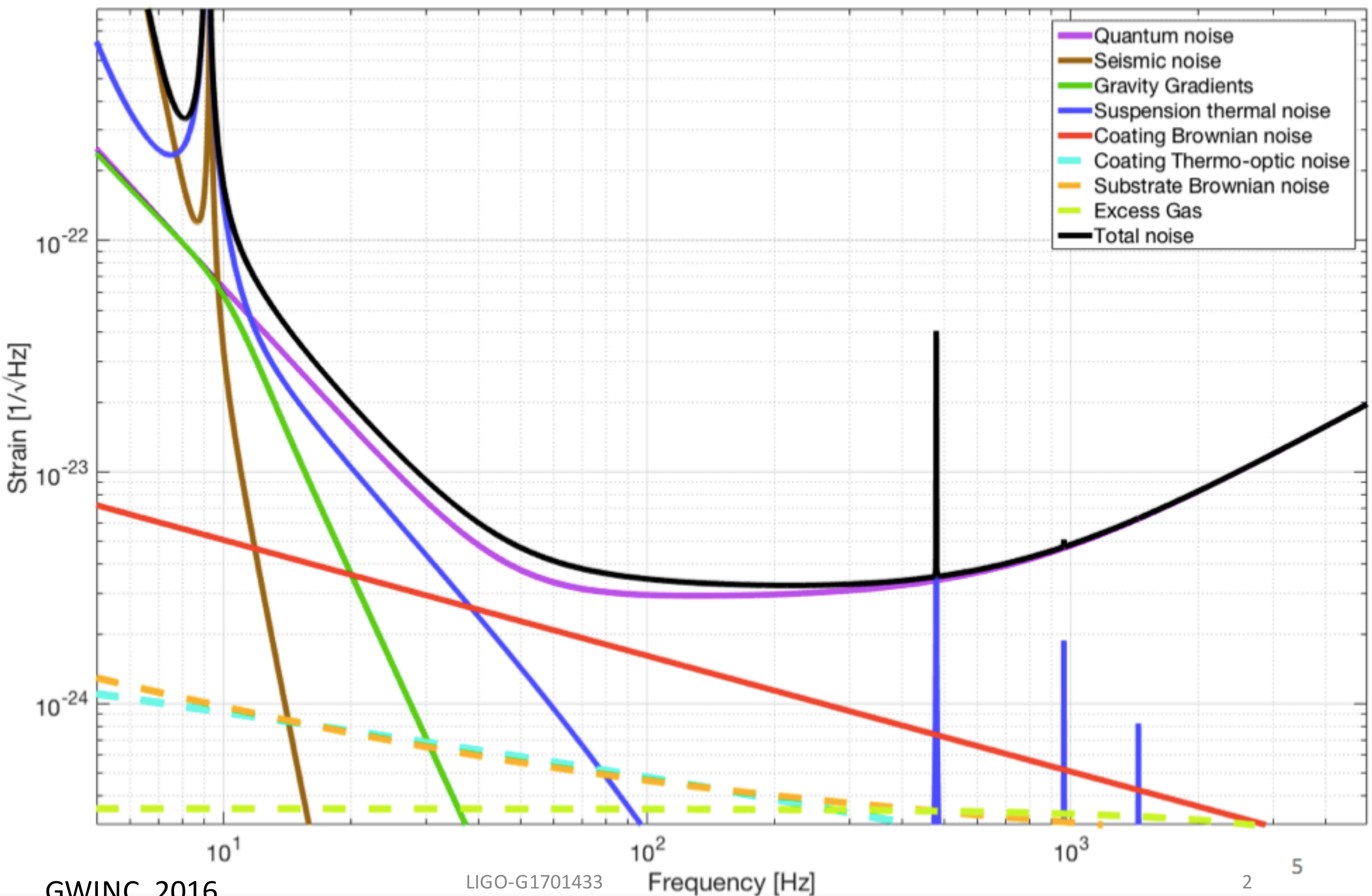
SURF 2017
Squeezing Quantum Noise Using Waveguides

Dhruva Ganapathy

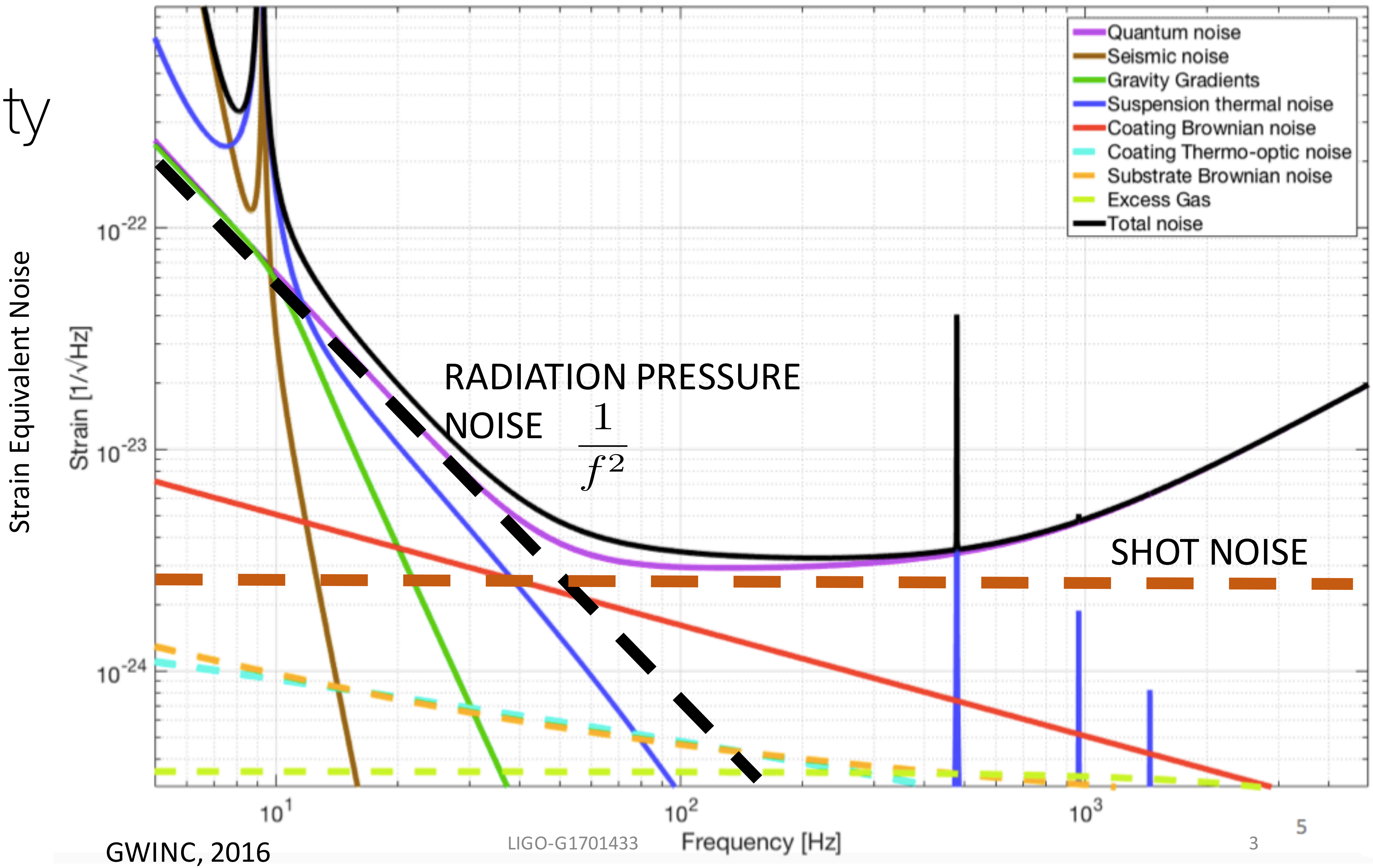
aLIGO Sensitivity Curve

Strain Equivalent Noise



GWINC, 2016

aLIGO Sensitivity Curve



GWINC, 2016

Quantized EM Fields

Electric Field is Quantized –

$$E(t) = \sqrt{\frac{\hbar\omega}{\epsilon_0 V}}(a(t)^{-i\omega t} + a^\dagger(t)e^{i\omega t})$$

$$X(t) = a(t) + a^\dagger(t)$$

$$Y(t) = -i(a(t) - a^\dagger(t))$$

$$E(t) = \sqrt{\frac{\hbar\omega}{\epsilon_0 V}}(X(t)\cos\omega t + Y(t)\sin\omega t)$$

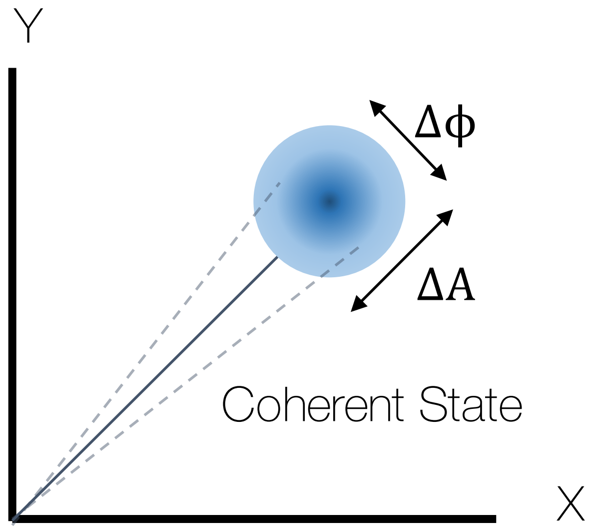
Quadratures Follow Heisenberg's Uncertainty Principle.

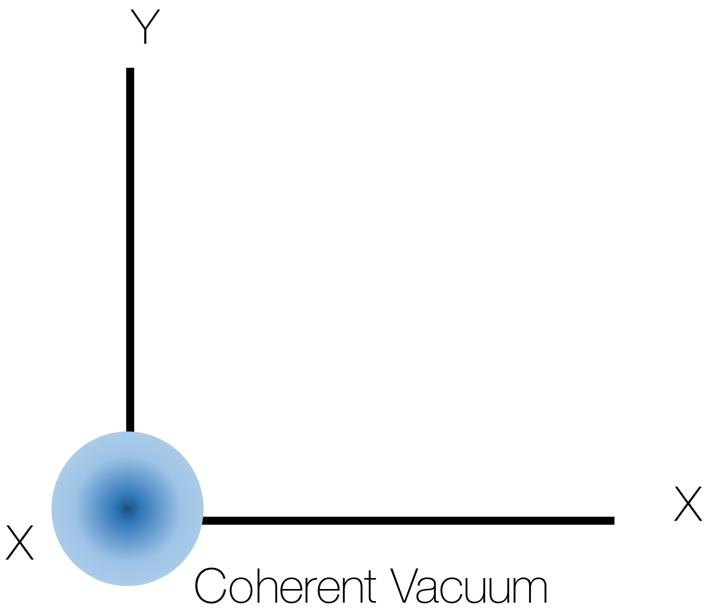
$$[X, Y] = 2i \qquad \Delta X \Delta Y \geq 1$$

Coherent Light

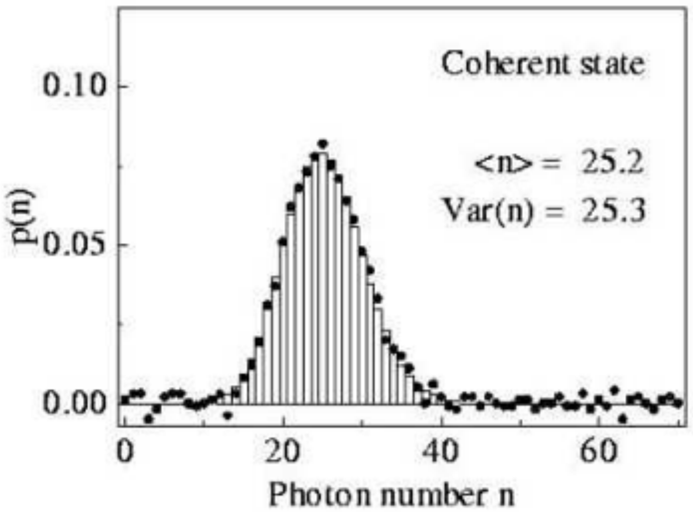
Laser light is coherent –

$$|\alpha\rangle = e^{-\frac{|\alpha|^2}{2}} \sum_{n=0}^{\infty} \frac{\alpha^n}{\sqrt{n!}} |n\rangle$$





Photon number measurements give Poisson Distribution

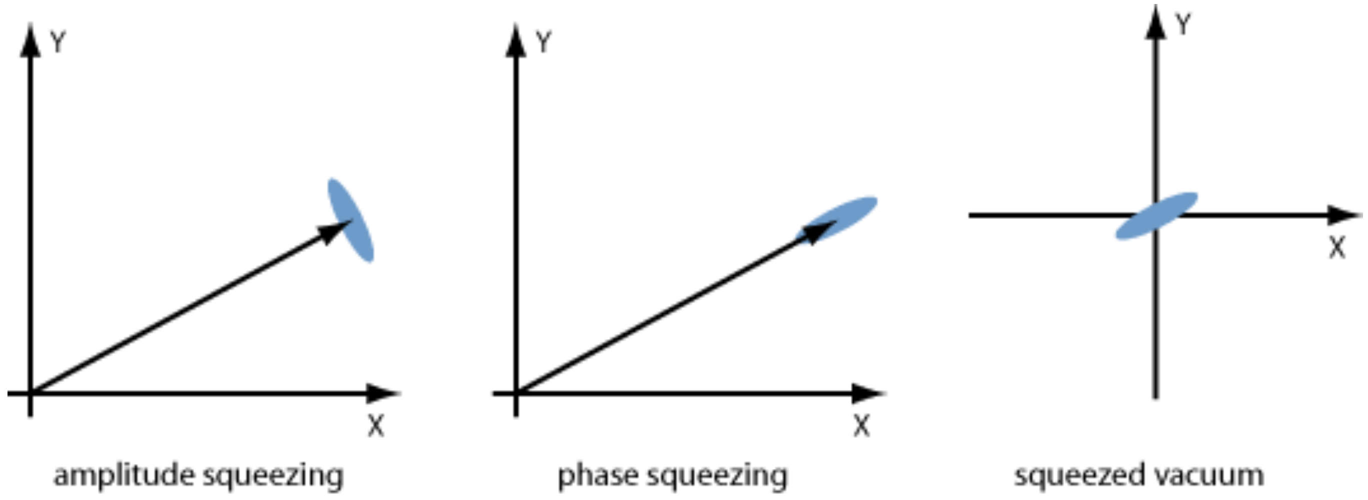


Quantum state reconstruction of classical and nonclassical light and a cryogenic opto-mechanical sensor for high-precision interferometry – Breitenbach, Gerd

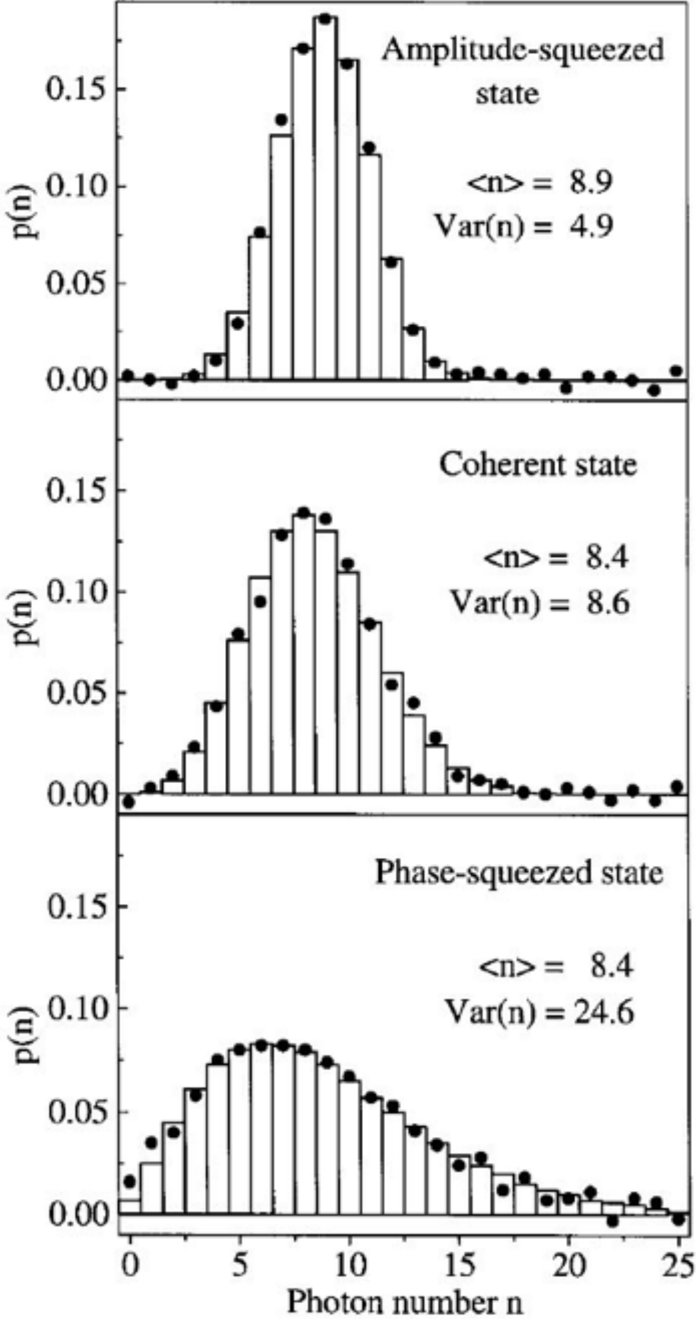
$$\Delta X \Delta Y \geq 1$$

Squeezed Light

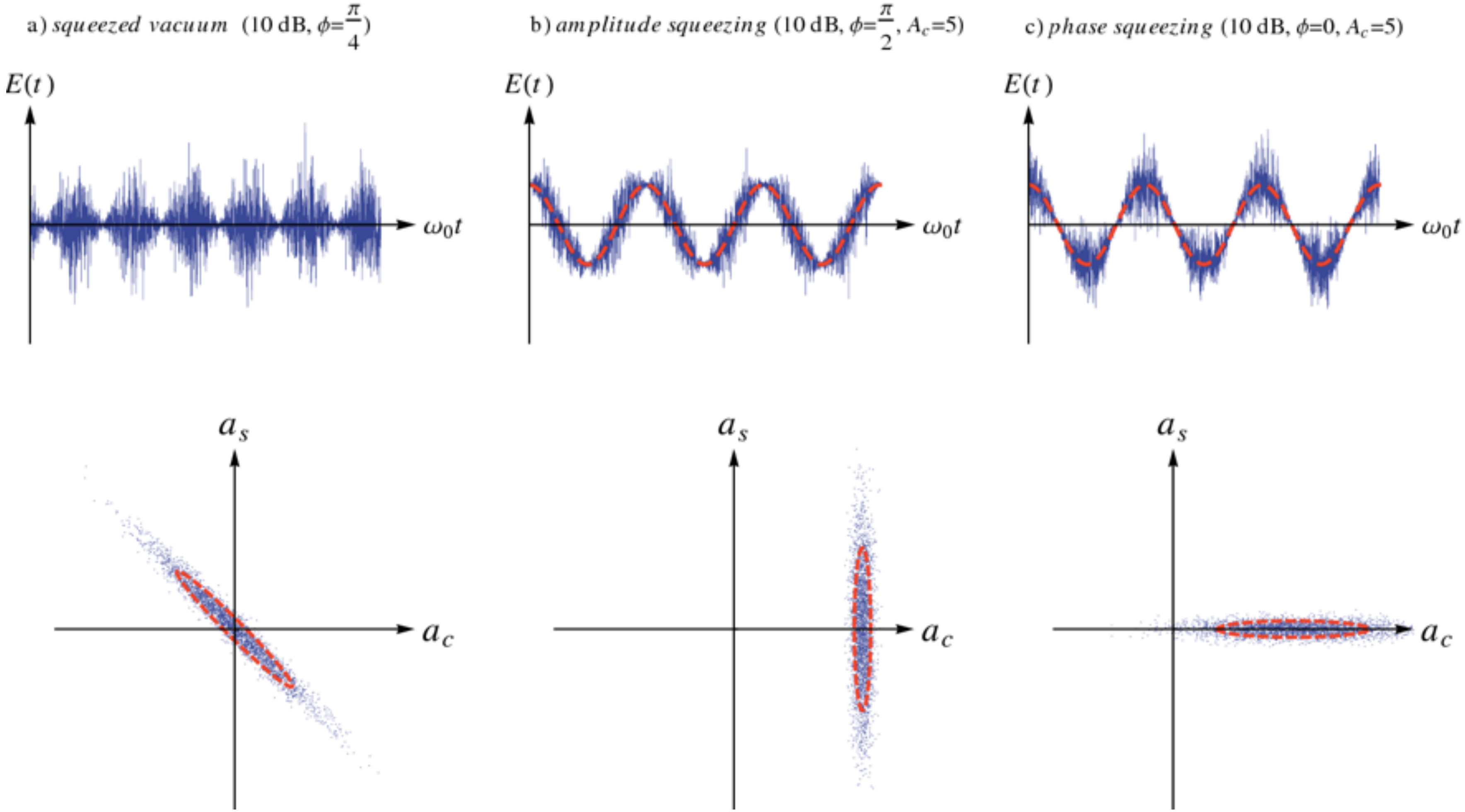
Squeezing decreases phase/amplitude noise.



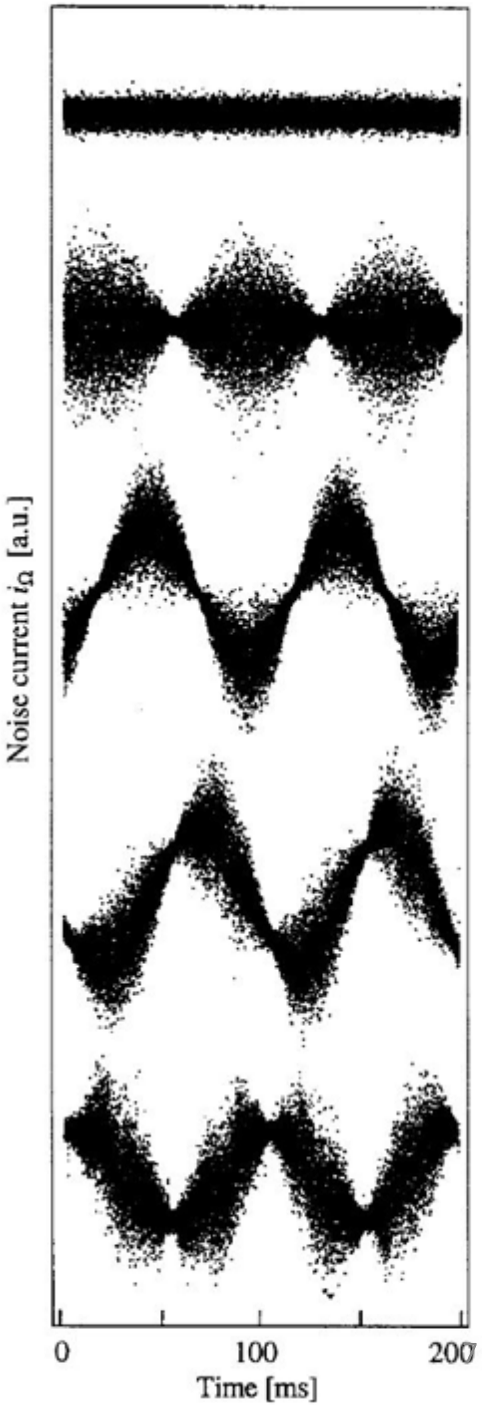
https://www.rp-photonics.com/img/squeezed_light.png



Quantum state reconstruction of classical and nonclassical light and a cryogenic mechanical sensor for high-precision interferometry – Breitenbach, Gerd



Quantum Measurement Theory in Gravitational-Wave Detectors - Danilishin, Stefan L. *et al.* Living Rev.Rel. 15 (2012) 5 arXiv:1203.1706 [quant-ph]

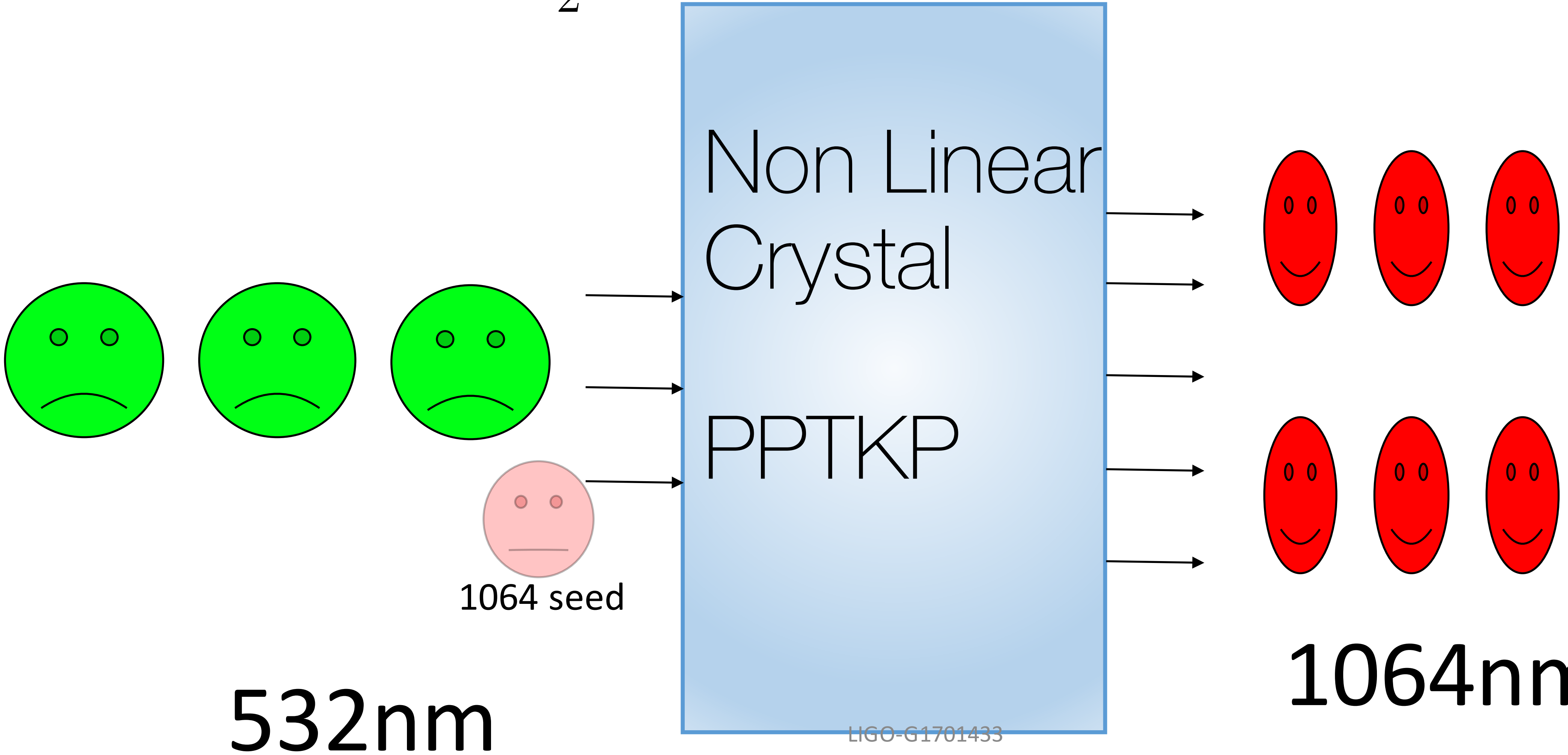


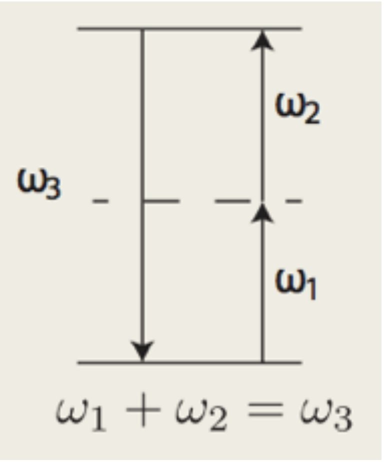
Quantum state reconstruction of classical and nonclassical light and a cryogenic opto-mechanical sensor for high-precision interferometry – Breitenbach, Gerd

Optical Parametric Oscillator Squeezer (SPDC)

$$H = \hbar\omega a^\dagger a + \hbar(2\omega)b^\dagger b + i\frac{\hbar}{2}\kappa(a^{\dagger 2}b - a^2 b^\dagger)$$

$$P(t) = \epsilon_0(\chi^1 E(t) + \chi^2 E^2(t) + \chi^3 E^3(t) + \ldots)$$

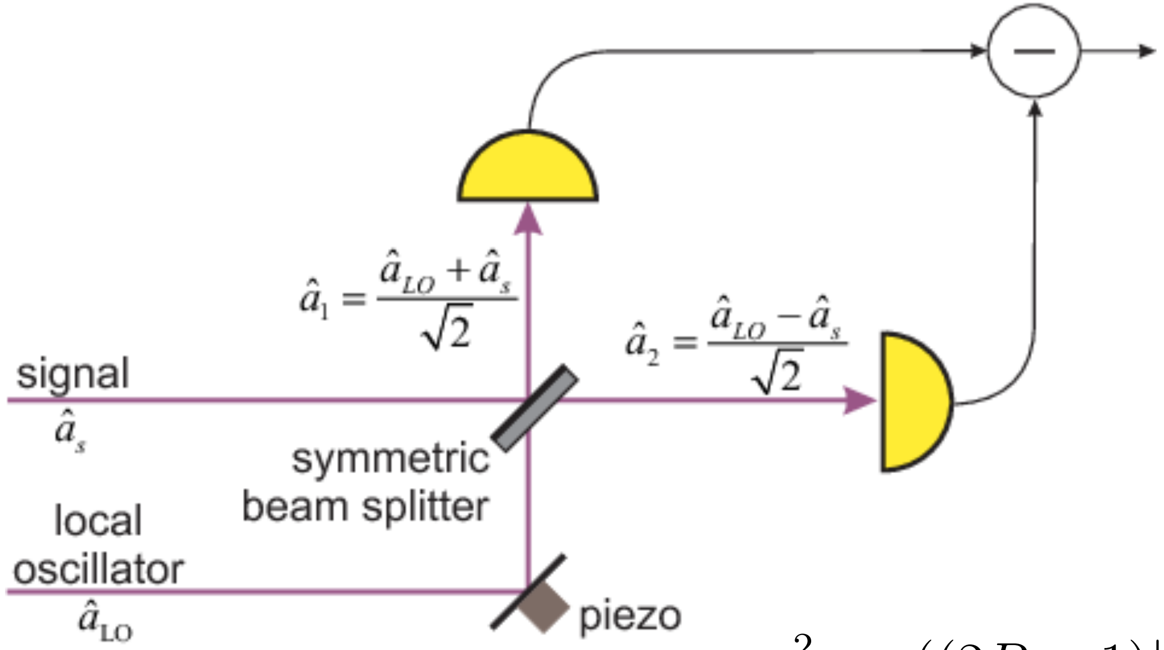




SPDC as a source of squeezed light

- A non-linear crystal behaves like a phase dependent amplifier.
- Seed crystal with vacuum.
- The quantum noise gets (de)amplified differently at different phases leading to generation of squeezed light thereby different uncertainties (Squeezing!).

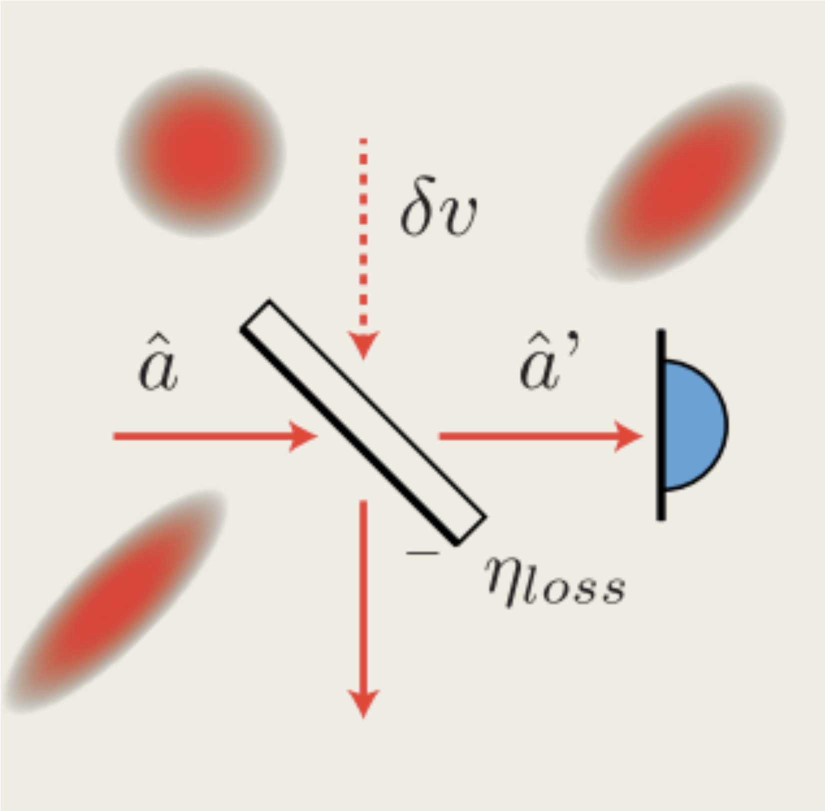
Balanced Homodyne Detection



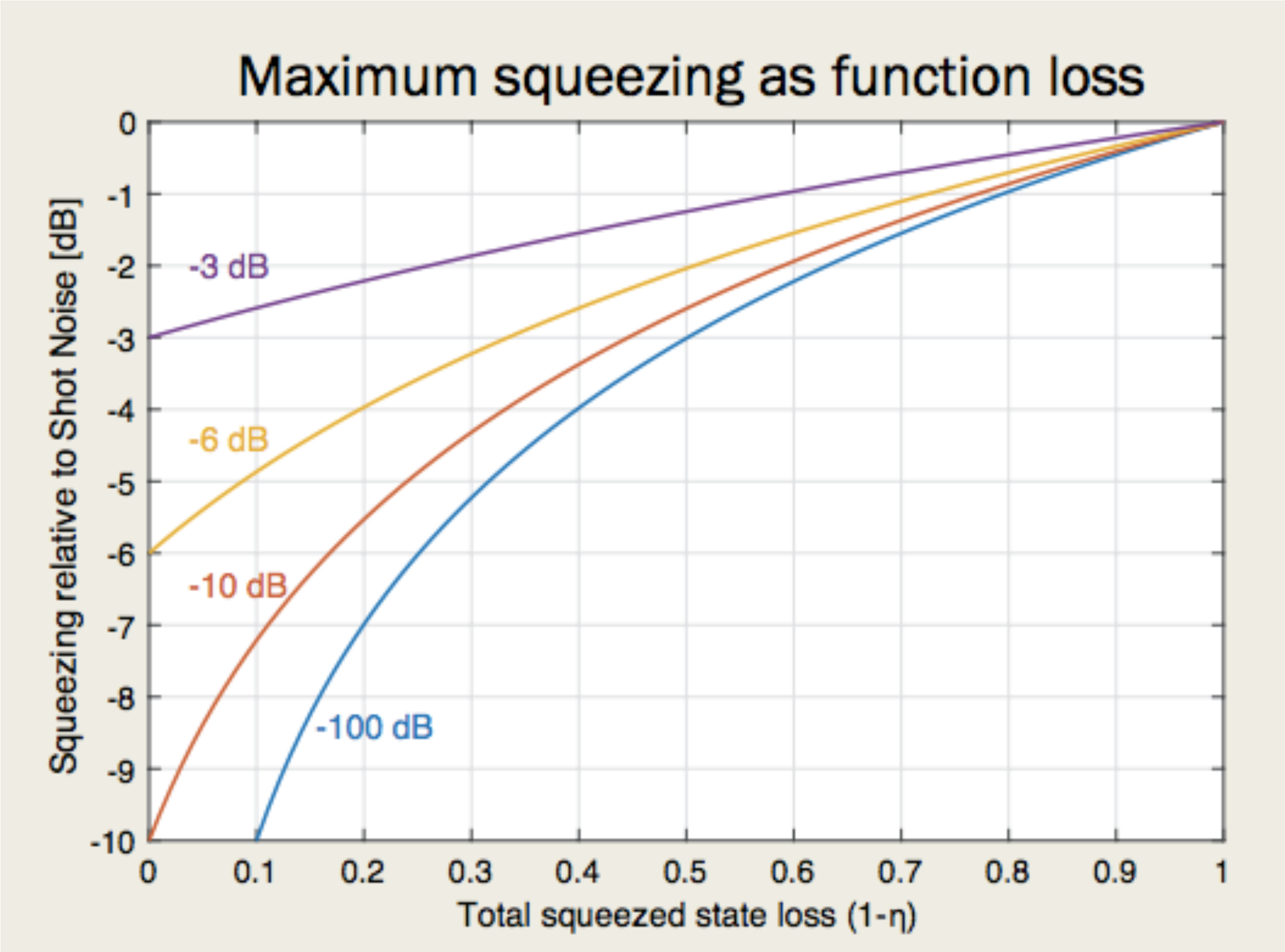
$$\epsilon_0^2\eta_{PD}((2R-1)|a_s^2| + i\sqrt{R(1-R)}(a_{LO}a_s^\dagger - a_{LO}a_s^\dagger) + (1-2R)|a_{LO}^2|$$

Squeezed light - Lvovsky, A.I. arXiv:1401.4118 [quant-ph]

How does loss affect squeezing?



$$V_{a'}^{out} = \eta_{loss} V_a^{in} + (1 - \eta)$$



Waveguide Optical Parametric Oscillator Setup

Couple Light into Fibers

Mode Matching

→

Produce Squeezed Light (SPDC)

Phase Matching

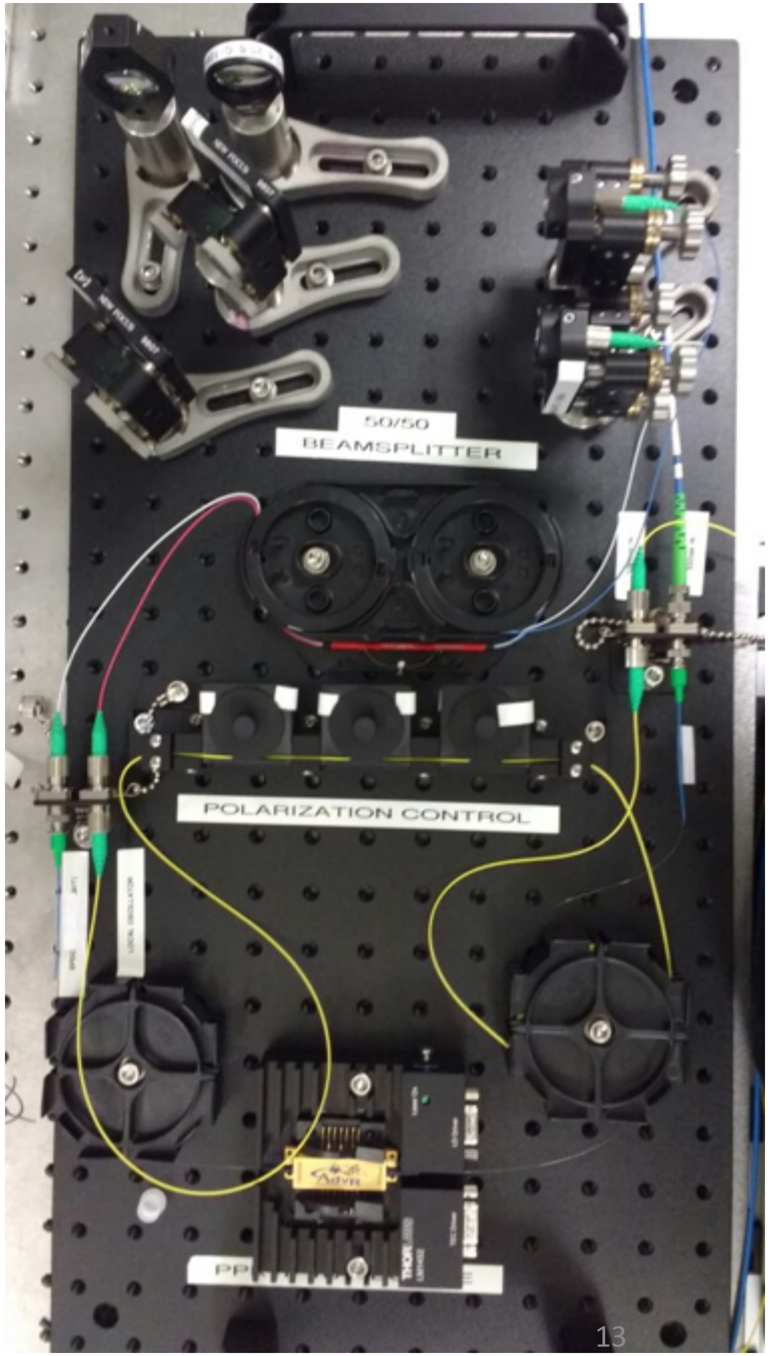
→

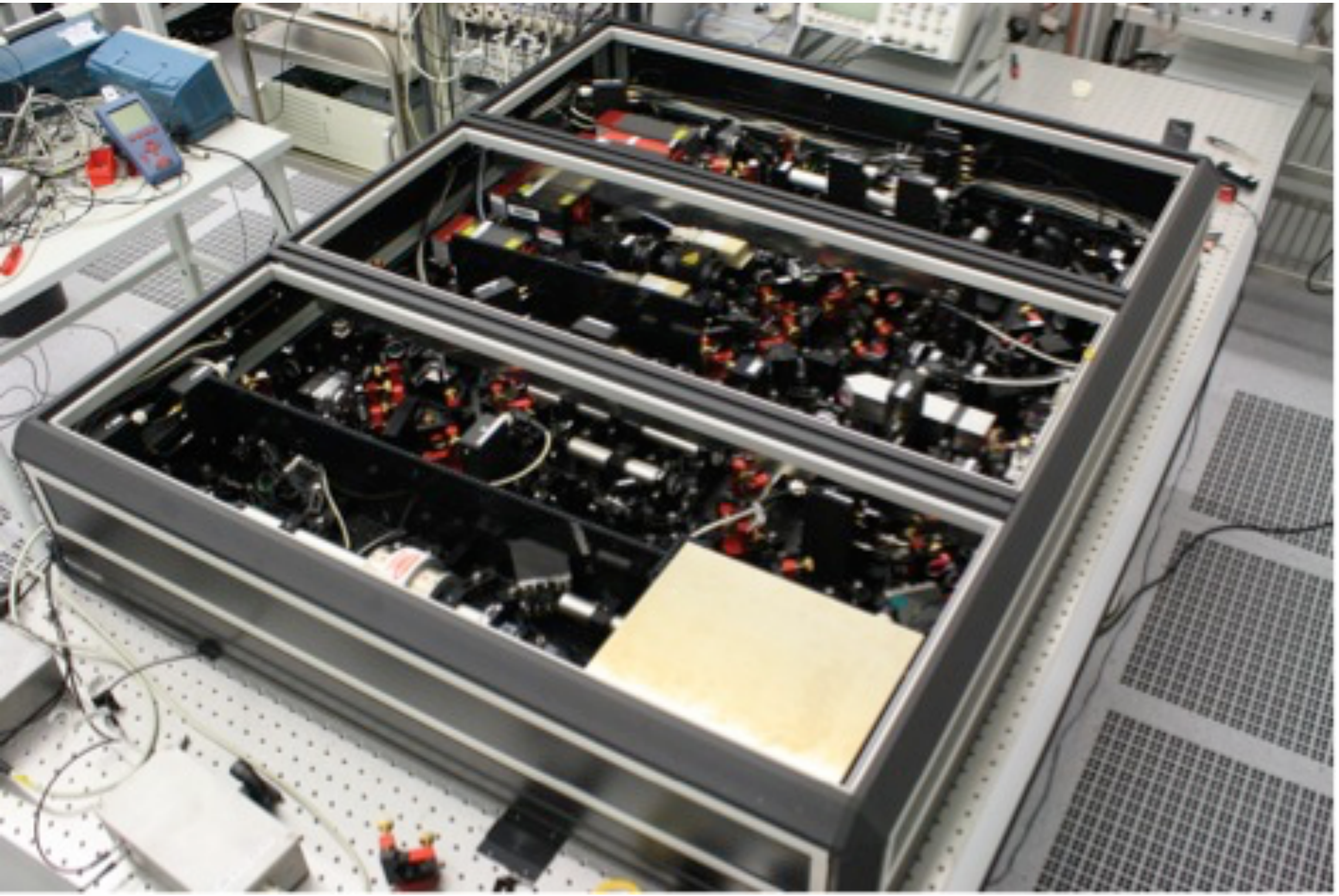
Detect Squeezed Light

Homodyne Detection

WHY WOPO?

WOPO Squeezer





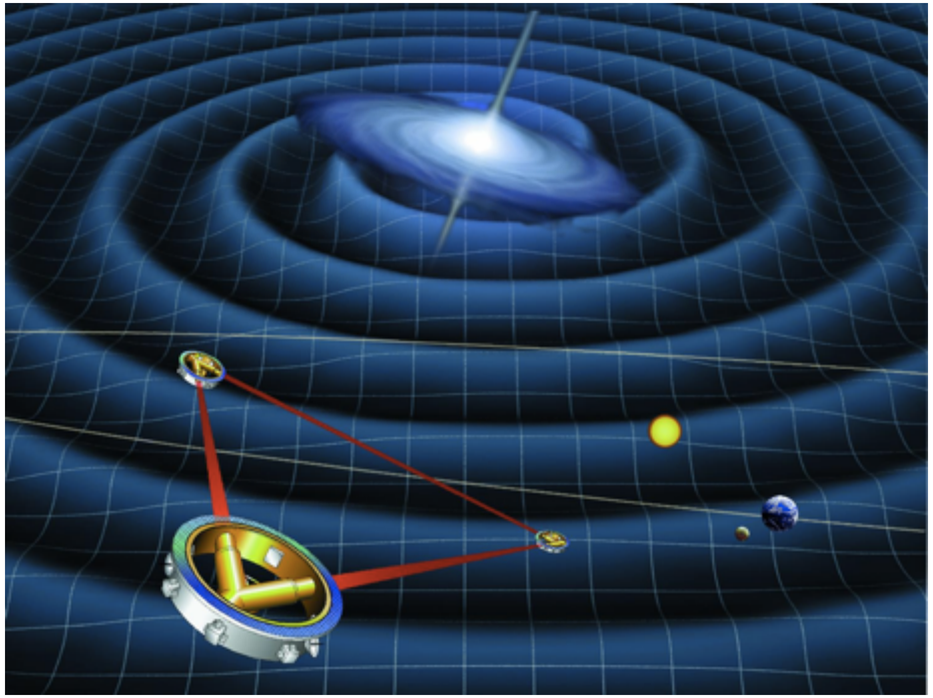
GEO600 Squeezer http://www.qi.aei-hannover.de/

It can be a neat and portable squeezer-in-a-box

Squeezer Applications

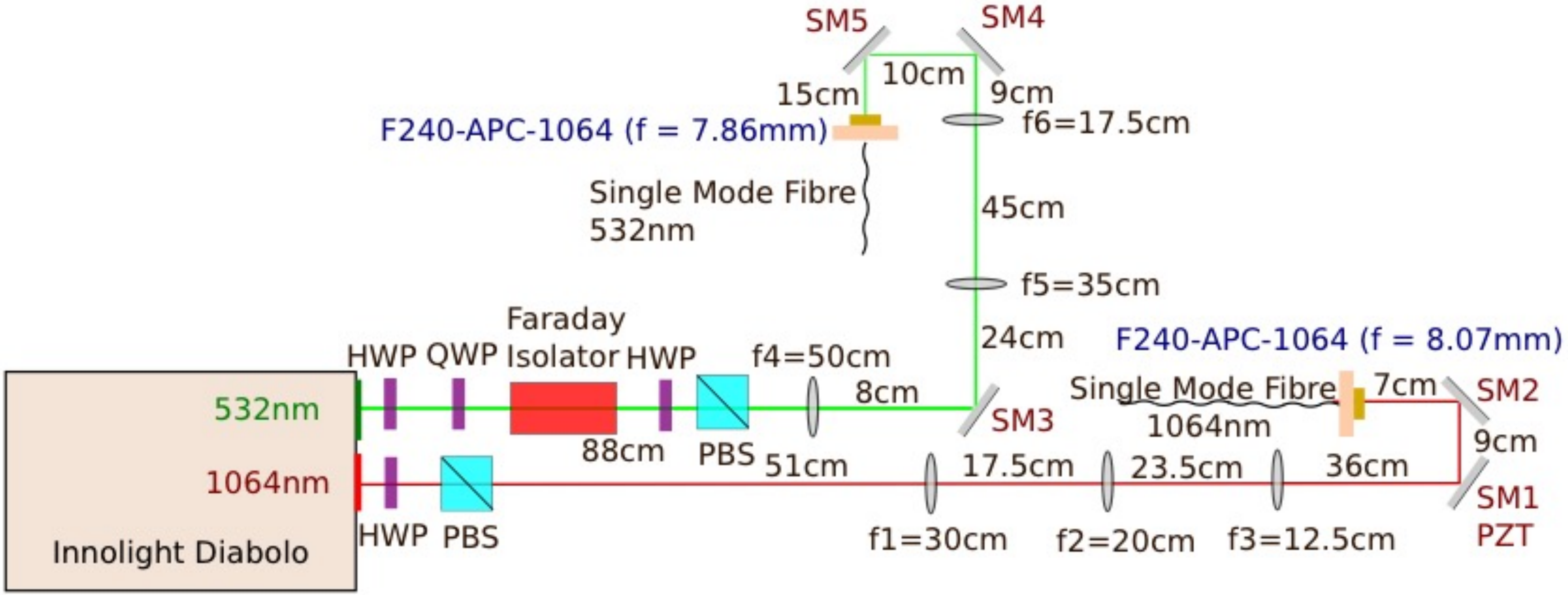
- Biology - Laser based particle tracking in conjunction with optical tweezers (increase sensitivity)

- Squeezers in space - LISA

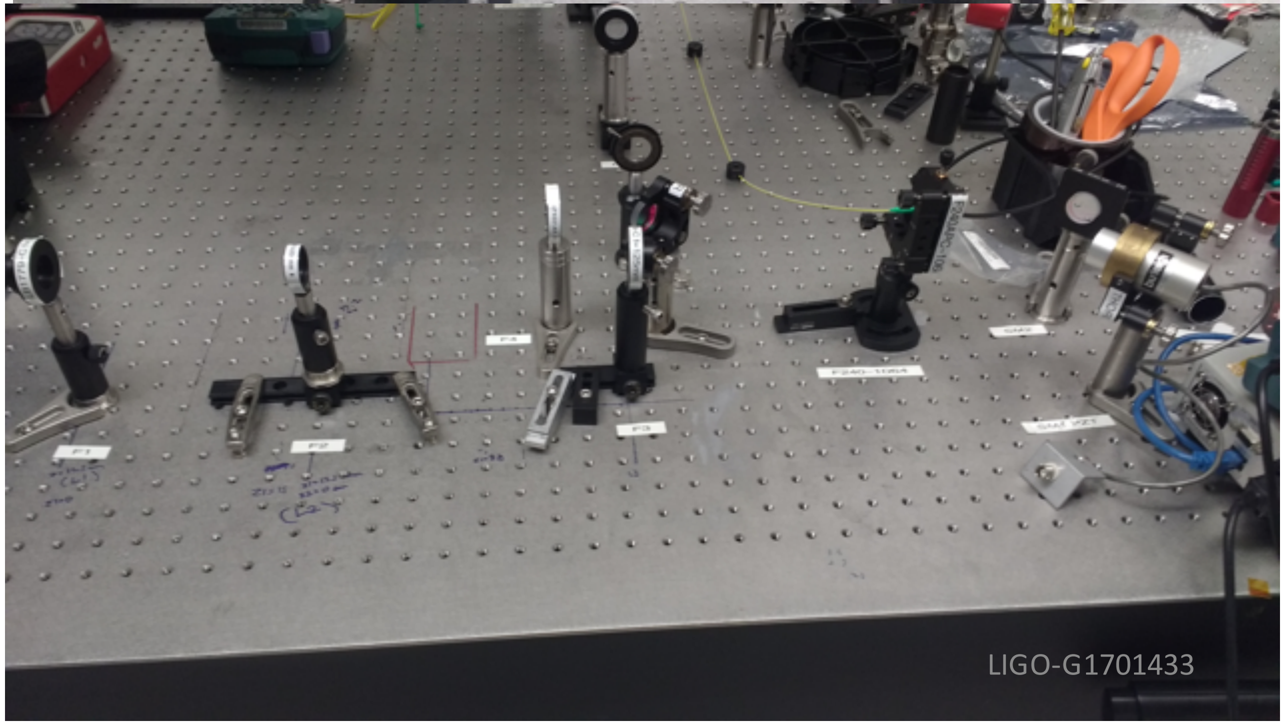


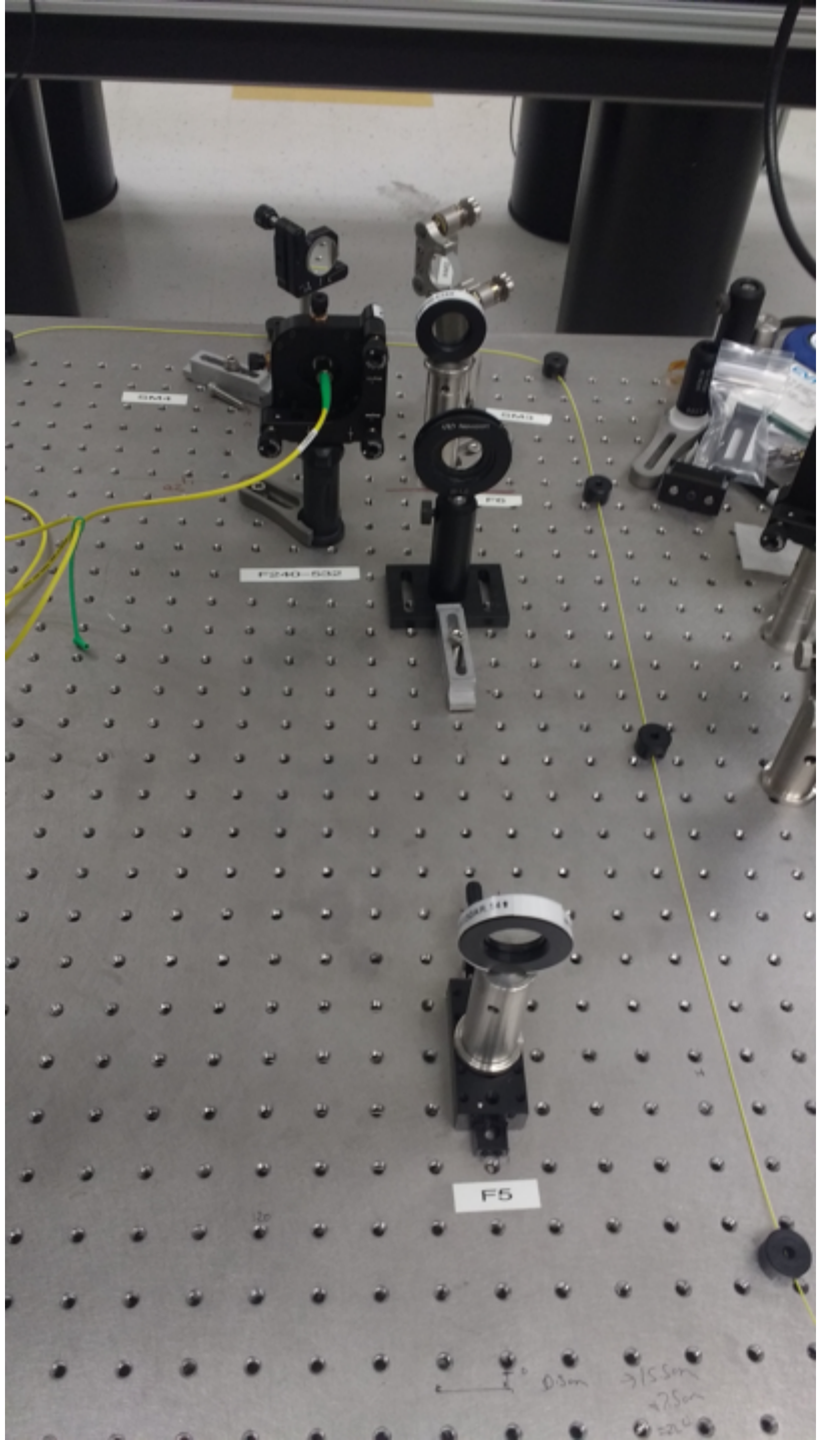
Biological measurement beyond the quantum limit – Taylor et al. DOI: 10.1038/NPHOTON.2012.346

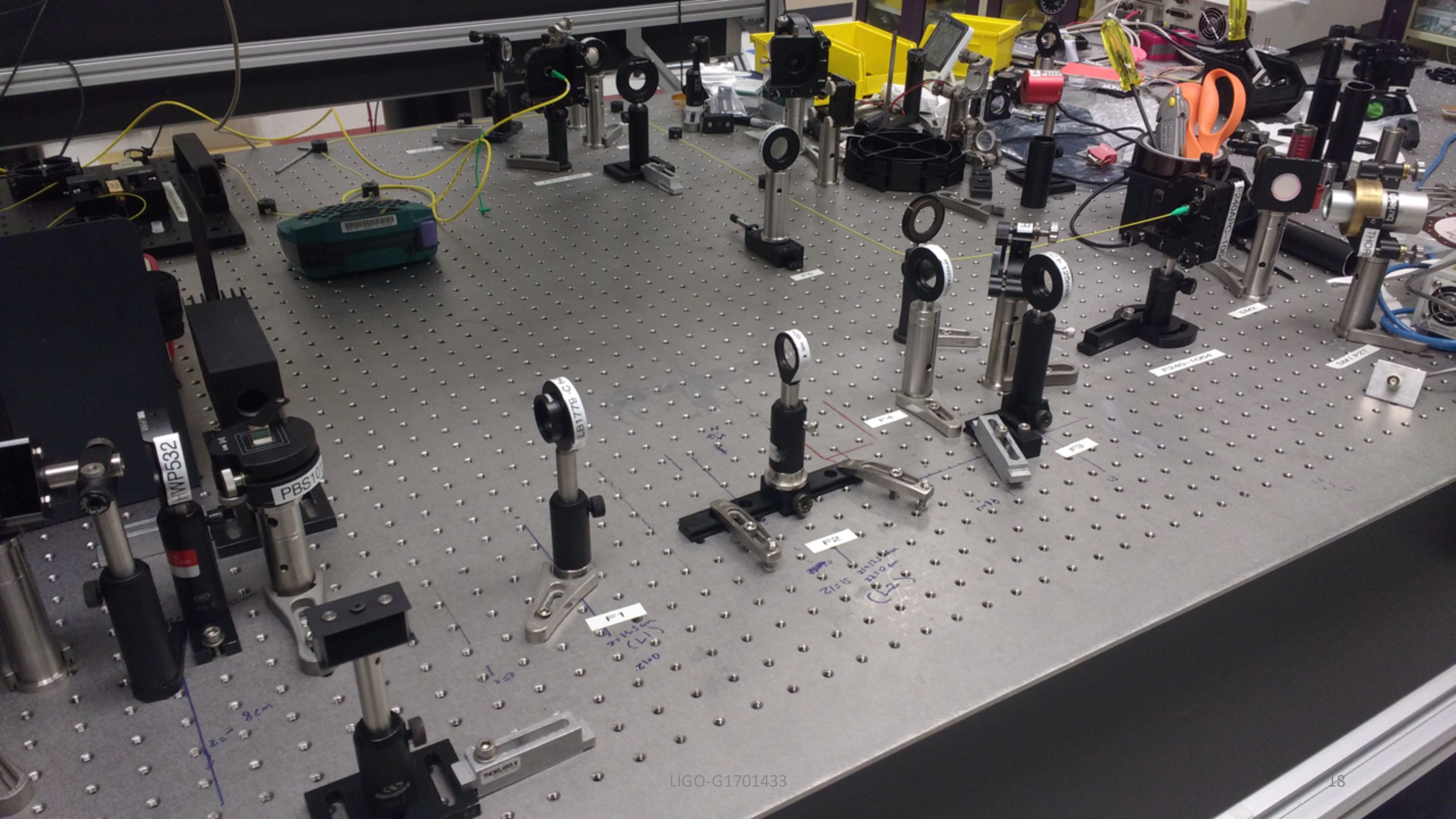
Mode Matching Into Fibers




HWP
PBS
WP532
F1



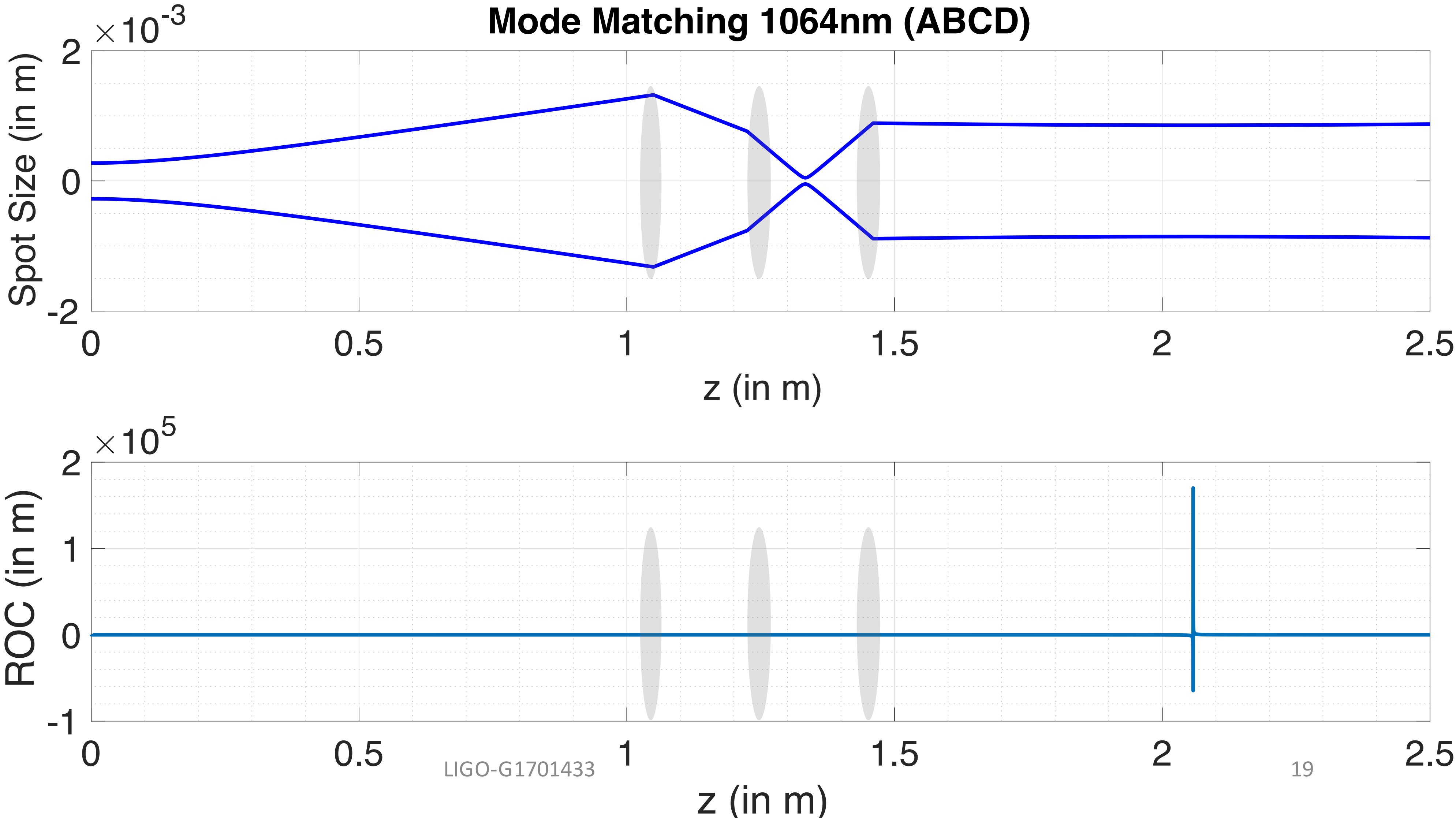

F5



HWP532
PBS101
LB1779-C
F1
F2
F3
F4

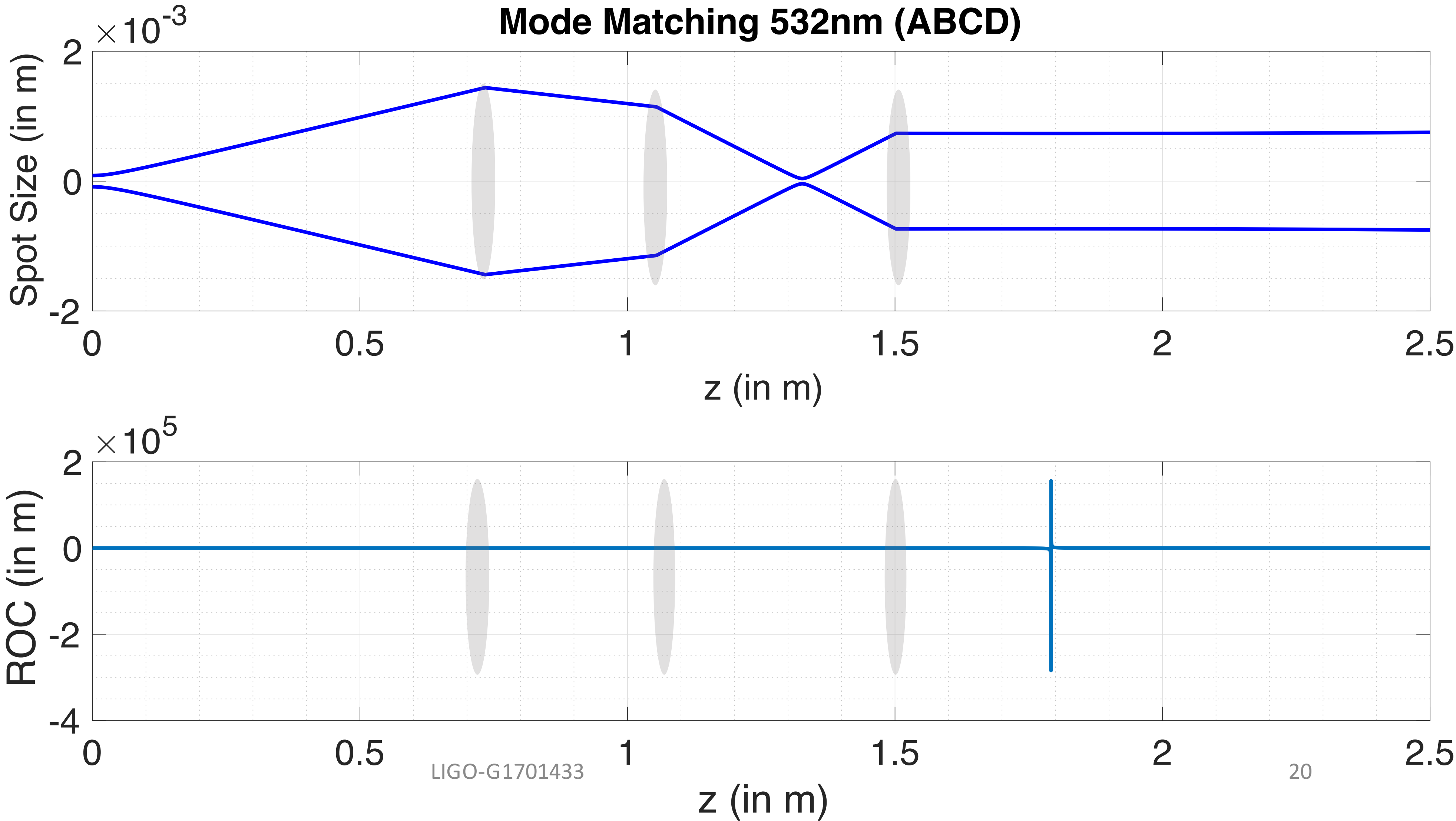
1064 nm Beam

77% efficiency achieved

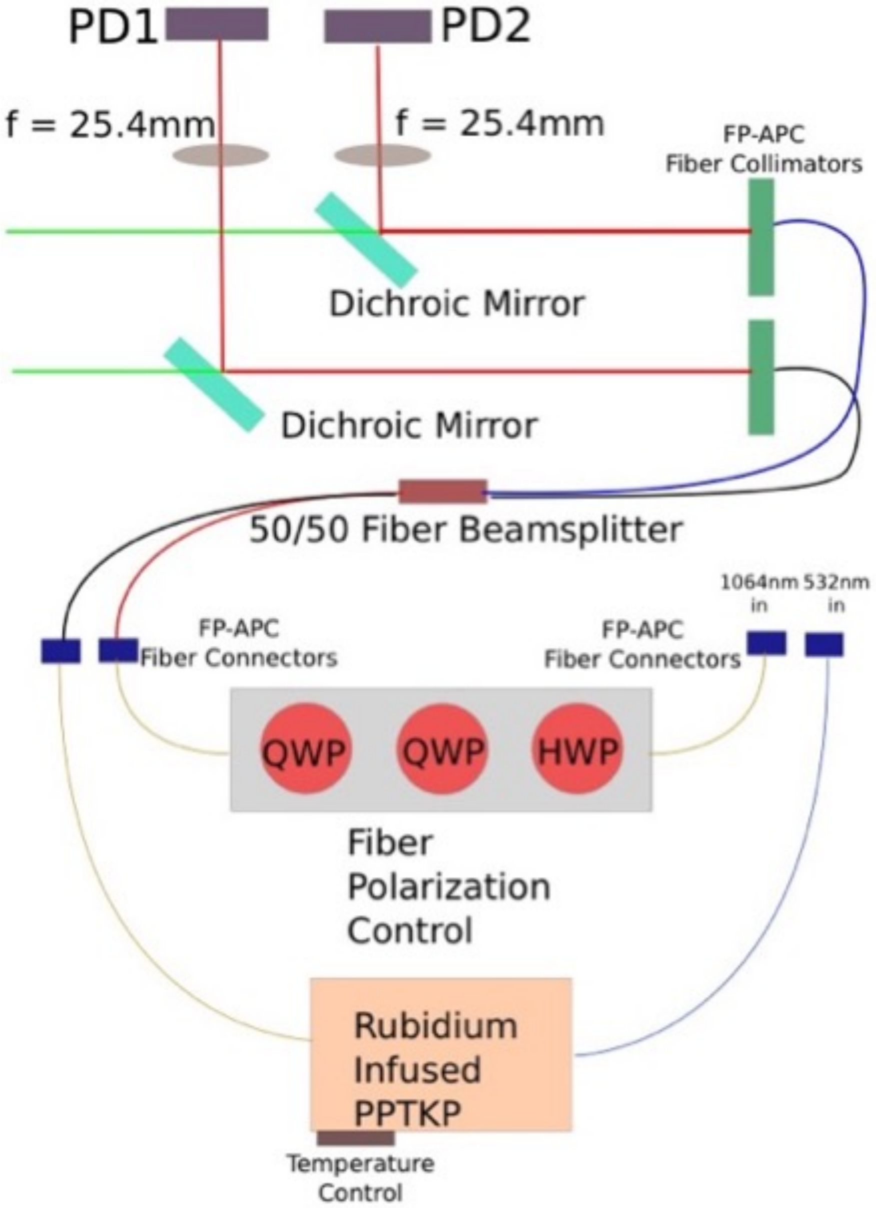


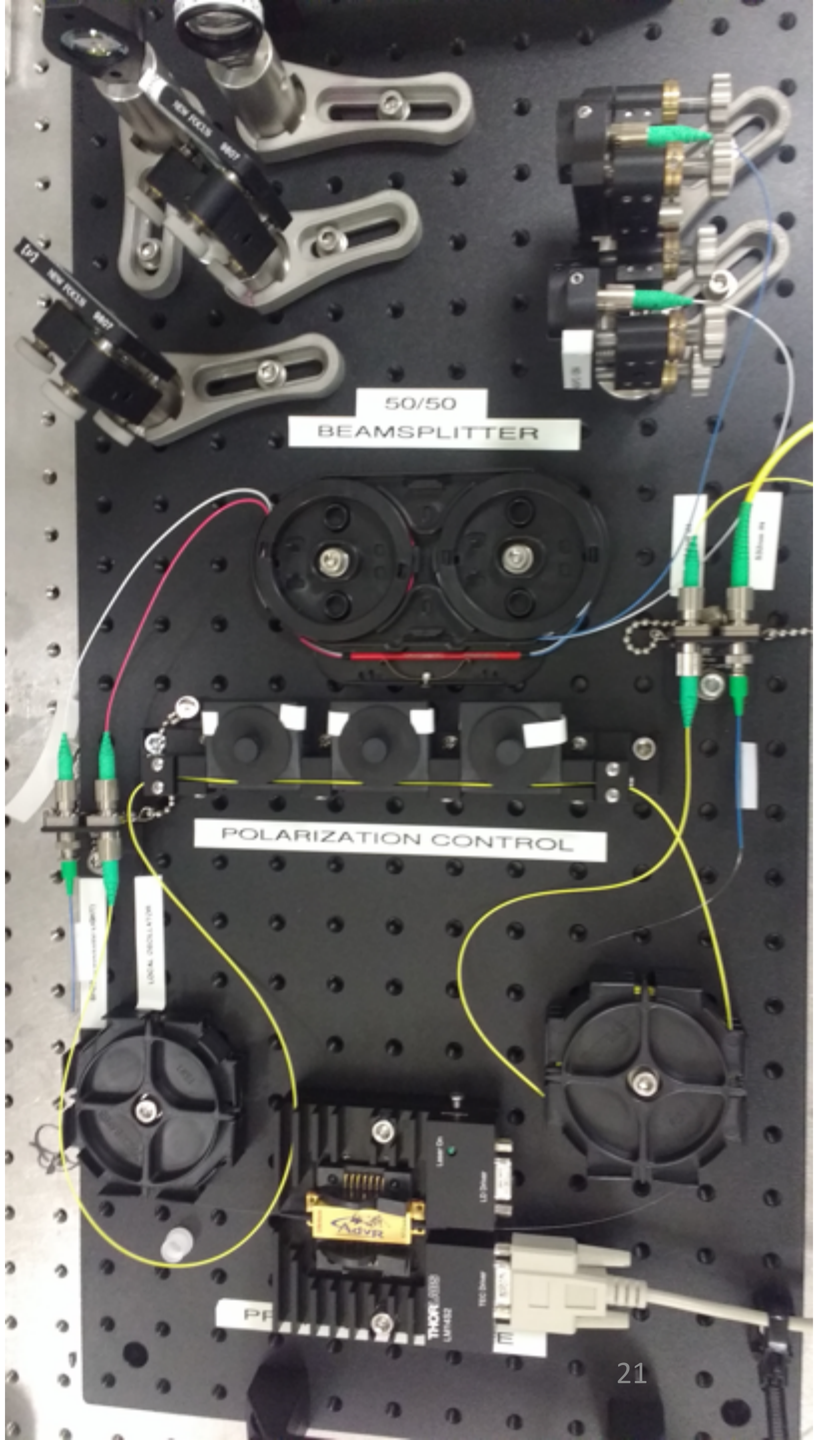
532 nm Beam

74% efficiency achieved



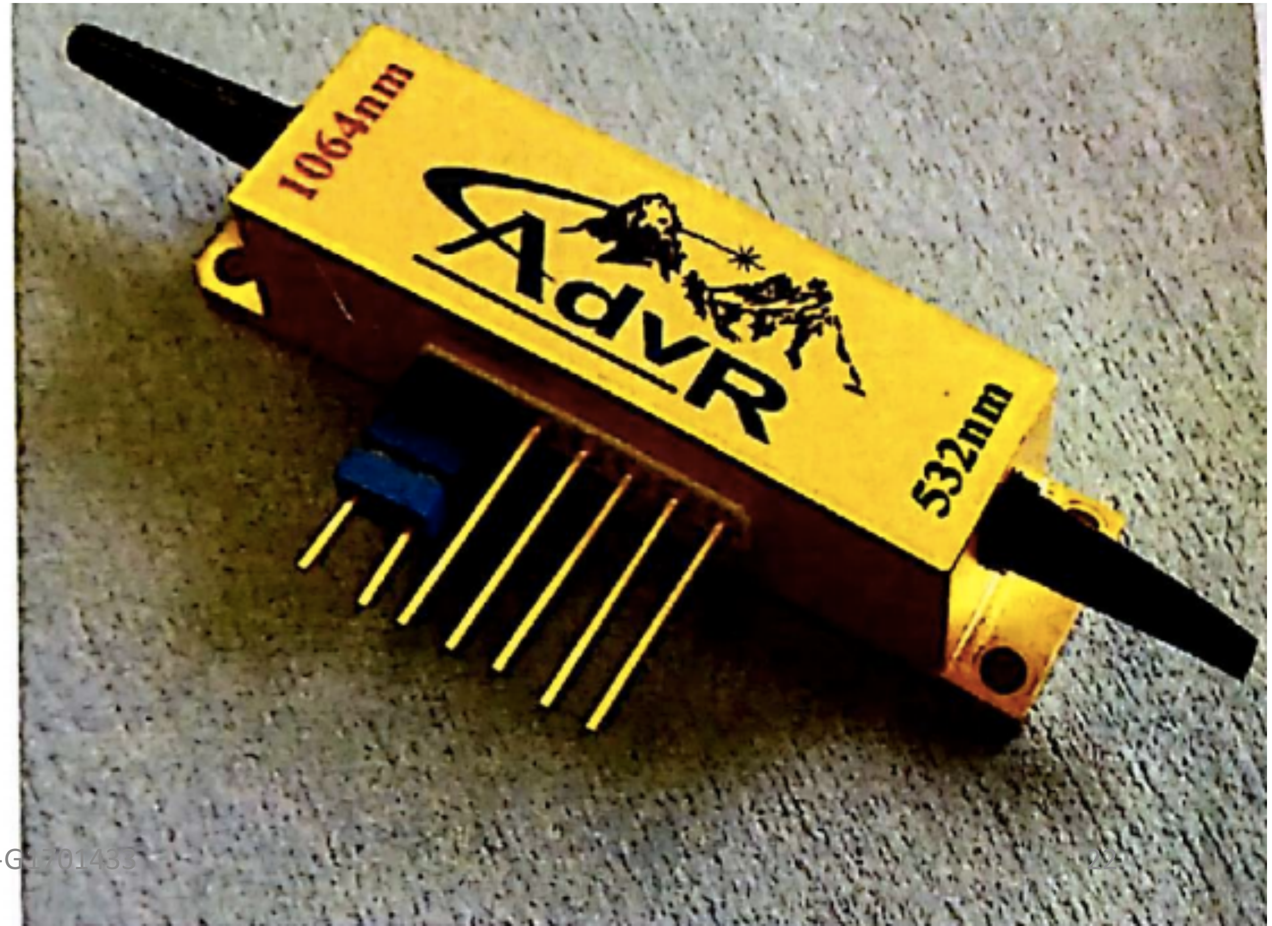
SPDC and Squeezing





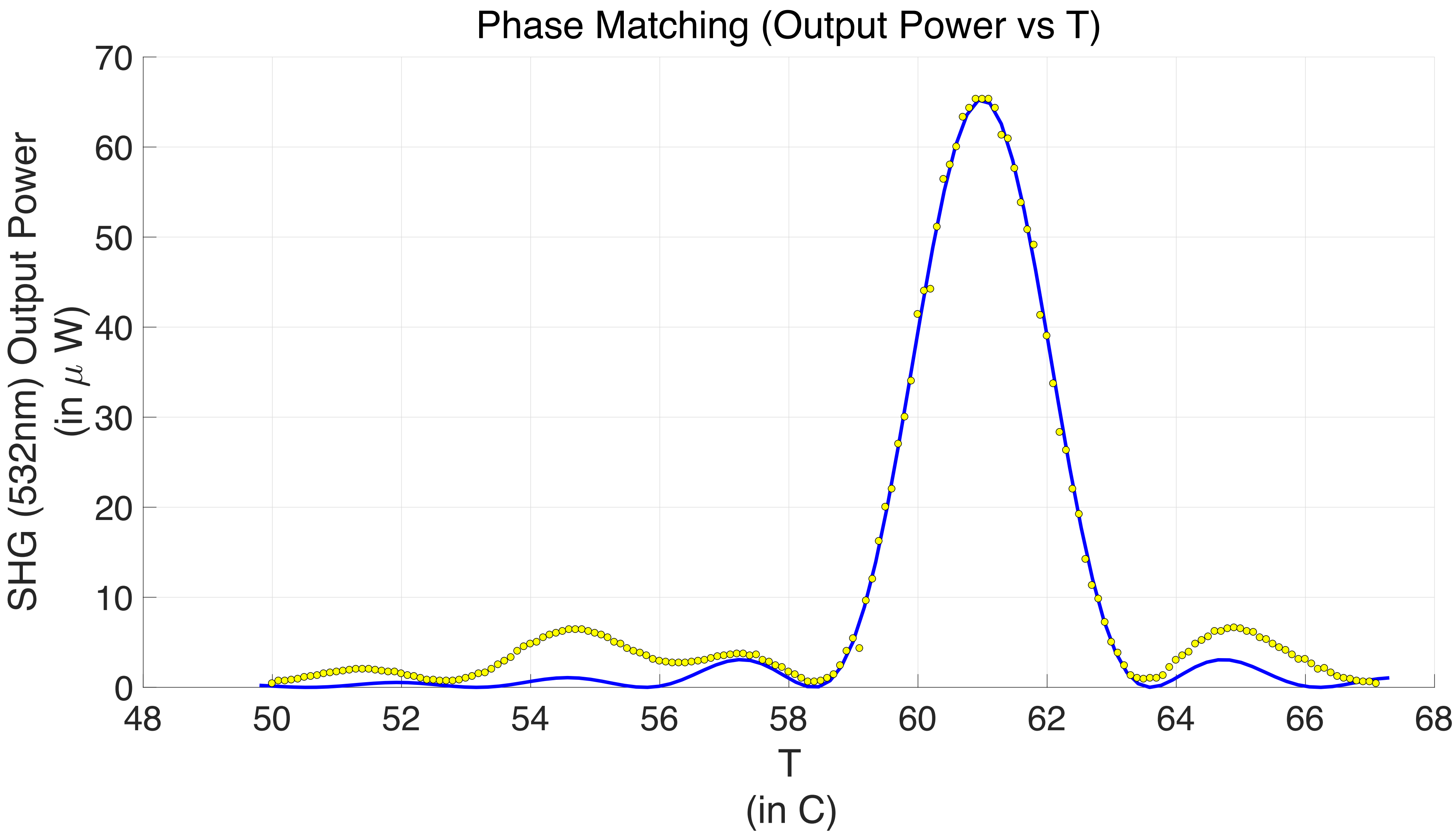
Non Linear Waveguide

Material	Rubidium Infused PPKTP
Fundamental Wavelength	1064nm
Harmonic Wavelength	532nm
Fibre Coupling Efficiency	50%
Conversion Efficiency	1.353% (at 19.3mW)
Phase Matching Temperature	60.99°C

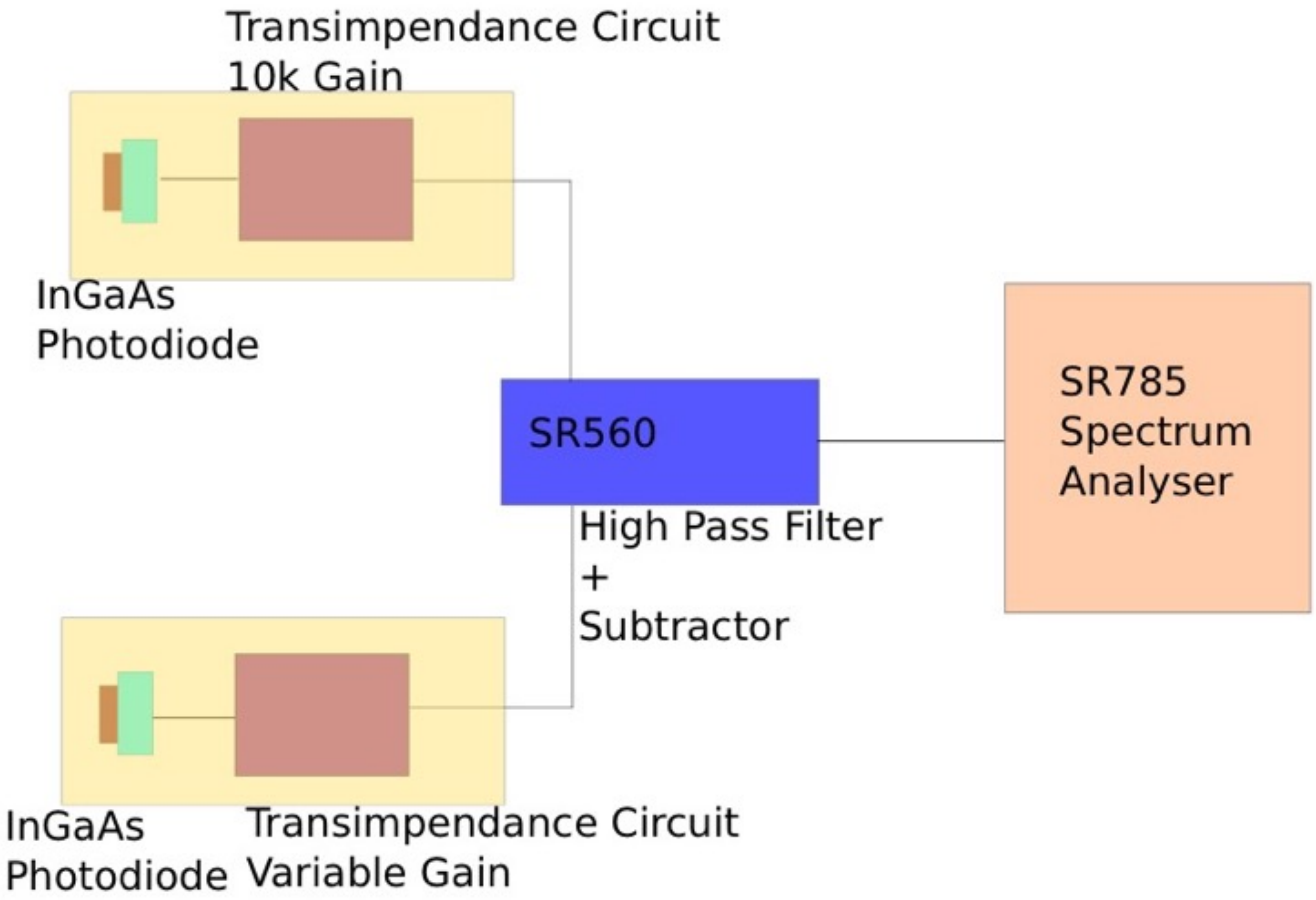


Phase Matching (Input Power 19.3mW)

Phase Matching Temperature 60.99°C



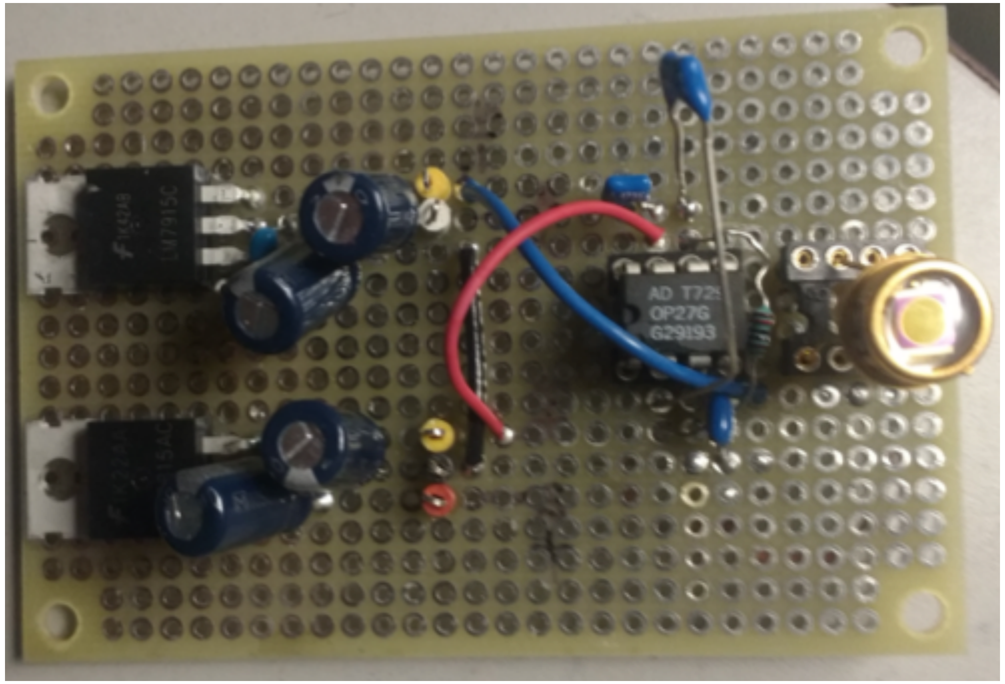
Homodyne Detection

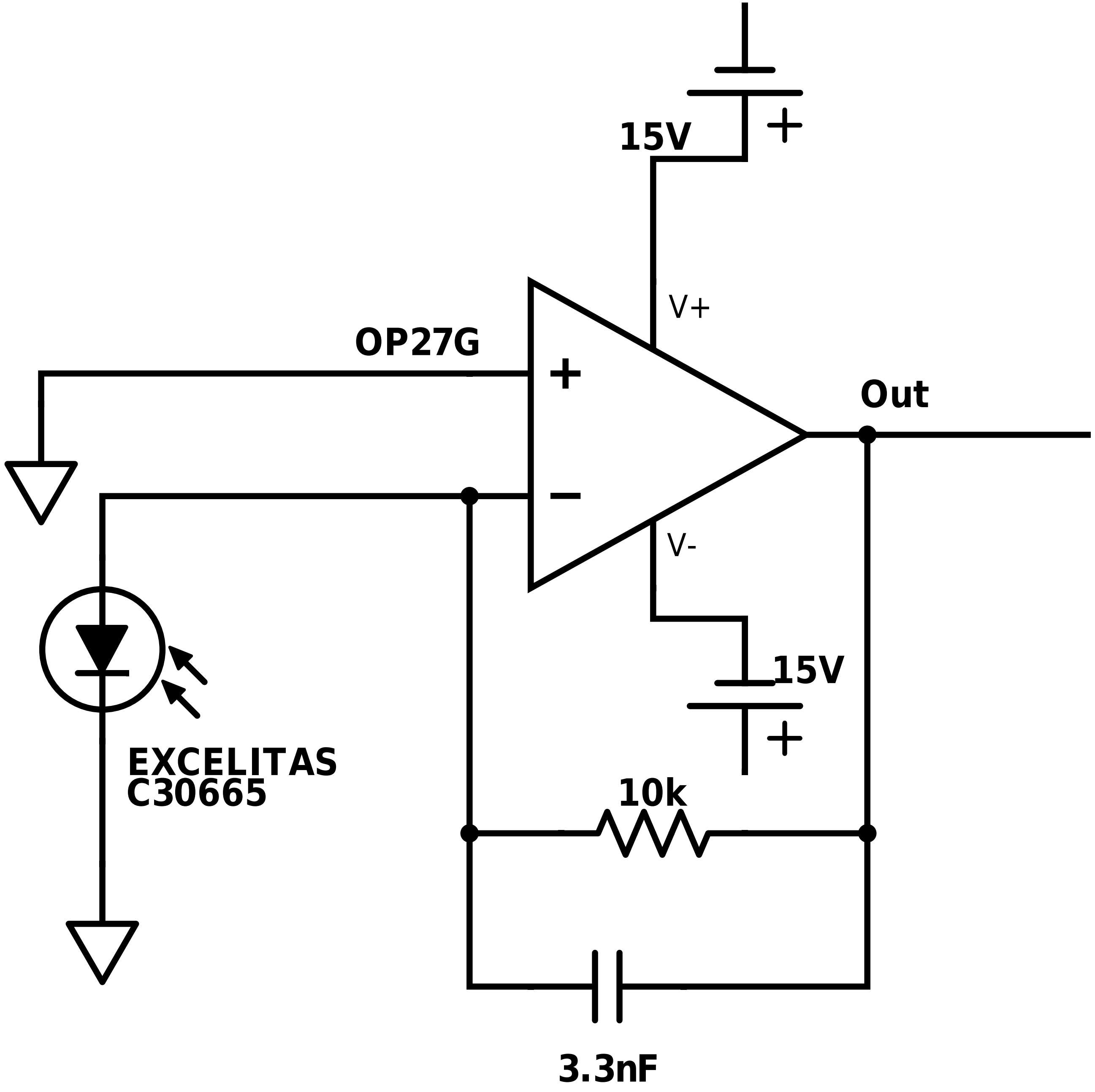


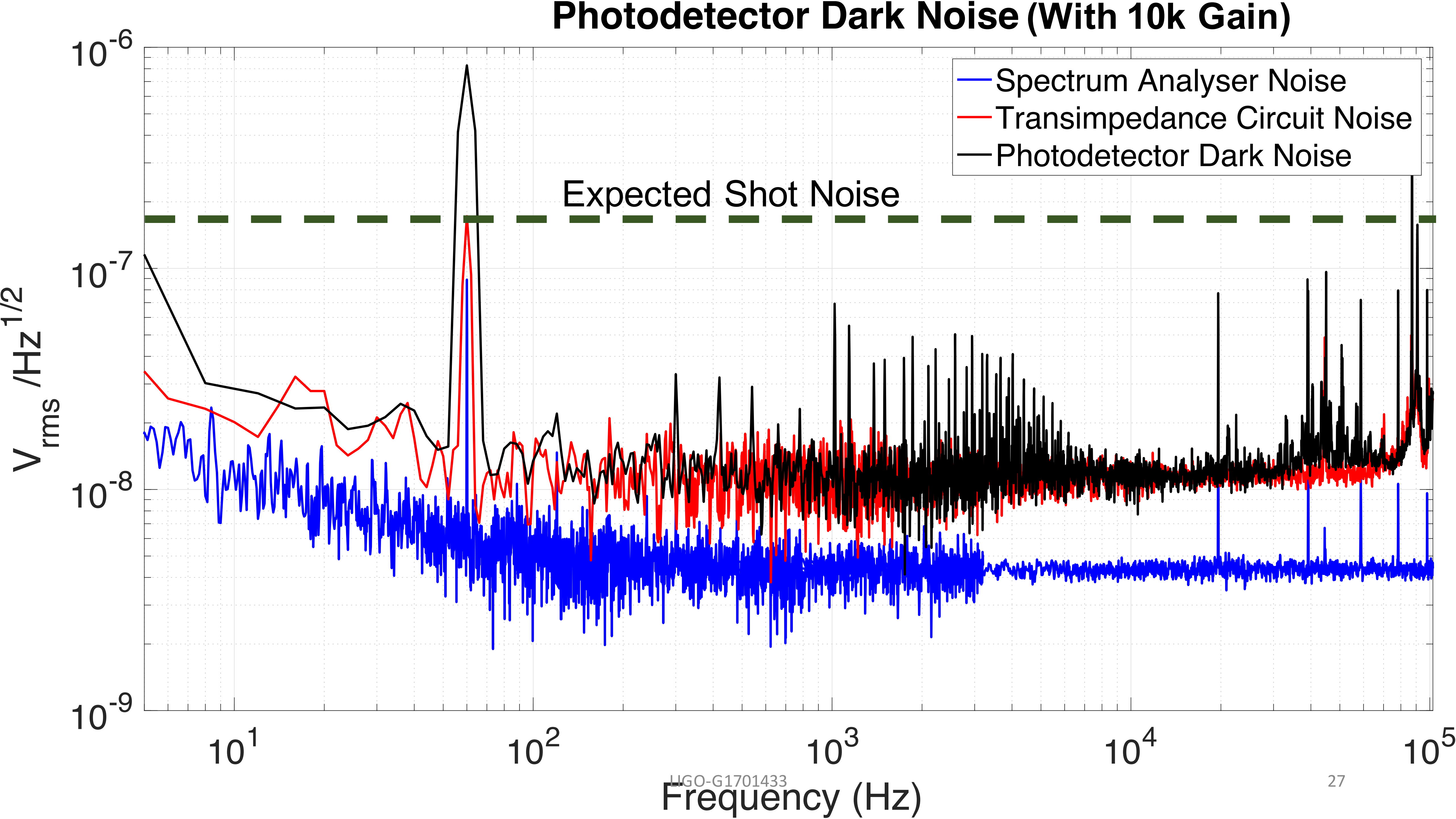
InGaAs Photodiode (Excelitas C30665)

- 87% Quantum Efficiency
- 3mm active diameter
- 1000—1250pF capacitance while unbiased. 400pF capacitance when biased at 2V.

Photodiode Amplifier Trans-impedance Circuit 1

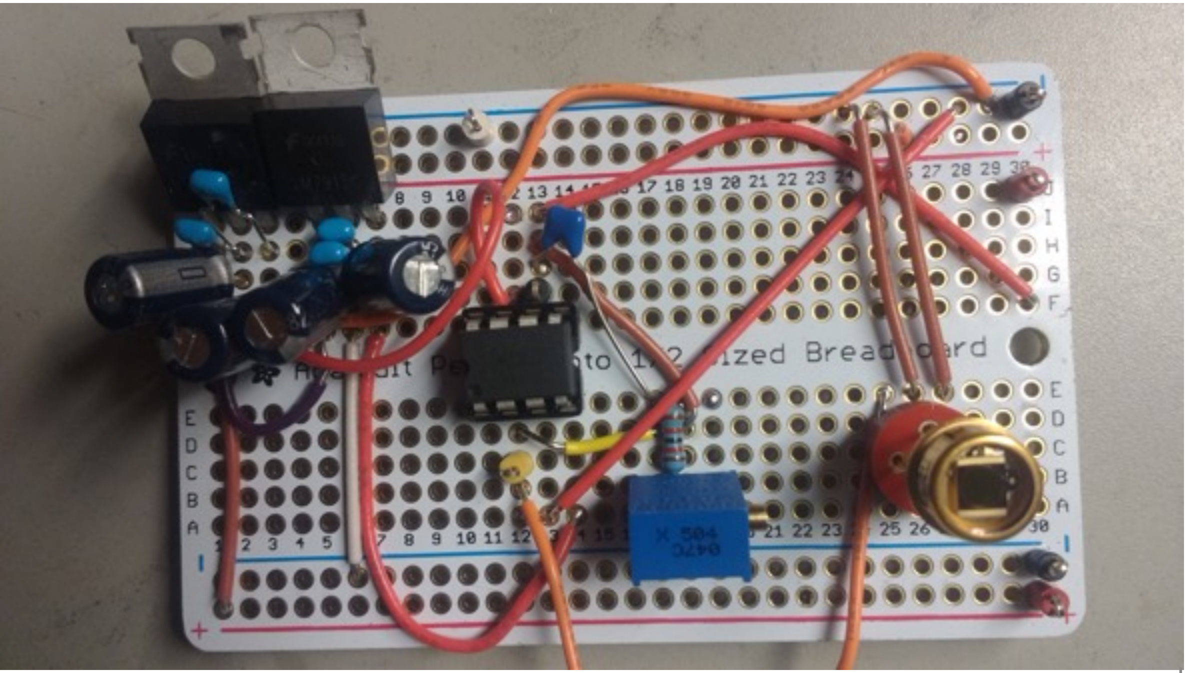


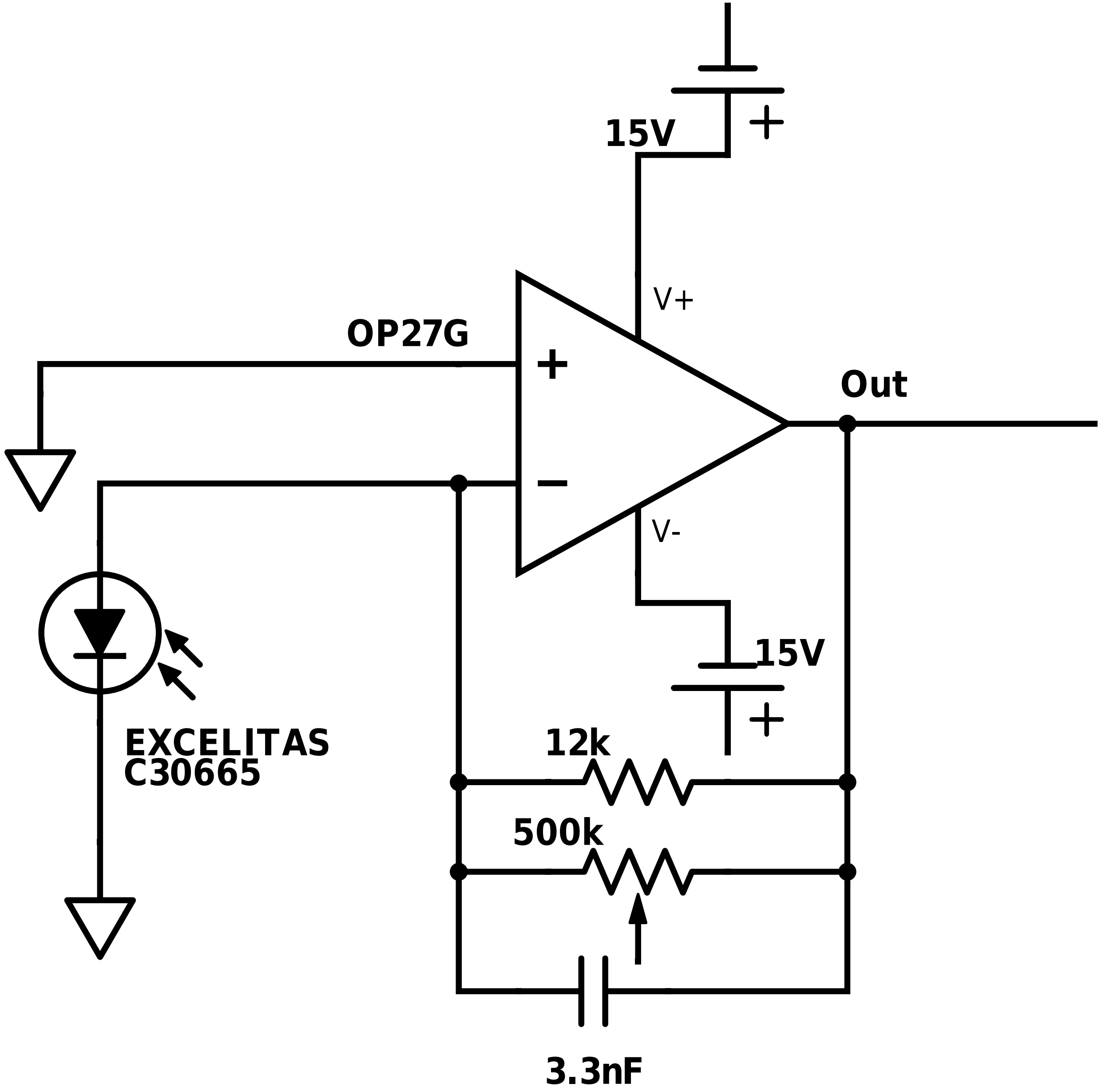




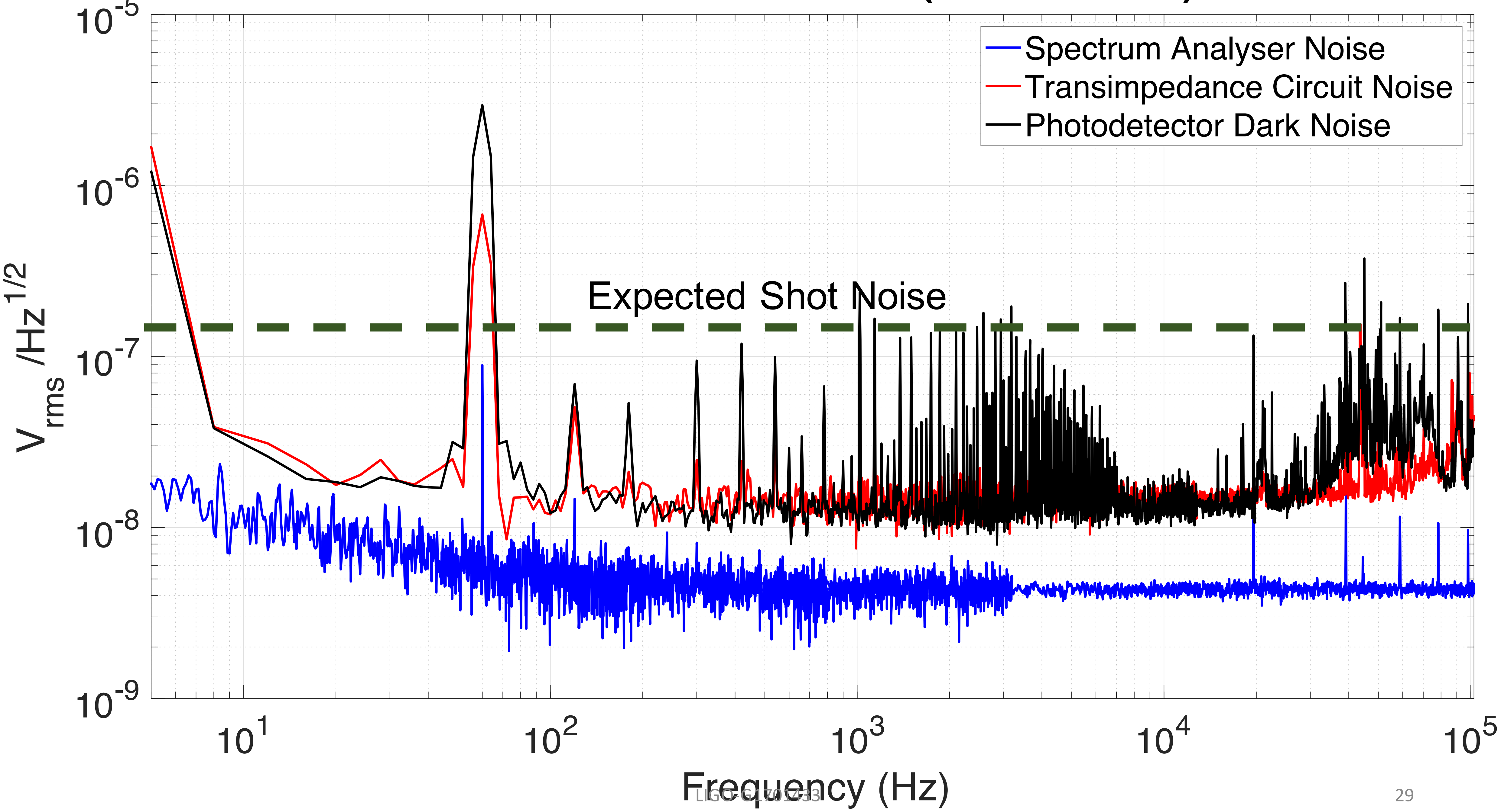
Photodetector Dark Noise (With 10k Gain)
Spectrum Analyser Noise
Transimpedance Circuit Noise
Photodetector Dark Noise
Expected Shot Noise
$V_{rms}/Hz^{1/2}$
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
Frequency (Hz)

Photodiode Amplifier Trans-impedance Circuit 2



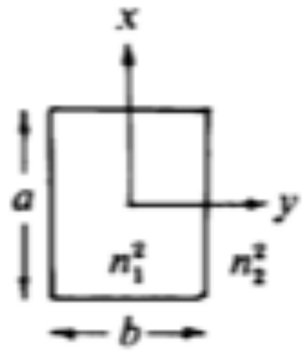


Photodetector Dark Noise (Variable Gain)



Major Squeezing Loss– Waveguide Mode

Waveguide is square. Mode not Gaussian
(3dB loss in coupling)



$$\psi = \begin{cases} A\cos\mu_1\xi\cos\mu_2\eta & \text{if}|\xi|\le 1, |\eta|\le 1 \\ \dfrac{A\cos\mu_2}{\exp[-(V_2^2-\mu_2^2)]^{\frac{1}{2}}}\cos\mu_1\xi\exp[-(V_2^2-\mu_2^2)\eta]^{\frac{1}{2}} & \text{if } |\xi|\ge 1, |\eta|\le 1 \\ \dfrac{A\cos\mu_1}{\exp[-(V_1^2-\mu_1^2)]^{\frac{1}{2}}}\cos\mu_2\eta\exp[-(V_1^2-\mu_1^2)\xi]^{\frac{1}{2}} & \text{if } |\xi|\le 1, |\eta|\ge 1 \\ \dfrac{\exp[-(V_2^2-\mu_2^2)\eta]^{\frac{1}{2}}\exp[-(V_1^2-\mu_1^2)\xi]^{\frac{1}{2}}}{\exp[-(V_1^2-\mu_1^2)]^{\frac{1}{2}}\exp[-(V_2^2-\mu_2^2)]^{\frac{1}{2}}} & \text{if } |\xi|\ge 1, |\eta|\ge 1 \end{cases}$$

where

$$\xi = (2x/a), \quad \eta = (2y/b), \quad V_1 = k_o\frac{a}{2}(n_1^2-n_2^2)^{\frac{1}{2}}, \quad V_2 = k_o\frac{b}{2}(n_1^2-n_2^2)^{\frac{1}{2}}$$

$$\mu_1 = \frac{a}{2}(k_o^2 n_1^2-\beta^2)^{\frac{1}{2}}, \quad \mu_2 = \frac{b}{2}(k_o^2 n_1^2-\beta^2)^{\frac{1}{2}}$$

Major Squeezing Loss– Waveguide Mode

Waveguide is square. Mode not Gaussian
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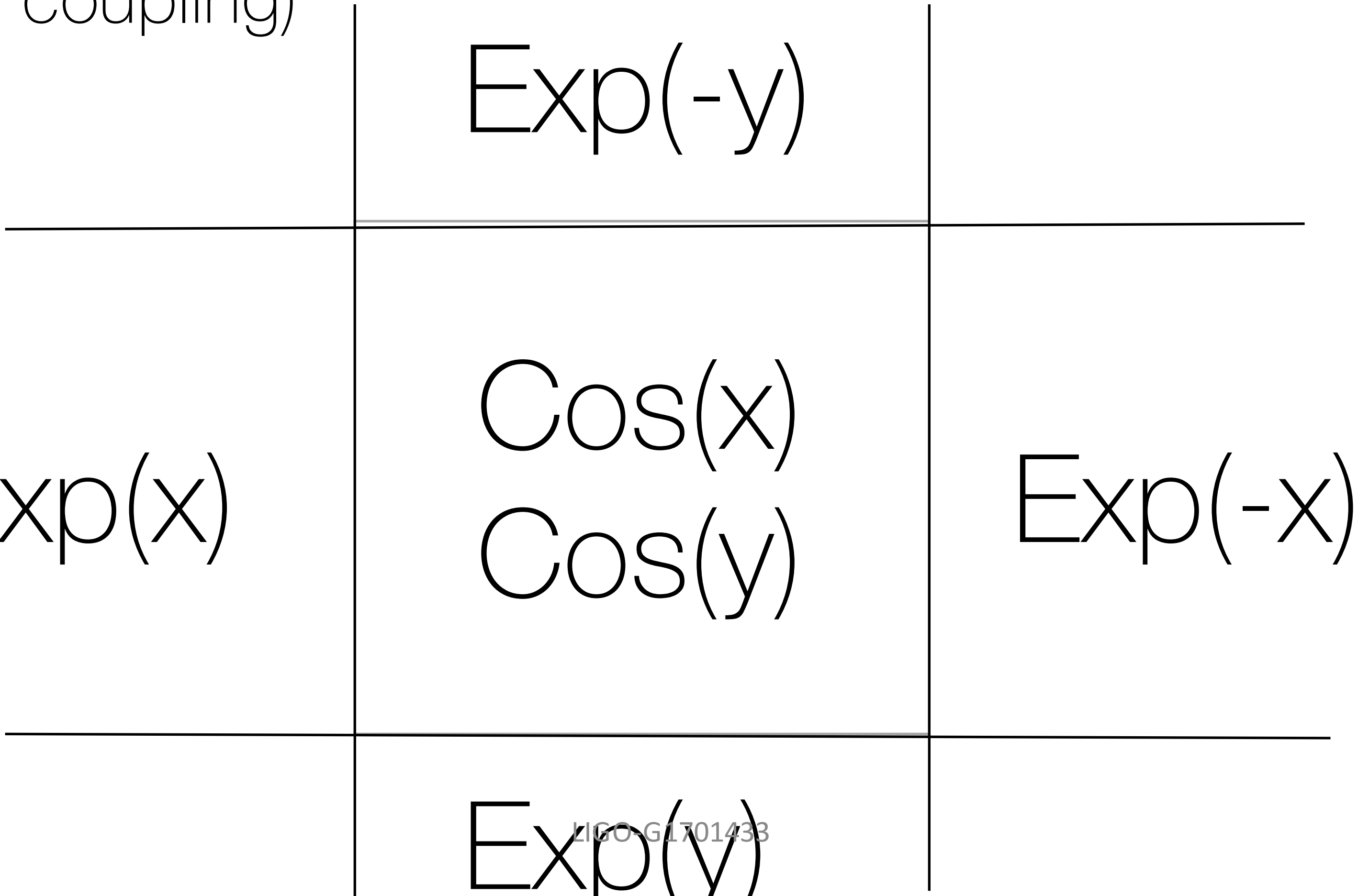
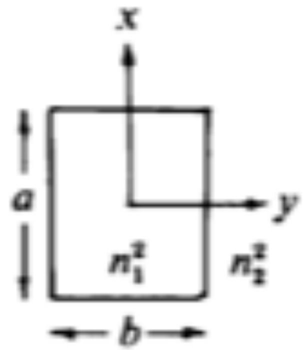
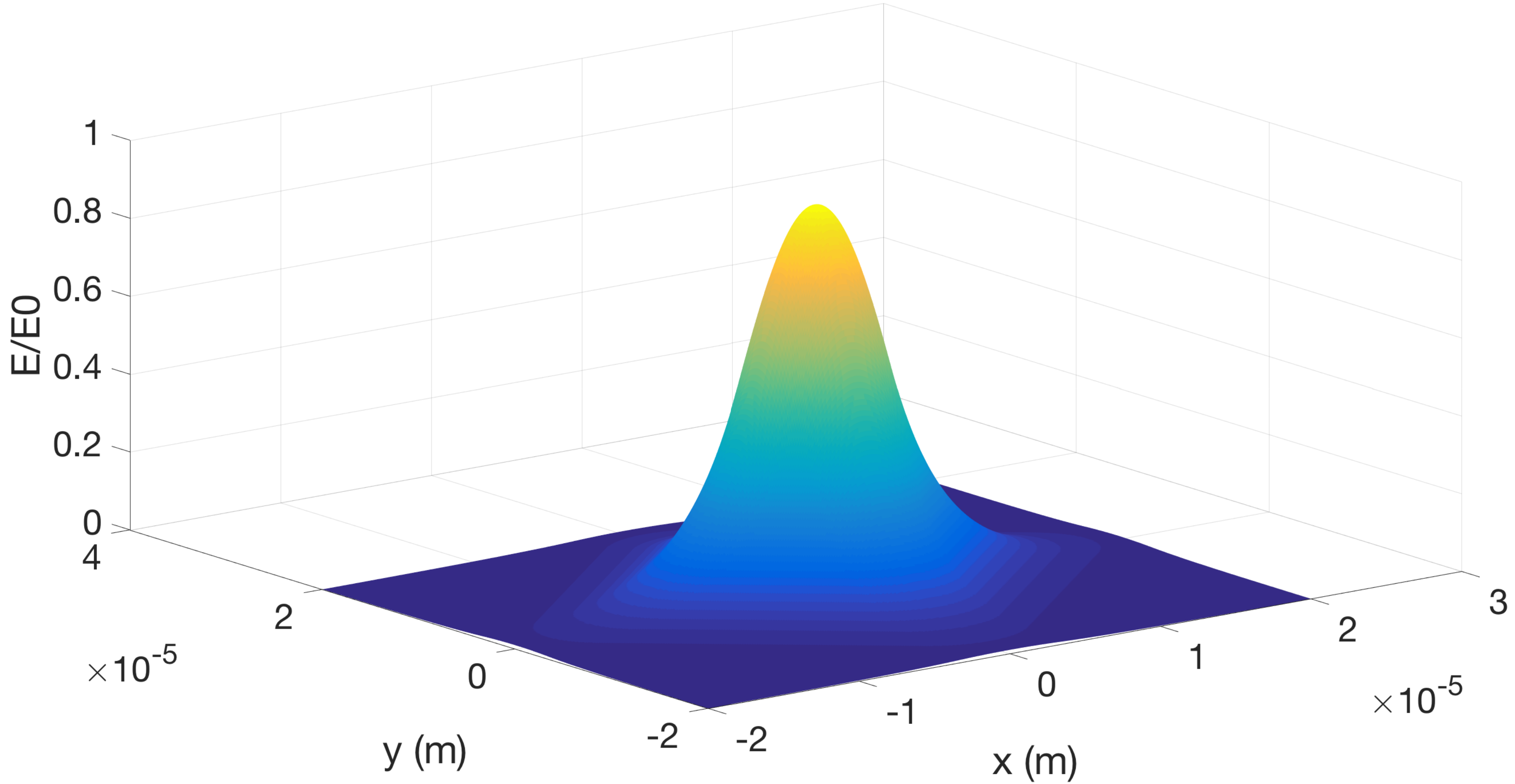




Waveguide Mode Shape

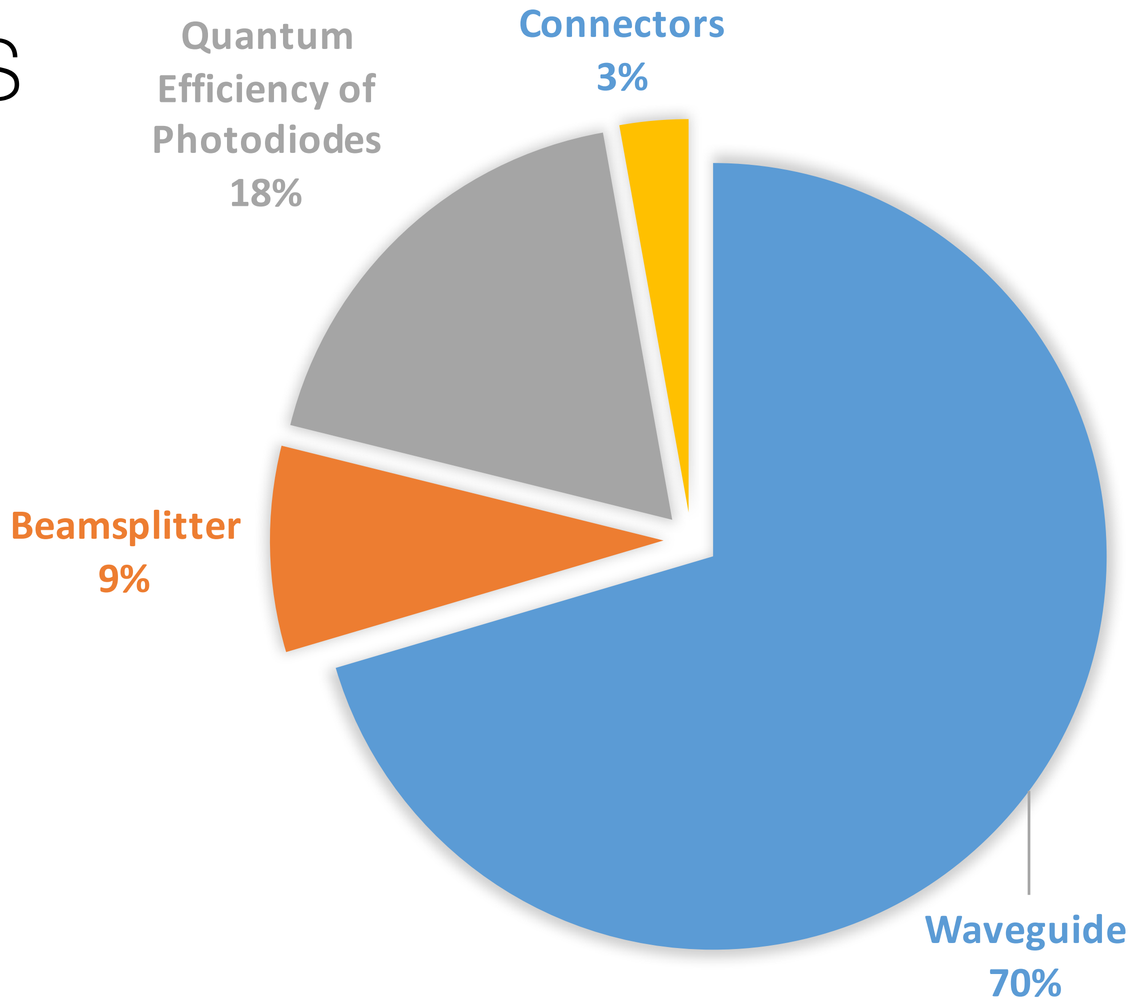


Mitigation

- Use a series of objectives after propagating this mode in free space
- Optimization using FFT Propagation Code.
- Custom Waveguide Design

List of Squeezing Losses

Component	Loss
Waveguide	~50%
Quantum Efficiency of Photodiode	~13%
Beam Splitter (3% Error)	~6%
FP-APC Connector Loss	~2%



Maximum Squeezing – 2.2dB

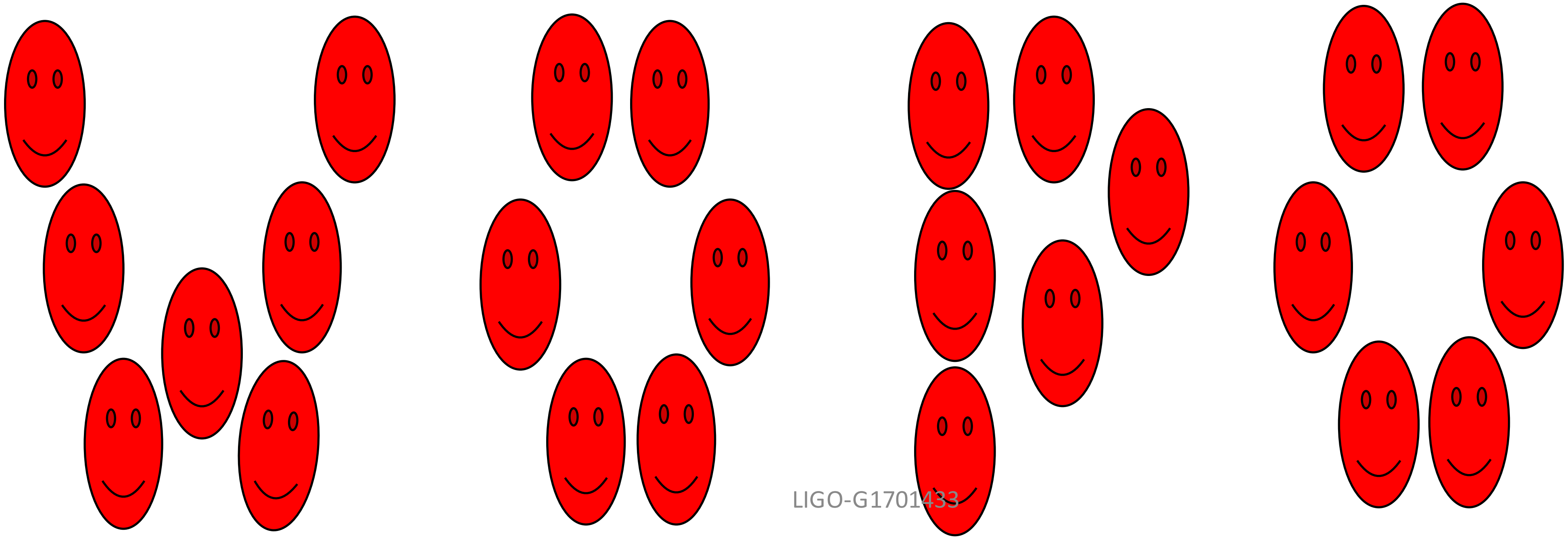
3dB Input – 1dB Output

Further Work

- Measure shot noise of 1064nm beam.
- Measure squeezing.
- Reduce squeezing loss at waveguide.

Thank You

Questions??



Supplementary – ABCD Propagation

- A Gaussian beam at a point can be characterised by the following quantity.

$$q = z + iz_r \qquad \frac{1}{q} = \frac{1}{R(z)} - \frac{i\lambda}{\pi w^2(z)}$$

$$q_2 = \frac{Aq_1 + B}{Cq_1 + D}$$

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} 1 & d \\ 0 & 1 \end{pmatrix}$$

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{pmatrix}$$

Supplementary – FFT Propagation

$$E(x,y,z) = \frac{i}{\Delta z \lambda} \iint E_0(x,y,z_0) K(x-u, y-v, \Delta z) du dv$$

$$\tilde{K}(p,q,\Delta z) = \exp\left(-i \frac{\Delta z (p^2+q^2)}{2k}\right)$$