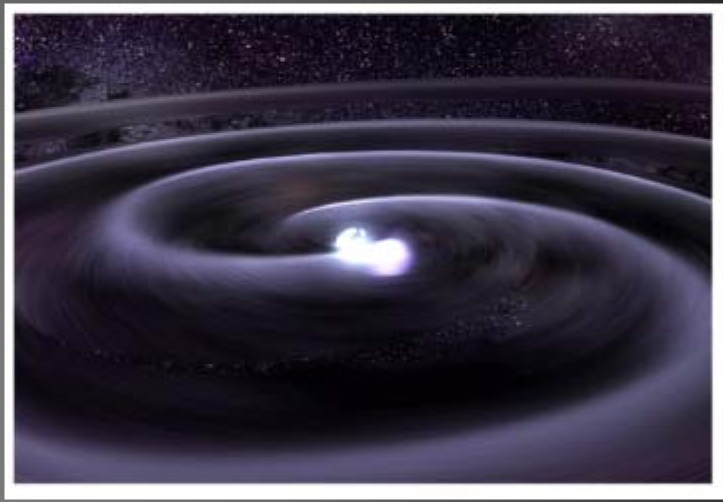
Quantum Enhanced Gravitational Wave Detector

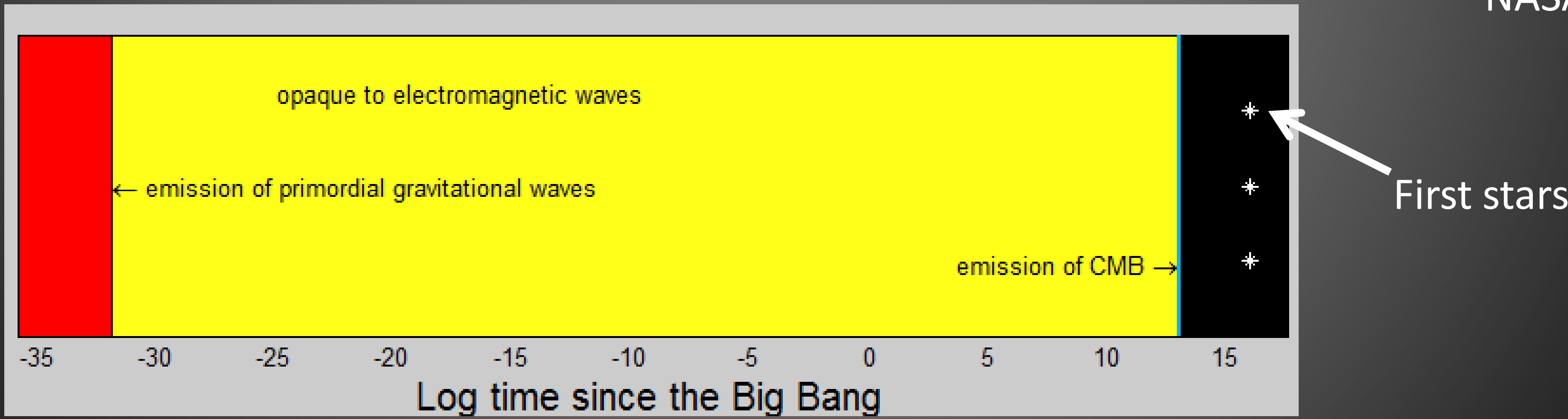
Squeezed state injection into a LIGO interferometer

Gravitational waves

- Predicted by general relativity
- Generated by large accelerating masses – astrophysical in origin
- An entirely new spectrum for astrophysics observations



NASA

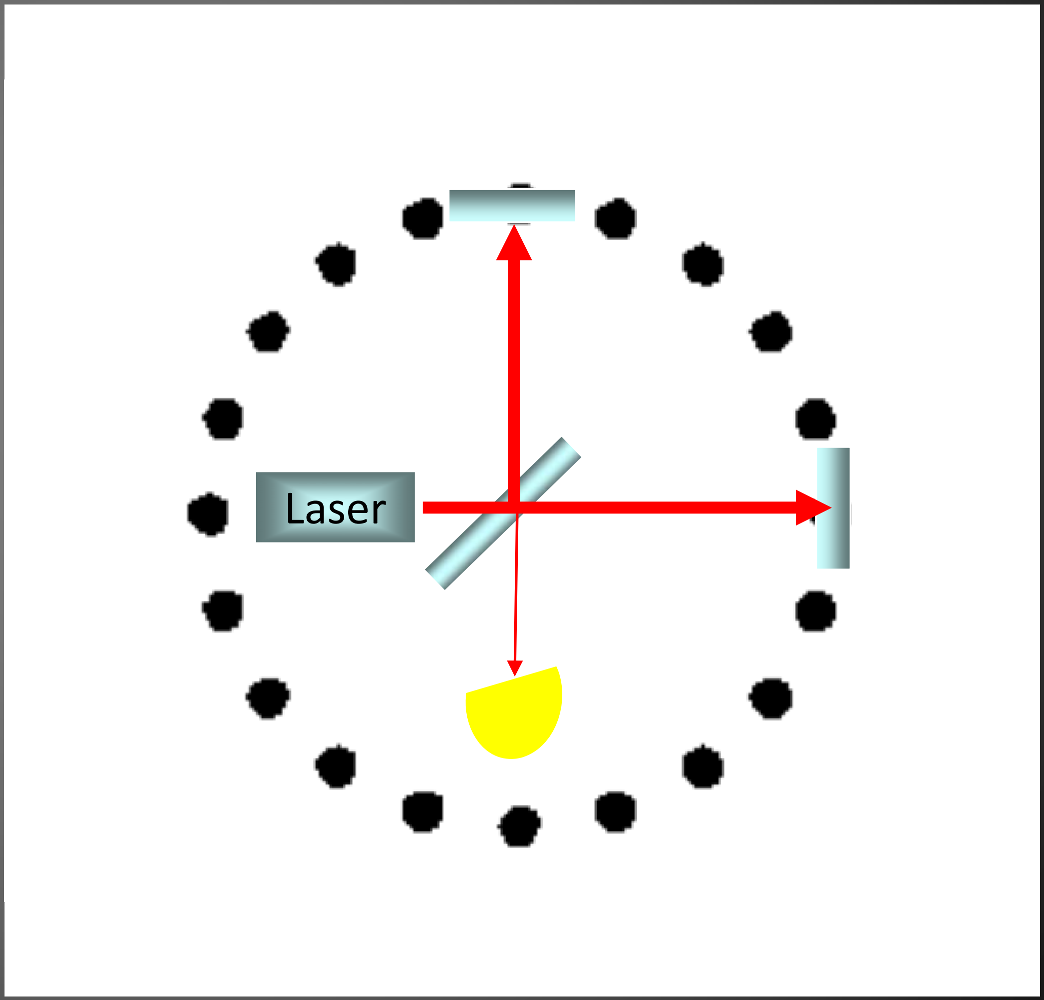


Gravitational waves interact weakly with matter

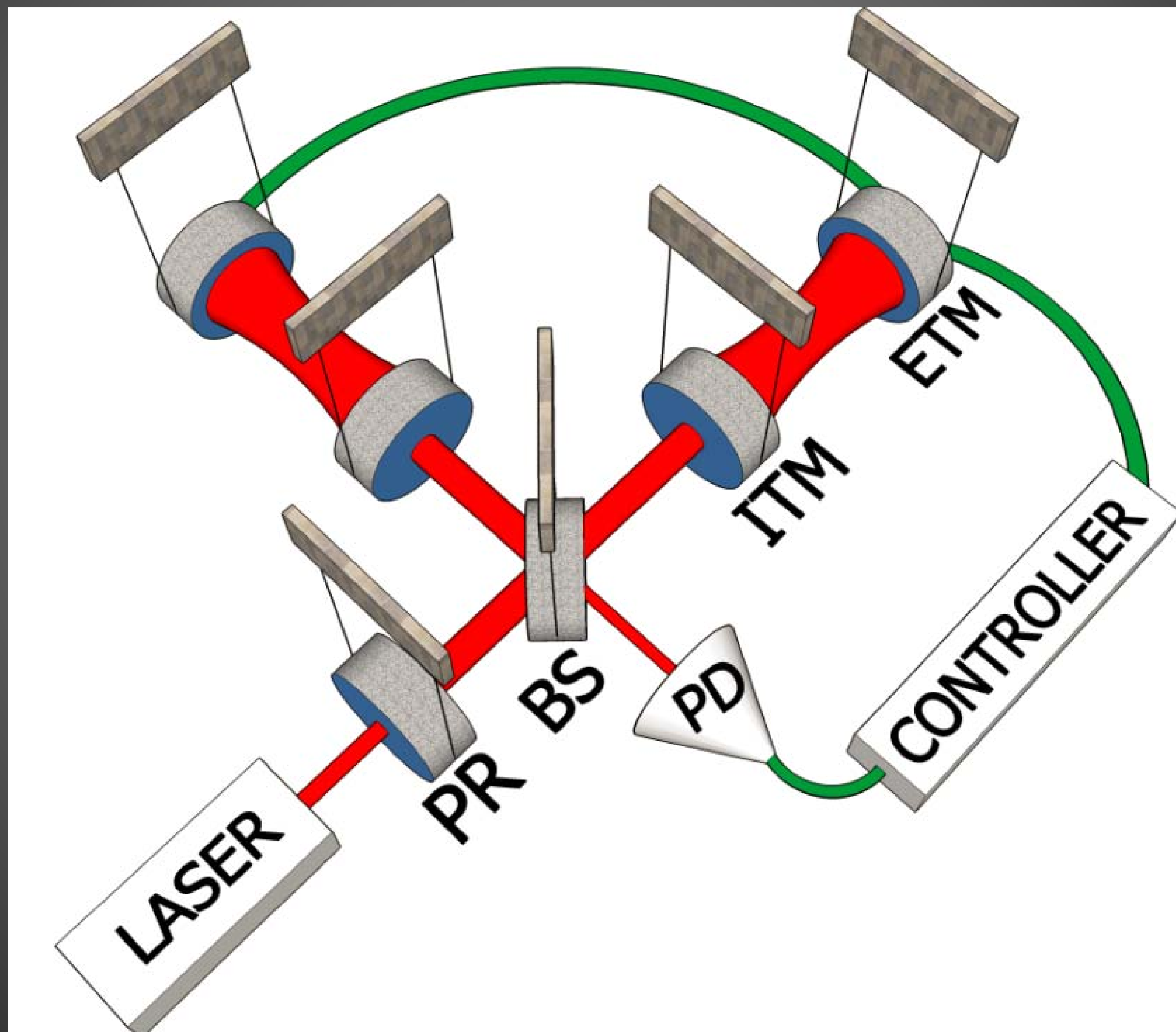
Gravitational waves also interact weakly with detectors

Detection is a real challenge

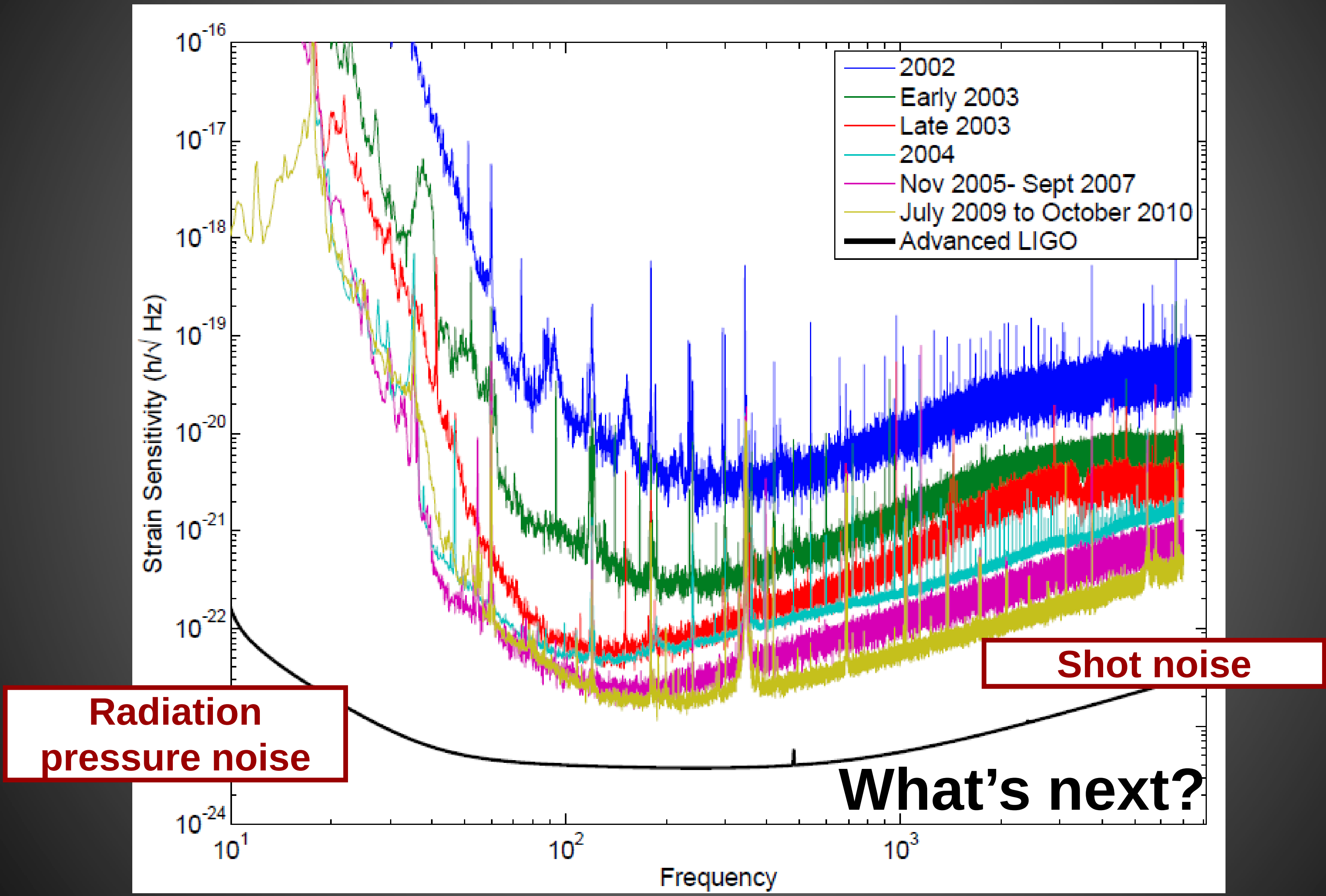
4 km arms
10^{-19} meter displacements
(proton radius 10^{-15} meters)
Frequencies 10Hz-10kHz



Initial LIGO interferometers



LIGO sensitivity limited by quantum noise



We will want to reduce quantum noise

Quadrature Field Amplitudes

$$\hat{E} = \hat{X}_1 \cos \omega t + i\hat{X}_2 \sin \omega t$$

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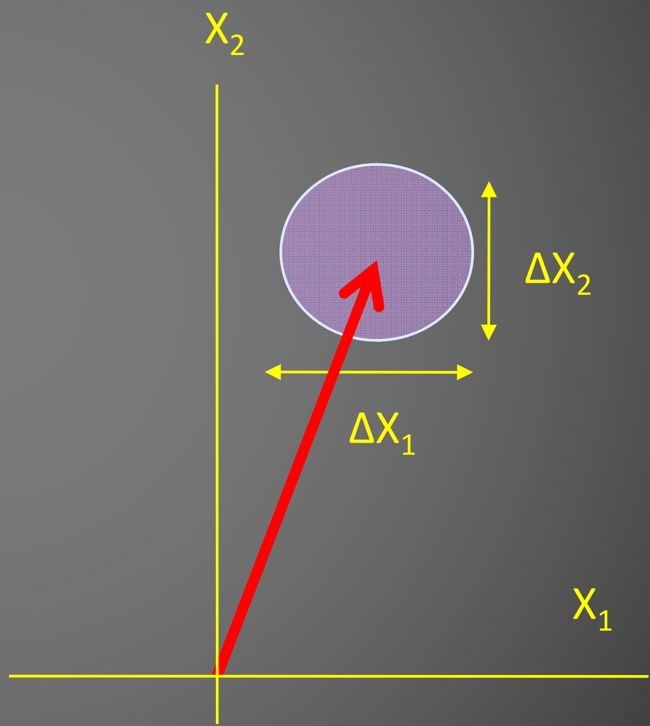

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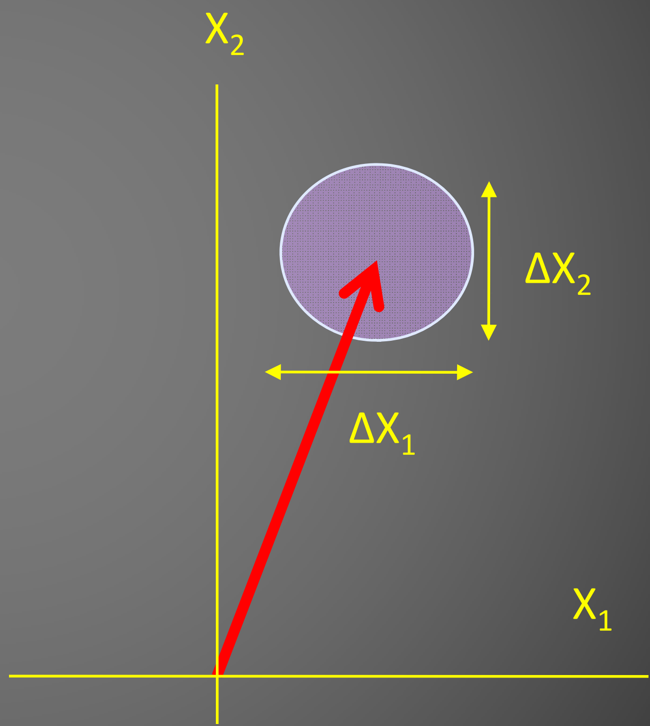
Quadrature Field Amplitudes

$$\hat{E} = \hat{X}_1 \cos\omega t + i\hat{X}_2 \sin\omega t$$

The uncertainty principle

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



Coherent State

Quantized Electromagnetic Field

Quadrature Field Amplitudes

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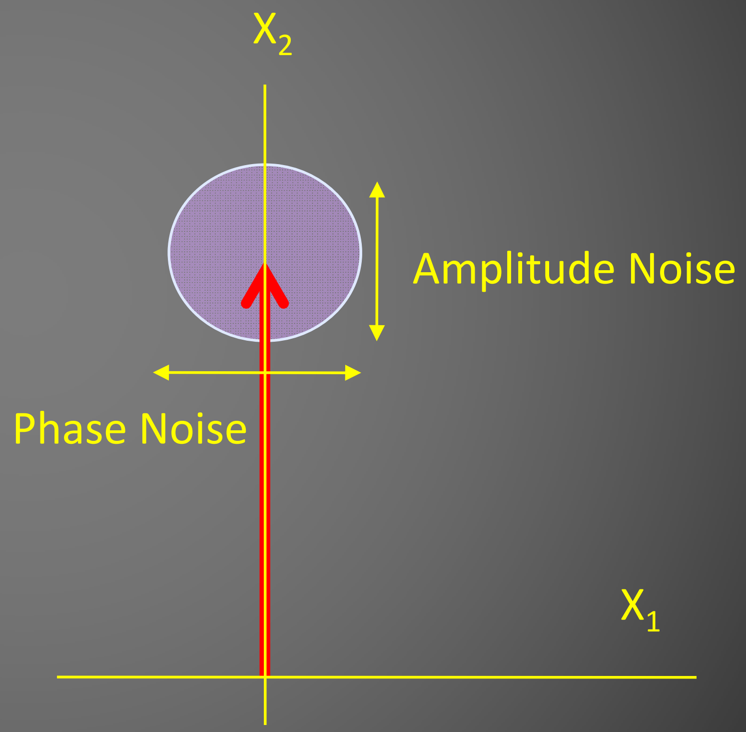


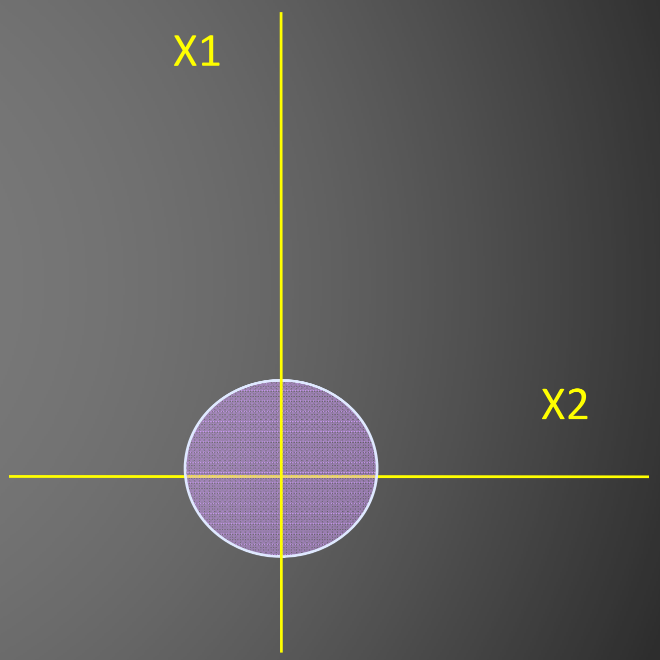
Coherent State

Vacuum Fluctuations

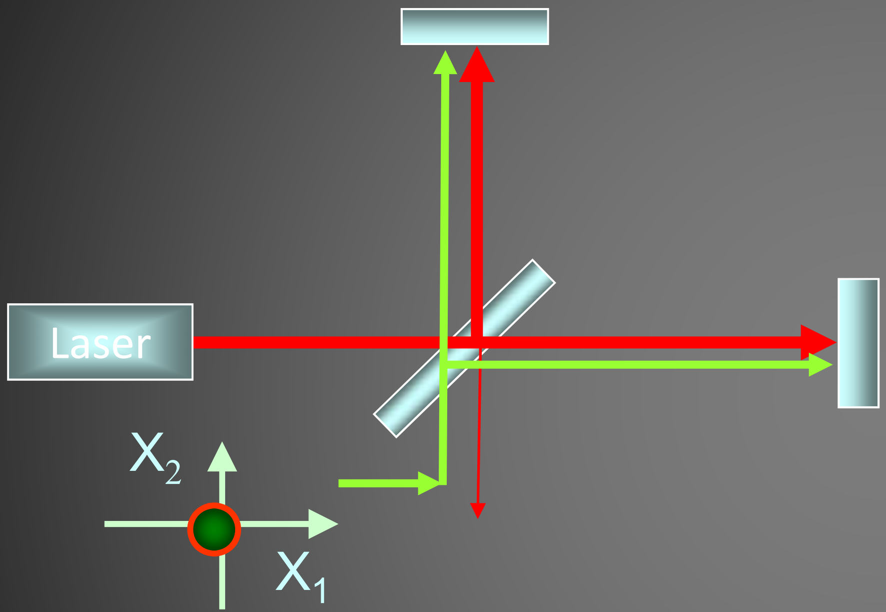
•When average amplitude is zero, the variance remains

•Vacuum fluctuations are everywhere that classically there is no field.

•Need to consider the effect of vacuum on the interferometer to understand quantum noise.

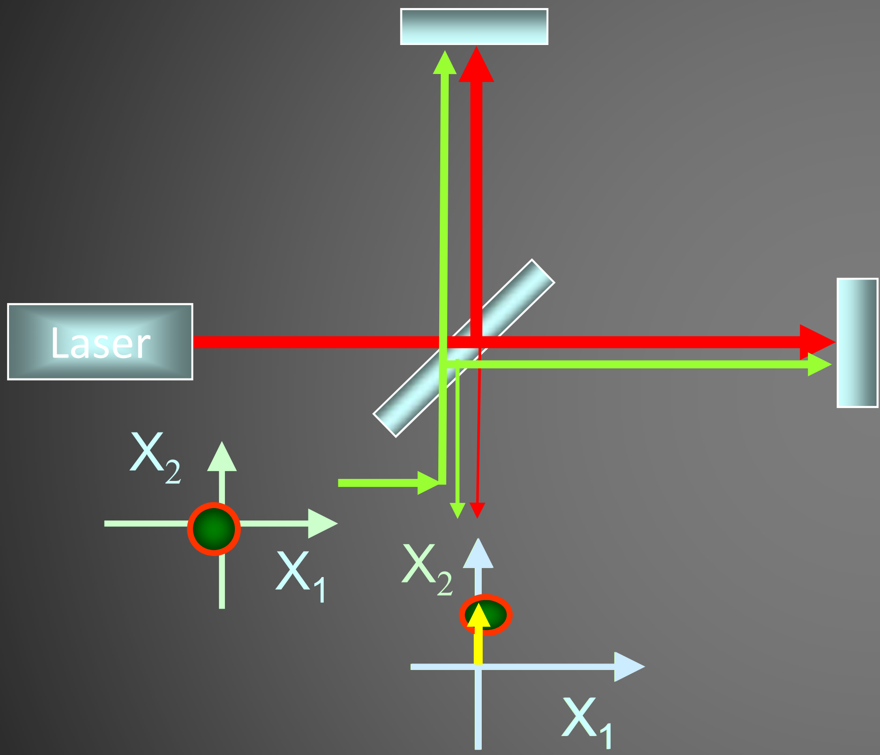


Quantum Noise in Interferometers



•Vacuum fluctuations enter at the unused port of the beam splitter.

Quantum Noise in Interferometers



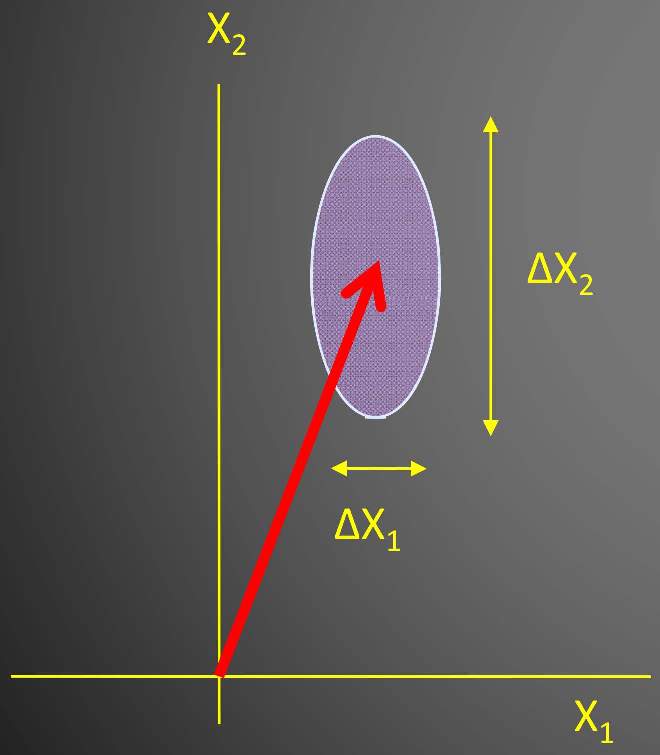
•Vacuum fluctuations enter at the unused port of the beam splitter.

•Vacuum fluctuations entering from the dark port cause quantum noise in interferometers.

• Understood that this would limit the sensitivity of GW detectors 30 years ago, squeezing proposed as a solution

Caves, Phys. Rev. D (1981)
Yuen, PRA (1976)
Unruh

What is squeezing?



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

There is a minimum uncertainty product (area), but noise can be redistributed

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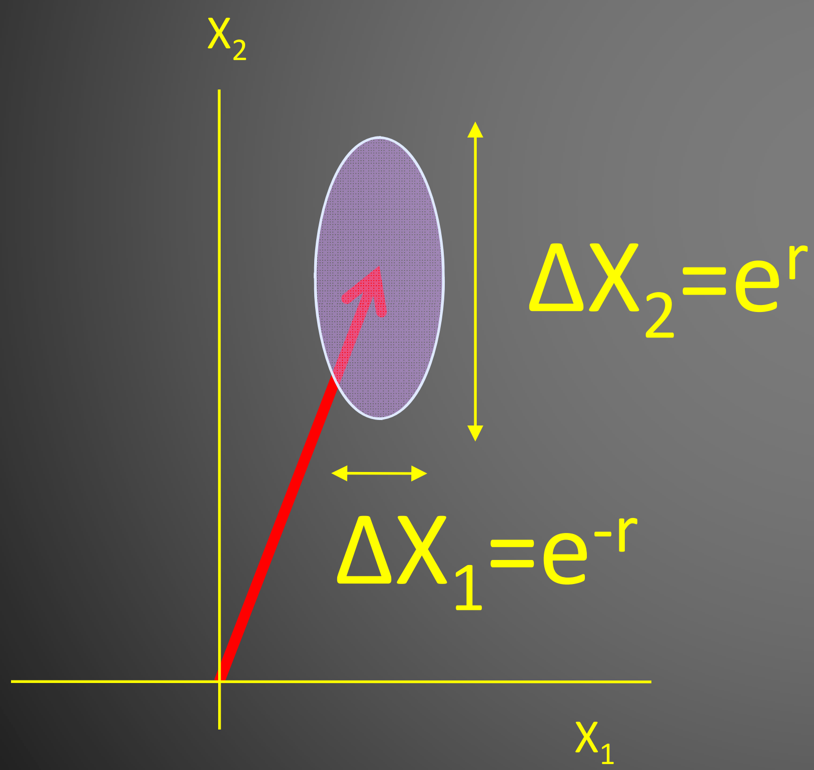

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Squeeze factor r describes level of squeezing and anti squeezing

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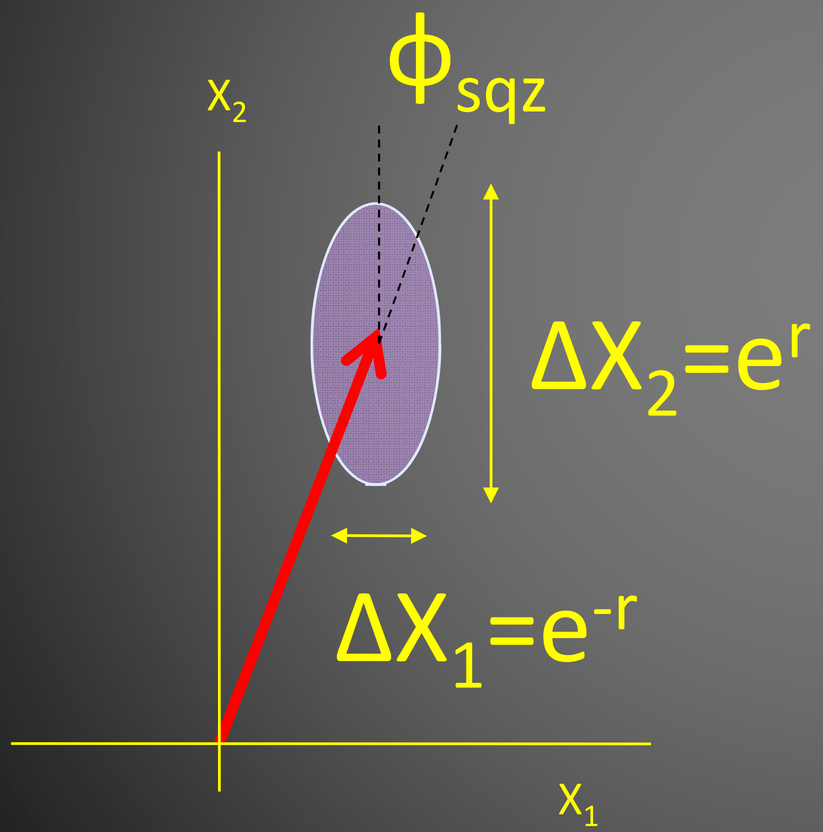


$$\Delta X_1 \, \Delta X_2 \geq 1$$

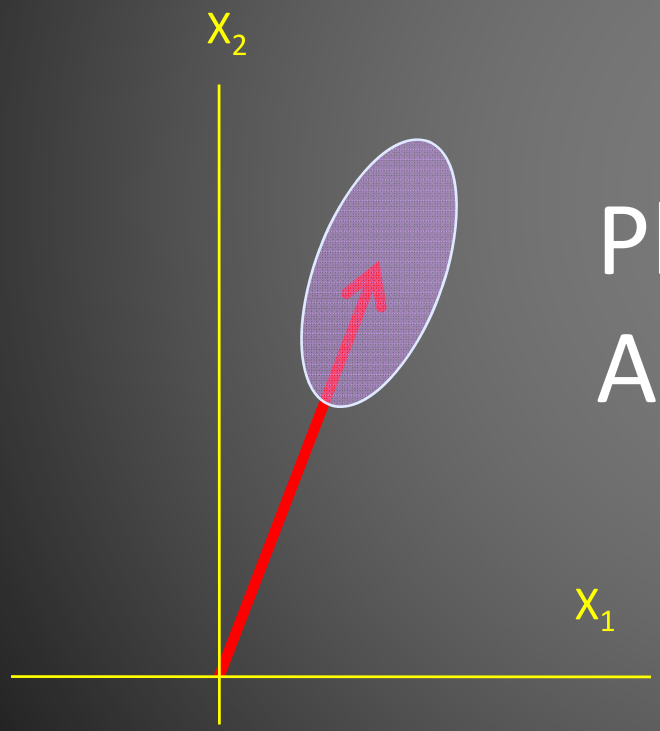
There is a minimum uncertainty product (area), but noise can be redistributed

Squeeze factor r describes level of squeezing and anti squeezing

Squeezing angle φ_{sqz} describes which quadrature is squeezed

What is squeezing?

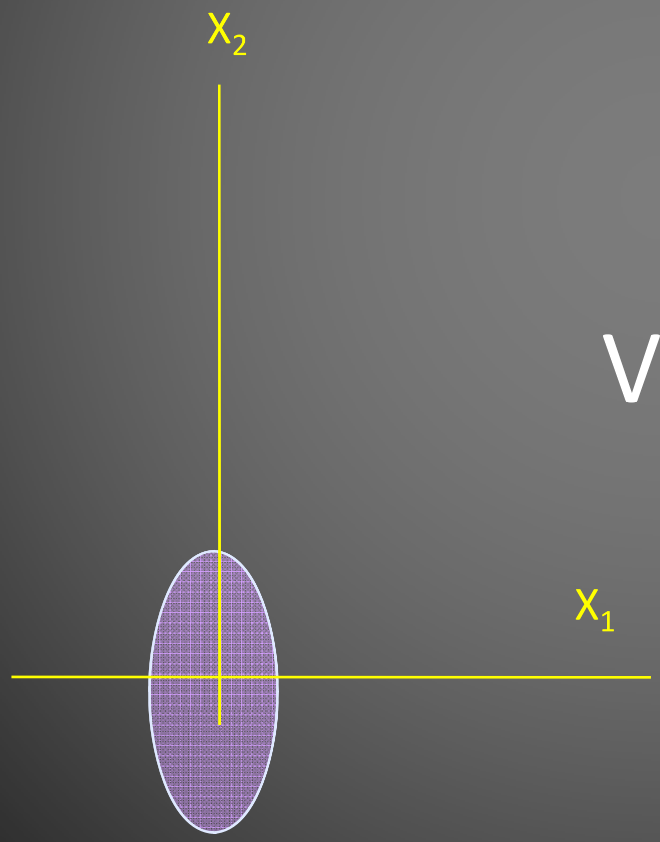
$$\Delta X_1 \, \Delta X_2 \geq 1$$



Phase squeezing

Amplitude anti squeezing

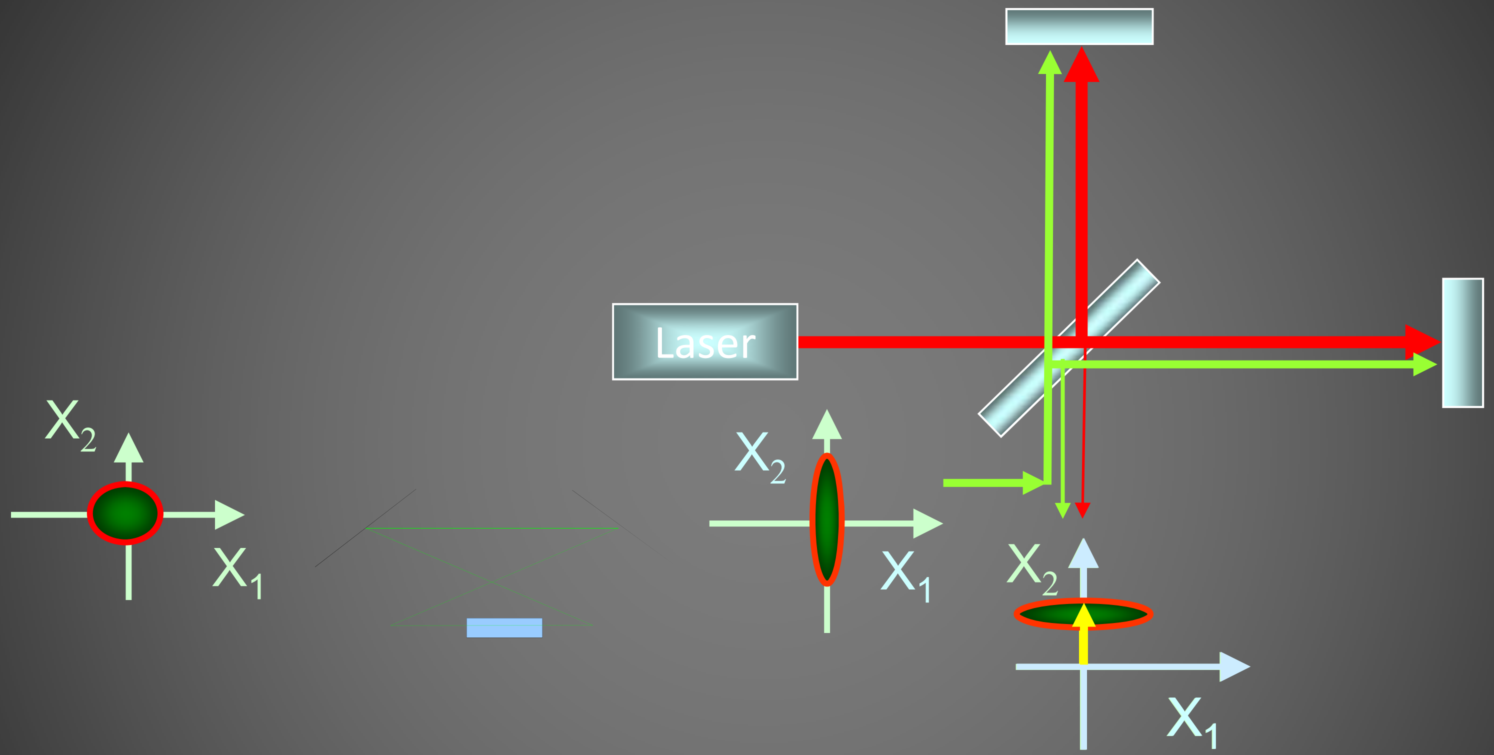
What is squeezing?



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

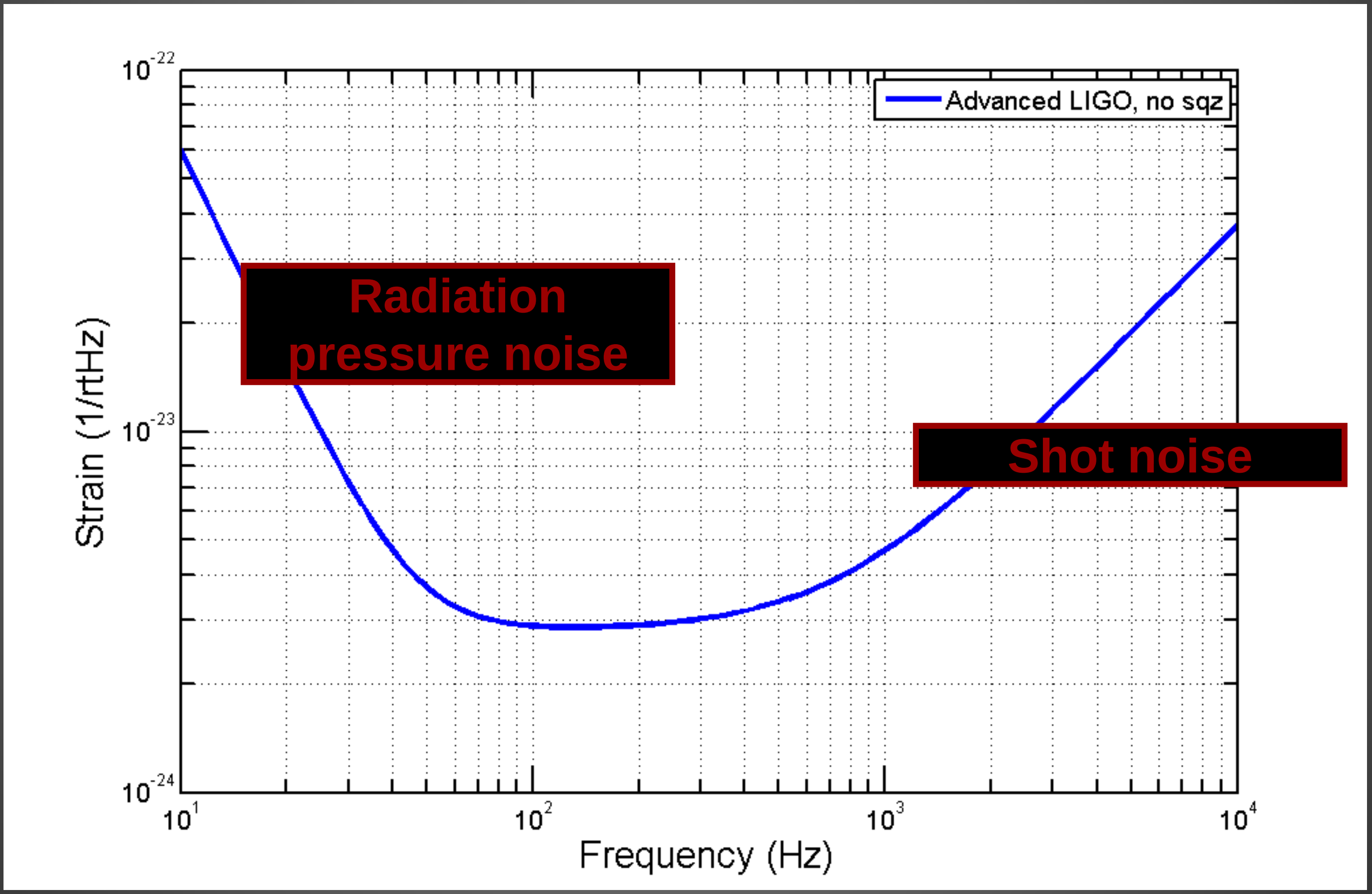
Vacuum Squeezing

Squeezed states in an interferometer

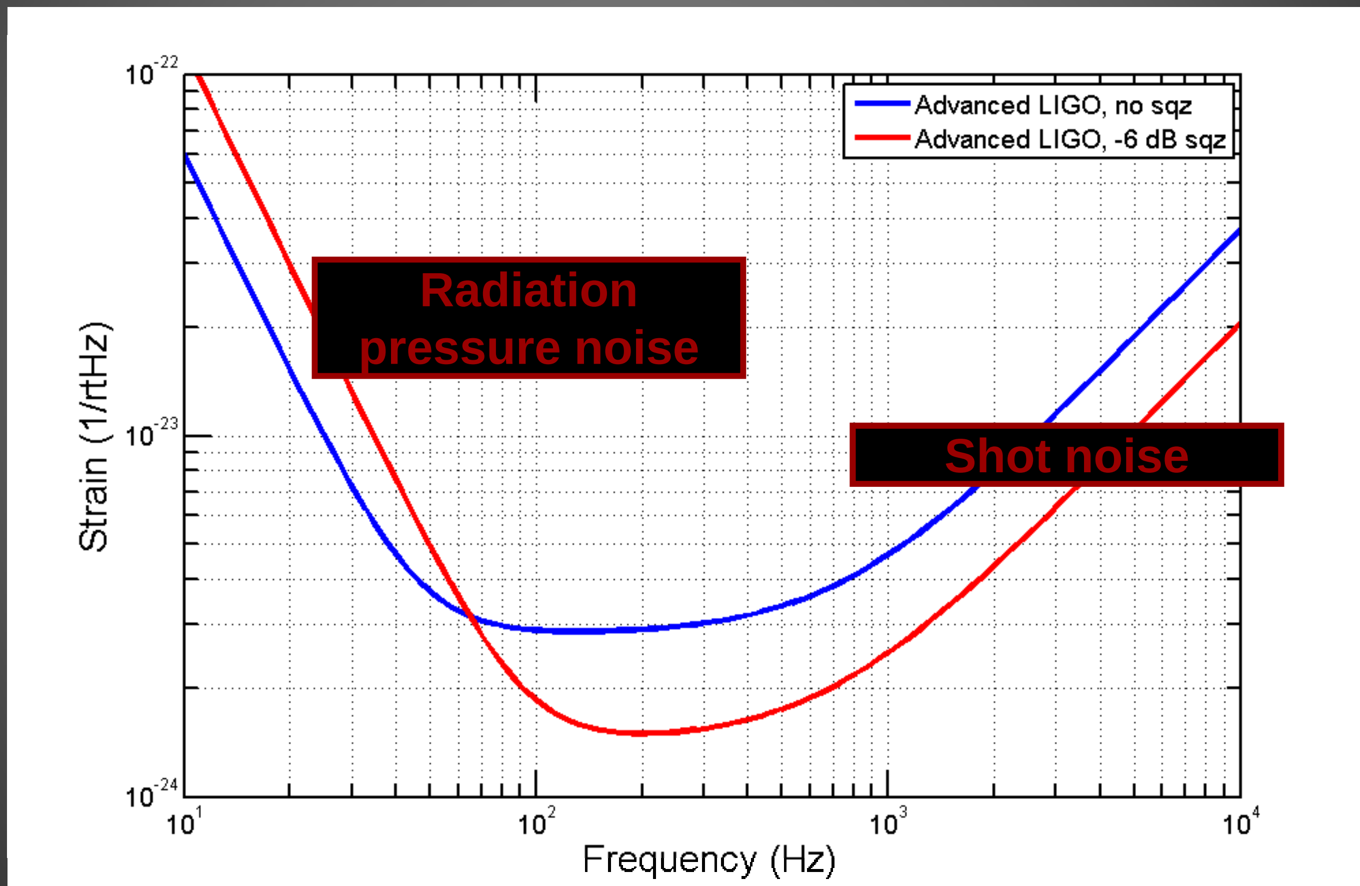


Squeezing the field entering the dark port reduces quantum noise on the gravitational wave readout.

Quantum Noise in Advanced LIGO

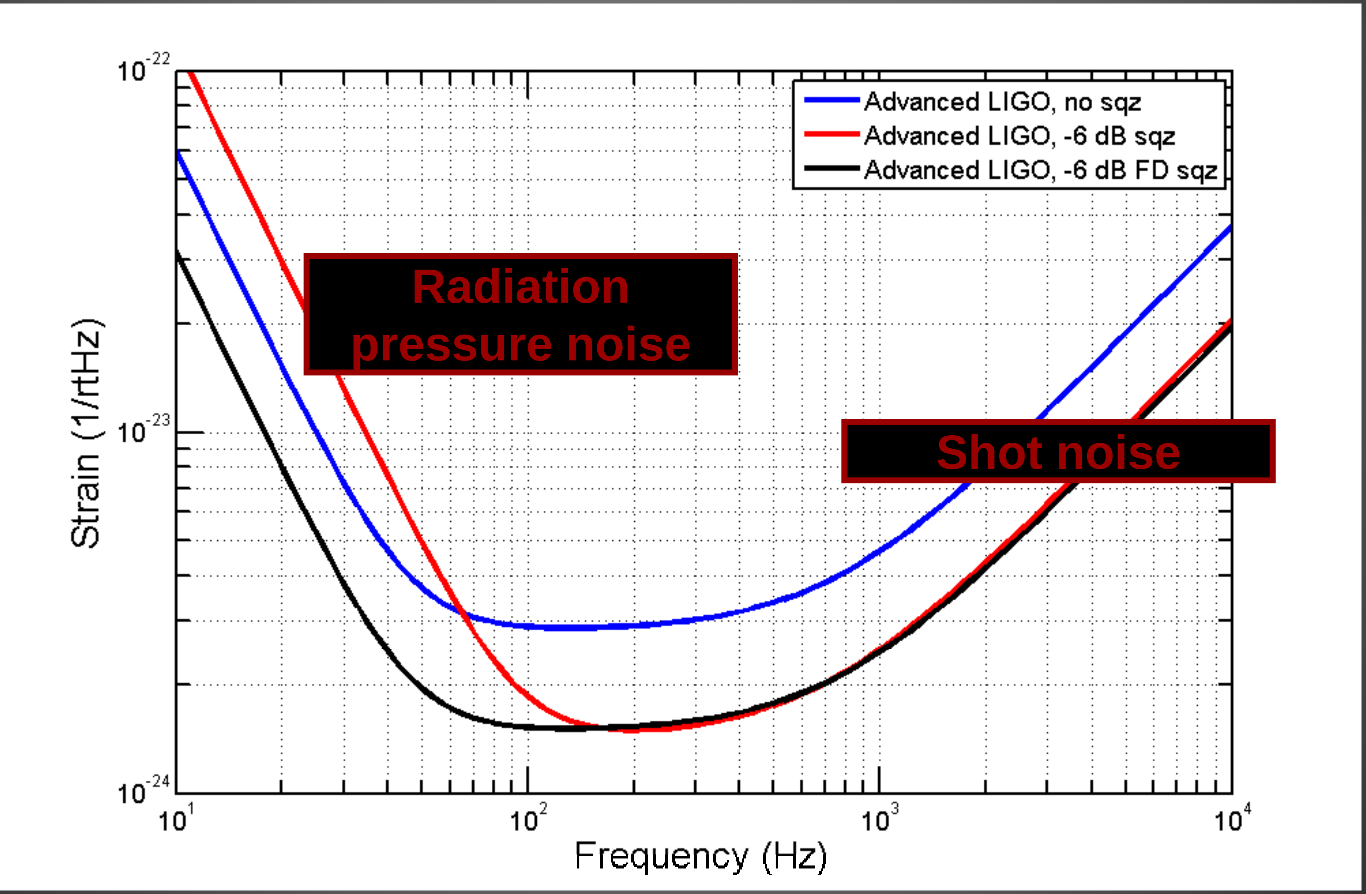


Advanced LIGO with squeeze injection



6dB= factor of 2 reduction in noise
equivalent to a factor of 4 increase in laser power

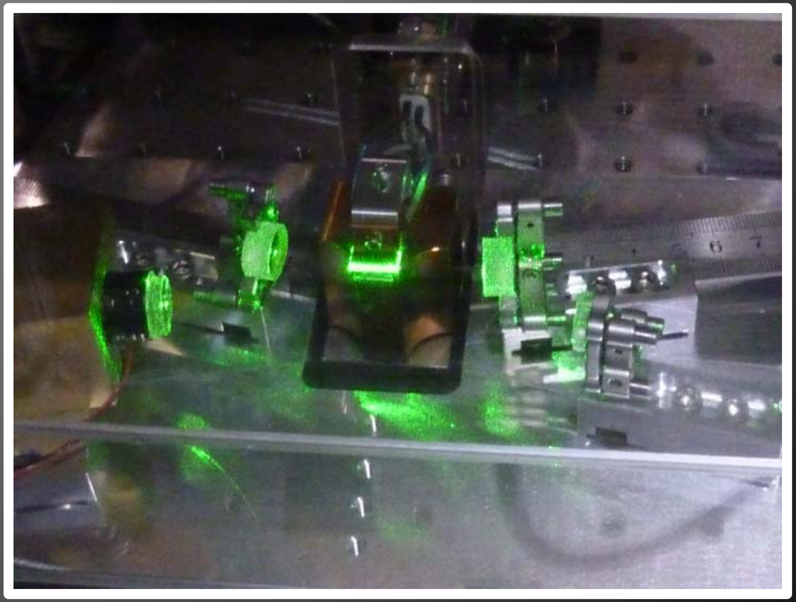
Advanced LIGO with squeeze injection



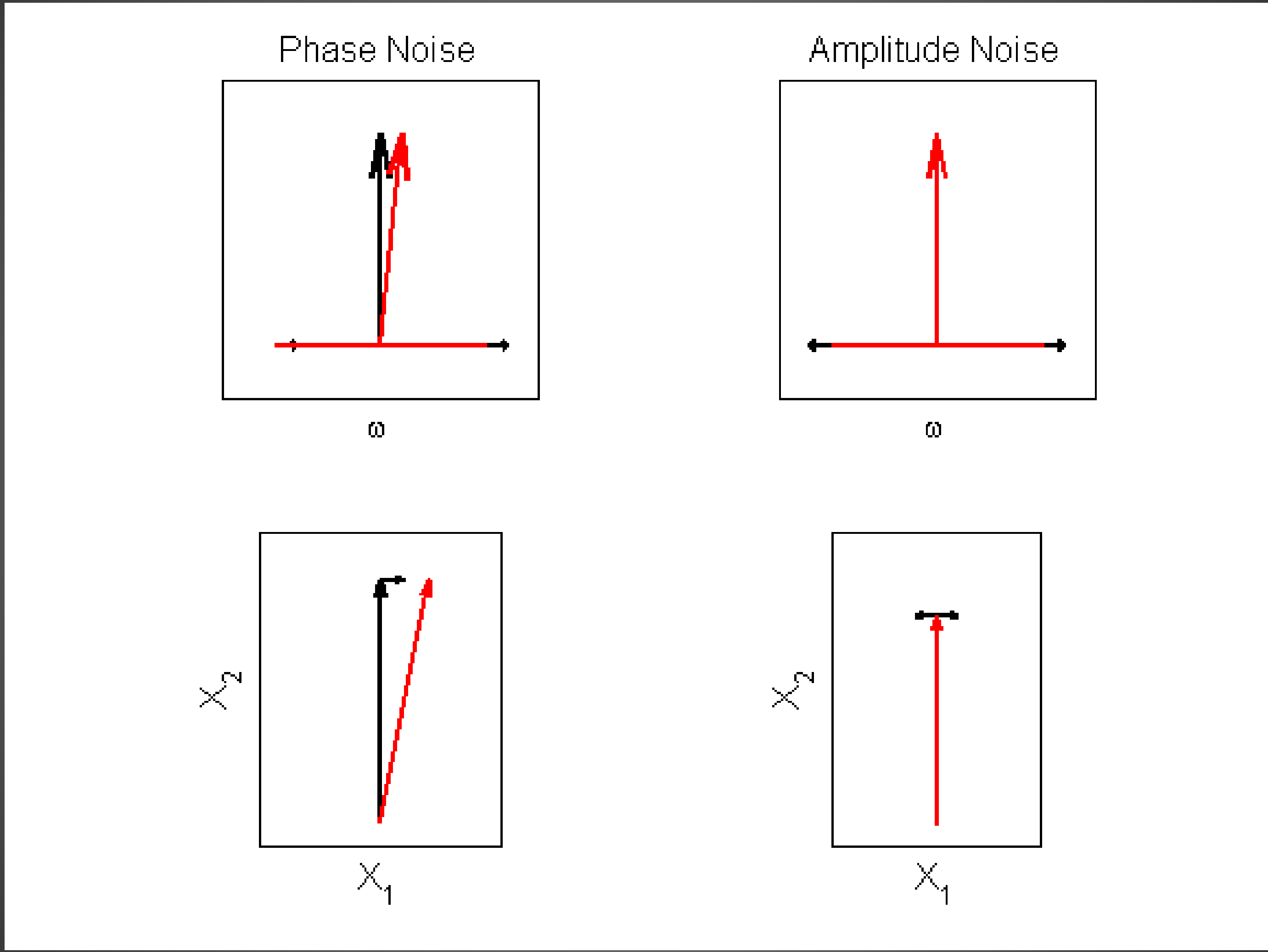
Frequency dependant squeezing will allow reduction of quantum noise at all frequencies.

Our Squeezer

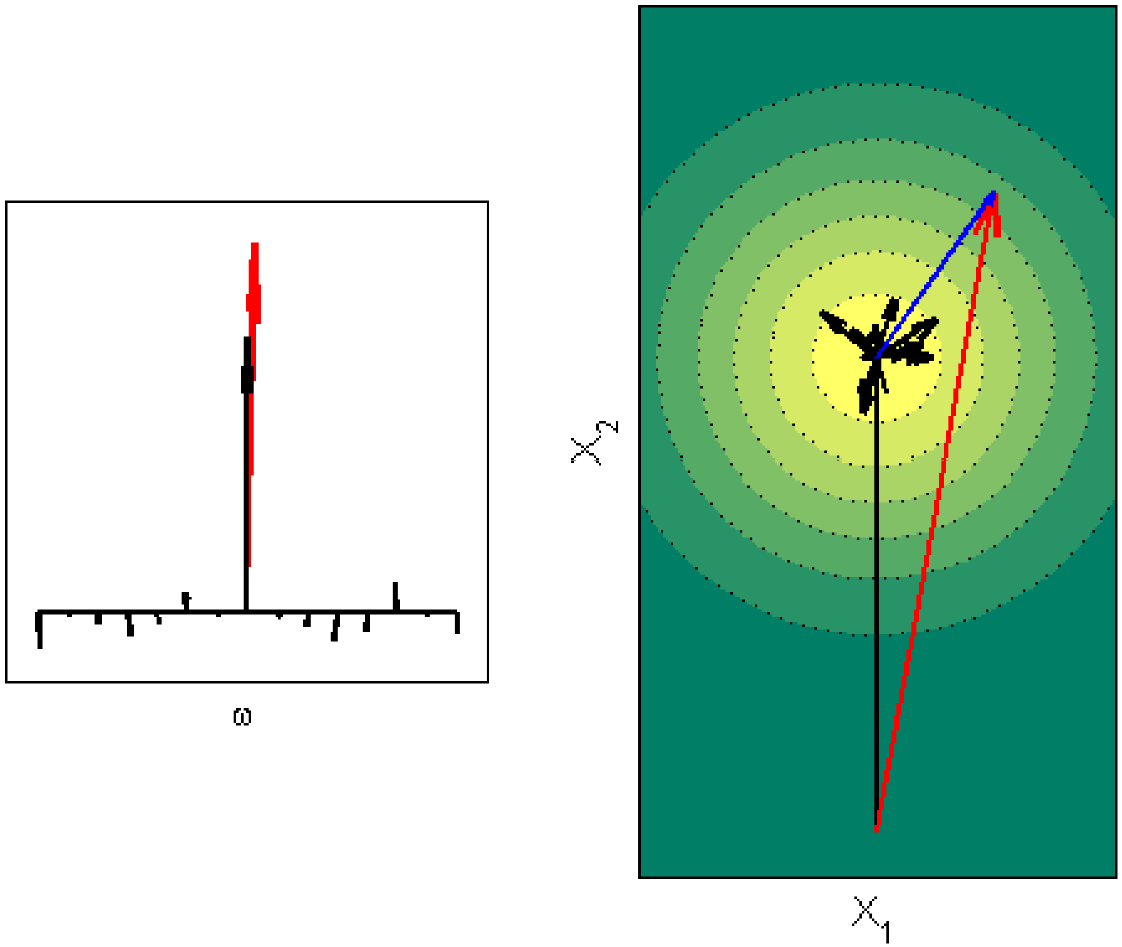
Uses nonlinear optics to squeeze vacuum fluctuations by creating correlations between symmetric sidebands



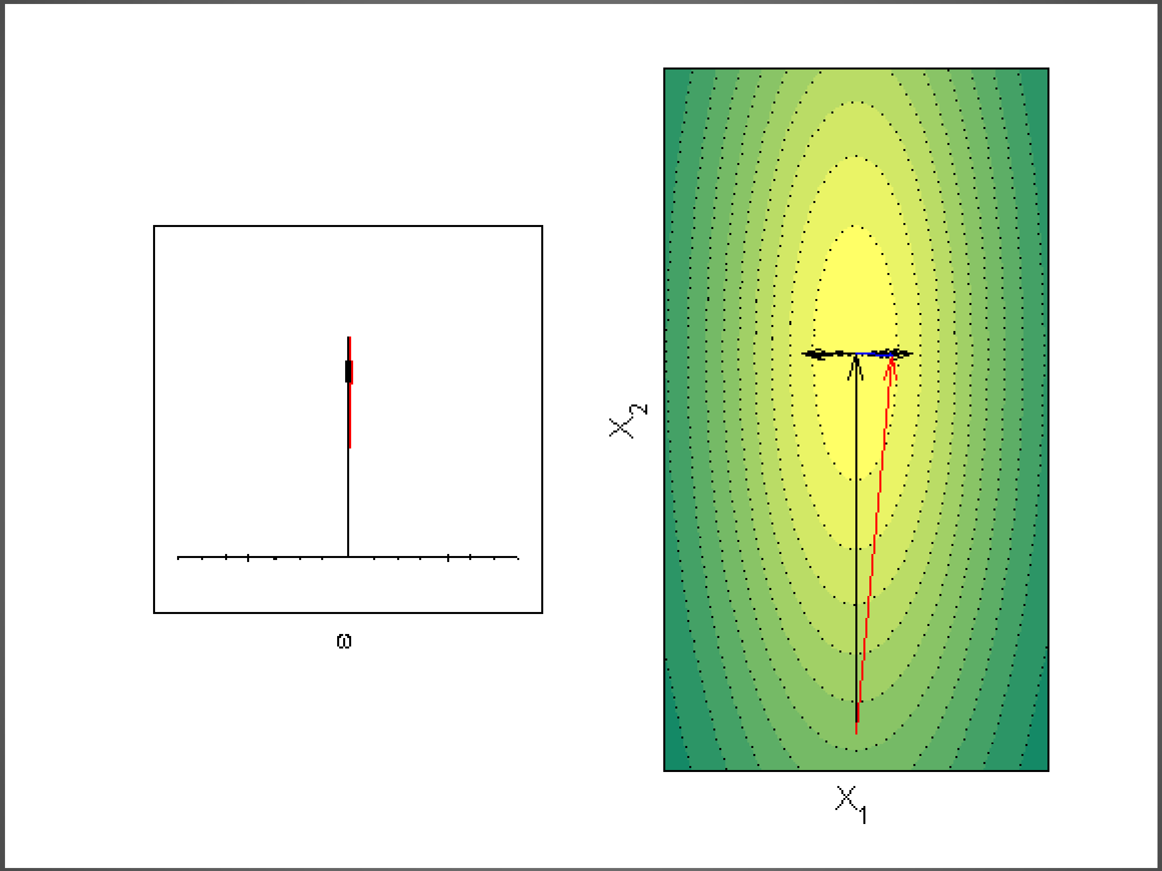
Noise Sidebands



Uncorrelated sidebands make a coherent state

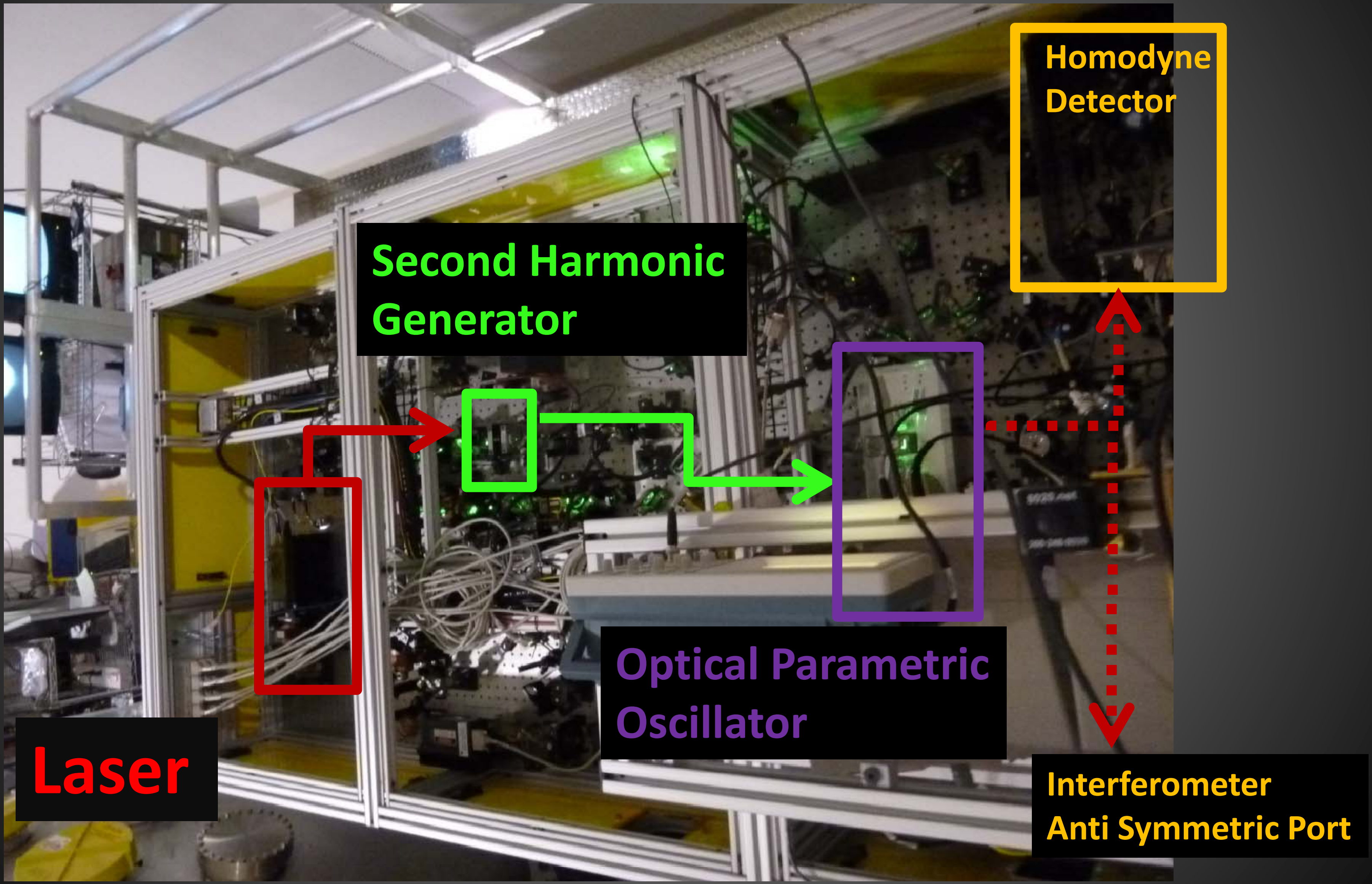


Correlated sidebands make a squeezed state

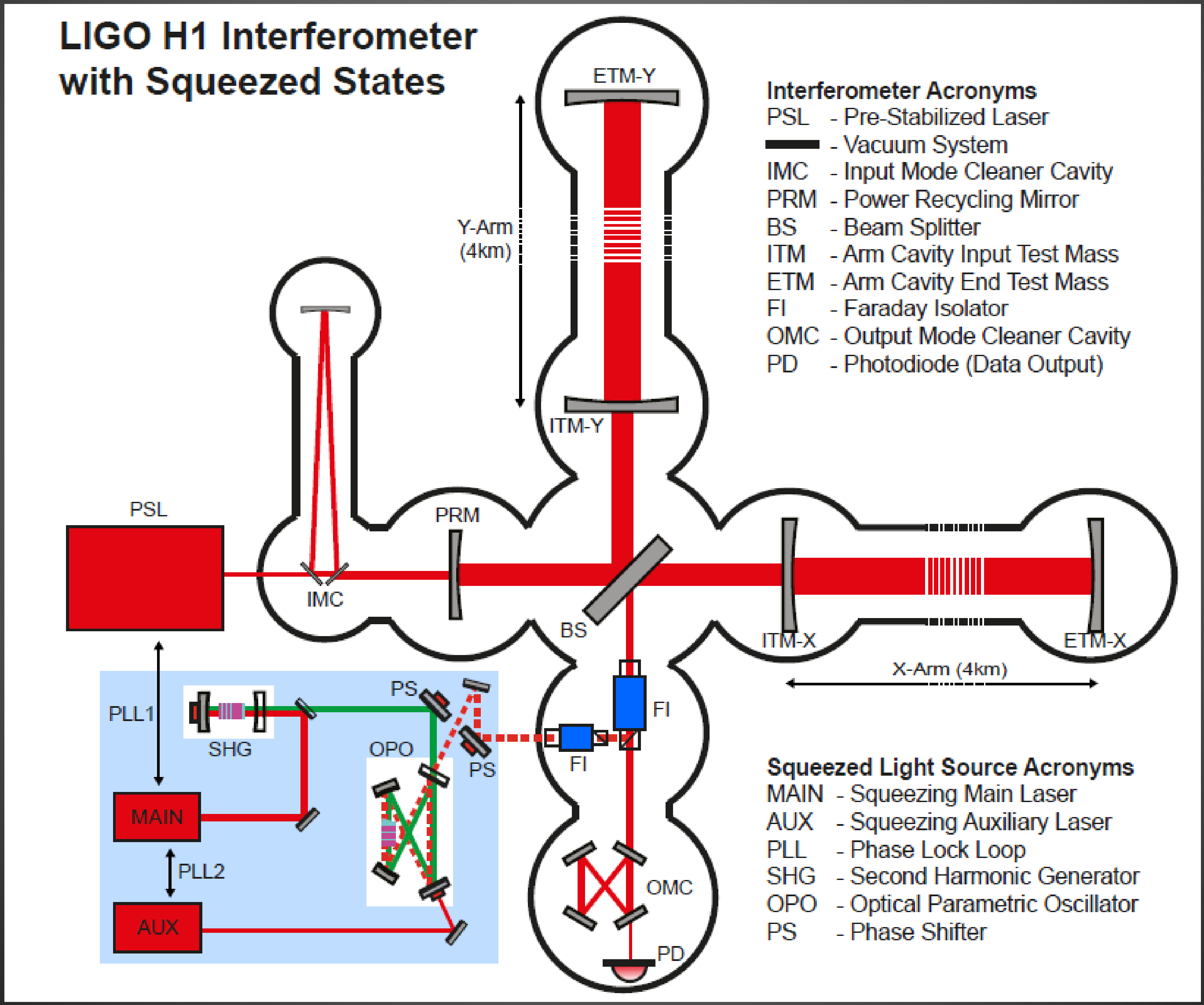


X_2

A squeezer table



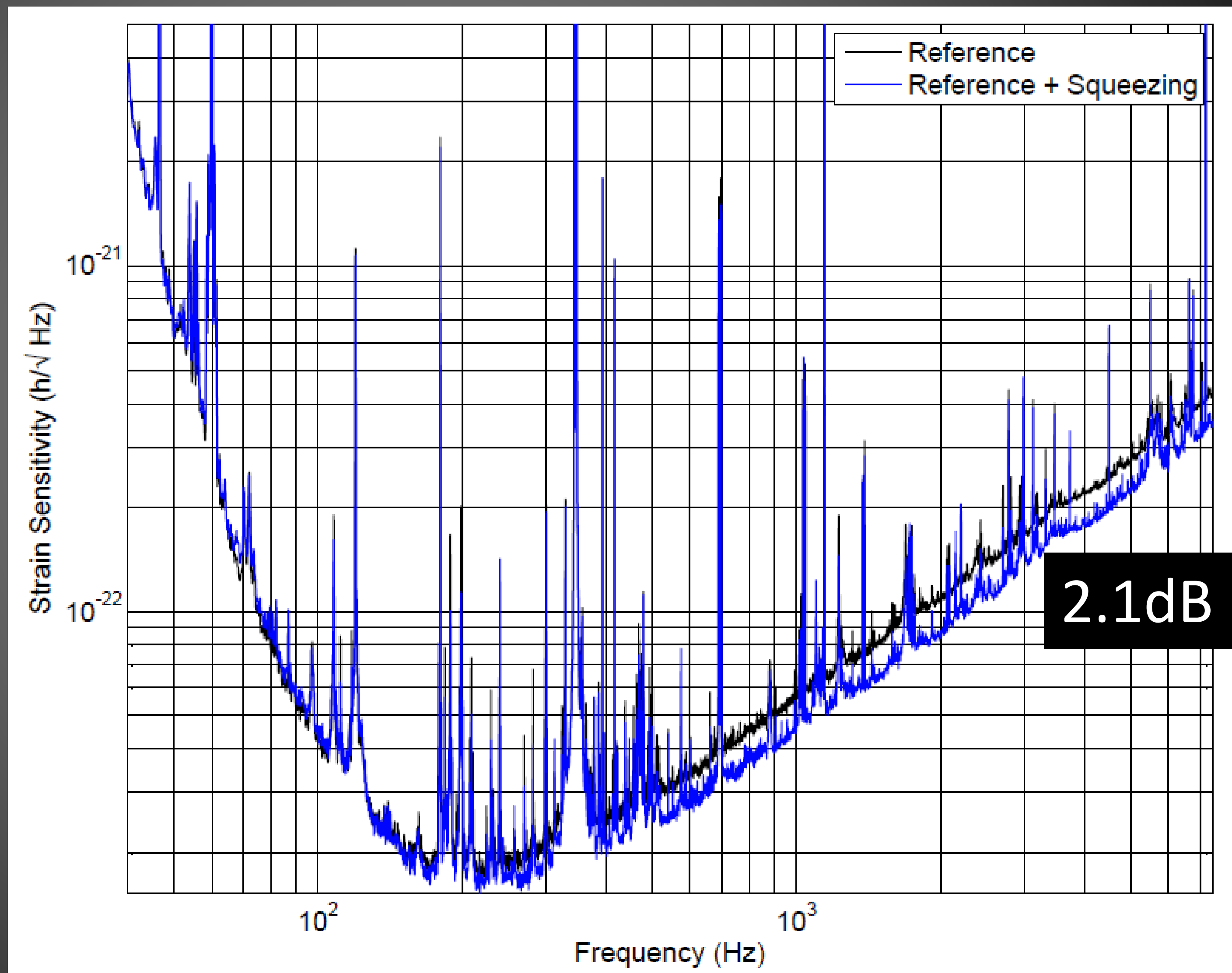
Experimental Layout



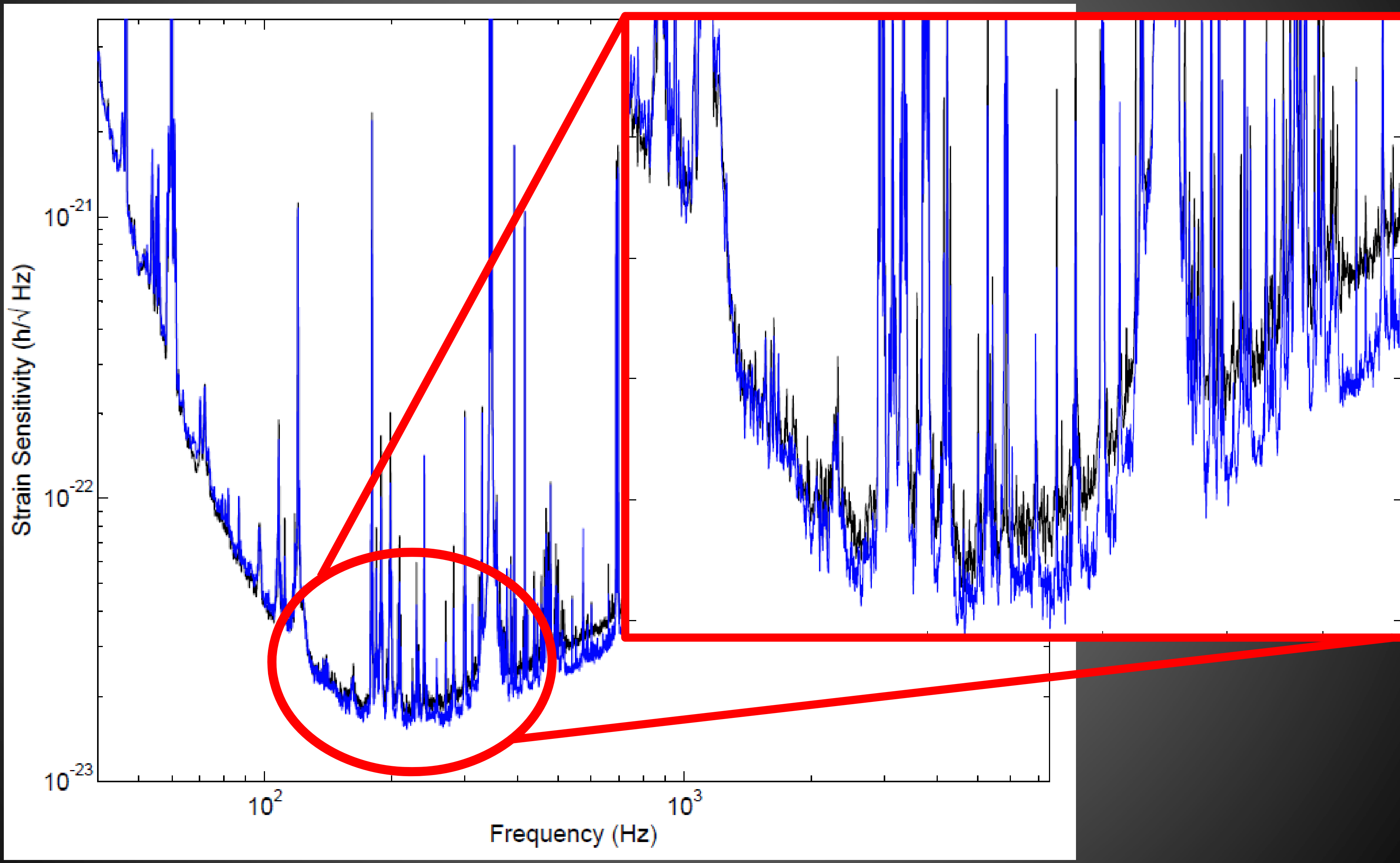
Results

Squeezing does not add noise at any frequency

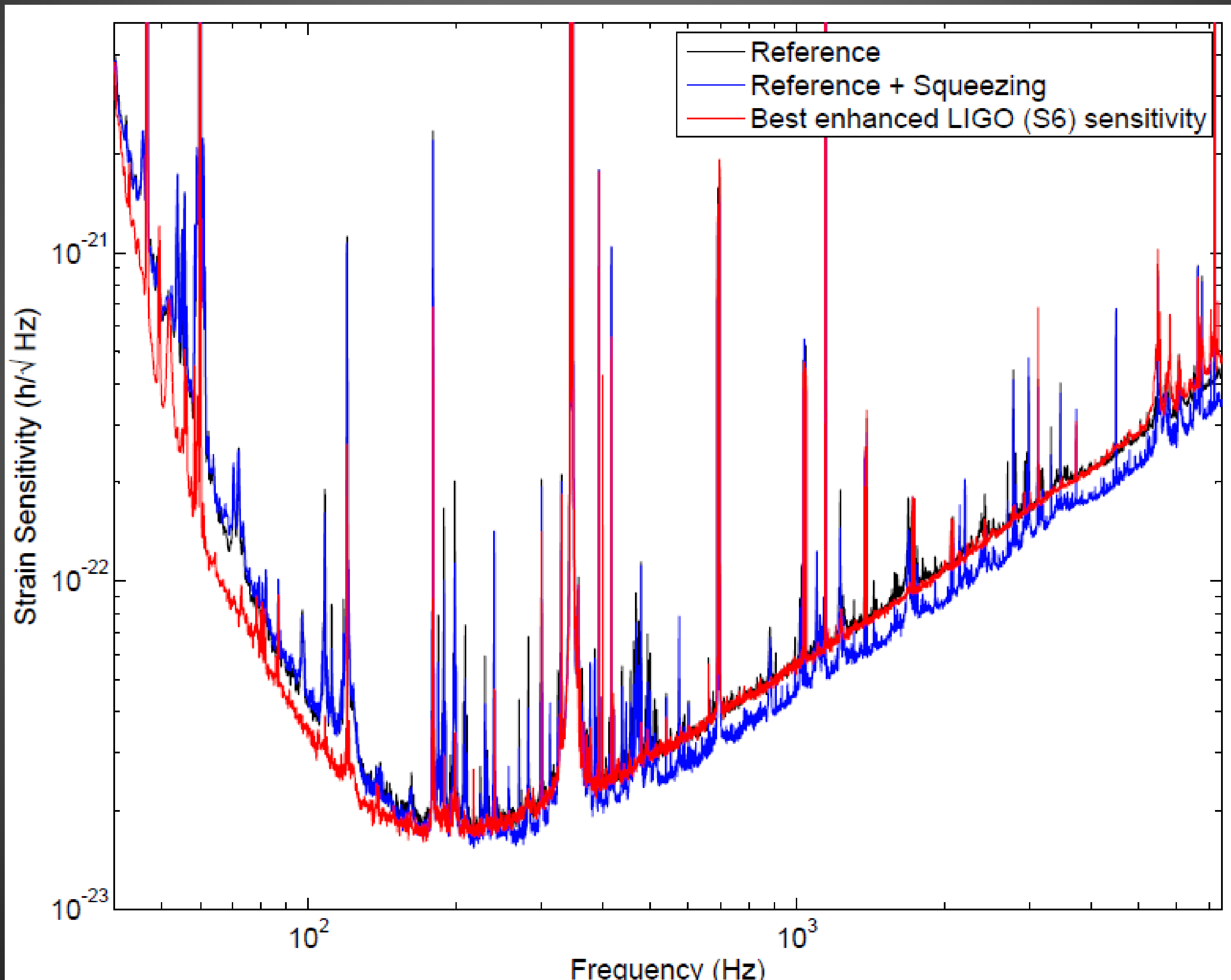
Inspiral Range improved by 1Mpc (5%)



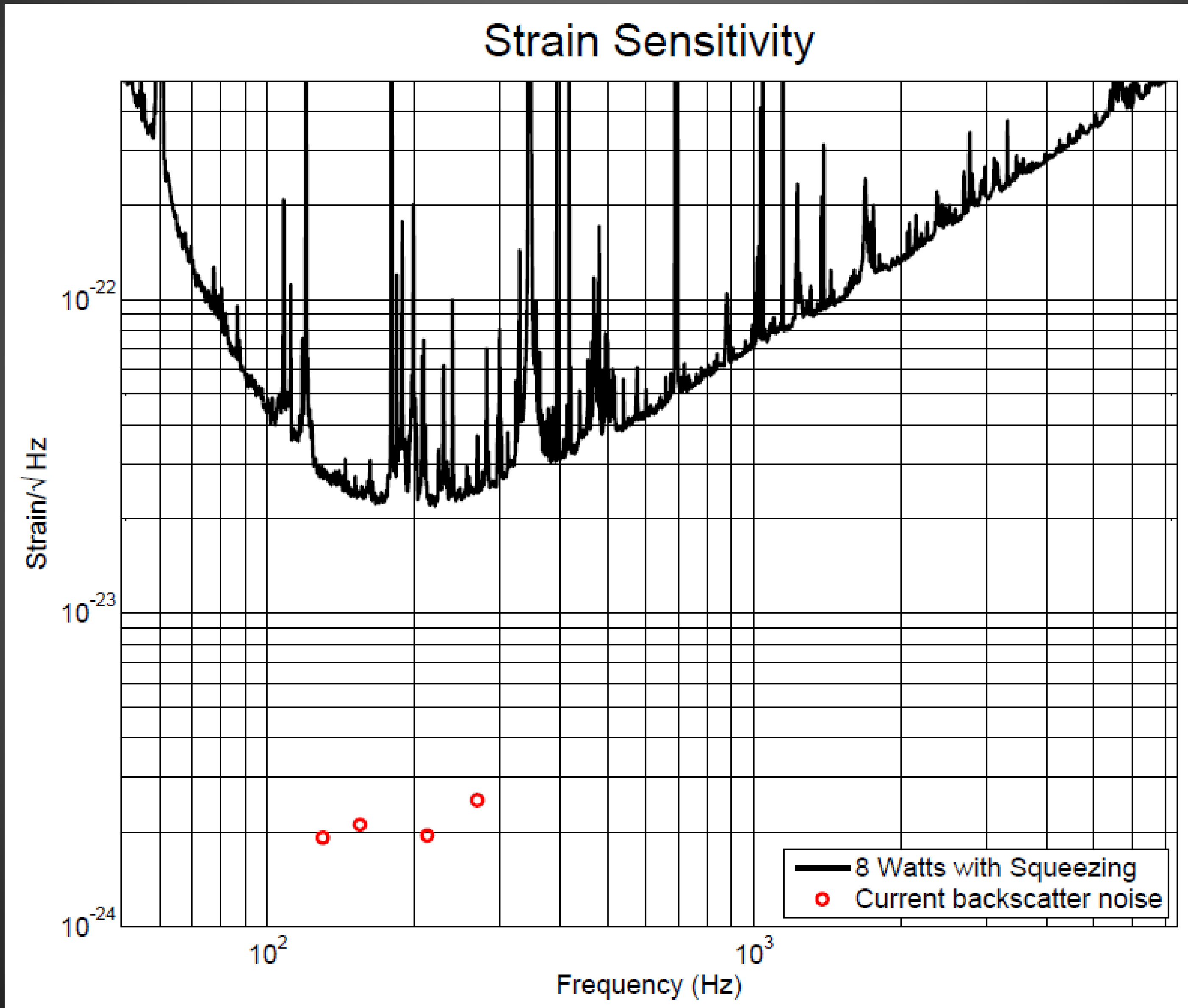
Enhanced LIGO with squeezing



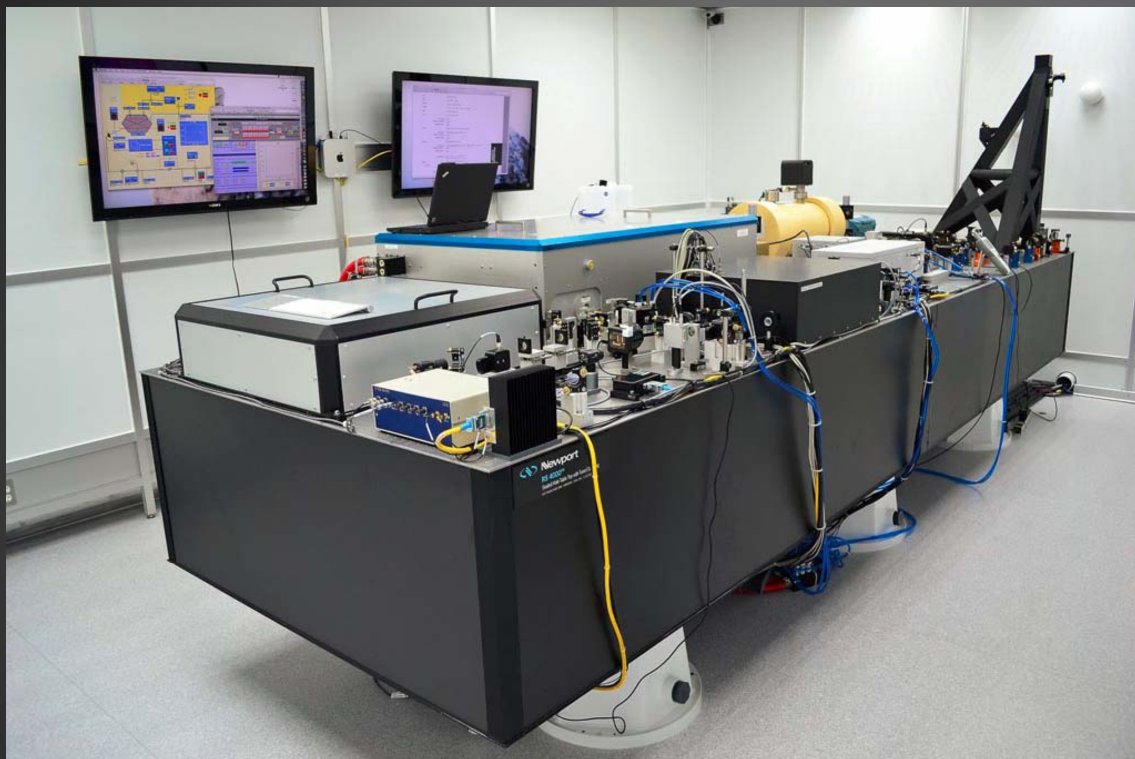
Best broadband sensitivity



Acoustic Noise Coupling



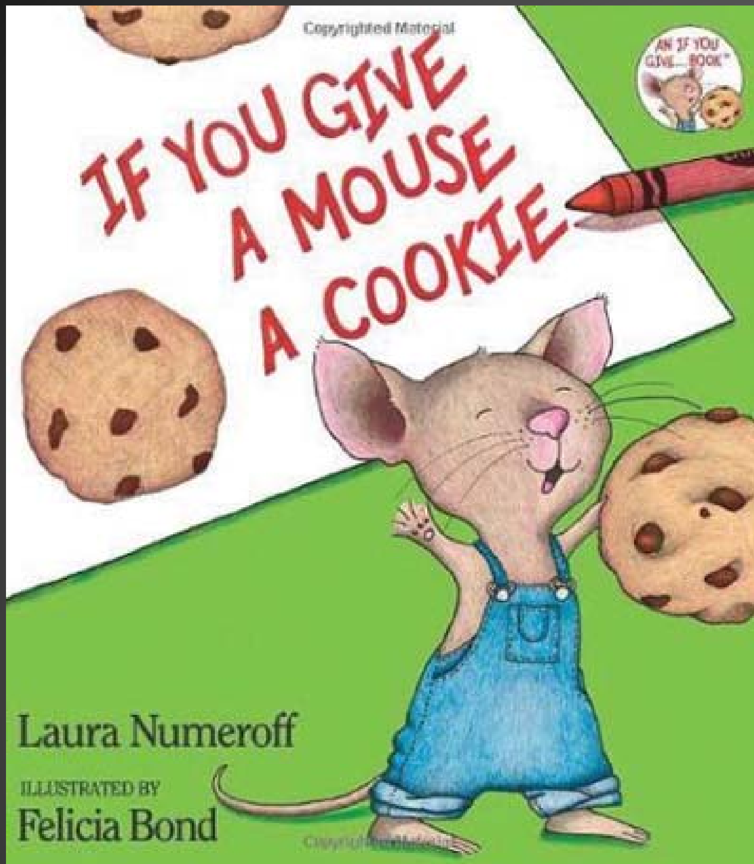
Mitigate Acoustic couplings



Reduce relative motion between squeezer and interferometer

Advanced LIGO Pre Stabilized Laser enclosure and table: Factor of 10 reduction in motion demonstrated

Other options:
Improved isolation from Faradays (factor of 3)
Move OPO in vacuum onto seismic isolation table

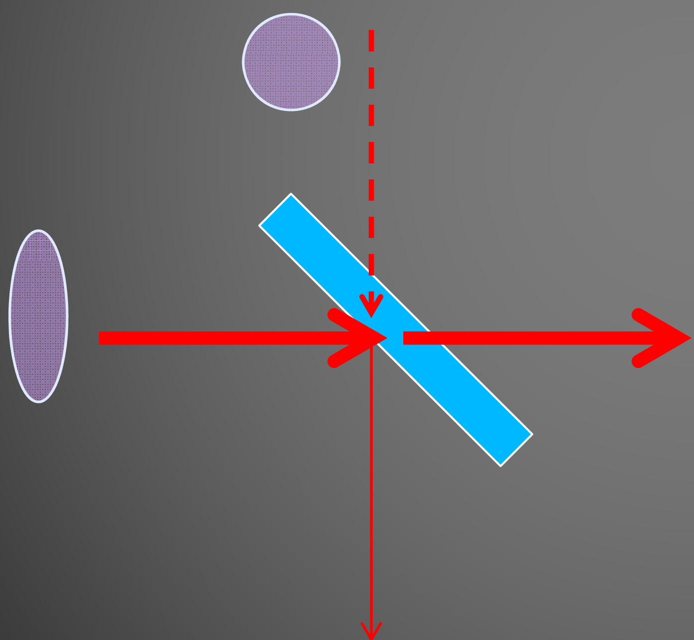


He’ll ask for 6dB of squeezing…

Limits to detecting squeezing :

- Technical Noise
- Losses
- Phase Noise

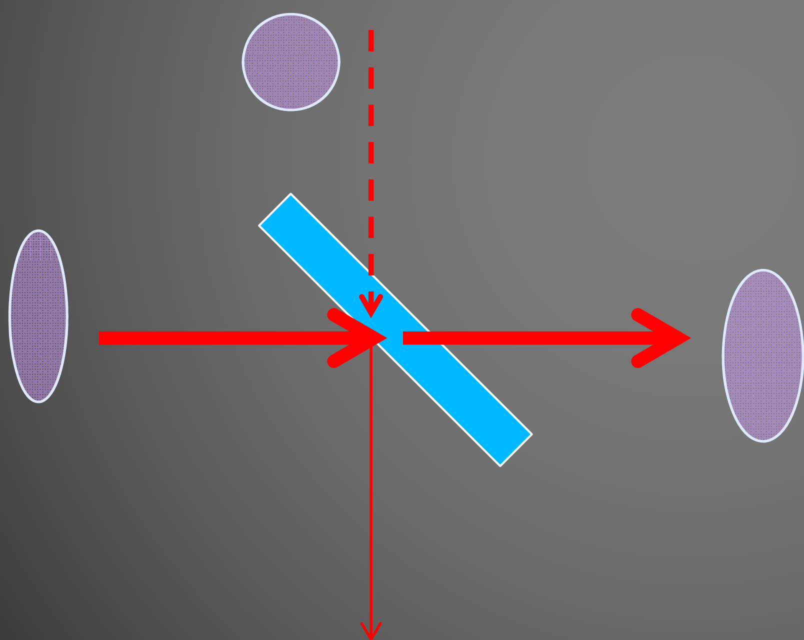
Losses destroy squeezing



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

- A loss allows vacuum state to "leak" into the beam

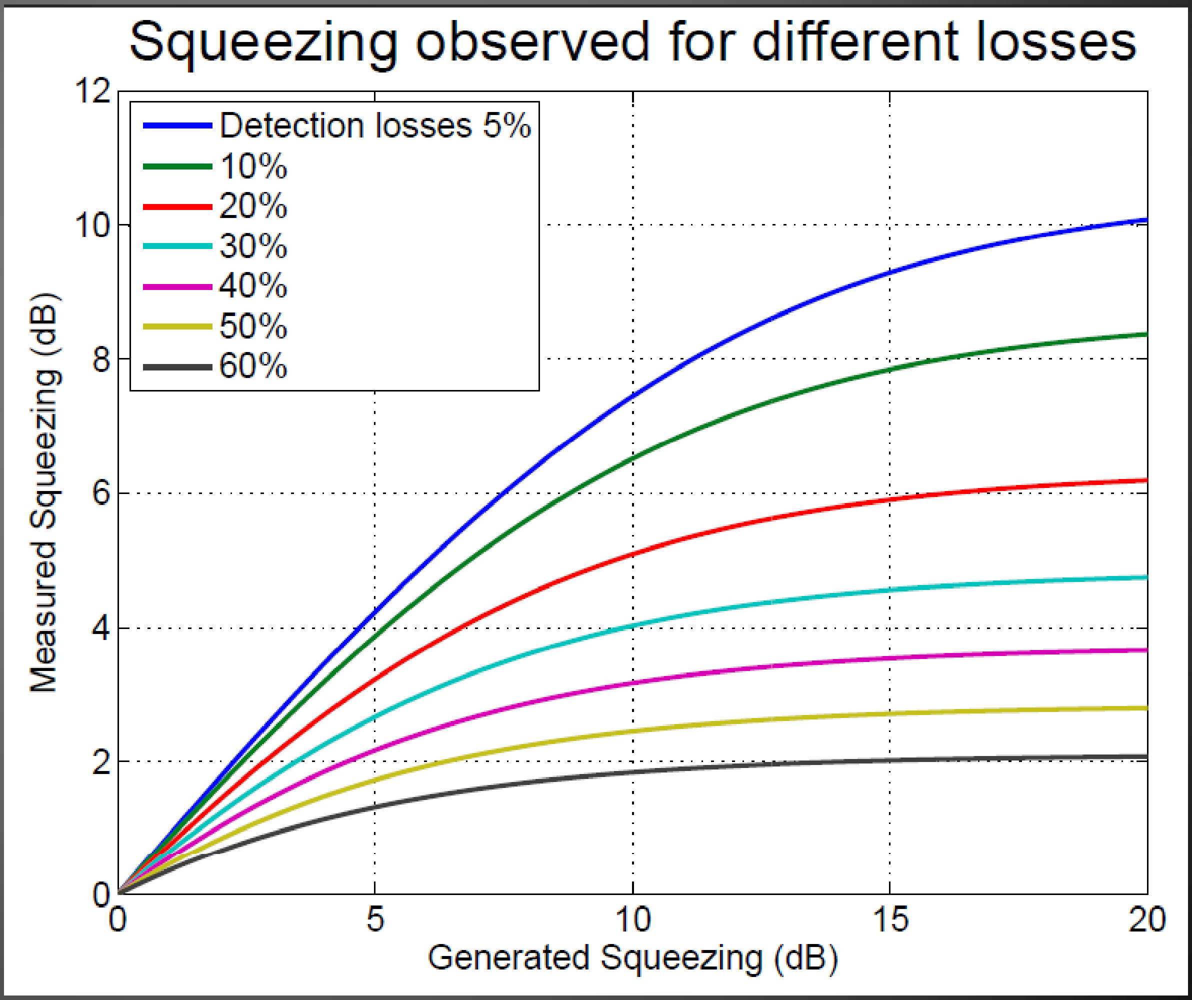
Losses destroy squeezing



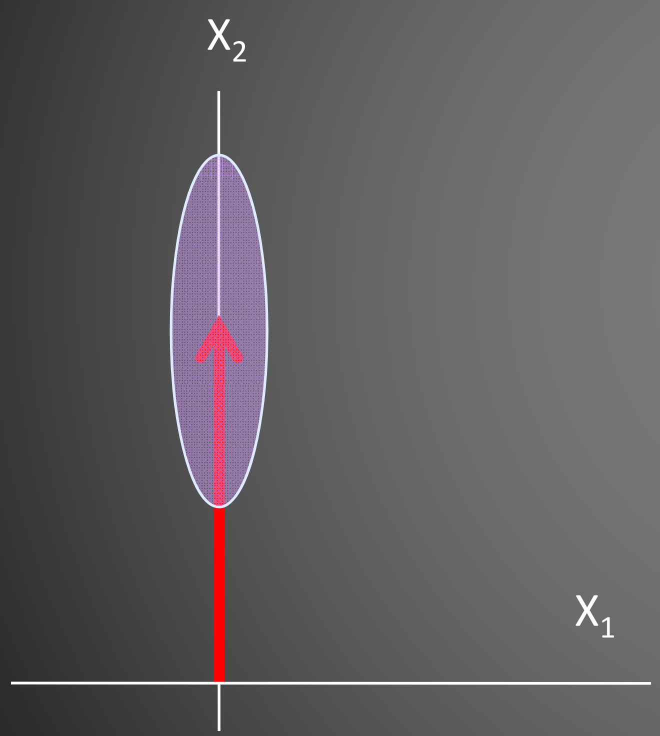
- Every loss can be seen as a beamsplitter with power transmission η_{loss}
- Beamsplitter mixes the squeezed state with vacuum state
- Resulting state has higher noise in squeezed quadrature

Losses limit squeezing

- Losses place a limit on the amount of squeezing that can be detected
- High loss detectors are not very sensitive to the amount of squeezing injected



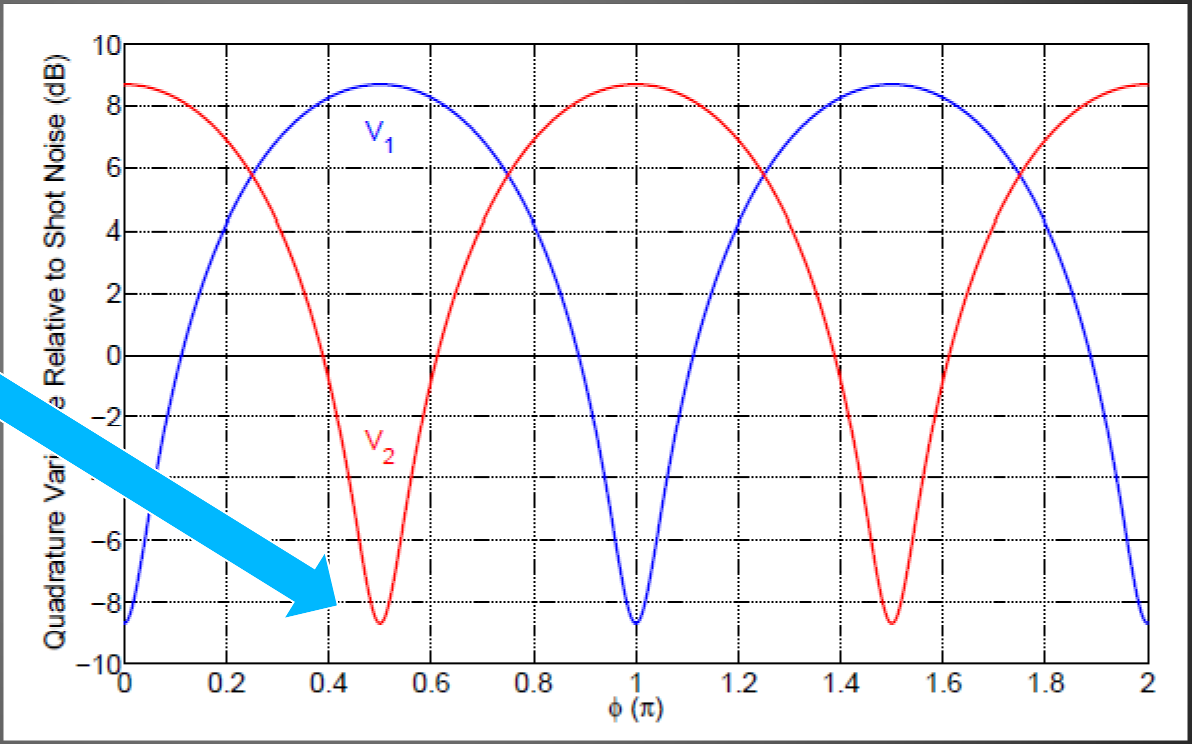
Phase Noise



- Phase noise of the squeezing angle mixes squeezed and anti-squeezed quadrature
- Total rms phase noise decreases the level of squeezing broadband

Phase Noise

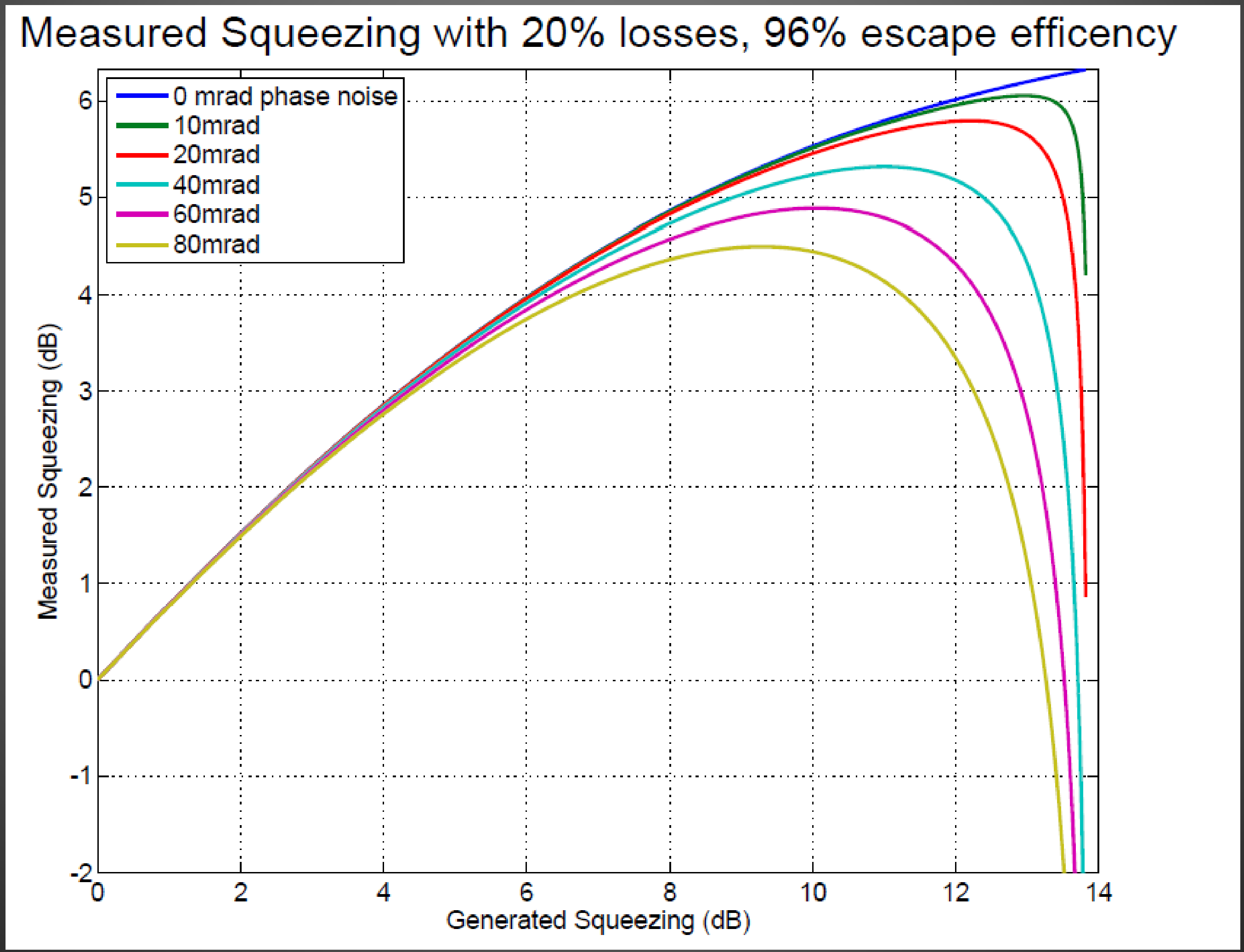
Operating point is at a minimum, any fluctuation leads to an increase in noise



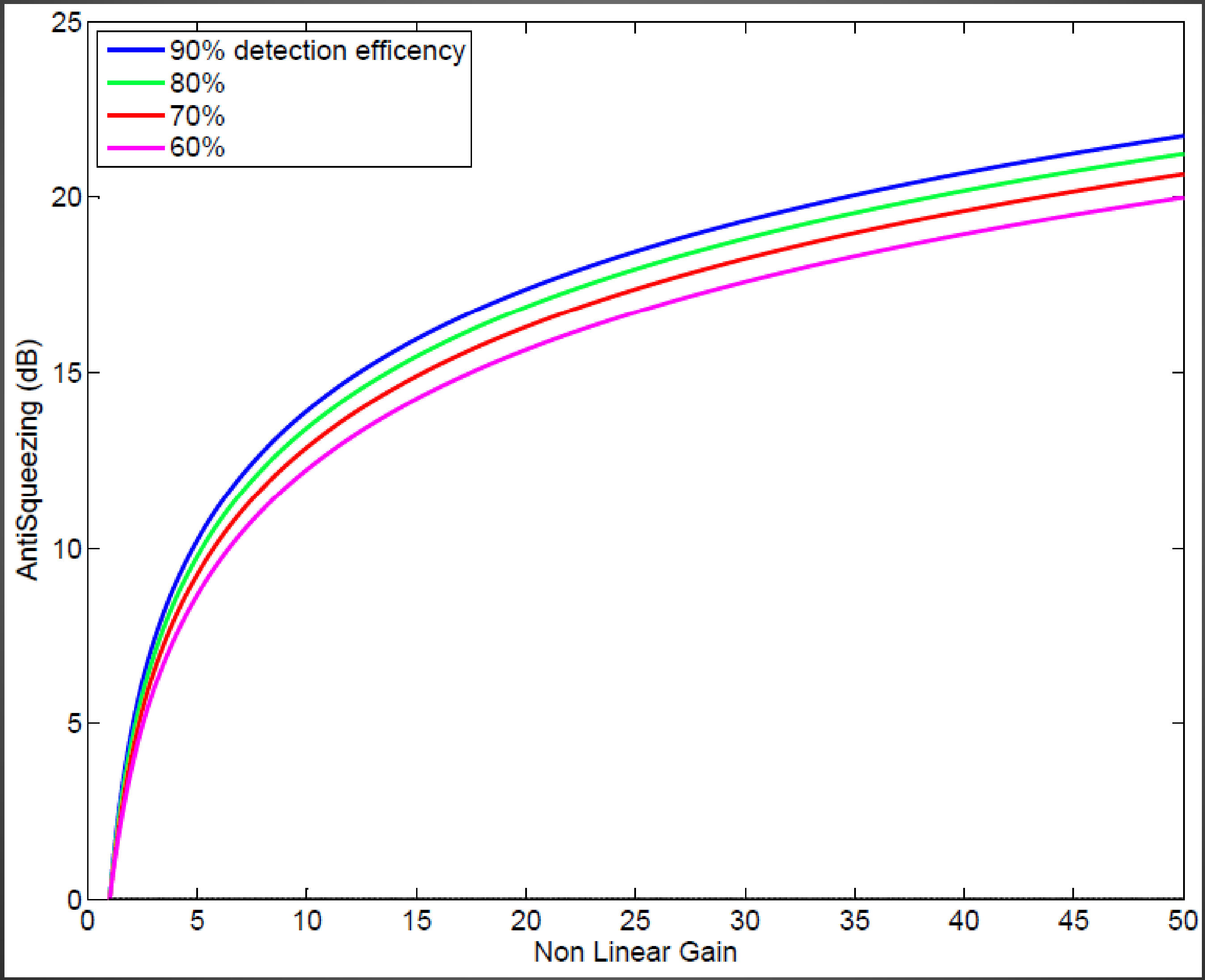
Goda

For higher levels of squeezing, the “dip” gets steeper so phase noise has a larger effect

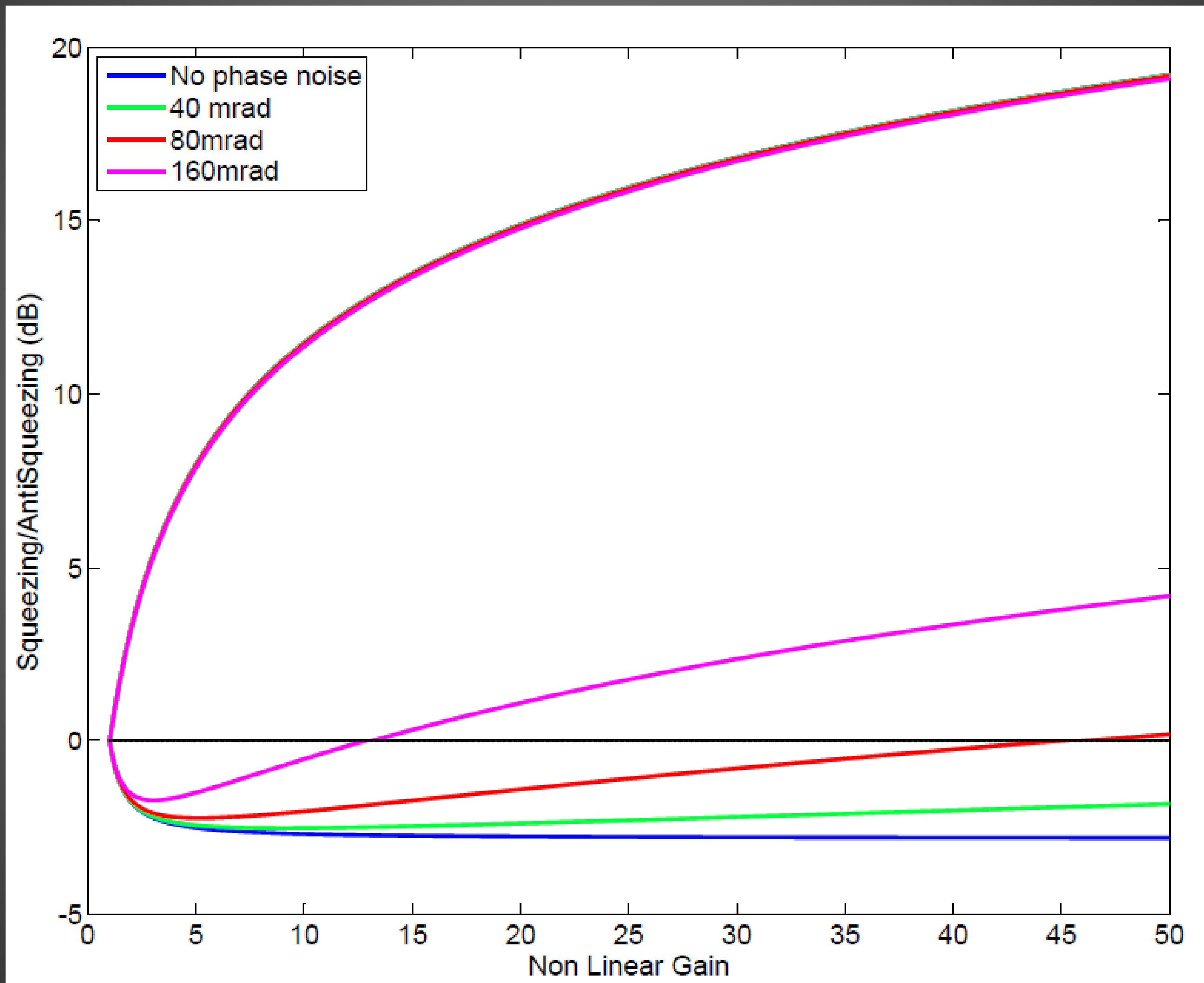
Phase Noise also limits squeezing



Total losses ($1-\eta_{esc}\eta_{det}$)

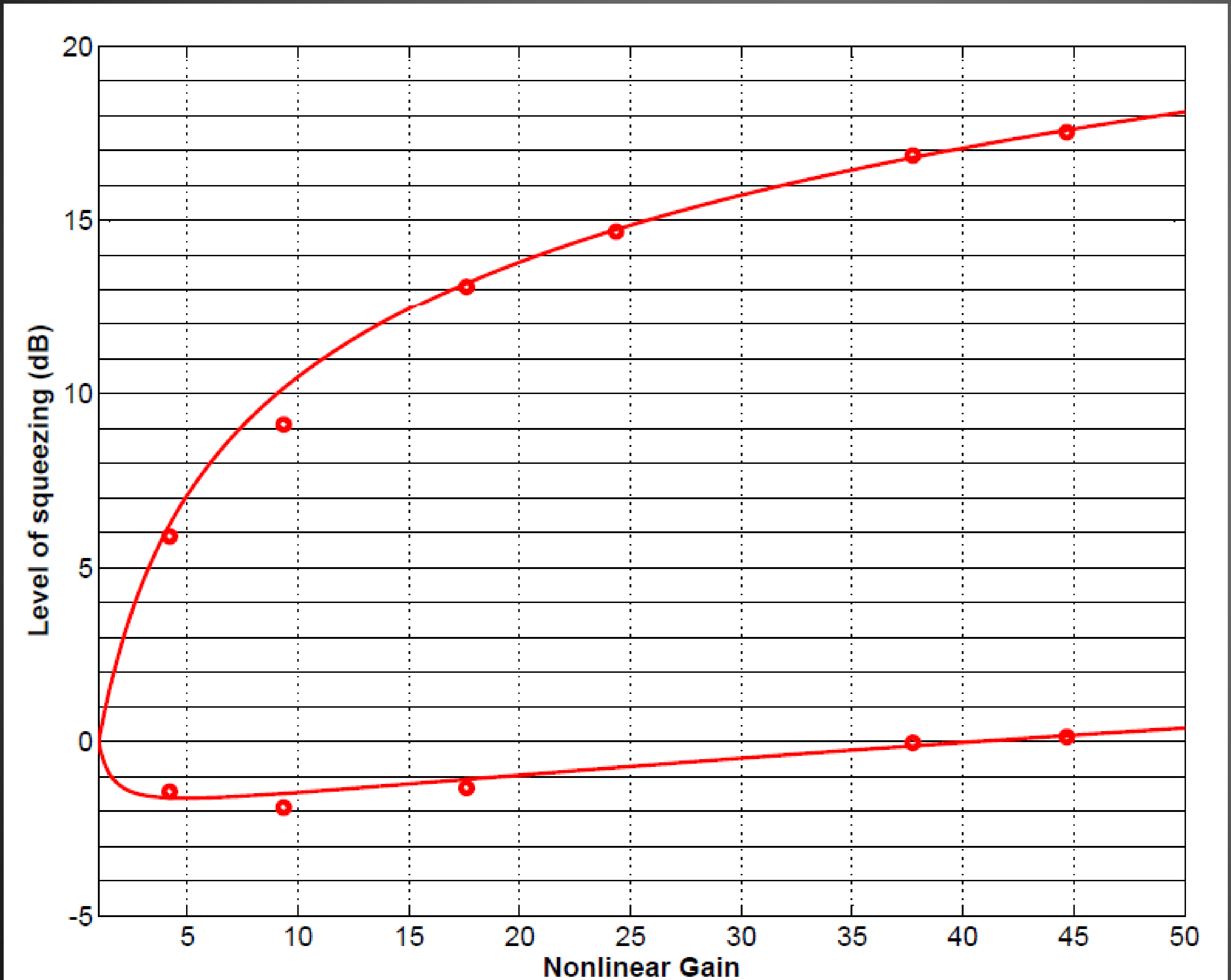


Total Phase Noise



Increasing the amount of anti squeezing allows us to measure total phase noise accurately.

Enhanced LIGO as a squeezing detector



60% losses
85 mrad phase noise
shown here

Best measurements:
55% losses, 35 mrad
phase noise

Loss budget and goals

	Our Experiment	Advanced LIGO design	Goals for 3rd generation
3 faraday passes	5% each	3% each	Aim for all less than 0.2%
Signal recycling cavity@100 Hz		2.5% (Tsrm=35%)	
Squeezer mode matching to OMC	30%	4%	
OMC transmission	19%	1%	
Total losses	55-60%	20%	
Detected Squeezing	2+dB	6dB	10-15dB

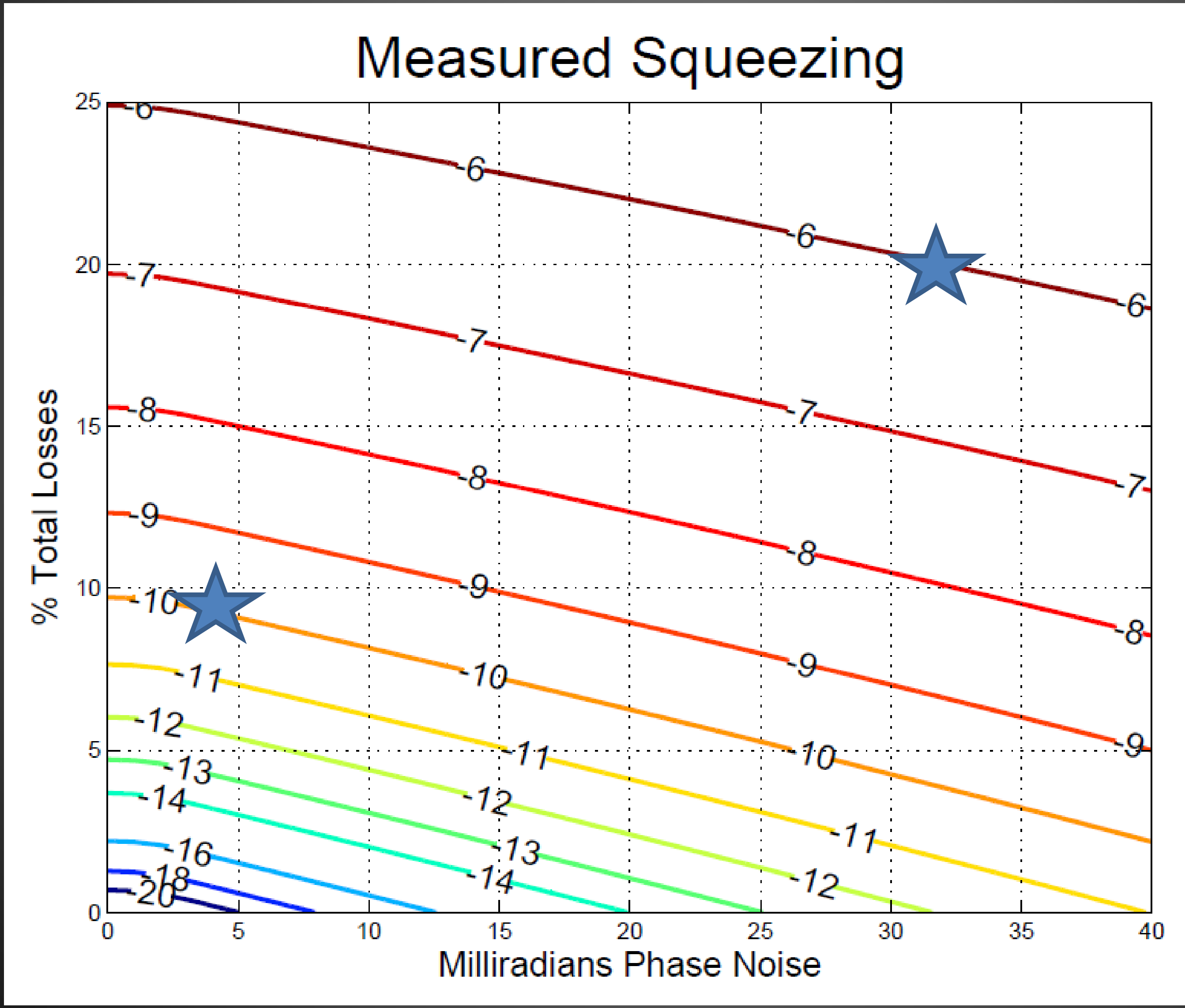
Based on tally of 11 different loss sources

Phase Noise budget and goals

	Past	Present	Future
RF sidebands	1.3 mrad	same	Reduce all to less than 1 mrad
Sources on squeezer table	≤22		
Beam jitter	30 mrad		
Total phase noise	37mrad		
Detected Squeezing	2+dB	6dB	10-15dB

Our sensor for the squeezing angle is sensitive to alignment, couples beam jitter to phase noise

Paths to better squeezing



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

Summary and lessons learned

- 2dB of squeezing in Enhanced LIGO
- No extra noise added
- Some benefit from squeezing down to 150 Hz
- Backscatter should not be a problem for aLIGO
- We will need to reduce losses and phase noise to get higher levels of squeezing

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

(maybe it already is)

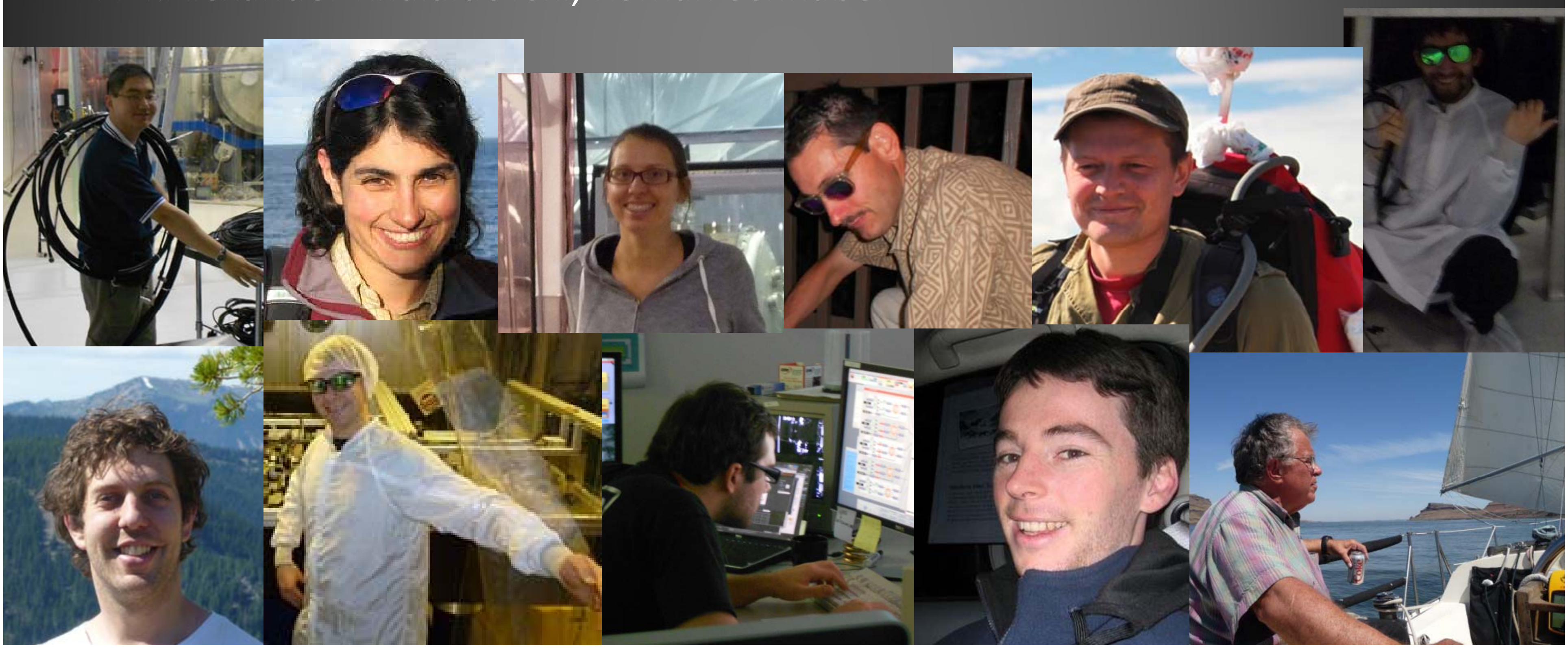
Thank you!

LHO: Daniel Sigg, Keita Kawabe, Robert Schofield, Cheryl Vorvick, Dick Gustafson, Max Factourovich, Grant Meadors, everyone else at LHO

MIT: Lisa Barsotti, Nergis Mavalvala, Nicolas Smith-Lefebvre, Matt Evans

ANU: Sheon Chua, Michael Stefszky, Conor Mow-Lowry, Ping Koy Lam, Ben Buchler, David McClelland

AEI:Alexander Khalaidovski, Roman Schnabel



Nonlinear interactions

$$\vec{D} = \vec{E} + \chi^{(2)} \vec{E}^{\,2}$$

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$$\hat{H} = i\,\hbar\,\kappa \left(\hat{a}^{\dagger} \hat{a}^{\dagger} \hat{b} - \hat{a}\hat{a}\hat{b}^{\dagger} \right)$$

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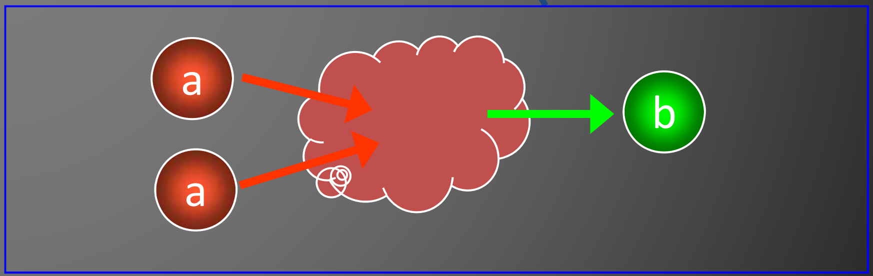

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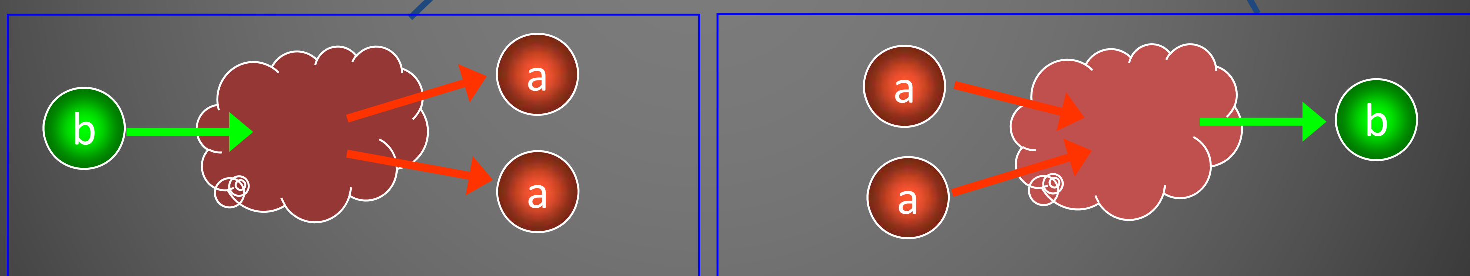

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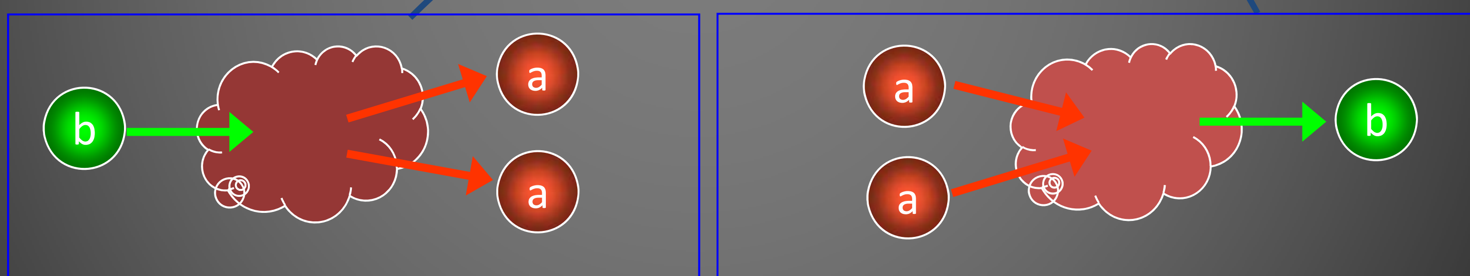

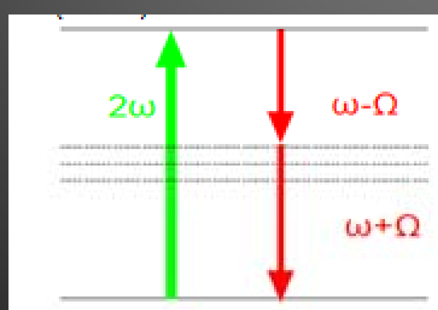

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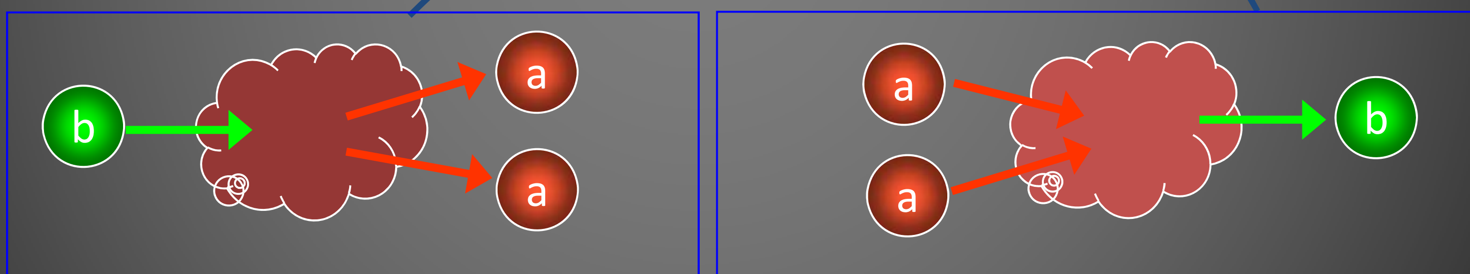
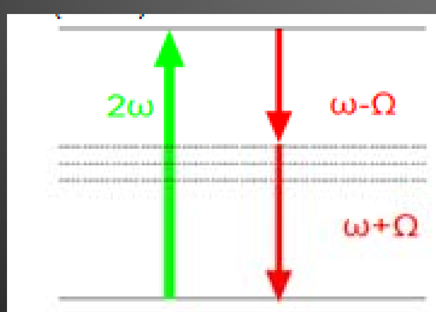
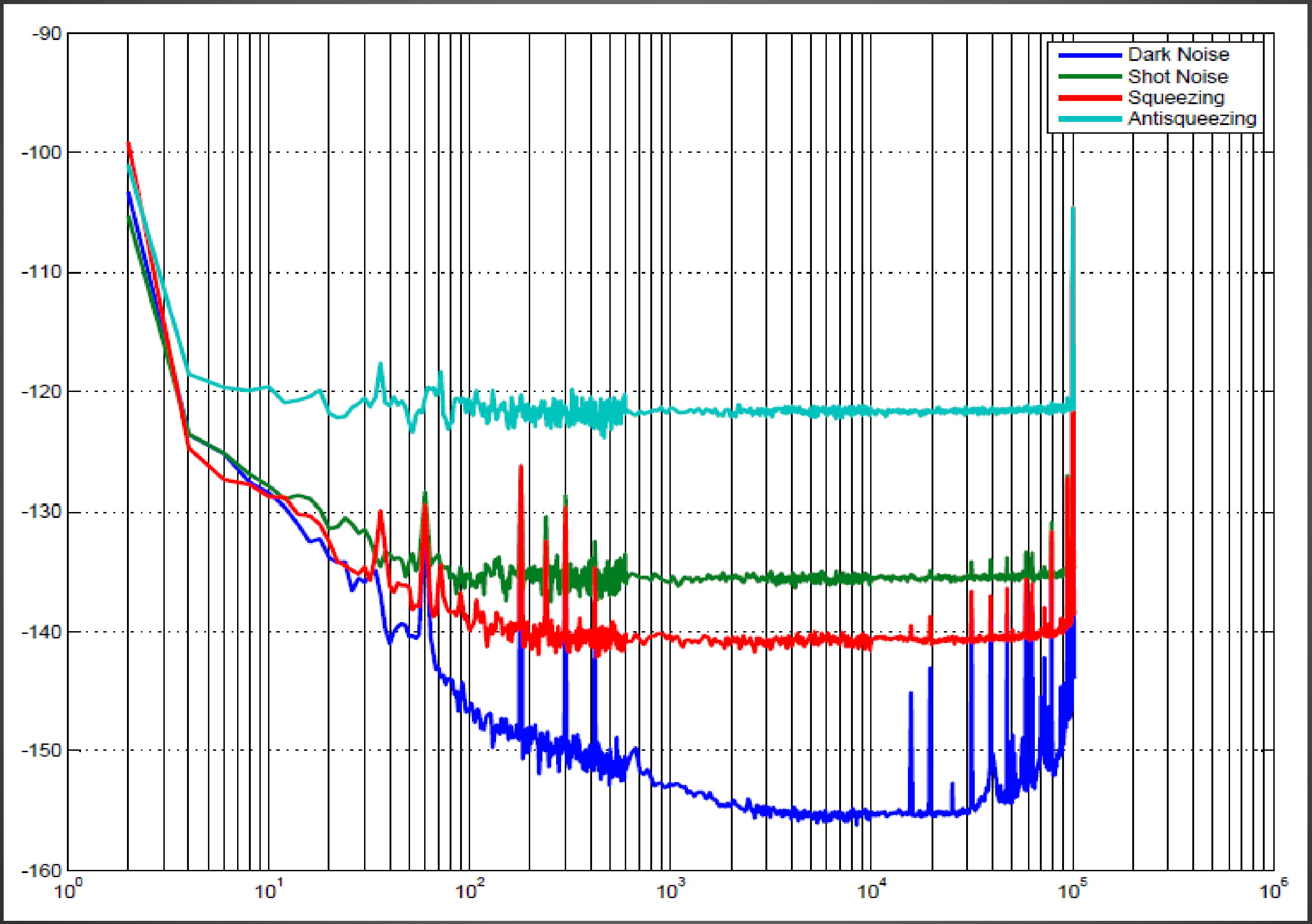




Phases of the red photons become correlated, making a squeezed state.

Squeezer performance

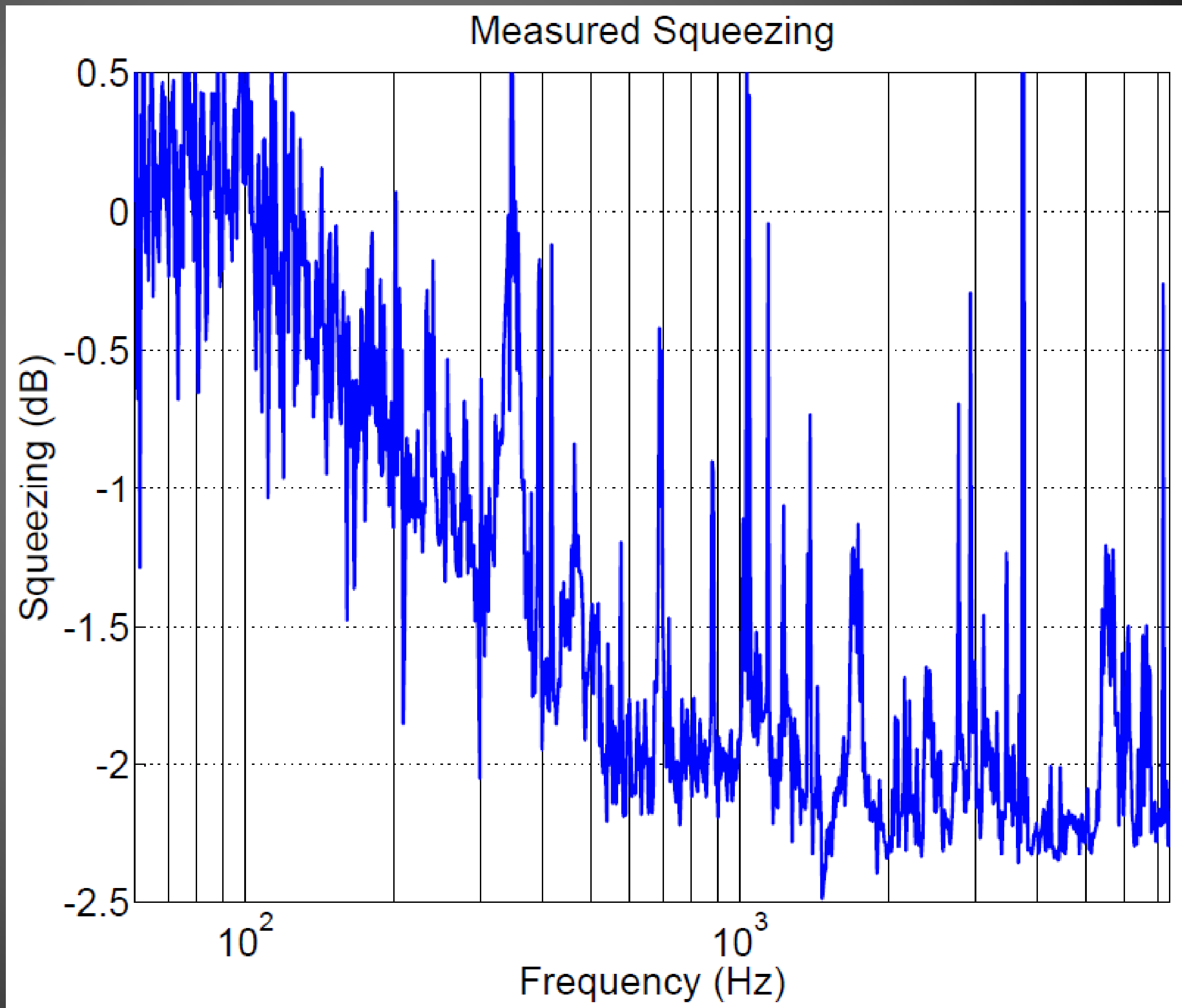


Gravitational wave detectors need low frequency squeezing

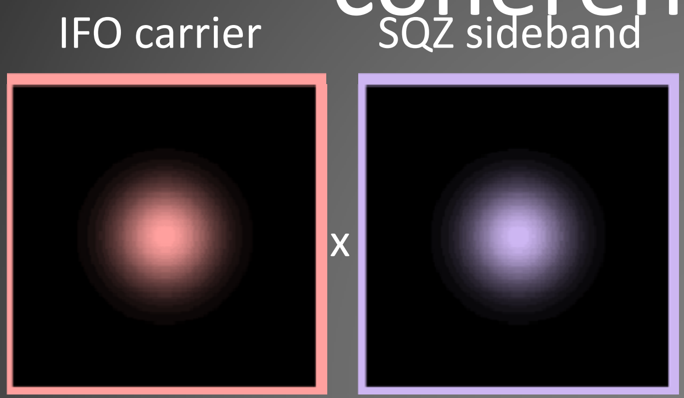
Acoustic Coupling (backscatter)

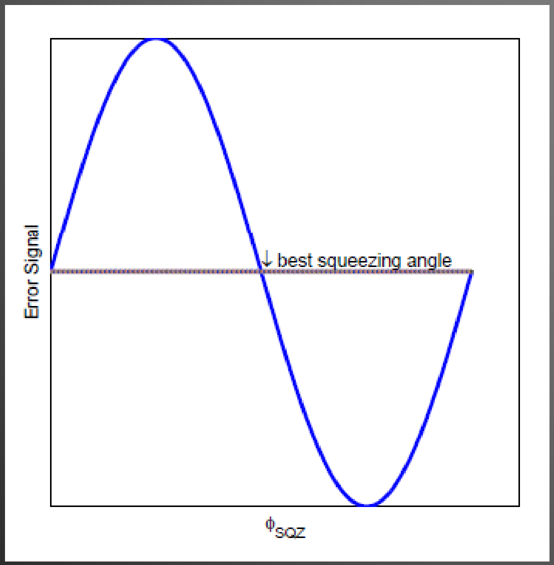
Squeezing Results

- 2.25 dB quantum enhancement
- Some squeezing down to nearly 100 Hz
- Technical noise from IFO causes peaks



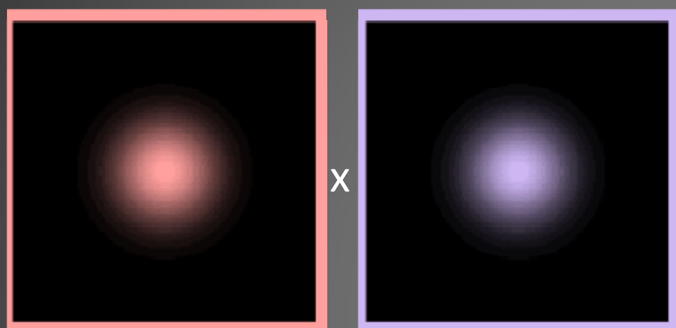
Coherent locking of squeezing angle inject frequency shifted sideband with coherent amplitude



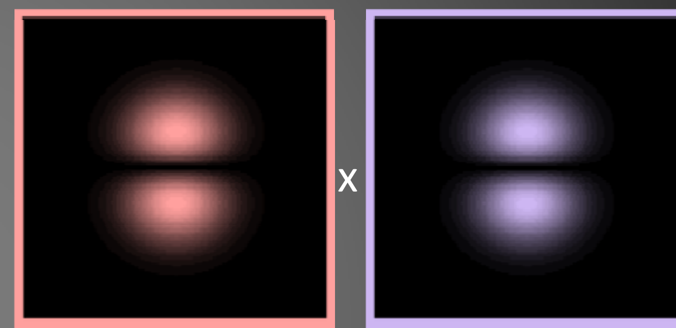


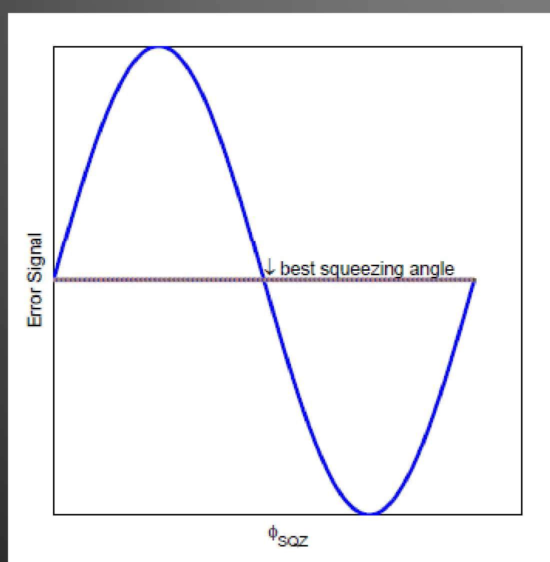
Squeezing angle error signal

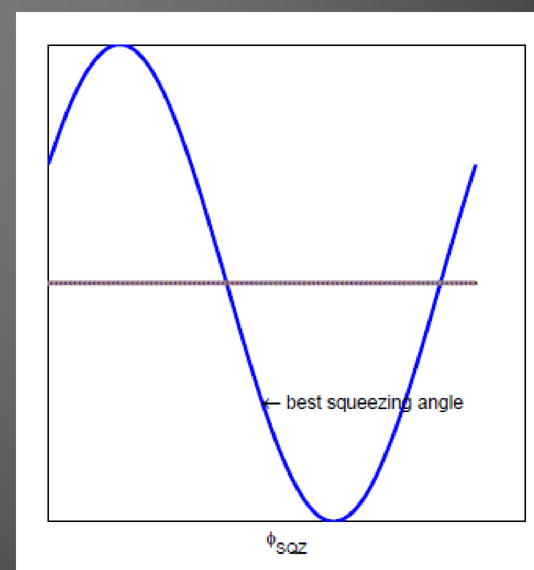
IFO carrier SQZ sideband



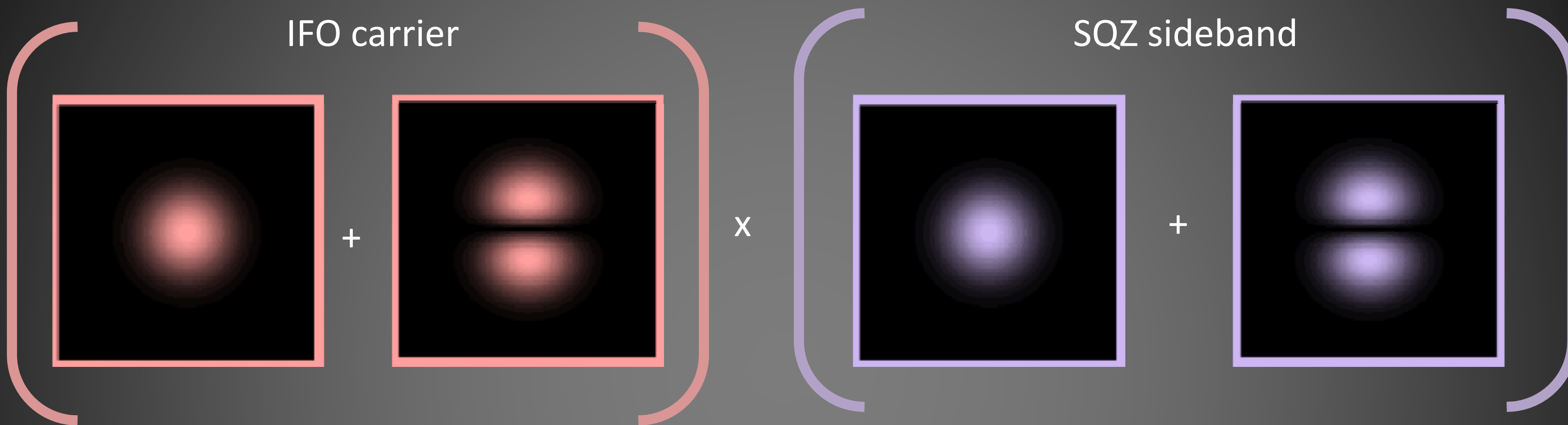
IFO carrier SQZ sideband

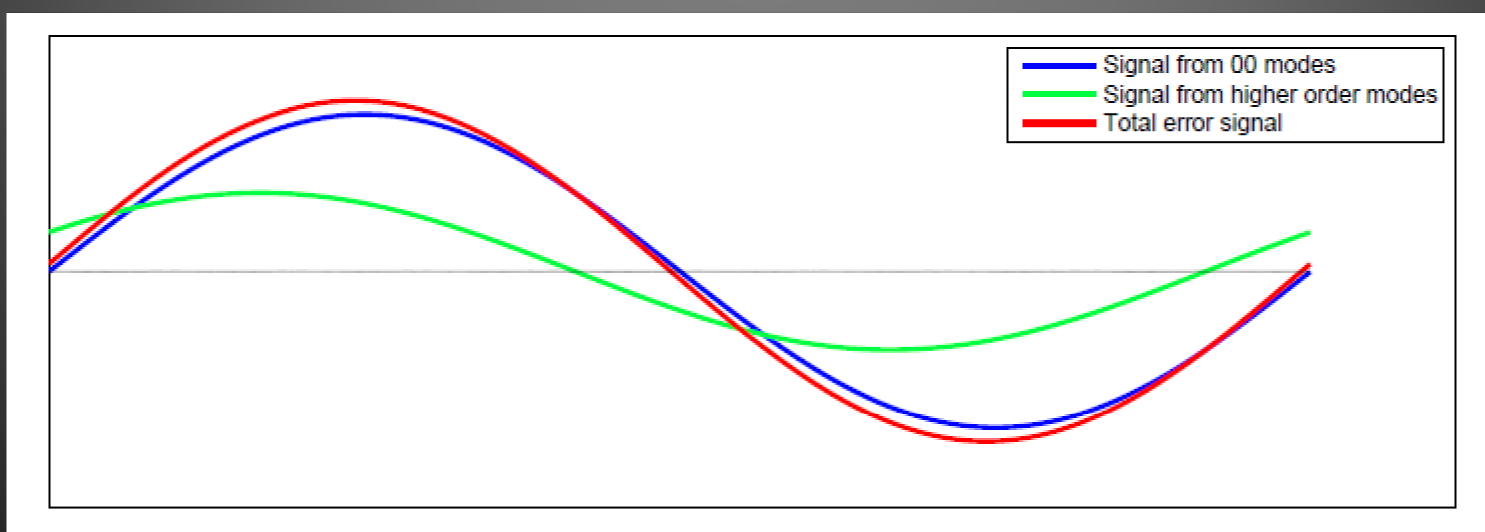




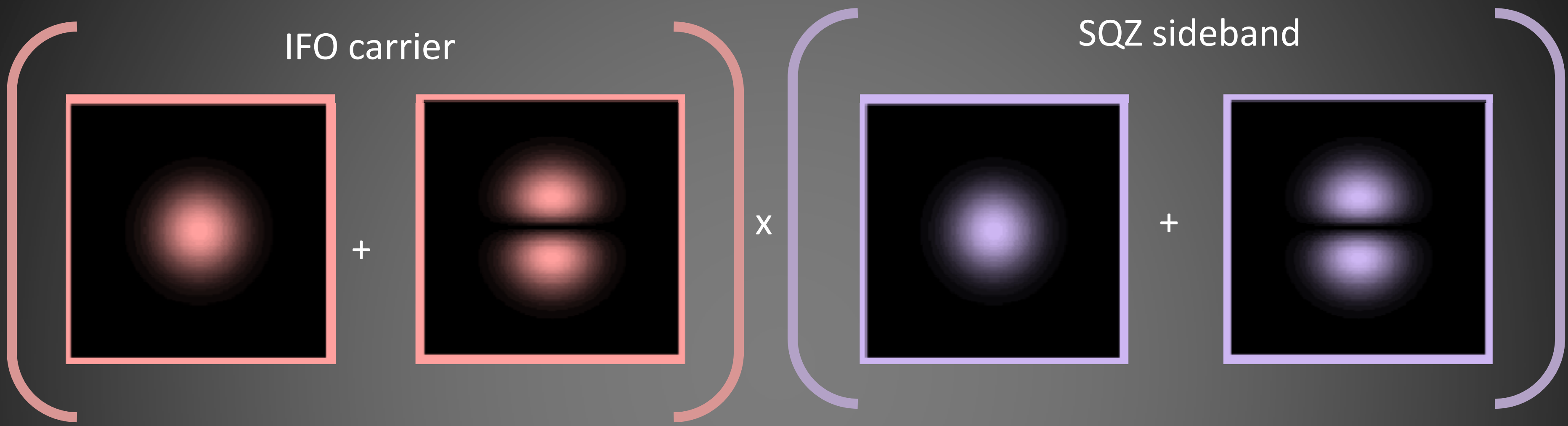


Squeezing angle error signal



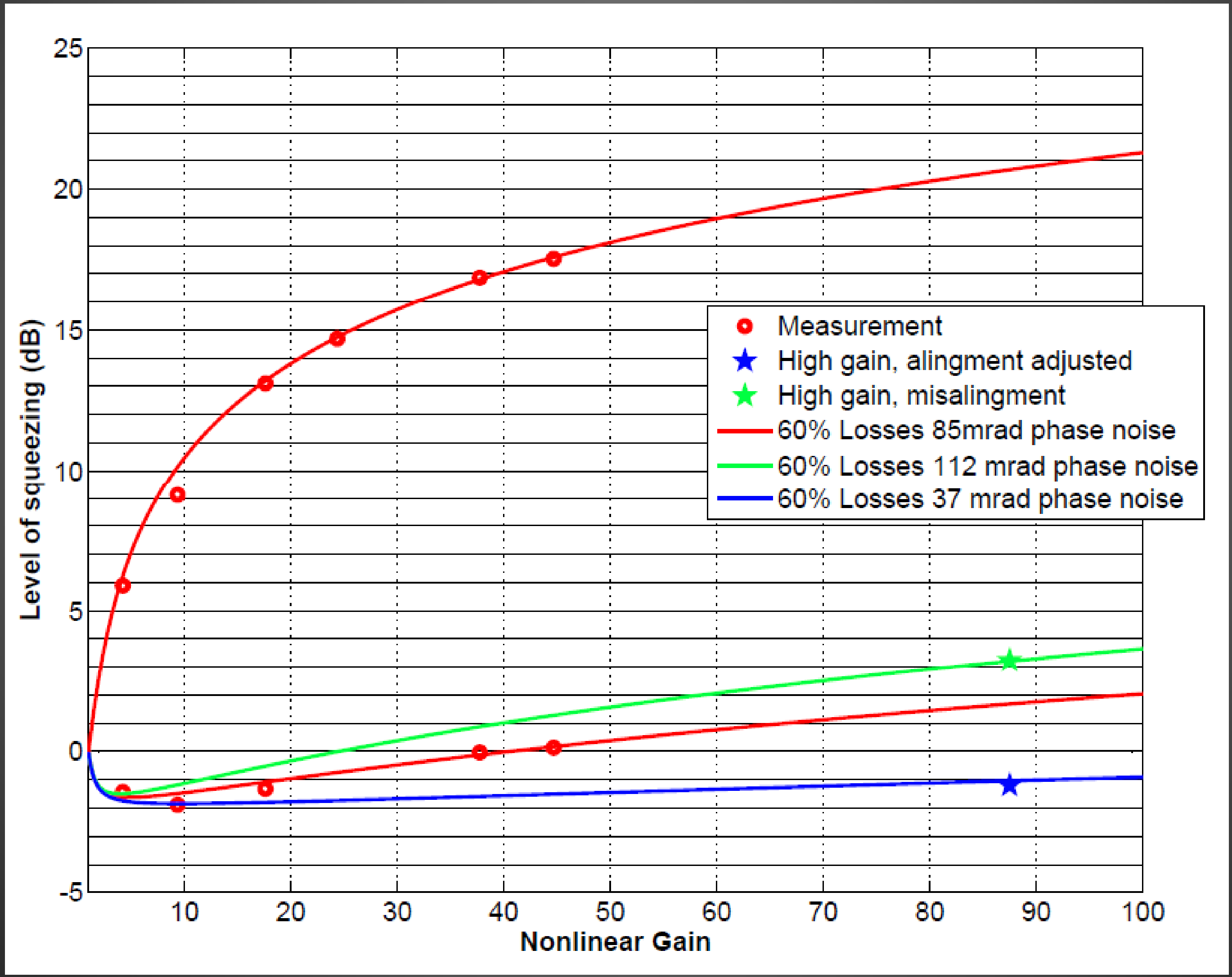


Squeezing angle error signal

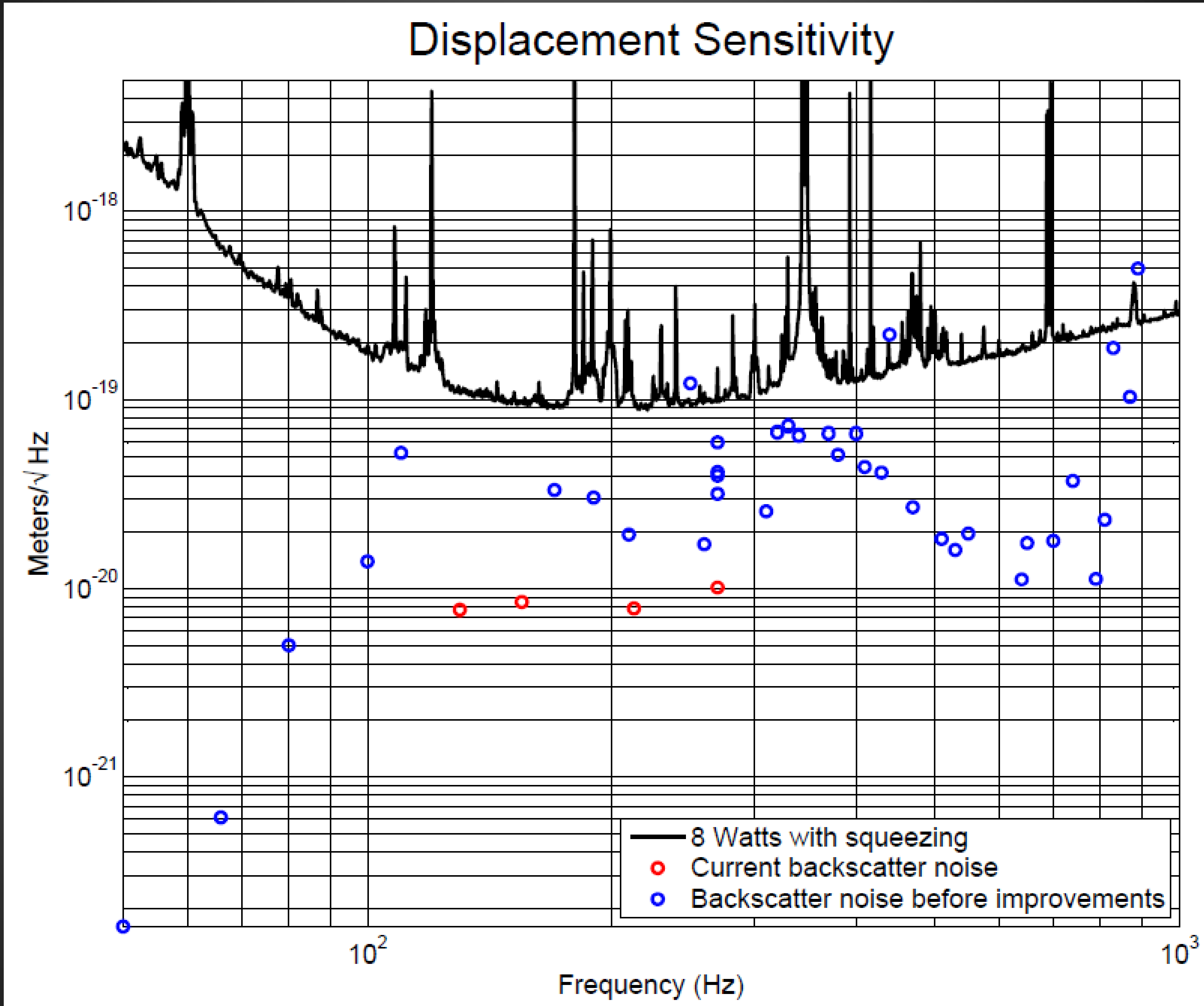


- Static misalignments will cause a change in the demodulation phase needed to detect the maximum squeezing
- Beam jitter will add phase noise, especially when beating against a static misalignment.

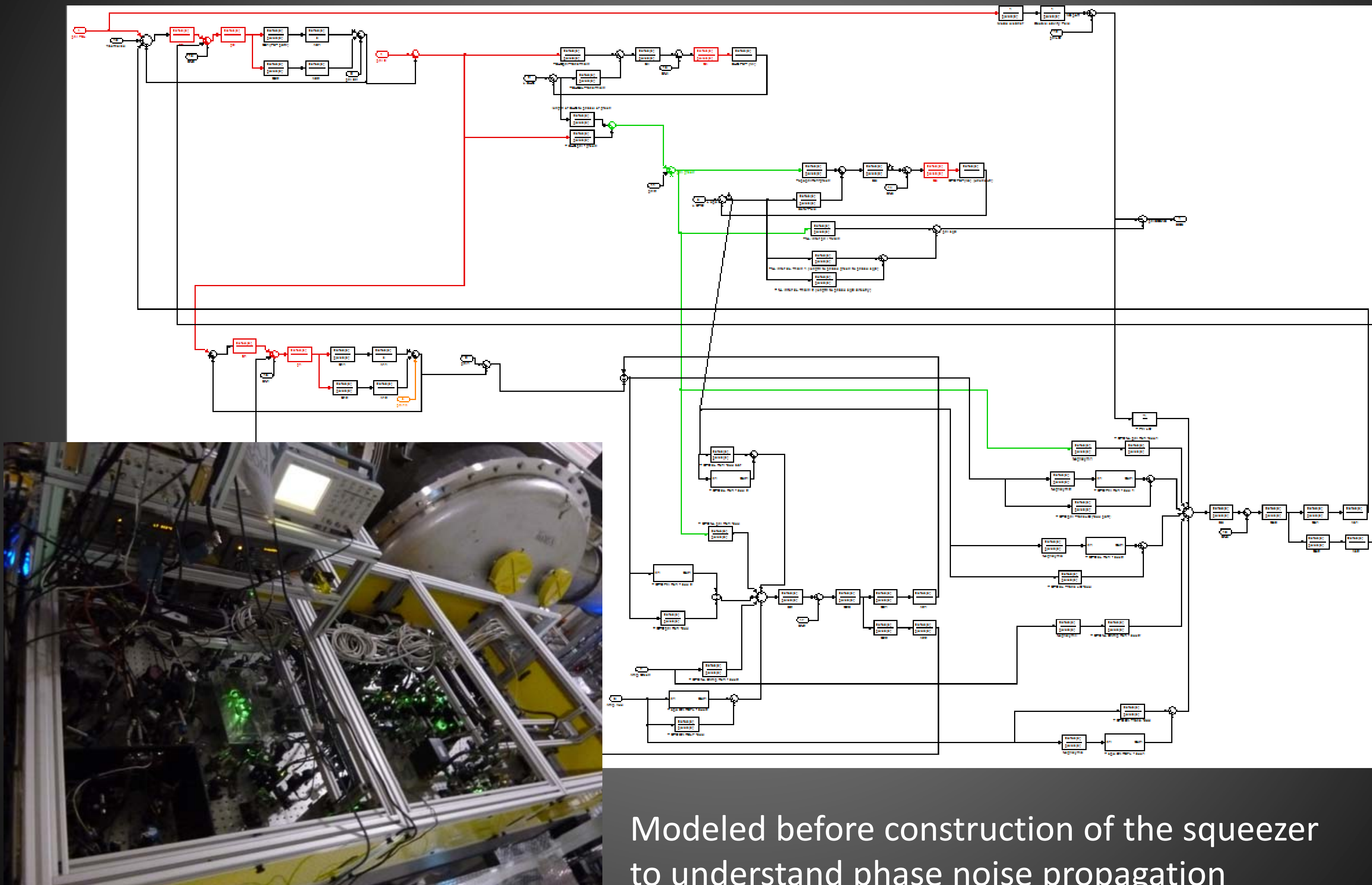
Phase noise reduced by changing IFO alignment



Auto alignment may reduce phase noise, keep it more stable


Displacement Sensitivity
Meters/√ Hz
10^-18
10^-19
10^-20
10^-21
10^2
10^3
Frequency (Hz)
8 Watts with squeezing
Current backscatter noise
Backscatter noise before improvements

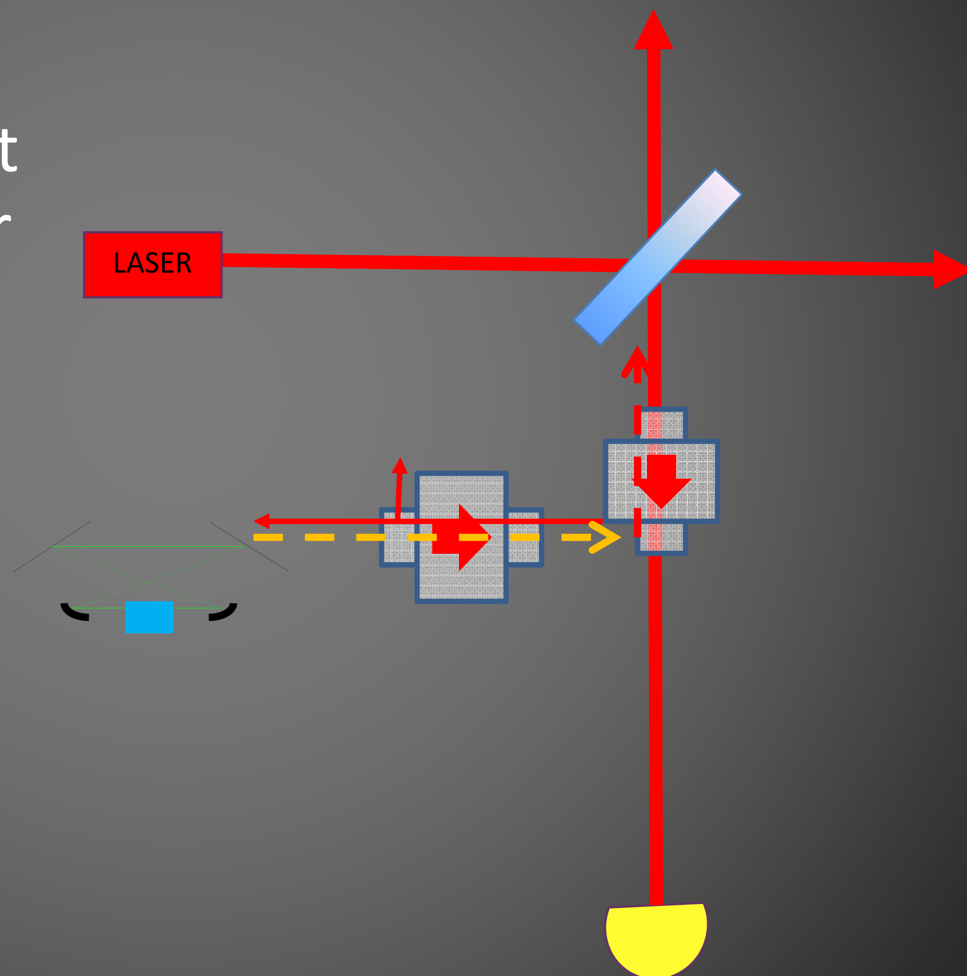
Control Scheme



Modeled before construction of the squeezer to understand phase noise propagation

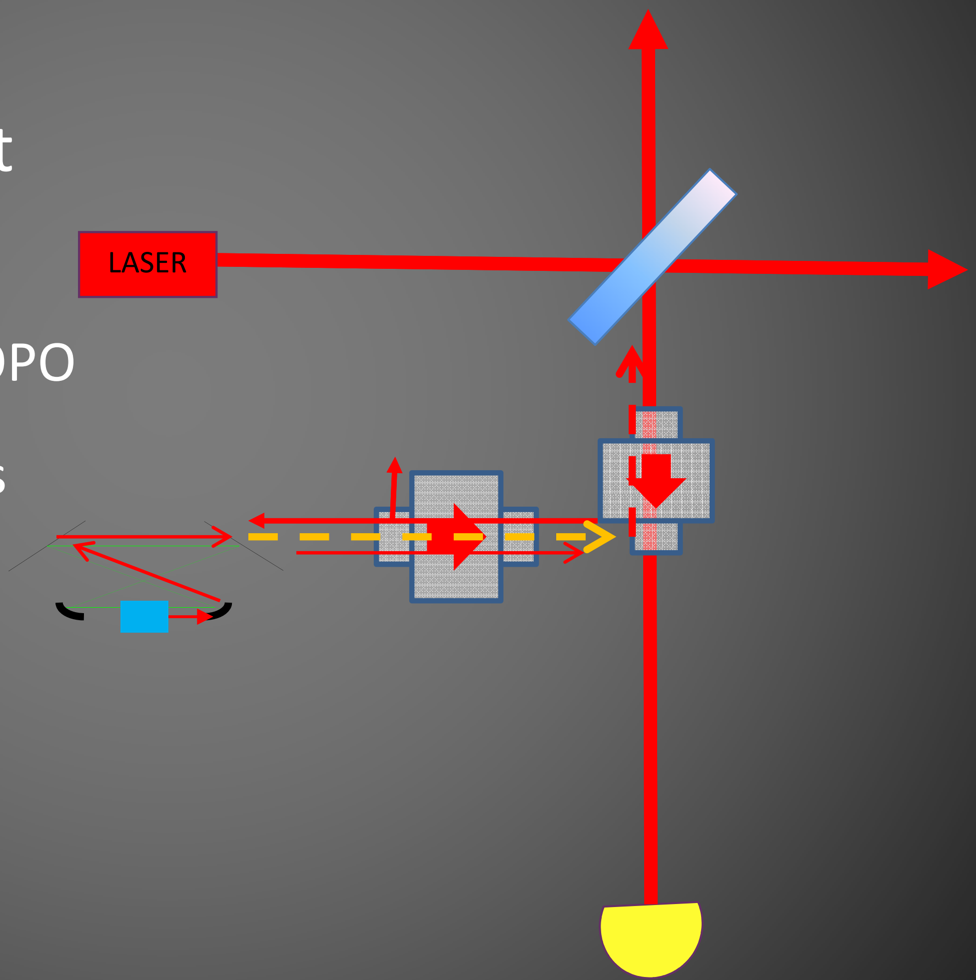
Backscatter

- Some light from the interferometer is sent towards the squeezer



Backscatter

- Some light from the interferometer is sent towards the OPO
- Backscattering inside the OPO sends light back to interferometer, which adds noise to the spectrum.



Backscatter

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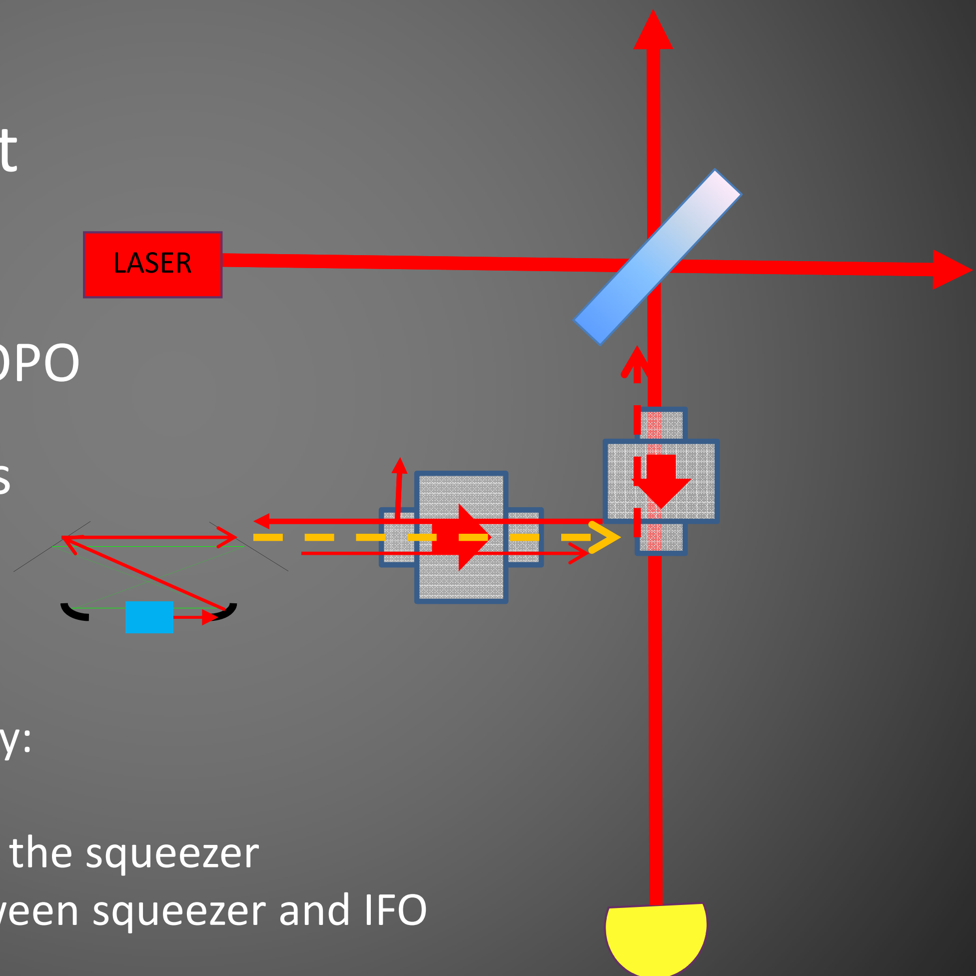

- Backscatter noise can be reduced by:
  - Improve isolation
  - Reducing scattering sources in the squeezer
  - Reducing relative motion between squeezer and IFO