Noise Characterizations in Table-top Waveguided Optical Parametric Amplification (WOPA) Process

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Introduction

How does LIGO detect Gravitational Waves?

- **Detection:** Phase shift from differential arm length change
- **Sensitivity:** Detects strain $\sim 10^{-22}$
- **Limitation:** Sensitivity constrained by **Quantum noise**

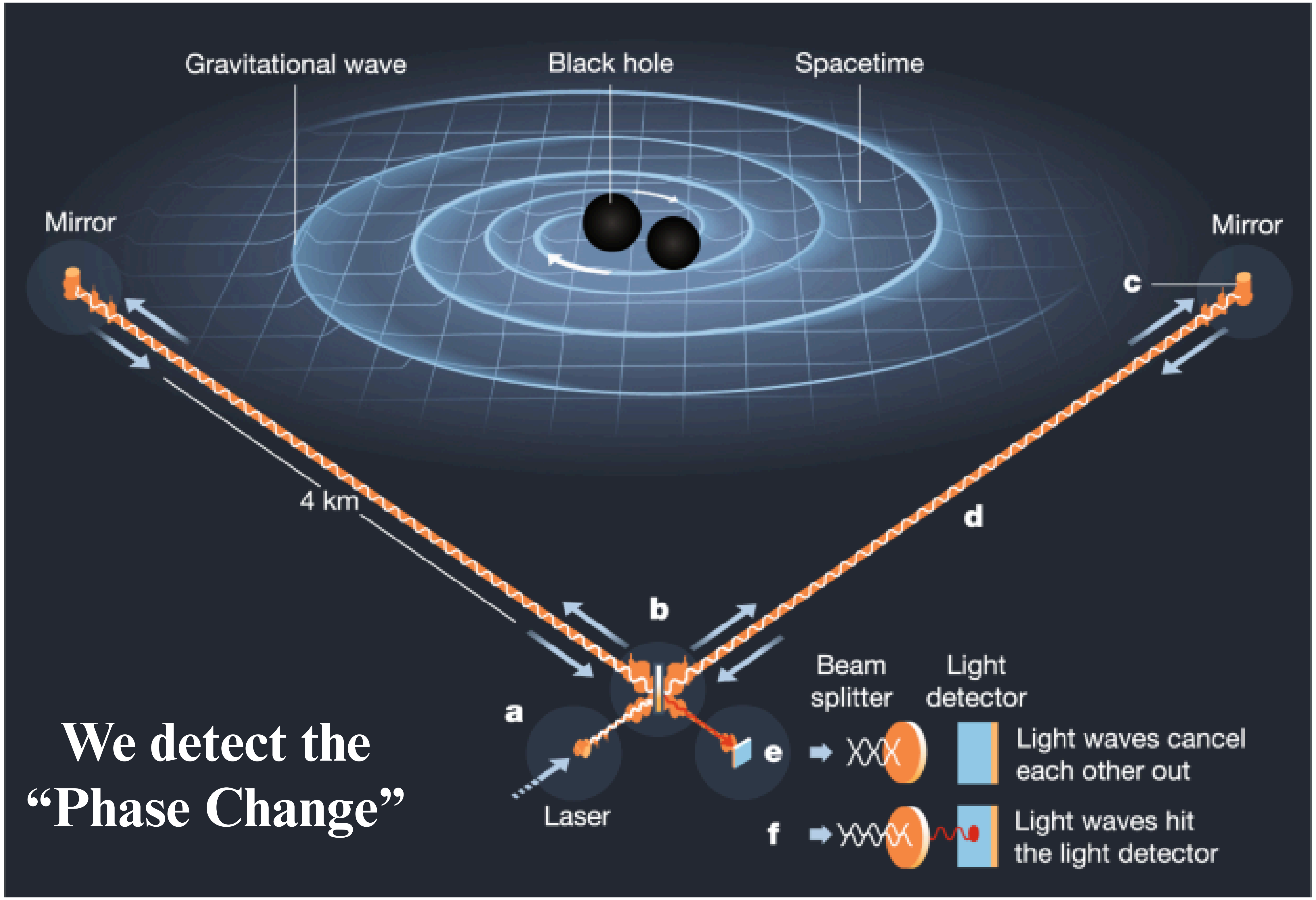


Fig: Schematic of the LIGO

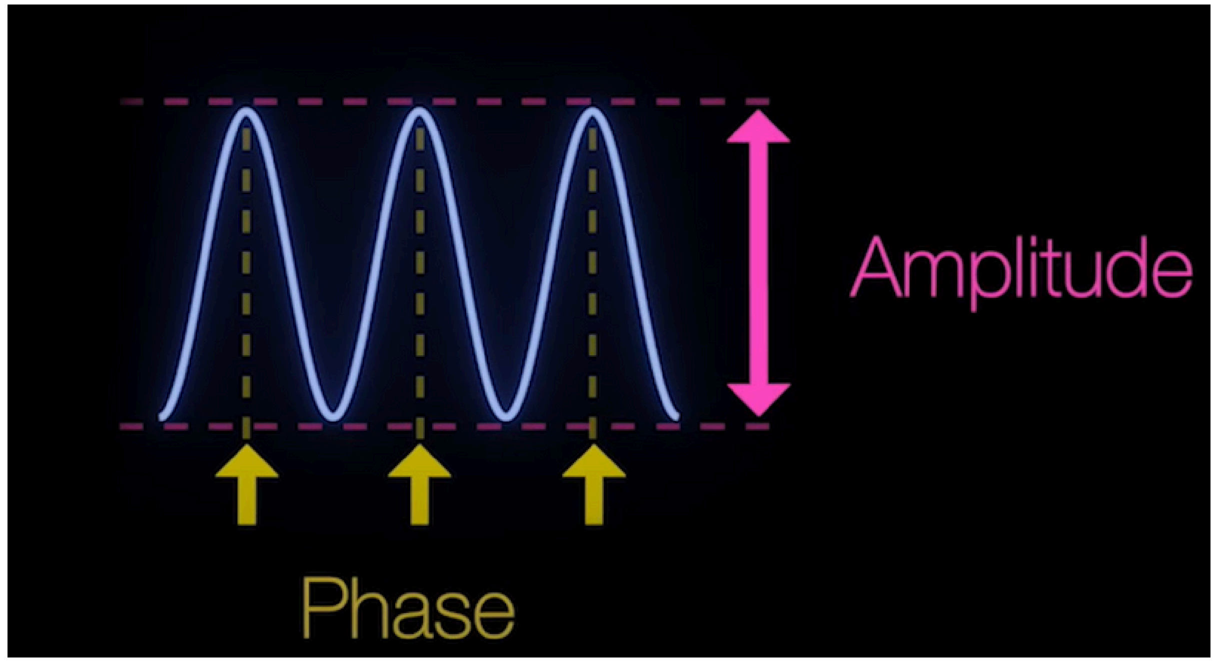
LIGO

Quantum Noise

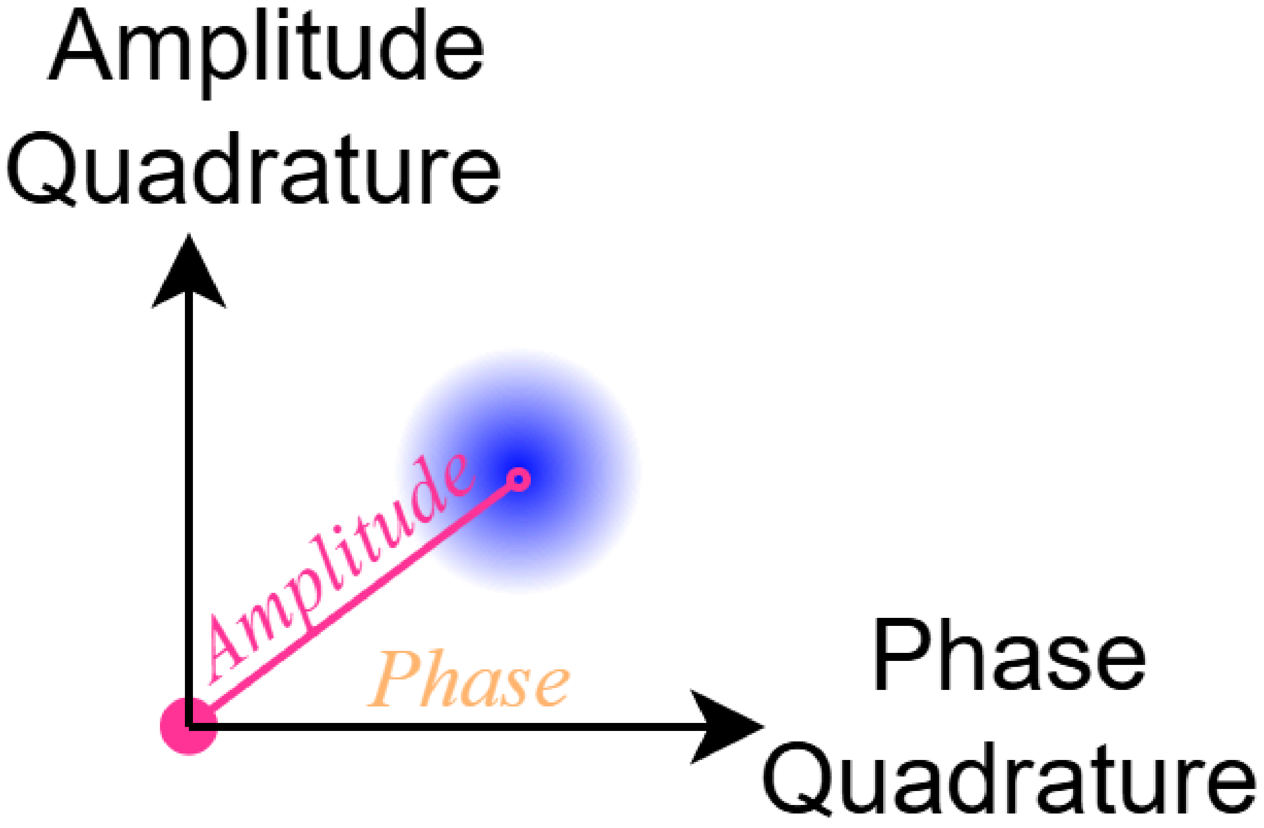
- Heisenberg's uncertainty principal=

$$\Delta A \Delta P \geqslant \frac{h}{4\pi}$$

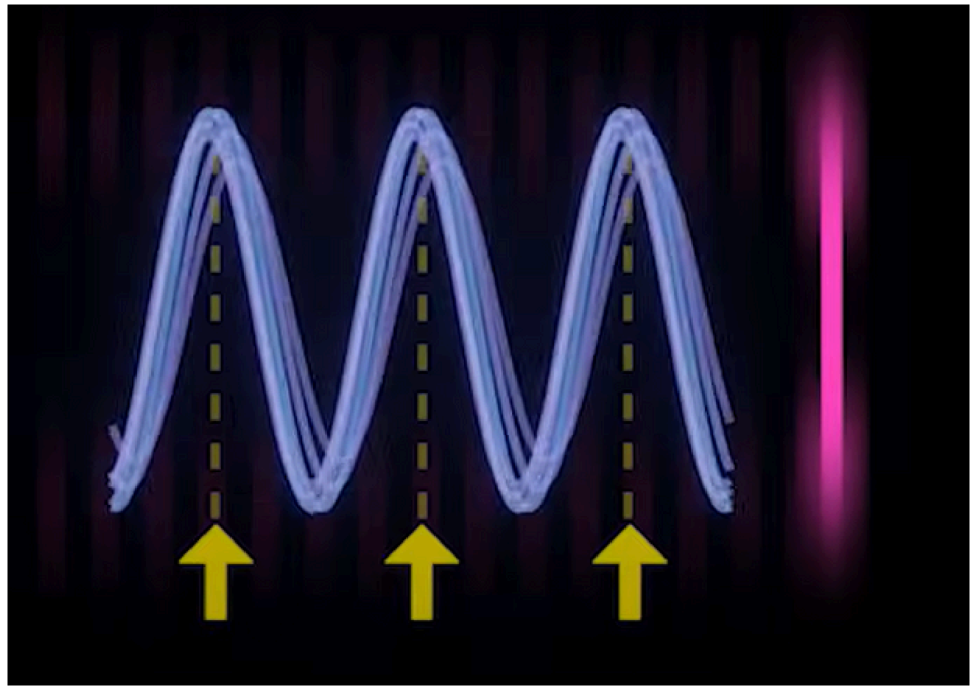
$\Delta A =$ Amplitude variance
$\Delta P =$ Phase variance

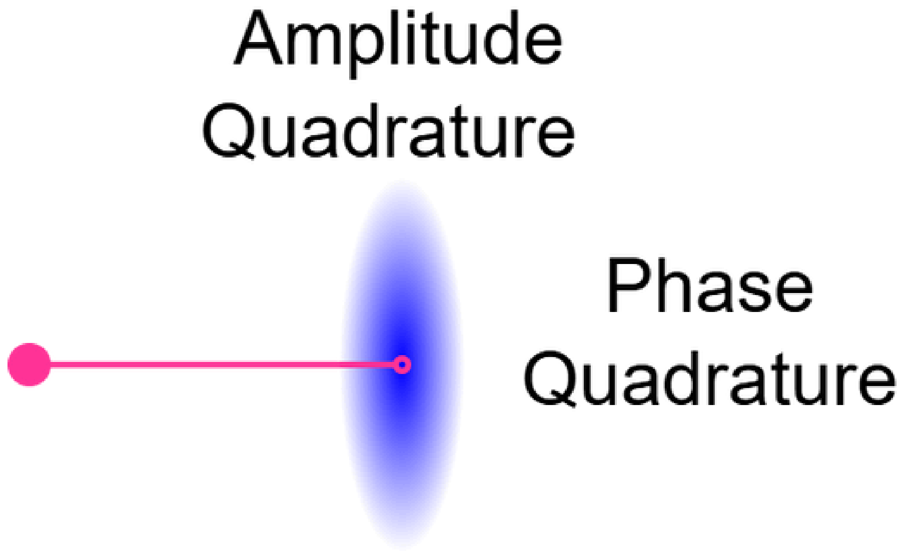


- Equal Uncertainty in both quadratures

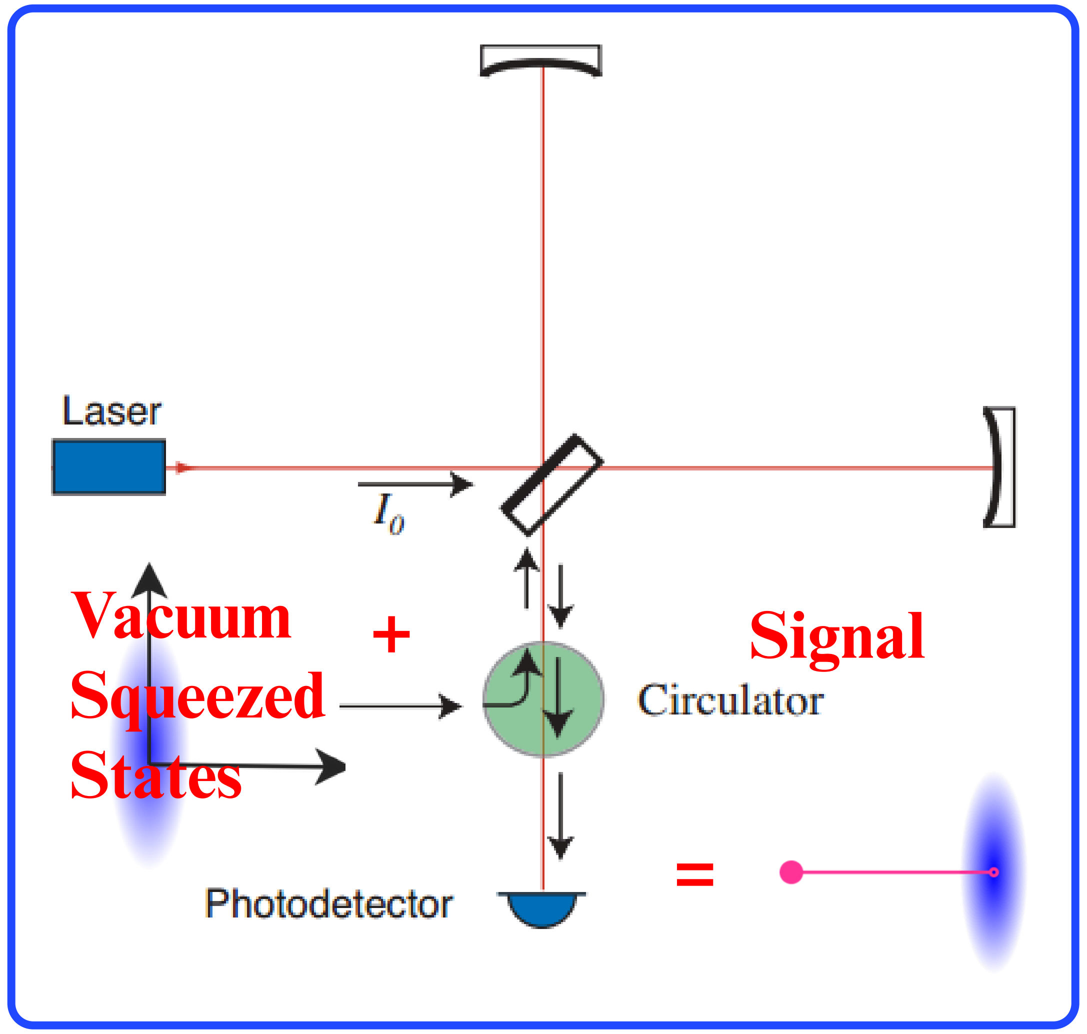


Phase Squeezed

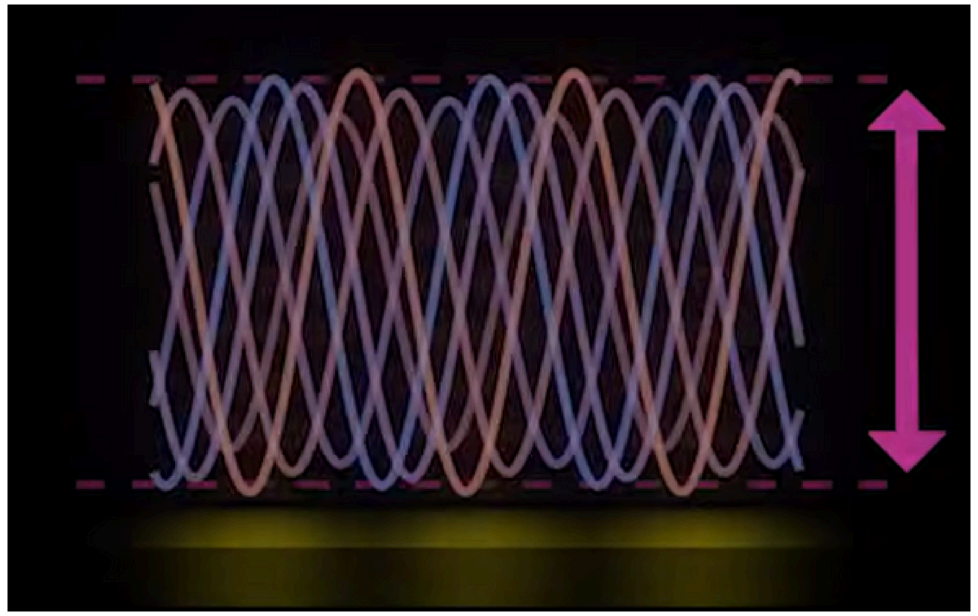


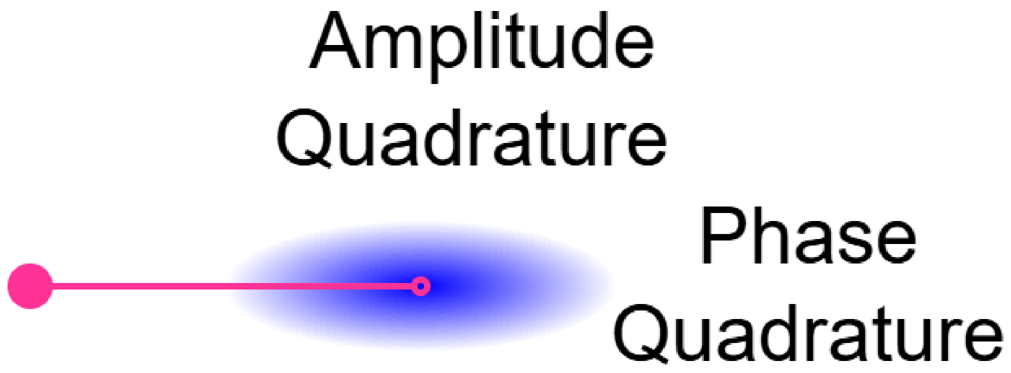


Reduces Shot Noise
(High Frequency Regime)



Amplitude Squeezed



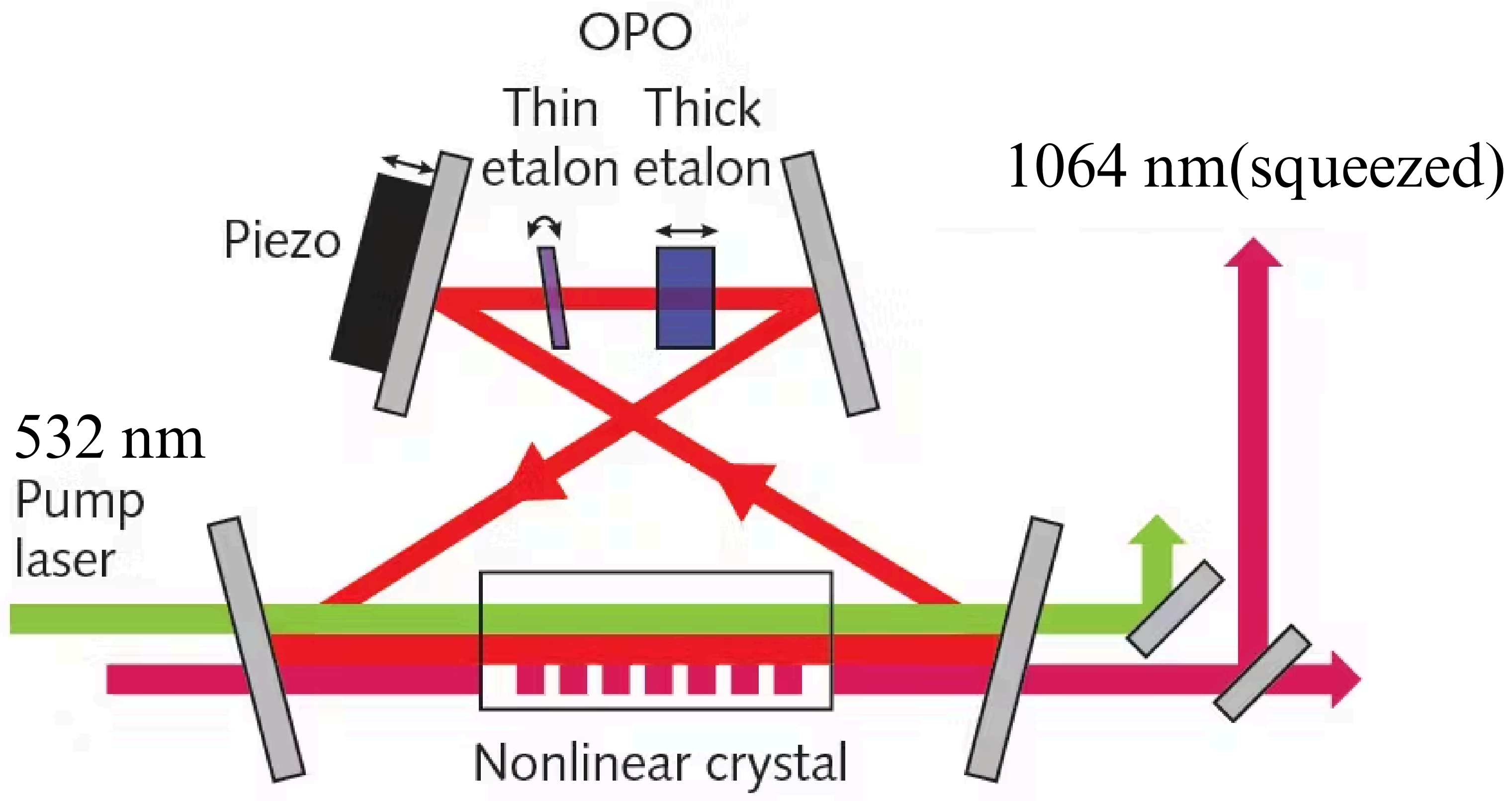


Reduces Radiation Pressure Noise
(Low Frequency Regime)

With Squeezed States we have up to 65% better detection of Binary Neutron Stars

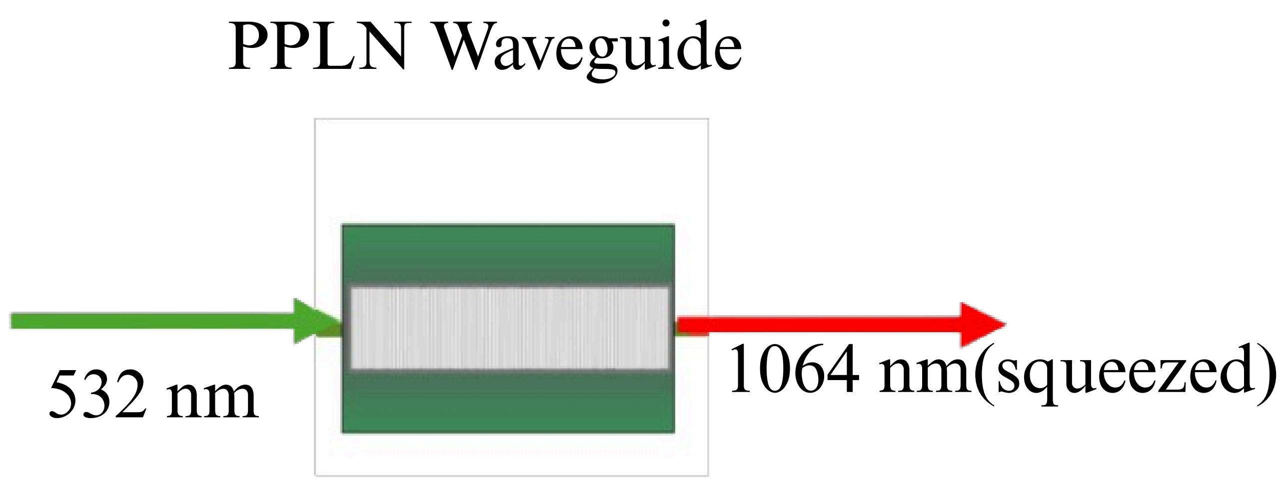
How are squeezed states generated?

Current LIGO method:
Optical Parametric Oscillators



- Uses Bulk crystal- Diffraction- Less effective power
- Needs Resonant cavity- active cavity length stabilization
- Complex, Has weeks timescale stability
- Can produce 10 dB of squeezing

Our proposed alternative:
Waveguided Optical Parametric Amplification



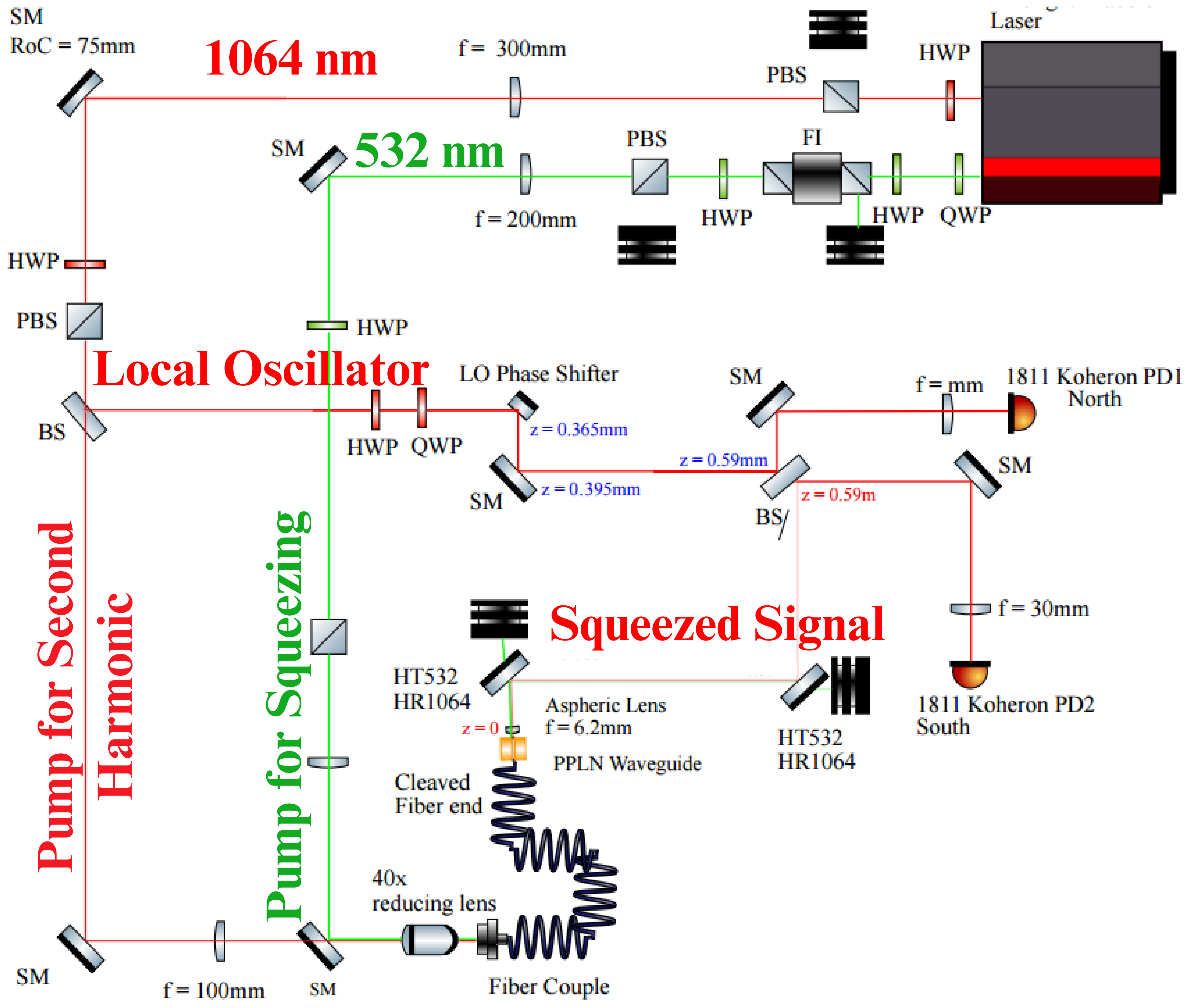
- Uses nonlinear **Periodically Poled LiNbO3 waveguide**: Higher nonlinear interaction due to confinement
- More squeezing with less pump & small waveguide
- Single-pass operation – no cavity
- Simpler, stable, compact setup, broadband, easier long-term operation

LIGO

Experimental Setup

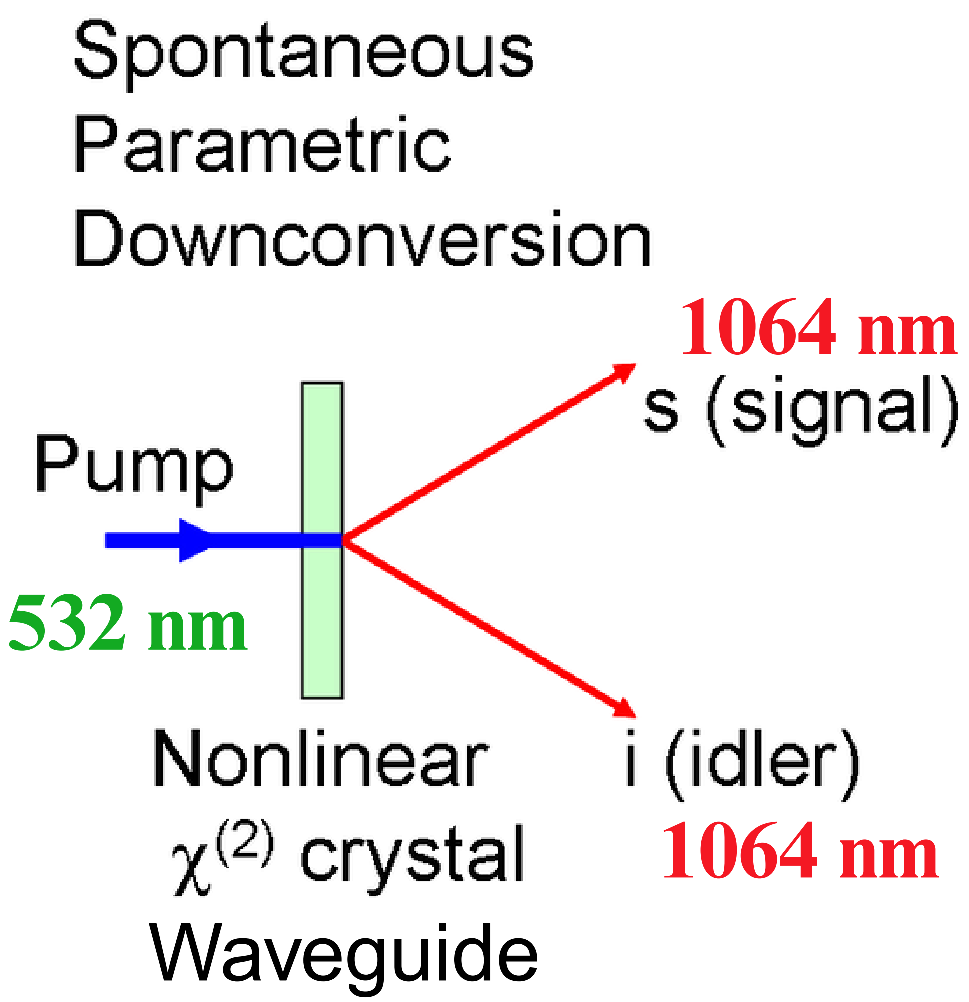
Goal:

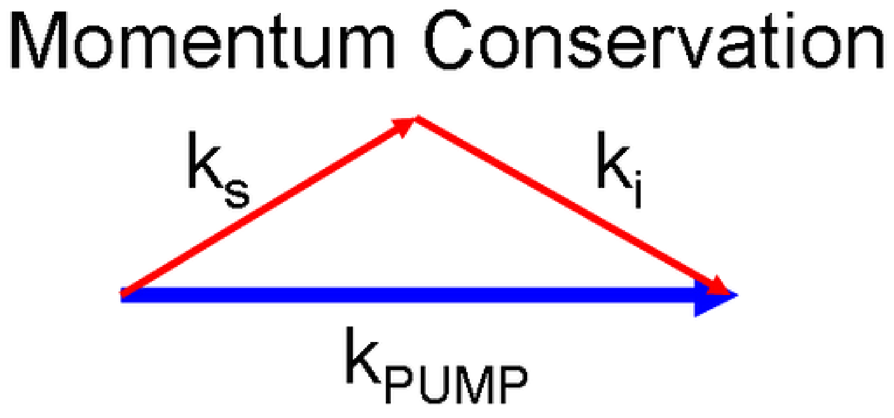
- Demonstrate ~4 dB (150mW 532 pump) squeezing in this tabletop setup (crystal-limited),
- A step toward scalable higher than current squeezing for LIGO

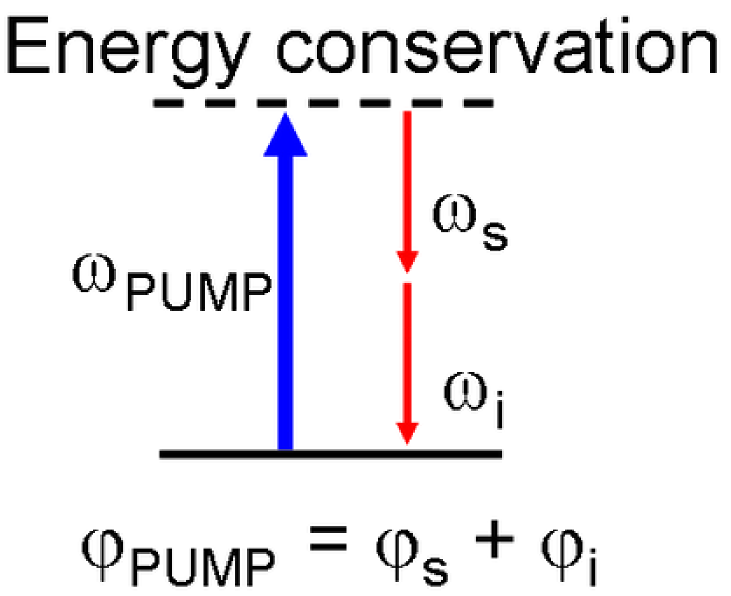


Generation of Squeezed States

Spontaneous Parametric Down Conversion







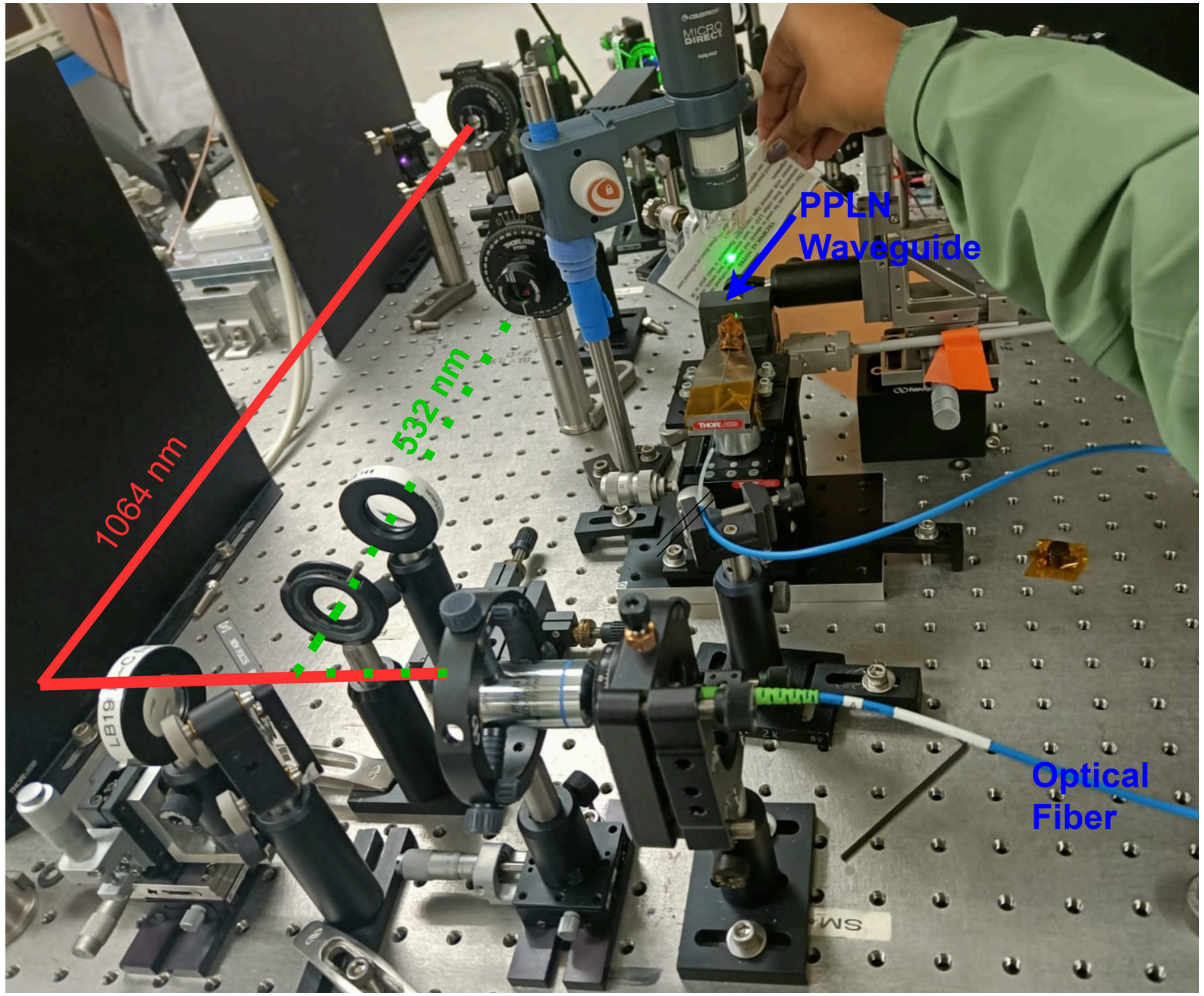
$$\omega_s = \omega_i = \omega_{PUMP}/2$$

- In SPDC, high-freq pump photon (532 nm) spontaneously splits into two correlated lower-freq photons (1064 nm).
- At high pump power (un depleted pump approx), these photon pairs interfere phase-sensitively:
  - Constructively (one quadrature) → **anti-squeezing**
  - Destructively (orthogonal quadrature) → **squeezing**

Squeezing Measurement

1. **<u>Waveguide Coupling with SHG Alignment</u>**

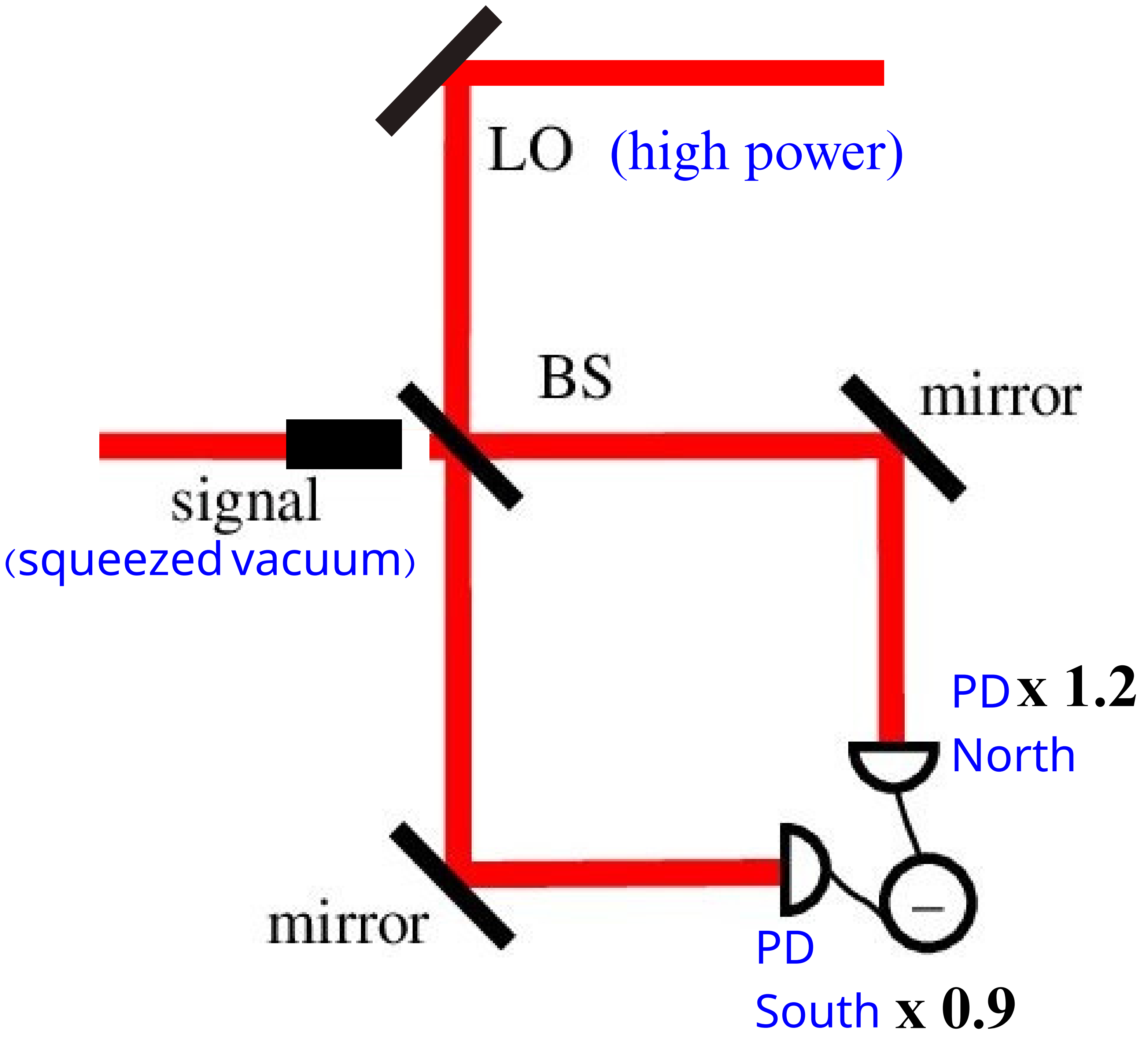
- Blocking 532 path, 1064 allowed to couple with waveguide giving 532 by **Second Harmonic Generation (SHG)**
- **SHG** is like the reverse of SPDC
- SHG maximized ~60%/W/cm efficiency

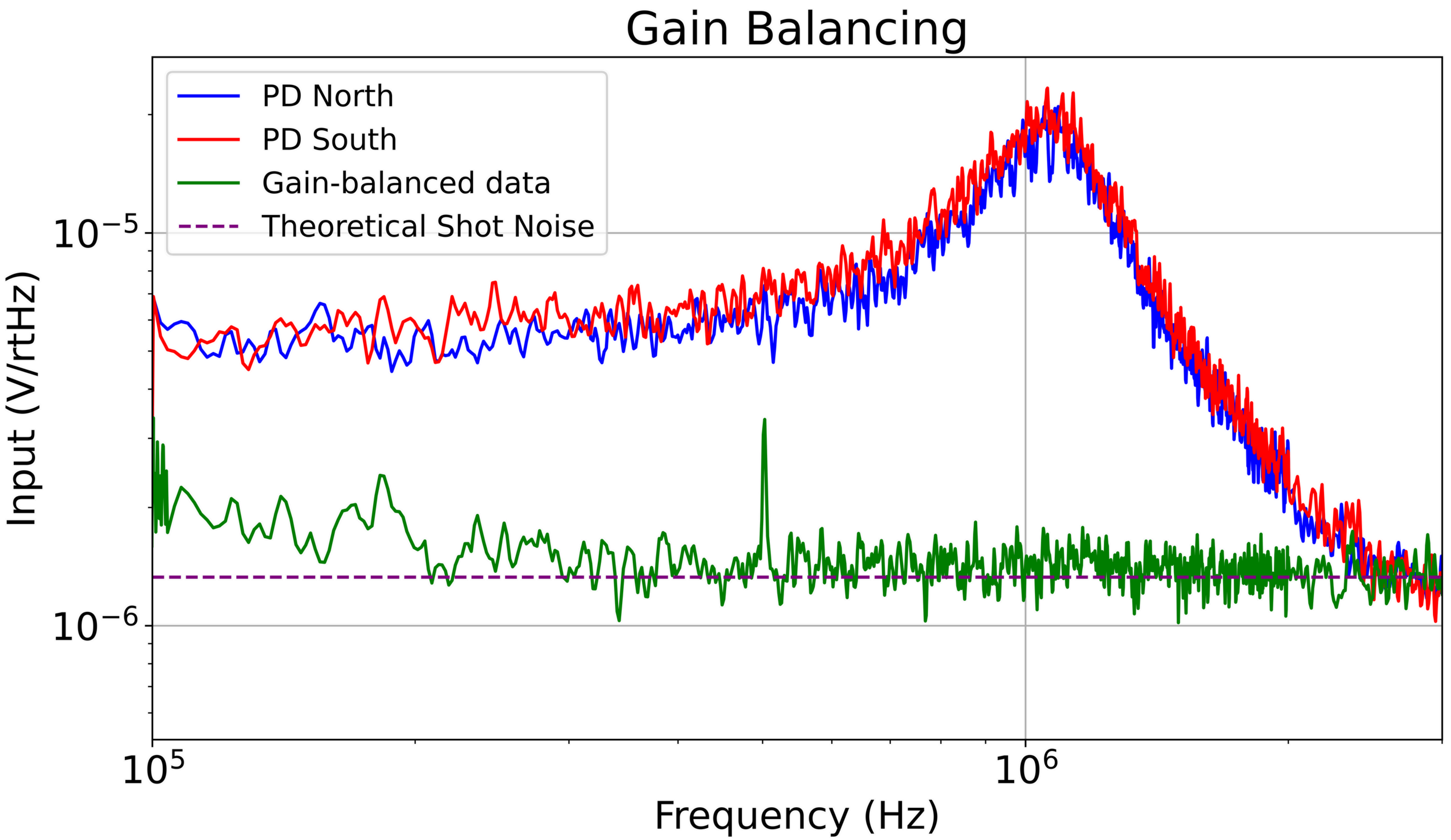


<u>Second Harmonic Generation (SHG)</u>

2. Detection of Squeezed States
Balanced Homodyne Detection

- **Gain balancing:**
  - Squeezed Signal Blocked. Strong 1064 Local Oscillator (LO) send to both Photodiodes (PD).
  - The power received in PDs are scaled and subtracted to leave alone shot noise eliminating common laser intensity noise.
  - This creates the matched photodiodes



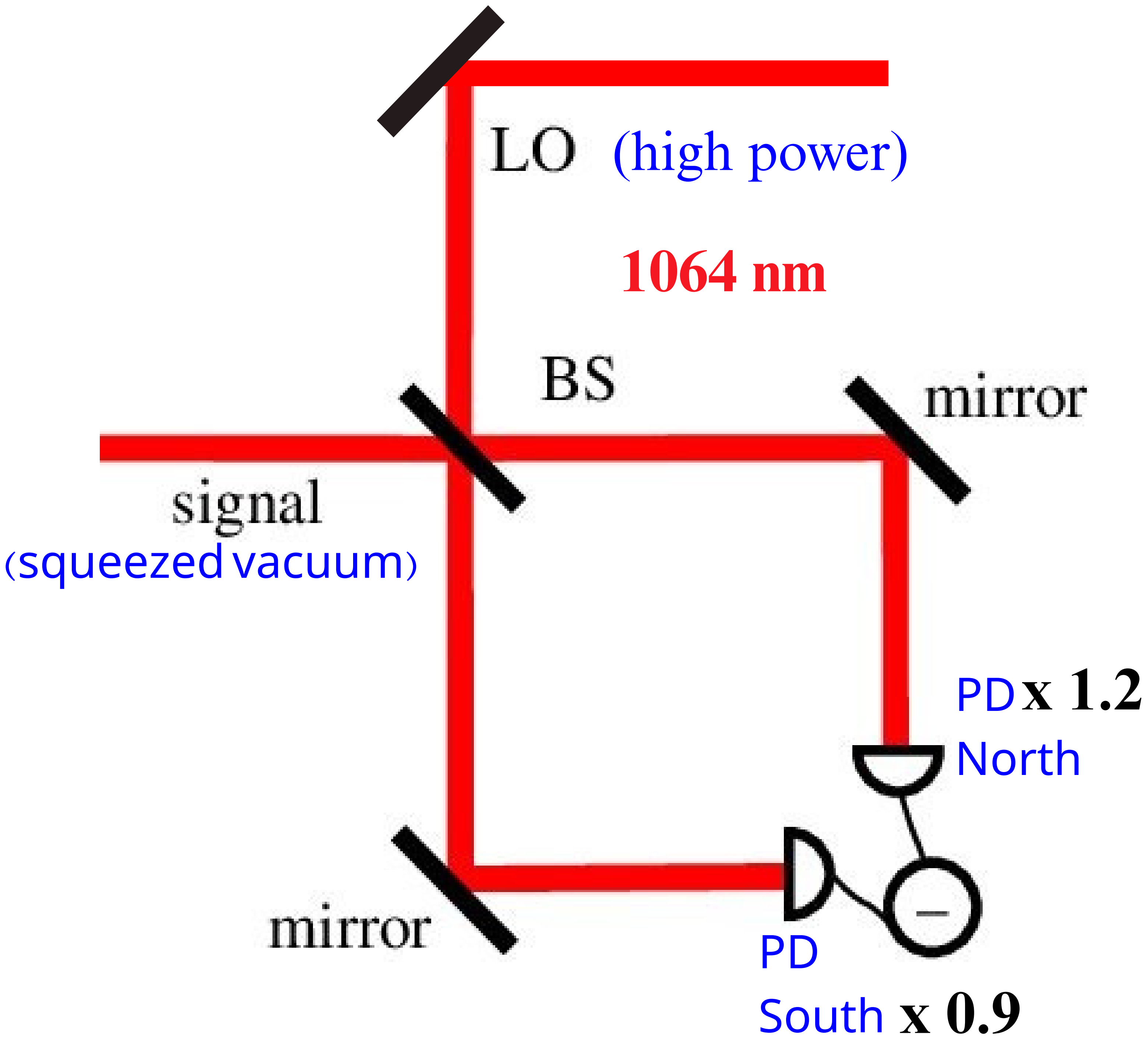

Gain Balancing
PD North
PD South
Gain-balanced data
Theoretical Shot Noise
10^{-5}
10^{-6}
Input (V/rtHz)
10^{5}
10^{6}
Frequency (Hz)

2. Detection of Squeezed States

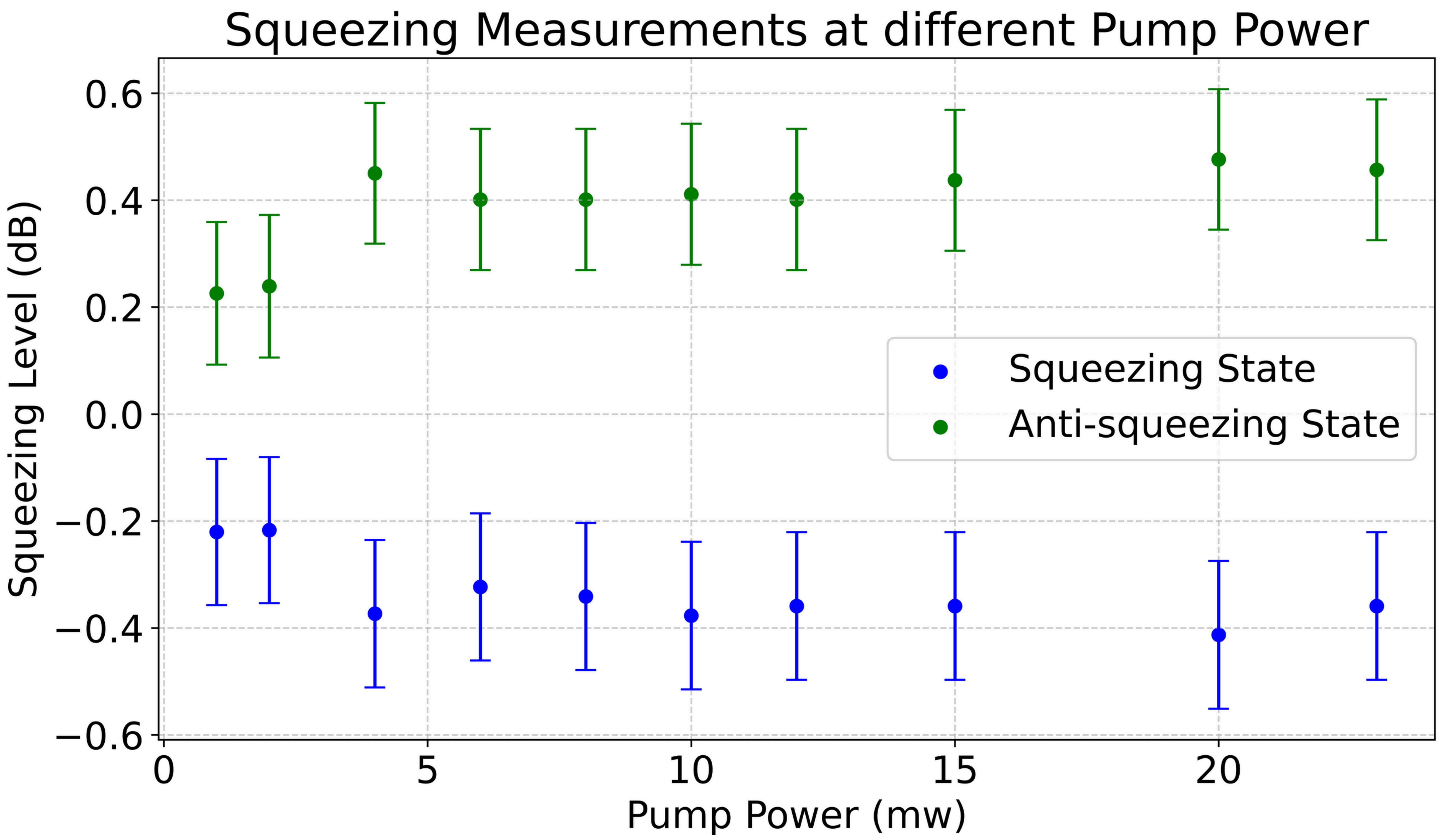
Balanced Homodyne Detection

- Signal + LO (1064 nm) mixed on 50:50 beam splitter
- Mode Matching: Beam waists aligned → Visibility ≈ 0.6
- Outputs detected on matched photodiodes

Variation in the shot noise level of Subtracted PD output over time shows-
Decreased Shot noise- Phase squeezing
Increased Shot noise- Phase anti-squeezing



At different incident pump power (532 nm):



Result:
(25mW pump power)

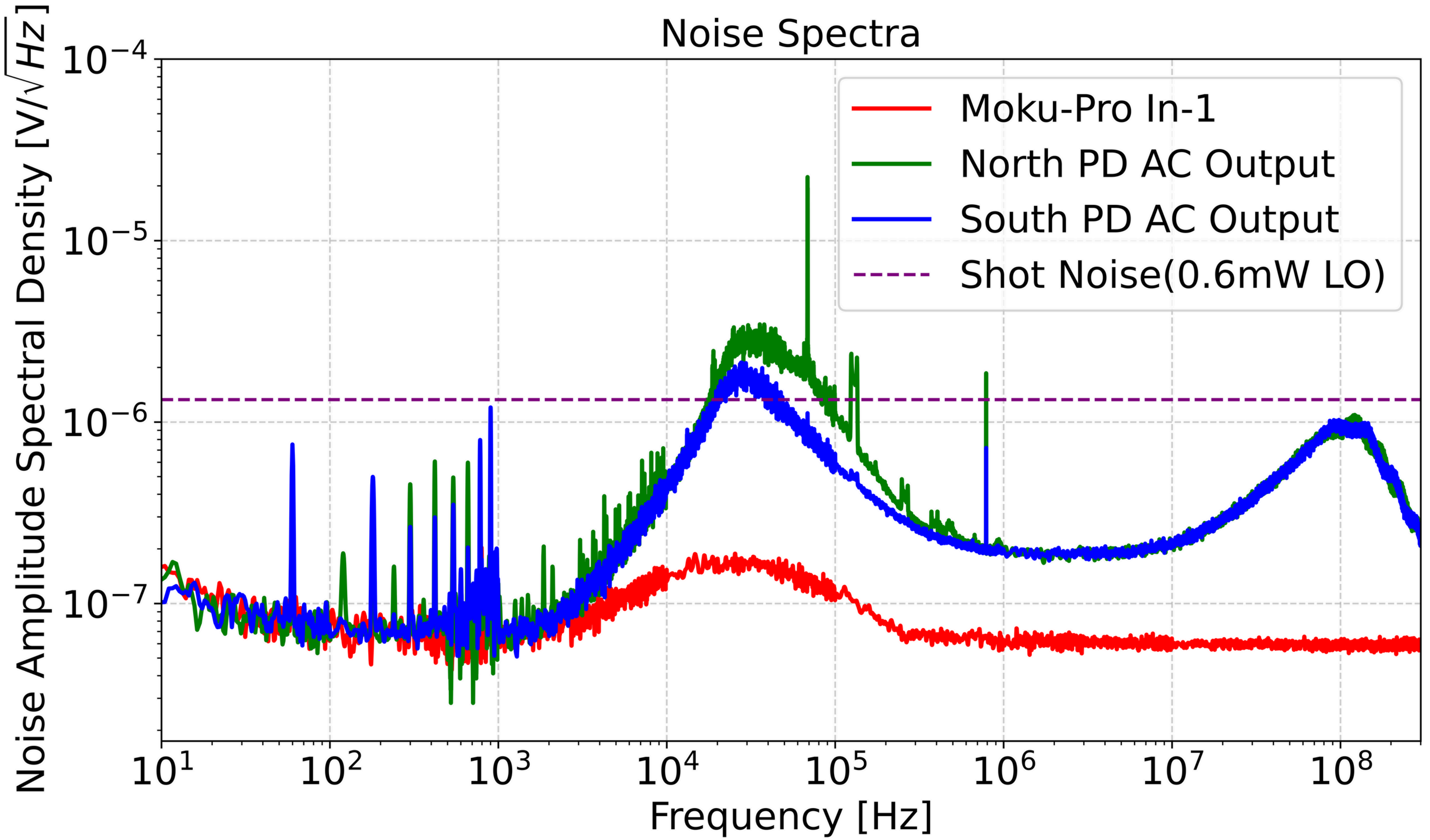
Max Squeezing: ~−0.4 dB
Max Anti-squeezing: ~+0.4 dB

$Squeezing \; \alpha \; \sqrt{P_{PUMP}}$

$\sim -0.9dB(150mV)$

Technical Noise Characterizations

- **Objective:** Total system noise < shot noise
- **Concern:** ADC & Photo Diode noise may mask squeezing

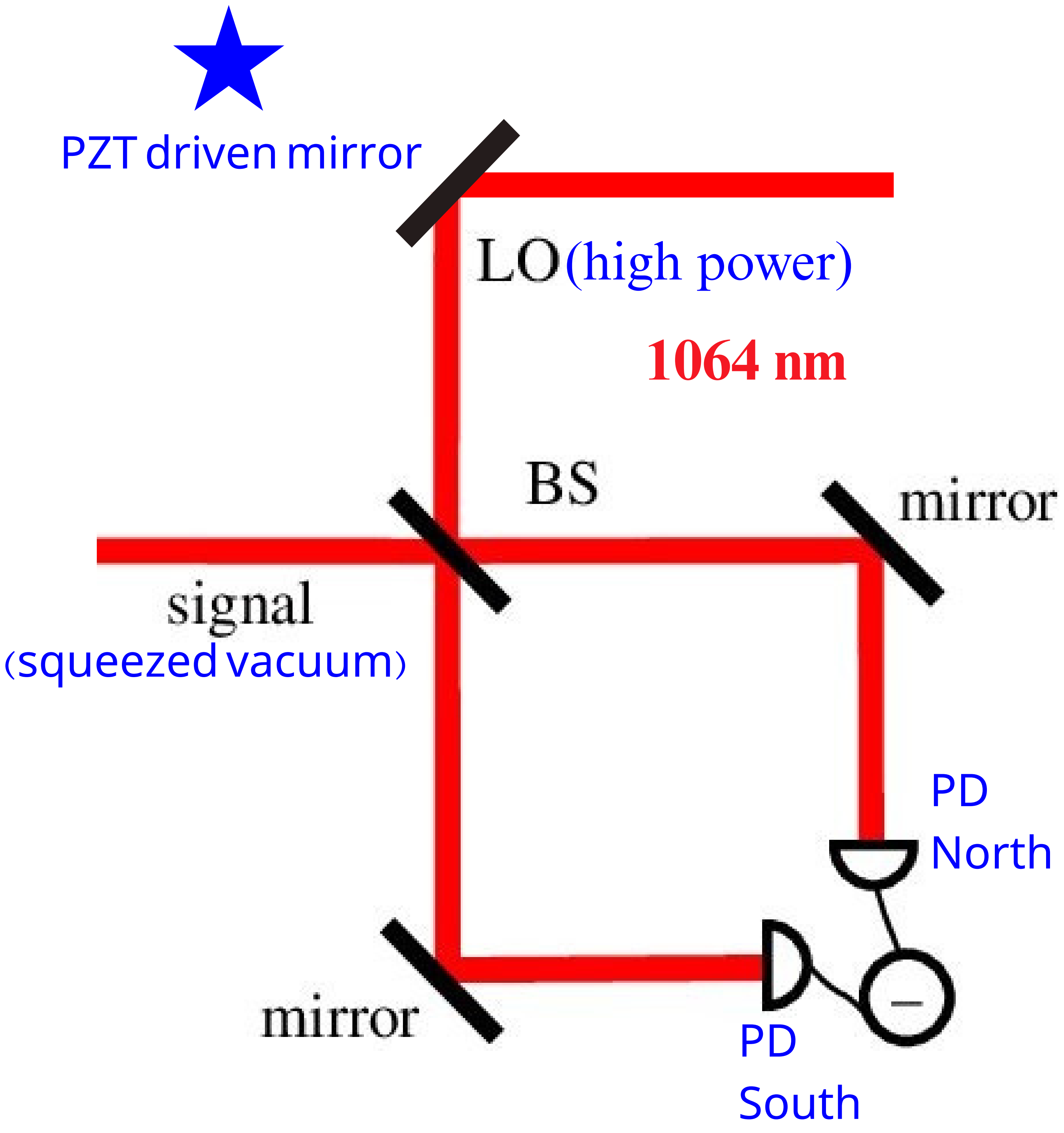


Result:

- Moku-Pro ADC Noise
  Noise floor: $\sim 1 \times 10^{-7}$ V/√Hz
- Photodiode Dark Noise
  Max Noise: $\sim 1 \times 10^{-6}$ V/√Hz
- With ~1 mW LO power, shot noise > ADC & PD noise → squeezing detectable

Active Phase Modulation between LO and Signal

- **Objective:** Enable controlled phase modulation between the Local Oscillator (LO) and squeezed signal using a Piezoelectric Transducer (PZT)-mounted mirror
- **Concern: Thermal/mechanical phase drifts can obscure squeezing** → require active stabilization for reliable measurements



LIGO

Phase Sweep Characterization

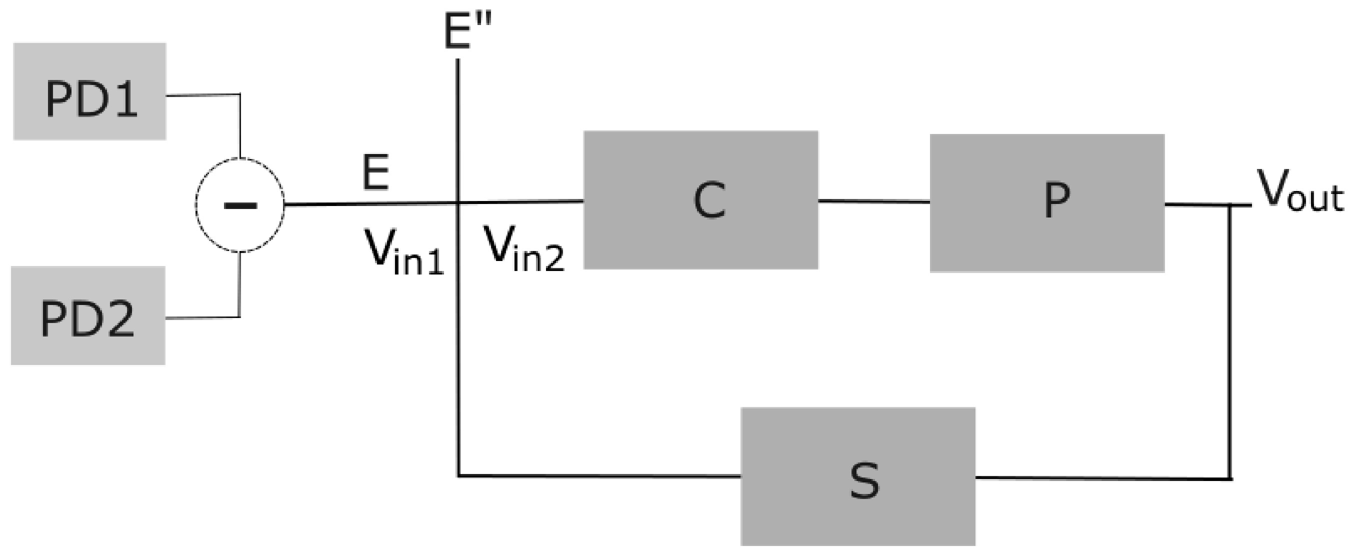
1λ- 2 Squeezing +2 Anti-Squeezing

- ~1λ phase sweep @75 V

Transfer Function Measurement

Needed to identify Resonant Frequencies

- Phase Drift(LO) noise locked via feedback loop
- Different frequency Sine wave injected
- Measured: Vin_1, Vin_2 → Calculated open-loop transfer function



$$G_{open}(f) = \frac{V_{in1}(f)}{V_{in2}(f)} = C(f) \cdot P(f) \cdot S(f)$$

$V_{in1}(f)$= Error signal measured at the photodiodes (after excitation)

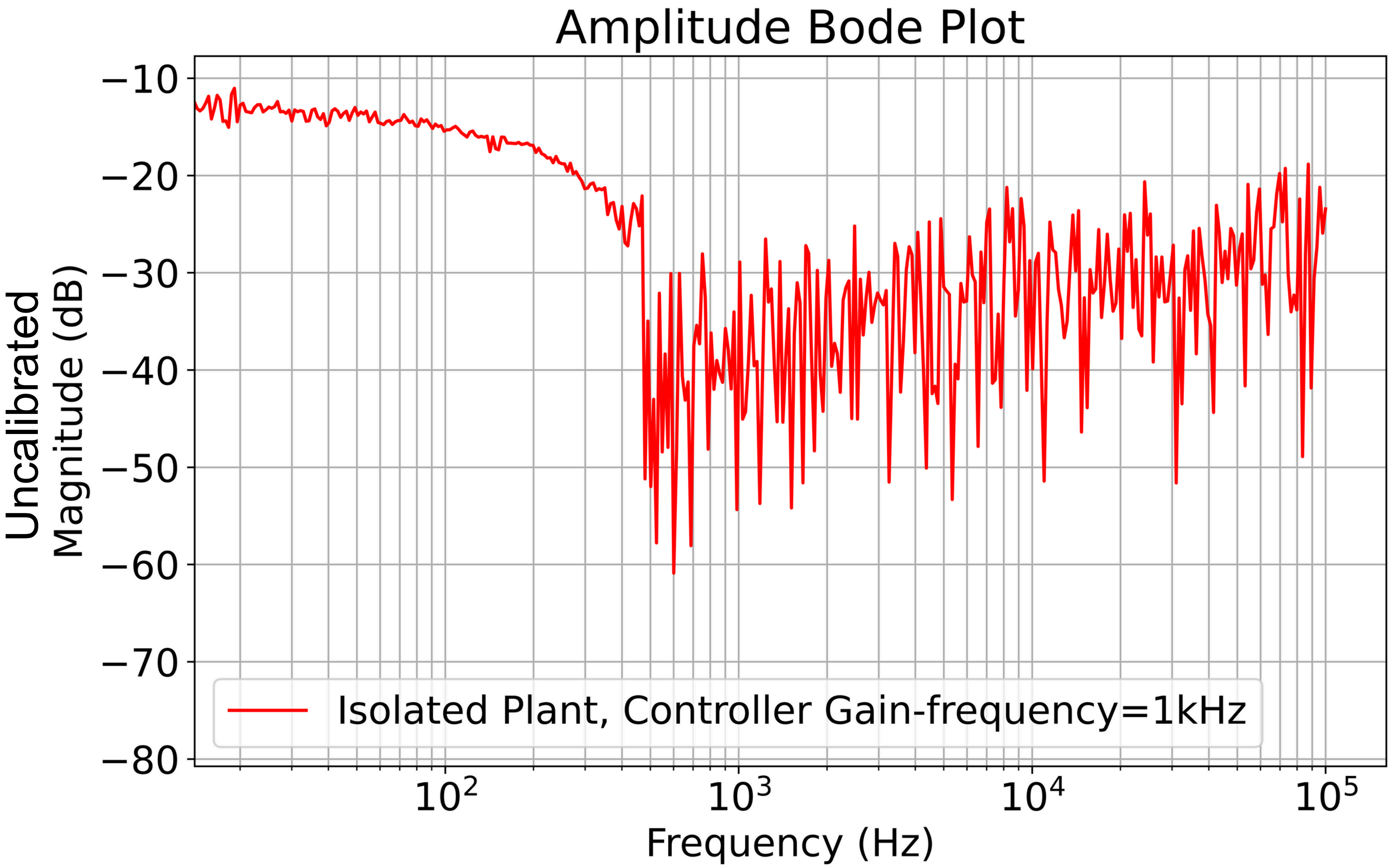
$V_{in2}(f)$= Combined signal input to the PZT (error + excitation).

$C(f)$= Known controller transfer function (integrator).

$P(f)$= Desired transfer function of the PZT + mirror system.

$S(f)$= Sensor response assumed as unity

PZT Characterization



Result:

- Stable response from **15 Hz–1 kHz.**
- No strong resonances observed in this band.
- PZT will be driven at **50 Hz** for squeezing

Non-Linear Gain Measurements

Objective:

- Use Optical Parametric Amplification (OPA) 1064 gain - to optimize alignment of the 532 nm pump with the waveguide for future squeezing measurements.
- Estimate the expected level of squeezing

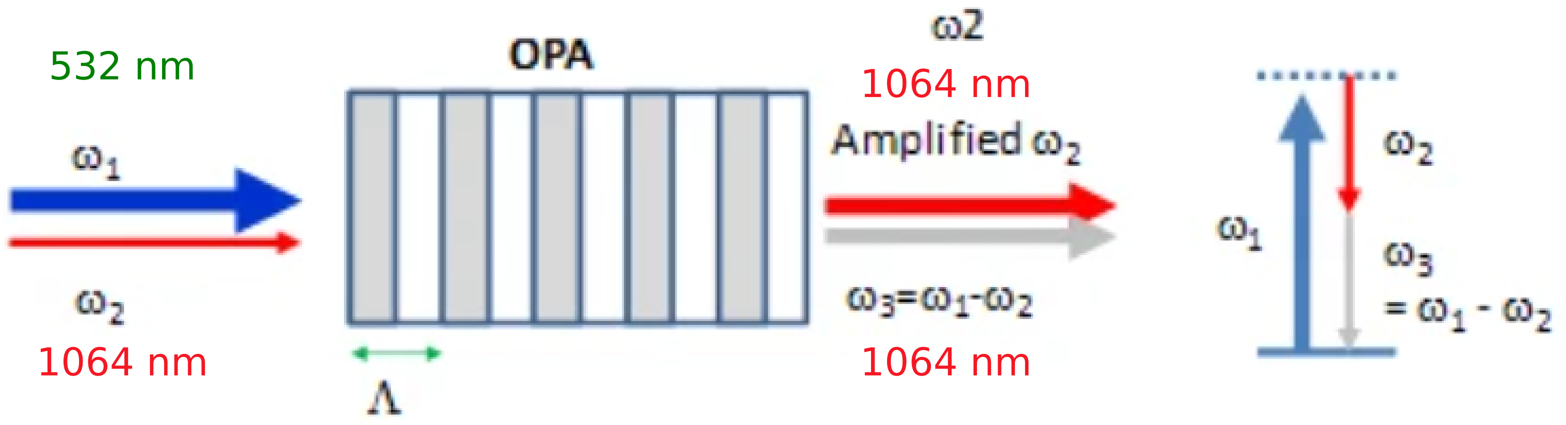
Relation of squeezing Parameter & OPA Non-Linear Gain

- Assumptions: $\frac{dE_p}{dl} = 0$, $\Delta k = 0$
- Coupled Wave Equations: $\frac{dE_s}{dl} = ik_s E_p E_i^*$, $\frac{dE_i}{dl} = ik_i E_p E_s^*$
- Gain Coefficient: $g^2 = k_s k_i |E_p|^2$
- Total Gain: $(k_s k_i + 1)\sinh^2(gl) + 1 \sim e^{2z}$

Here,

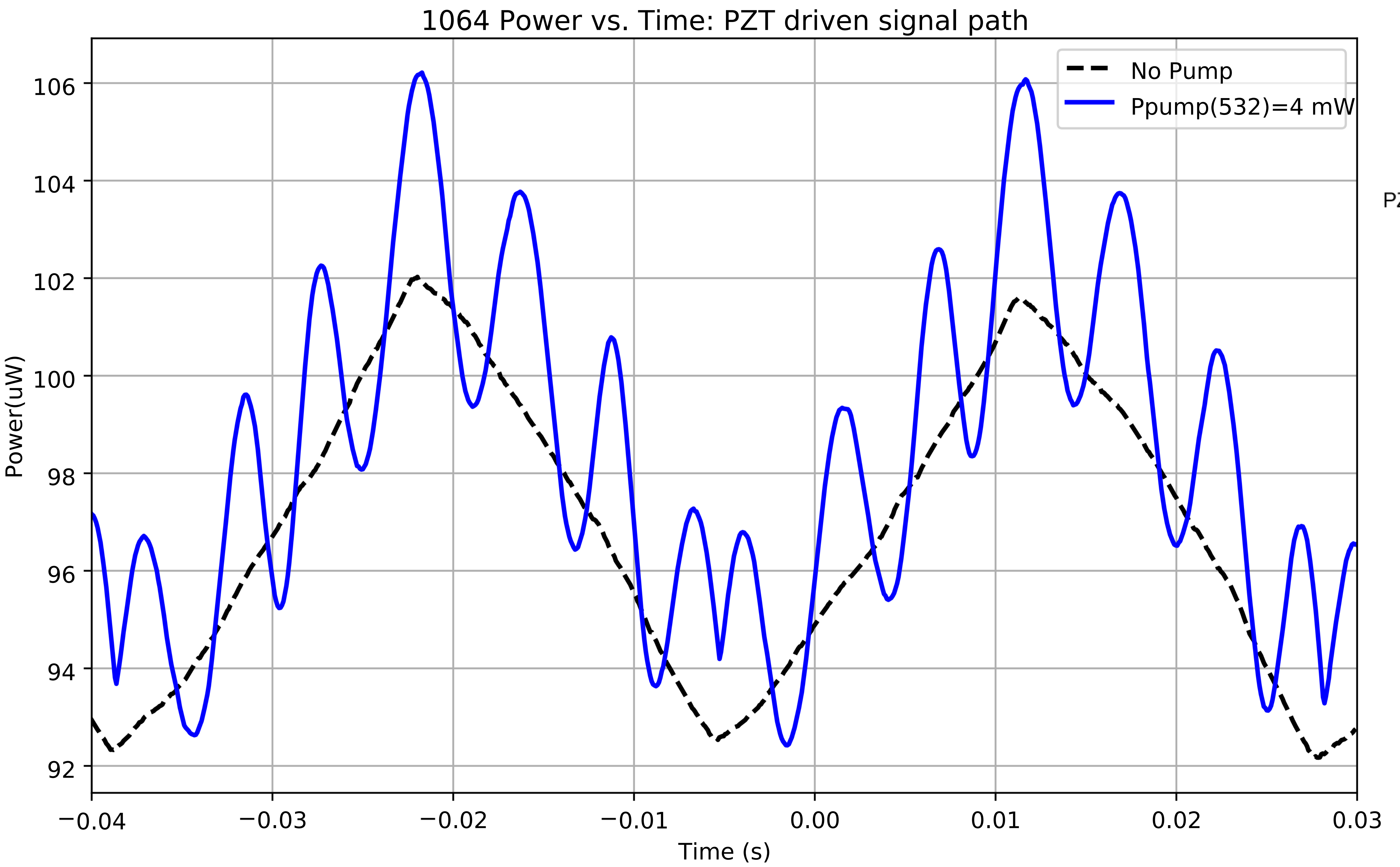
l= Length of Crystal

z= Squeezing Parameter

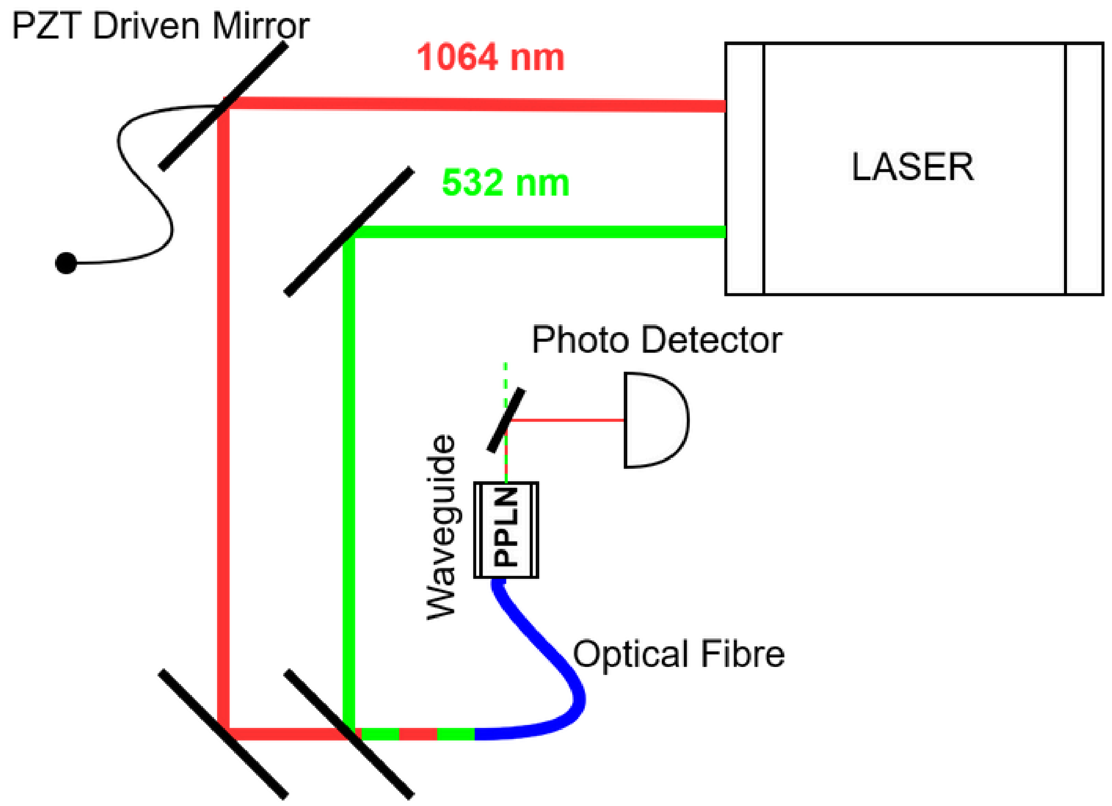


Experimental Measurement

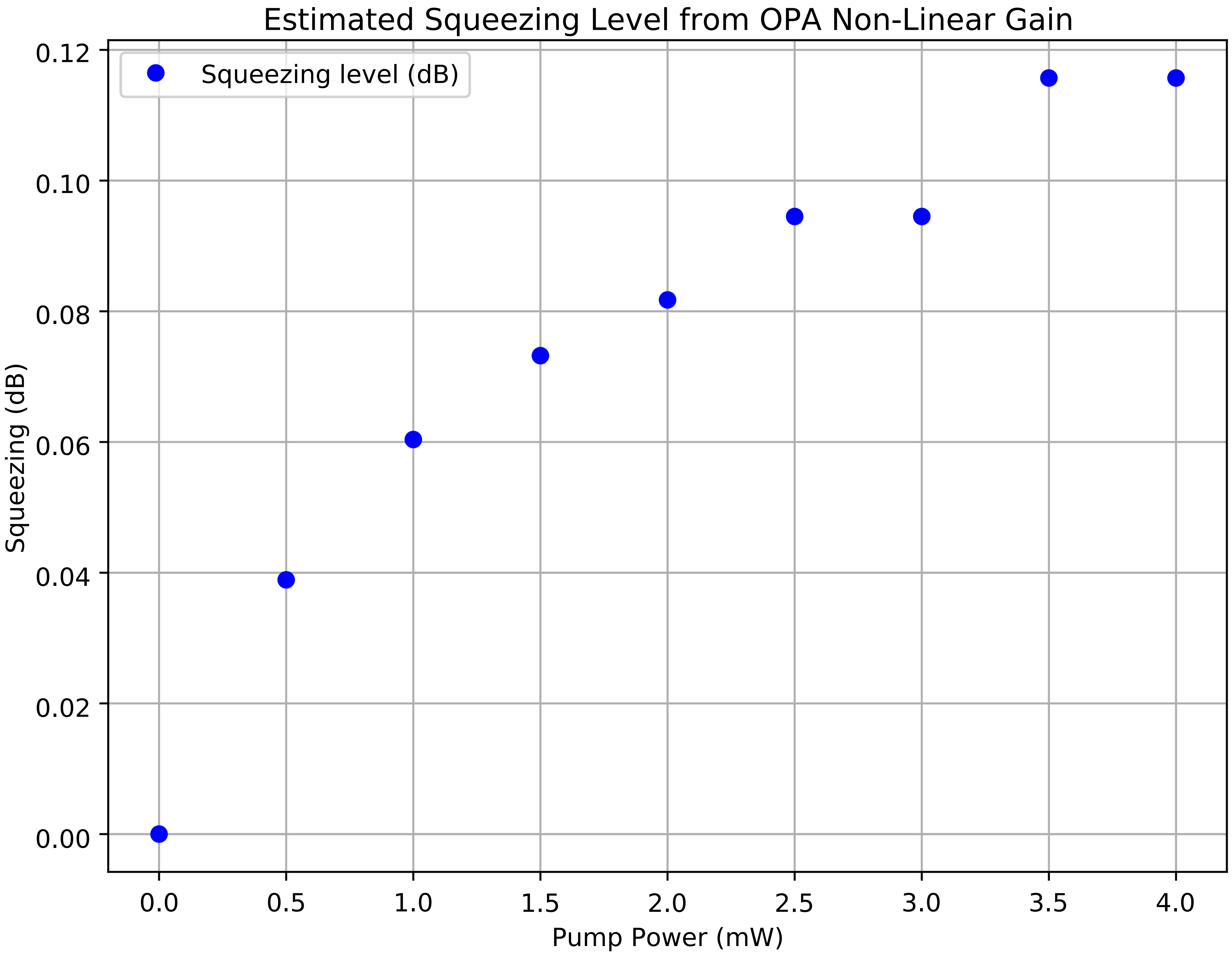
- 1064 nm signal: 100 μW
  532 nm pump: 0–4 mW
- PZT-mounted mirror modulated in signal path with triangular wave of 30 Hz, 15 Vpp



"Phase-dependent amplification/deamplification"



$$G_{\mathrm{dB}} = 10\log_{10}\left(\frac{P_{\mathrm{in}}+\mathrm{Mean}_{\mathrm{peak}}}{P_{\mathrm{in}}}\right)$$



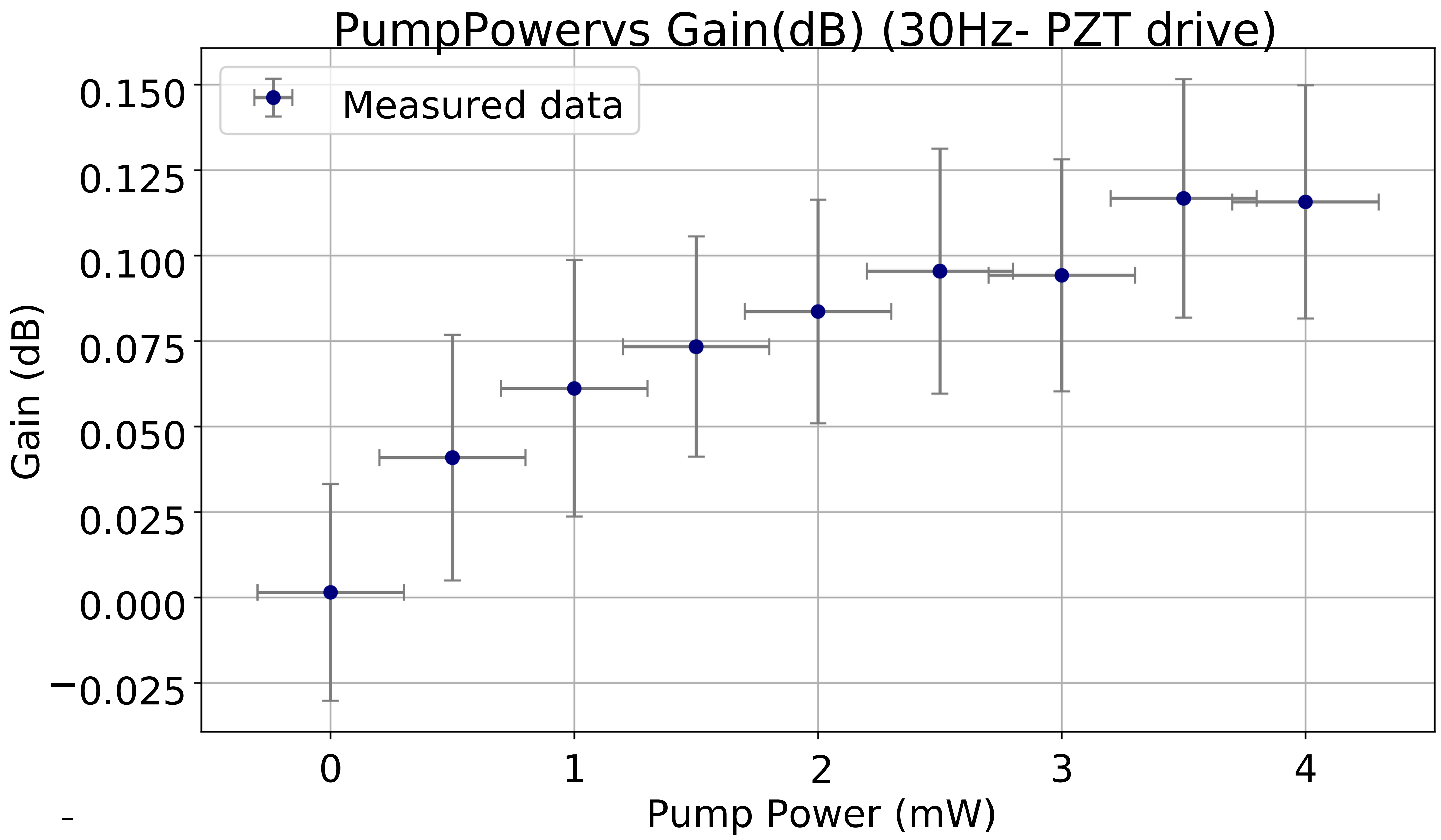
Estimated squeezing is close to the Measured squeezing ~0.1 dB at 4mW Pump power(532 nm)

$$Squeezing\ Level(dB) = -10\log_{10}\left(\frac{\Delta X_{squeezed}}{\Delta X_{unsqueezed}}\right)$$

$$Here, z = Squeezing\ Parameter$$

$$\Delta X = Variance = \frac{e^{-2z}}{4}$$

LIGO



Result:

- Experimentally measured gains in 1064 power were on the order of 0.1 dB for a pump power of 4 mW at 532 nm.

Optimizing alignment and Polarization by maximizing 1064 power gain

By maximizing the OPA non-linear gain (**14 %**)-

- All the optics before the crystal was aligned
- The input polarization of the 1064 nm signal and 532 nm pump into the waveguide was adjusted

Future Goals

- **Fiber-Induced Polarization Drift Diagnosis:**

80% loss in 532 power on passing through fiber +waveguide. Replace the fiber with a single mode fiber and compare performance.

- **Mode Matching:** Use Gaussian beam propagation tools (e.g., Finesse or ABCD

matrix formalism) to model the 1064 nm signal and LO paths. Align experimentally to achieve >95% overlap at the beam splitter in the BHD and verify using beam profiling.

- **Fast Squeezing Measurement:** Increase Pump power. Implement fast squeezing measurement using lock-in detection filtering sideband frequency <100 kHz and modulating LO path with a PZT driven mirror by driving it with 50 Hz sine wave.

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