LIGO SURF 2026

Improving Mode-Matching for Detection of Squeezing

by
Nishant Pawar
with
Peter Carney, Prof. Rana X Adhikari

24th July 2026

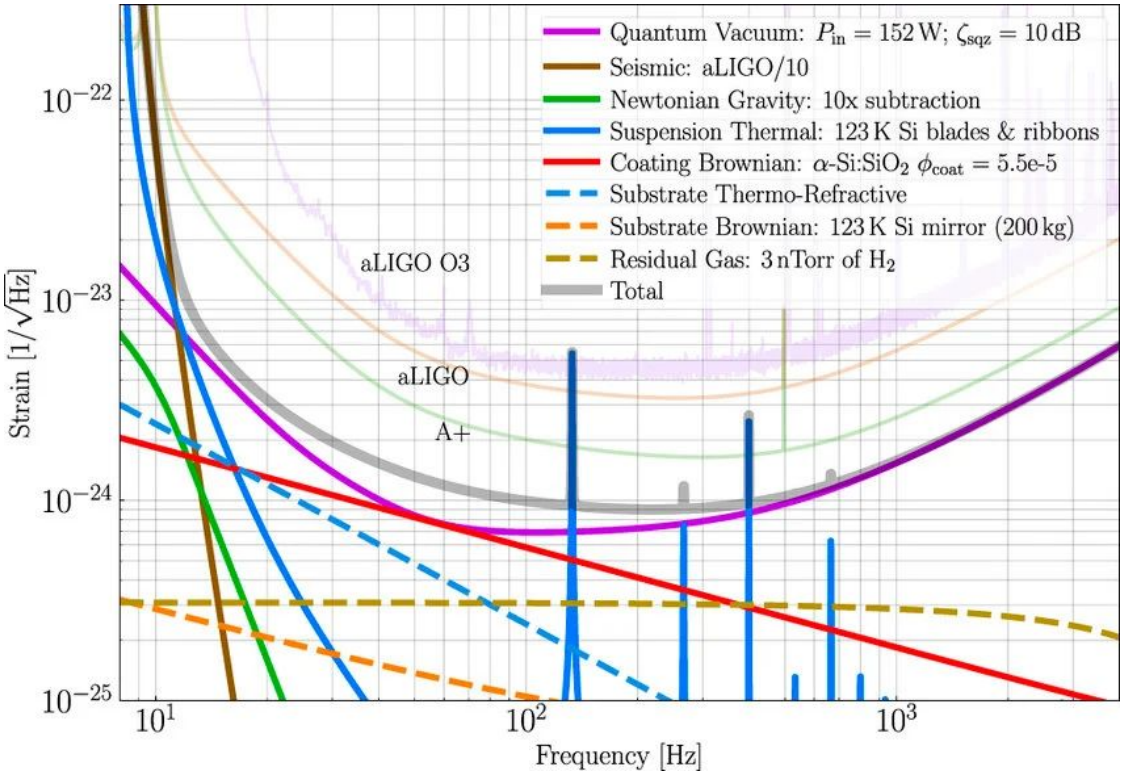
CALTECH
Student-Faculty Programs

Overview:

- Motivation
- Background
- WOPA setup
  - Waveguide
  - Balanced Homodyne Detection (BHD)
- Beam Profiling
- Mode matching
  - Solution
  - Visibility
- Squeezing measurements
- Acknowledgments

Motivation:

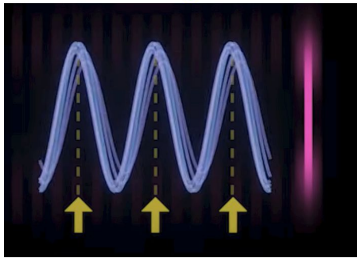
- Reduction of Quantum noise
- Squeezed states of light



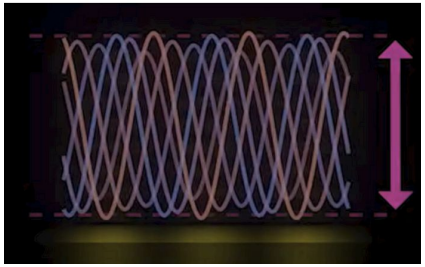
LIGO DCC

Background theory:

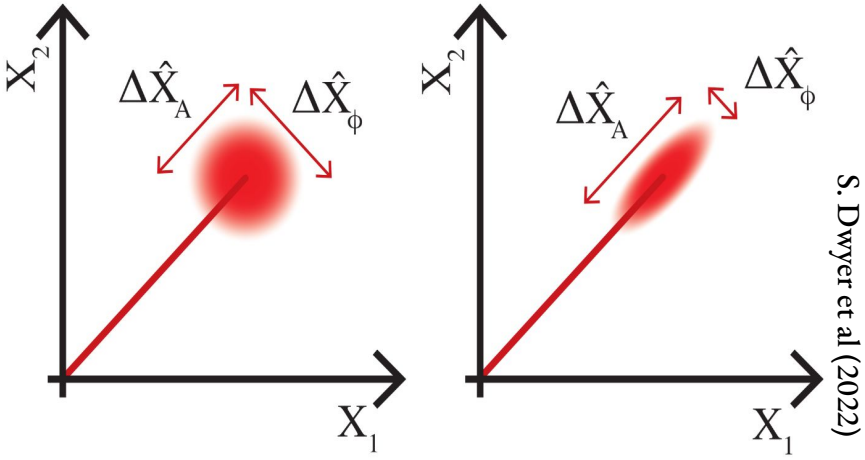
- Quantization of EM field.
- Phase and Amplitude quadratures
- Uncertainty principle
- Nonlinear optical processes

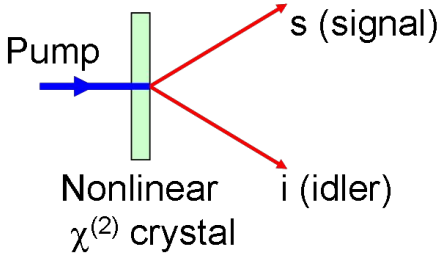


Phase squeezed



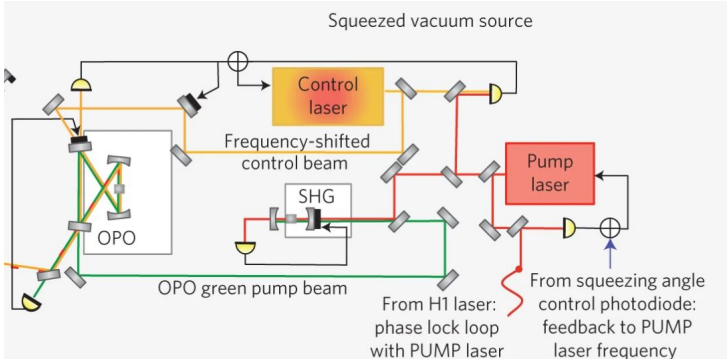
Amplitude squeezed





Motivation:

- Reduction of Quantum noise
- Squeezing
- OPA Cavity in LIGO



Aasi, J., Abadie, J., Abbott, B. et al. (2013)

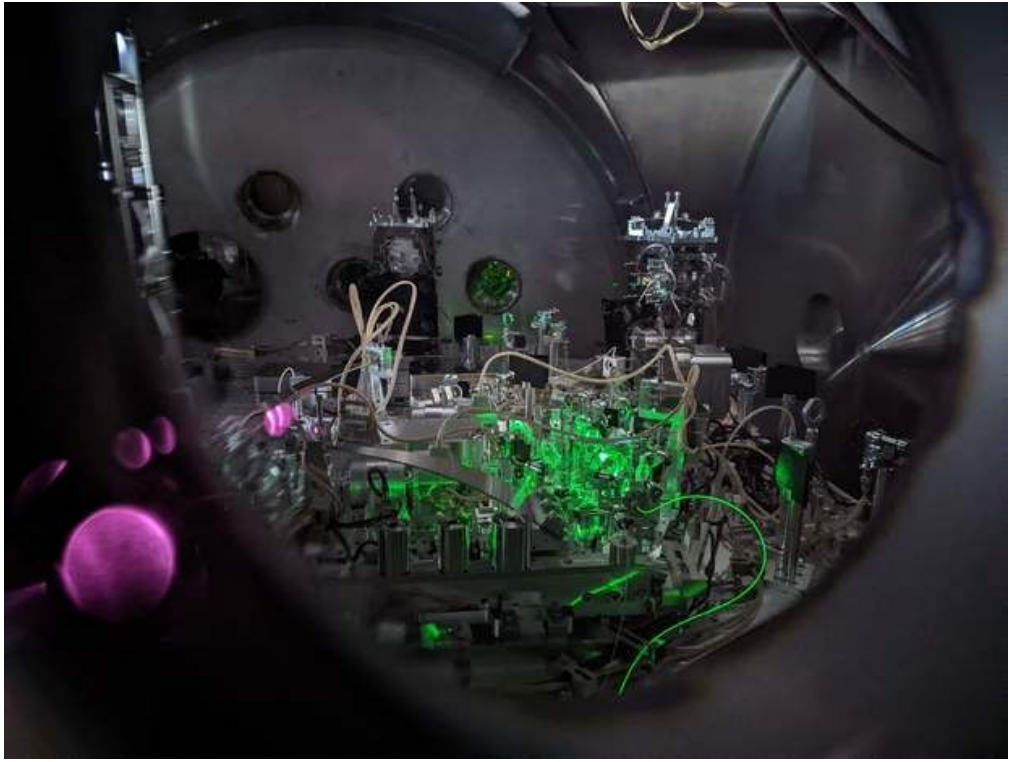
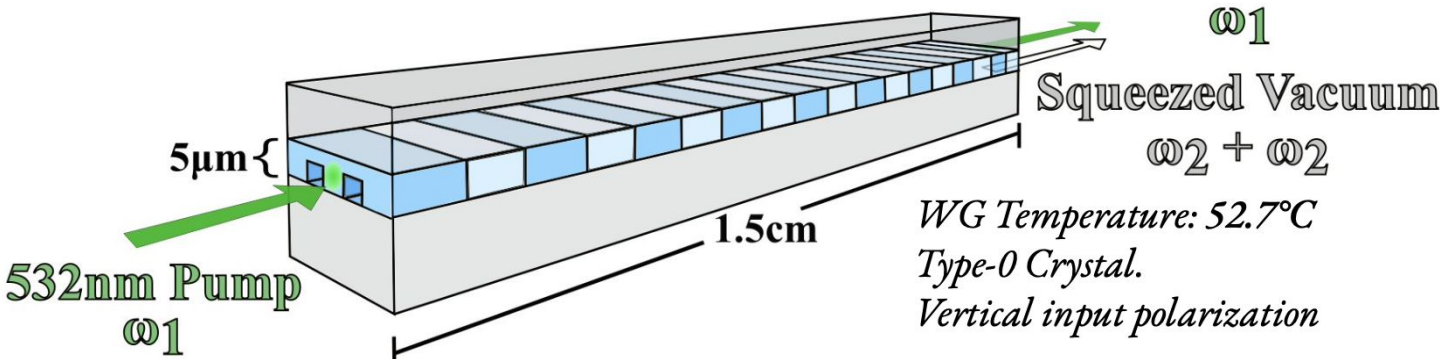


Image credit: Wenxuan Jia/MIT

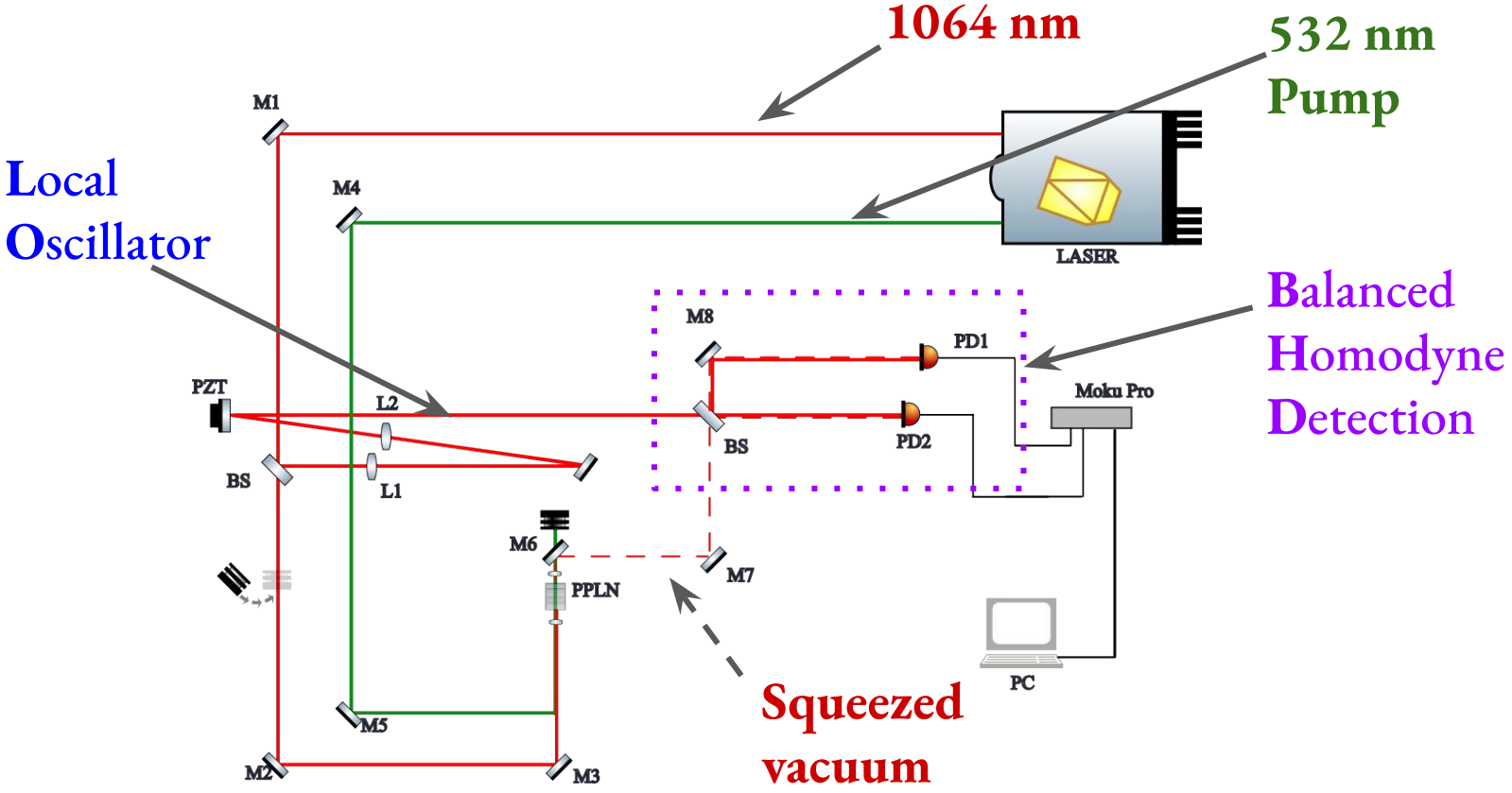
WOPA:

- Waveguide-based Optical Parametric Amplification
  - Single pass, no cavity
  - Higher non-linear interaction
  - Broadband

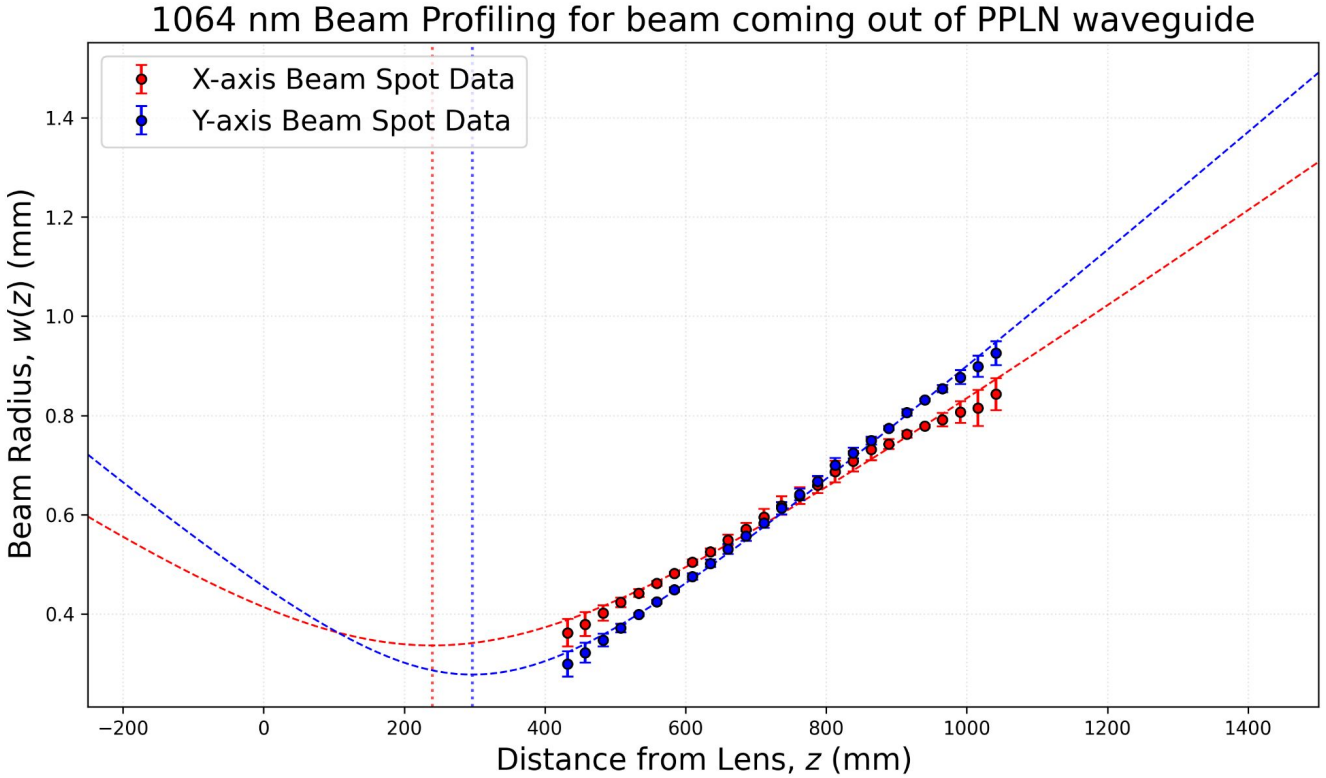


P. Carney. et al. (GWADW 2026)

WOPA Setup:

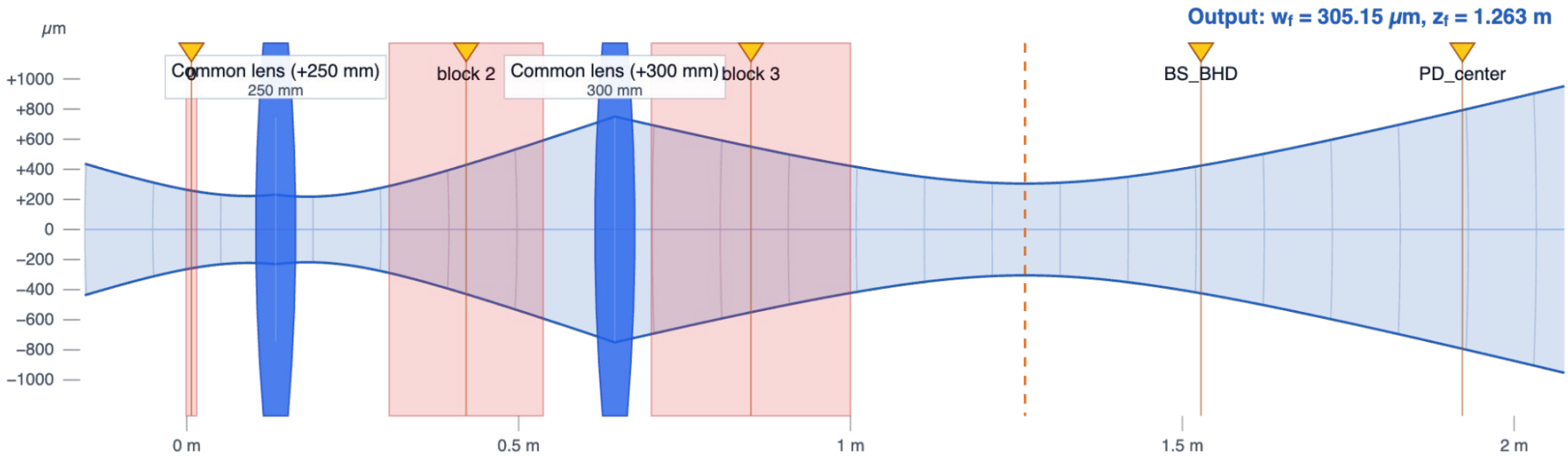

1064 nm
532 nm
Pump
Local
Oscillator
Balanced
Homodyne
Detection
Squeezed
vacuum
M1
M4
LASER
M8
PD1
PZT
L2
Moku Pro
BS
PD2
BS
L1
M6
M7
PPLN
PC
M5
M2
M3

Beam Profiling:



Elliptical 1064 nm beam coming out of waveguide

Mode-Matching:



Mode-Matching solution with **f250 mm** and **f300 mm** lenses

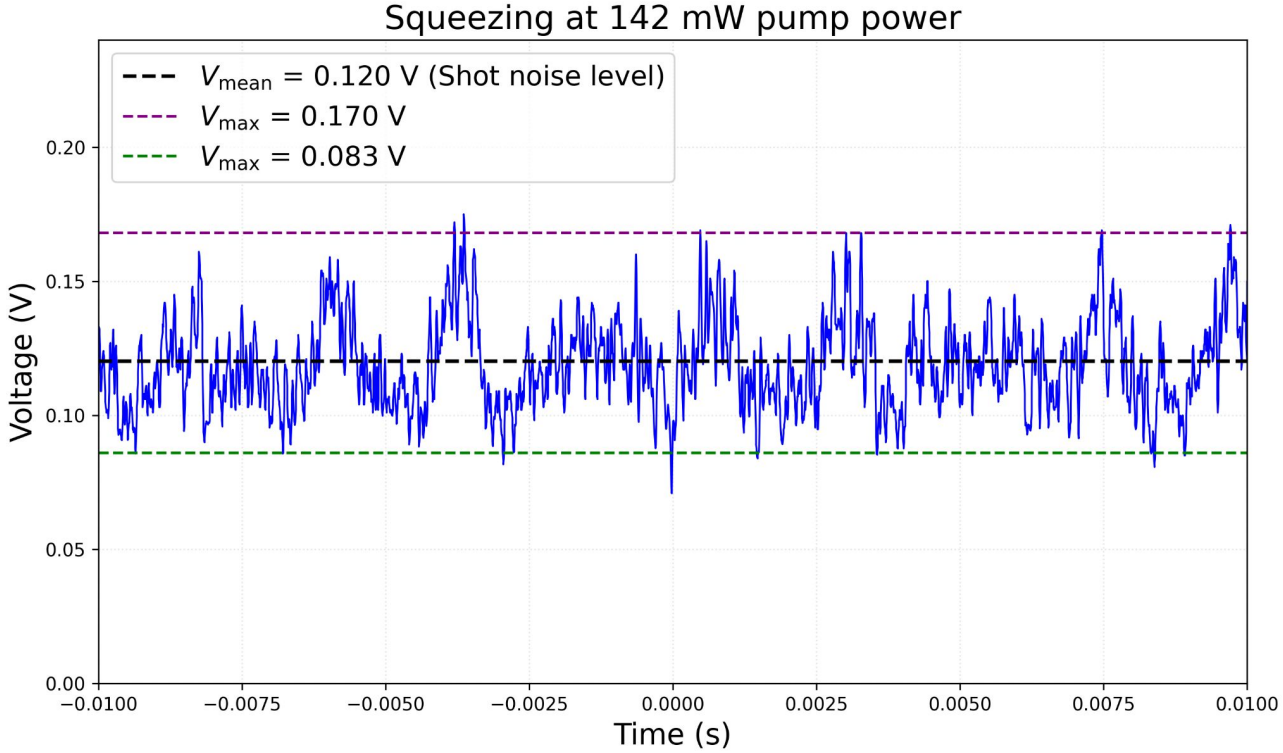
Visibility:

- Test for measurement of mode-matching
- Interfere the mode matched beams
  - Phase/PZT scan and observe the PD output

$$V = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

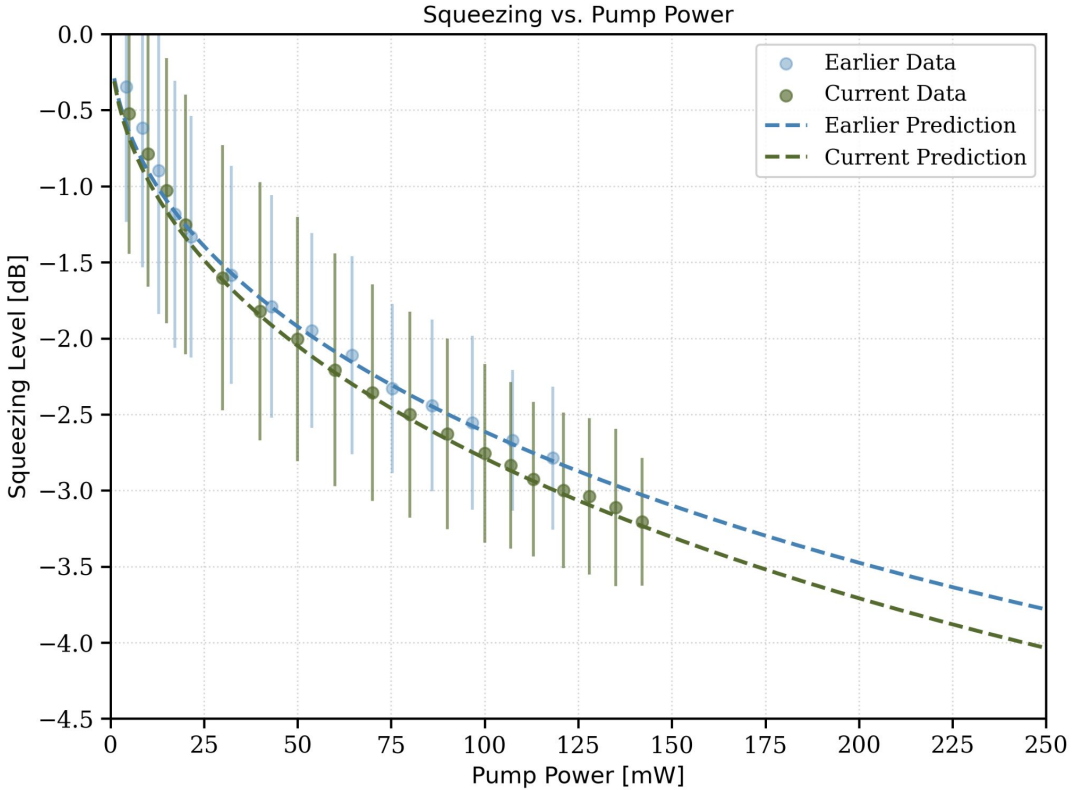
Improved BHD visibility ~ 90 % → ~ **91.2** %

Squeezing Measurement:



Observed Squeezing of ~ **-3.20 dB** and anti-squeezing of 3.28 dB

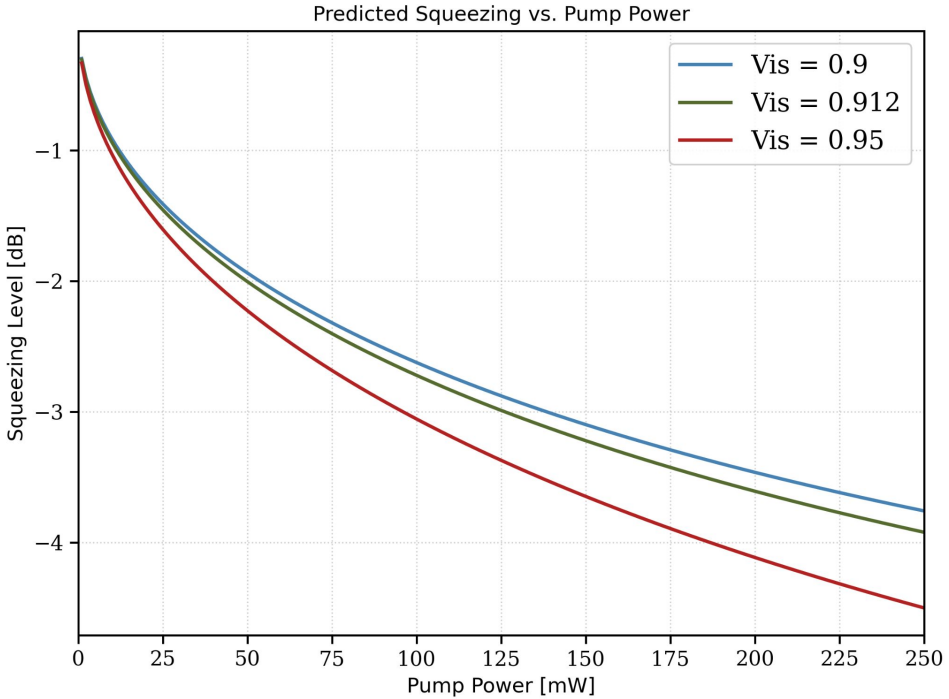
Squeezing Measurement:



Comparison of the squeezing measurements

Future Goals:

- Beam profiling 1064 nm with strong 532 nm pump (inside waveguide)
- Higher Visibility
- Compact and robust setup



Expected squeezing with higher visibility

Acknowledgements

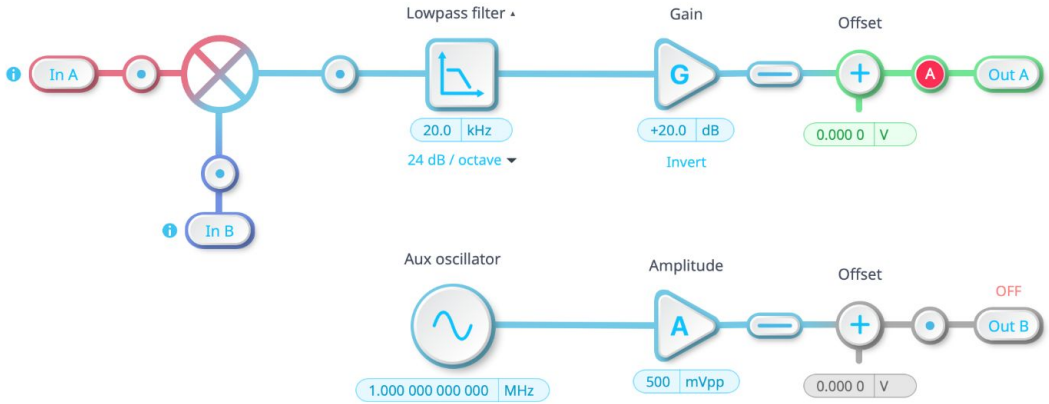
- Thanks to Peter, Rana and other lab members
- LIGO SURF cohort
- LIGO Labs and SFP Organising team

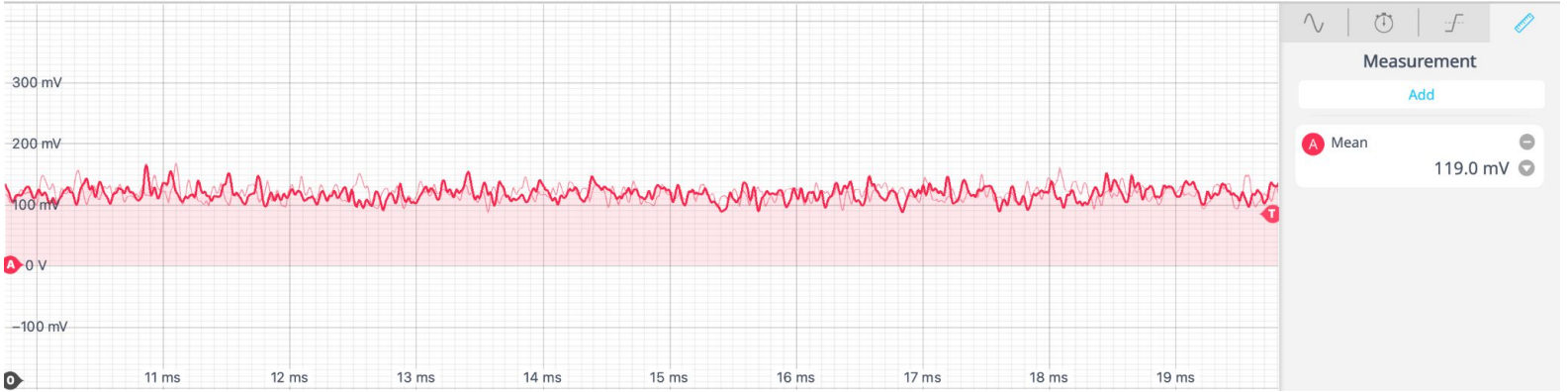






Appendix: Shot-noise baseline





Appendix: Visibility for power imbalance

$$V_{\max} = \frac{2\sqrt{r}}{1+r}$$

$$r = \frac{p_2}{p_1}$$

Appendix: Squeezing equations

Detection efficiency $\eta_{\text{eff}} = \eta_{\text{P}} \cdot \text{Vis}^2 \cdot \text{QE}$

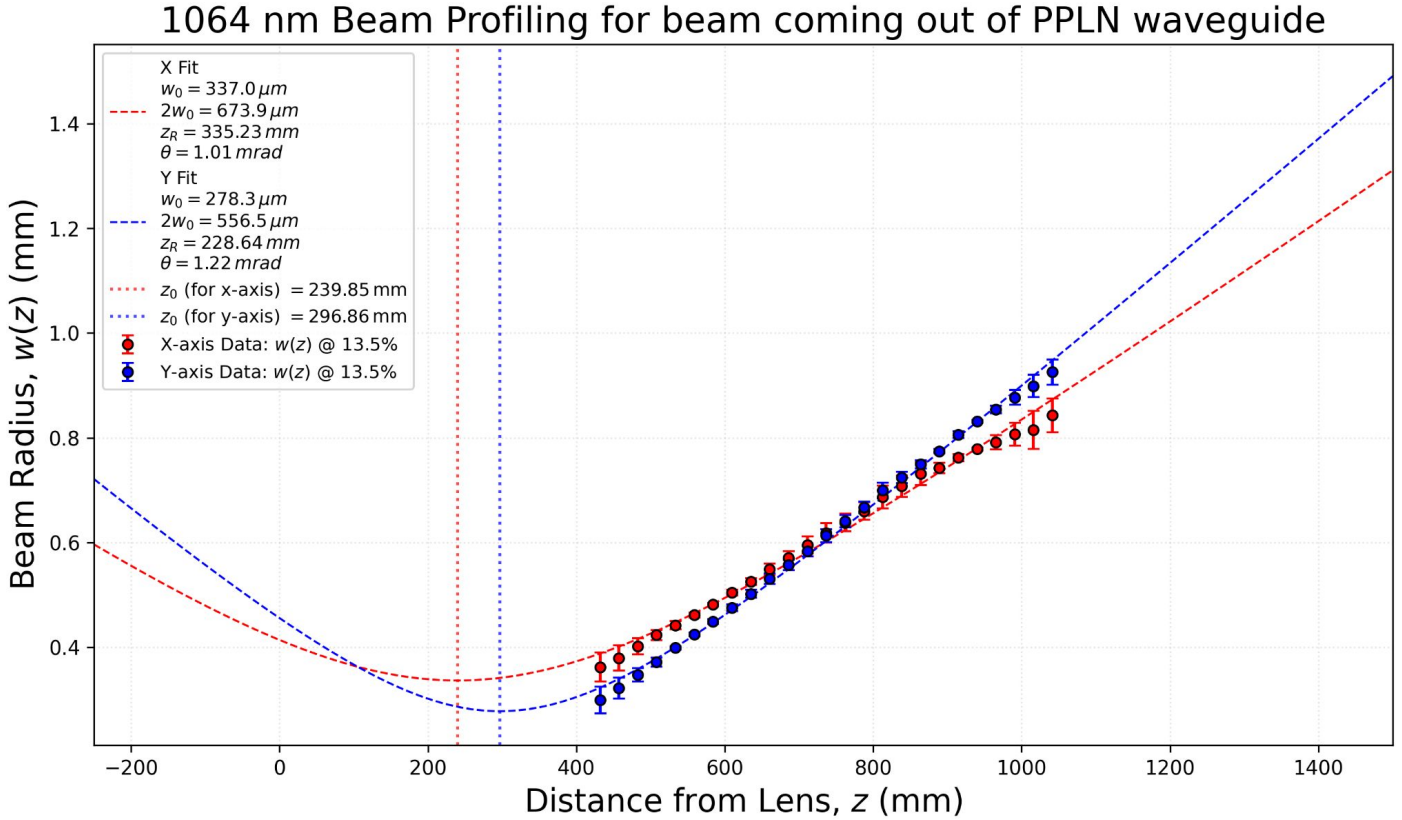
Squeezing parameter $r = \sqrt{\eta \cdot 1.5^2 \cdot p \cdot \text{CE}}$

$$S = 10 \log_{10}(X)$$

$$X = \eta_{\text{eff}}(1 - \phi_{\text{rms}}^2)\left(e^{-2r}\cos^2\theta + e^{2r}\sin^2\theta\right) + \eta_{\text{eff}}\,\phi_{\text{rms}}^2\left(e^{2r}\cos^2\theta + e^{-2r}\sin^2\theta\right) + (1 - \eta_{\text{eff}})$$

$$\text{Squeezing (dB)} = 20\log_{10}\left(\frac{V_{min}}{V_{shot}}\right) \qquad \text{Anti-squeezing (dB)} = 20\log_{10}\left(\frac{V_{max}}{V_{shot}}\right)$$

Appendix: 1064 nm beam profile (with param.)



Appendix: LO beam profile (with param.)

