Twin Michelson interferometer with Einstein–Podolsky–Rosen squeezing

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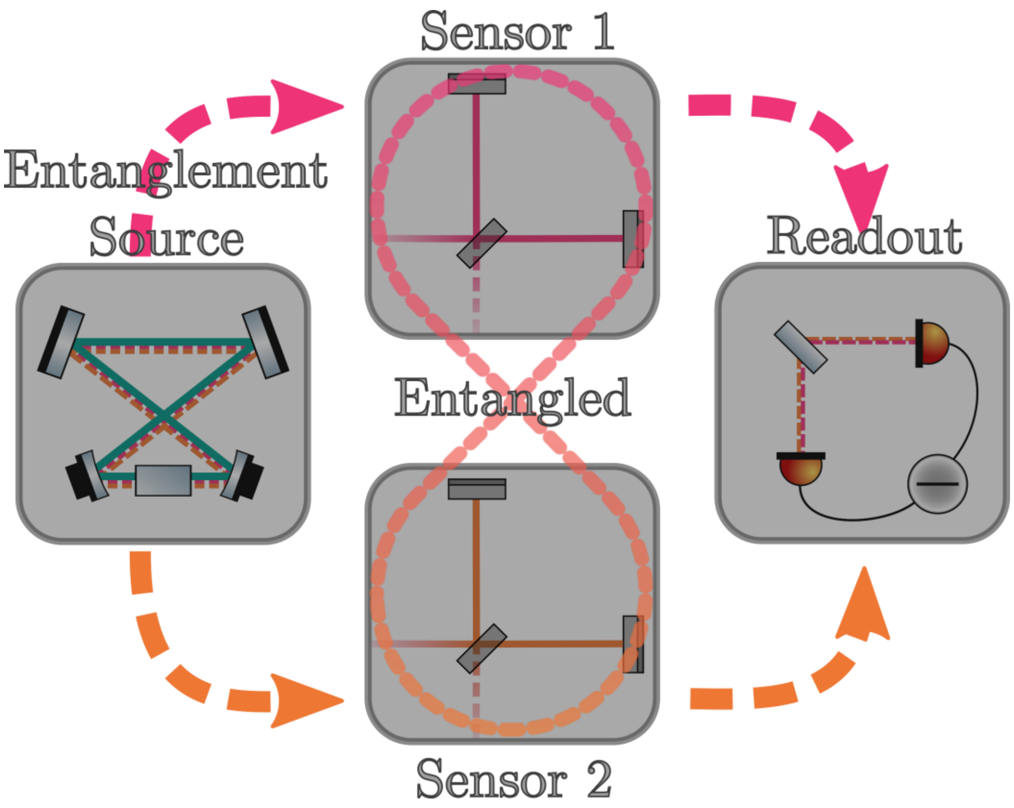
1. Australian National University.
2. KTH Royal Institute of Technology
3. Max Planck Institute for Gravitational Physics

Key Ideas:

- **Twin Sensors**
- **Correlated signals**
- **Entangled Noise**
- **Combined Heterodyne Readout**



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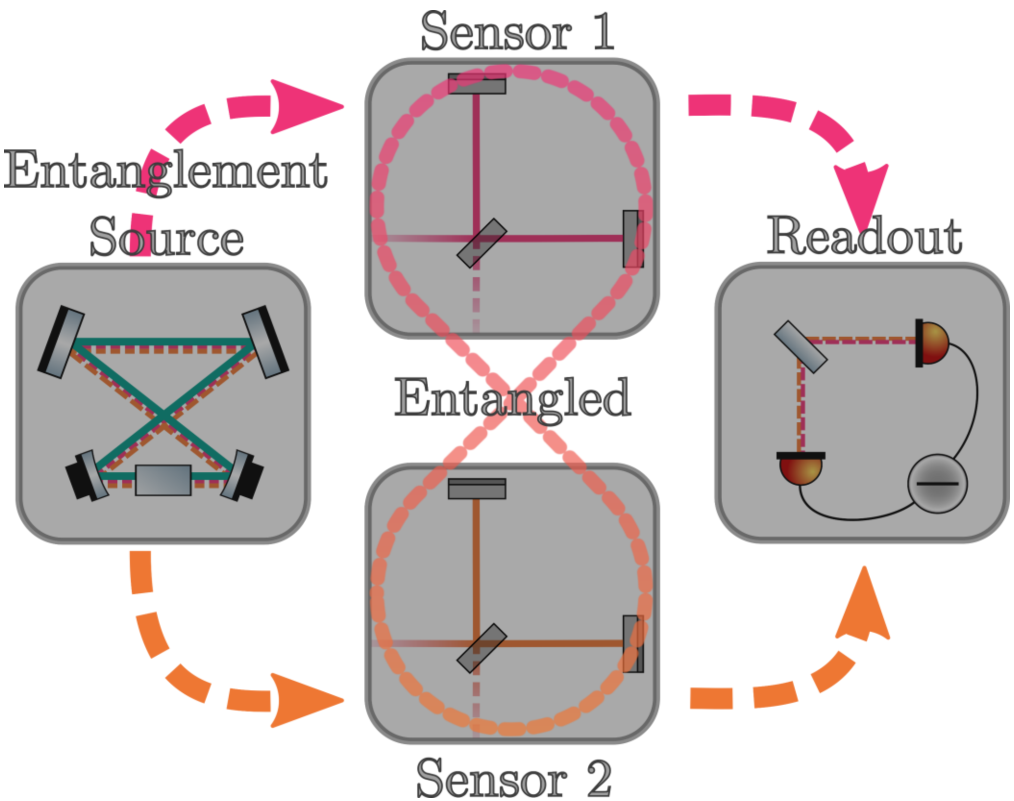
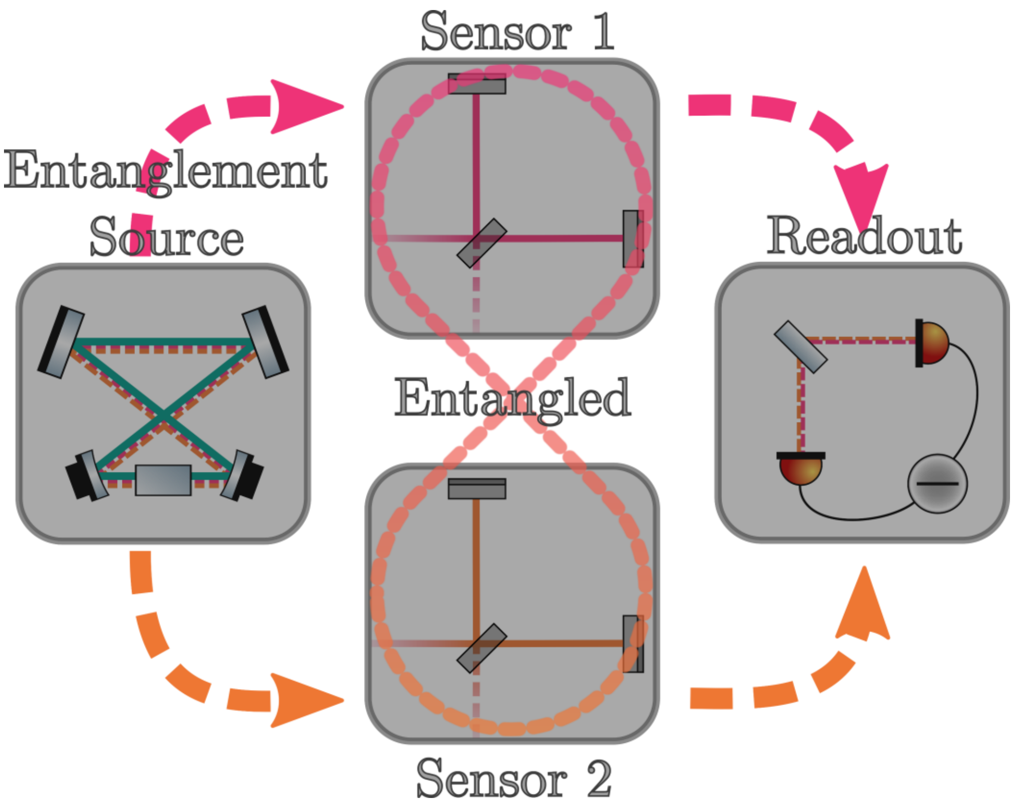
Challenges:

- **Optical losses**
- **Phase control**
- **Technical noises**
- **Signal calibration**

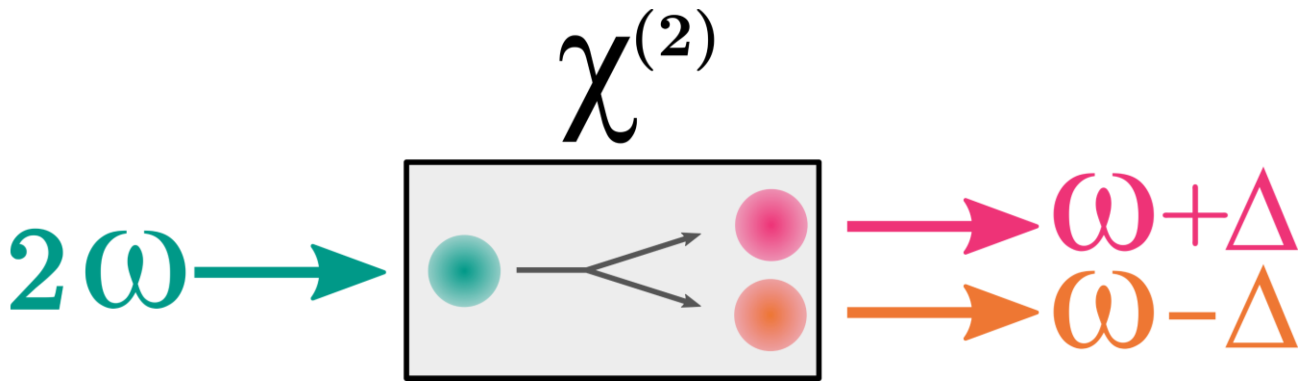


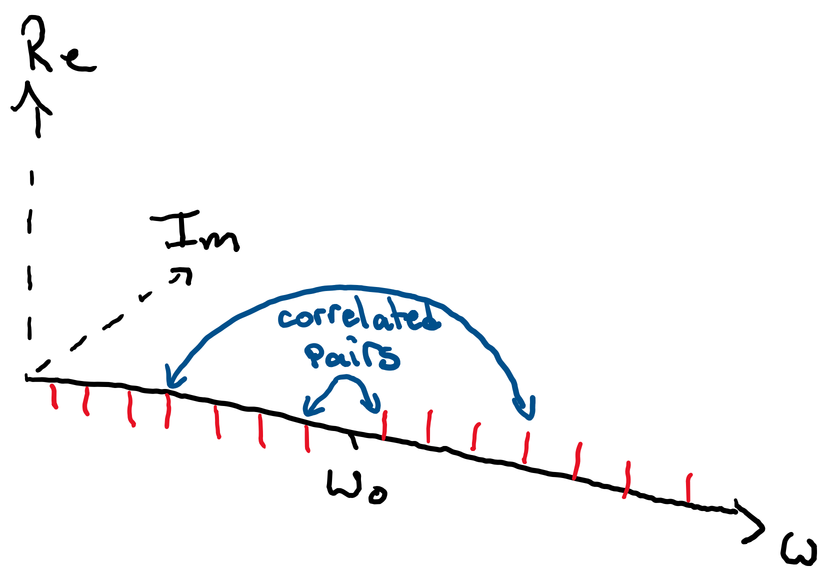
<u>Want to show :</u>

- **Audio band SNR improvement**
- **Coherent signal interactions**
- **Heterodyne Readout**



Squeezing


$\chi^{(2)}$
2ω
$\omega+\Delta$
$\omega-\Delta$


Re
Im
correlated pairs
ω_0
ω

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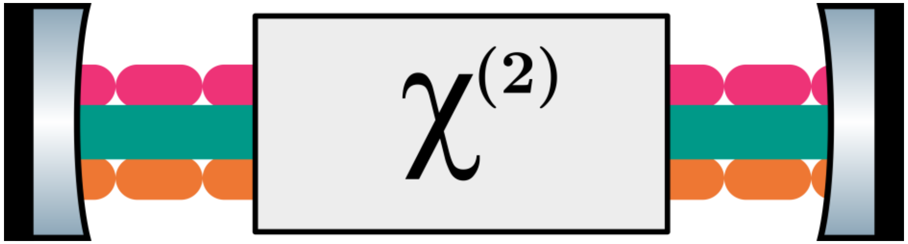
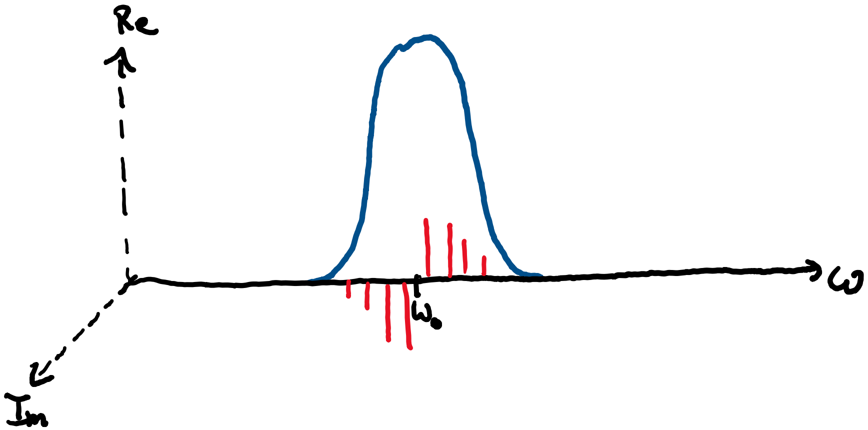
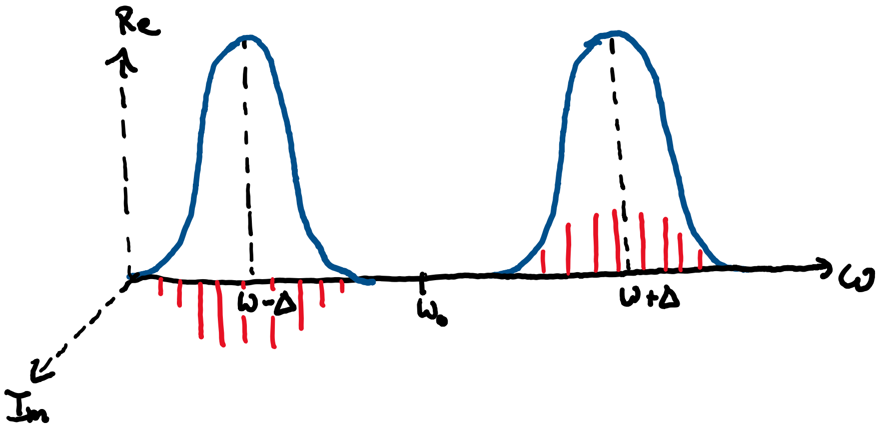
Squeezing



Degenerate Squeezed state



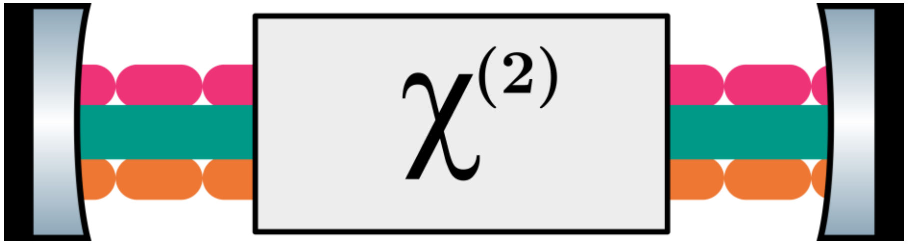
Non-Degenerate Squeezed State (EPR)



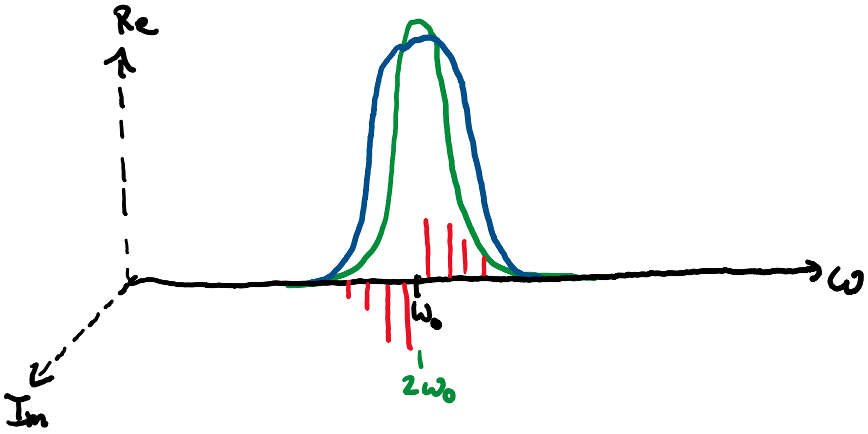
Squeezing

Details

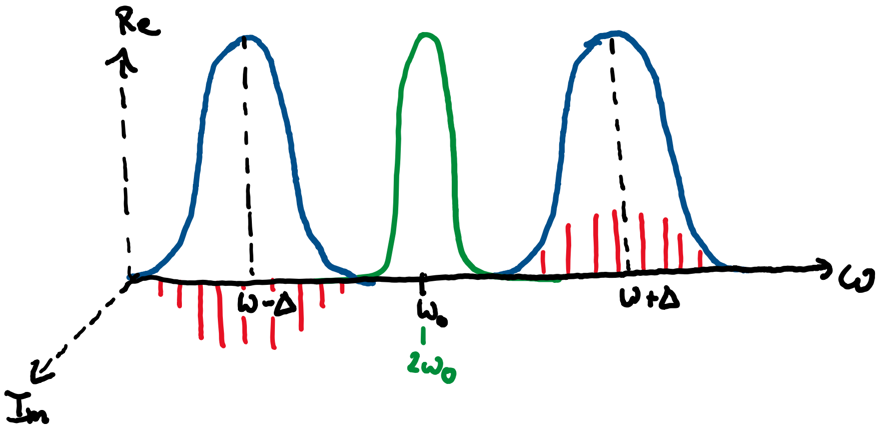
- Type 1
- Dual resonant bowtie cavity
- 1064 FSR of 850 MHz



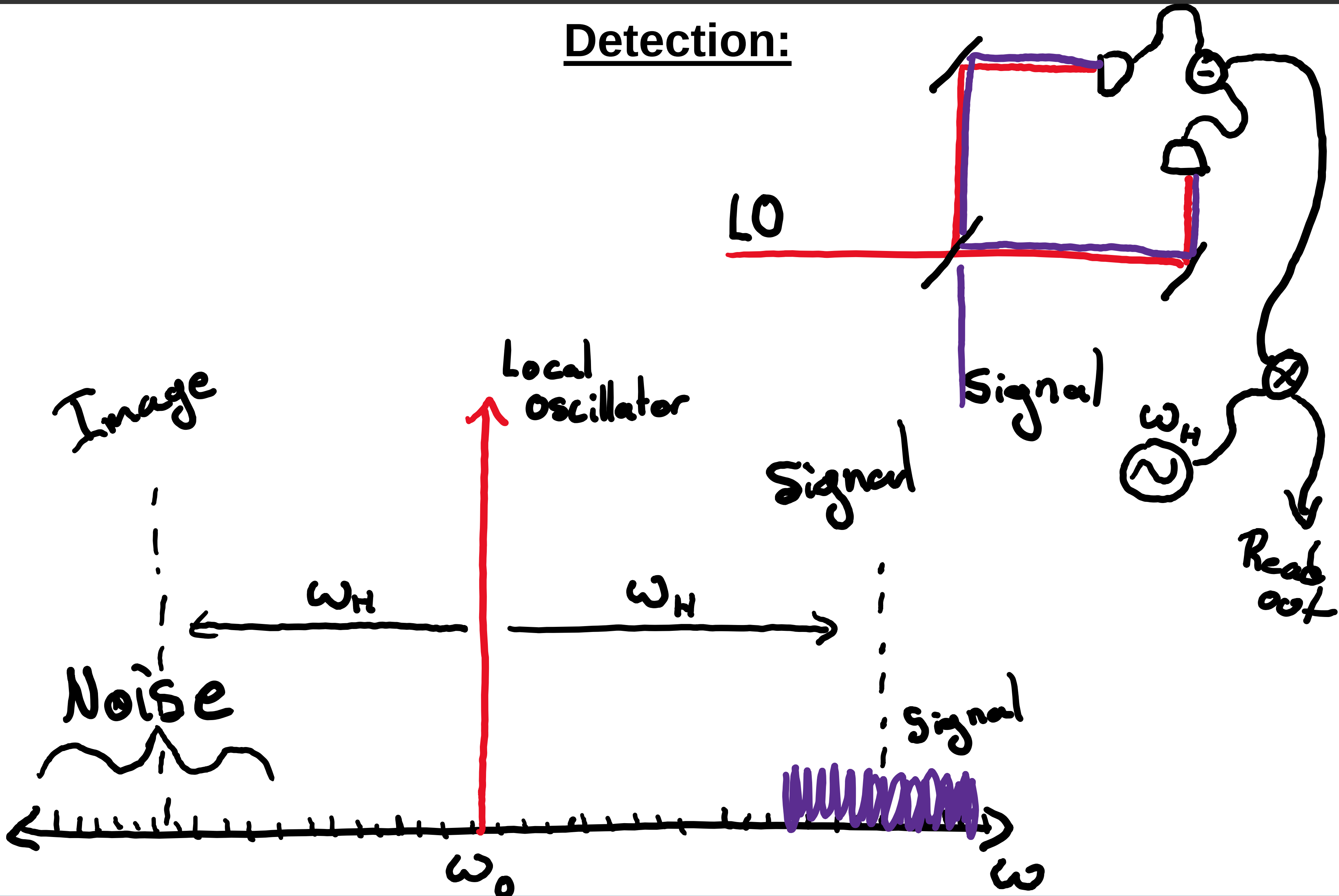
Degenerate Squeezed state



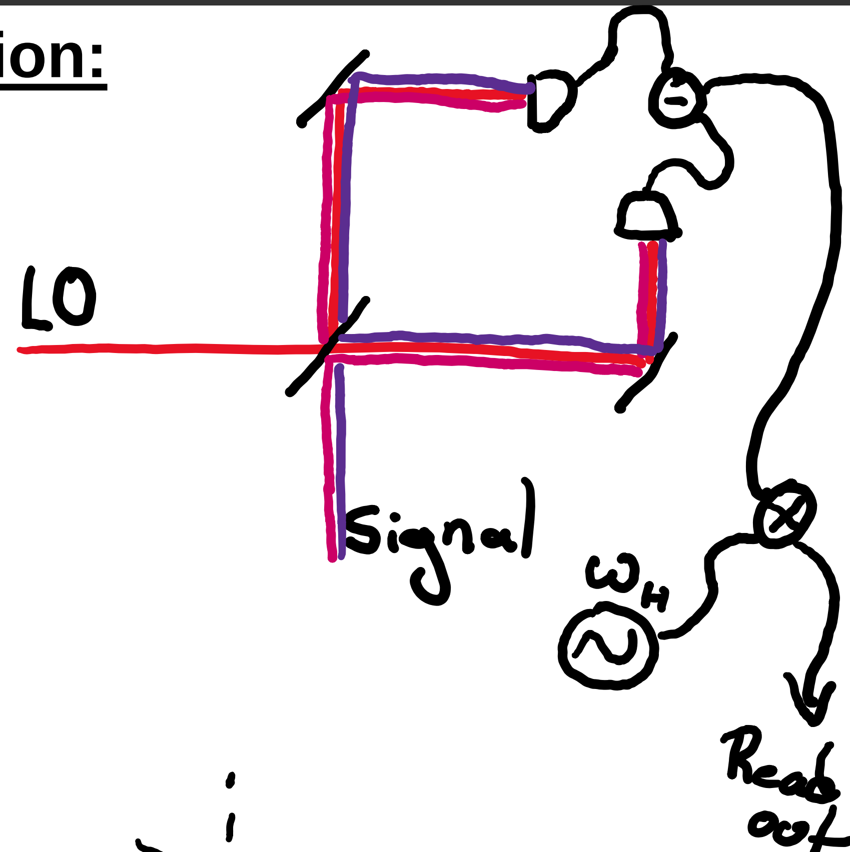
Non-Degenerate Squeezed State (EPR)

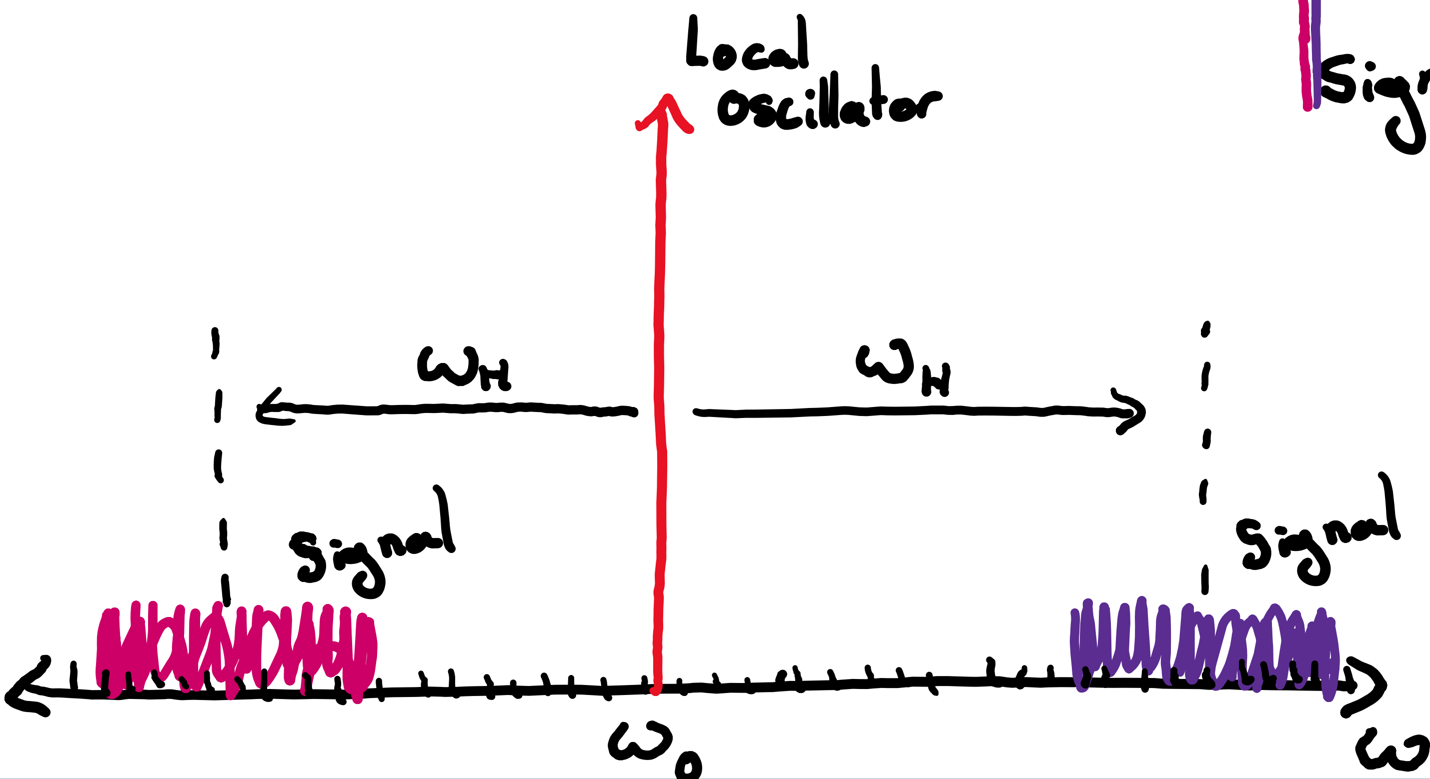


Detection:

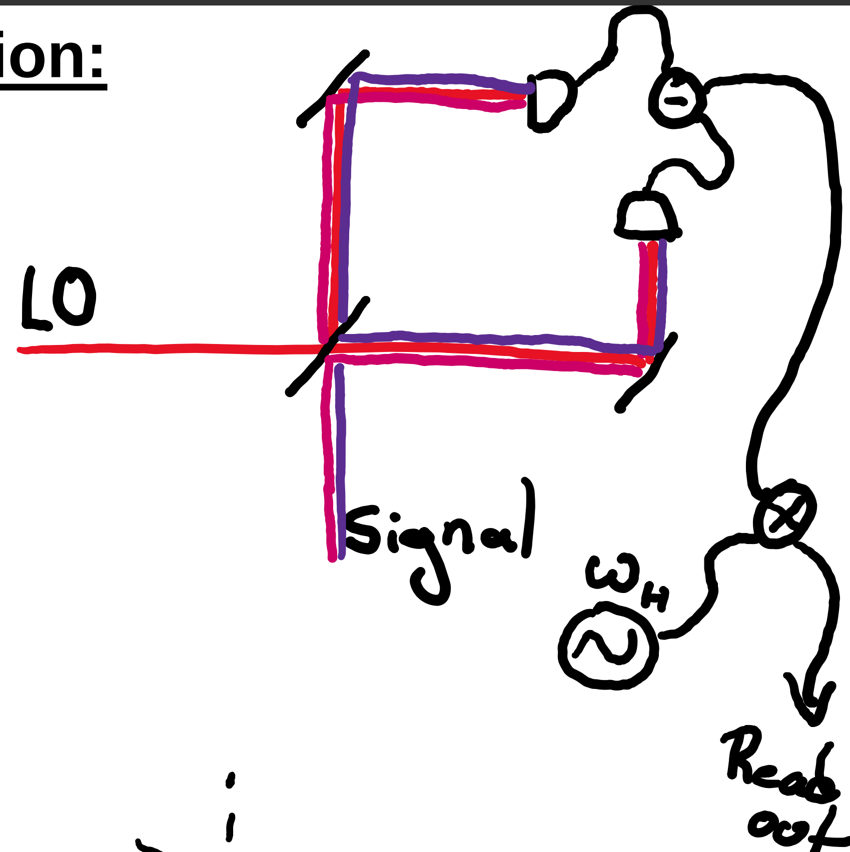

LO
Signal
ω_H
Read out
Local oscillator
Image
Signal
ω_H
ω_H
Noise
Signal
ω_0
ω

Detection:


LO
Signal
ω_H
Read out

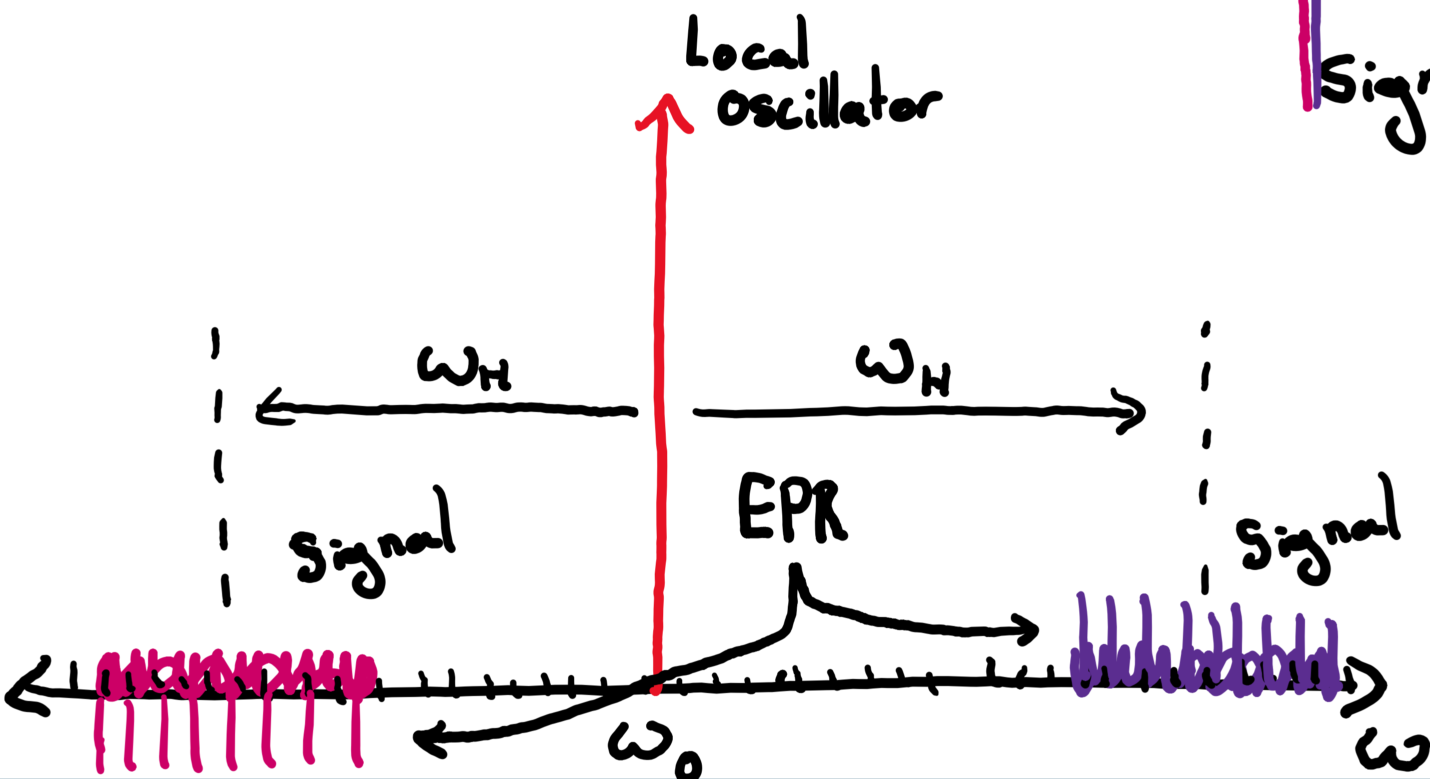

Local oscillator
ω_H
ω_H
Signal
Signal
ω_0
ω

Detection:

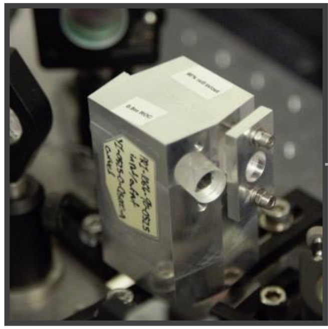


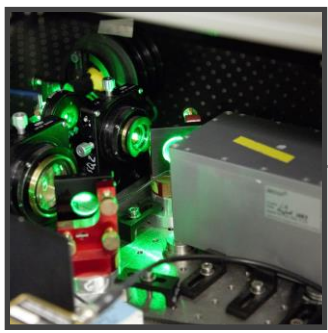
Details

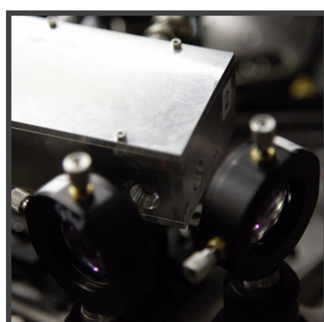
- 425 MHz Separation of local oscillator and signals
- EPR Squeezing modes centred at same separation frequency

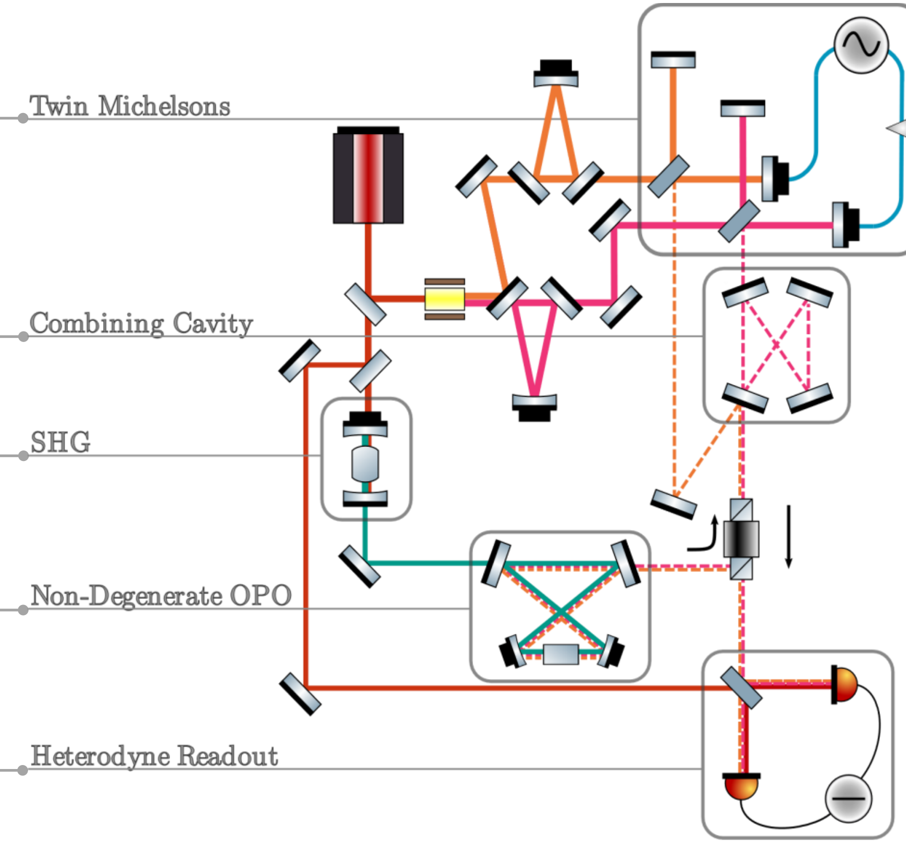


Experimental Layout:

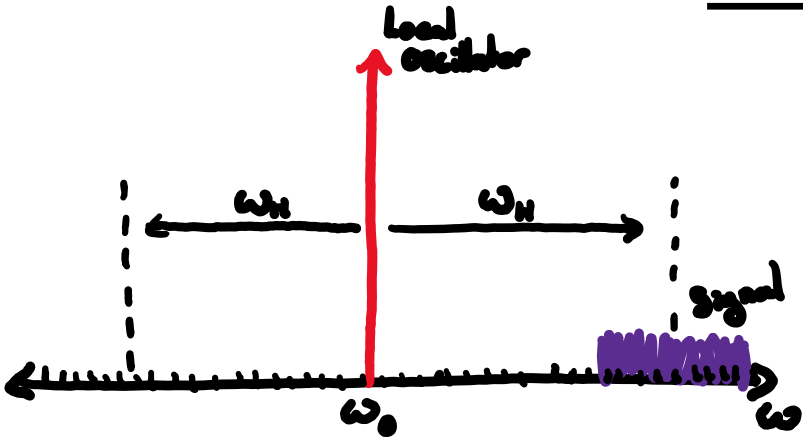


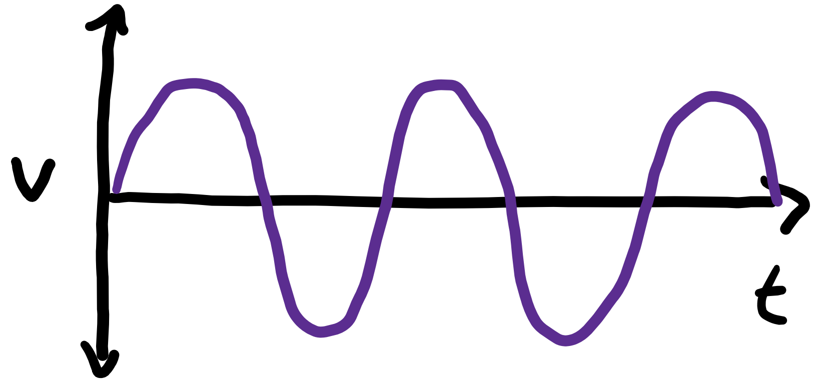


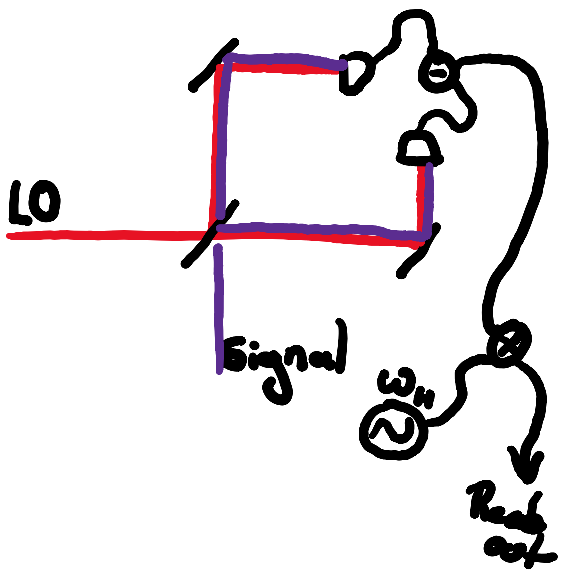


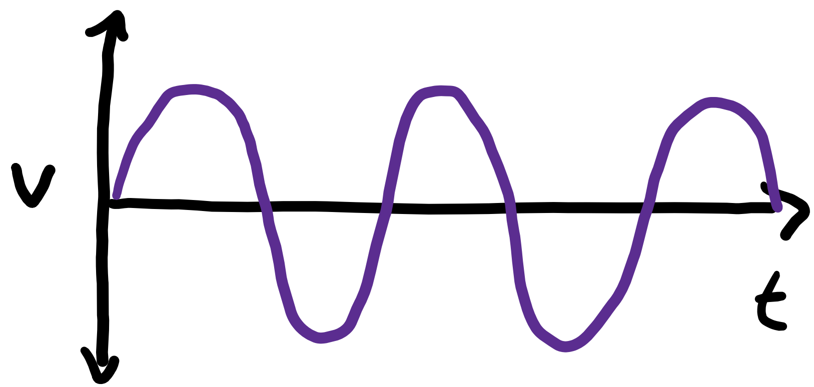


Picking Phase:

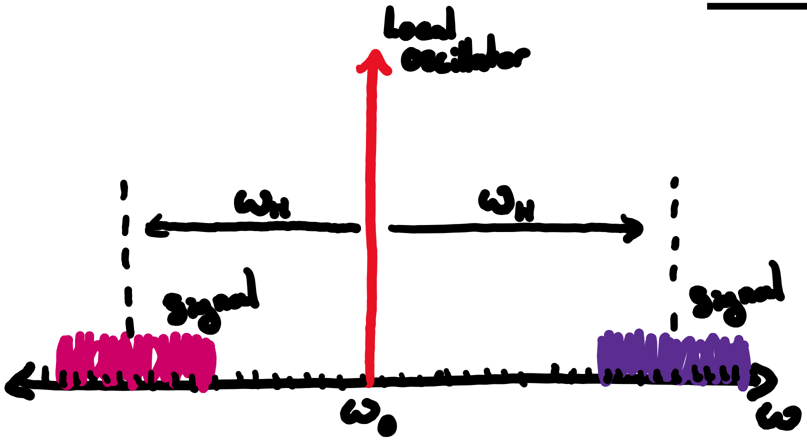


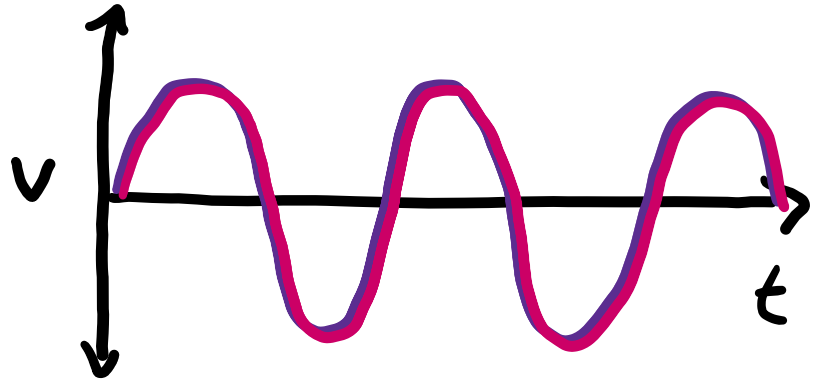


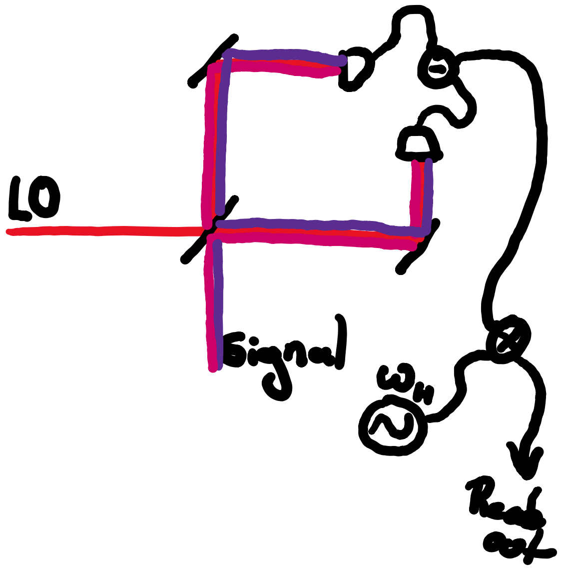


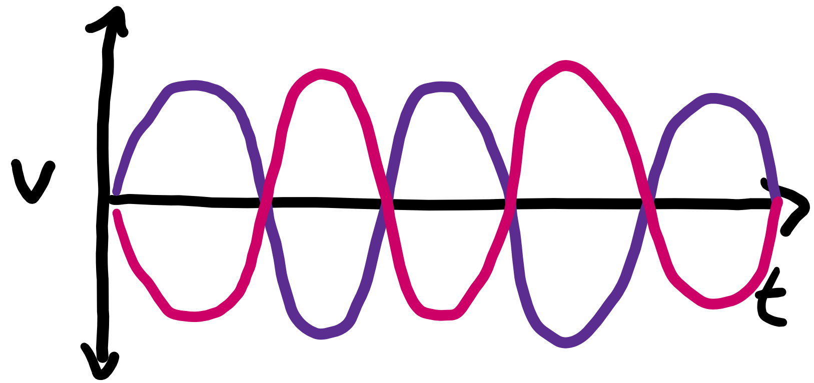


Picking Phase:

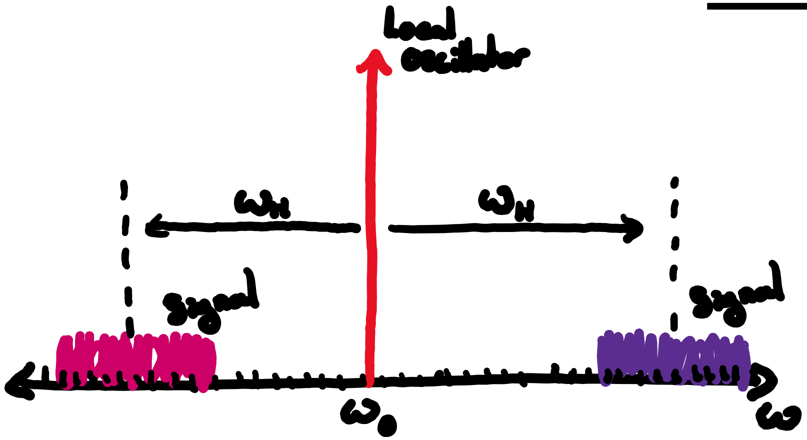


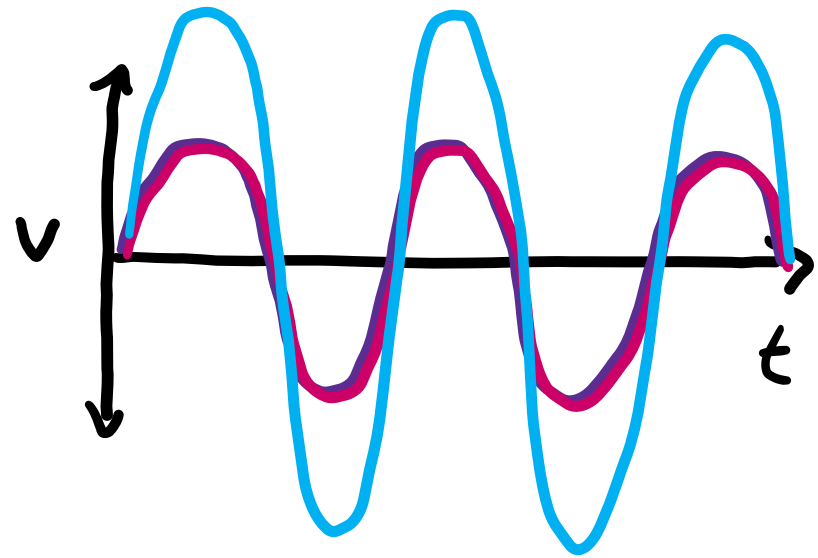


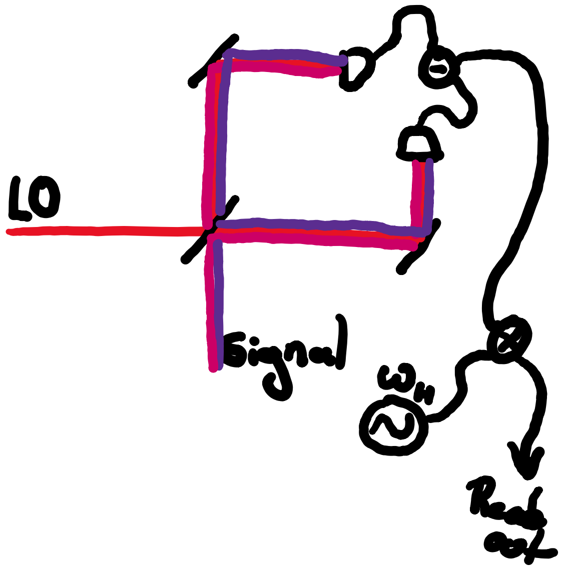


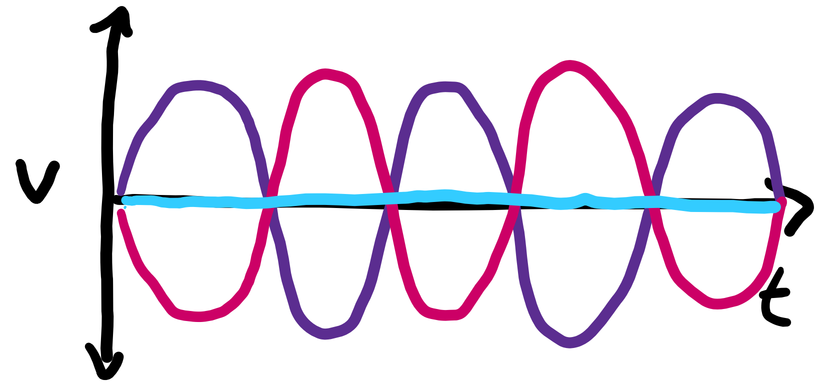


Picking Phase:

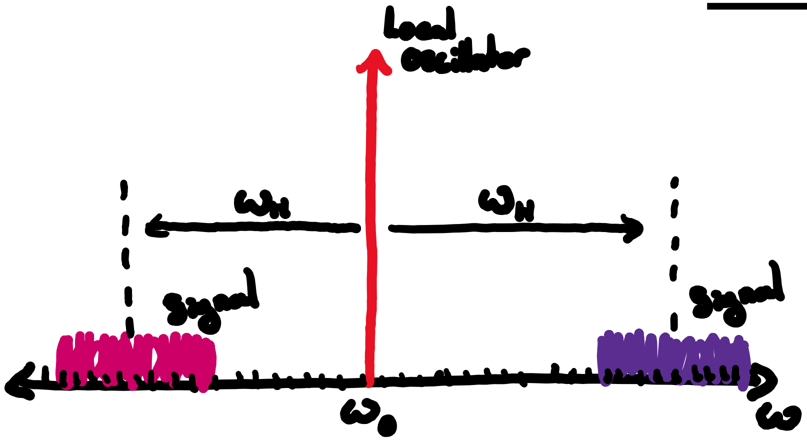


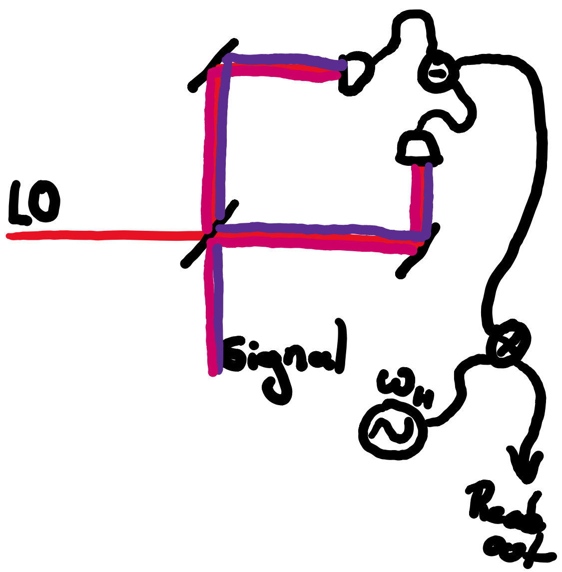






Picking Phase:





Choices with phase:

- **Set arbitrary phase lock between upper and lower sidebands**
- **Choose a optical local oscillator lock point**
- **Choose a electronic local oscillator demodulation phase**

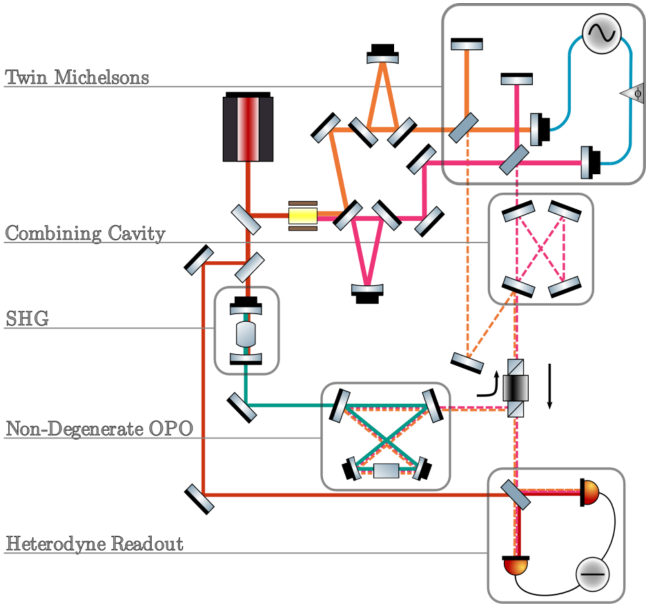
Result of I and Q demodulation:

Sum of amplitude quadrature and difference of phase quadrature

OR

Sum of phase quadrature and difference of amplitude quadrature

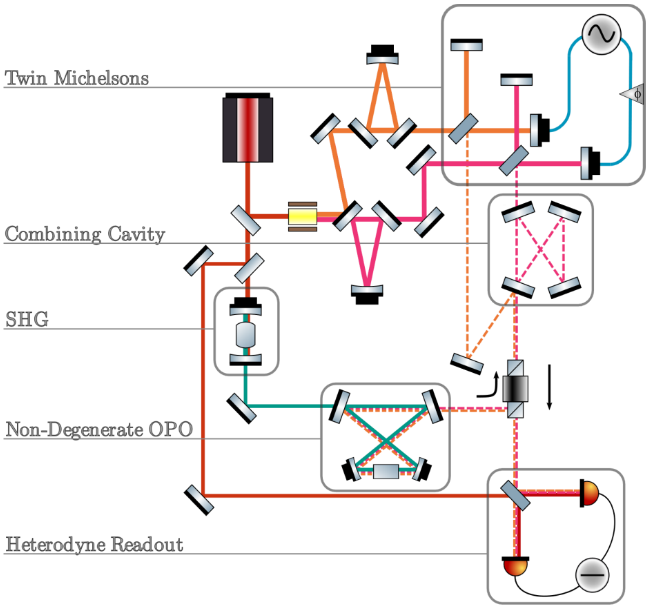
Results:

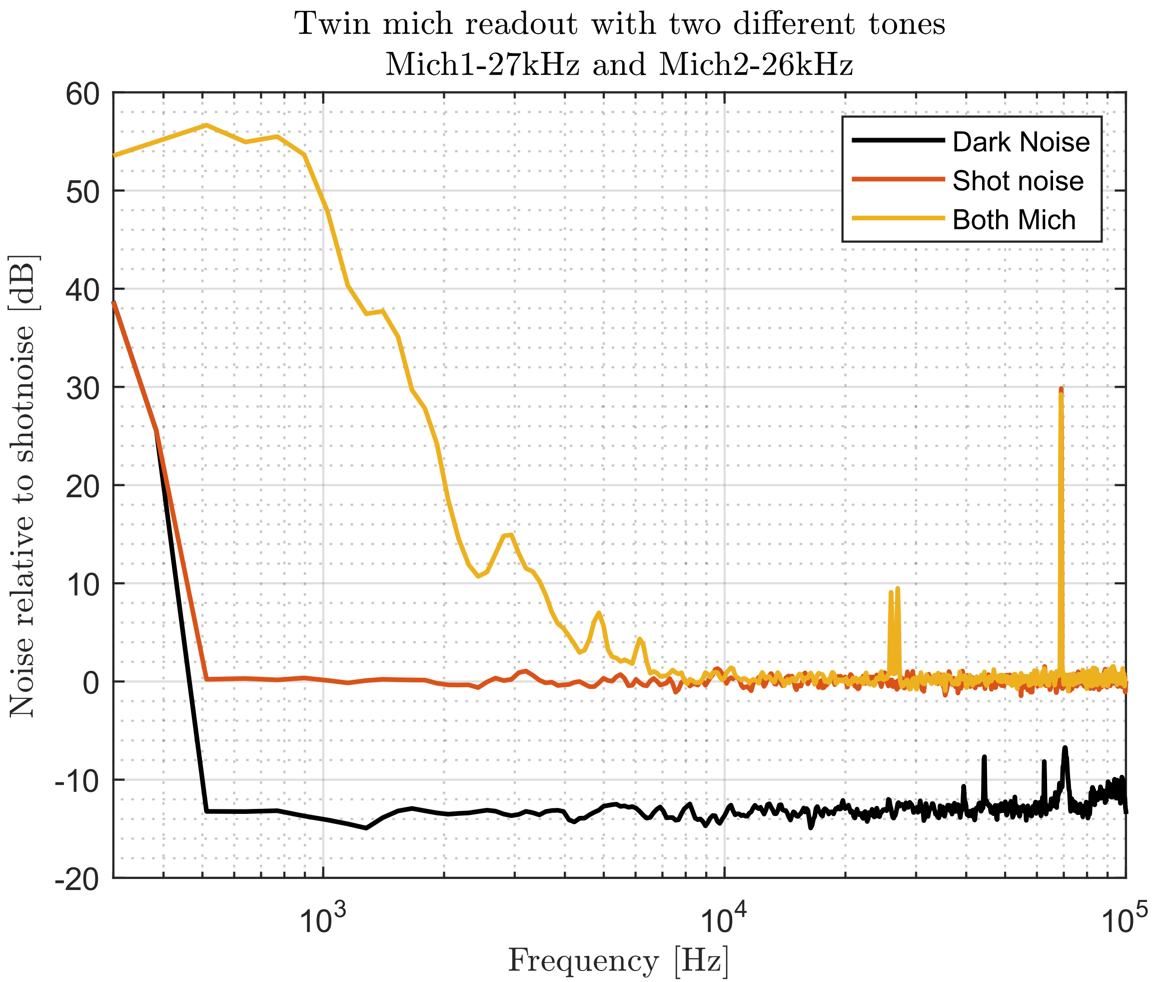


Details

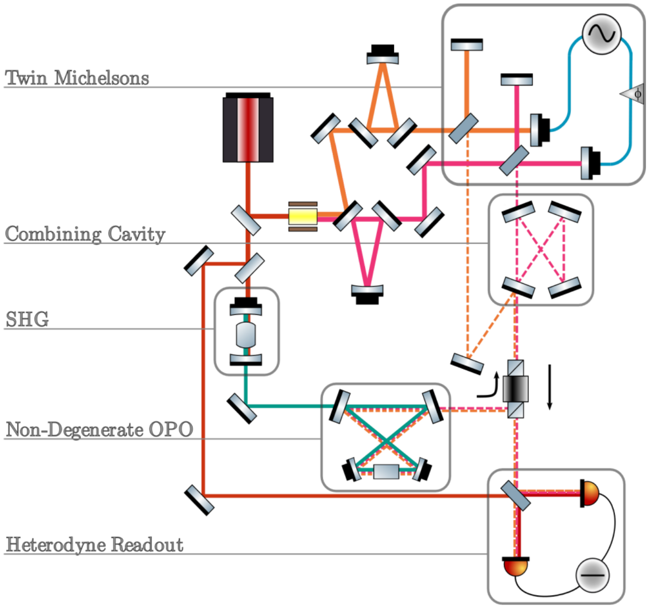
- 20 uW of power in each Michelson signal field
- 20 nW of power leaked through each Michelson as an offset from dark fringe
- Michelson contrast >99.7%

Results:

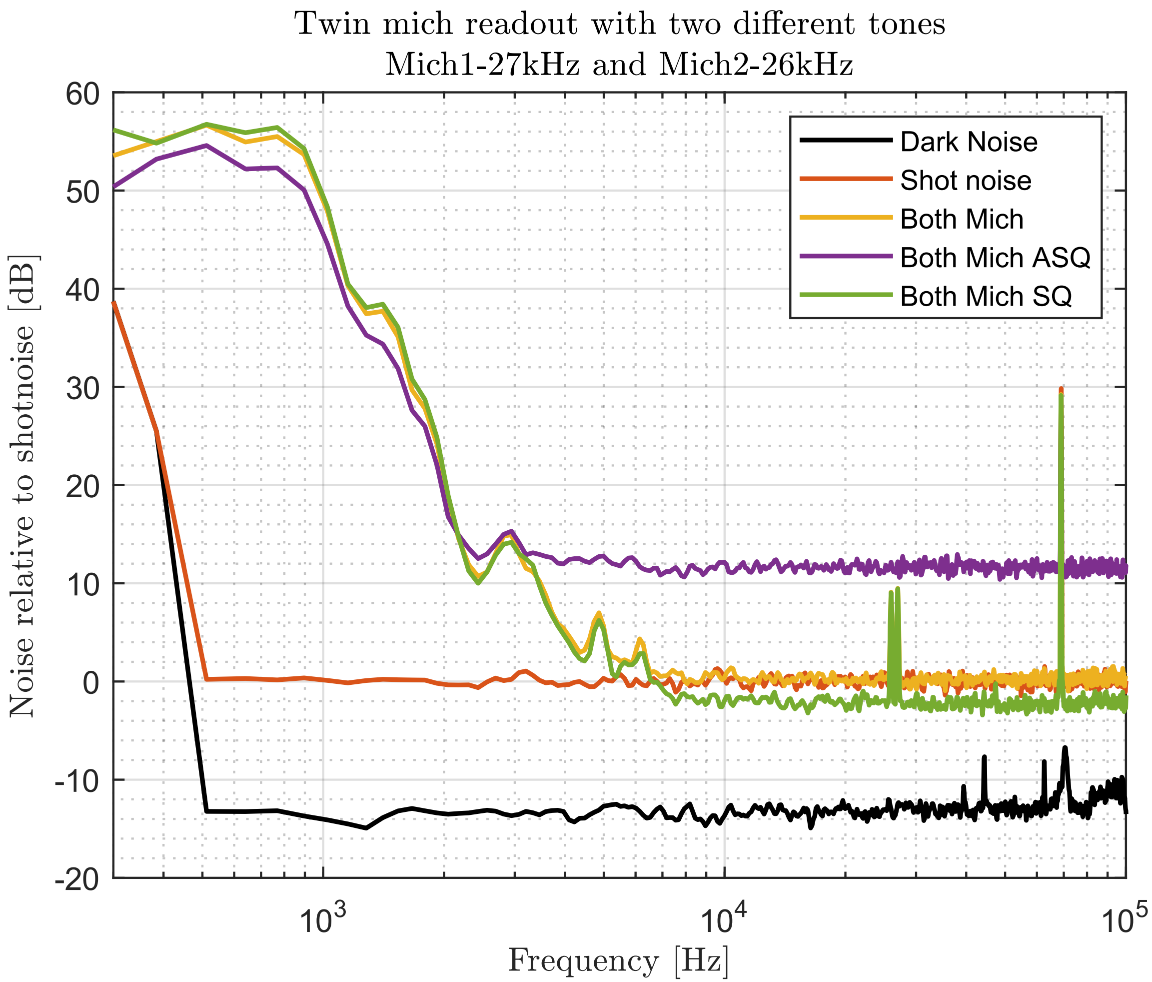

Twin Michelsons
Combining Cavity
SHG
Non-Degenerate OPO
Heterodyne Readout


Twin mich readout with two different tones
Mich1-27kHz and Mich2-26kHz
Noise relative to shotnoise [dB]
Frequency [Hz]
Dark Noise
Shot noise
Both Mich
60
50
40
30
20
10
0
-10
-20
10^3
10^4
10^5

Results:

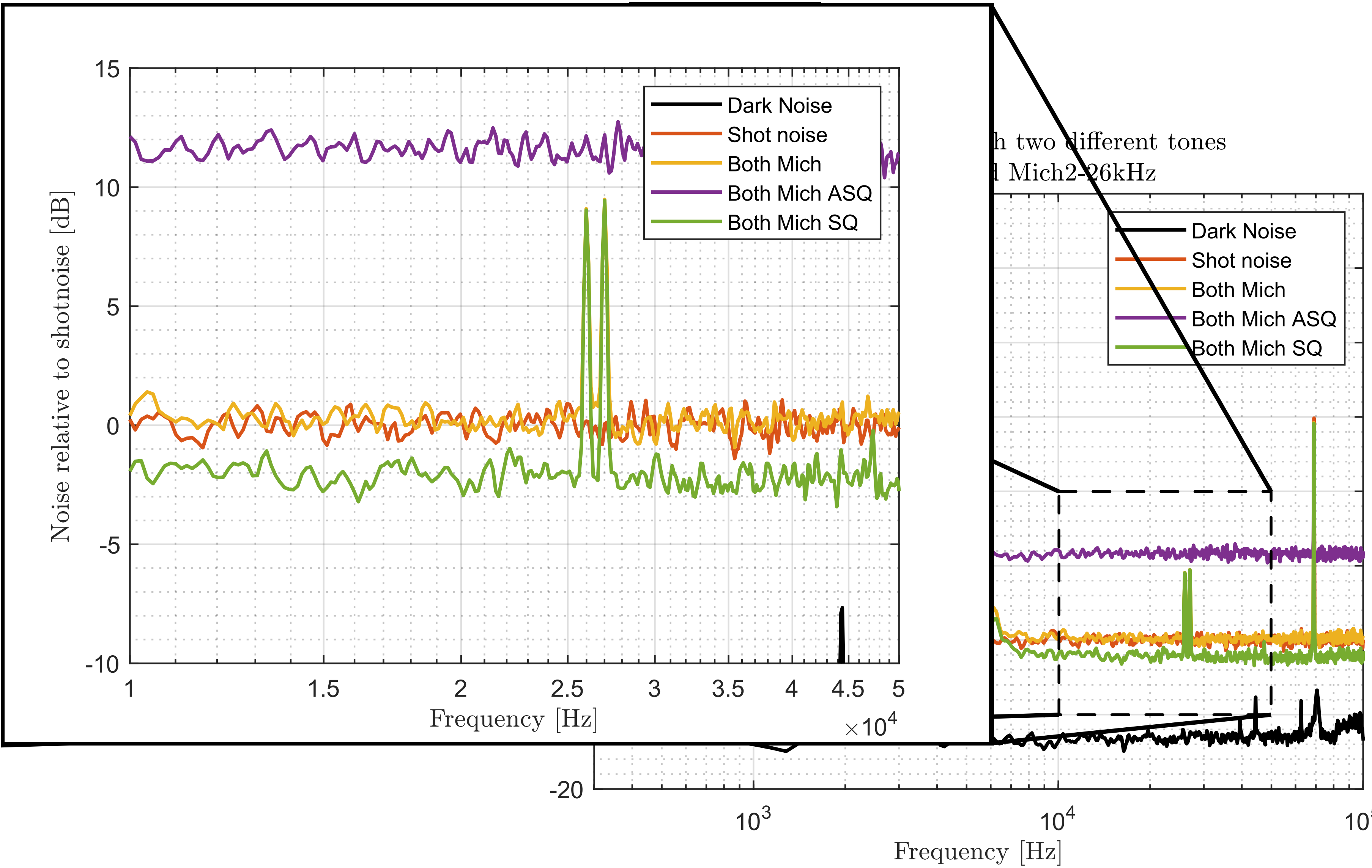


Twin Michelsons
Combining Cavity
SHG
Non-Degenerate OPO
Heterodyne Readout

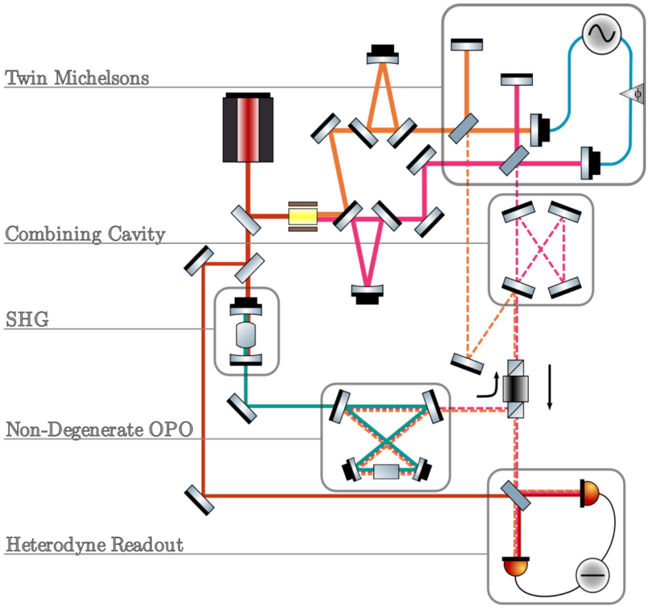


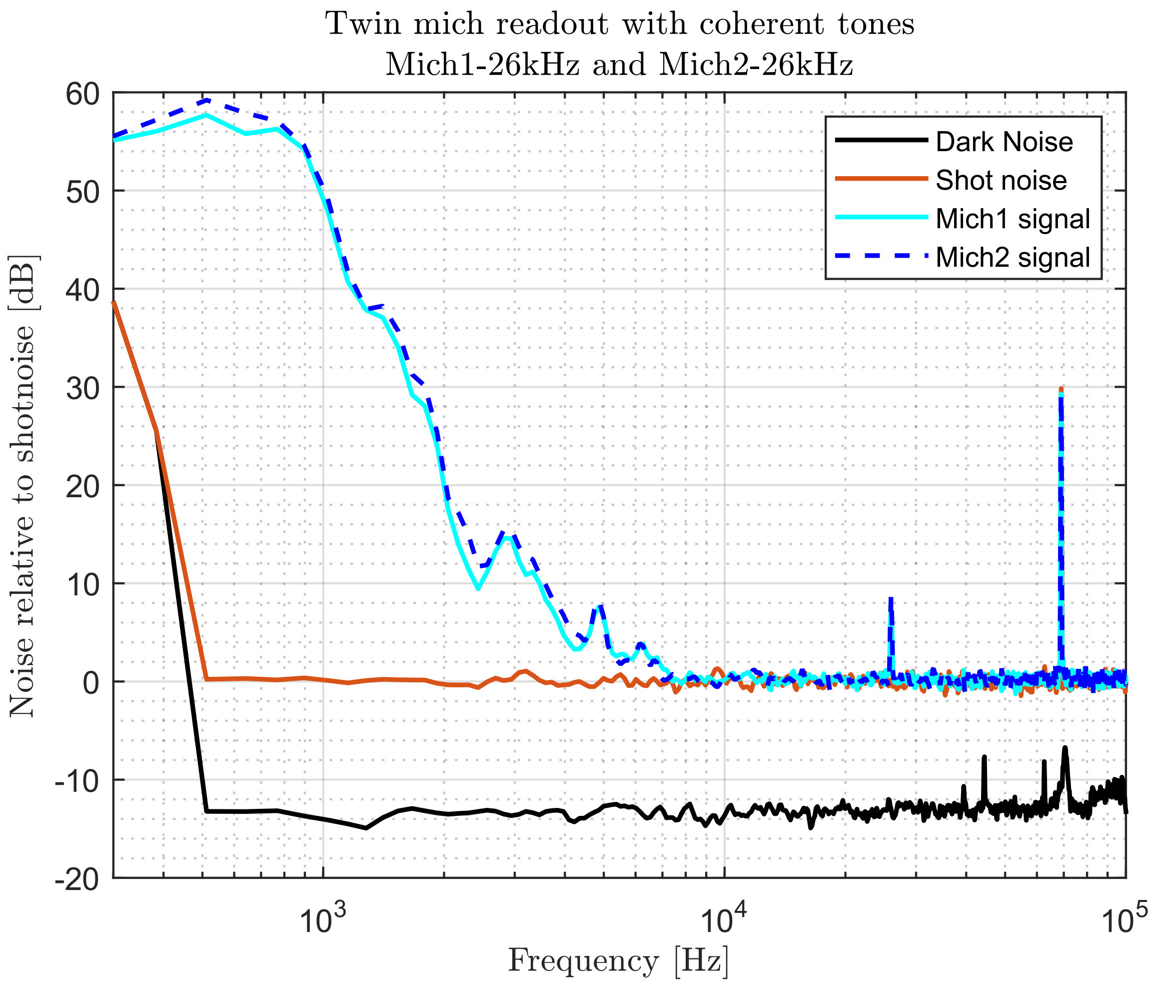
Twin mich readout with two different tones
Mich1-27kHz and Mich2-26kHz
Noise relative to shotnoise [dB]
Frequency [Hz]
Dark Noise
Shot noise
Both Mich
Both Mich ASQ
Both Mich SQ

Results:

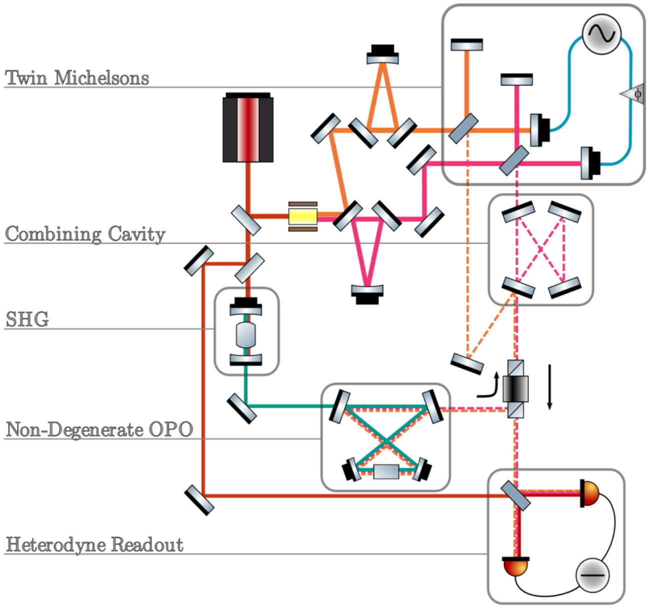

h two different tones
l Mich2-26kHz
Noise relative to shotnoise [dB]
15
10
5
0
-5
-10
-20
1
1.5
2
2.5
3
3.5
4
4.5
5
Frequency [Hz]
$\times 10^4$
10^3
10^4
10^5
Dark Noise
Shot noise
Both Mich
Both Mich ASQ
Both Mich SQ

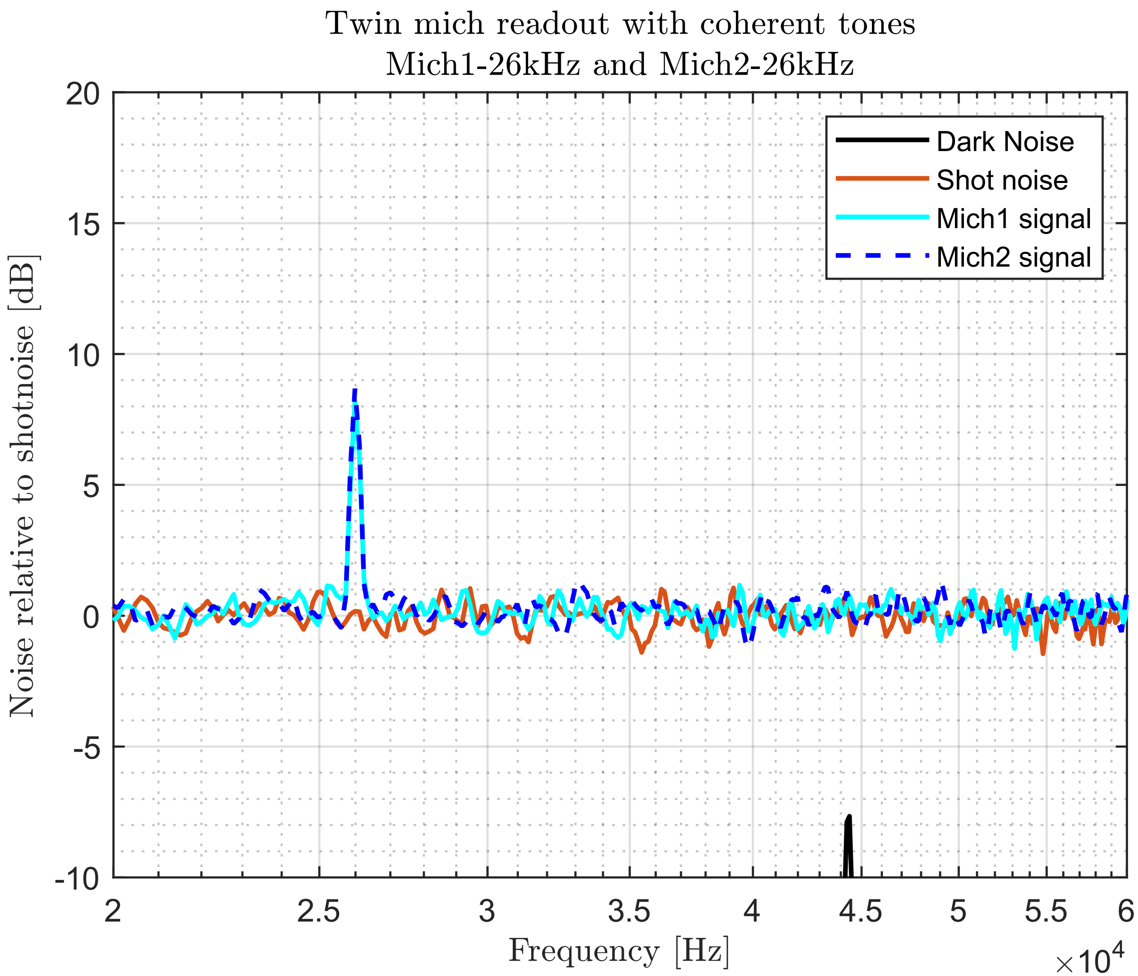
Results:


Twin Michelsons
Combining Cavity
SHG
Non-Degenerate OPO
Heterodyne Readout

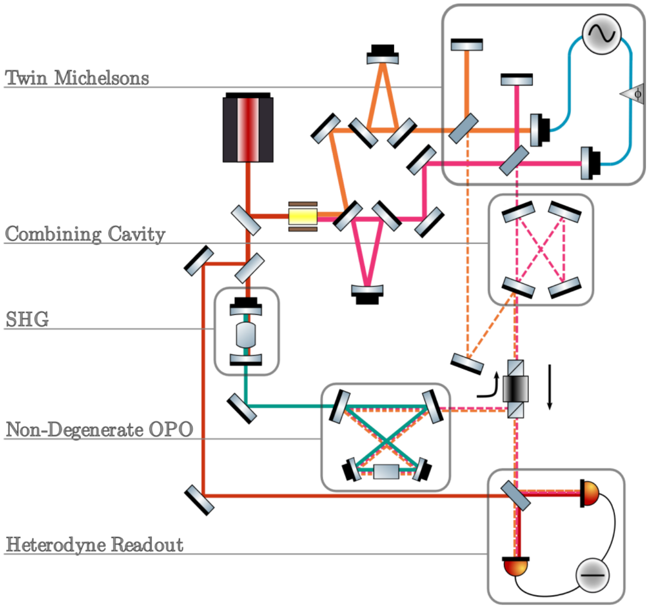

Twin mich readout with coherent tones
Mich1-26kHz and Mich2-26kHz
Dark Noise
Shot noise
Mich1 signal
Mich2 signal
Noise relative to shotnoise [dB]
Frequency [Hz]
60
50
40
30
20
10
0
-10
-20
10^3
10^4
10^5

Results:


Twin Michelsons
Combining Cavity
SHG
Non-Degenerate OPO
Heterodyne Readout


Twin mich readout with coherent tones
Mich1-26kHz and Mich2-26kHz
Noise relative to shotnoise [dB]
Frequency [Hz]
×10^4
Dark Noise
Shot noise
Mich1 signal
Mich2 signal
20
15
10
5
0
-5
-10
2
2.5
3
3.5
4
4.5
5
5.5
6

Results:


Twin Michelsons
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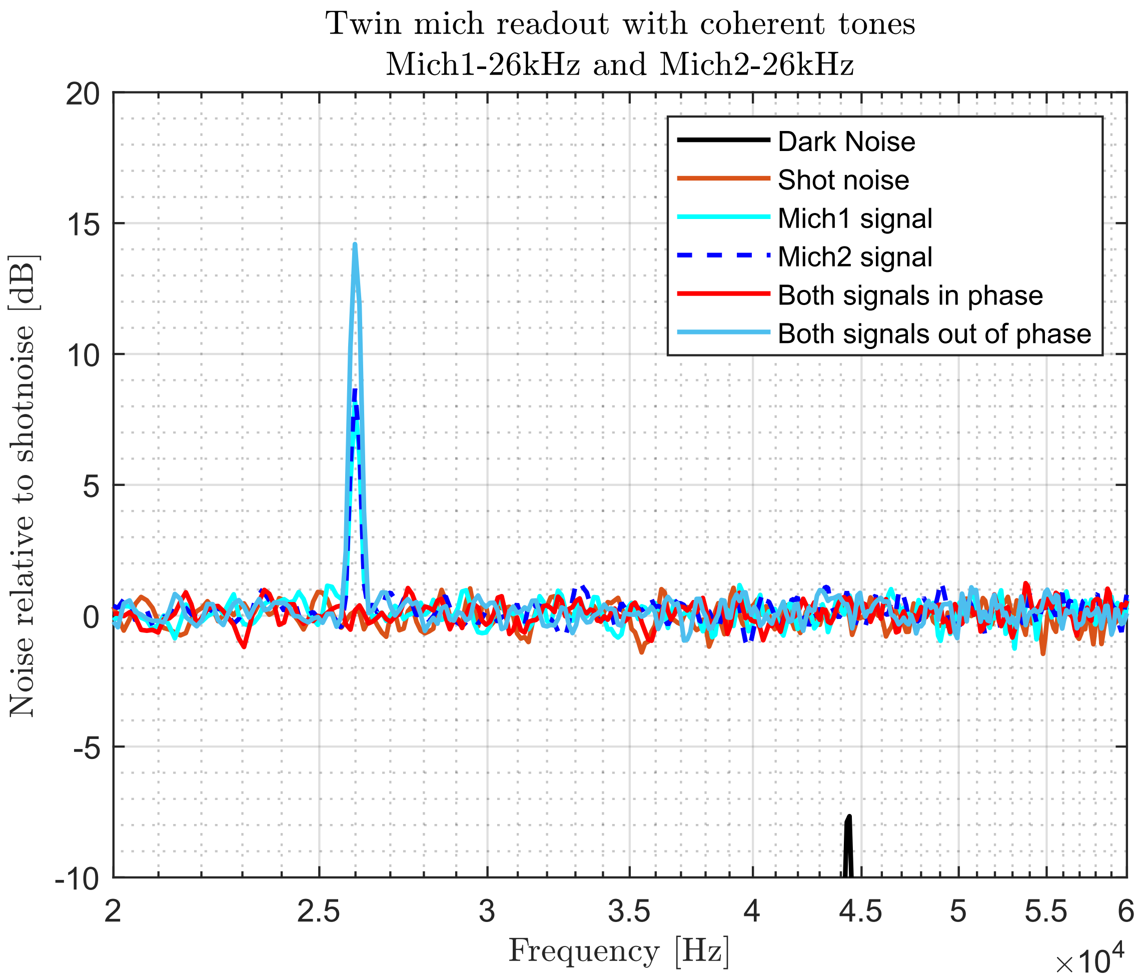
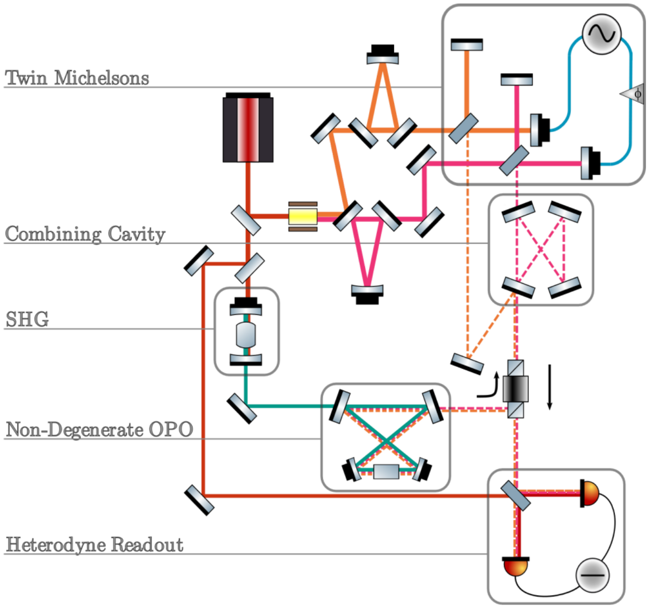
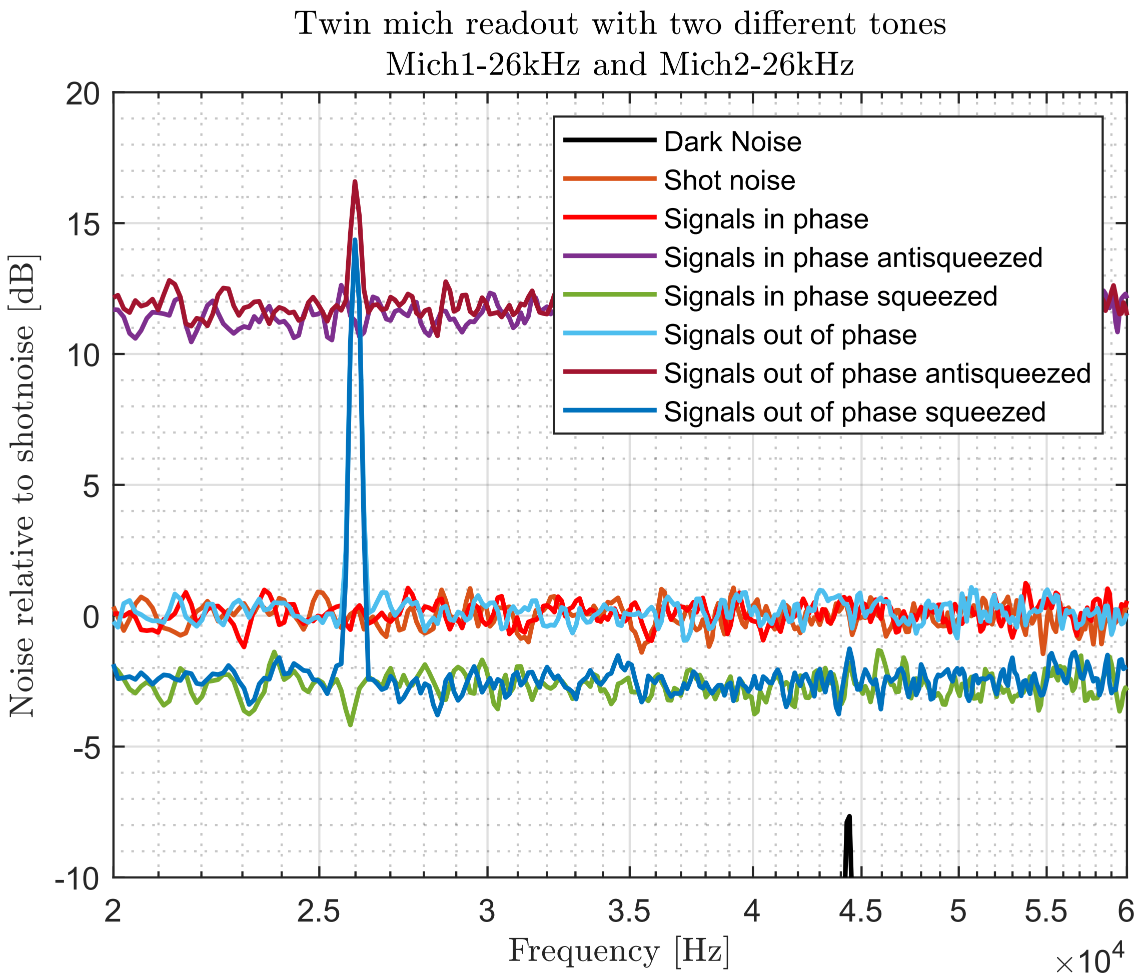

Twin mich readout with coherent tones
Mich1-26kHz and Mich2-26kHz
Dark Noise
Shot noise
Mich1 signal
Mich2 signal
Both signals in phase
Both signals out of phase
Noise relative to shotnoise [dB]
Frequency [Hz]
$\times 10^4$
20
15
10
5
0
-5
-10
2
2.5
3
3.5
4
4.5
5
5.5
6

Results:

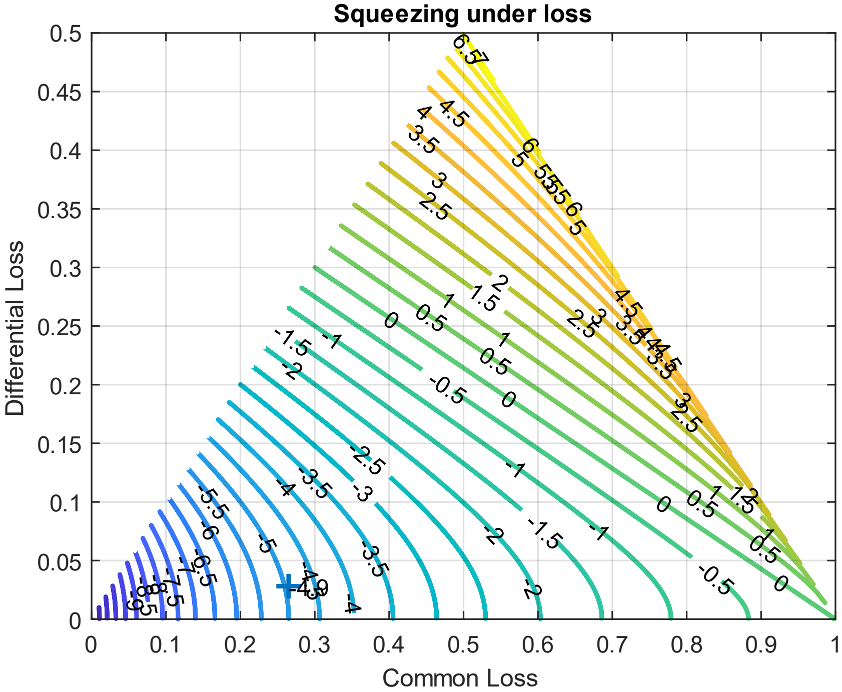


Twin Michelsons
Combining Cavity
SHG
Non-Degenerate OPO
Heterodyne Readout



Twin mich readout with two different tones
Mich1-26kHz and Mich2-26kHz
Noise relative to shotnoise [dB]
Frequency [Hz]
×10^4
20
15
10
5
0
-5
-10
2
2.5
3
3.5
4
4.5
5
5.5
6
Dark Noise
Shot noise
Signals in phase
Signals in phase antisqueezed
Signals in phase squeezed
Signals out of phase
Signals out of phase antisqueezed
Signals out of phase squeezed

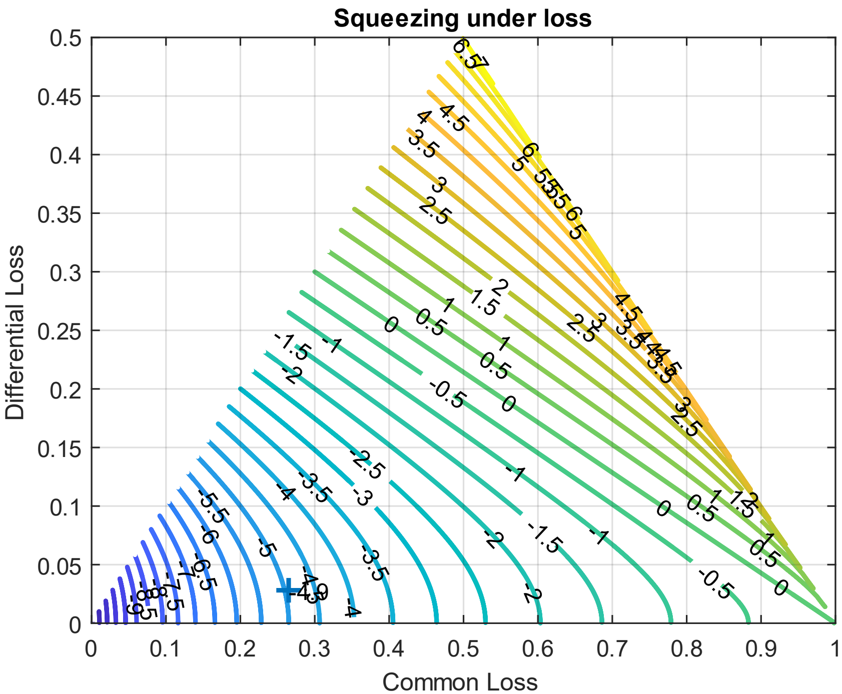
Expected levels of squeezing:



Common Loss = $\dfrac{L_1 + L_2}{2}$

Differential Loss = $\dfrac{|L_1 - L_2|}{2}$

Expected levels of squeezing:

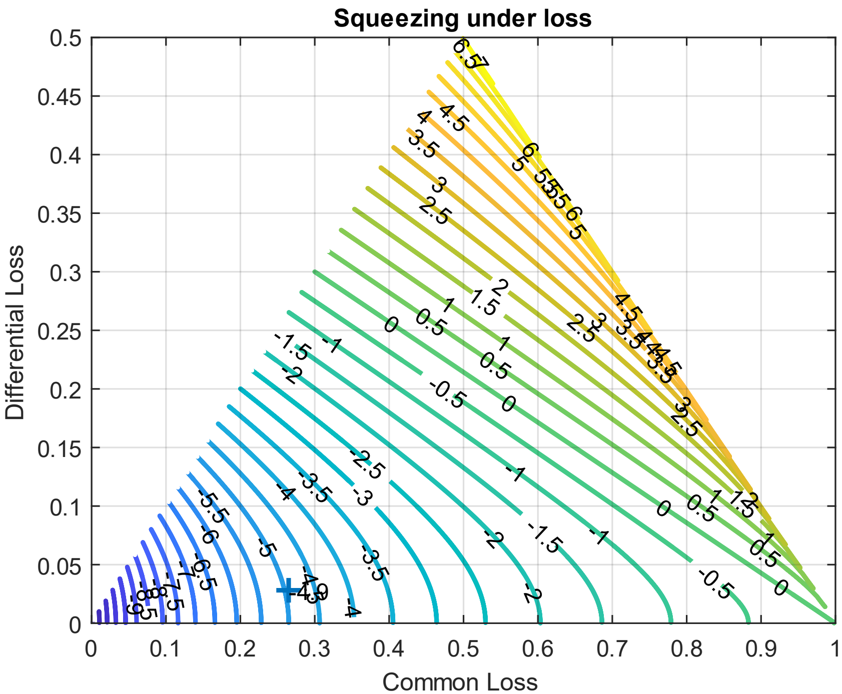


Common Loss = $$\frac{L_1 + L_2}{2}$$

Dephasing

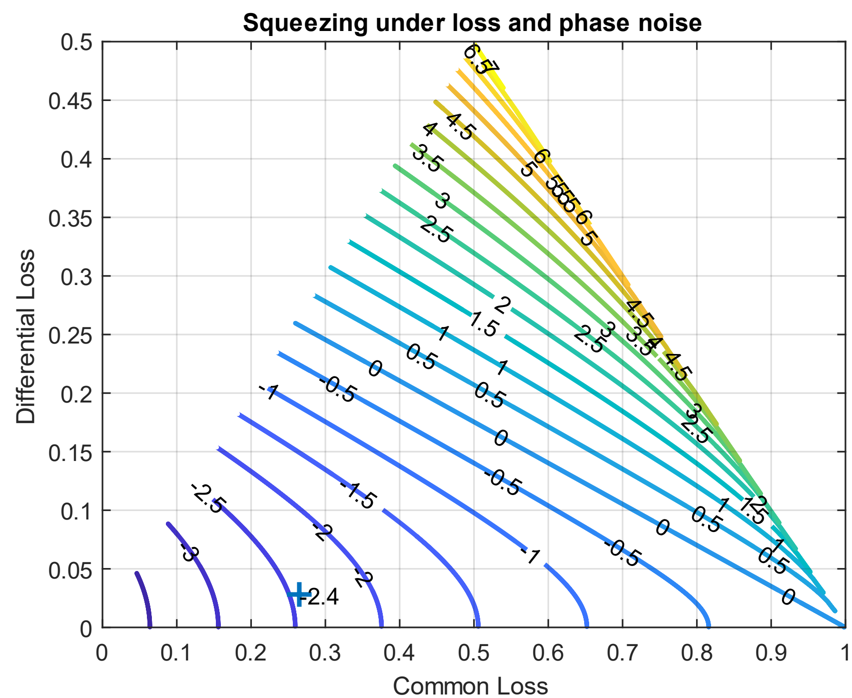
Di[illegible]oss = $$\frac{|L_1 - L_2|}{2}$$

Expected levels of squeezing:



Details

- **26% common Loss 3% differential loss**
  OR
  path 1 = 23% loss, path 2 =29% loss
- **Approx 140mrad phase noise**



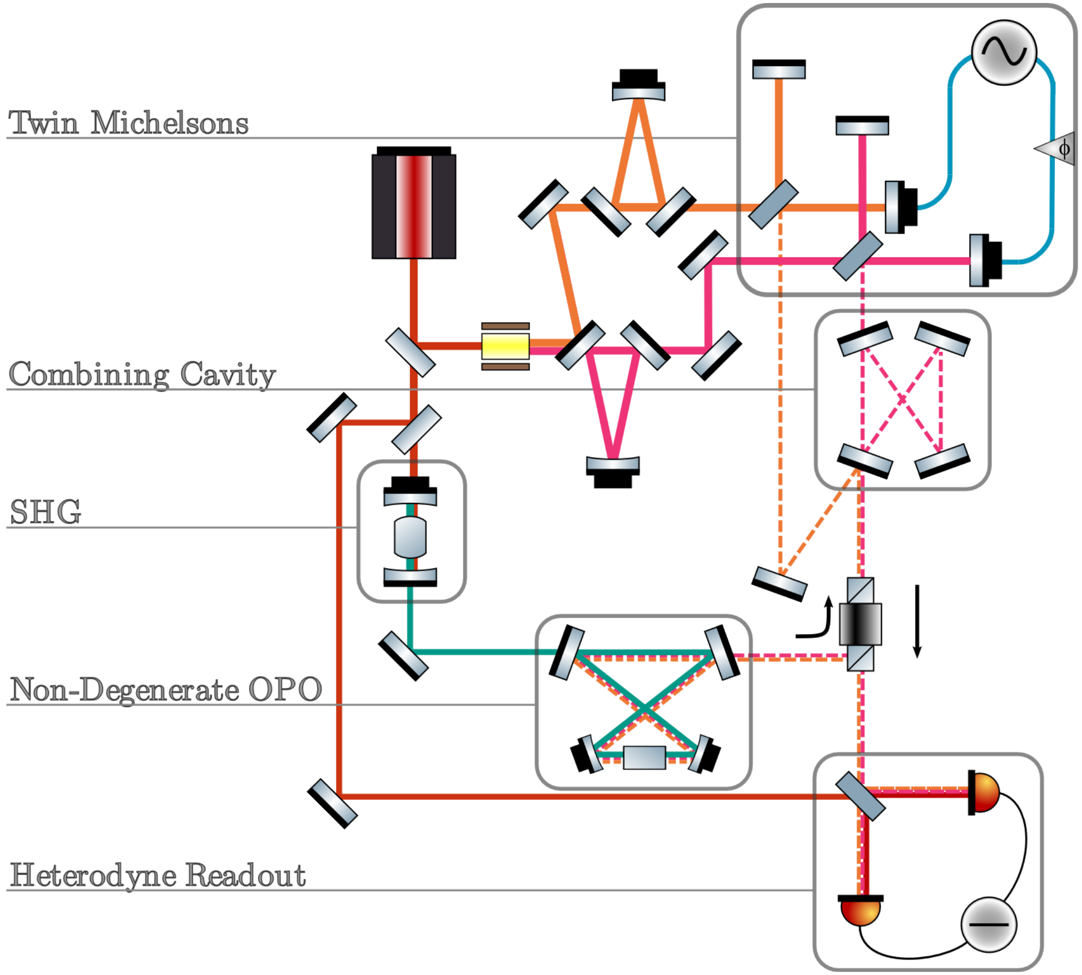
Common Loss = $$\frac{L_1 + L_2}{2}$$

Differential Loss = $$\frac{|L_1 - L_2|}{2}$$

Dephasing

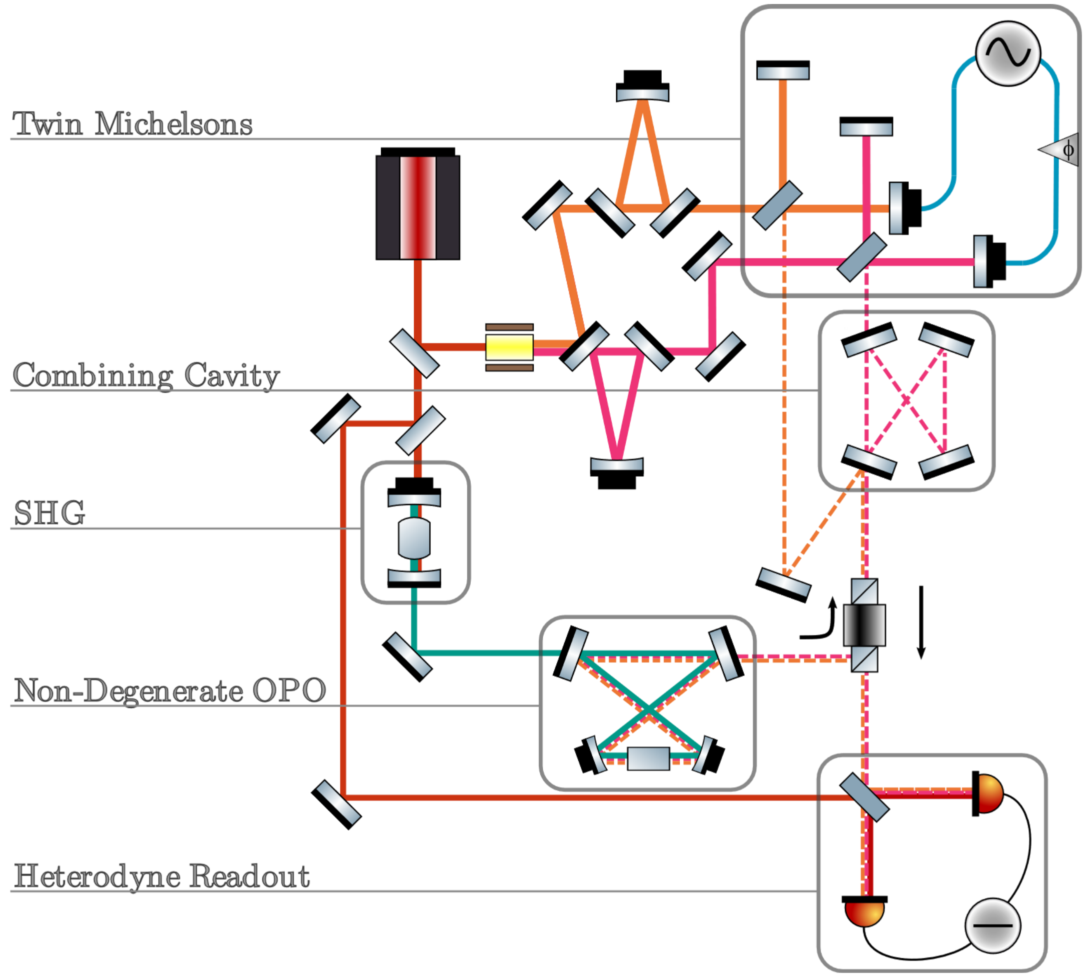
<u>Interesting points:</u>

- **Coherent noise addition/subtraction**
- **Avoid signals on Heterodyne local oscillator**
- **I and Q measurements simultaneously**
- **Choice of sum or difference readout**

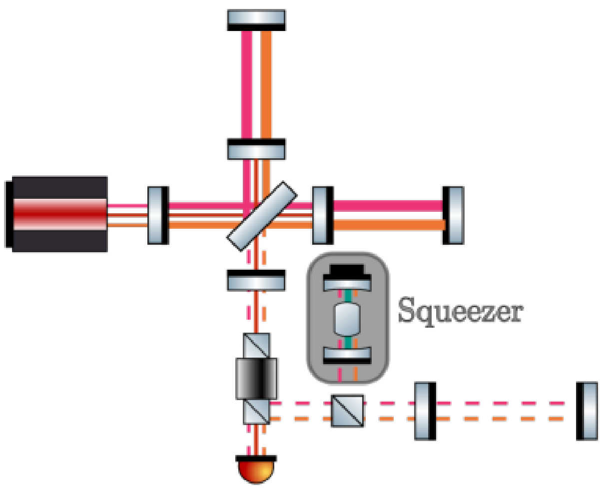


Things to do:

- Improve losses
  - Combining cavity
  - Faraday
  - Mode matching
- Calibrate sensitivity
- Squeezing phase lock
- Full readout phase control

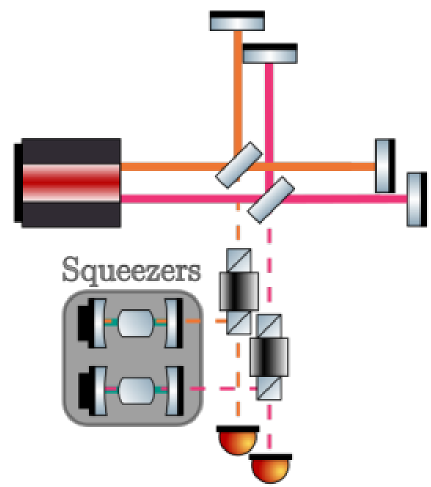


Gravitational Wave Detectors



Adapted from T. Zhang et al. 2021 Phys. Rev. Lett. 126, 221301

Quantum-Gravity Detector



Adapted from S. T. Pradyumna et al. 2020 Communications Physics 3,104 & S. M. Vermeulen et al. 2021 Classical and Quantum Gravity 38, 085008

Thanks for listening