Filter Cavity Experiment and Frequency Dependent Squeezing

MIT
Tomoki Isogai

Outline

- What is squeezing?
- Squeezing so far
- Why do we need frequency dependent squeezing?
- Filter Cavity Experiment at MIT
- Frequency Dependent Squeezing Expectations

Classical Optics

- Amplitude
- Phase

$$E = |E|e^{i\phi}$$

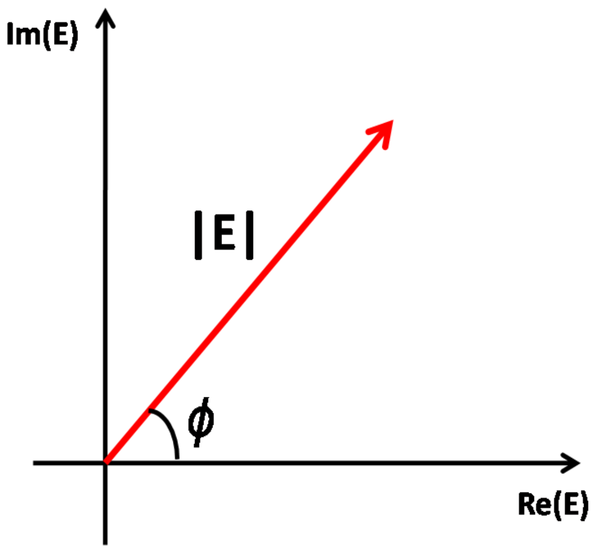
- Power

$$P = EE^*$$

- Phaser Representation

Length → amplitude

Angle → phase



Quantum Optics

- Annihilation / Creation operator

$$a, a^\dagger$$

- Photon Number

$$n = a^\dagger a$$

- Define a Hermitian operator pair

$$\hat{X}^+ = \hat{a}^\dagger + \hat{a}$$

$$\hat{X}^- = -i(\hat{a} - \hat{a}^\dagger)$$

$$E = X^+ \cos\omega t + X^- \sin\omega t$$

Quantum Optics

$$E = X^+ \cos\theta + X^- \sin\theta$$

- Uncertainty Principle:

  No measurement can be completely deterministic in two non-commuting observables

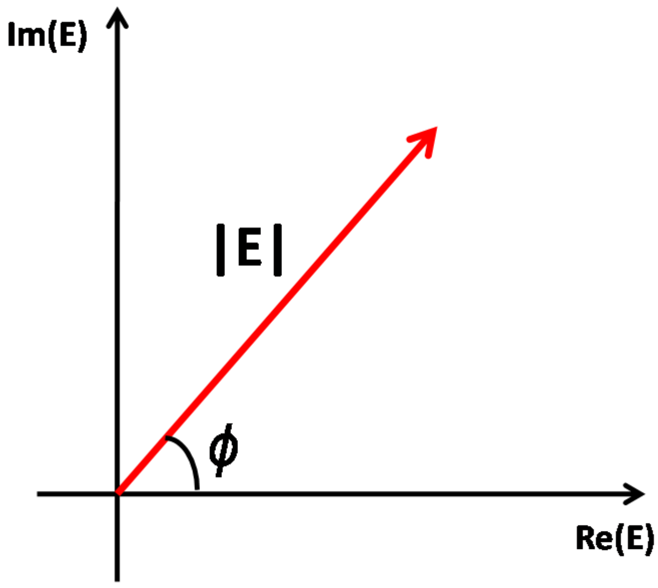
- E.g.

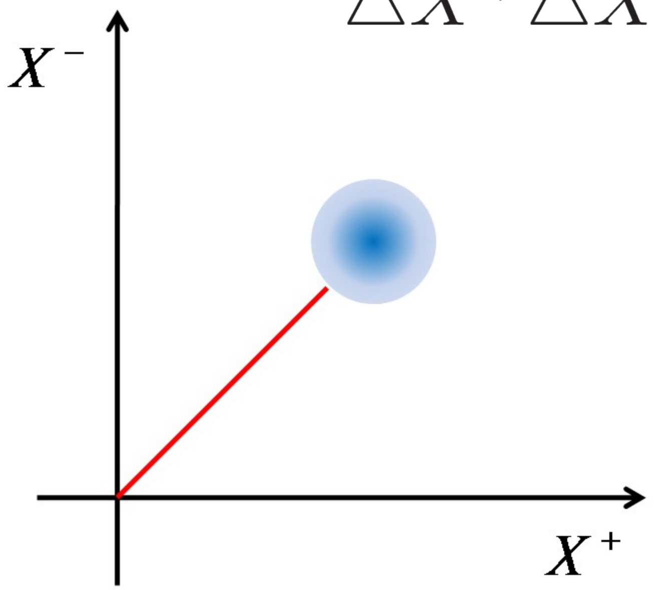
  $$\triangle x \triangle p \geq \hbar/2$$

- Similarly for EM field,

  $$\triangle X^+ \triangle X^- \geq 1$$

Phaser Representation

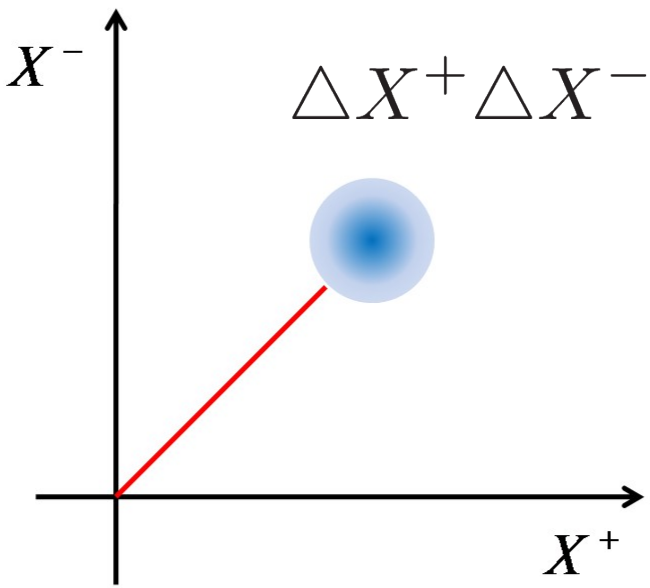




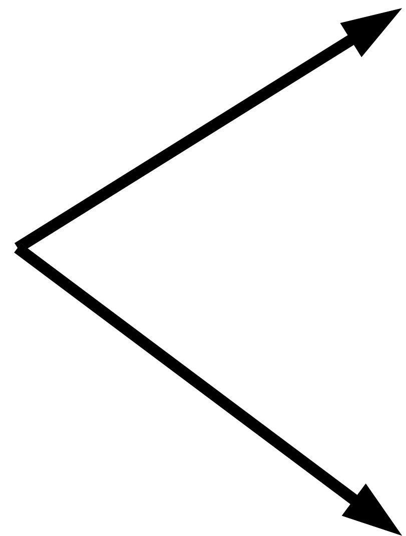
$$\triangle X^+ \triangle X^- \geq 1$$

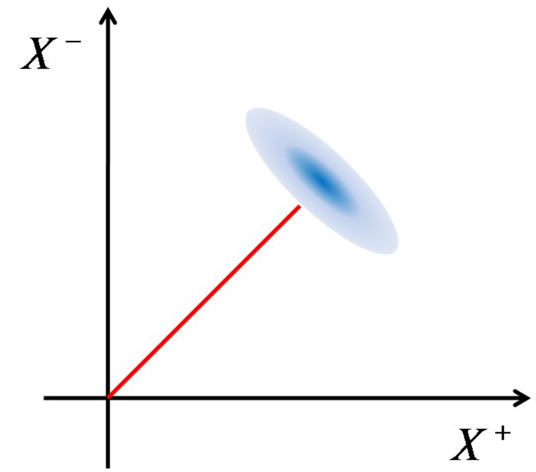
Analogous to the phaser diagram
Stick $\rightarrow$ DC term
Ball $\rightarrow$ fluctuations

Squeezing

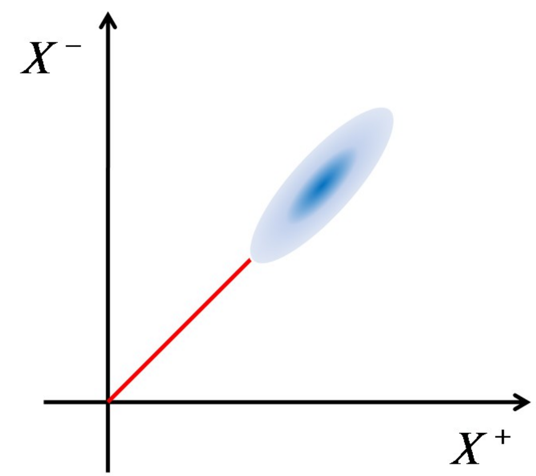


There is a minimum uncertainty product (area), but noise can be redistributed



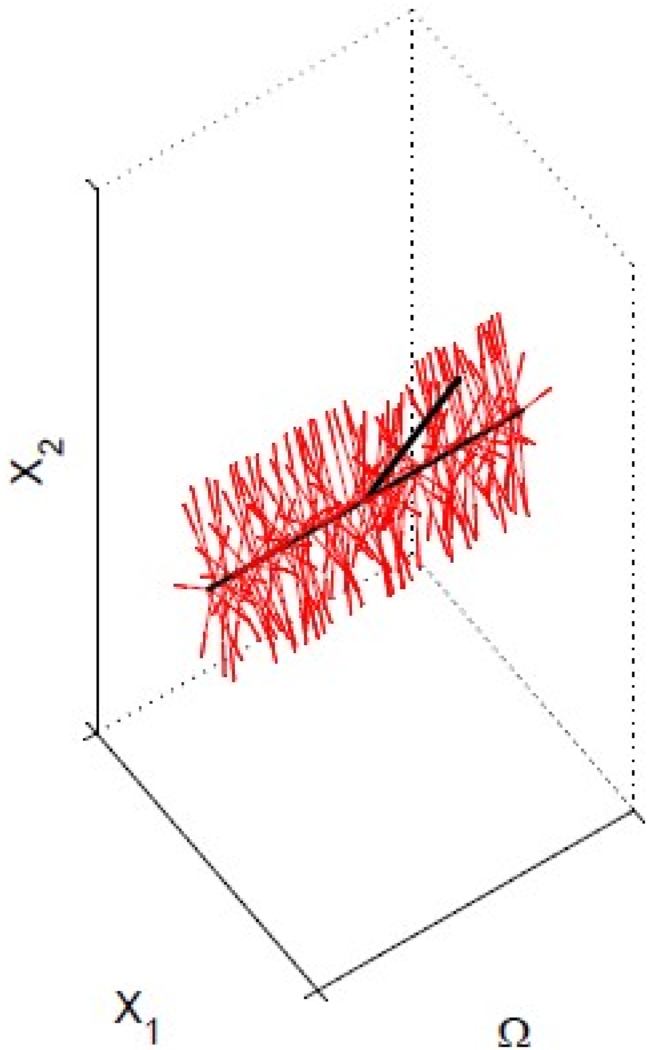


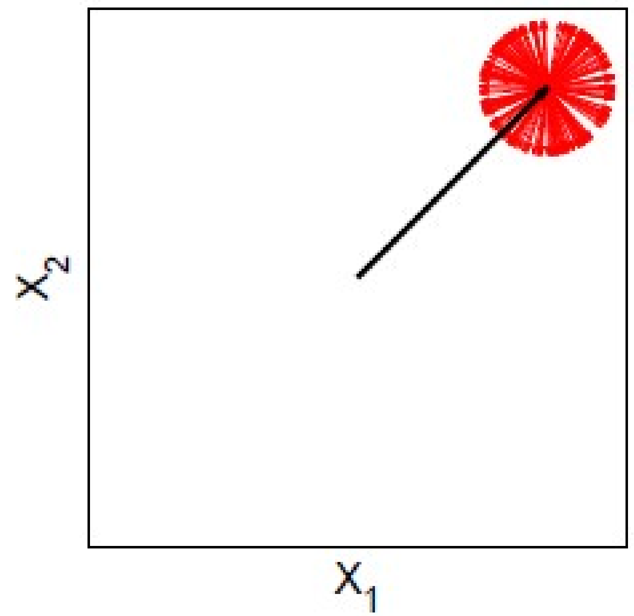
Amplitude Squeezed State



Phase Squeezed State

Sideband Picture



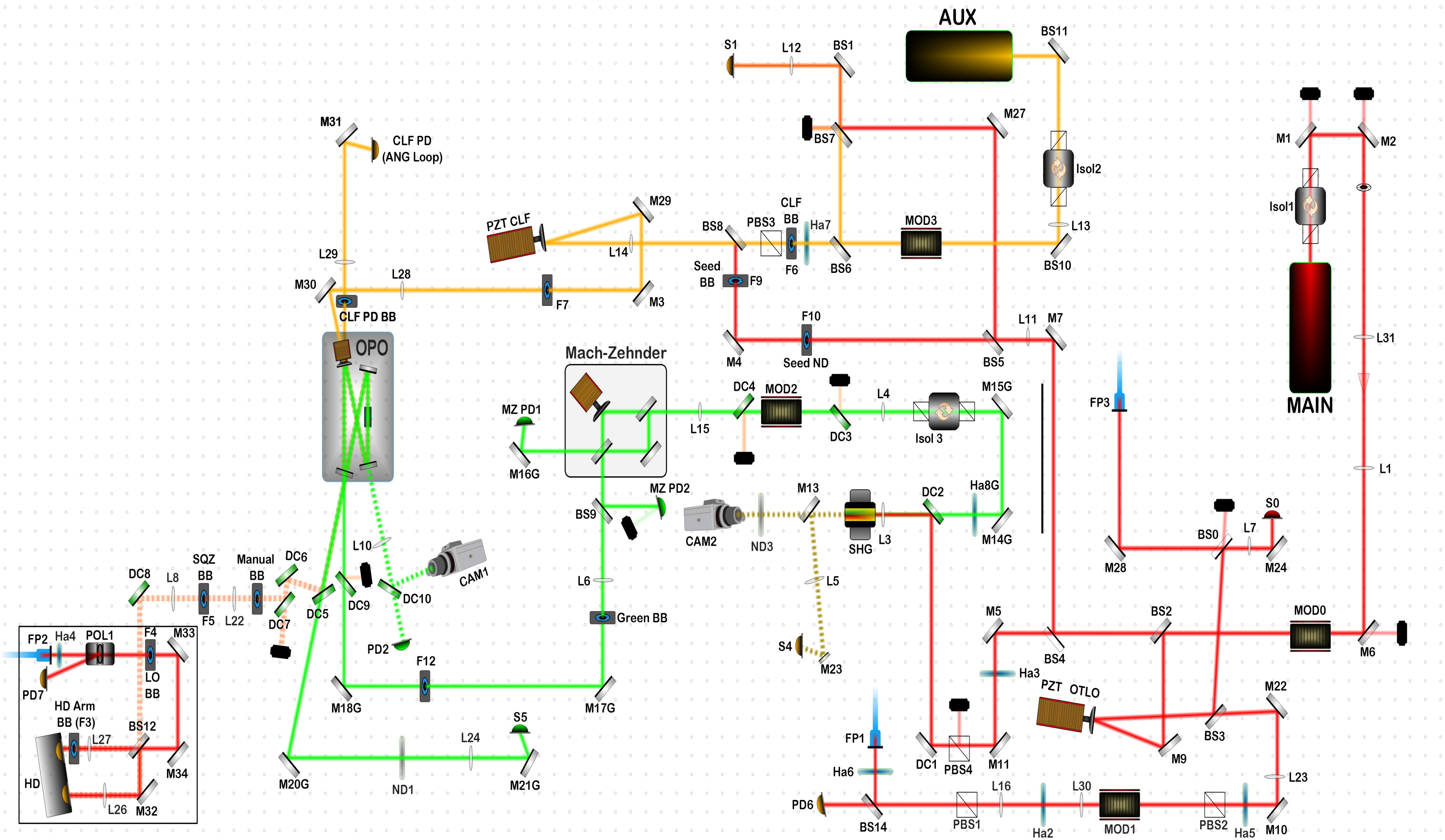


Sheila Dwyer Thesis

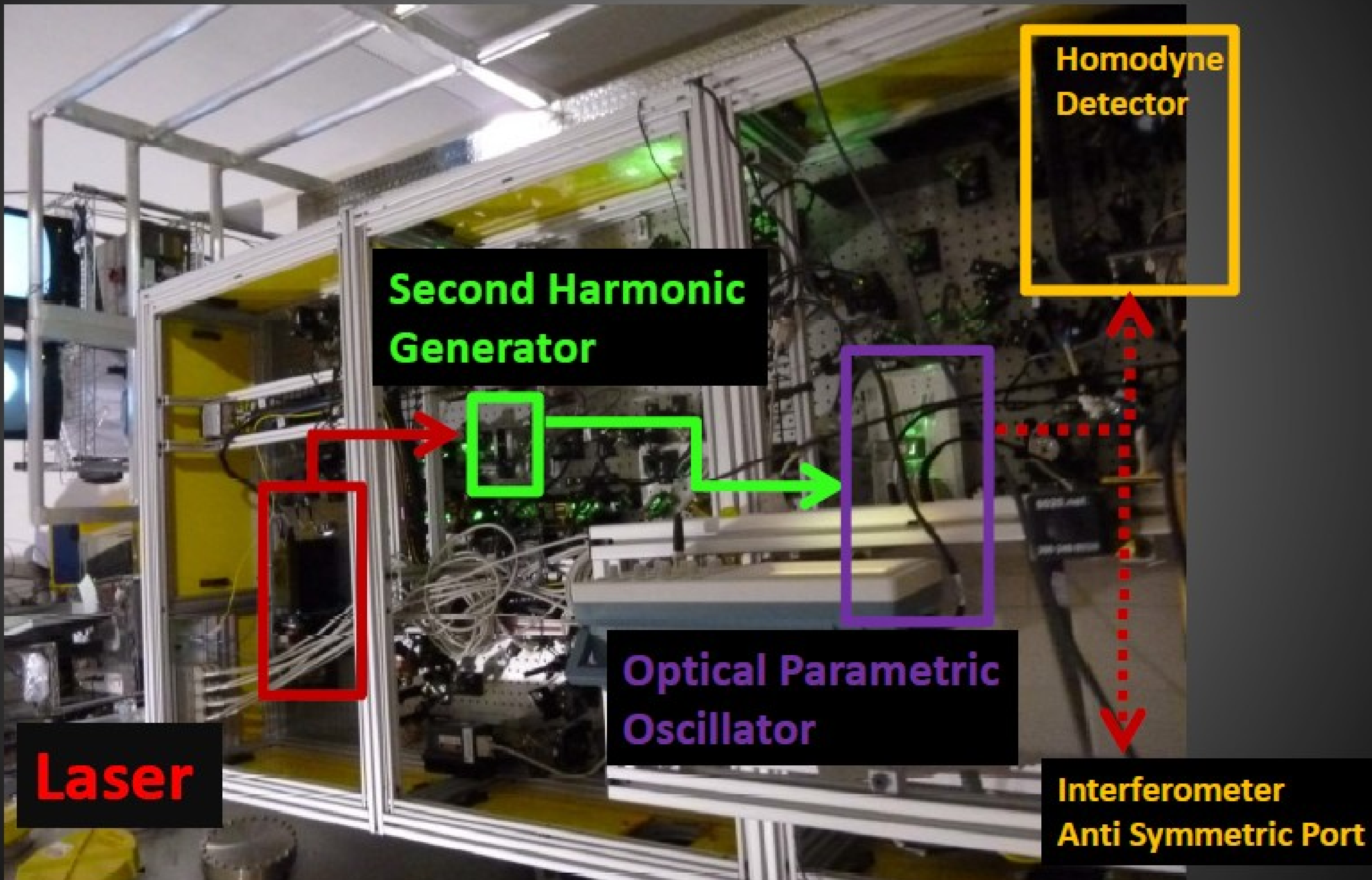
How to squeeze?

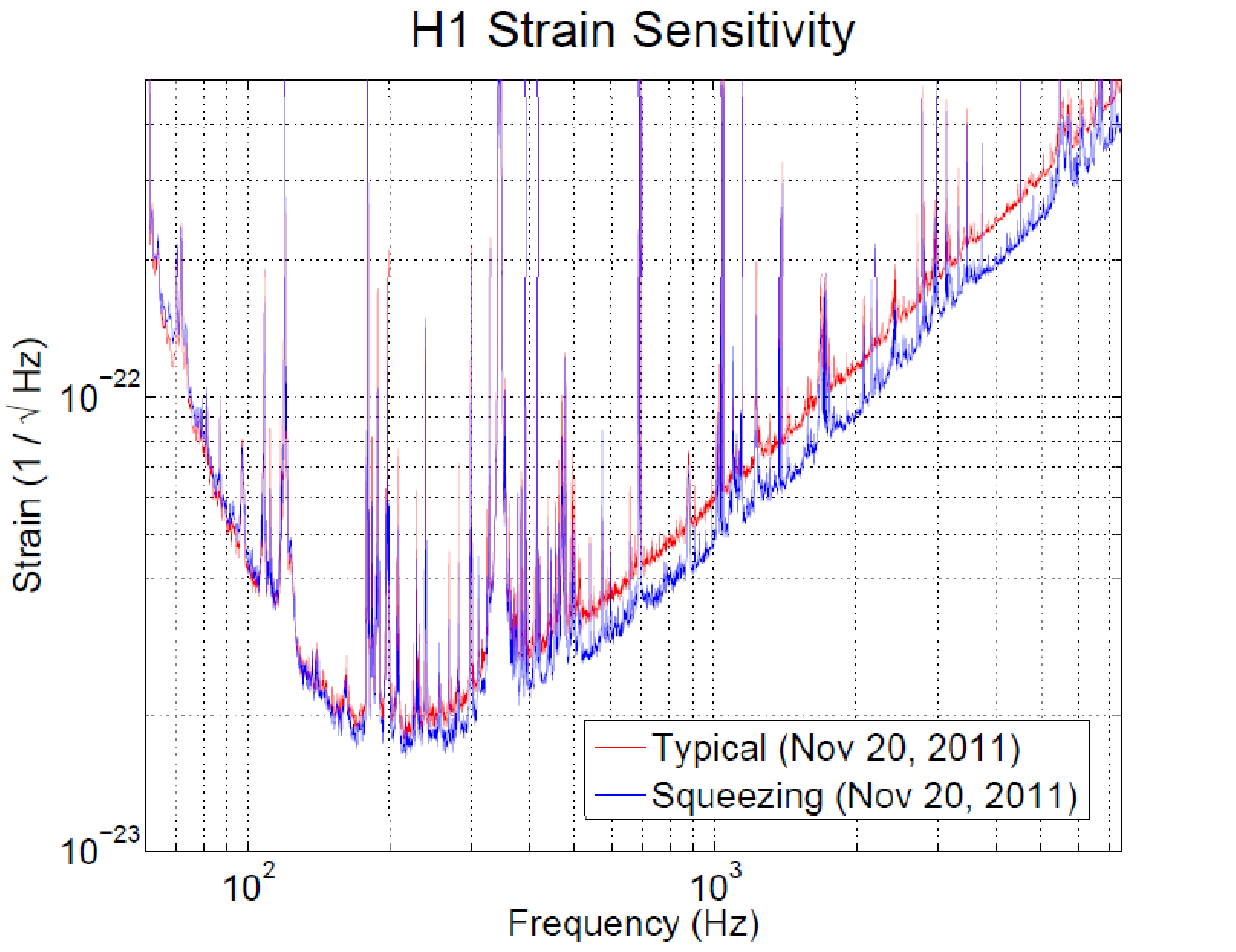
- A tight hug
- Non-linear crystal
- Ponderomotive

LHO SQZ table layout
last updated on 2012.04.20
reflects changes made on 2012.04.12



A squeezer table

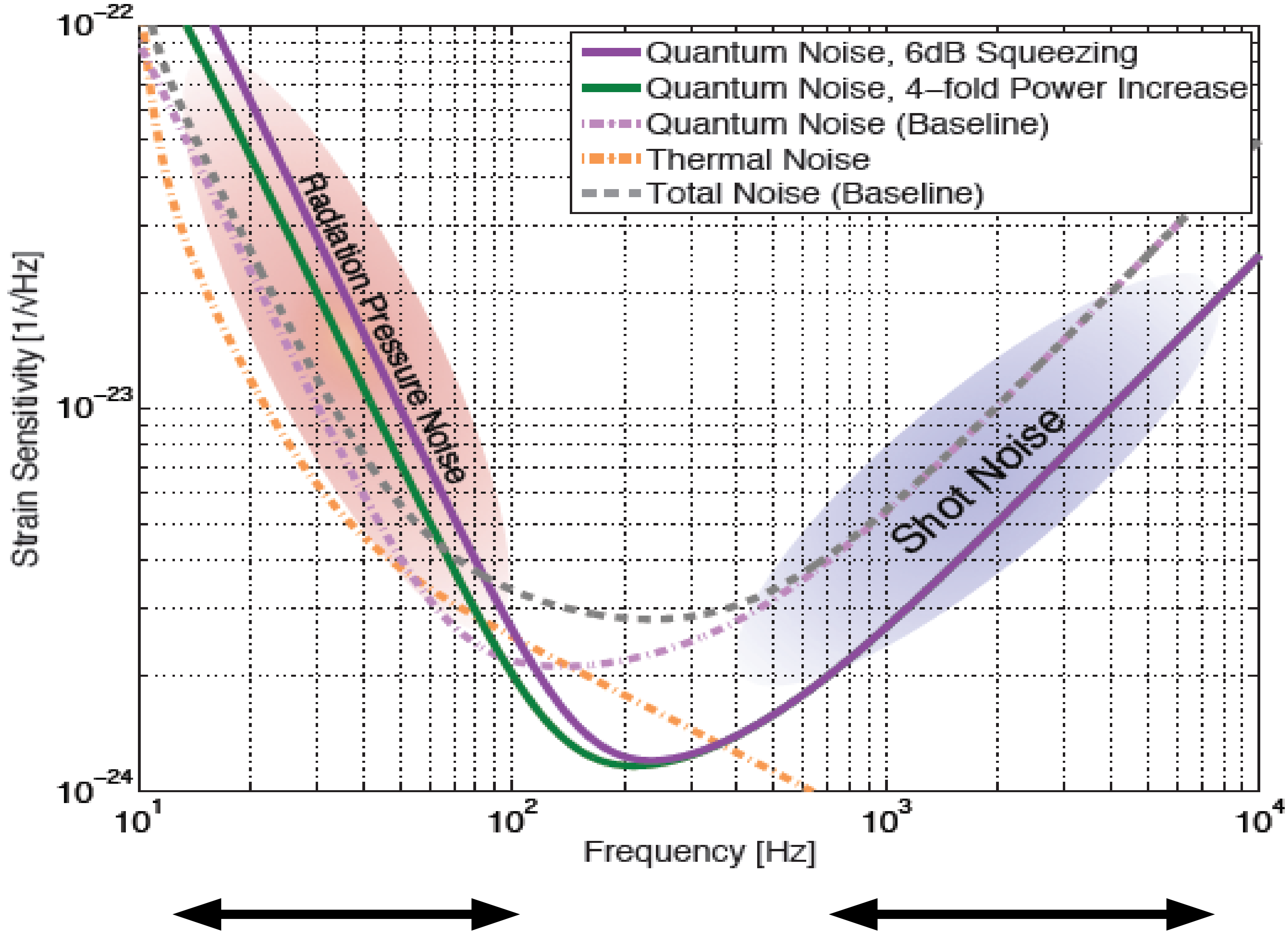



H1 Strain Sensitivity
Strain (1 / √ Hz)
10^-22
10^-23
10^2
10^3
Frequency (Hz)
Typical (Nov 20, 2011)
Squeezing (Nov 20, 2011)

H1 Squeezer Summary

- 2.25dB quantum noise reduction
- Some squeezing down to nearly 100Hz
- Inspiral range was improved by 1 Mpc
- Squeezing did not add noise at any frequency
- Noise model and characterization

Catch



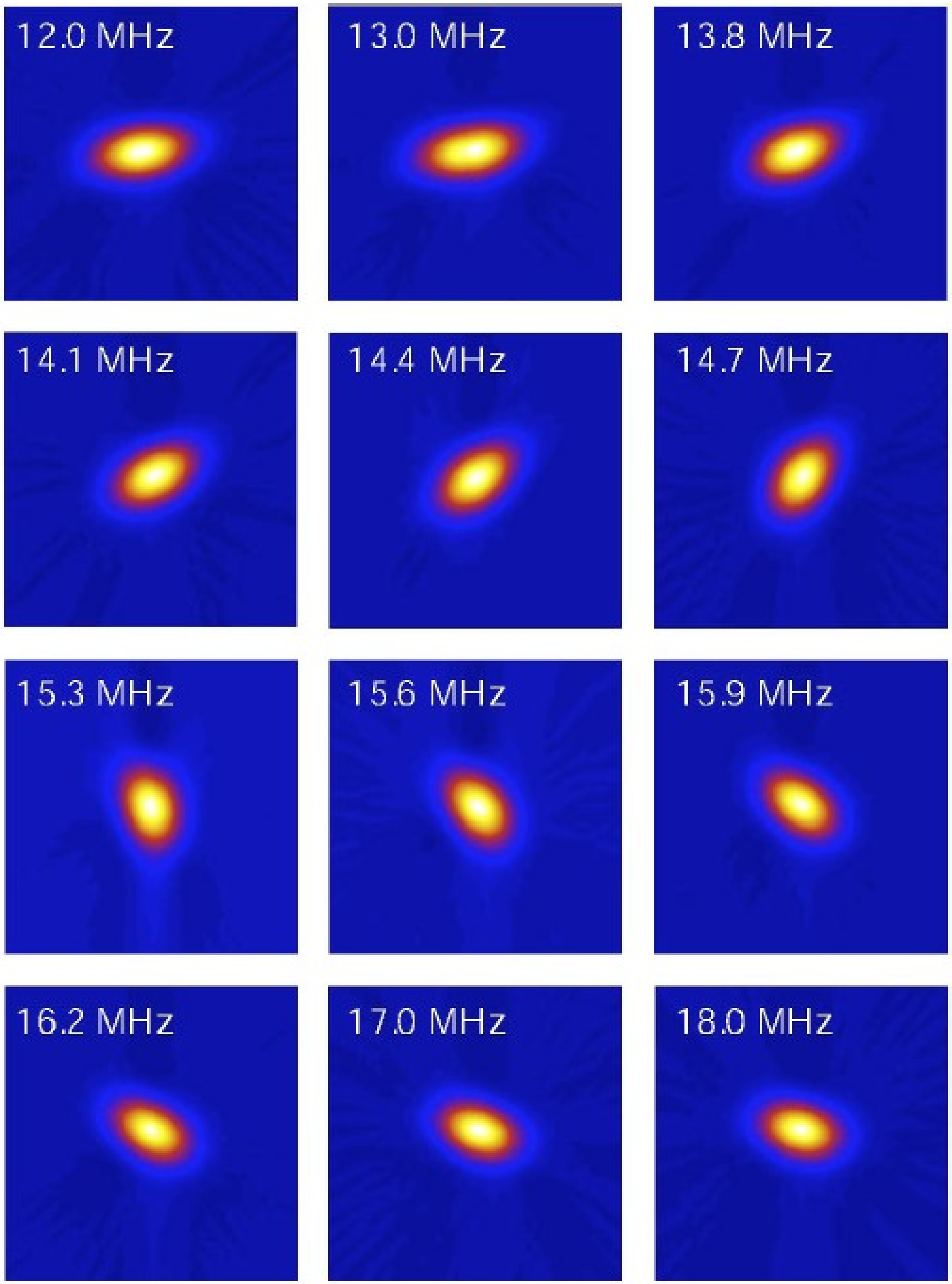
Require Amplitude Squeezing

Require Phase Squeezing

Frequency Dependent Squeezing

- Theoretically frequency dependent squeezing is well understood (ref. H.J. Kimble et al., Phys. Rev. D 65, 022002, 2001)
- Using a simple two mirror Fabry-Parot cavity (called filter cavity), we can rotate our squeezing angle depending on frequency
- We can reflect frequency INDEPENDENT squeezed light off a cavity, and get frequency DEPENDENT squeezing

- Proof of principle experiment is done at high frequency (ref. S. Chelkowski et al., Phys. Rev. A 71, 013806, 2005)



MIT Filter Cavity Experiment

Objective 1: Measuring optical Losses to determine Advanced LIGO filter cavity design

• Mirrors have absorption and scattering loss

• Loss degrades the squeezing by mixing with the vacuum state

• Cavity loss determines how long filter cavity we need for GW detector (16m? 100m? 4km?)

Barsotti, Evans, Isogai, (Kwee), Miller

MIT Filter Cavity Experiment

Objective 2: Implementing practical filter cavity control scheme

• Squeezed vacuum doesn't have coherent amplitude, so how do we control the filter cavity?

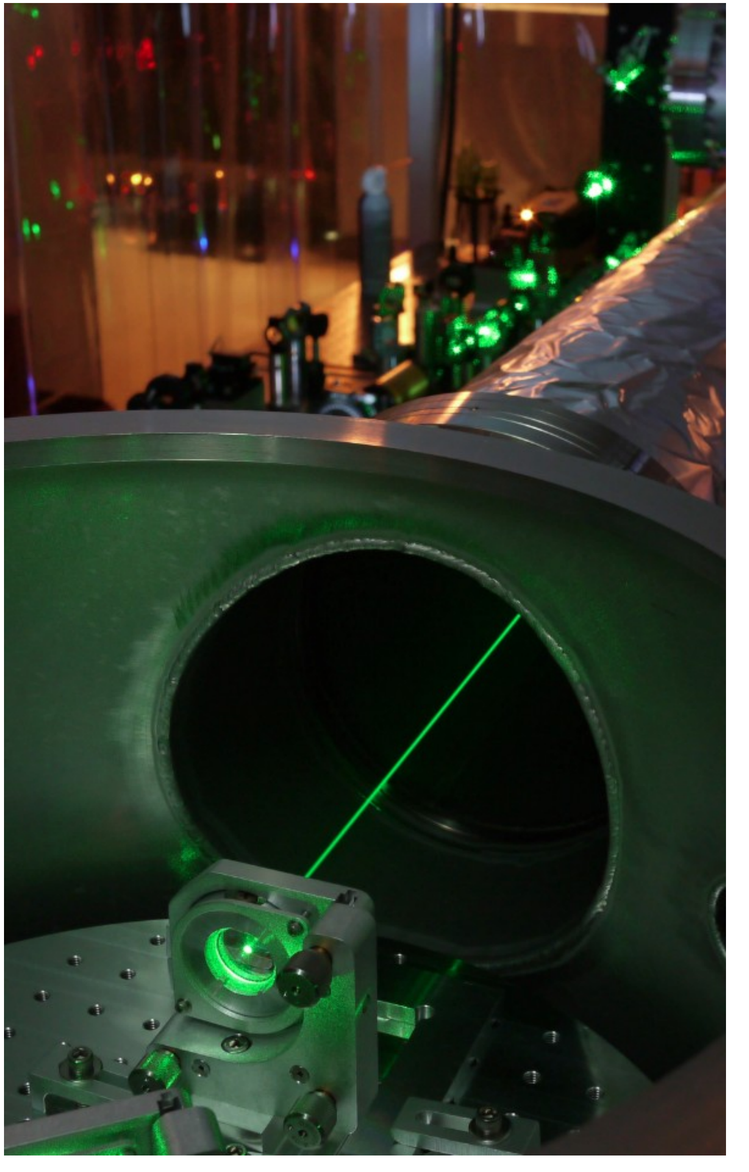
• We could use green light

• We'll check the stability to see if this really works

Barsotti, Evans, Isogai, (Kwee), Miller

MIT Filter Cavity Experiment

Objective 3: Characterize technical noise and prepare for demonstration of audio-band frequency dependent squeezing

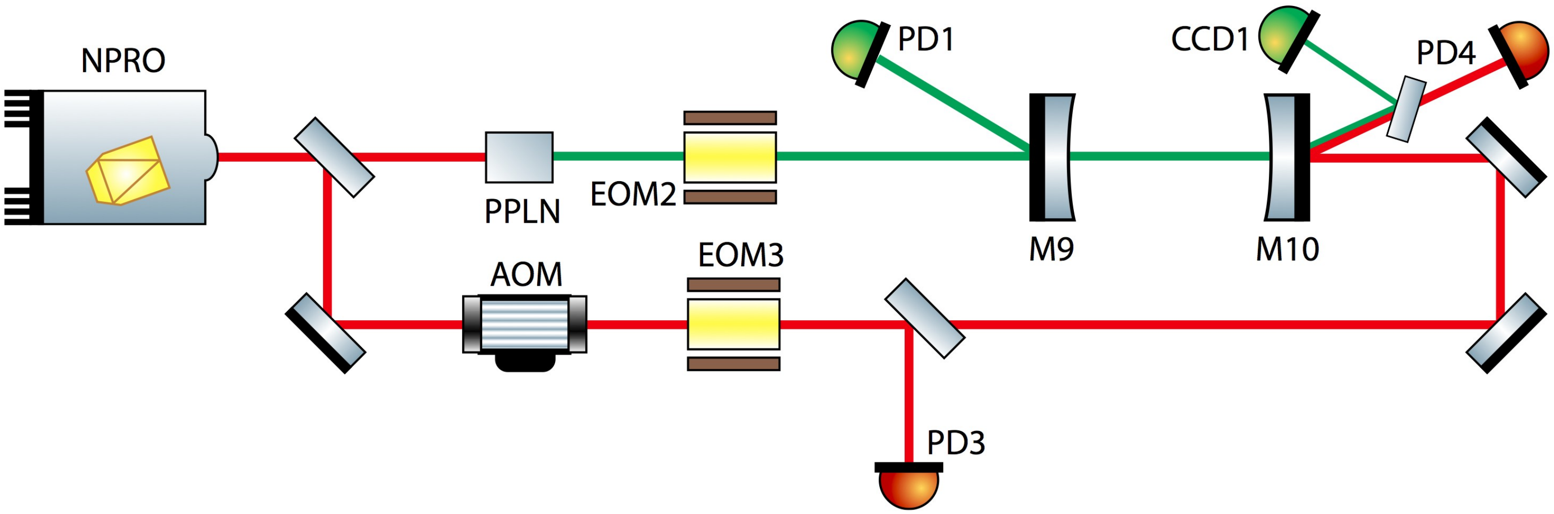


Barsotti, Evans, Isogai, (Kwee), Miller

Problem 1: Loss Measurement

- We assume that if the beam size is the same, scattering and absorption loss should be similar
- We prepared a concentric cavity very near its instability point, so that the beam size diverges very quickly as we change the cavity length, and we measure loss as a function of the beam size
- We extrapolate the results to longer cavity
- Use this info to infer what length we need for a realistic GW detector filter cavity

Experimental Setup

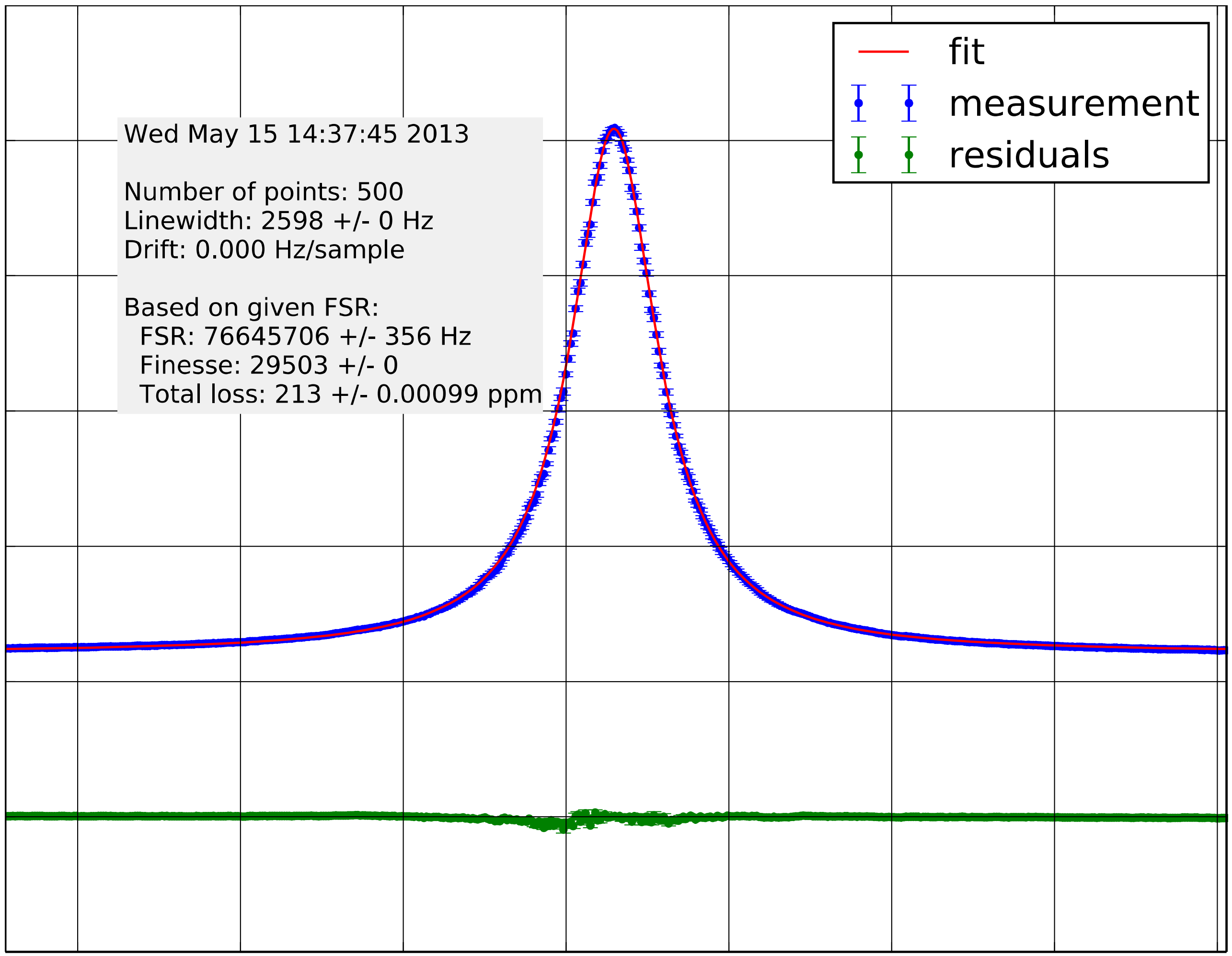


- Lock laser to cavity using green light
- Sweep AOM drive frequency to map out infrared resonance – linewidth measurement
- Cut AOM drive to extinguish infrared input beam – ringdown measurement

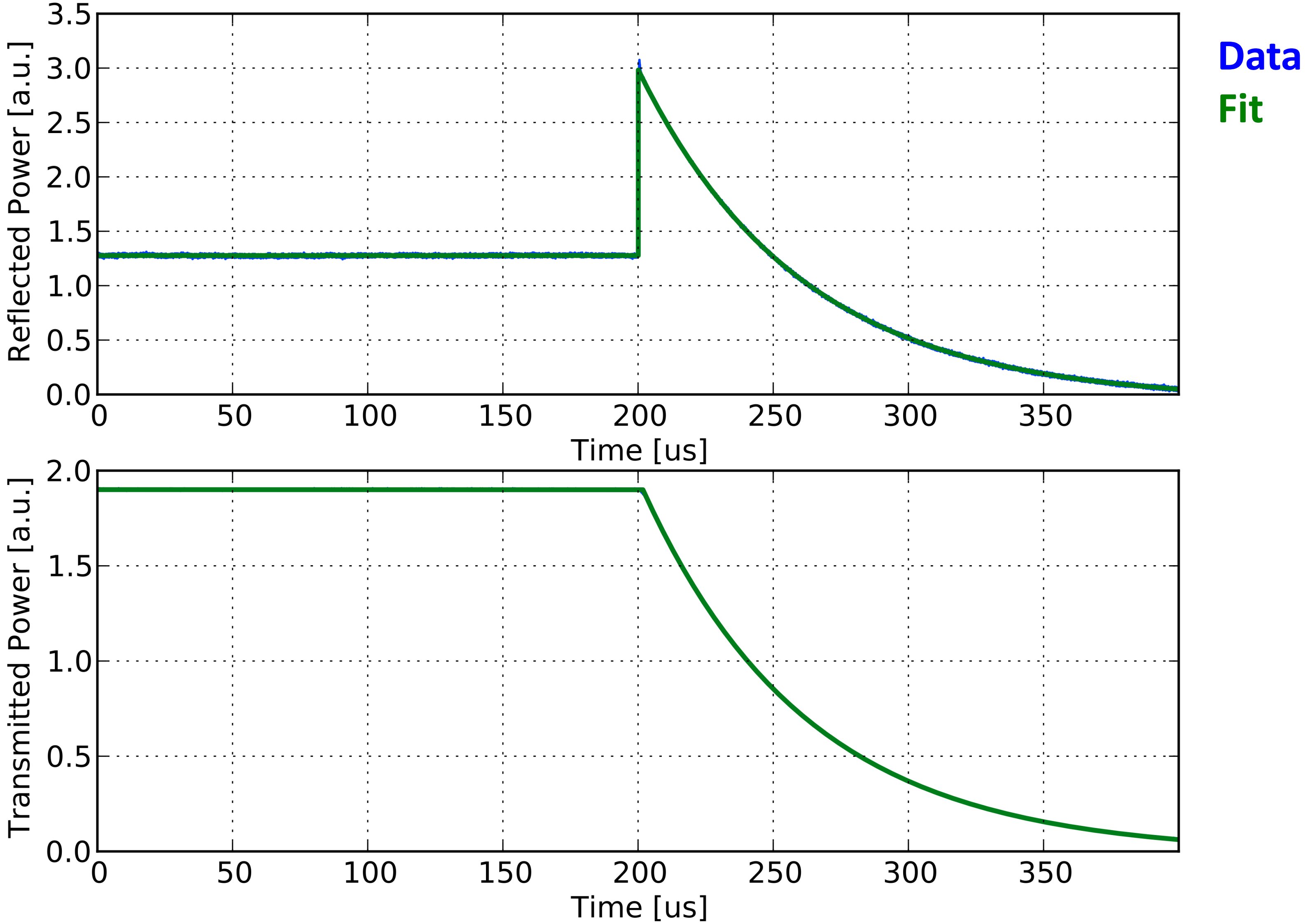
Loss Measurement

- With high precision (~ a few ppm)
- How do we gain confidence in our measurements and know if there are no systematic error?
- Various methods to measure total loss (ringdown both in refl and trans, line width, ringup both refl); they should all agree
- Independent measurements from Caltech, UC Fullerton

Linewidth Measurement



Ringdown Measurement



Result Summary

- Cavity Characteristics:

Finesse:	29990 +/- 102
Beam Radius at Mirror:	1.471 +/- 5.3e-6 mm
Confocal Length:	6.39 +/- 4.6e-5 m

- Total Loss:

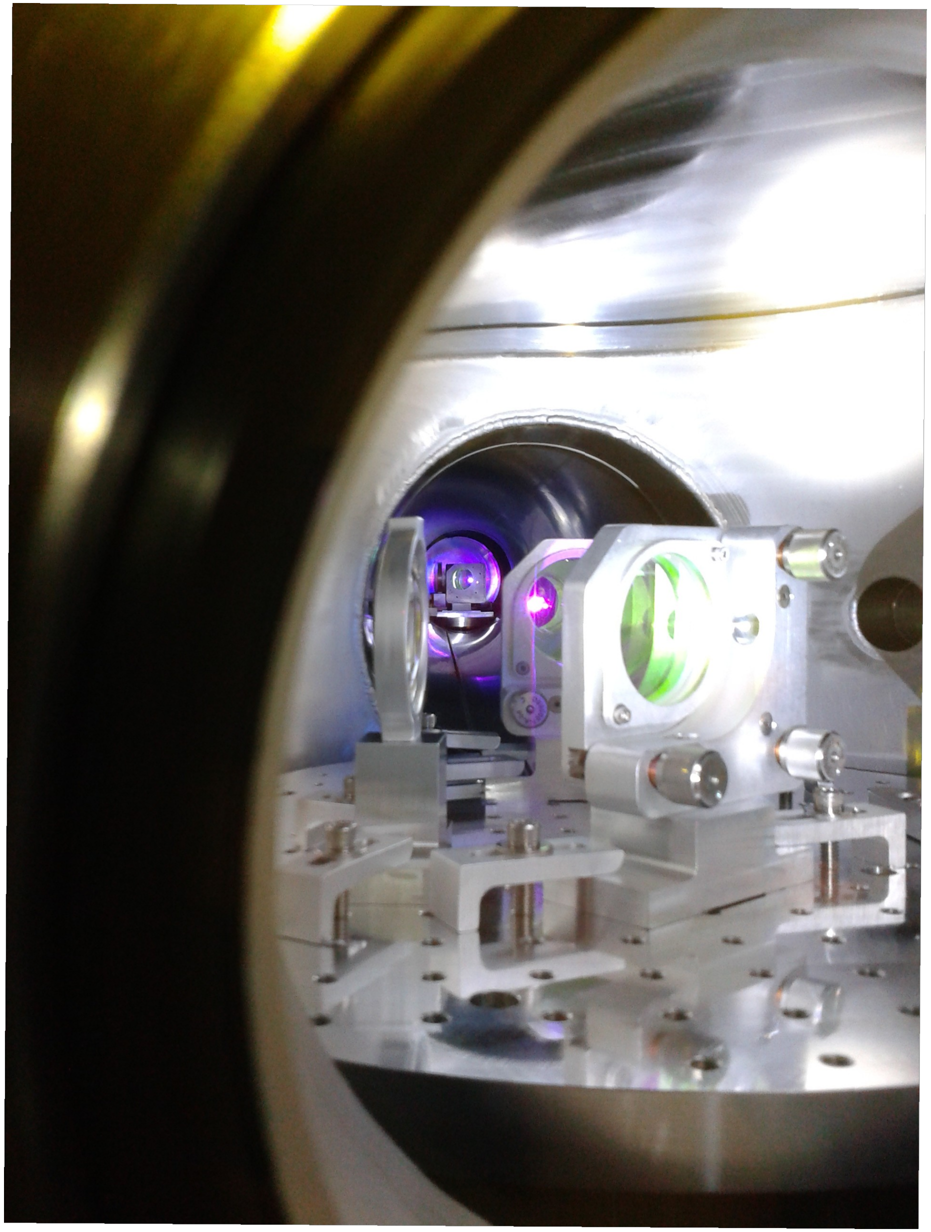
Linewidth:	209.2 +/- 4.2 ppm
Ringdown Refl:	210.0 +/- 0.4 ppm
Ringdown Trans:	208.5 +/- 0.8 ppm

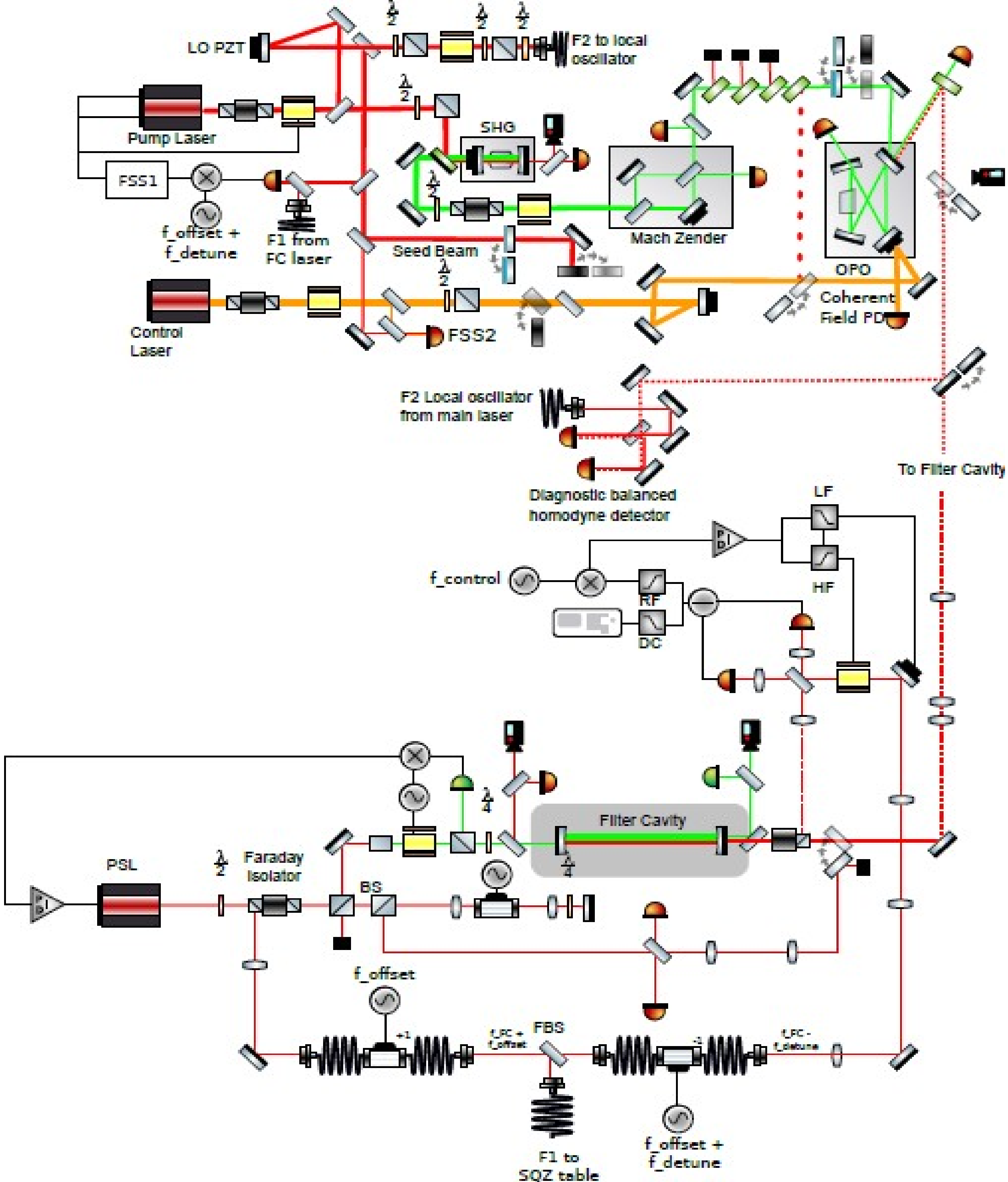
- Scattering & Absorption:

Measured:	10.1 +/- 0.4 ppm (1.6 +/- 0.1 ppm/m)

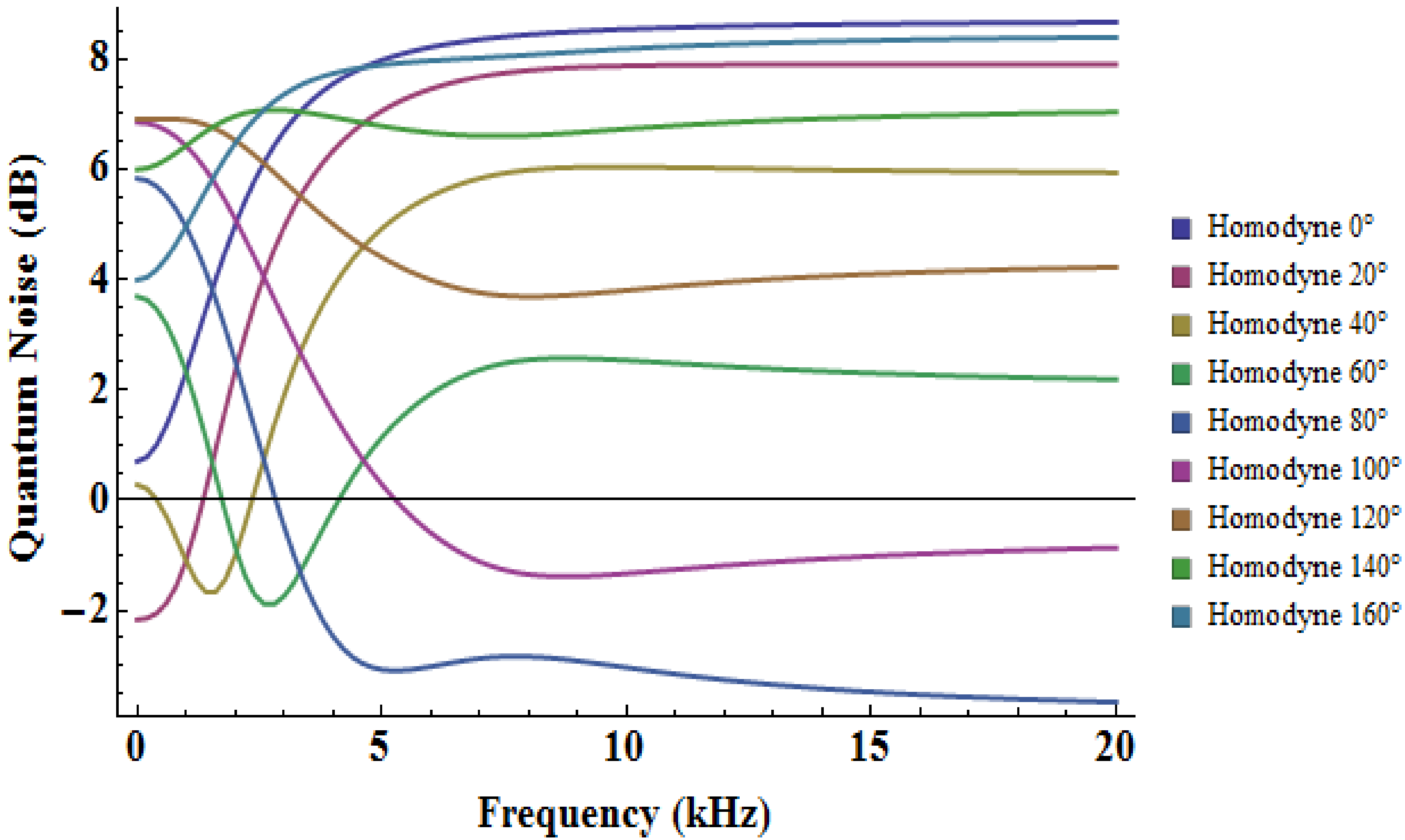
Status and Plans

- Linewidth, refl ringdown and trans ringdown give consistent results
- Beginning to investigate loss as a function of spot position and spot size
- Preparing for integration of cavity and squeezed light source

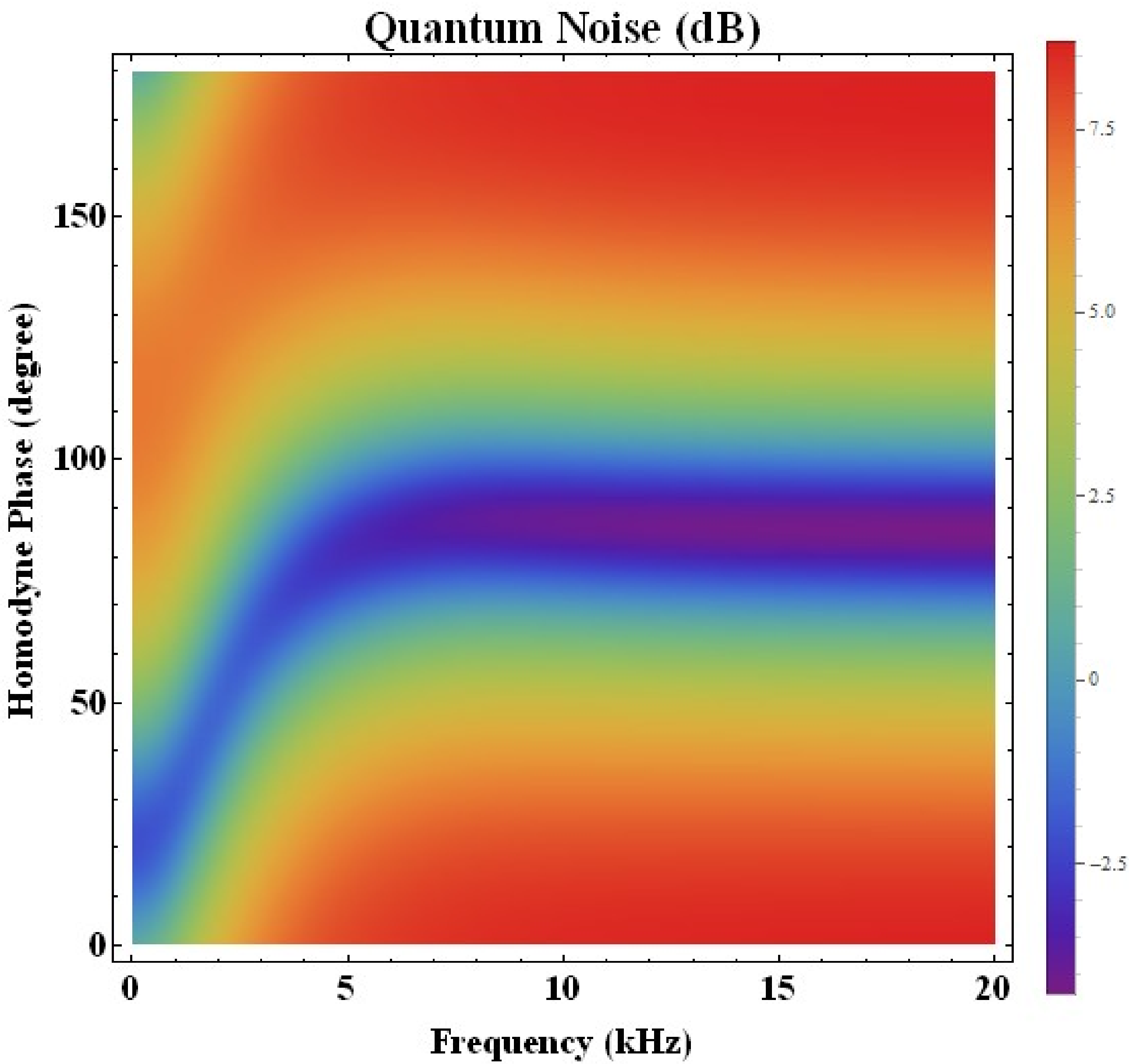




LO PZT
F2 to local oscillator
Pump Laser
SHG
FSS1
f_offset + f_detune
F1 from FC laser
Seed Beam
Mach Zender
OPO
Coherent Field PD
Control Laser
FSS2
F2 Local oscillator from main laser
Diagnostic balanced homodyne detector
To Filter Cavity
LF
HF
f_control
RF
DC
Filter Cavity
PSL
Faraday Isolator
BS
f_offset
FBS
F1 to SQZ table
f_offset + f_detune



Quantum Noise (dB)
8
6
4
2
0
−2
0
5
10
15
20
Frequency (kHz)
Homodyne 0°
Homodyne 20°
Homodyne 40°
Homodyne 60°
Homodyne 80°
Homodyne 100°
Homodyne 120°
Homodyne 140°
Homodyne 160°



Quantum Noise (dB)
Homodyne Phase (degree)
Frequency (kHz)
0
50
100
150
0
5
10
15
20
7.5
5.0
2.5
0
−2.5

Timeline

- Finish up the loss measurement by September 2013
- Start to combine the filter cavity with the squeezer and measure the frequency dependent squeezing by the end of March 2014

Motivation

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14:28:11 Wed Jun 5 2013 (Local)

Subentry

Topic: general Author: Lisa Barsotti This entry replaces a previous version. Wed Jun 5 18:28:11 2013 UTC

Official bet about frequency dependent squeezing

Tomoki and John bet that frequency dependent squeezing will be unambiguously measured with their filter cavity by the end of March 2014, and that their measurements will result in a clear "money plot".

I bet that there is no way they will be able to do that before the end of May 2014.

In case of ambiguity, the reference time will be the time (UTC) at which the measurements are completed, to be compared with midnight of March 31, and midnight of May 31 (UTC).

The winner will pick a restaurant for dinner, the looser will pay.

- Lisa

- *Lisa Barsotti* http://www.ligo.mit.edu/il (ref url)

FILTERCAVITY

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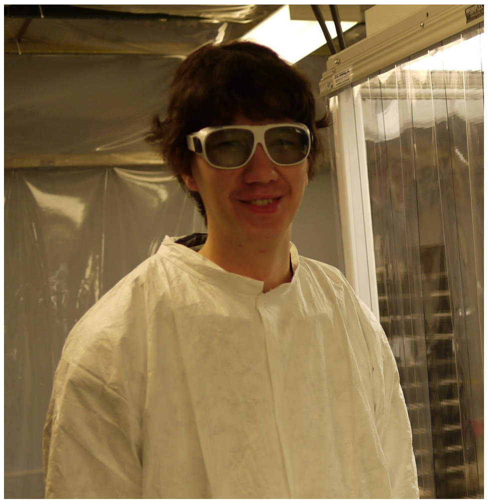
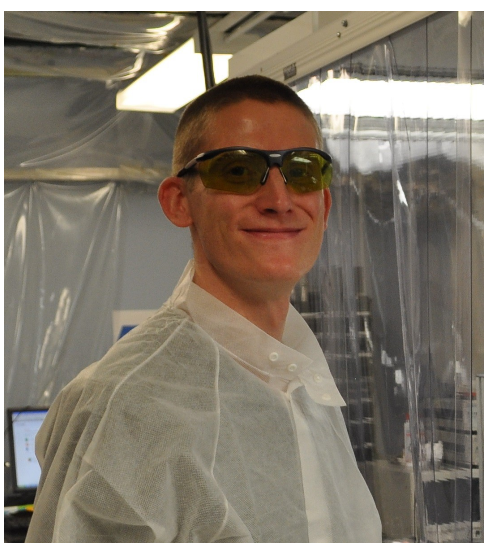
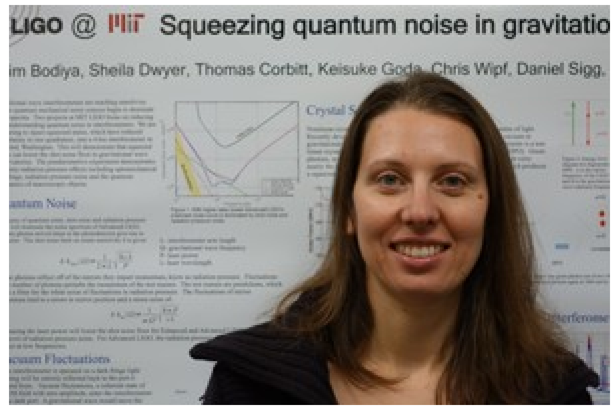
Filter Cavity Team



Patrick Kwee



John Miler



Lisa Barsotti

Mattew Evans

Nergis Mavalvala

H1 Squeezer People

- Lisa Barsotti
- Sheon Chua
- Sheila Dwyer
- Max Factourovich
- Keita Kawabe
- Aleksandr Khalaidovski
- Ping Koy Lam
- Nergis Mavalvala
- David McClelland
- Conor Mow-Lowry
- Roman Schnabel
- Daniel Sigg
- Michael Stefszky
- Henning Vahlbruch
- Stan Whitcomb

Conclusions

- Future generation GW detectors will be limited by quantum noise limit, in almost all the frequency band
- Frequency dependent squeezing using a filter cavity seems to be a promising way to go beyond the quantum noise limit
- At MIT, the filter cavity experiment should inform us a realistic filter cavity design for advanced GW detectors

Filter Cavity Schematic