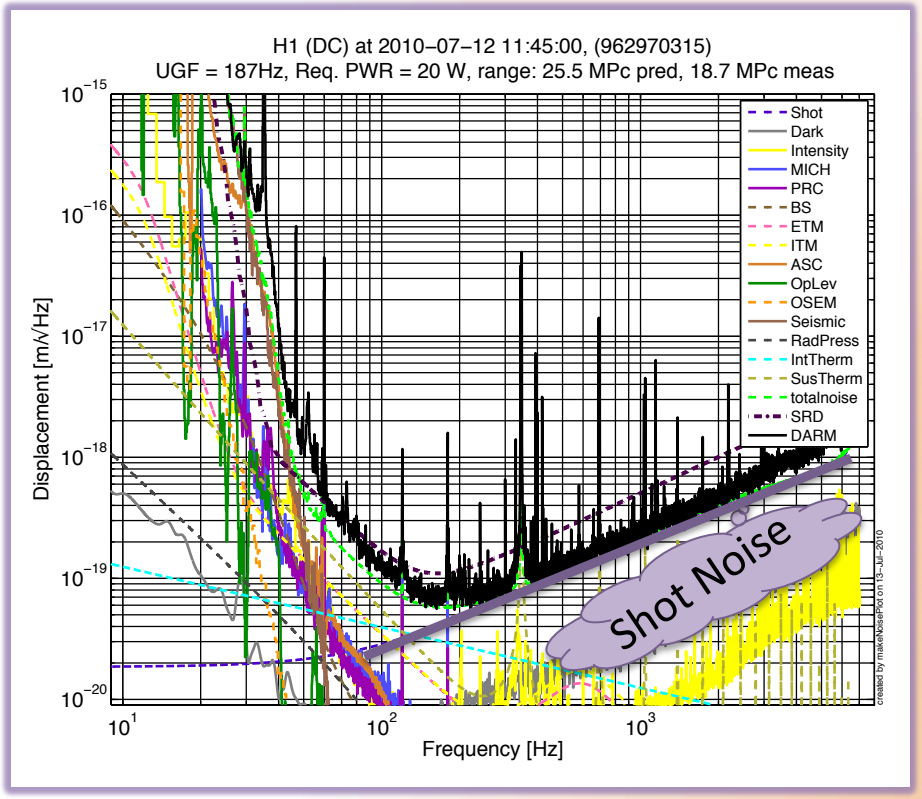
Squeezing in Gravitational Wave Detectors

Lisa Barsotti

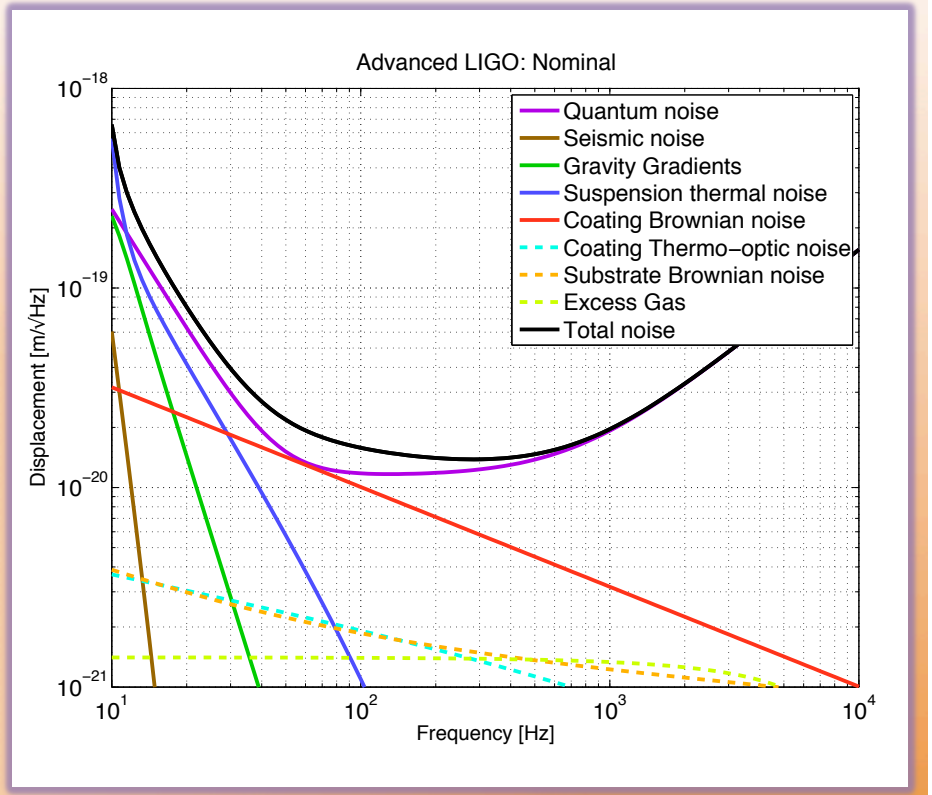
(LIGO-MIT)

Quantum Noise limits the Sensitivity of GW Detectors

1st Generation (Enhanced LIGO – H1)



2nd Generation (Advanced LIGO)



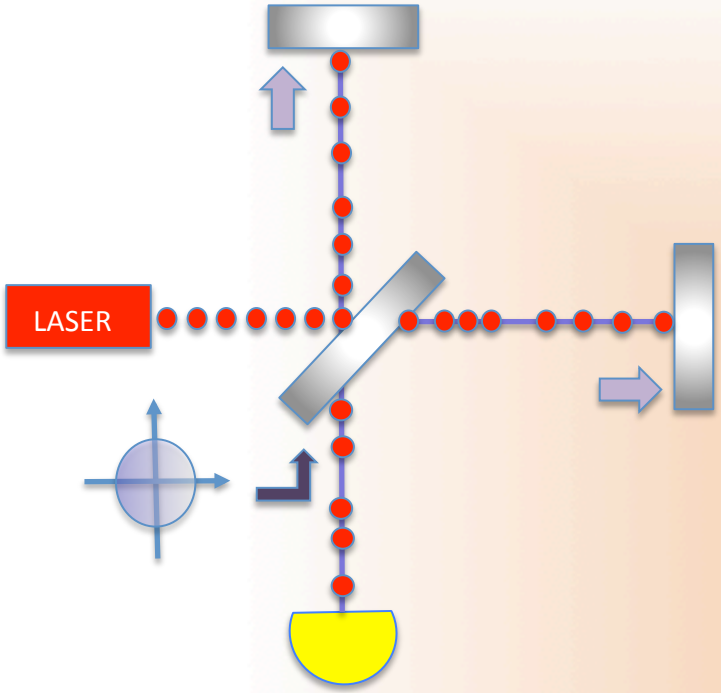
Squeezing can beat quantum noise

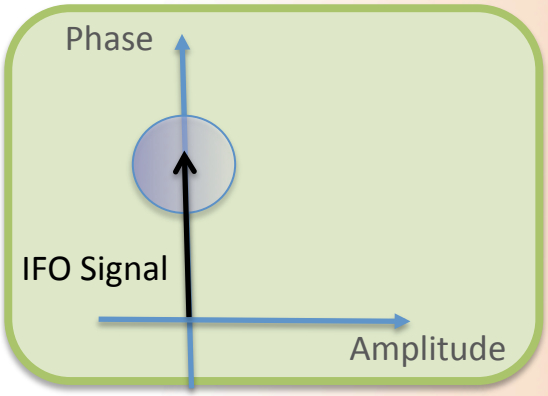
Btw, Squeezing What?

Nothing, really…

….but it takes a lot of work anyway!

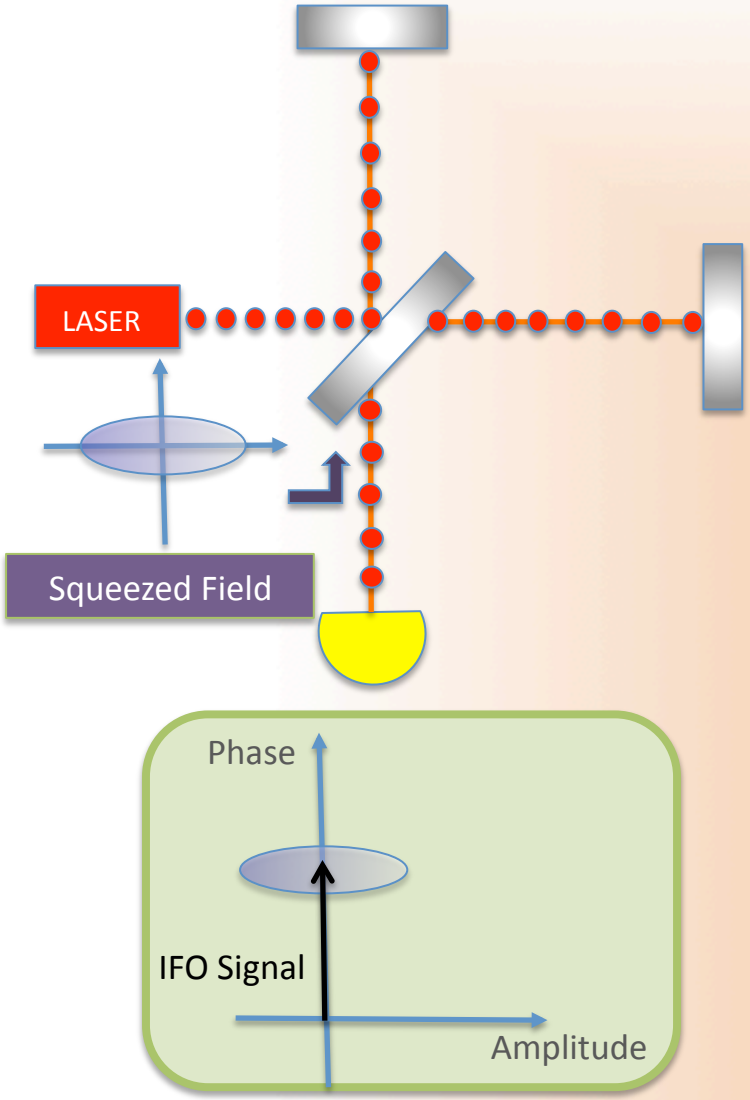
Quantum Noise and Vacuum





- Quantum noise is produced by vacuum fluctuations entering the open ports
- Vacuum fluctuations have equal uncertainty in phase and amplitude:
  - Phase: Shot-Noise (photon counting noise)
  - Amplitude: Radiation Pressure Noise (back-action)

Vacuum Getting Squeezed

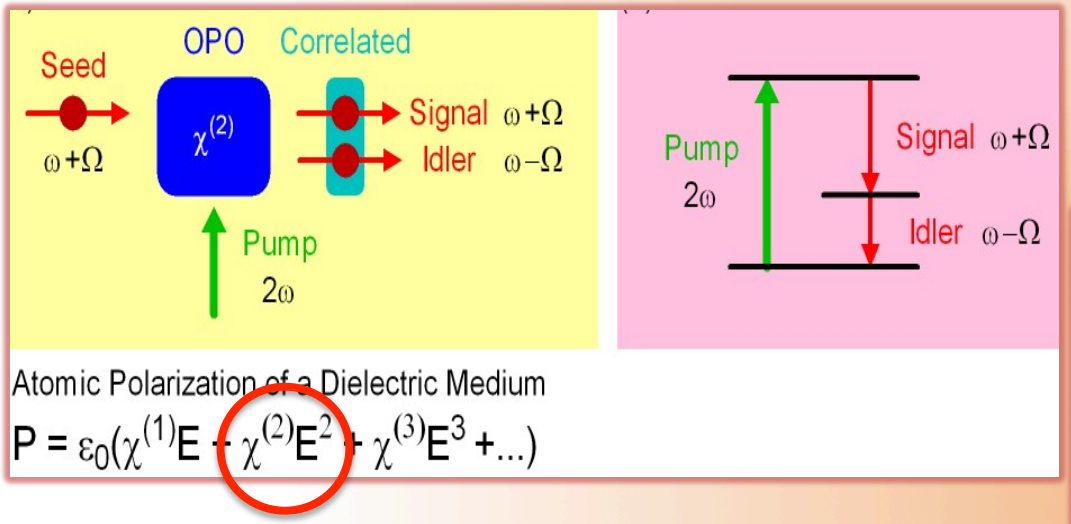


- Reduce quantum noise by injecting squeezed vacuum: less uncertainty in one of the two quadratures
- Heisenberg uncertainty principle: if the noise gets smaller in one quadrature, it gets bigger in the other one
- One can choose the relative orientation between the squeezed vacuum and the interferometer signal (squeeze angle)

How to make squeezed fields..

…. in theory

- ✧ Non linear medium with a strong second order polarization component
- ✧ Correlation of upper and lower quantum sidebands



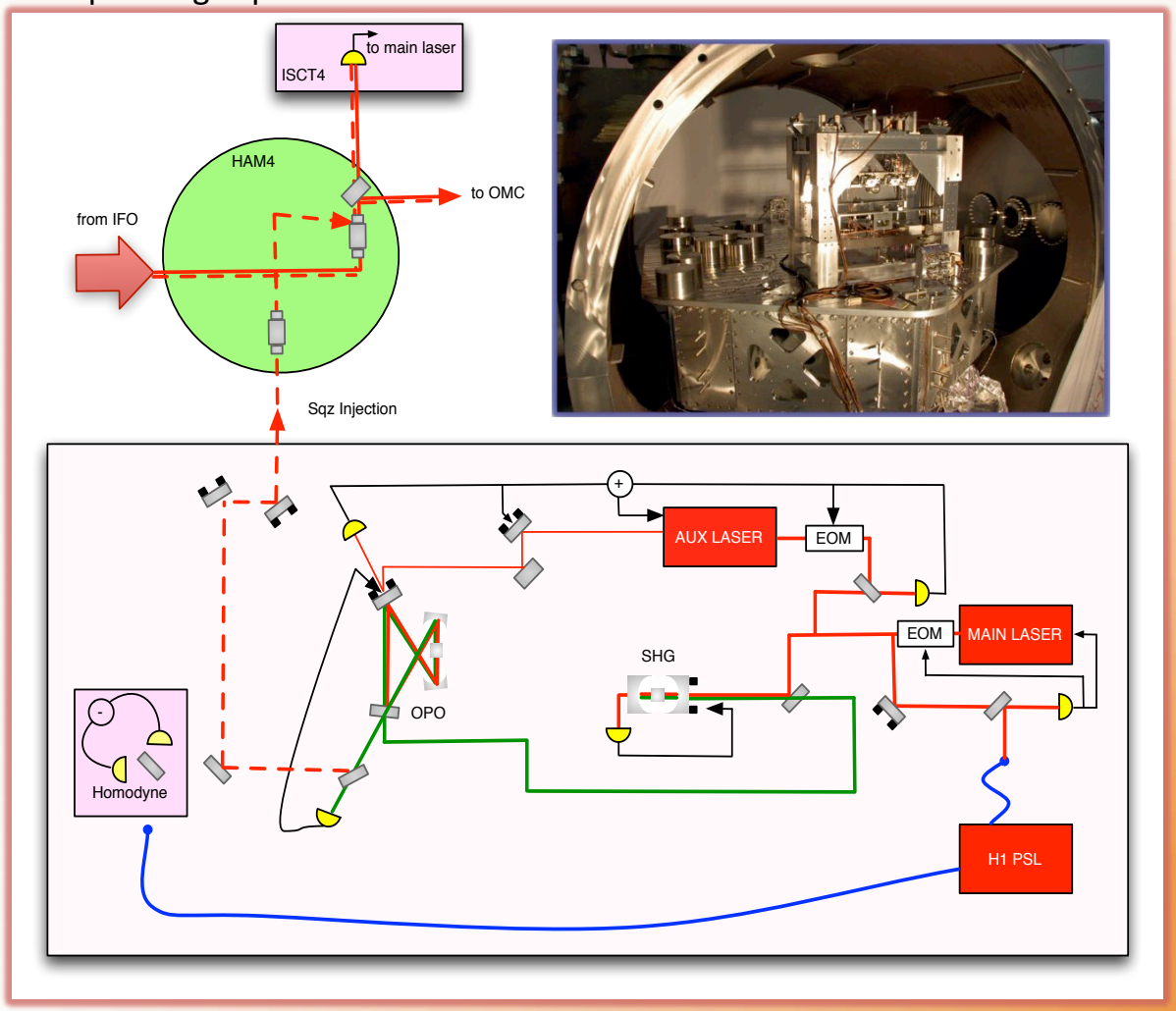
…. in practice

- ✧ Lasers, mirrors, control loops,..

Courtesy of Alexander Khalaidovski (AEI)

Squeezing Injection

H1 Squeezing Experiment



Squeezing in GW detectors: happening now!

- World wide effort to produce squeezing in the audio-frequency band and study applications for GW detectors (ANU, AEI, Caltech/MIT)
- Squeezer installed in GEO HF in 2010:
  - Already one year of experience!
- Advanced LIGO R&D: H1 squeezing experiment this year
  - Squeezer just installed in H1
  - First squeezing injection by the end of this summer

GEO HF: 1 year of Squeezing

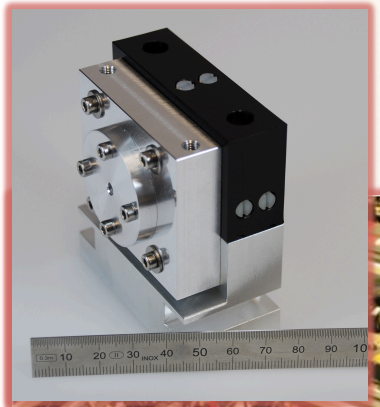
This afternoon:

"Status of the GEO 600 squeezed light laser"

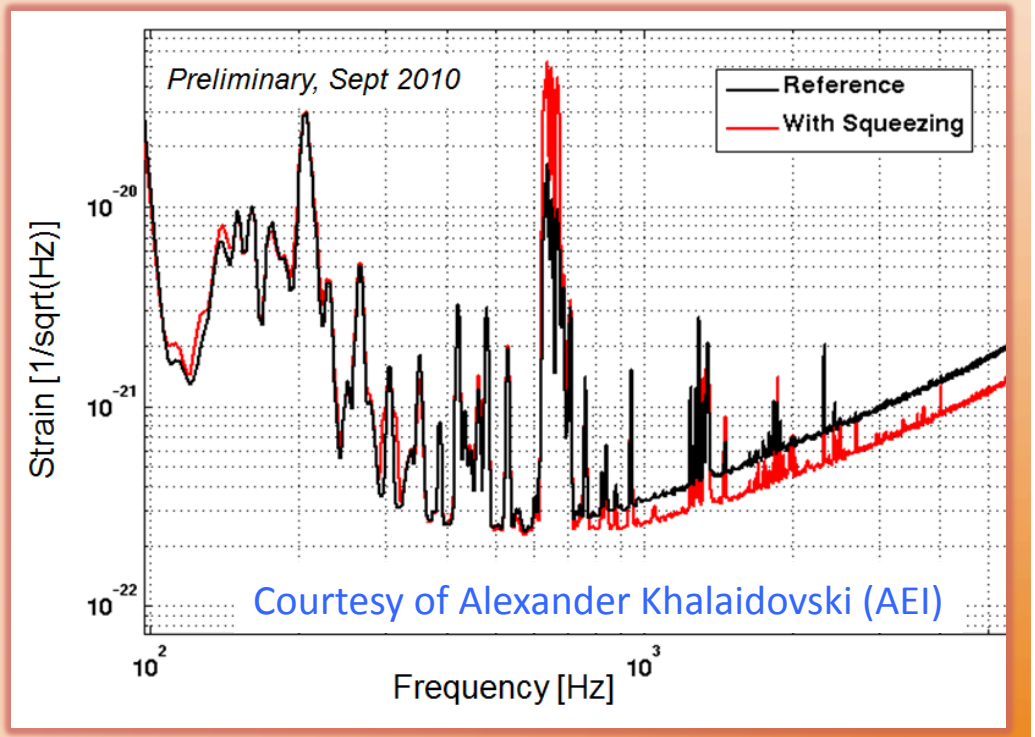
Alexander Khalaidovski (AEI)

Advanced Detector Technology

- ✧ GEO Squeezer: more than 10 dB available
- ✧ 3.5 dB of squeezing measured with GEO
- ✧ About 40% losses (Faradays, mode-matching)



➔ Linear OPO



H1 Squeezer Experiment Timeline

October 2010

End of S6

June 2011

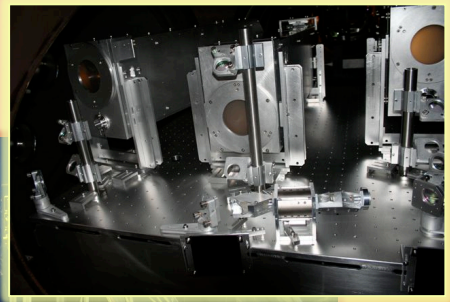
August 2011

December 2011

1) OPO Designed at ANU, squeezer assembled at MIT

2) Reassembling of the squeezer at LHO

3) Sqz installation



4) Sqz injection with short Michelson and full IFO

* Back scattering?
* Losses?
* Anti-Squeezing?
* Control noises?

aLIGO H1 installation starting in January 2012

H1 Squeezing Experiment Test
Acknowledgements

- LHO/MIT/Caltech/AEI
- ANU (Chua, Stefszky, Mow-Lowry, Shaddock, Lam, McClelland)
- M. Factourovich (Columbia University)
- G. Meadors, D. Gustafson (Univ. of Michigan)

H1 Squeezing Experiment: The Squeezer

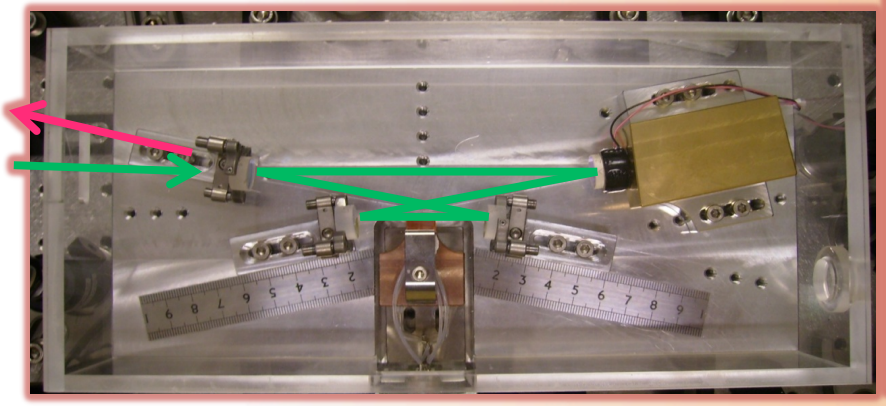
✧ Bow tie-cavity OPO:

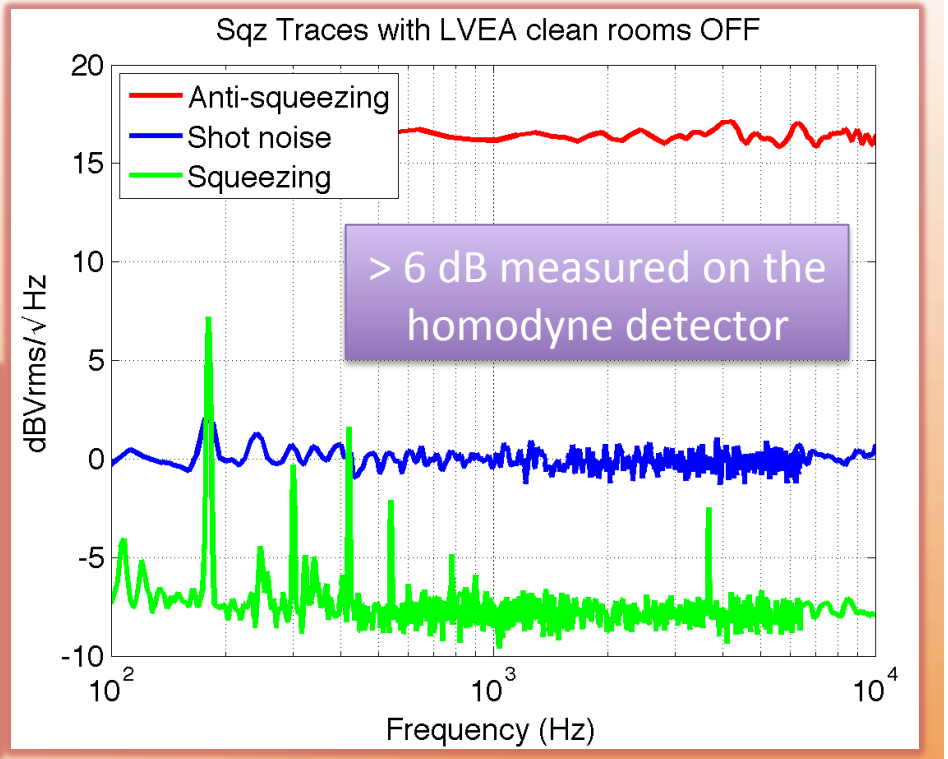
This afternoon:

"A back scatter tolerant squeezer for future generation GW detectors"

Michael Stefszky (ANU)

Advanced Detector Technology

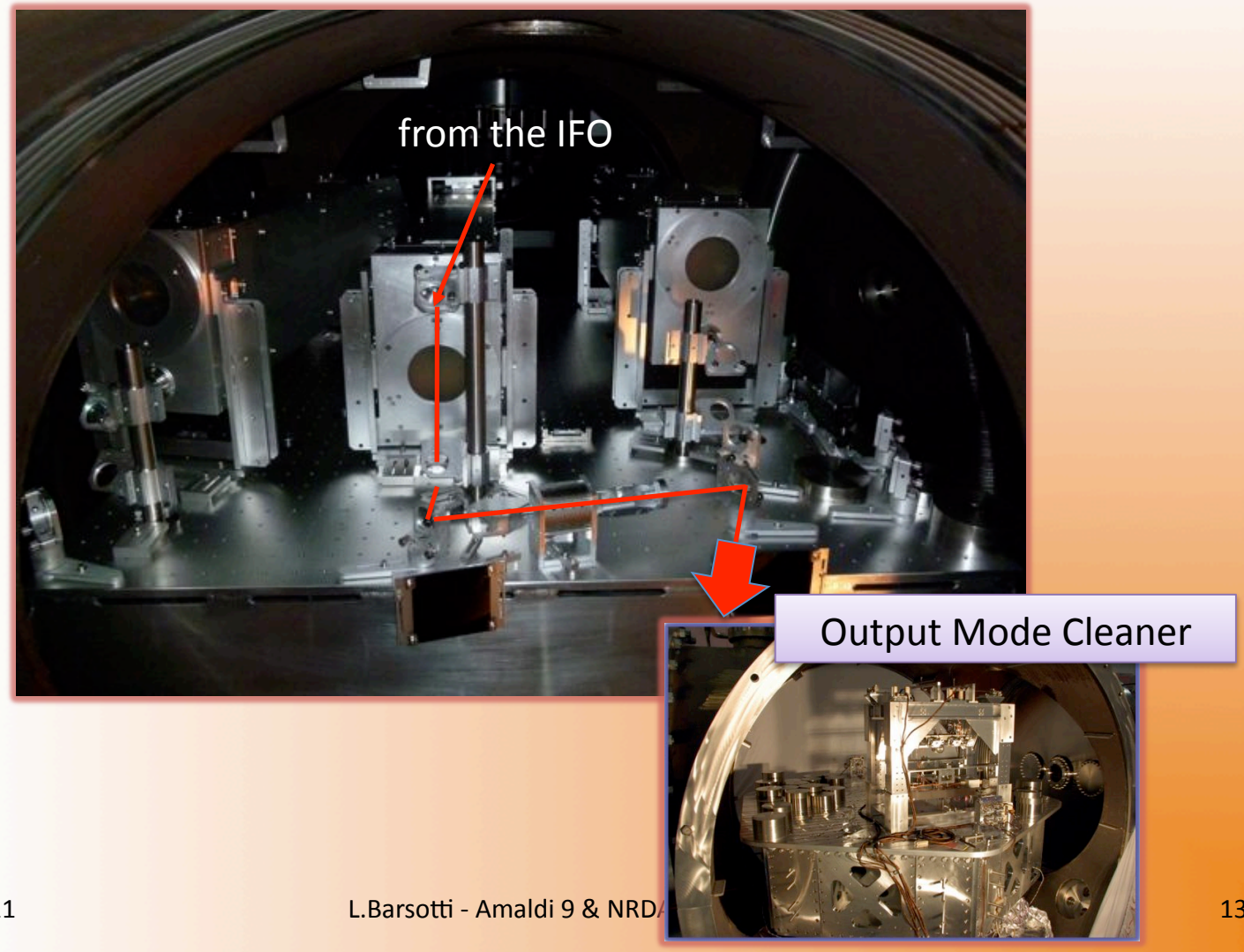




✧Advanced LIGO electronics

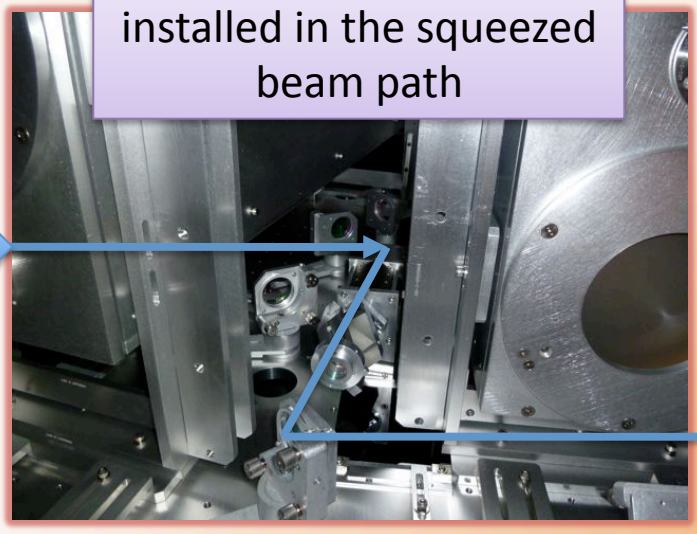
✧Squeezer integrated in the LIGO Control System

H1 Squeezing Experiment: (Old) Readout In-Vacuum Layout

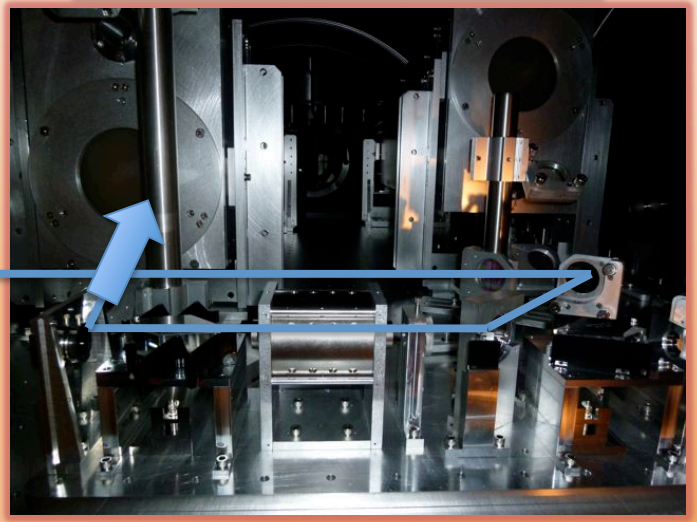


H1 Squeezing Experiment: Squeezer Installation (just done!)

Additional Faraday installed in the squeezed beam path



New H1 Output Faraday (first aLIGO unit)



Squeezer table craned to its final location

- ✧ Relocking H1 now
- ✧ First squeezing injection in August
- ✧ Plans depend on Advanced LIGO schedule
  - ✧ aLIGO installation on H2 started in October

Open Questions/Problems

- ✧Back Scattering
- ✧Losses
- ✧Interferometer stability with squeezing
  - ✧Analysis on going in GEO right now

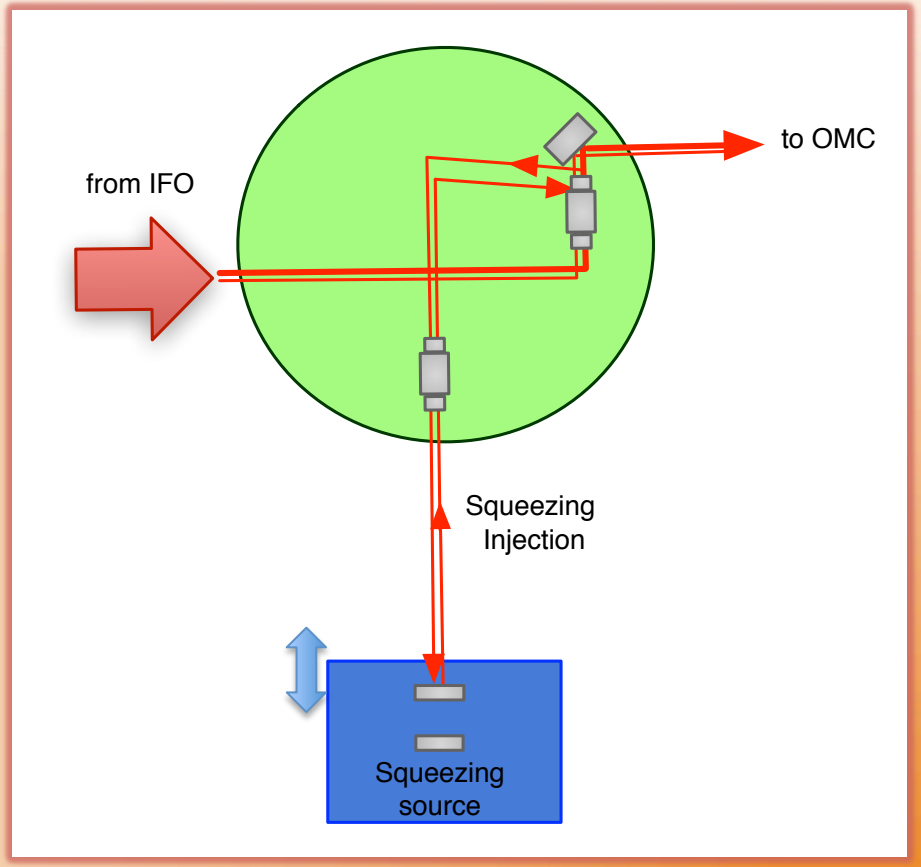
➔ In principle they are all “just” technical problems
➔ In practice, they need to be understood (now) to make squeezing ready for Advanced Detectors

Noise from Back Scattered Light

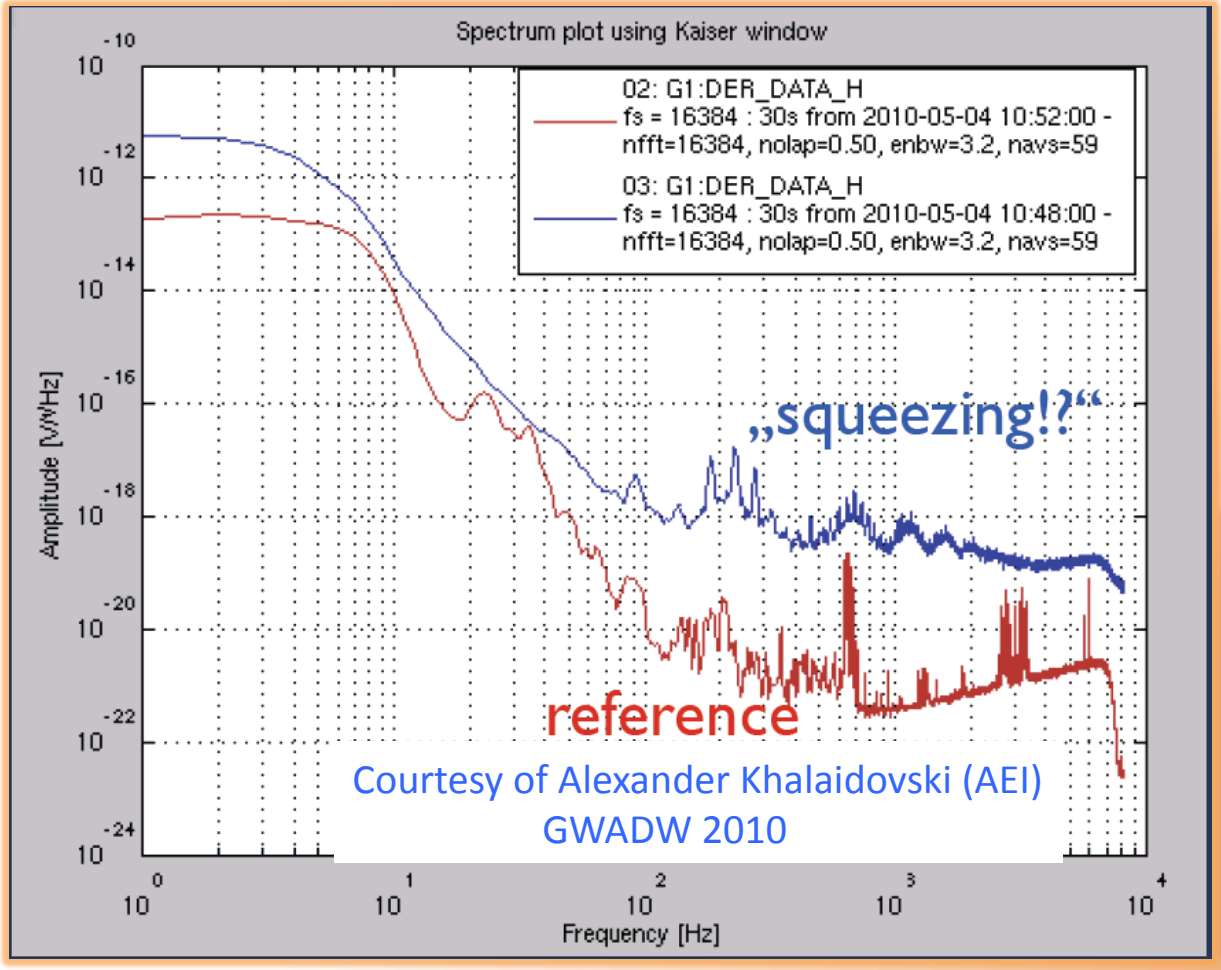
✧ Fraction of the light from the IFO is scattered back to the IFO by the squeezer

✧ Modulated by the squeezer motion

➔ it makes noise in the GW channel in the hundred Hz region
(where we care the most!)

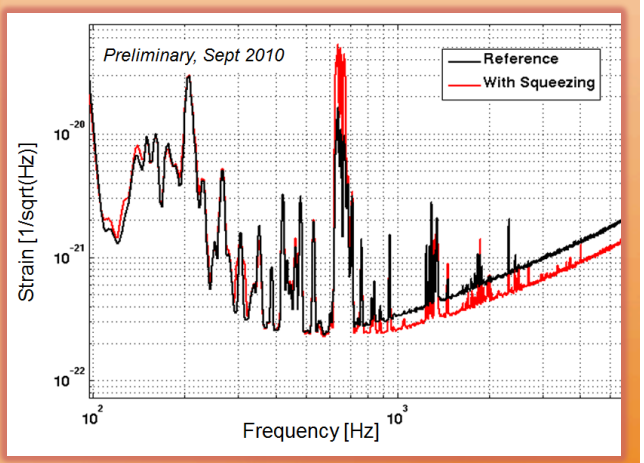


Back Scattering in GEO



✧ First squeezing injection: back scattered noise limits the sensitivity

✧ Additional Faraday to reduce back scattering and measure squeezing



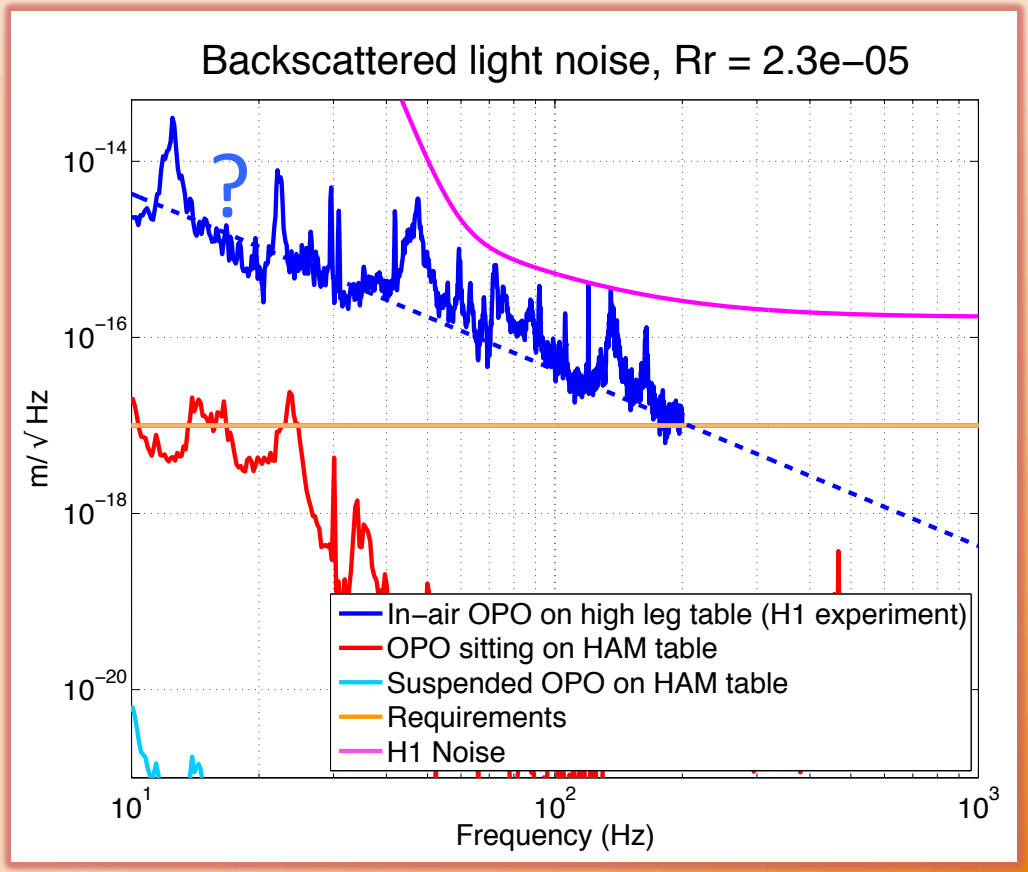
Back Scattering in H1 (Model! No data yet)

Motion of the scattering surface

Power reflectivity of the scattering surface

$$X_{sc}\sqrt{T_{Faraday}R_r}$$

➔ 46 dB of back scattering suppression from the bow-tie OPO measured at ANU (Michael's talk)

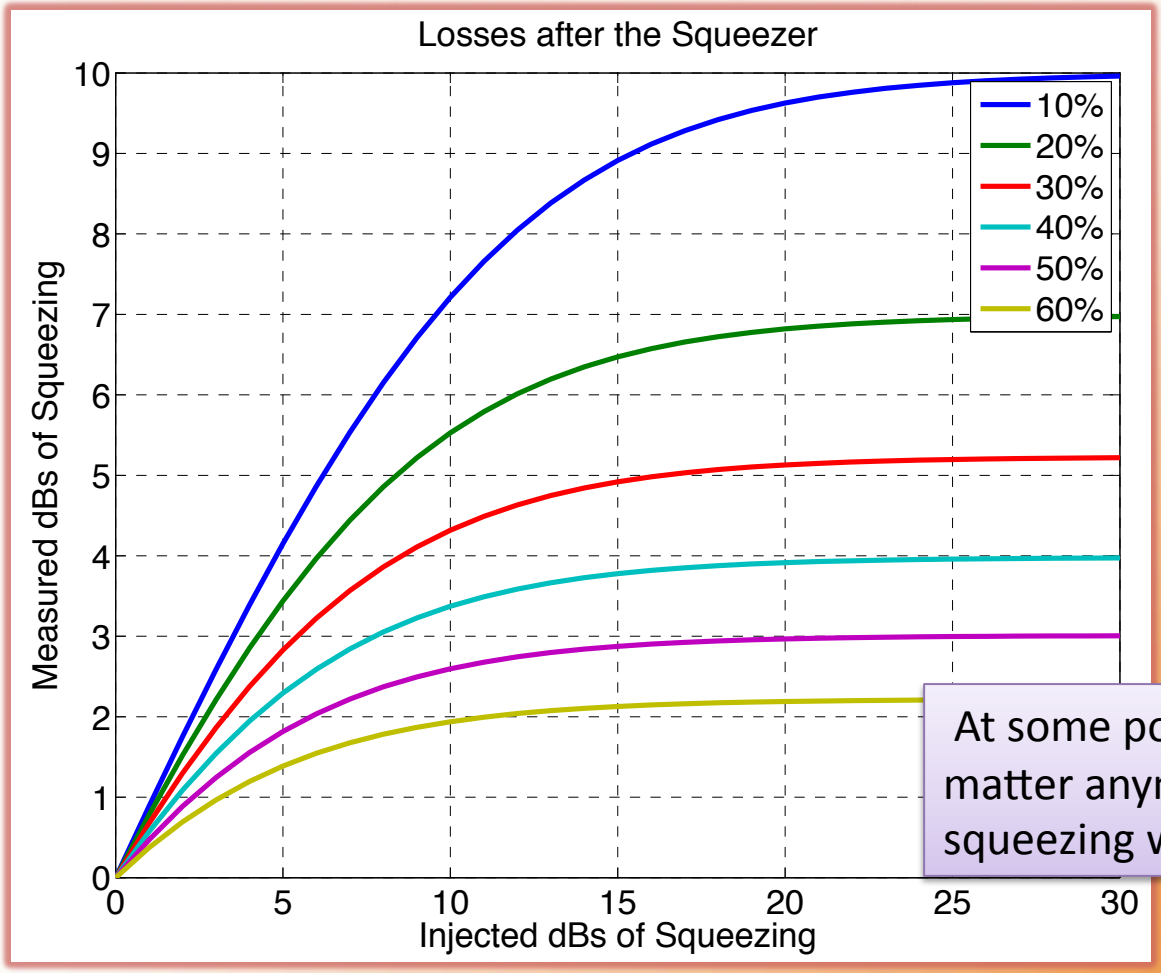


✧Current set-up ok for H1, it might be not optimal for Advanced LIGO

✧Waiting for the actual measurement to evaluate the best strategy to deal with it

Losses are Bad

✧ Losses degrade squeezing ("un-squeezed" vacuum gets in)



At some point it doesn't matter anymore how much squeezing we are injecting

Losses are Bad

- Plenty of losses in the squeezed beam path (from the squeezer to the GW photodiode):
  - Mode matching
  - Faradays

    (less back scattering = more Faradays = more losses)
  - Optical components (windows, mirrors, ..)

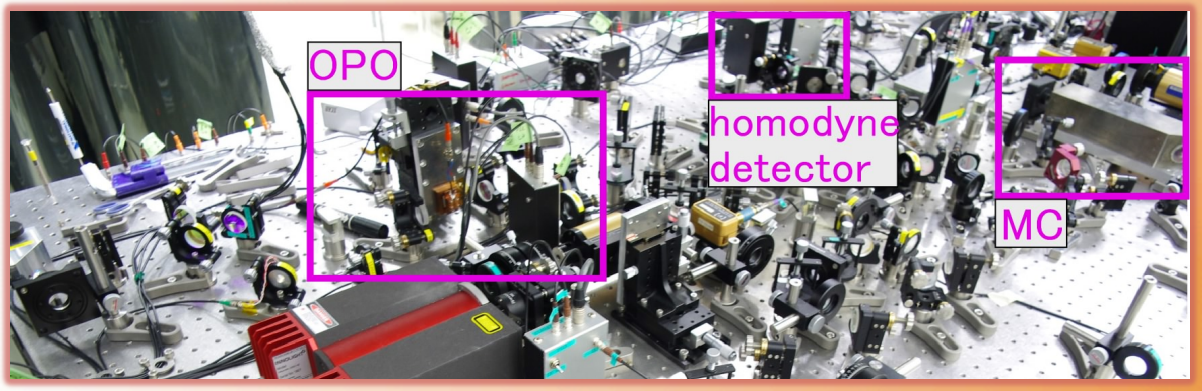
➔ Need to learn how to mode match more efficiently

➔ Need to be ready to make very low loss Faradays!

Where we are going from here

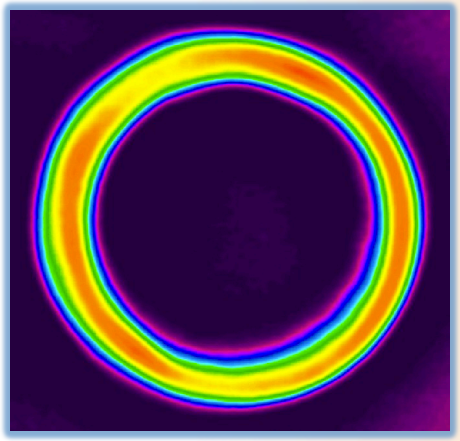
- ✧ Squeezing is not the baseline for Advanced Detectors (except GEO HF!), but..
- ✧ …recent progresses make squeezing closer than ever
- ✧ The GW community is “thinking” about it

Courtesy of Nobuyuki Matsumoto (University of Tokyo)

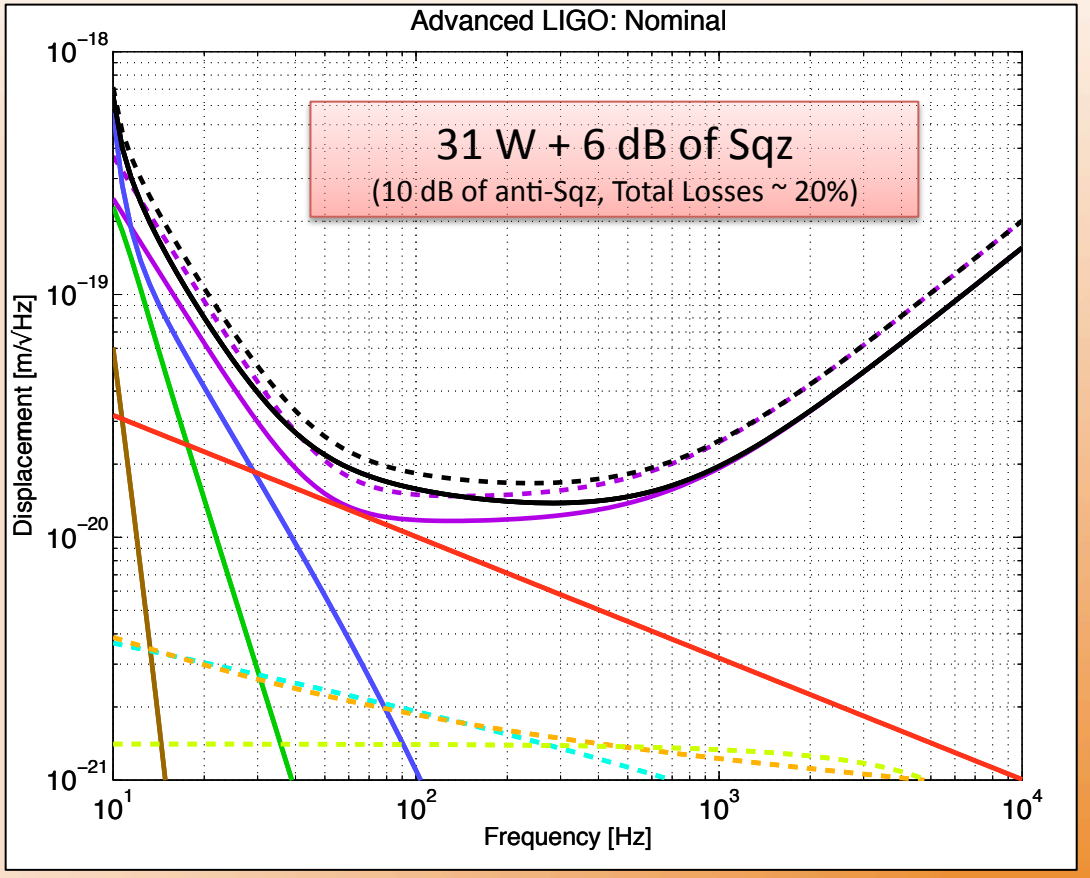


Advanced LIGO:
Risk mitigation for high power

- With 6 dB of perfect squeezing: need 4 time less power!

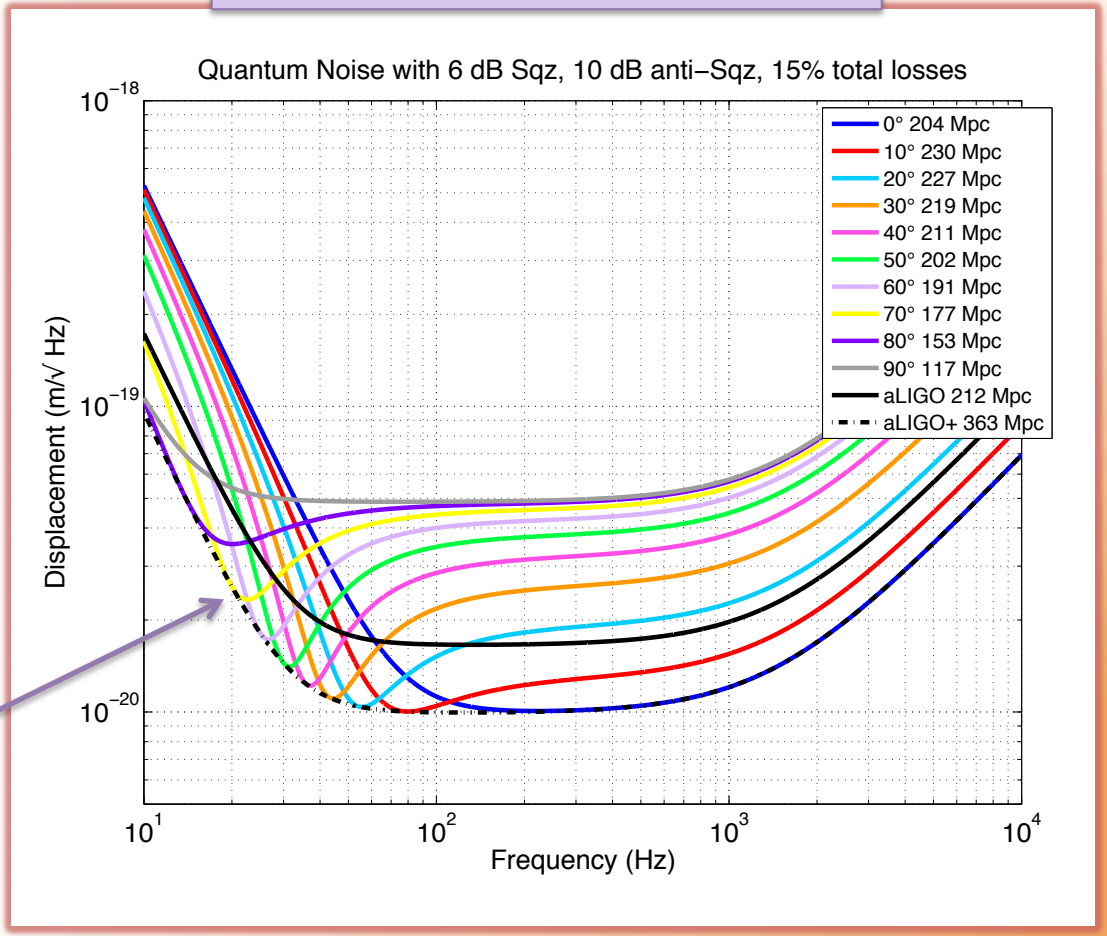


- We will have a squeezer ready to be installed if needed



Advanced LIGO and Beyond

Quantum noise shaped by tuning the squeeze angle



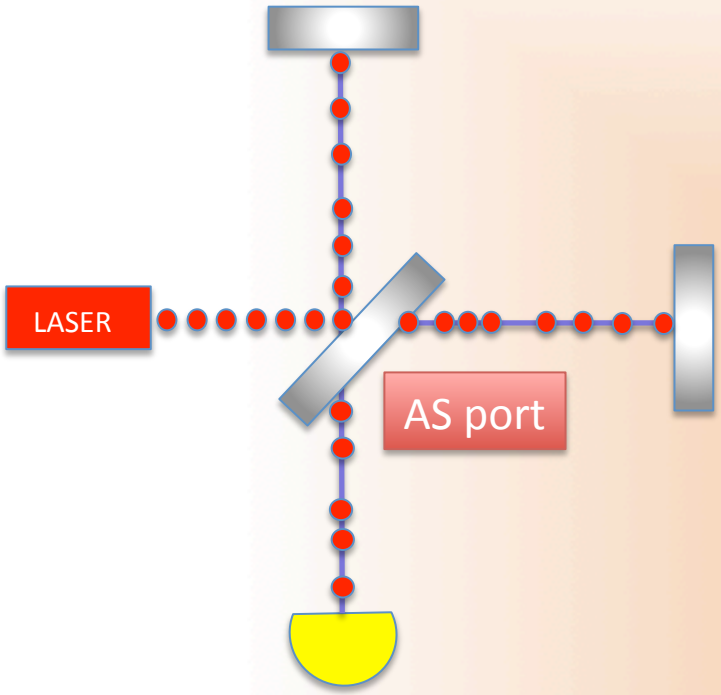
Filter cavities to beat quantum noise at all the frequency at the same time

The Message

- Large scale interferometers with squeezing: happening now!
- We need to understand issues / fix problems to be ready for Advanced Detectors…
- …that's what we are trying to do!

THANKS!

Shot Noise & Photon Arrival Time



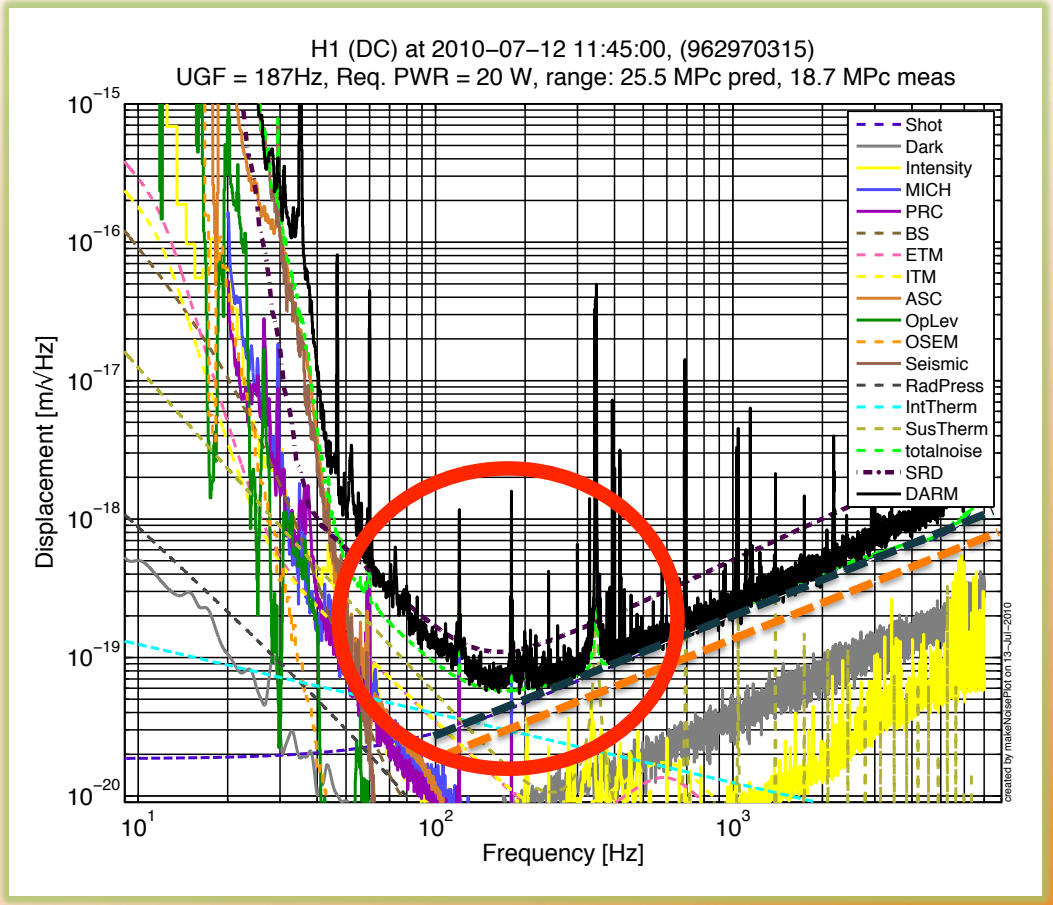
- Shot noise is the fundamental noise limiting the GW detector sensitivity at "high" frequency
- Shot noise originates from the Poissonian statistics of the arrival time of the photons on a photo-detector
- The minimal phase variation in the arms which can be measured is:

$$\delta\varphi \geq \frac{1}{\sqrt{N}}$$

N number of photons incident on the mirrors in the measurement time

H1 Experiment Goal:
Design the aLIGO Squeezer

- Inject 6 dB of squeezing at the asymmetric port of H1
- Improve the sensitivity by 3 dB (due to losses) above 400 Hz
- Understand the impact of squeezing at low frequency
- Find/fix “technical problems”

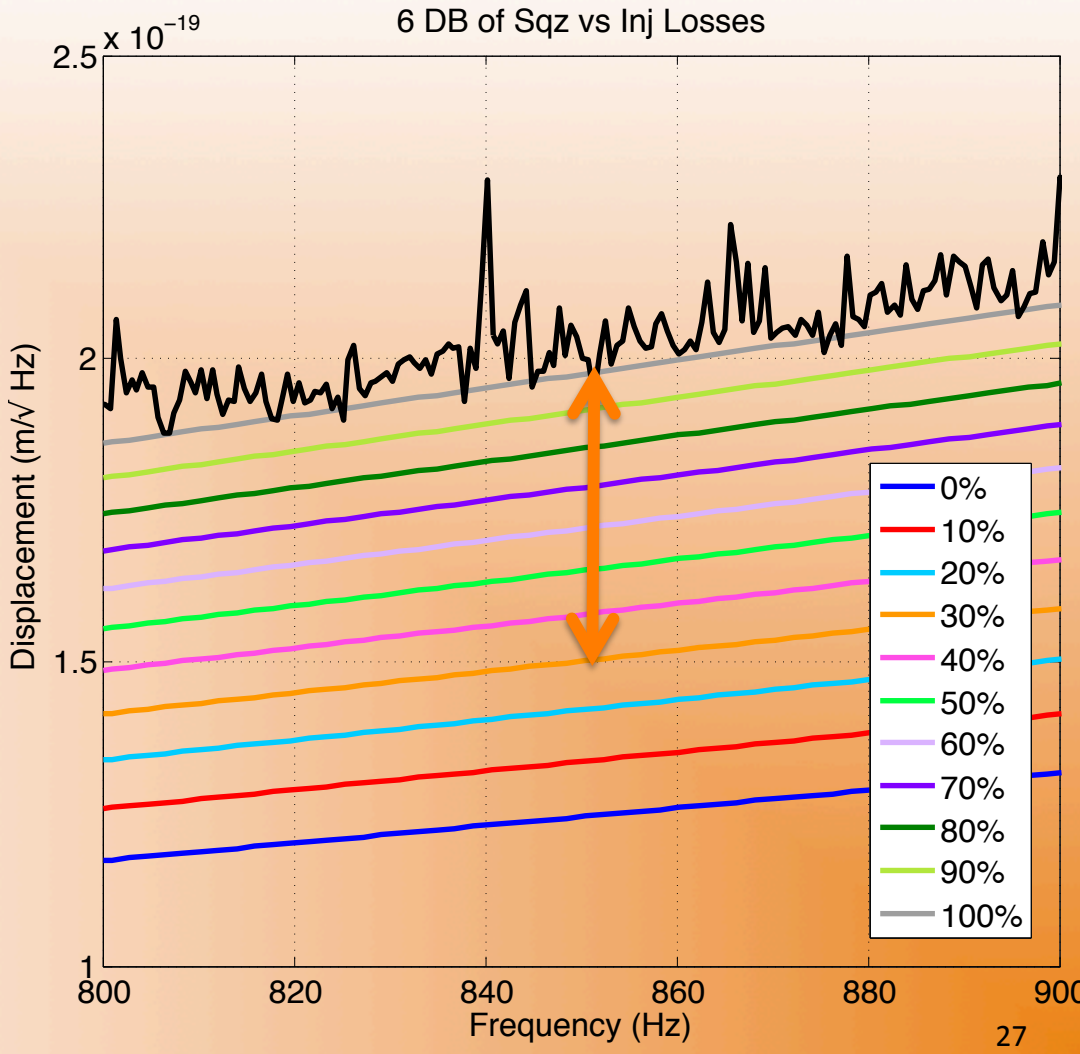


Squeezing Injection in H1

✧ About 20% losses in the output path (OMC, Faraday)

✧ About 10% losses in the sqz injection path

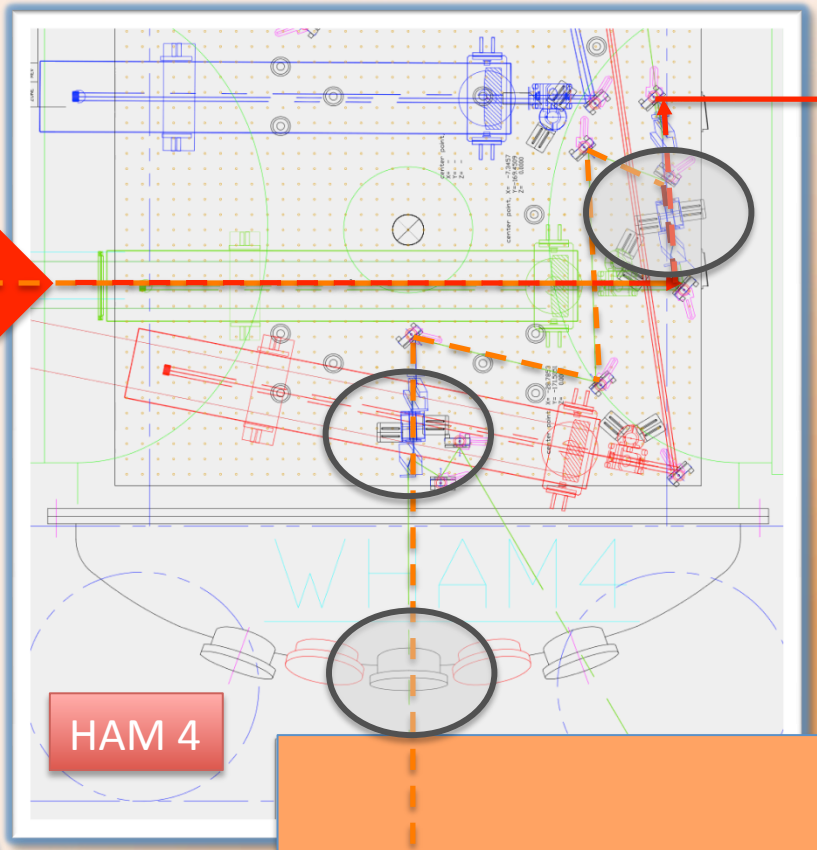
3 dB of Sqz observed with 6 dB of Sqz produced

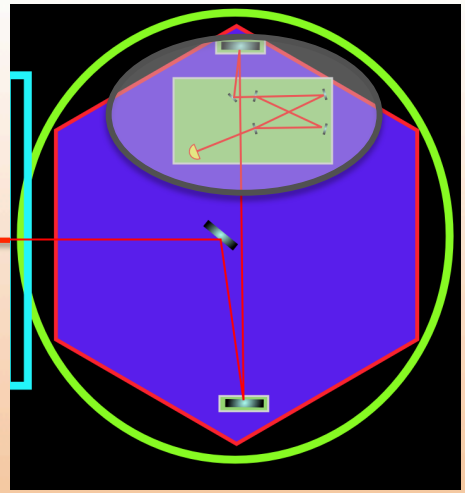


Losses

~20% losses in the IFO output path

IFO





~10% losses in the sqz injection path

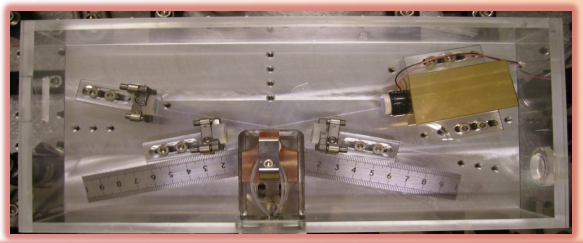
Squeezing Table

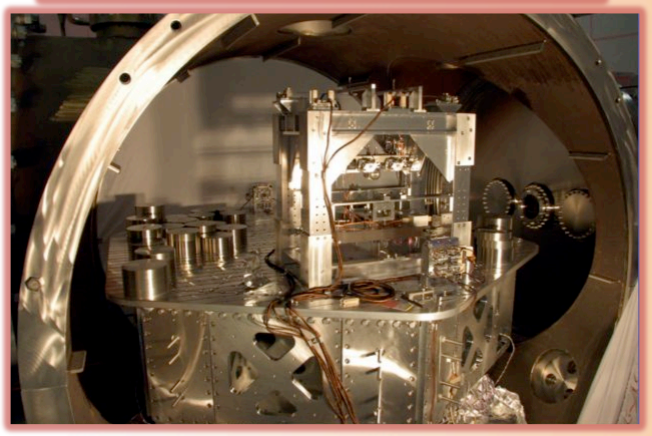
~ 30% TOTAL LOSSES

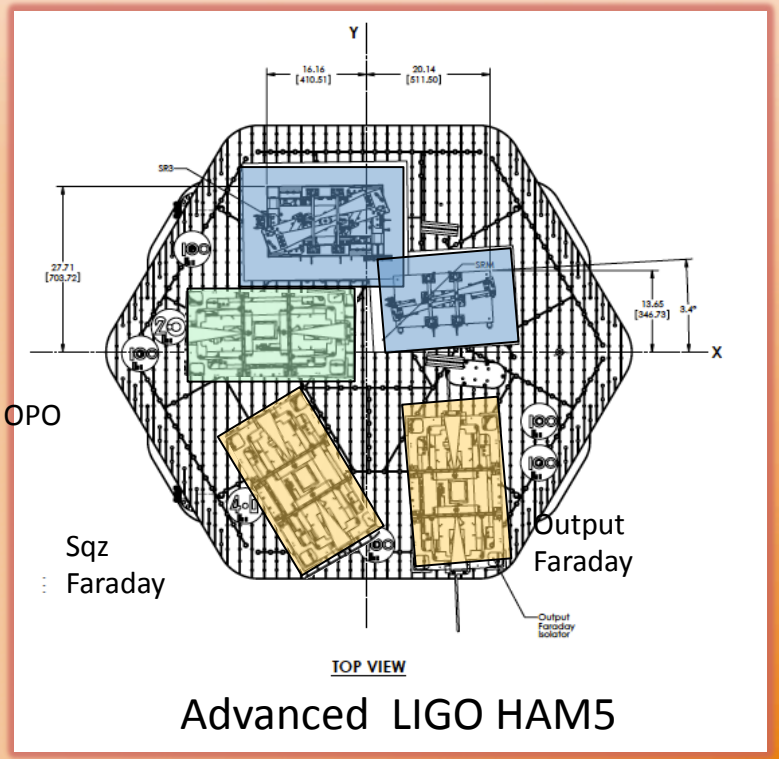
Speculations on the Advanced Squeezer

$$X_{sc}\sqrt{T_{Faraday}R_r}$$

- Two directions:
  - Reduce the light back to the squeezer (more Faradays, but Faraday=losses)
  - Reduce the motion of the scattering surface (OPO)







Advanced LIGO HAM5