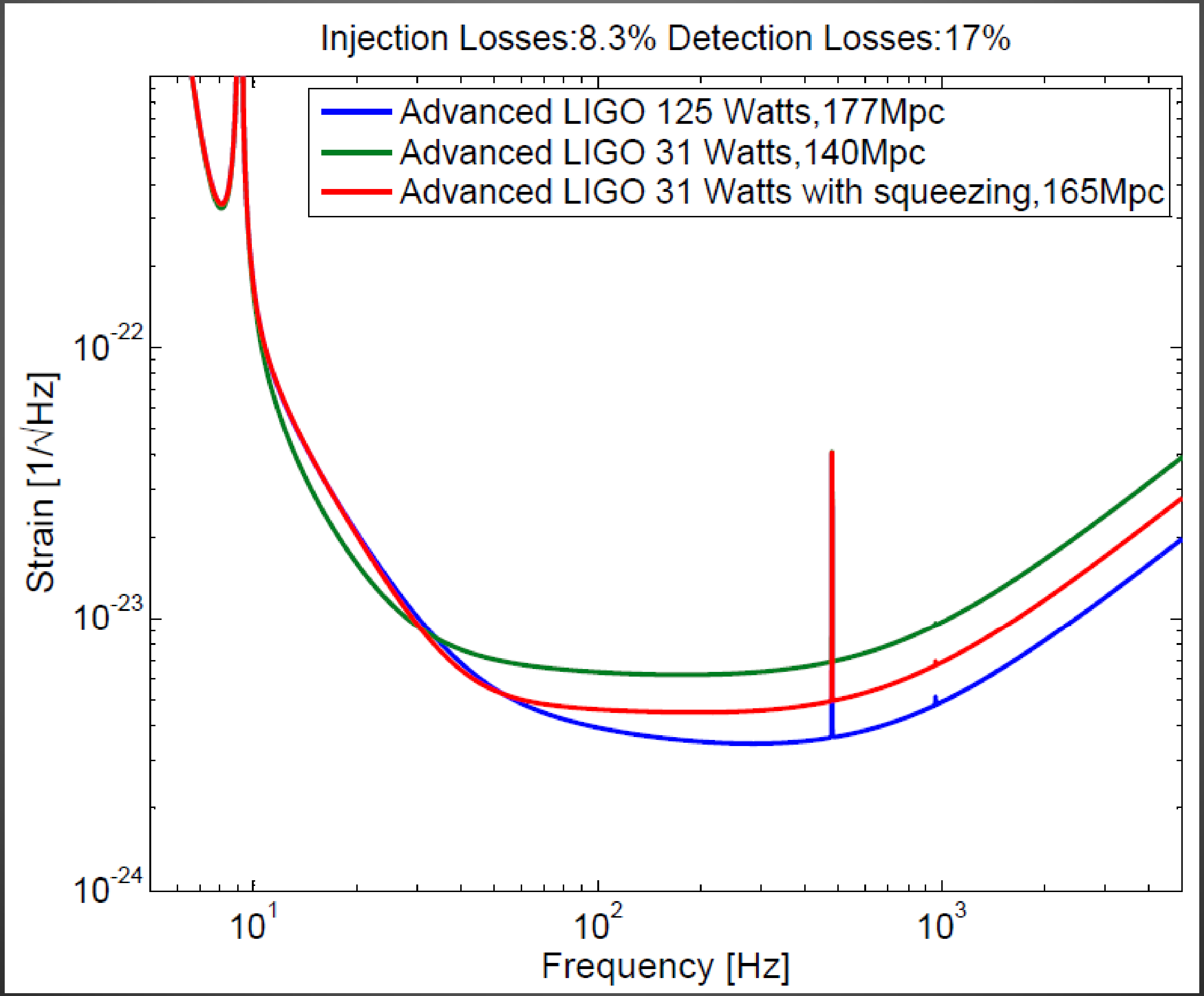
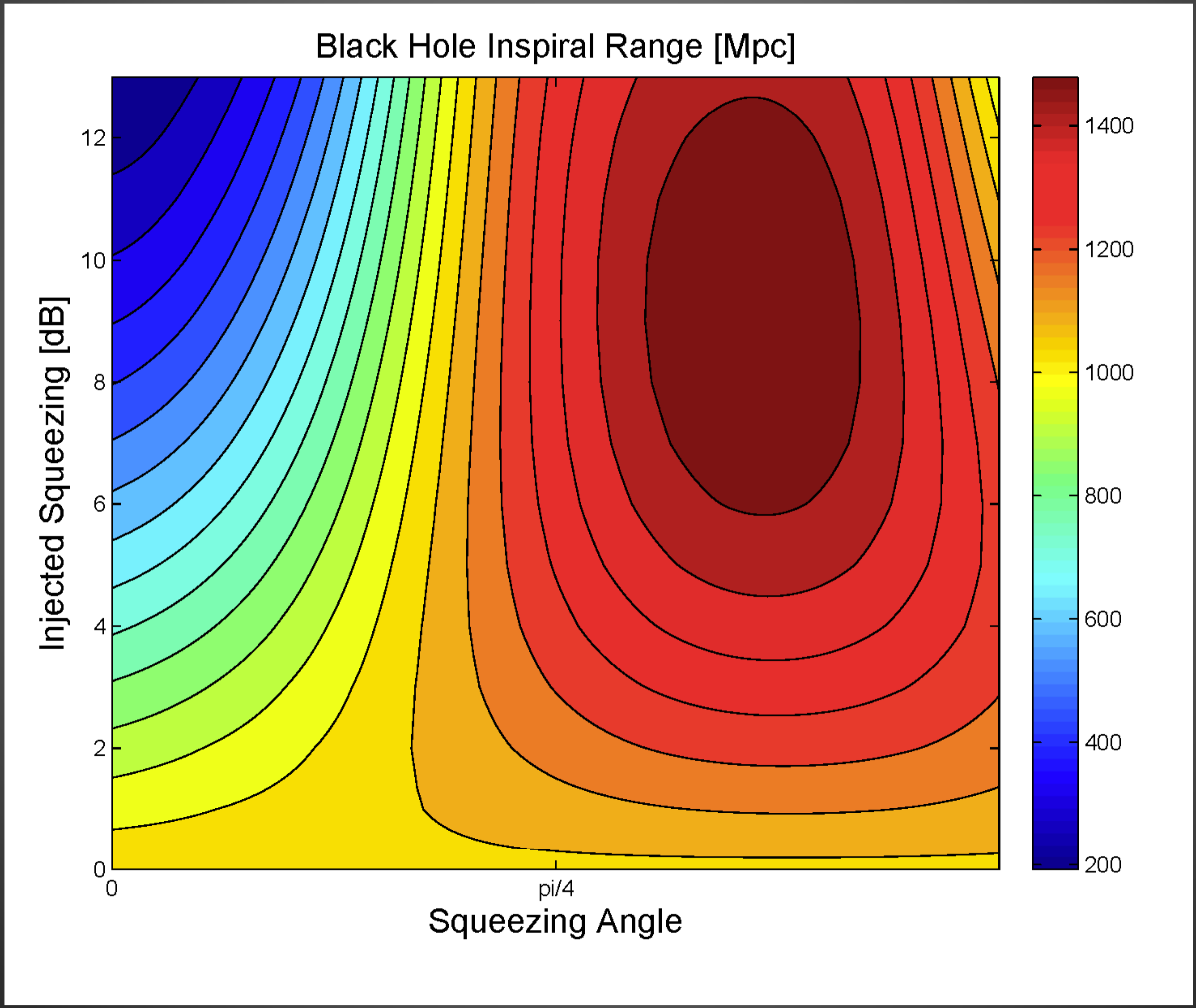
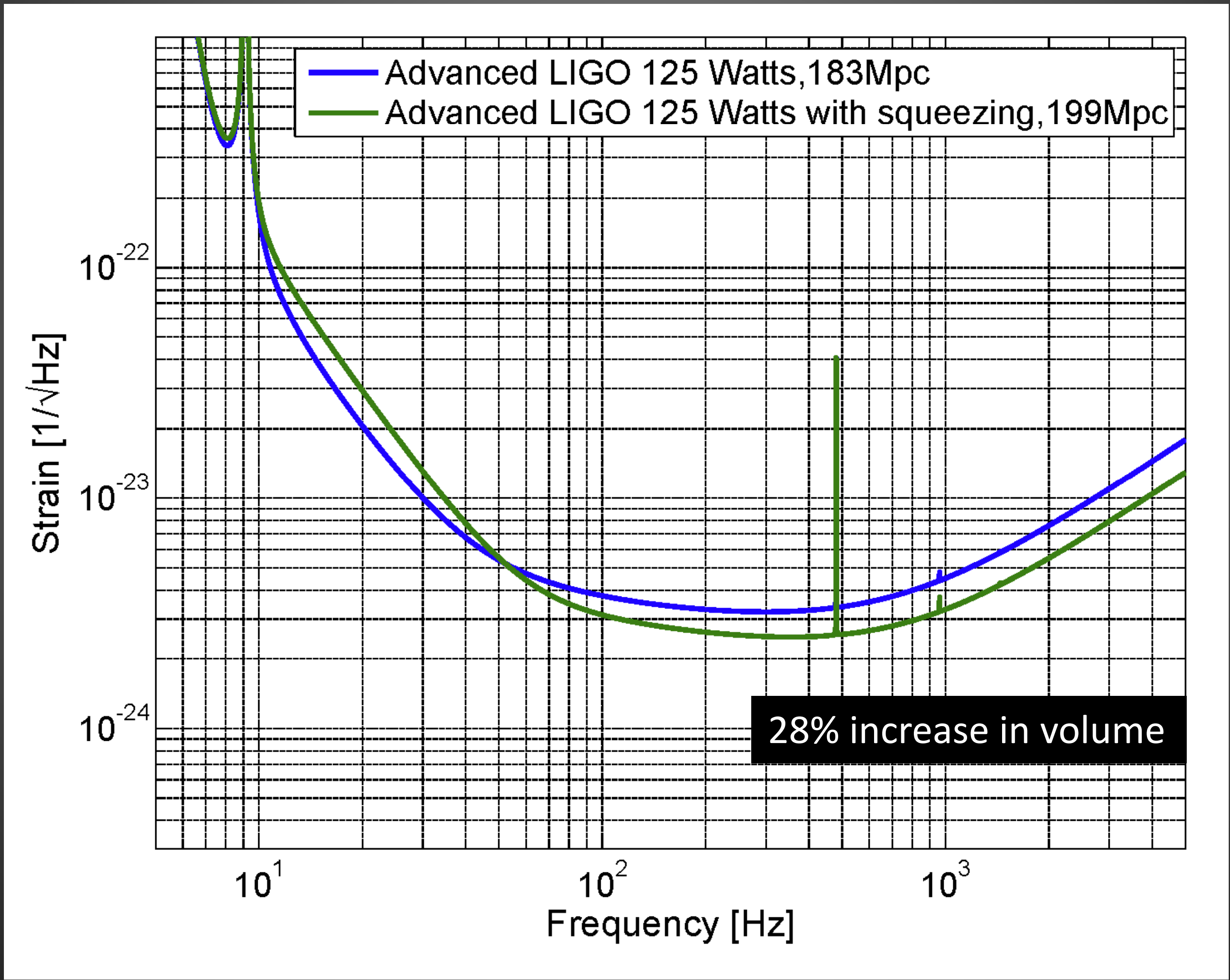
An alternative to high power operation in Advanced LIGO



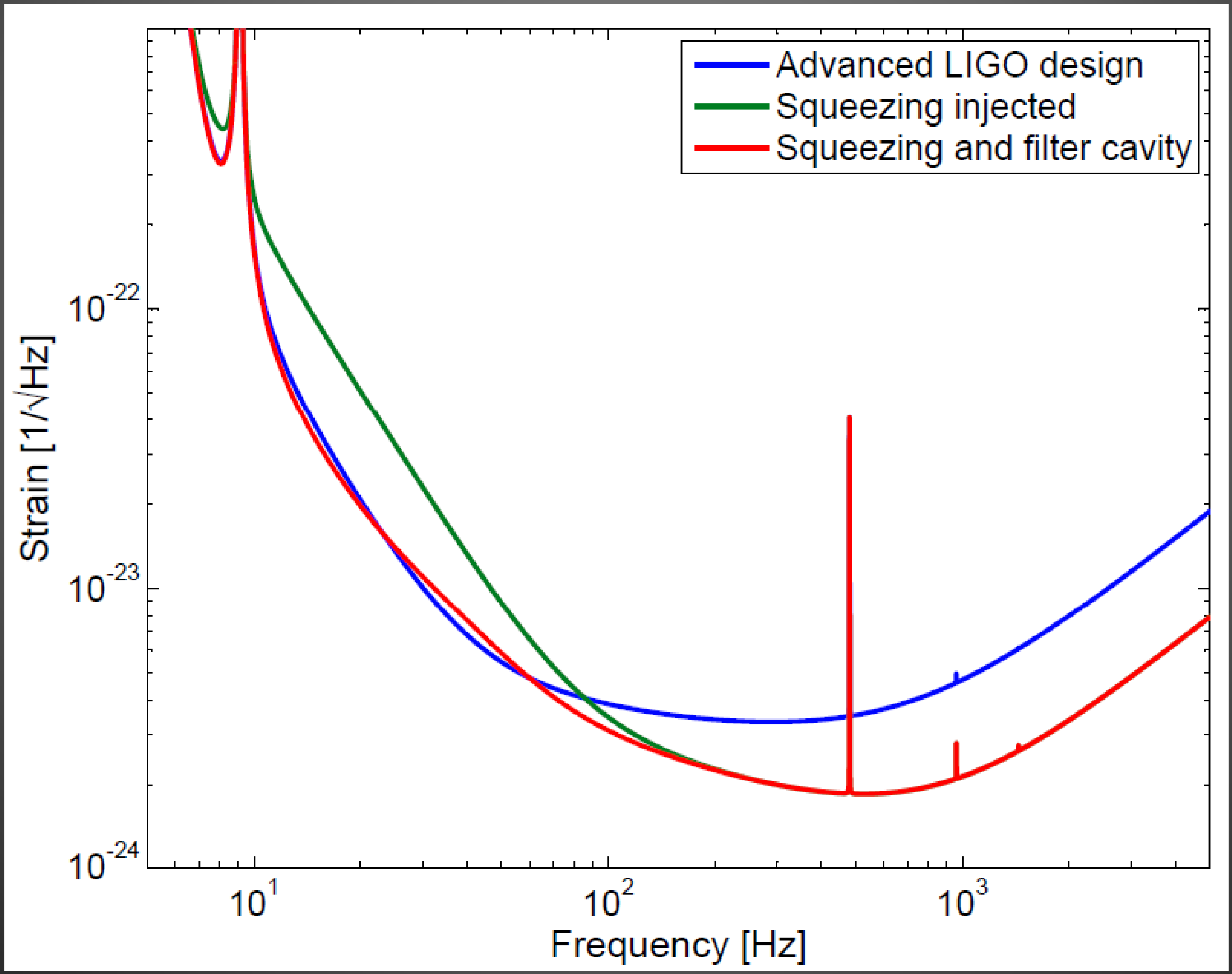
Squeezing in Advanced LIGO



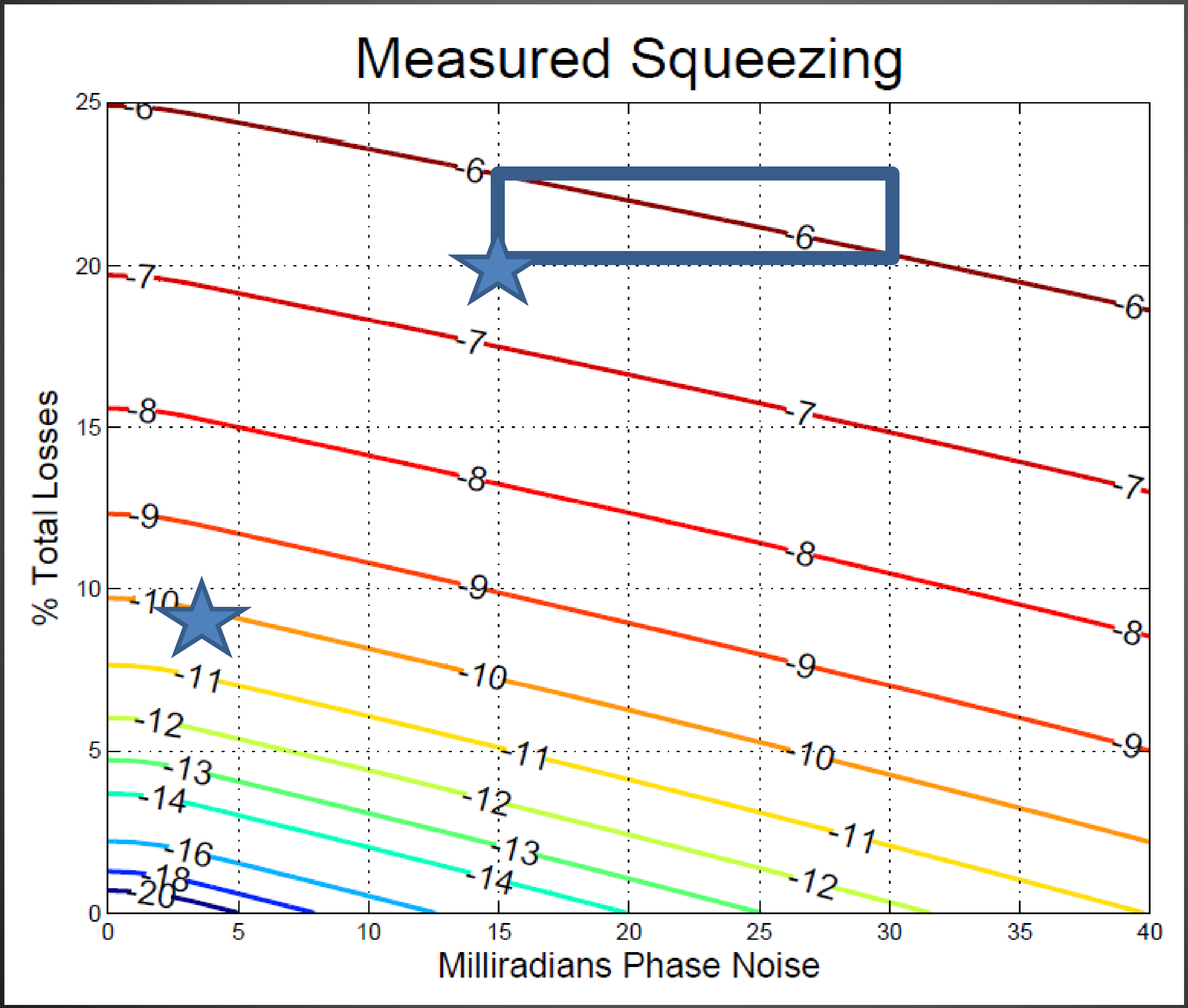
Squeezing with full power



Frequency Dependent Squeezing



Paths to better squeezing



Non linear gain optimized for shot noise limited interferometer, maximum pump power 80% of threshold

Summary

- 2dB of squeezing in Enhanced LIGO
- Squeezing compatible with low frequency sensitivity
- Backscatter should not be a problem for aLIGO
- To get higher levels of squeezing we will need to reduce interferometer losses and squeezing angle fluctuations

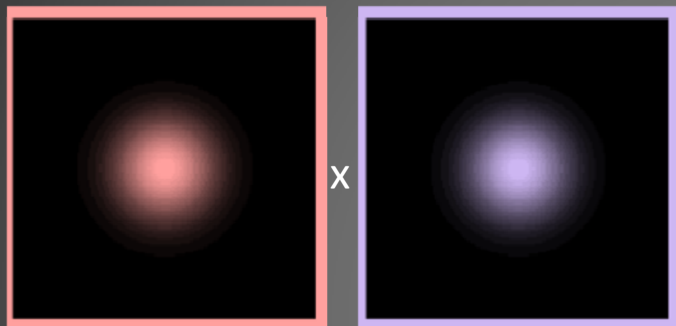
Squeezing will soon be the simplest way to improve LIGO’s sensitivity

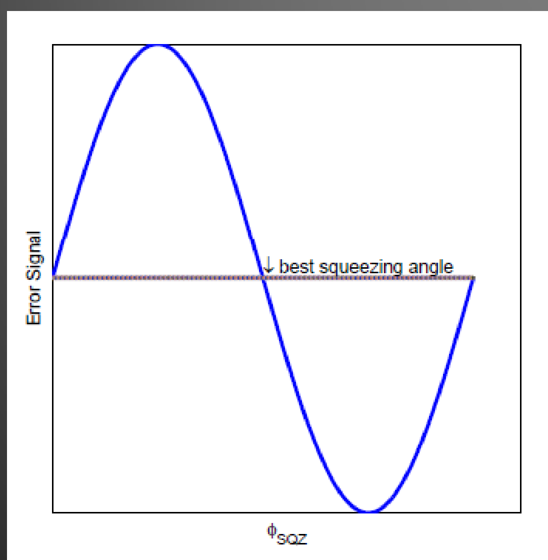
Thank you!

- My committee
- Mentors: Nergis Mavalvala, Lisa Barsotti, Daniel Sigg
- LIGO Lab at MIT, staff at Hanford, and all the squeezers

Coherent locking of squeezing angle inject frequency shifted sideband with coherent amplitude

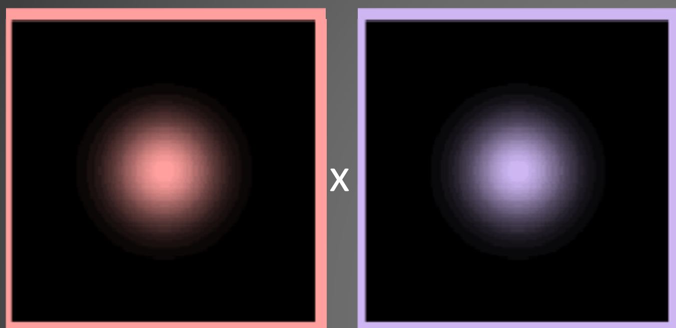
IFO carrier SQZ sideband



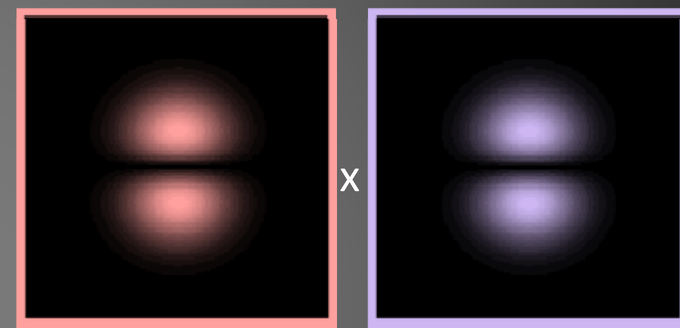


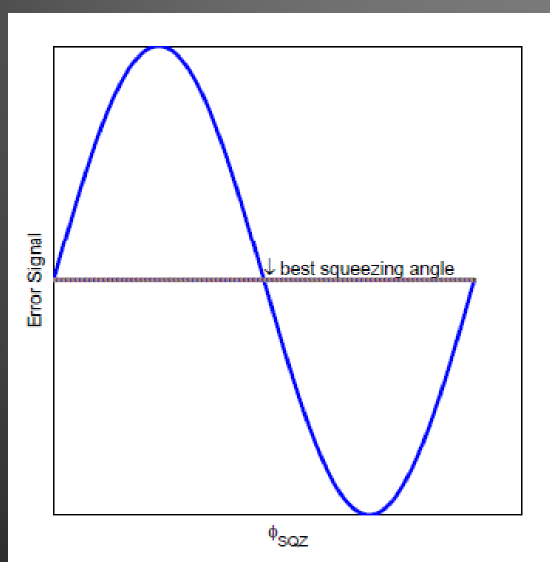
Squeezing angle error signal

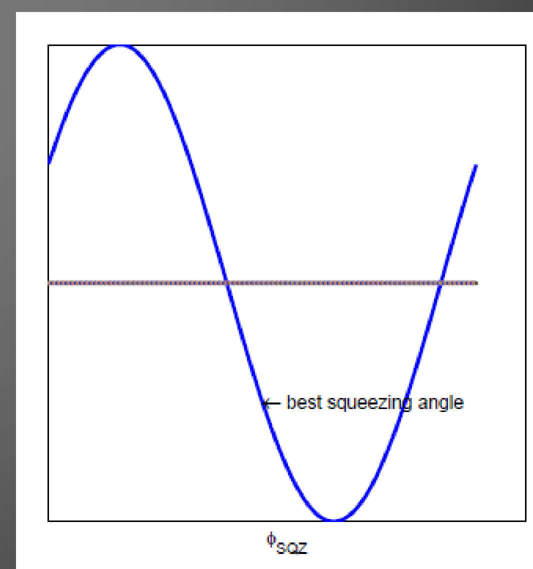
IFO carrier SQZ sideband



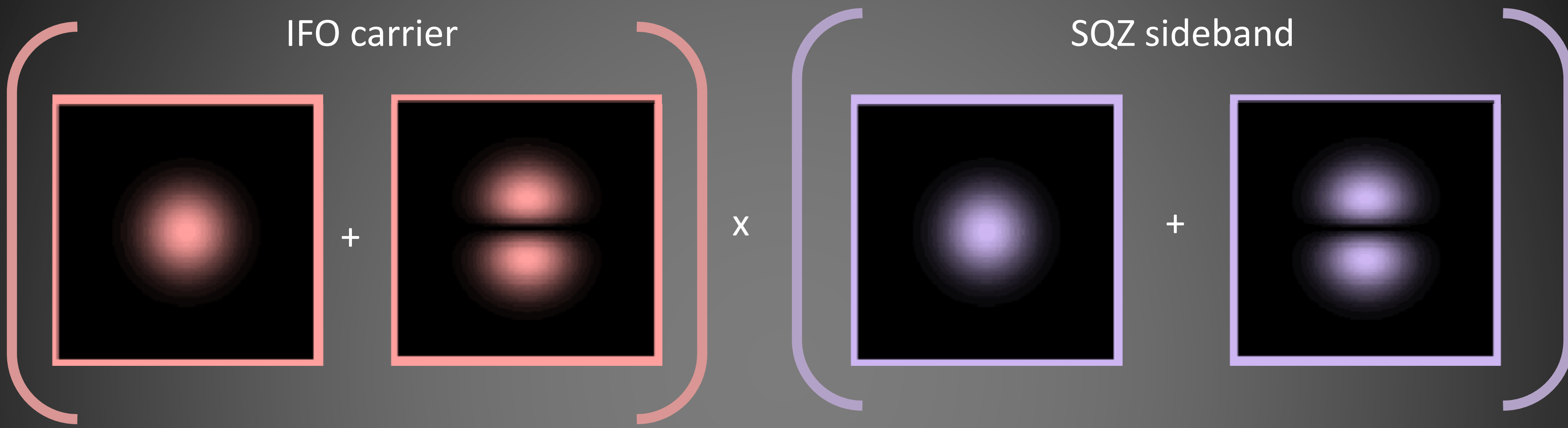
IFO carrier SQZ sideband

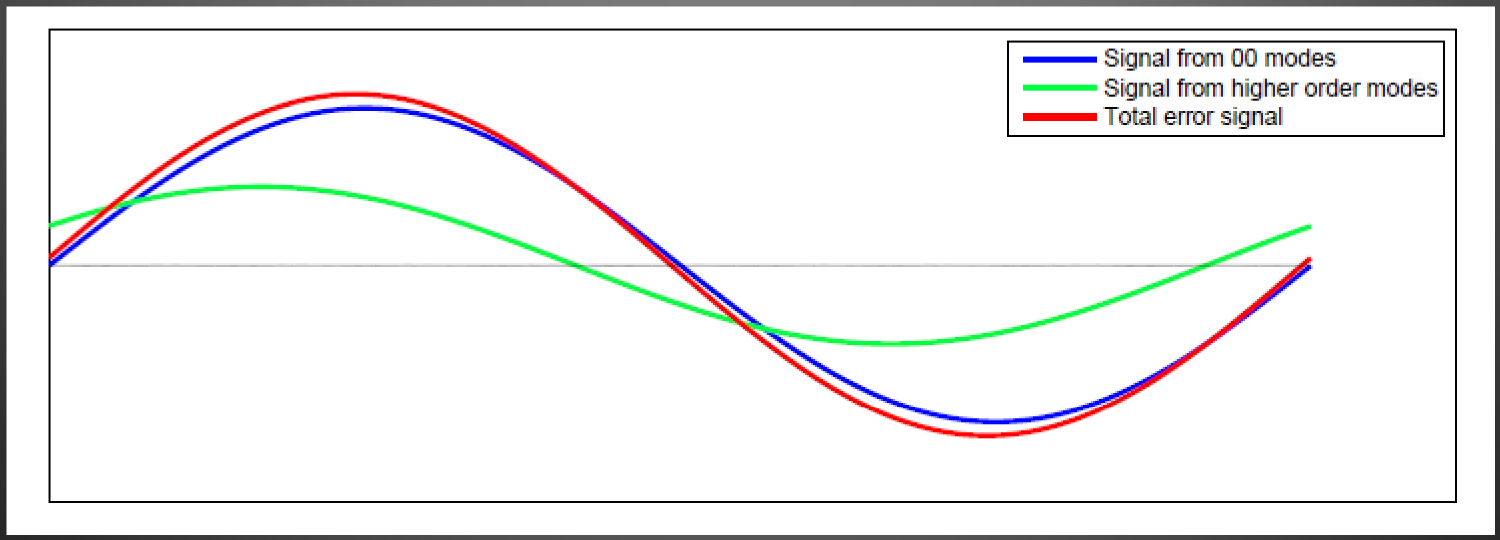




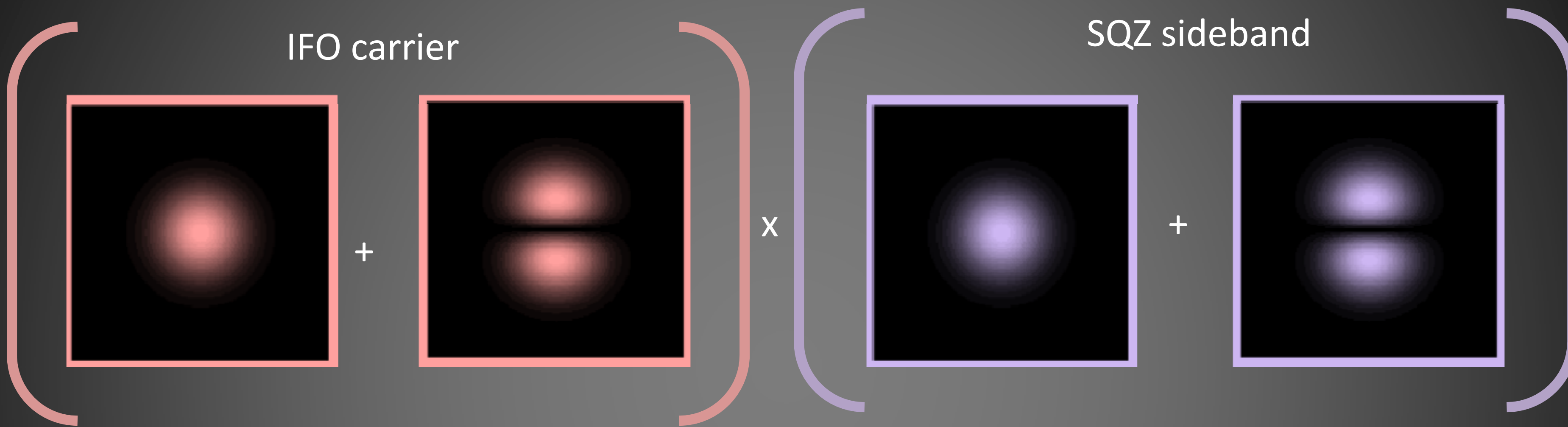


Squeezing angle error signal





Squeezing angle error signal



- Static misalignments will cause a change in the demodulation phase needed to detect the maximum squeezing
- Beam jitter will add phase noise, especially when beating against a static misalignment.