Einstein-Podolsky-Rosen (EPR) Squeezing Experiments from ANU & Hamburg

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GWADW 2019

Australian National University

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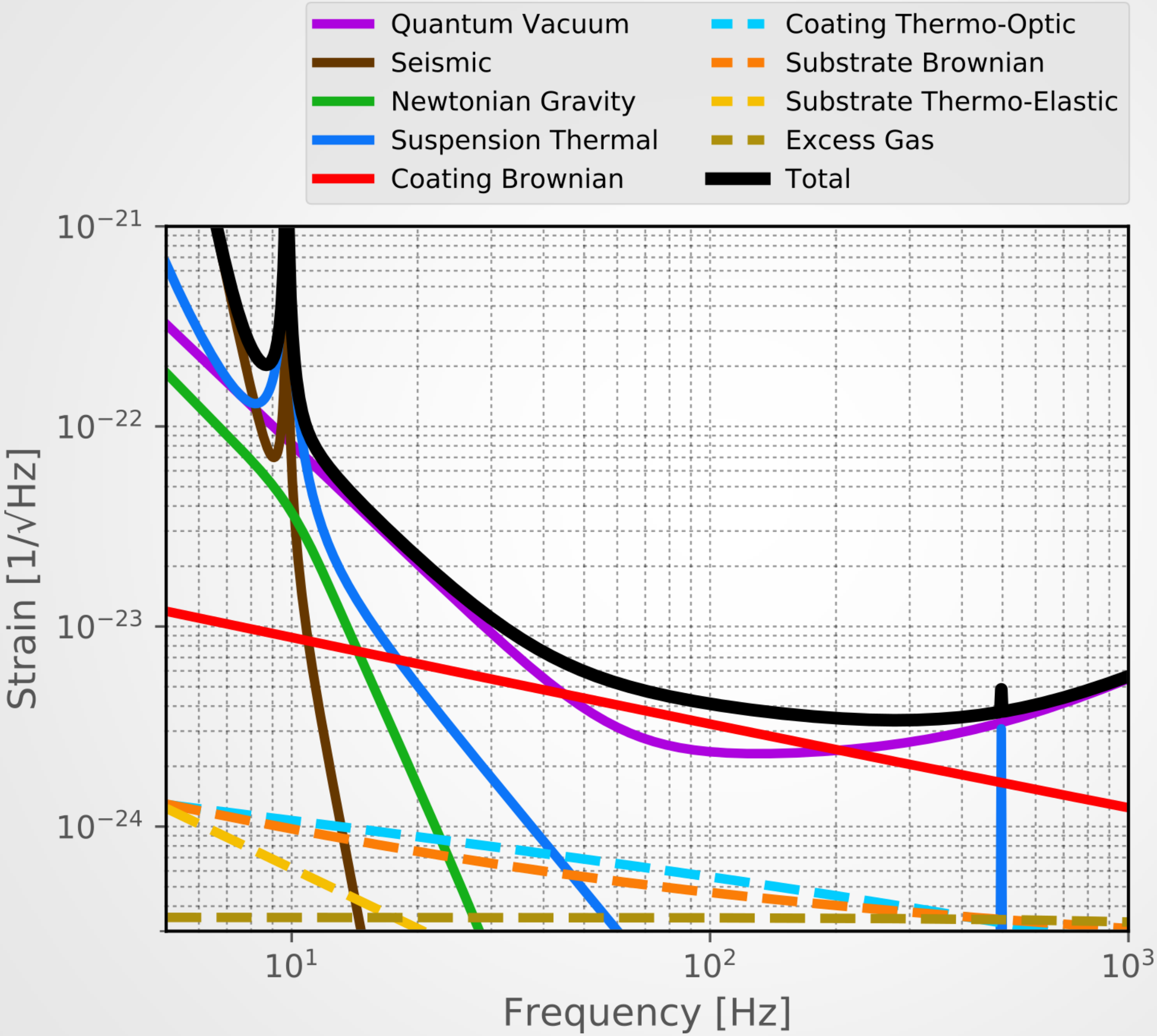
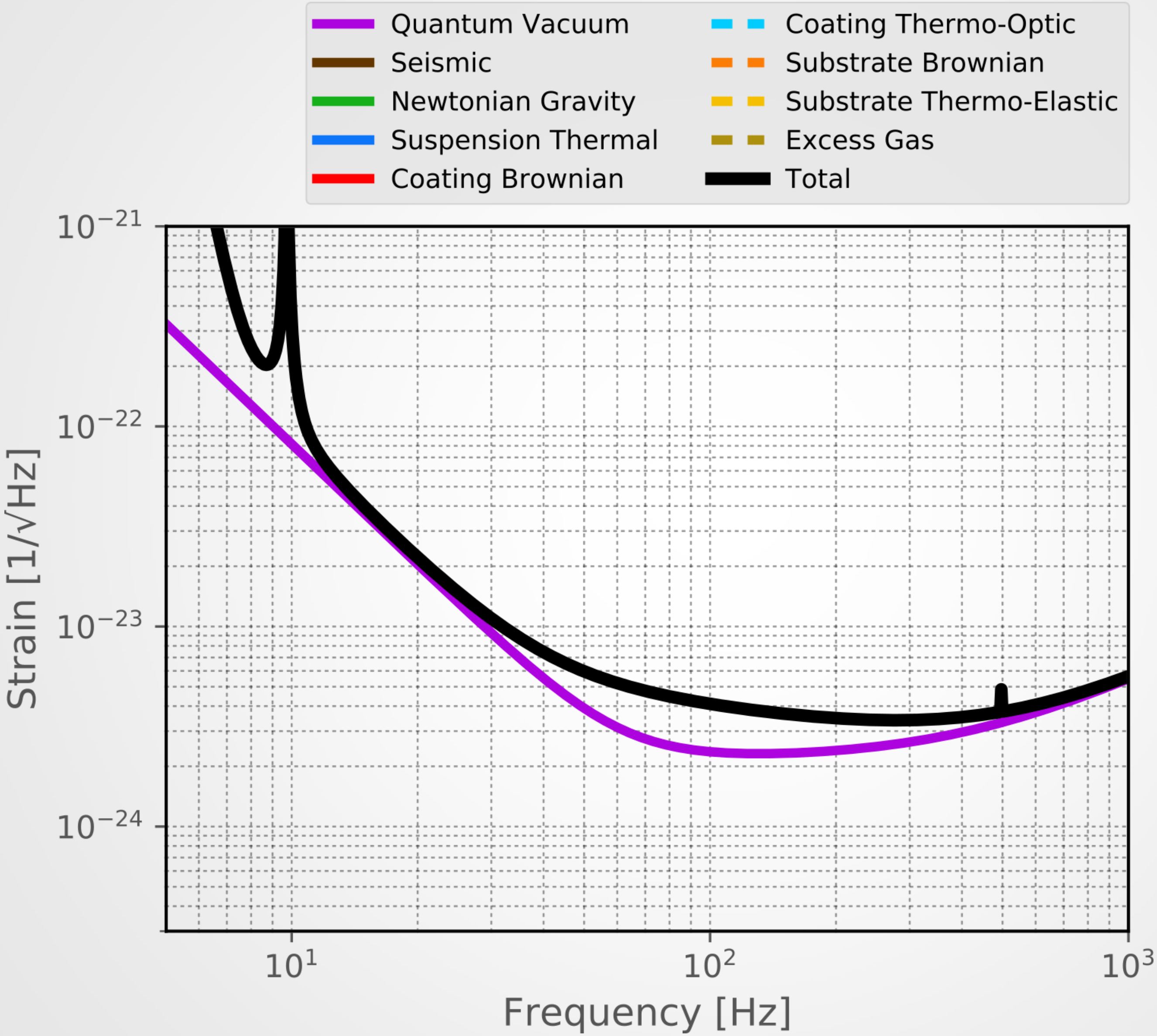
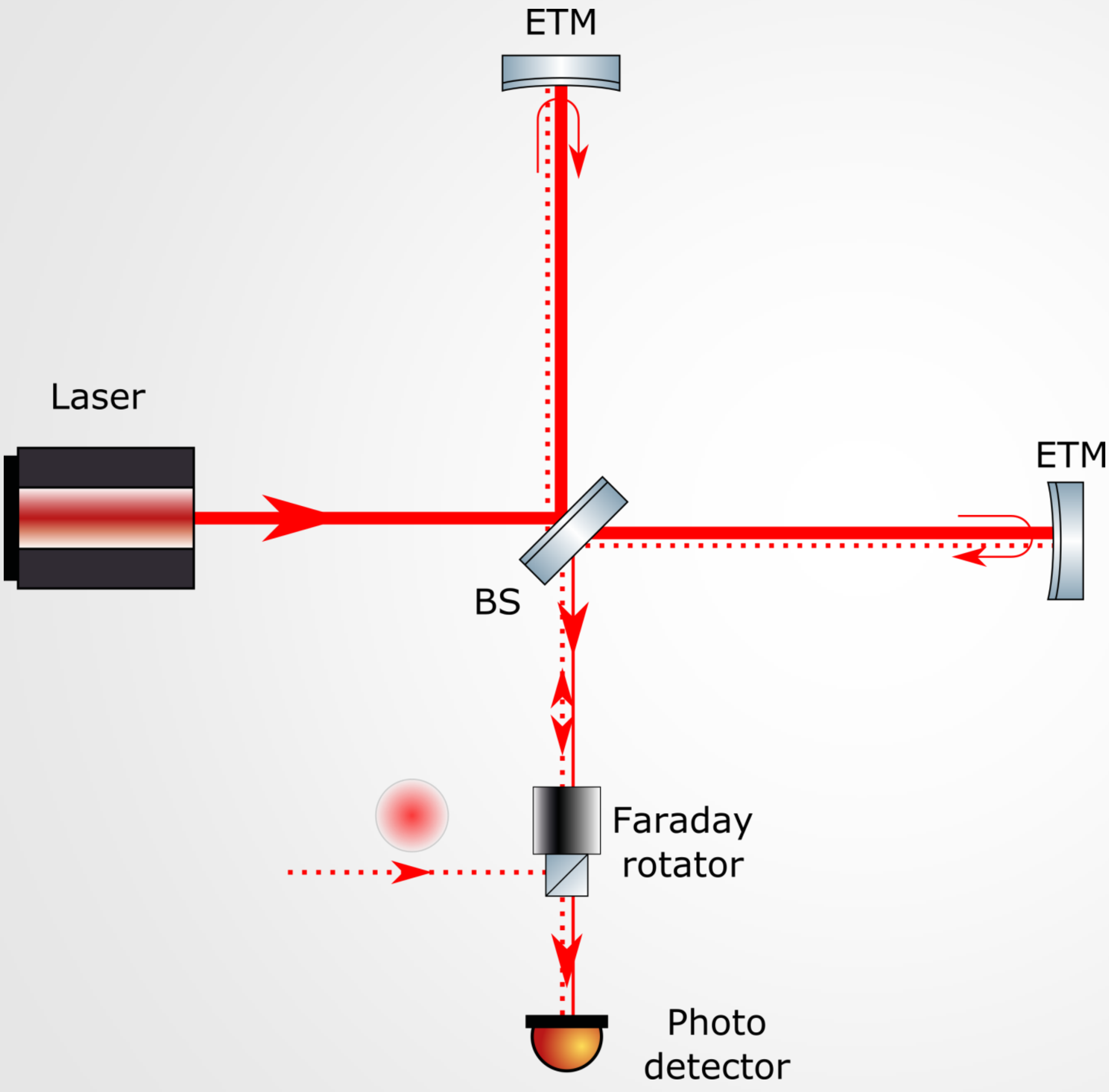
Noise Budget

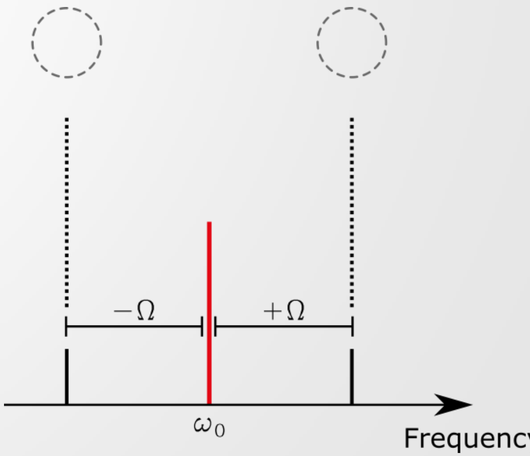


Noise Budget



Squeezed-Light Enhancement





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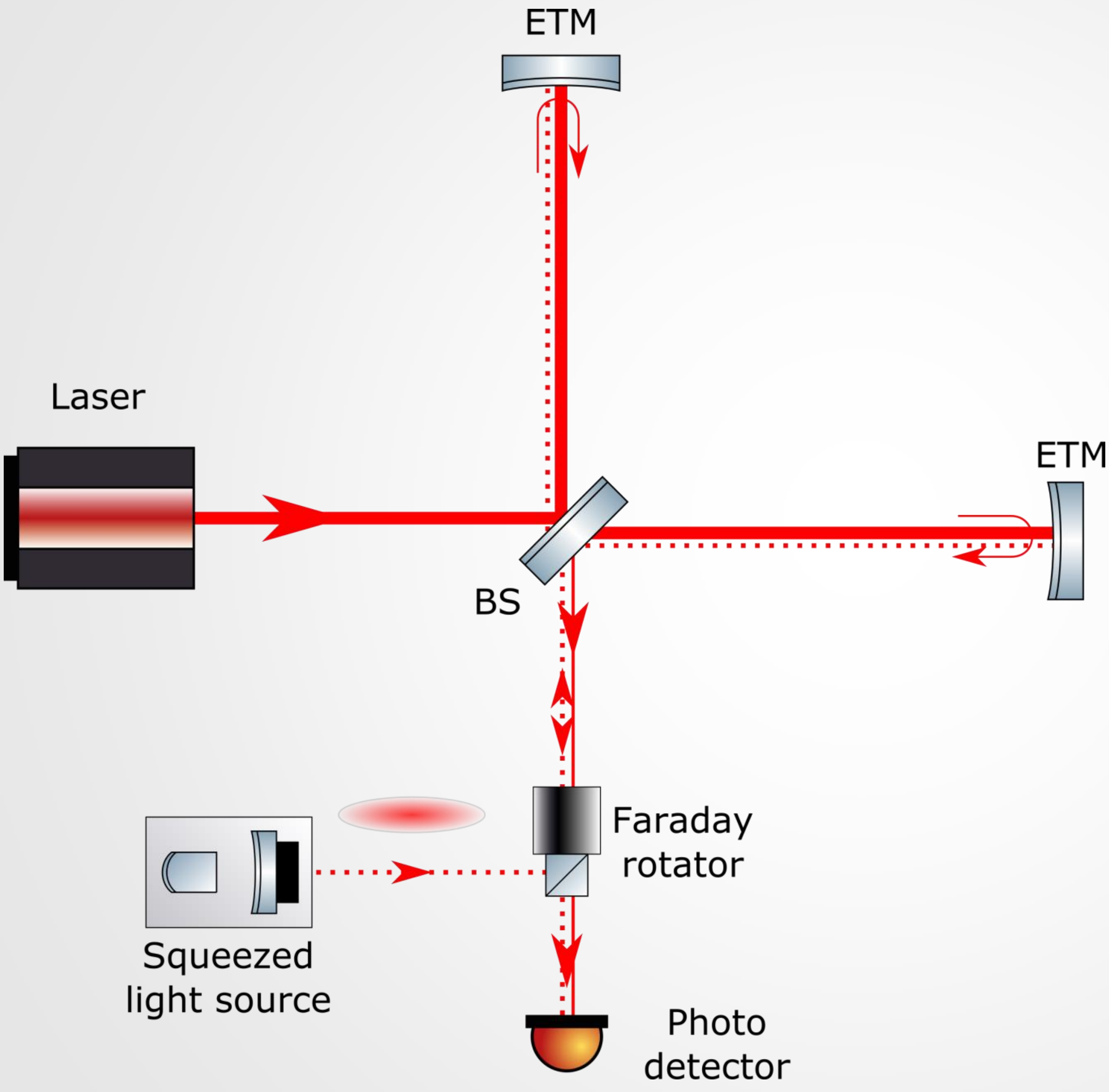
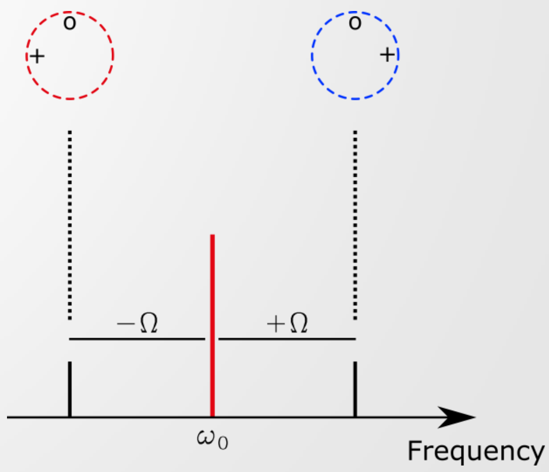
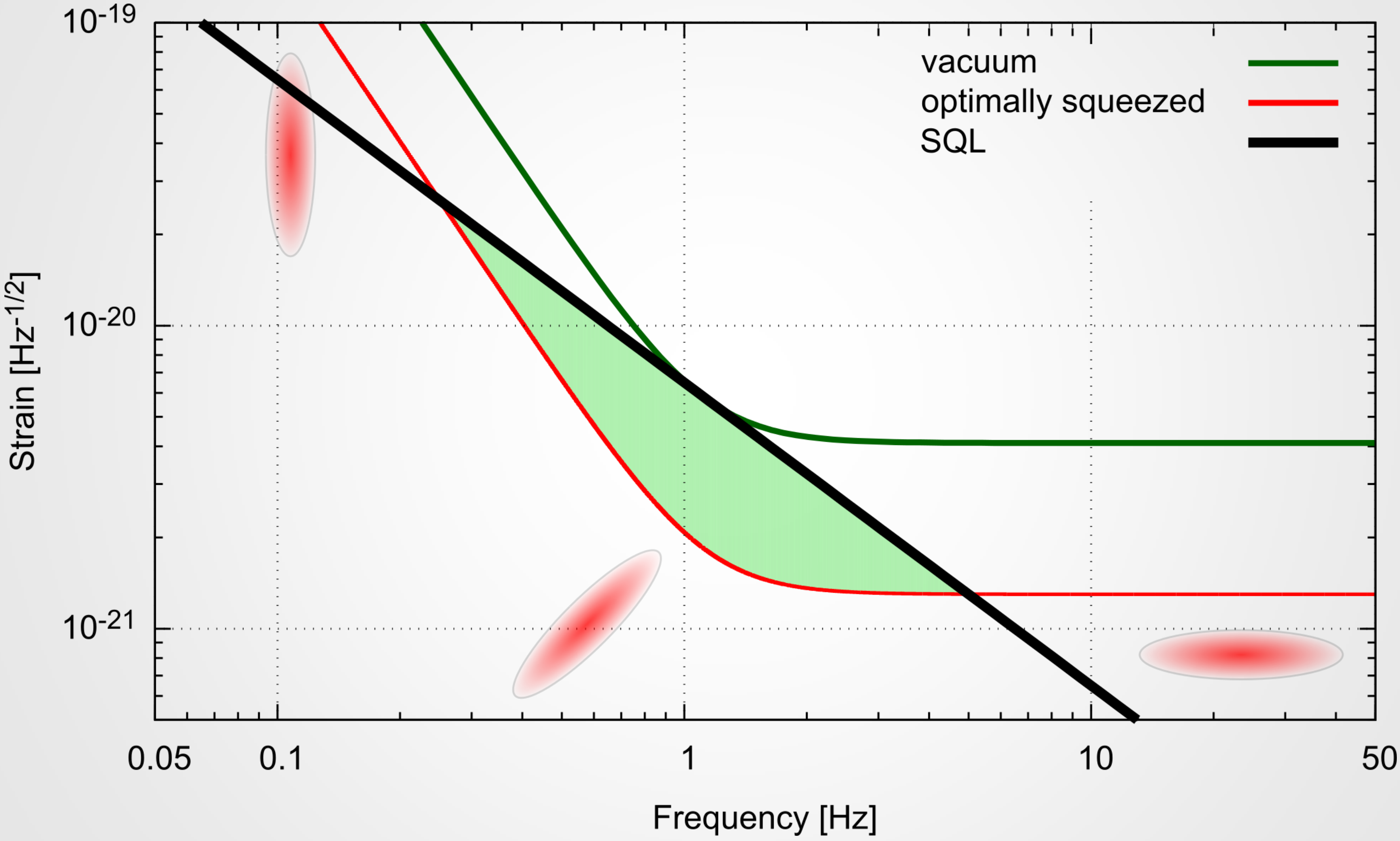
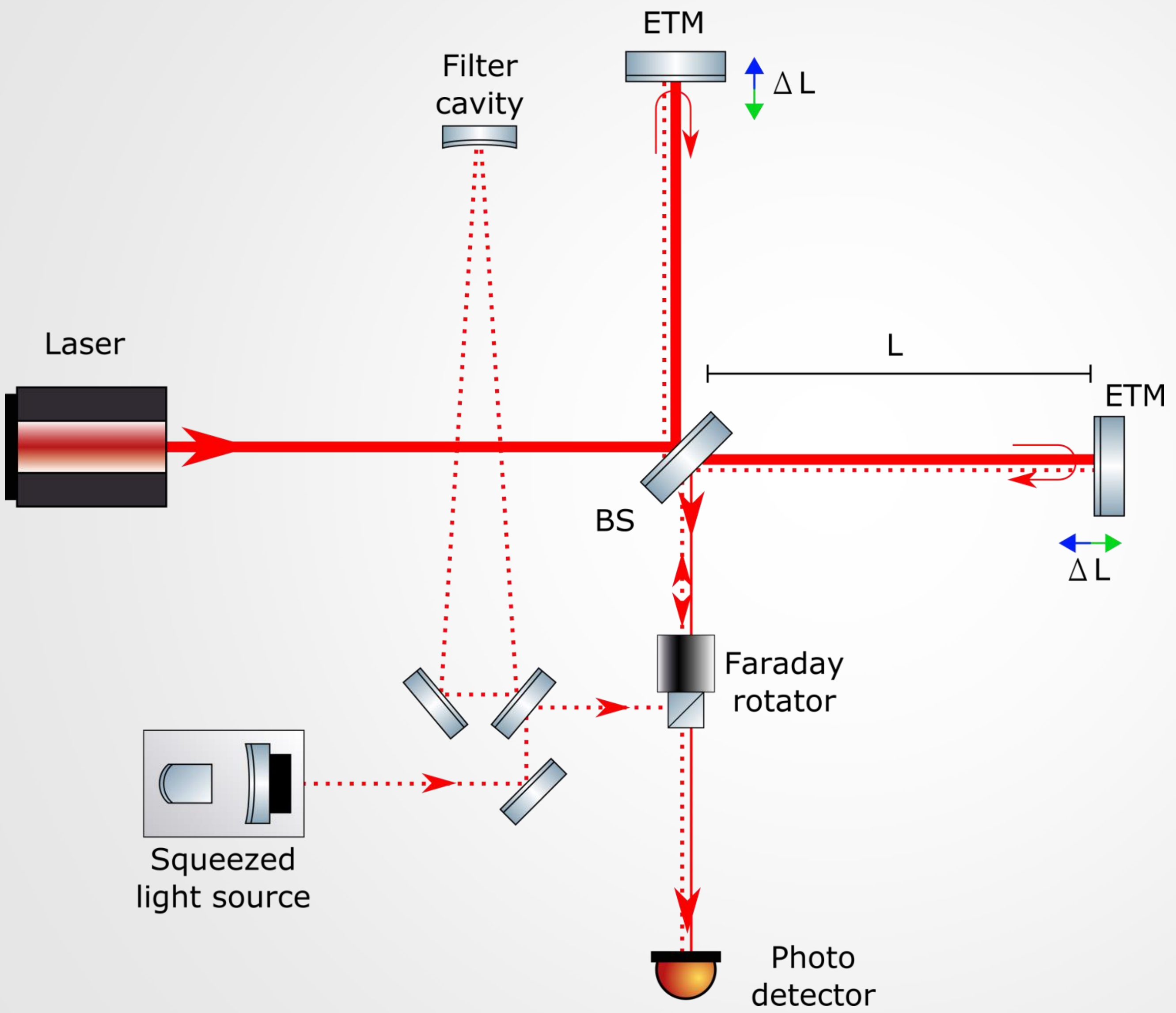




Squeezed Quantum Noise Spectra



Approach by Filter Cavities



Kimble et al. *Phys. Rev. D* **65** (2001)

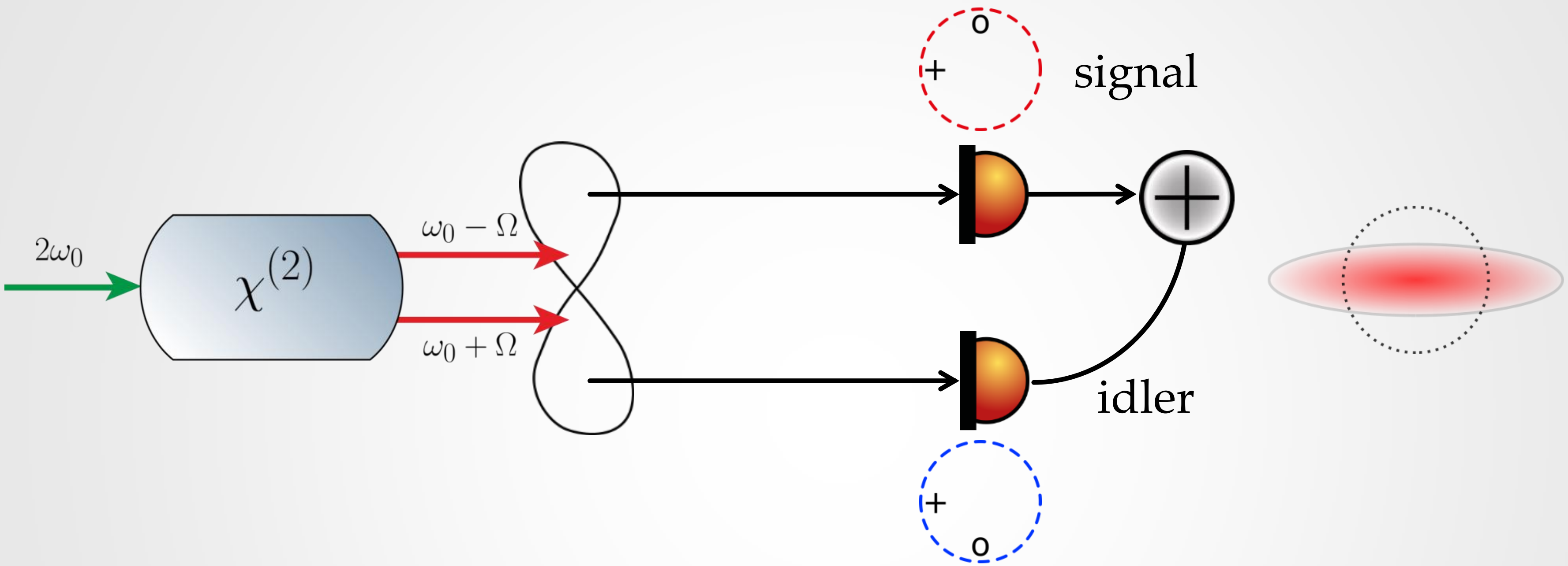
Proposal using EPR-Entanglement

ARTICLES
PUBLISHED ONLINE: 15 MAY 2017 | DOI: 10.1038/NPHYS4118
nature physics

Proposal for gravitational-wave detection beyond the standard quantum limit through EPR entanglement

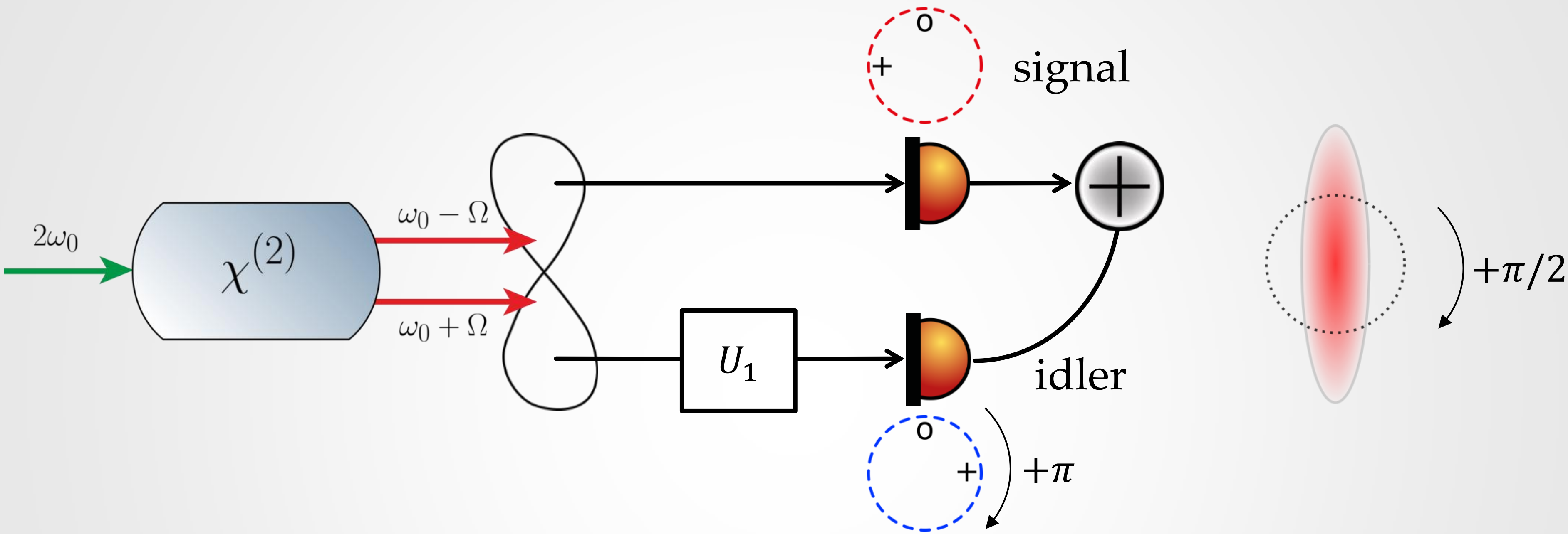
Yiqiu Ma[1*], Haixing Miao[2], Belinda Heyun Pang[1], Matthew Evans[3], Chunnong Zhao[4], Jan Harms[5,6], Roman Schnabel[7] and Yanbei Chen[1]

Proposal using EPR-Entanglement



Y. Ma et al. *Nature Physics* **13** (8) (2017)

Proposal using EPR-Entanglement



Y. Ma et al. *Nature Physics* **13** (8) (2017)

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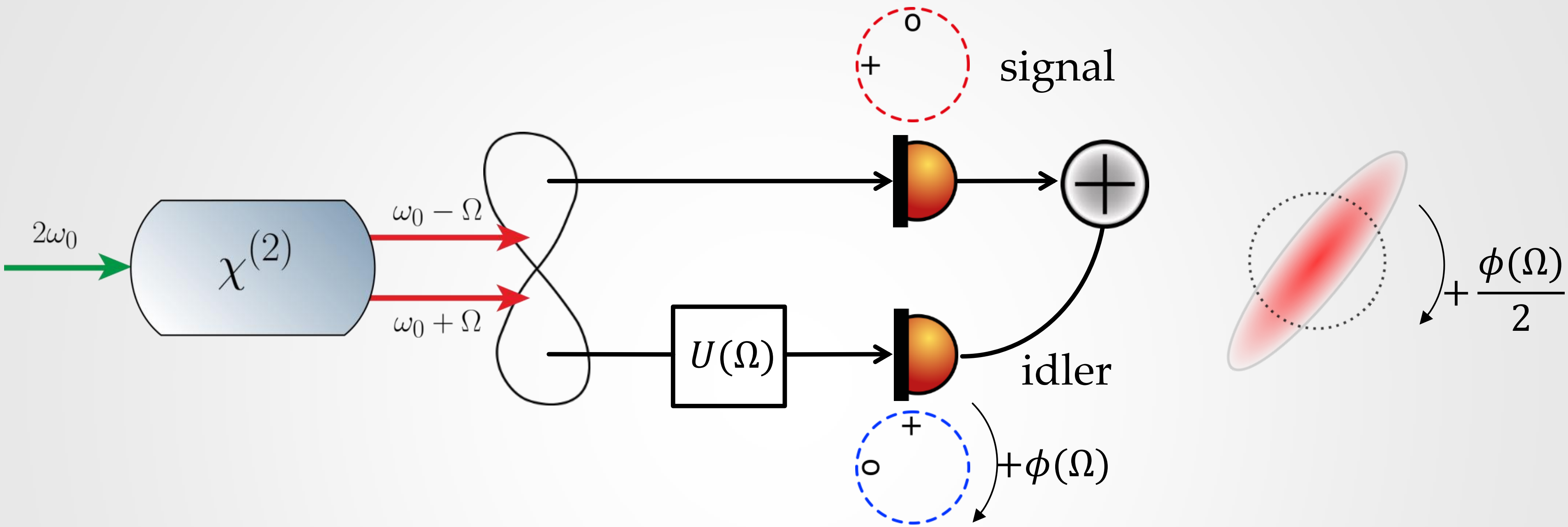

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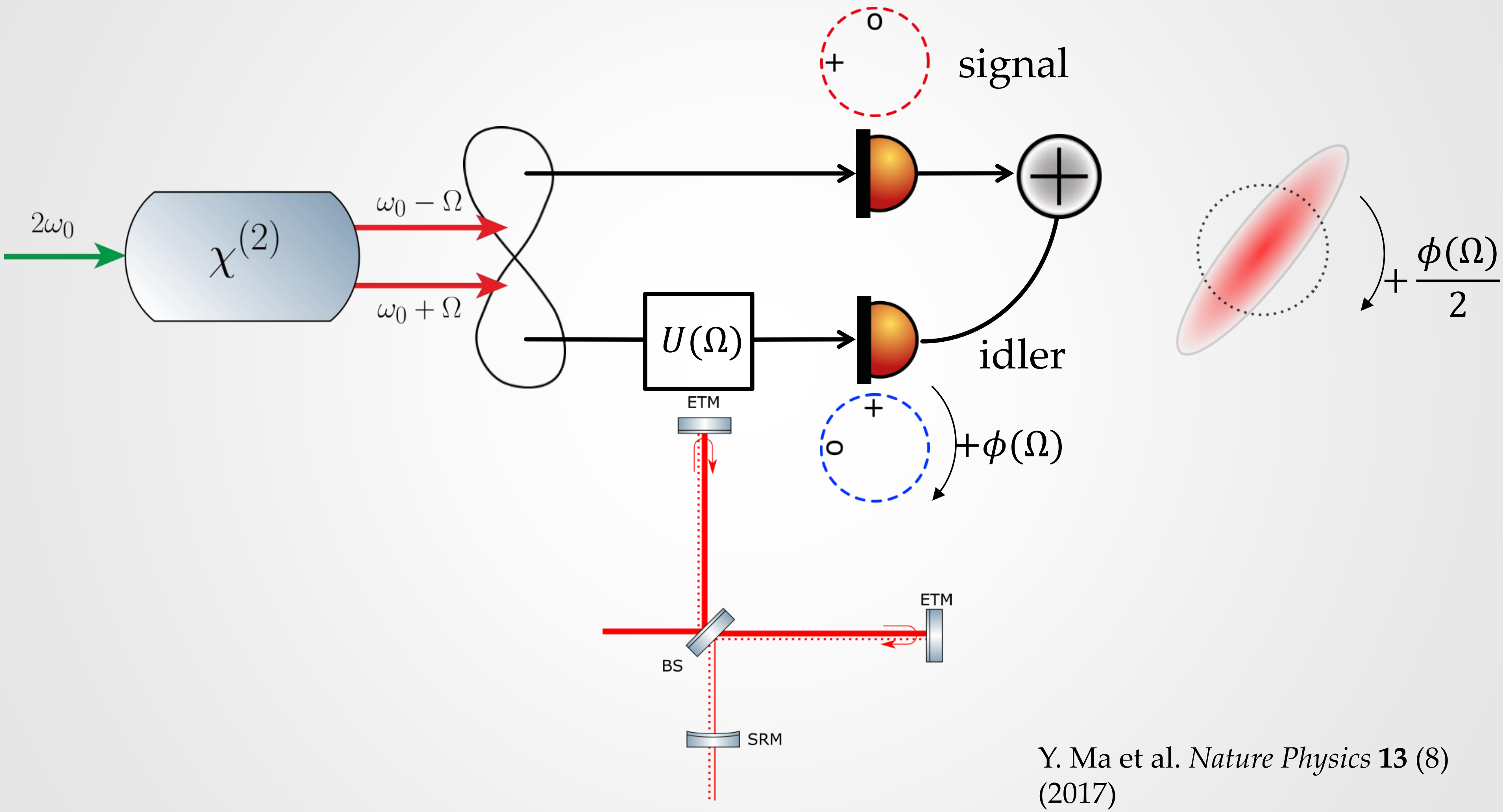

Y. Ma et al. *Nature Physics* **13** (8) (2017)

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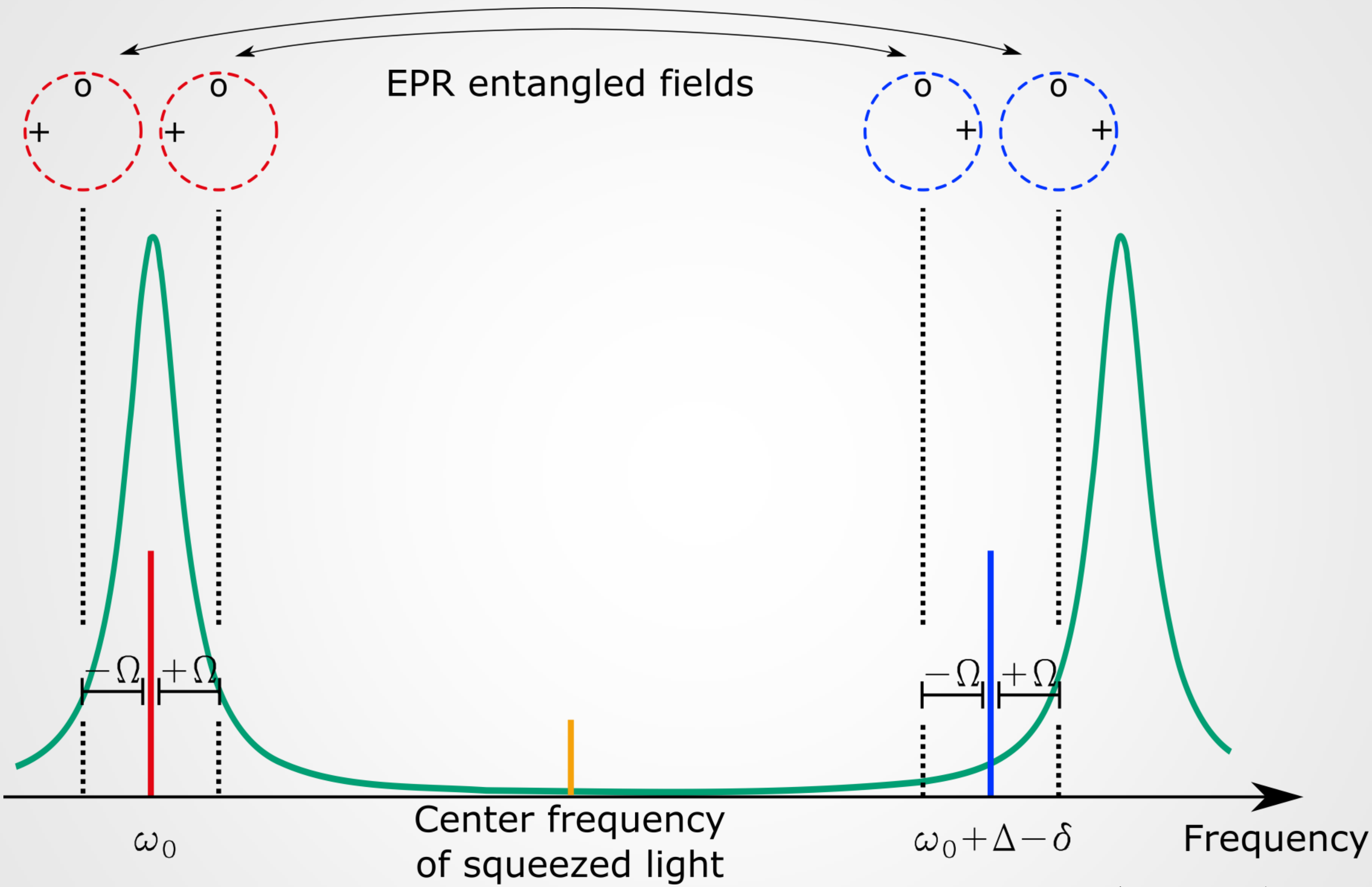
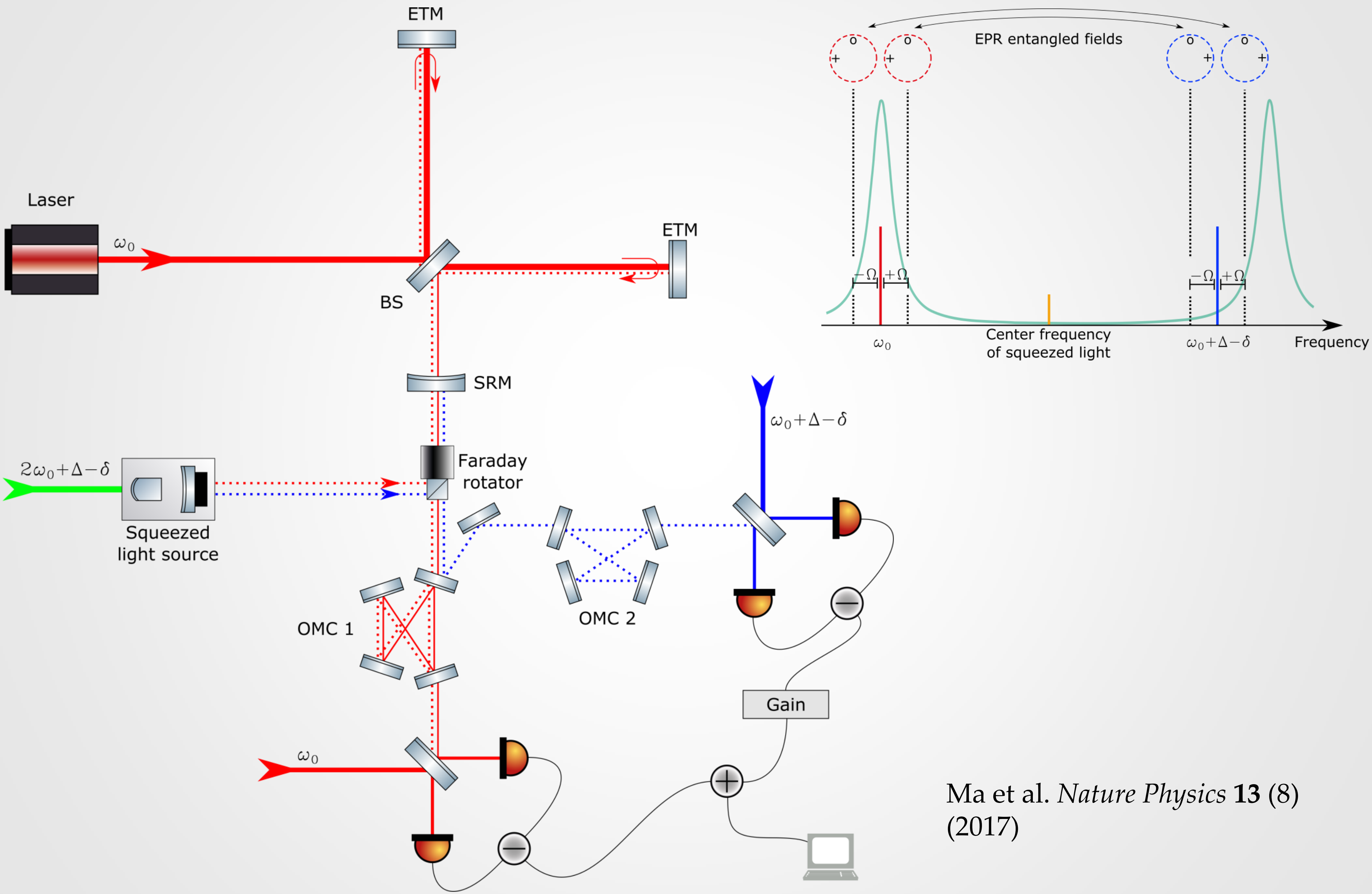


Ma et al. *Nature Physics* **13** (8) (2017)

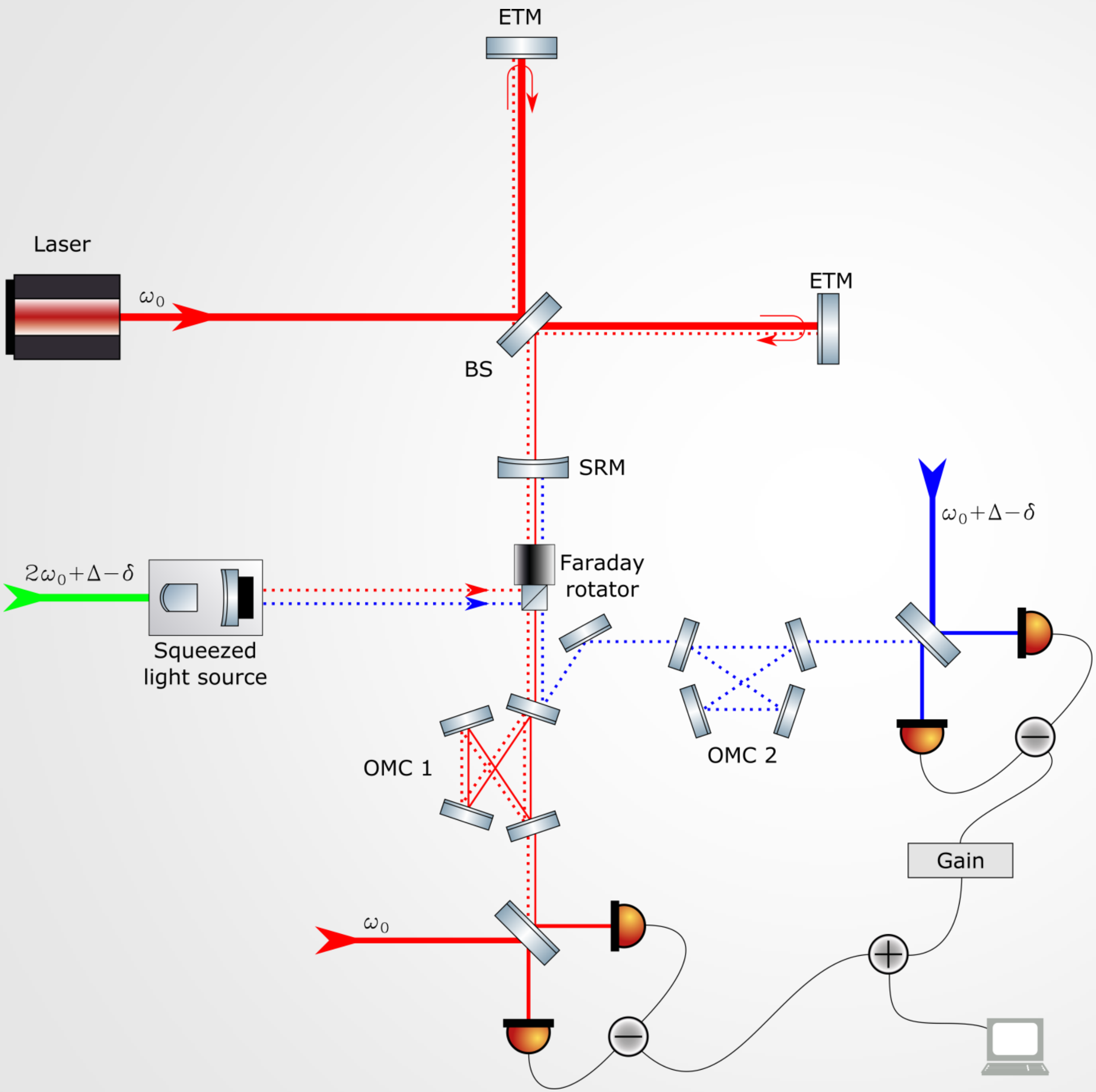
Proposal using EPR-Entanglement



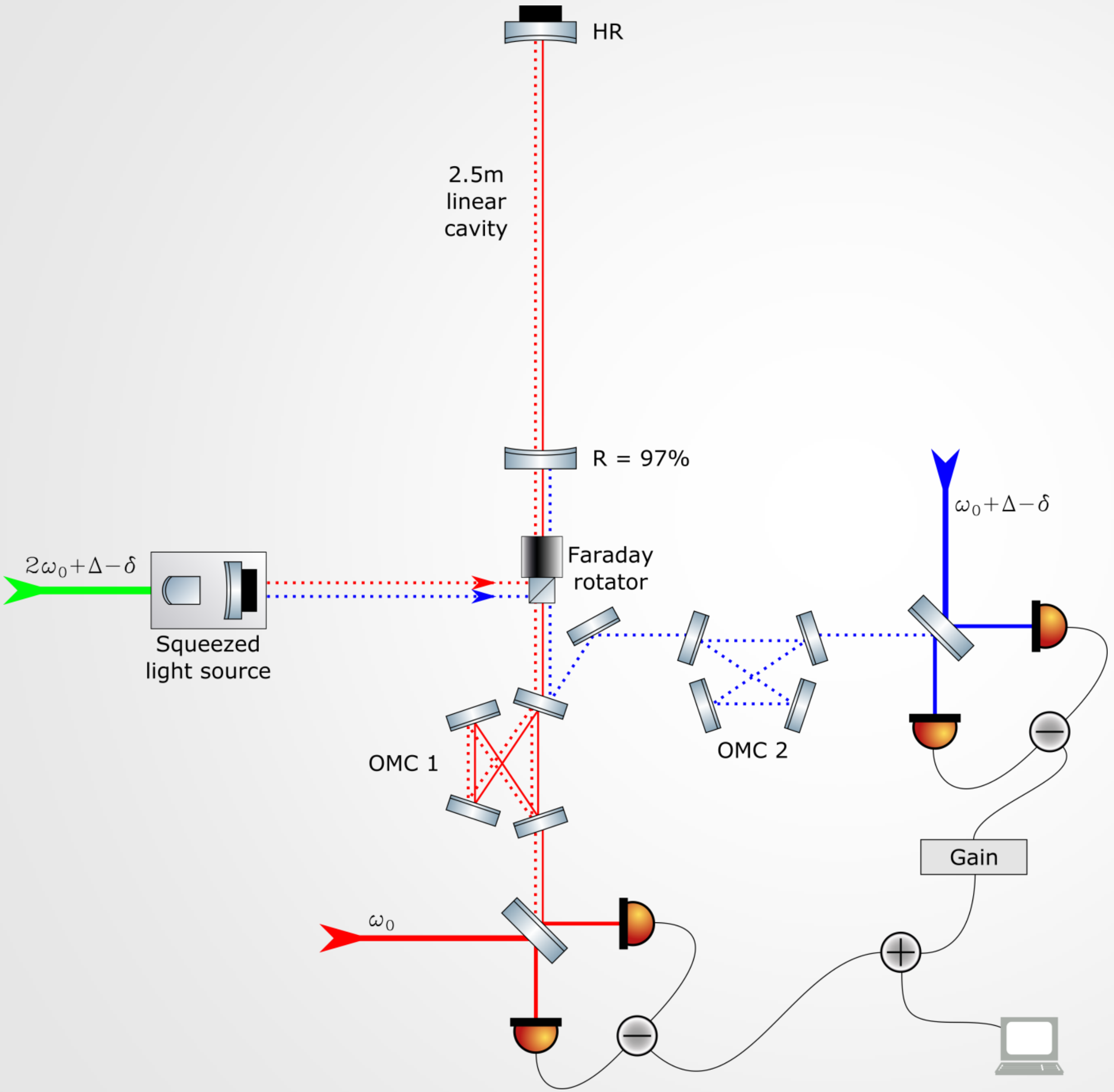
Ma et al. *Nature Physics* **13** (8) (2017)

EXPERIMENTAL REALIZATION IN HAMBURG

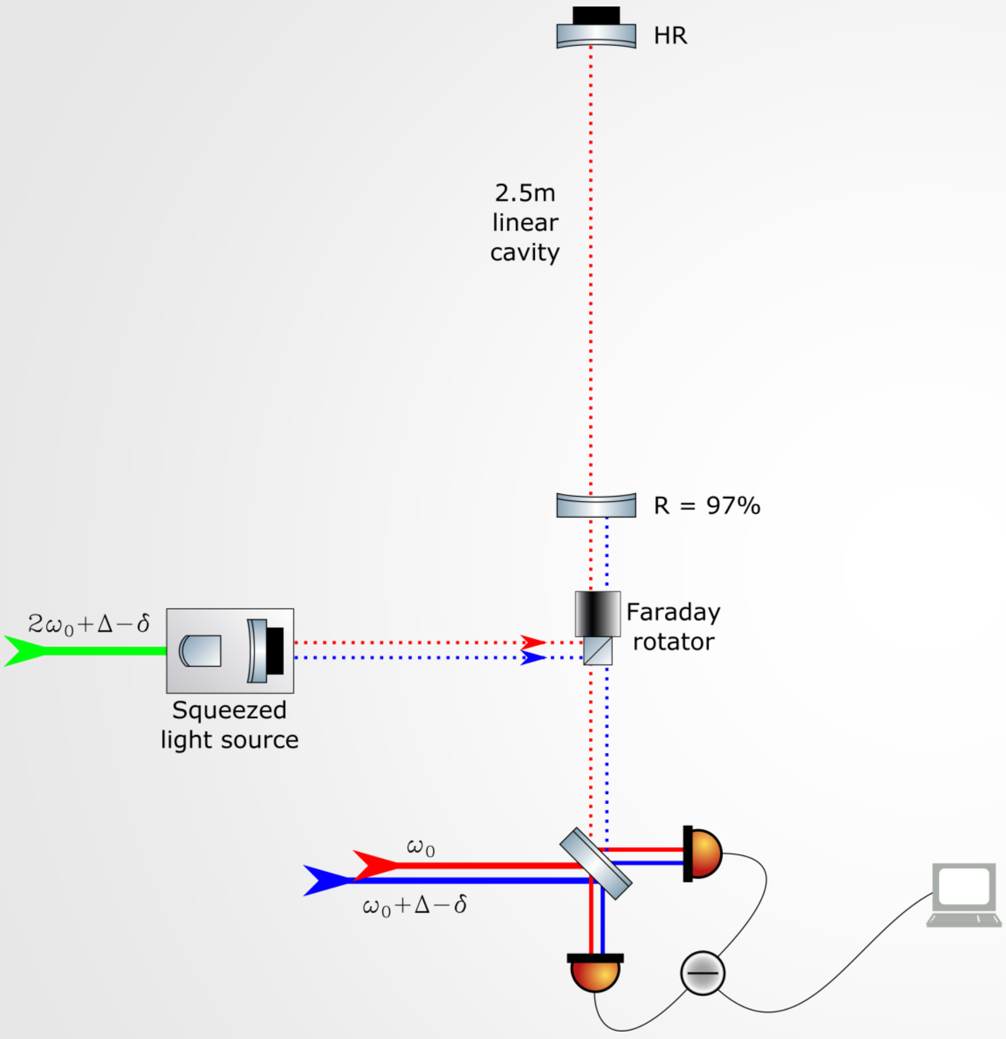
Experimental Realization Hamburg



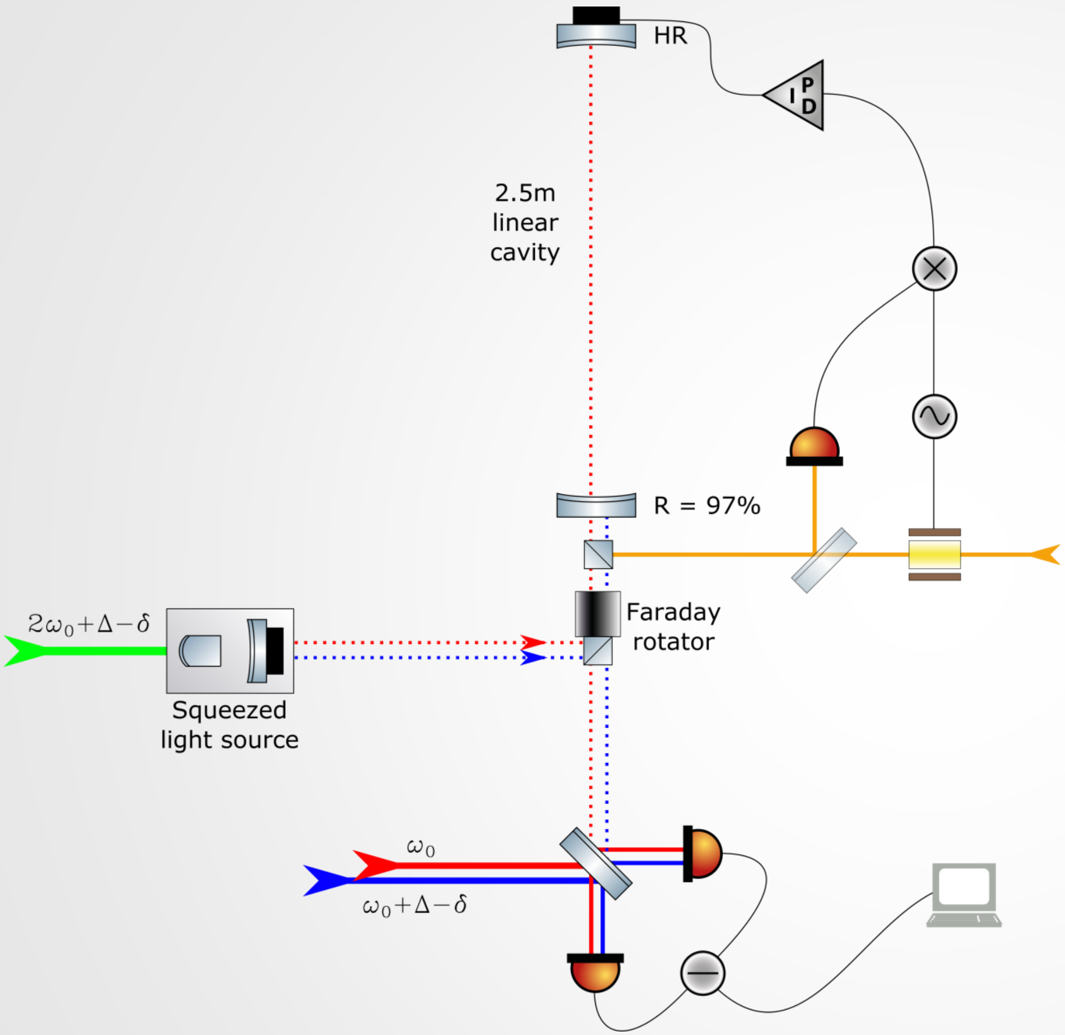
Experimental Realization Hamburg

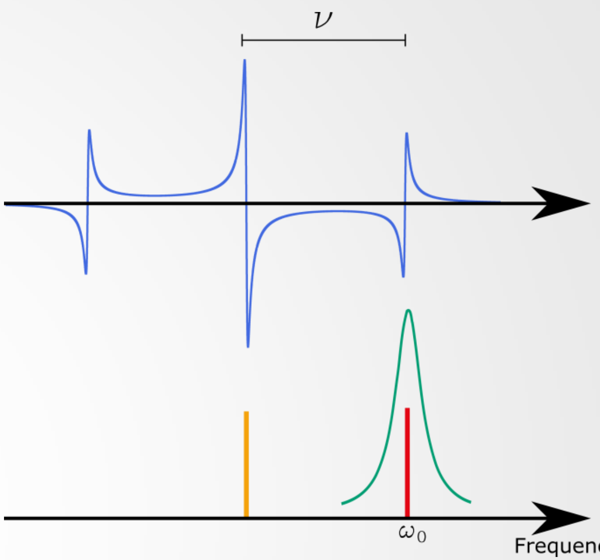


Experimental Realization Hamburg

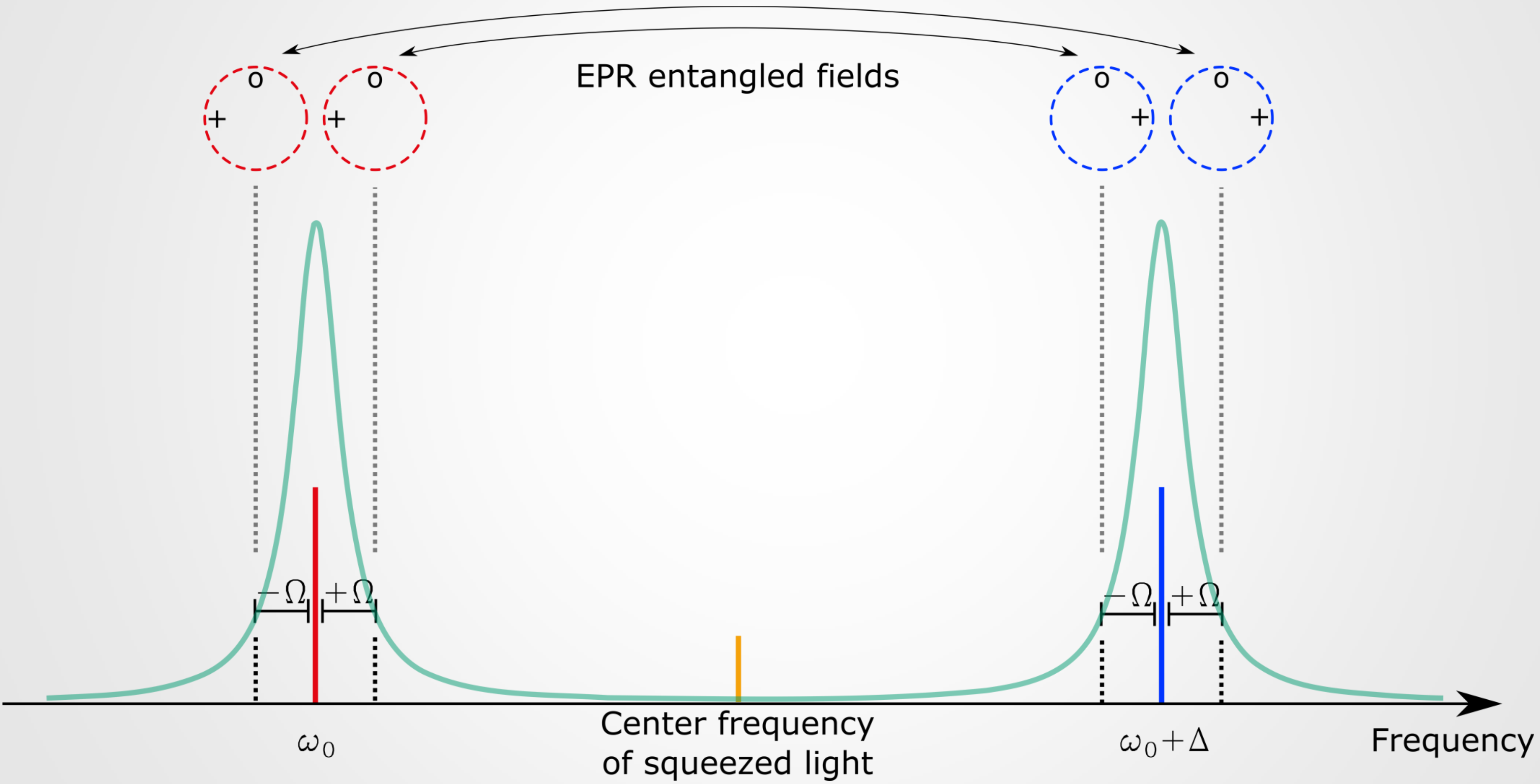


Experimental Realization Hamburg



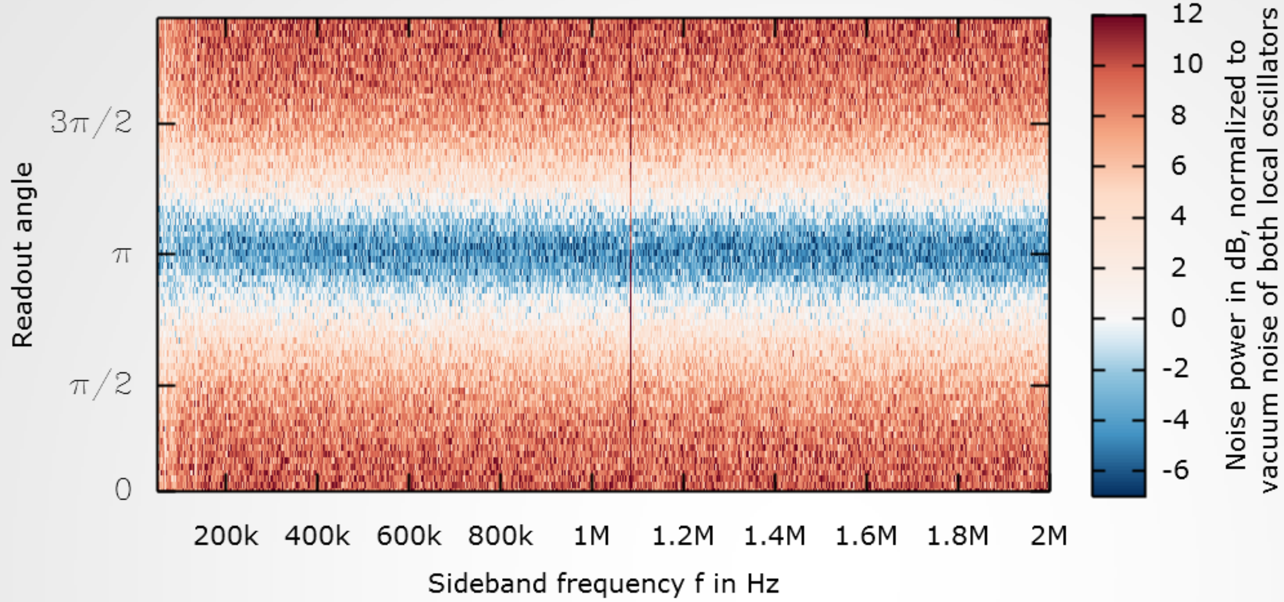


Results – No Detuning



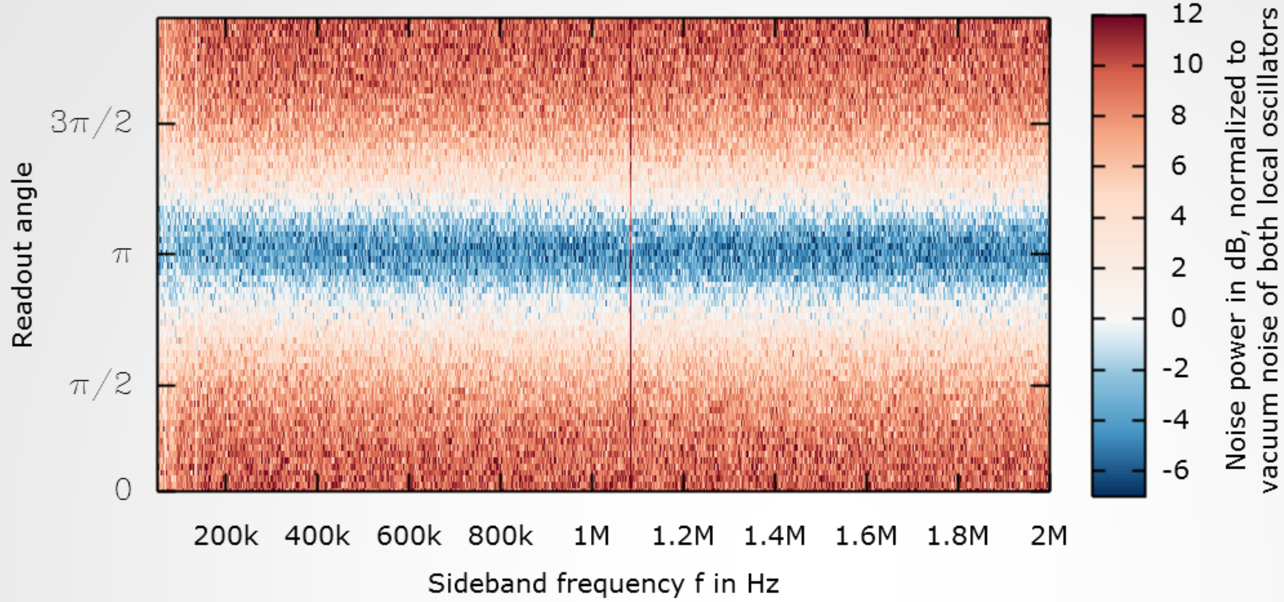
Results – No Detuning

Measurement

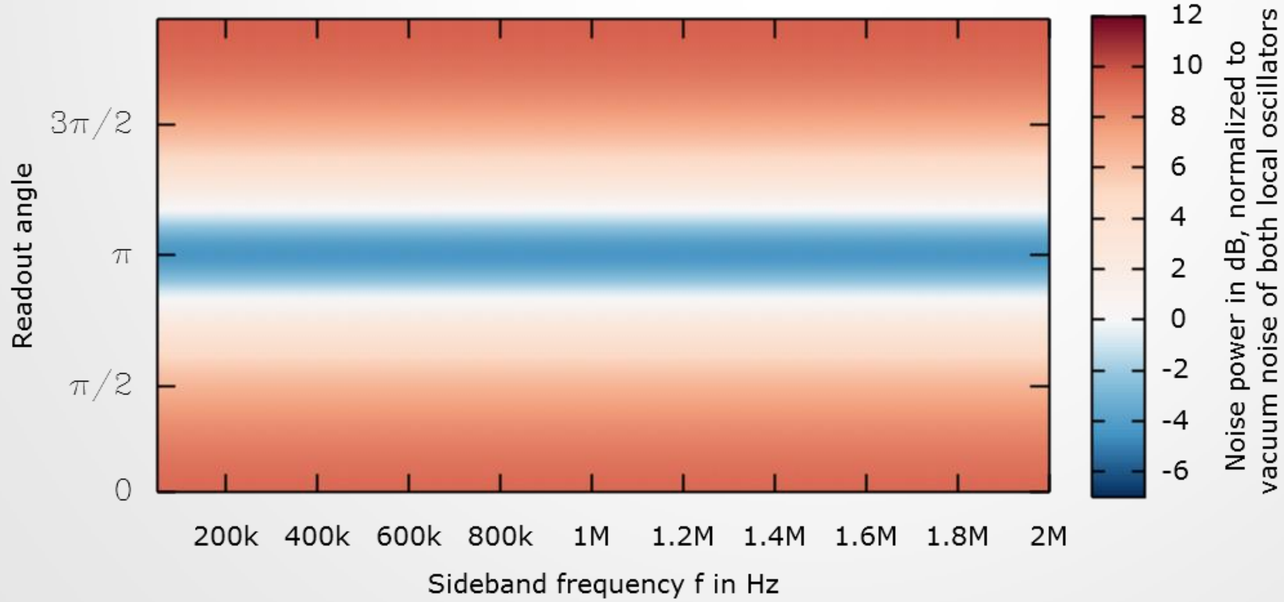


Results – No Detuning

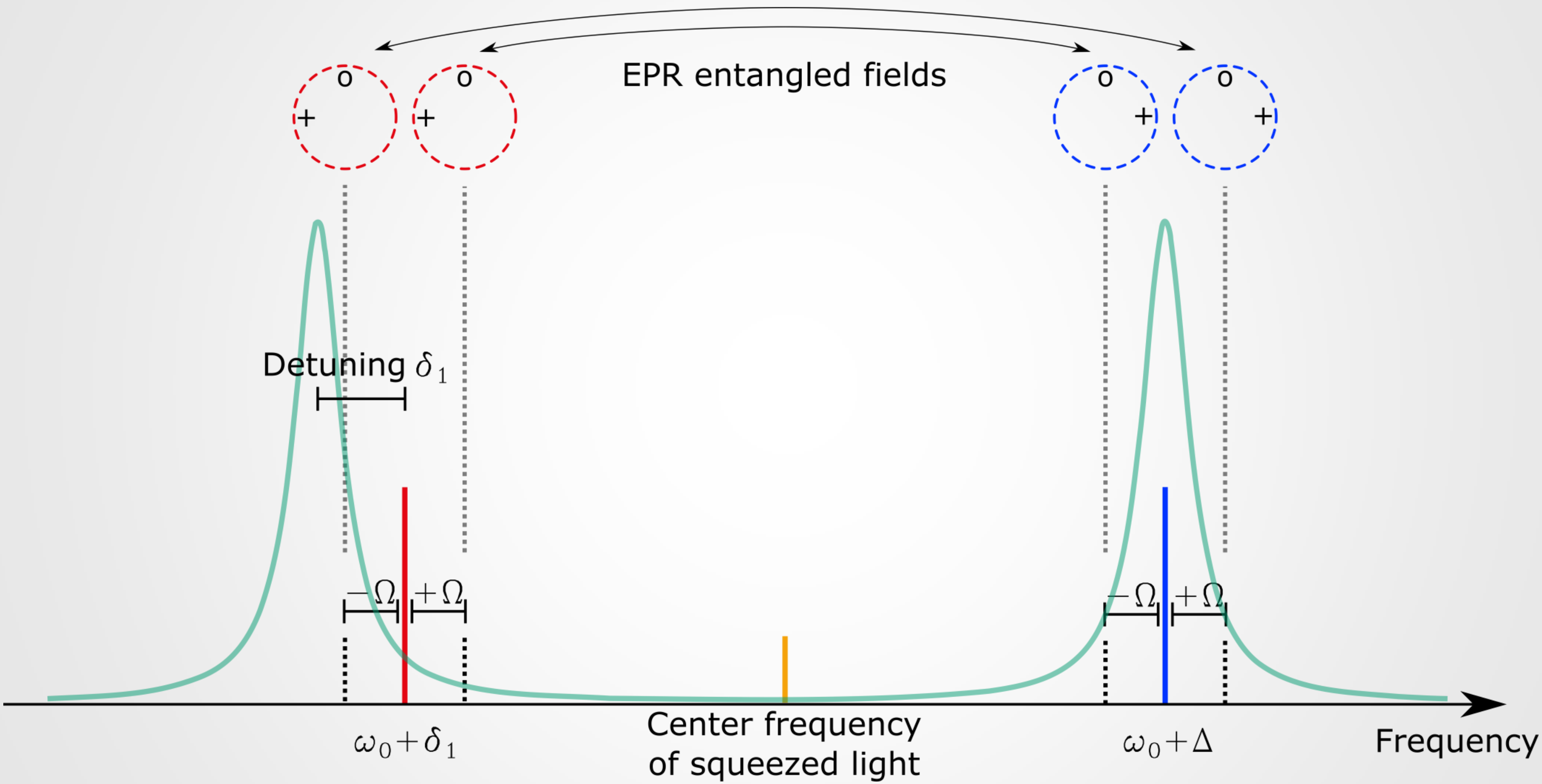
Measurement



Fitted model

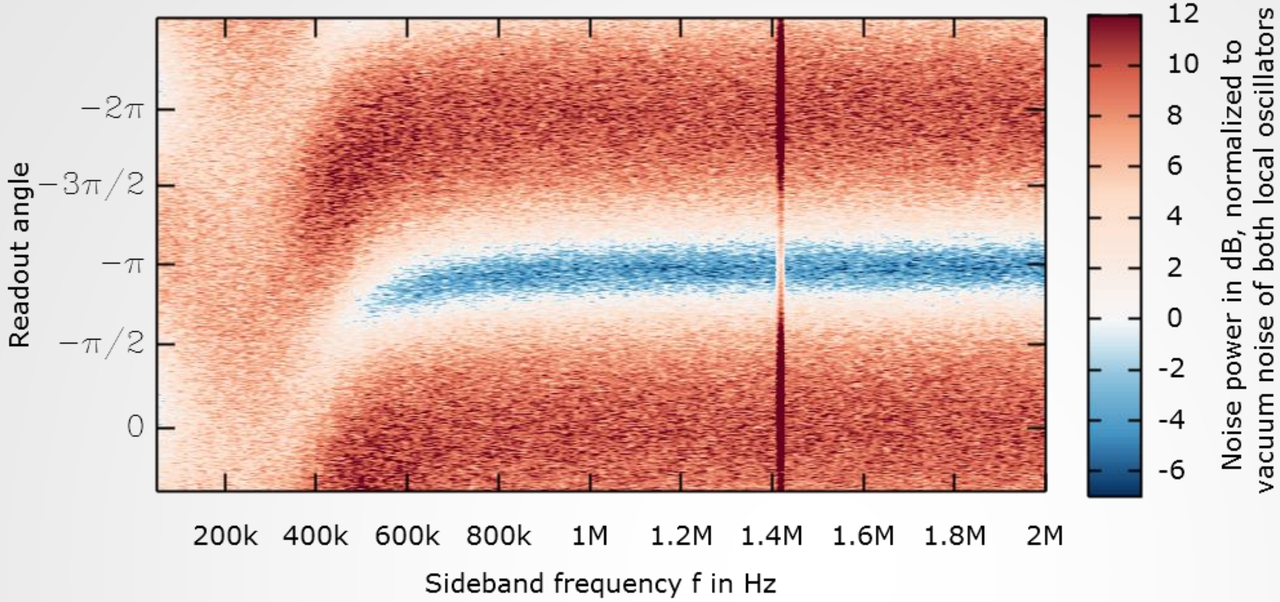


Results – Emulating Frequency Dependence



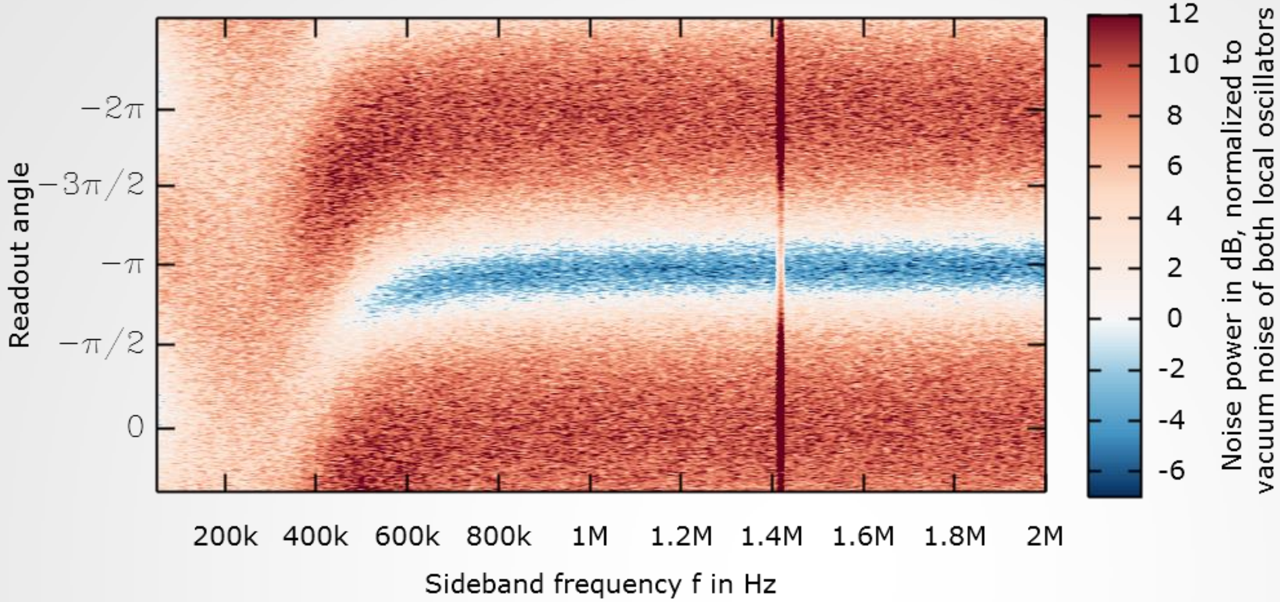
Results – Emulating Frequency Dependence

Measurement

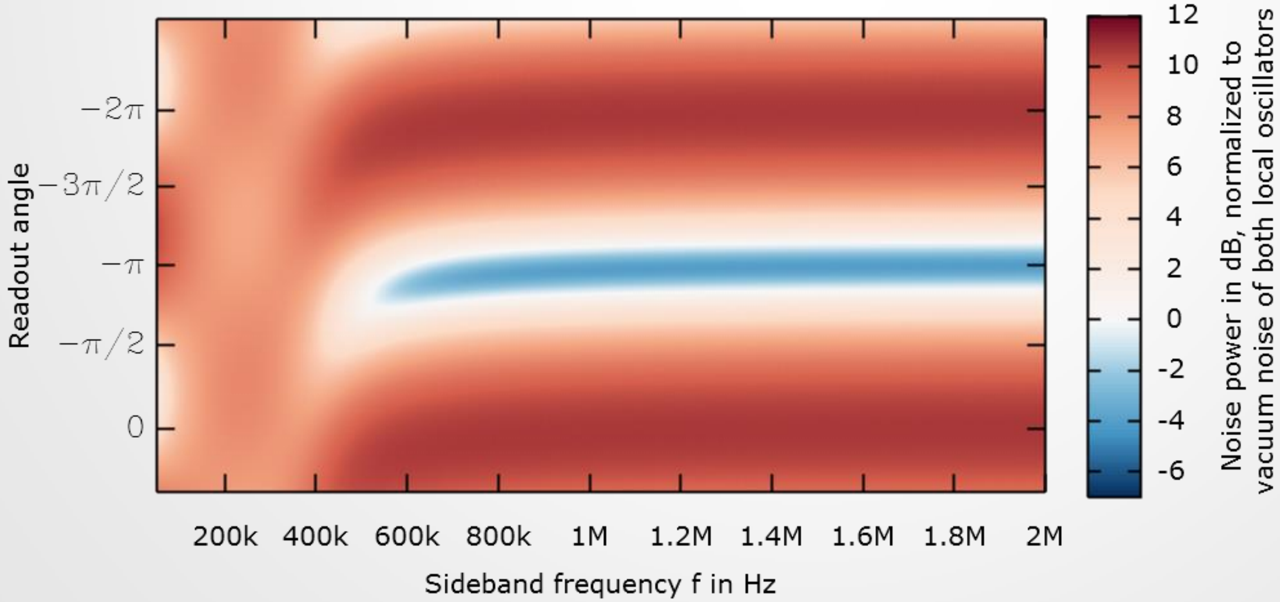


Results – Emulating Frequency Dependence

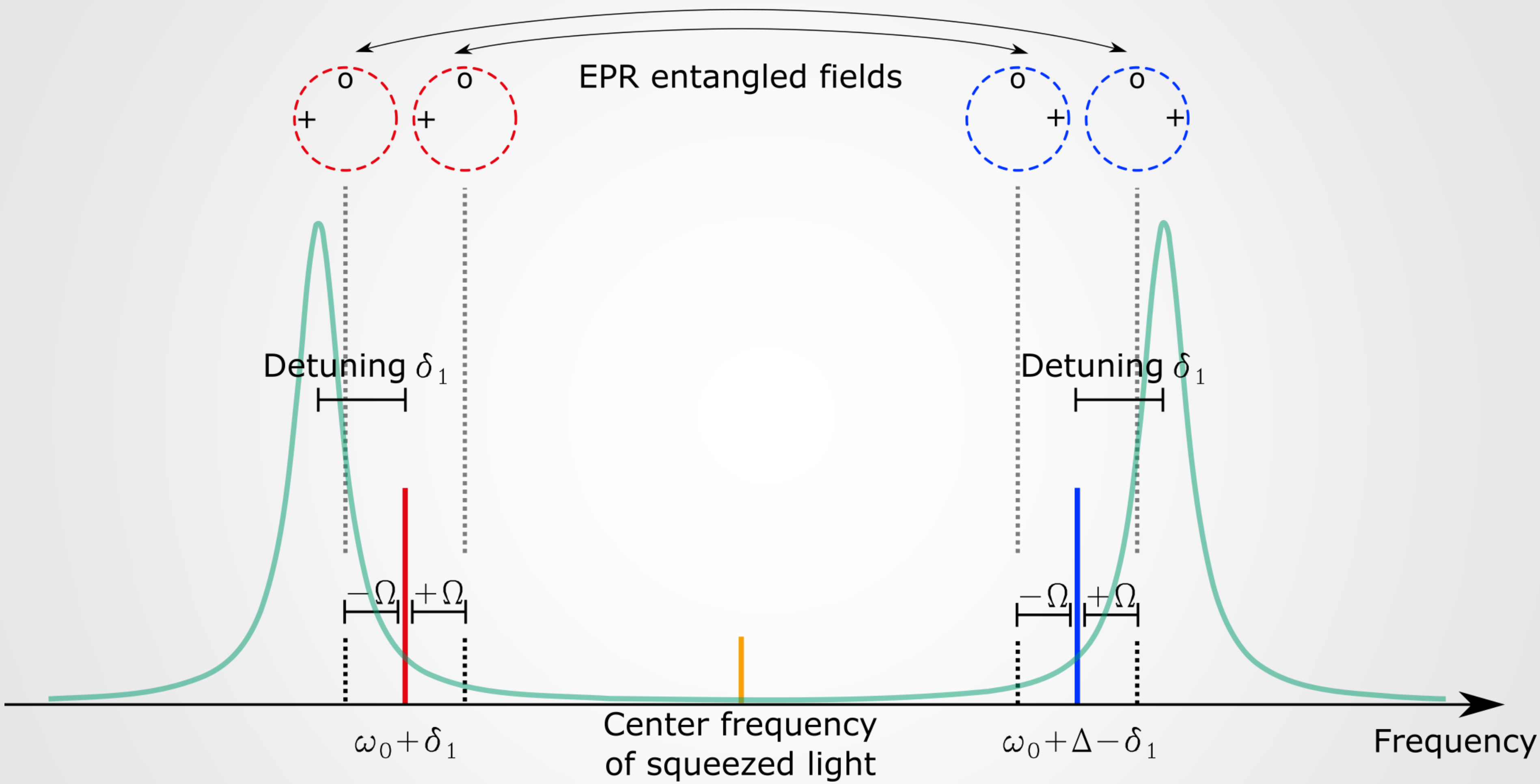
Measurement



Fitted model

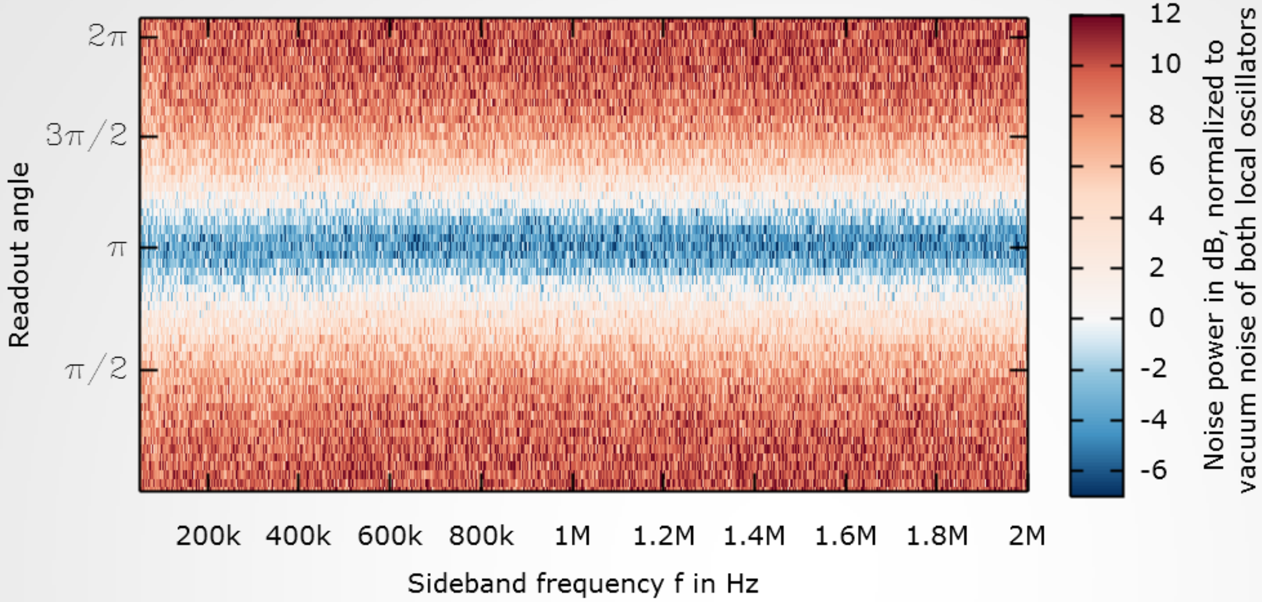


Results – Compensating Frequency Dependence



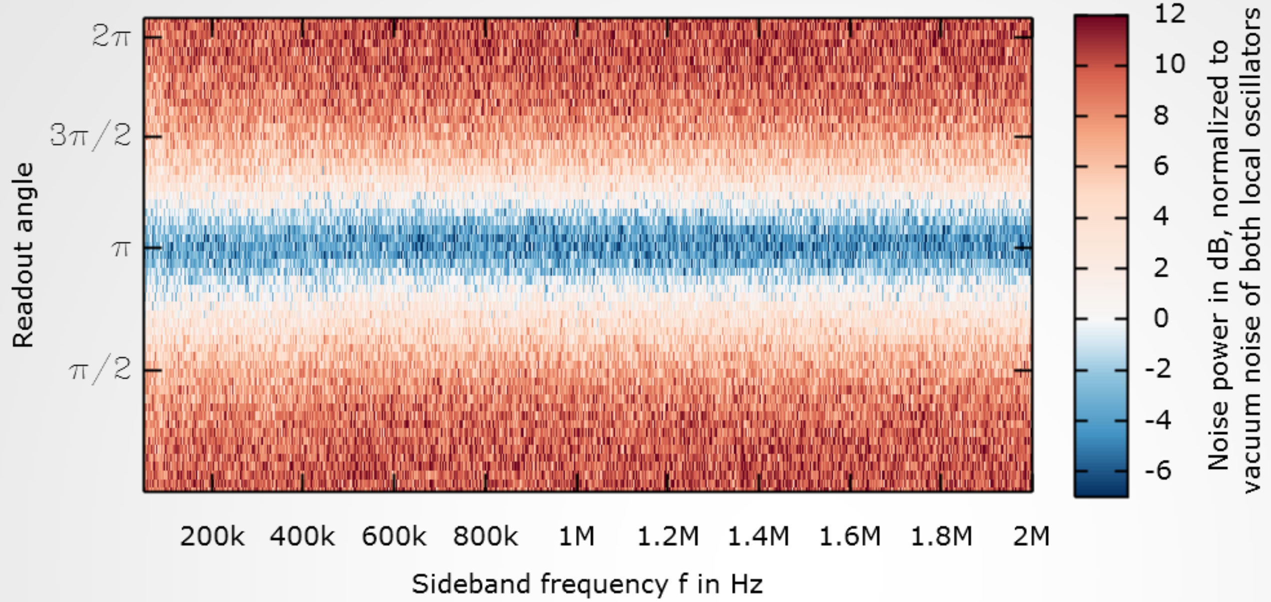
Results – Compensating Frequency Dependence

Measurement

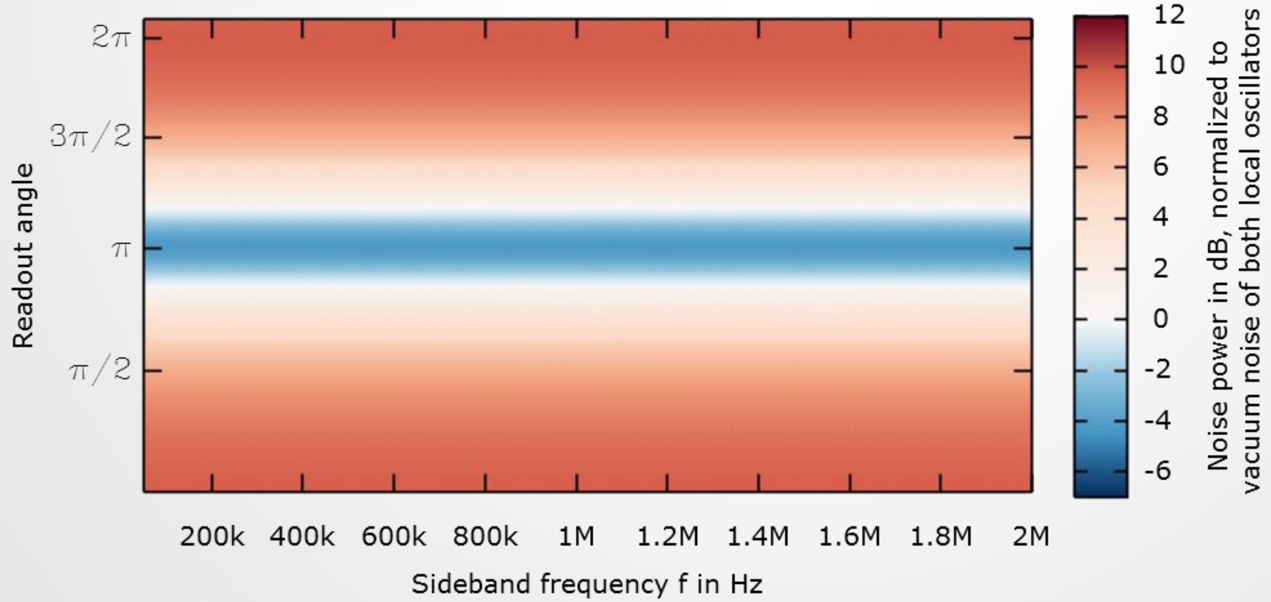


Results – Compensating Frequency Dependence

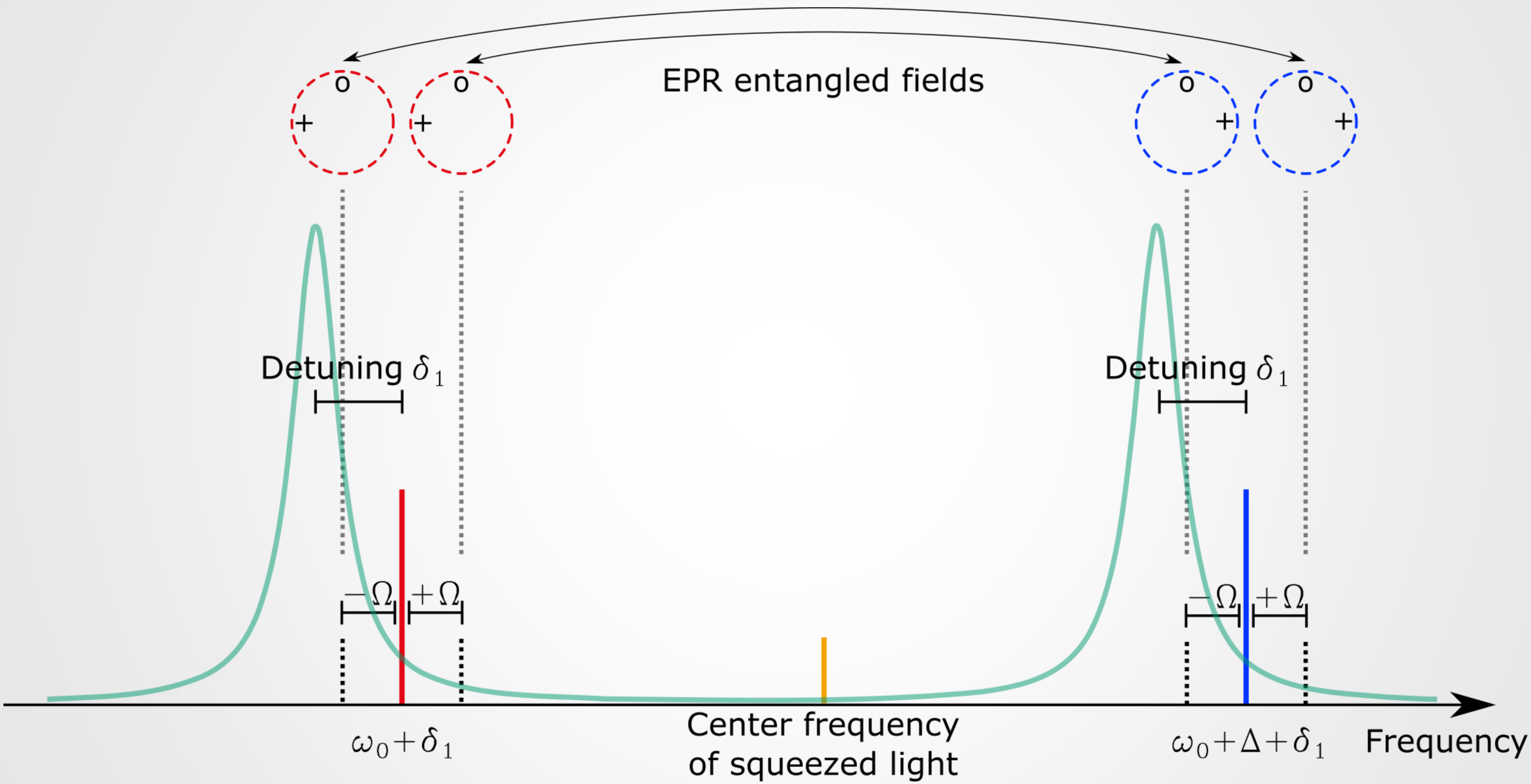
Measurement



Fitted model

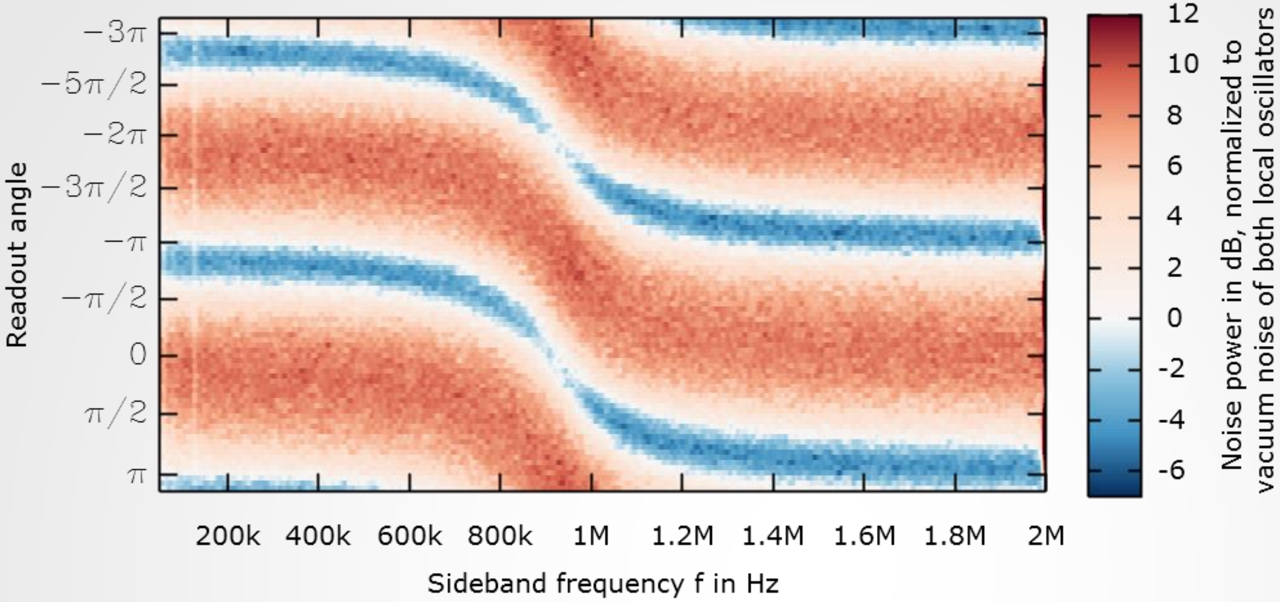


Results – Symmetric Detuning



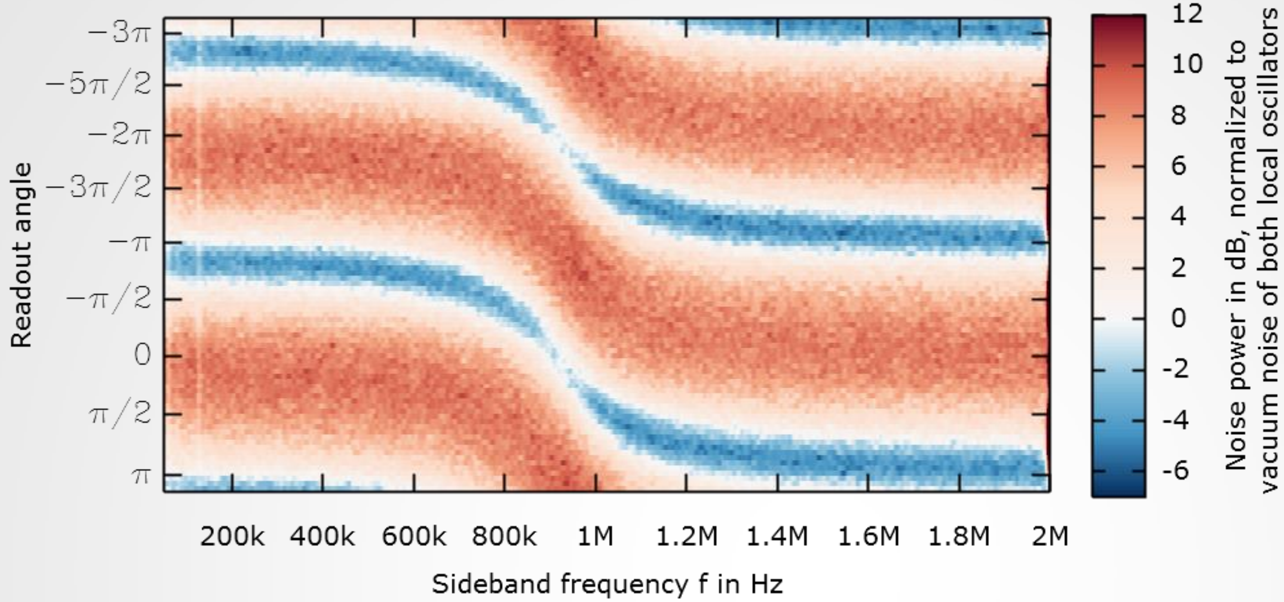
Results – Symmetric Detuning

Measurement

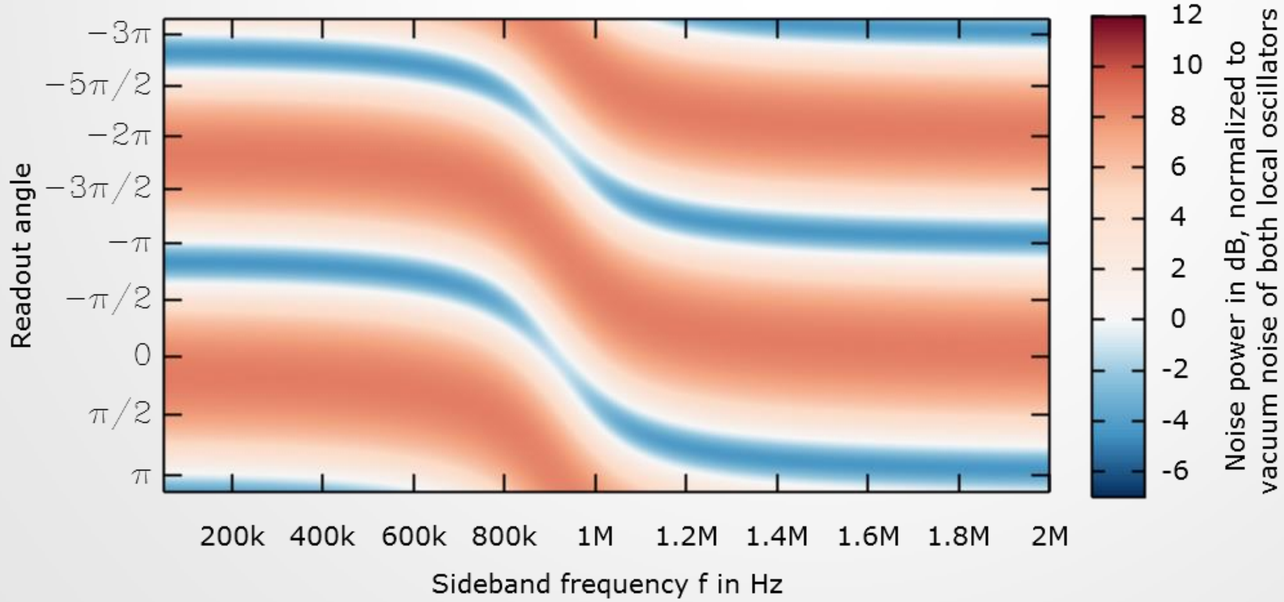


Results – Symmetric Detuning

Measurement

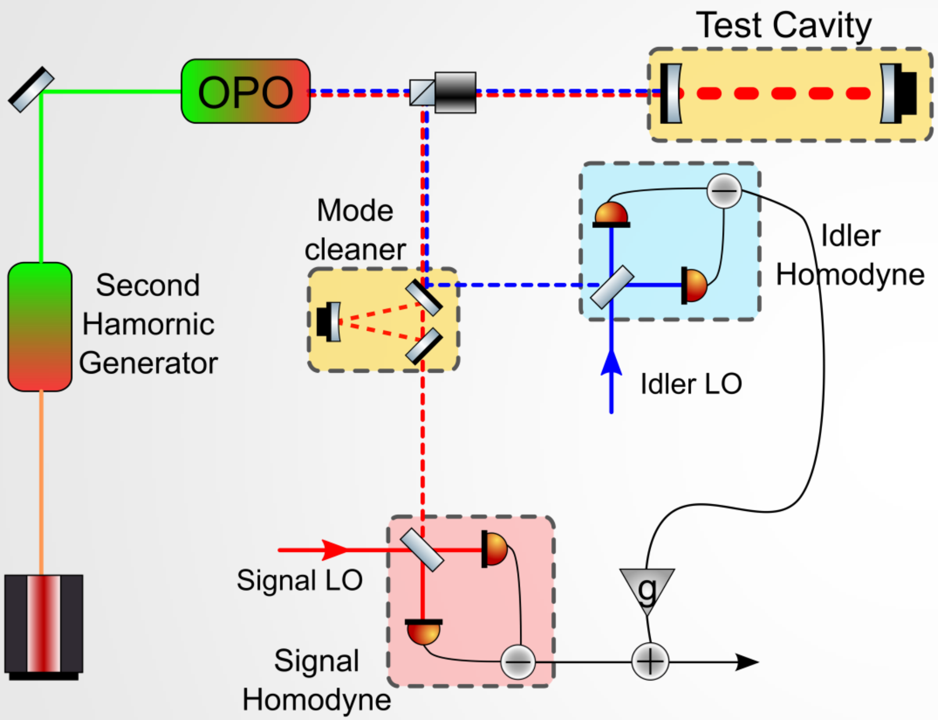


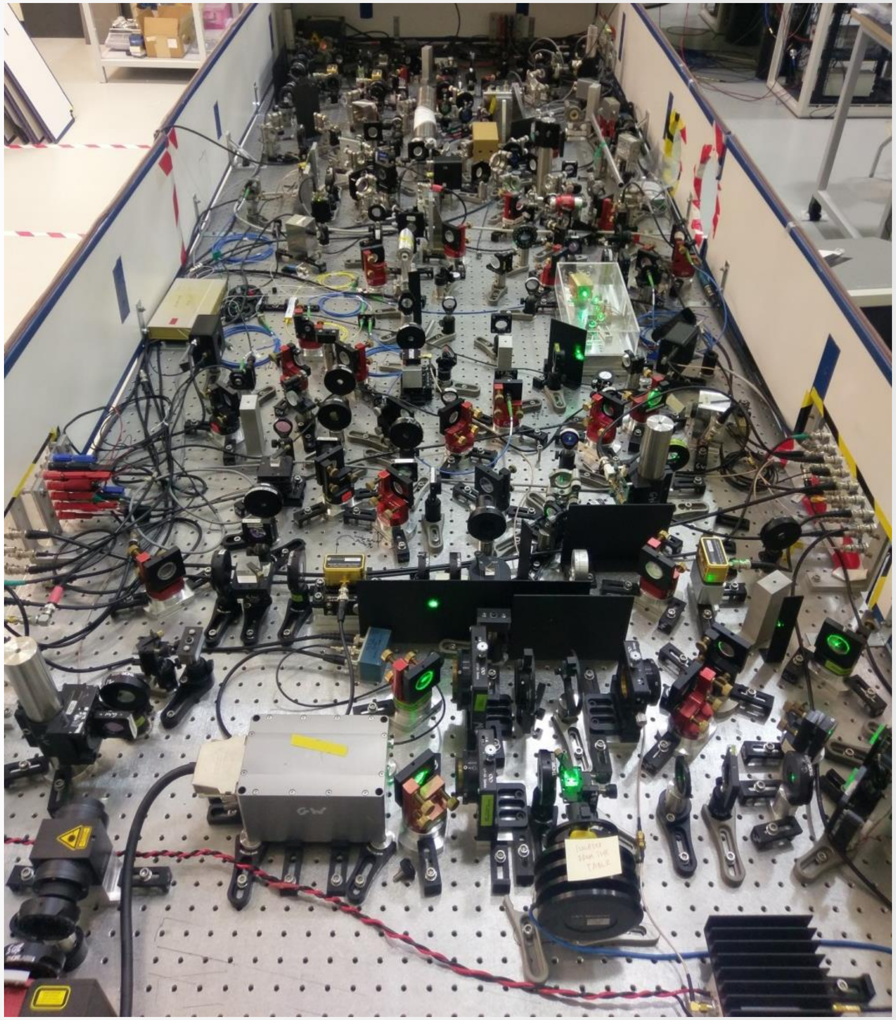
Fitted model



EXPERIMENTAL REALIZATION AT ANU

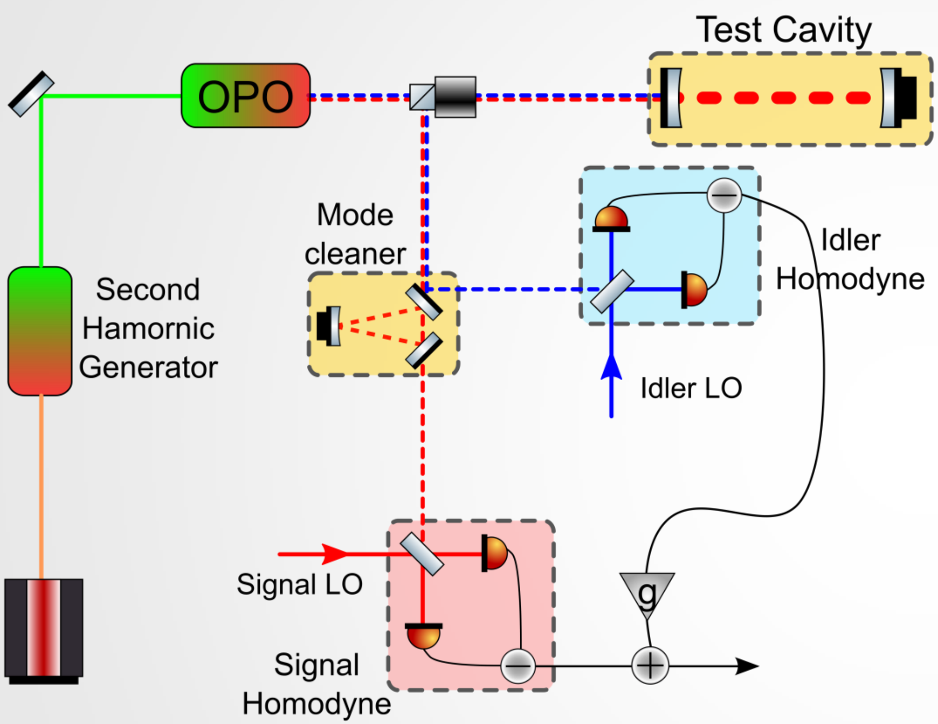
Proof of principle experiment





- Signal/Idler LO generated via phase modulation.
- Separated via additional mode cleaner cavities.

Proof of principle experiment



- Signal/Idler LO generated via phase modulation.
- Separated via additional mode cleaner cavities.

<u>OPO</u>

- Signal/Idler separation = ~850 MHz (OPO FSR)

<u>Test cavity</u>

- FSR = 283 MHz (L = ~0.5m)
- HWHM = 1.38MHz

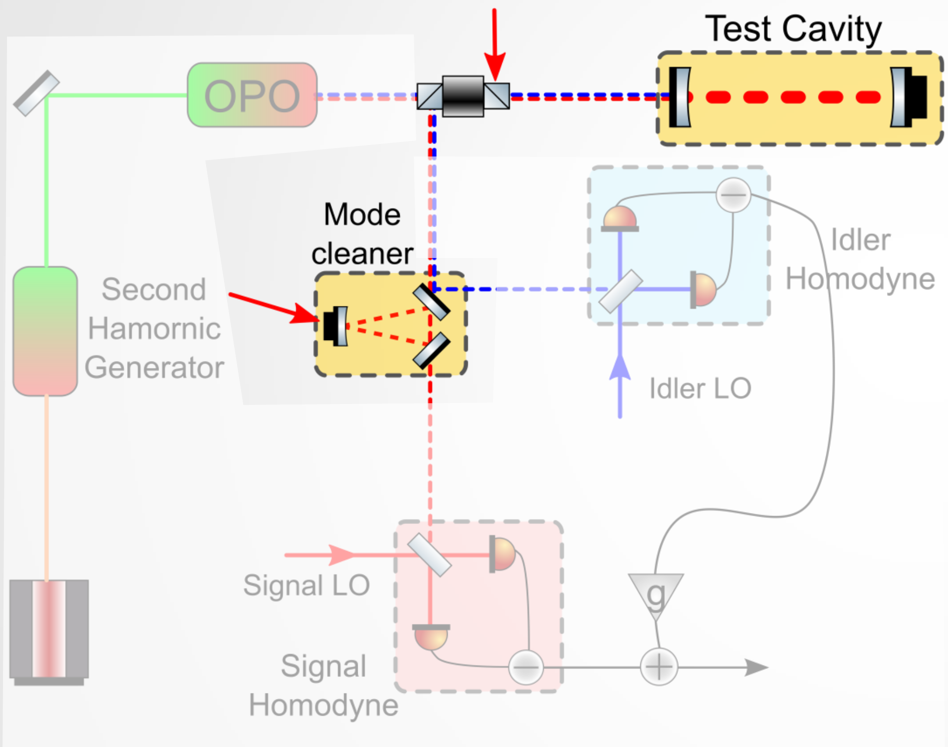
<u>OMC</u>

- HWHM = 60MHz

<u>Readout</u>

- Combined via passive combiner

Proof of principle experiment

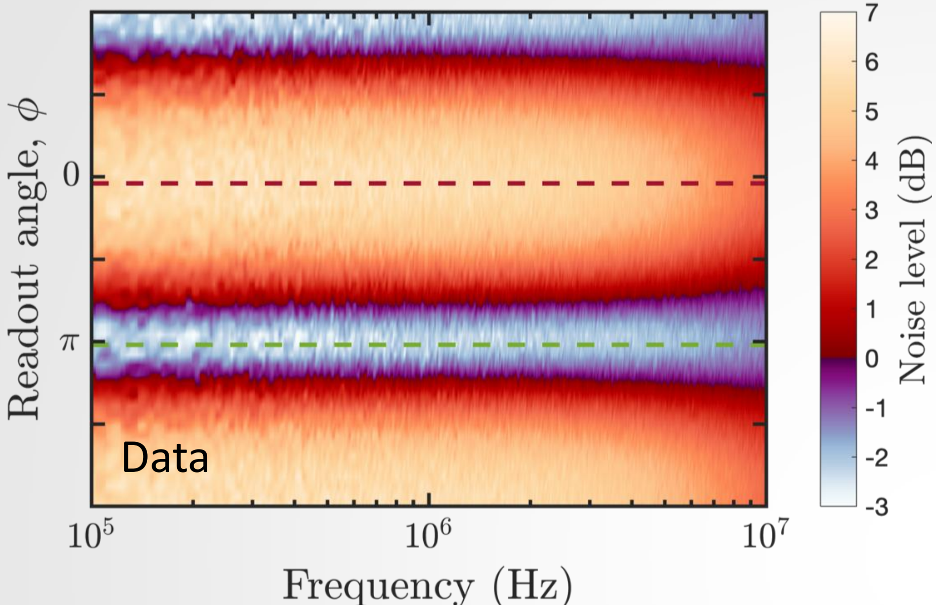


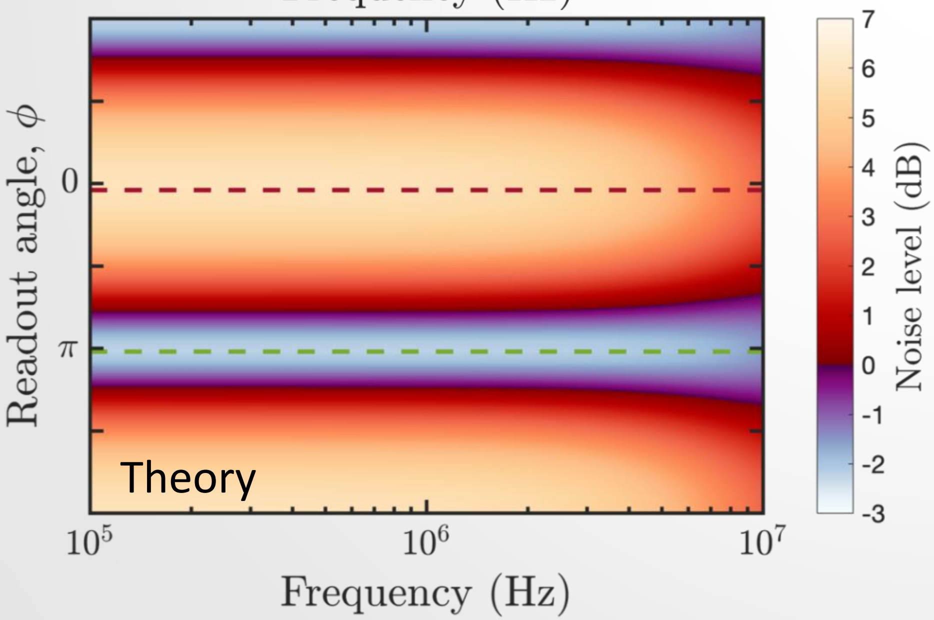
Locking scheme

Mode cleaner: counter-propagating field

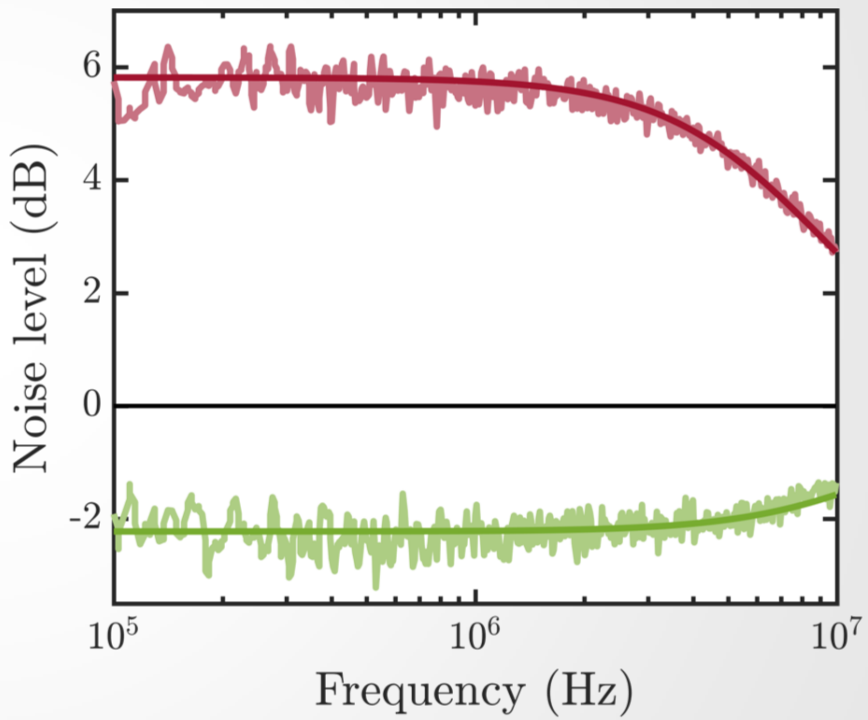
Test cavity: orthogonal polarization / AOM shifted

Results – no test cavity



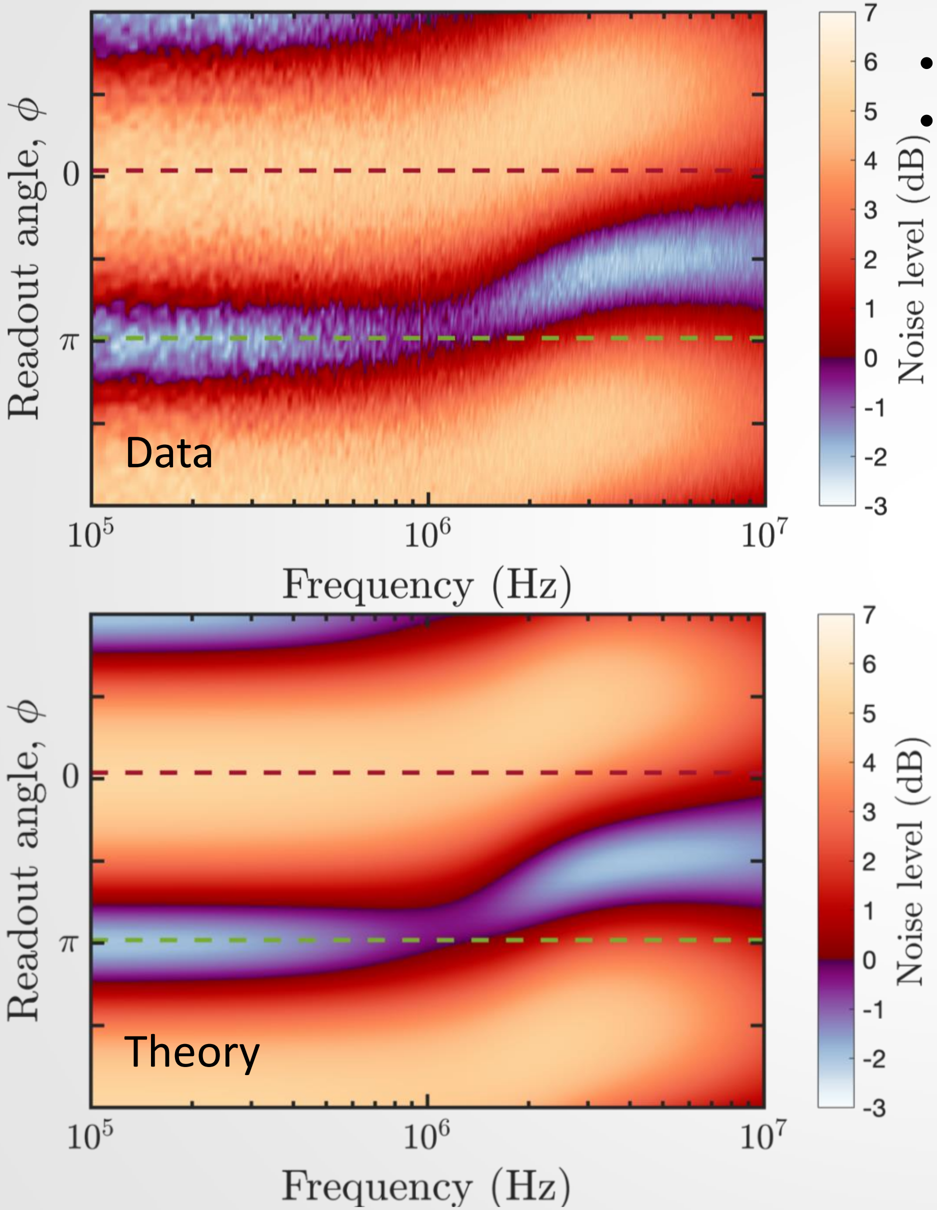


- Noise level of combined output
- Relative to shot noise level of both signal and idler field

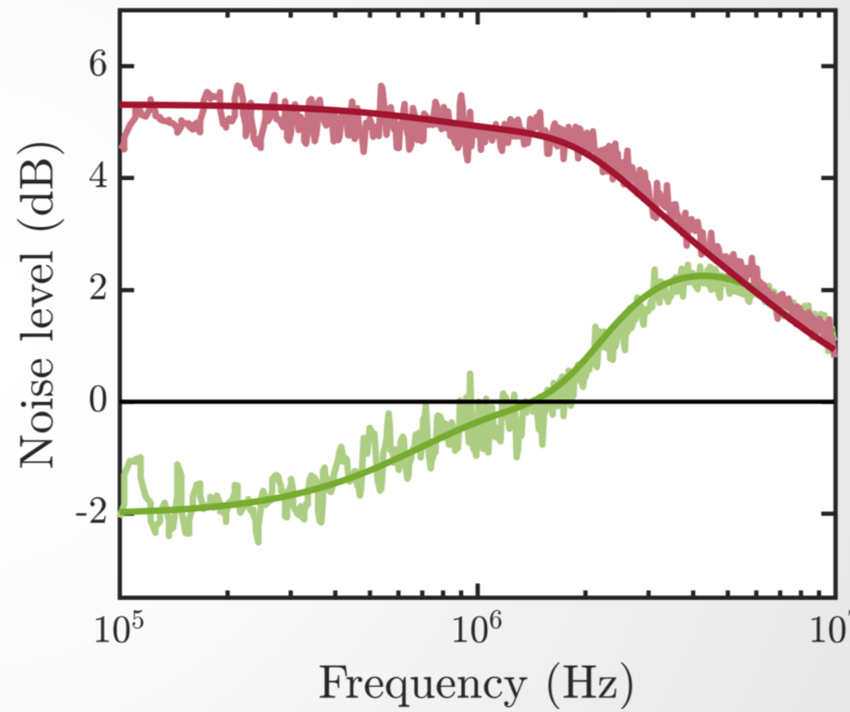


- Total loss = 53 ± 4%
- Limited by low QE diodes and double pass Faraday isolator.

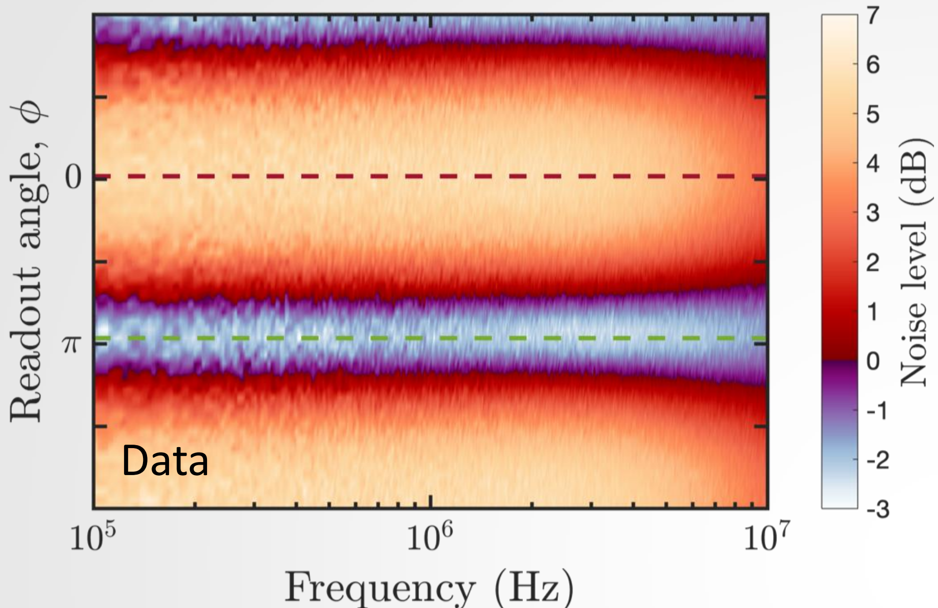
Results – only idler detuned

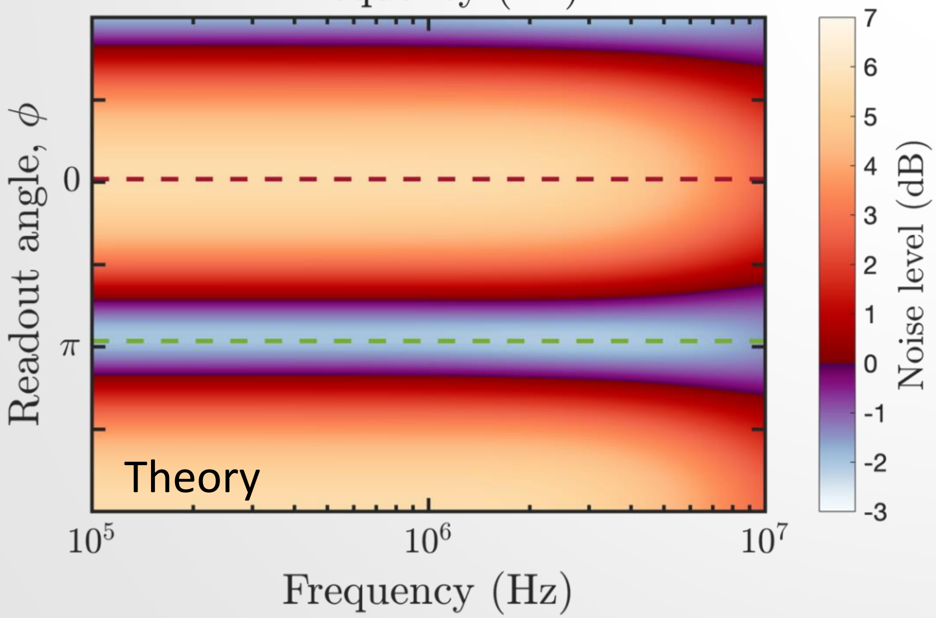


- Idler detuned by 1.38MHz (cavity HWHM)
- Signal on resonance

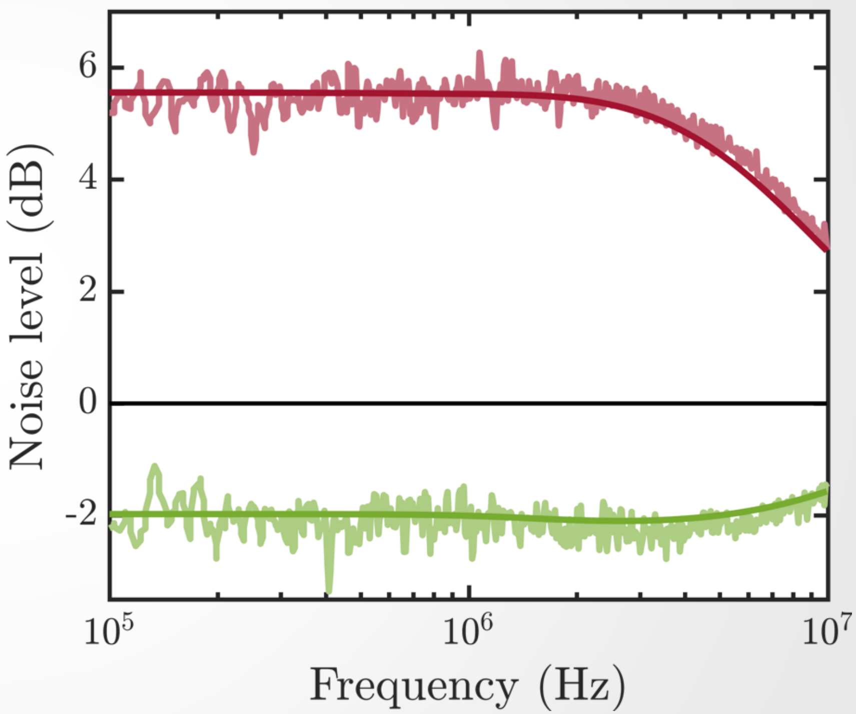


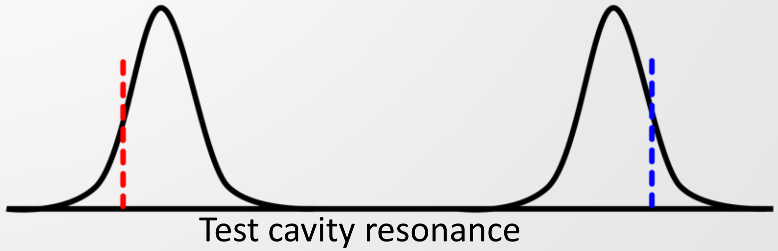
Results – detuned anti-symmetrically



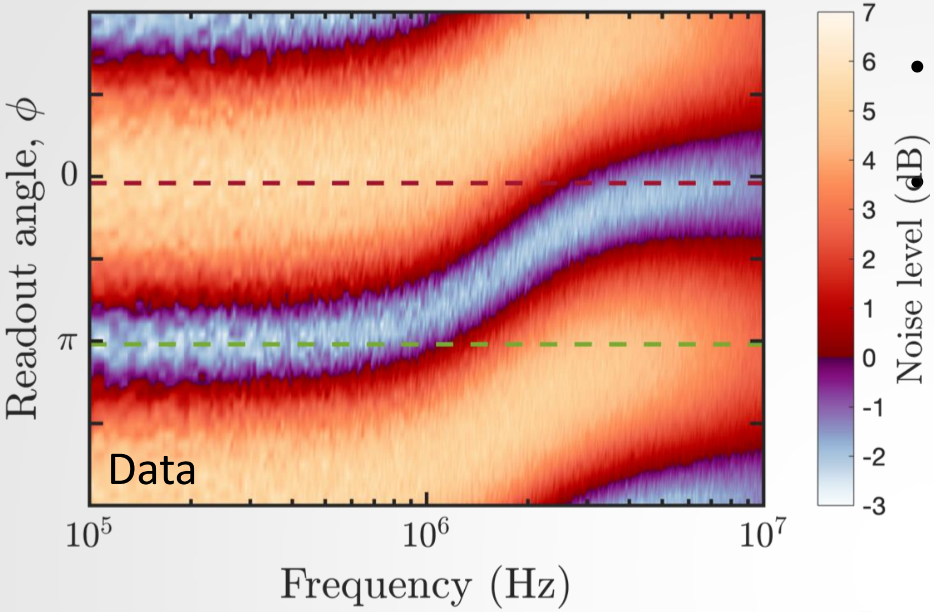


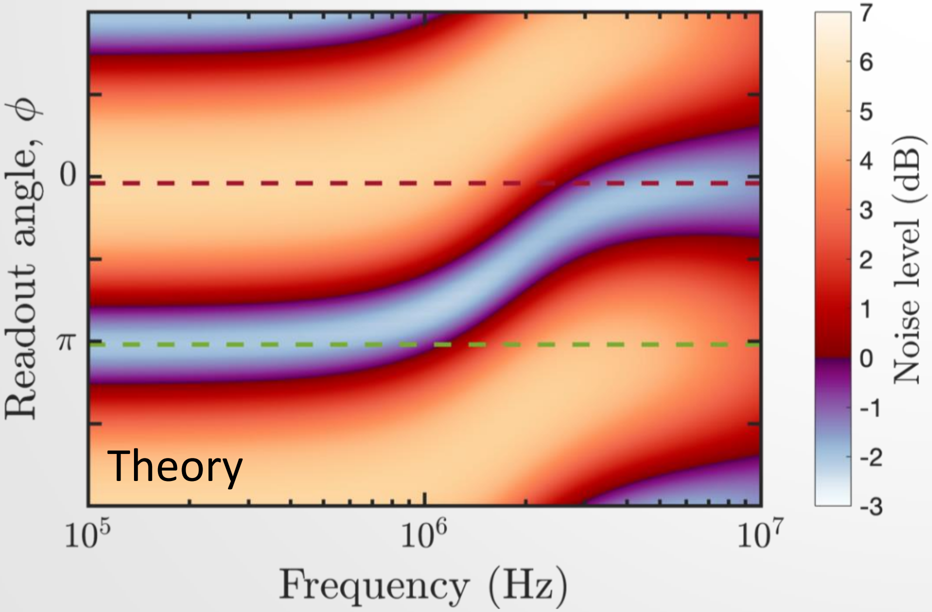
- Signal and idler detuned anti-symmetrically by 1.3MHz
- Case for detuned SRC



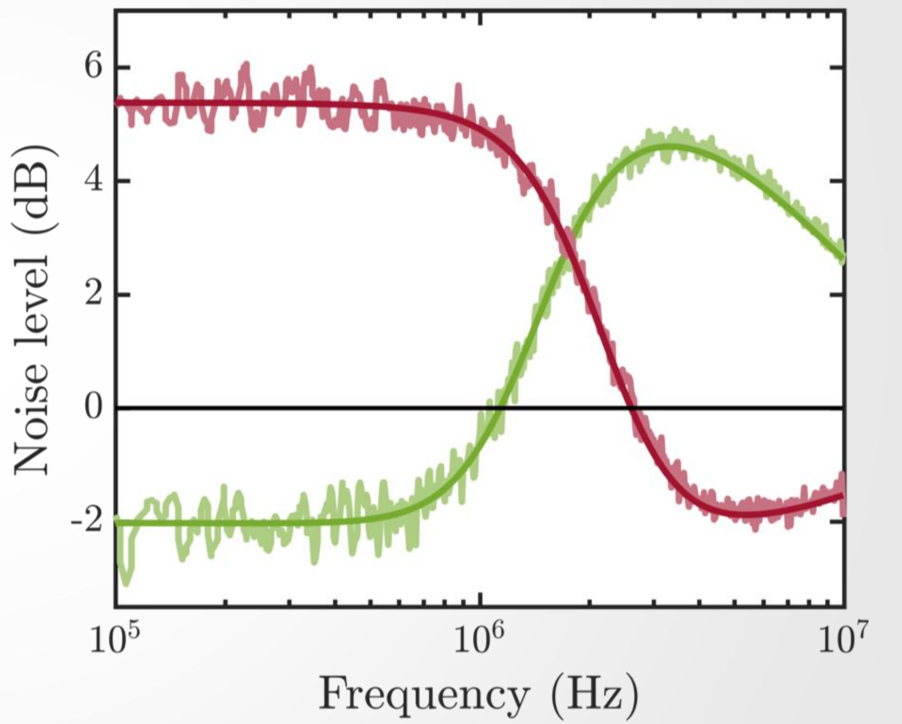


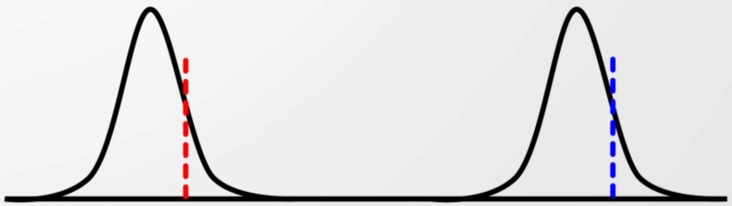
Results – signal and idler detuned



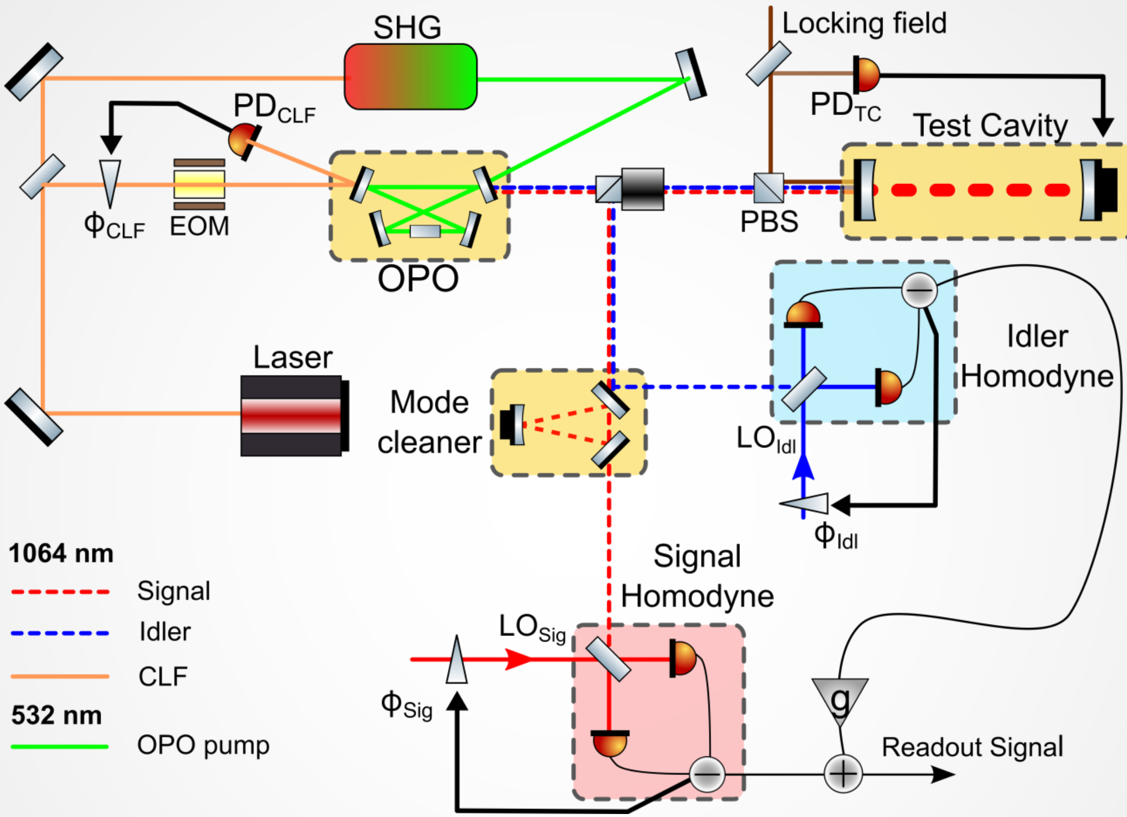


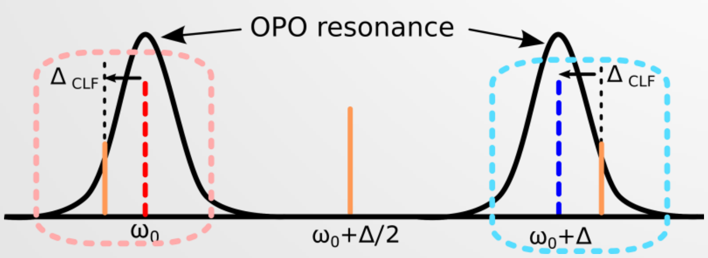
- Signal and idler detuned by 1.3MHz (~cavity HWHM)
- Equivalent to 'regular' FD squeezing





CLF locking scheme

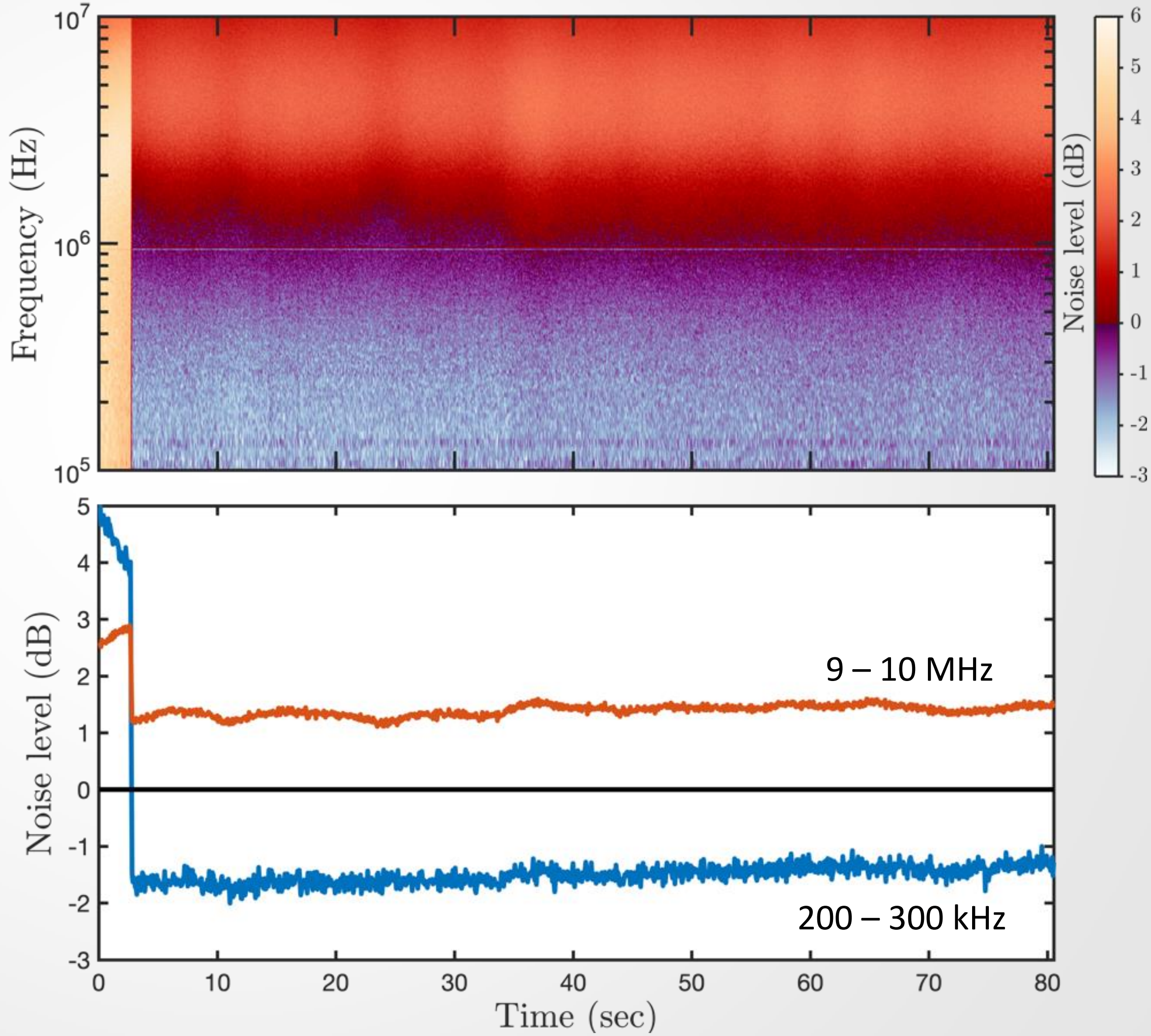




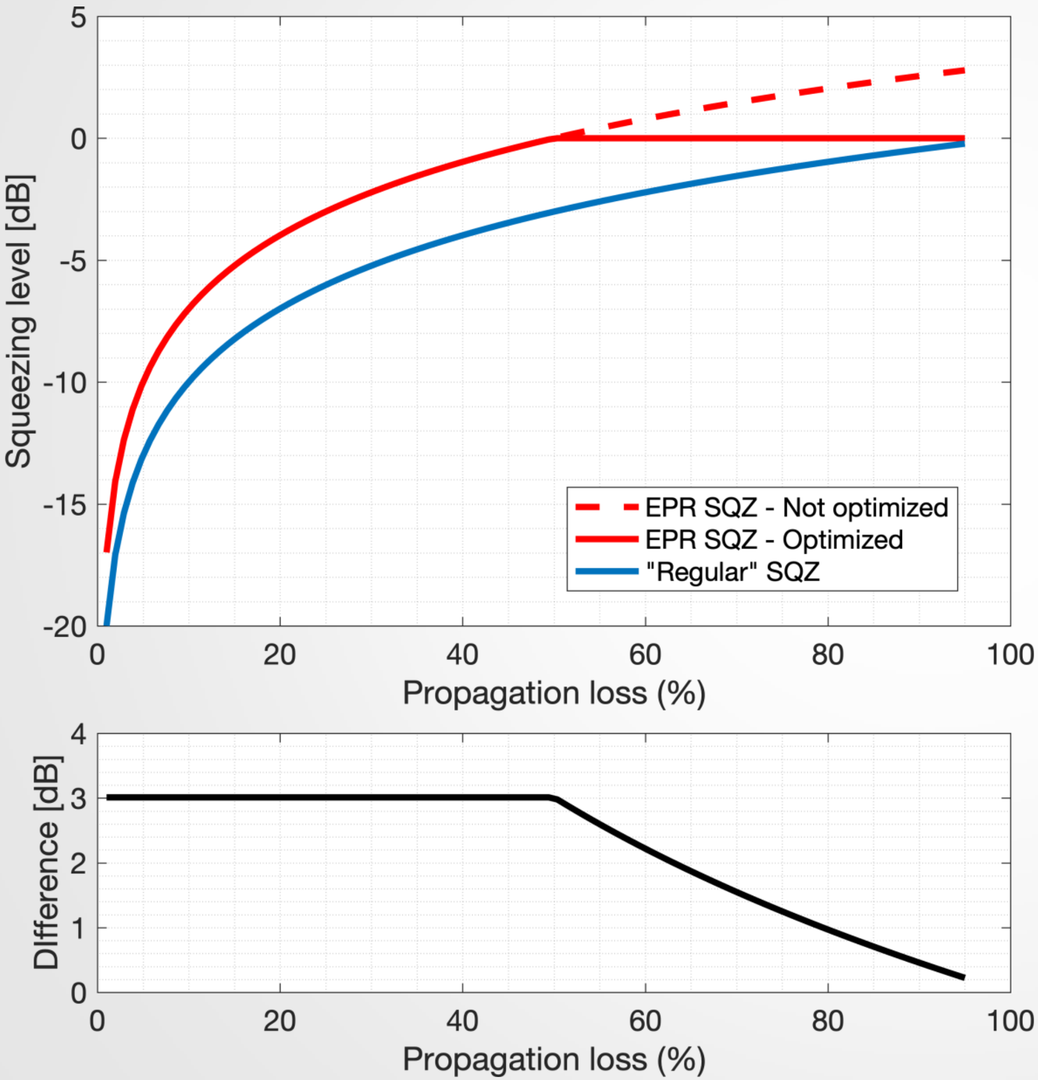
- CLF refl feedback to CLF phase
- Idler output feedback to idler LO phase
- Signal output feedback to signal LO phase
- CLF detuning = 12.07MHz

CLF engaged, squeezing angle locked

- Locked spectrum with 3 CLF lock engaged.
- Current limitations:
  - CLF error signal offset drift (drift in EOM residual AM)
  - Free running OMC



Is this a viable alternative to filter cavities?



Pros:

- No external filter cavity (FC phase locked to IFO).
- “Simpler” optical configuration (apart from an additional homodyne and OMCs)

Cons:

- 3dB loss penalty

Conclusion

- Demonstrated EPR squeezing is indeed possible.
- Developed a coherent phase control system for EPR squeezing

Future works:

- ➢ Improve CLF robustness
- ➢ Implement frequency dependent filtering

Thanks for listening!

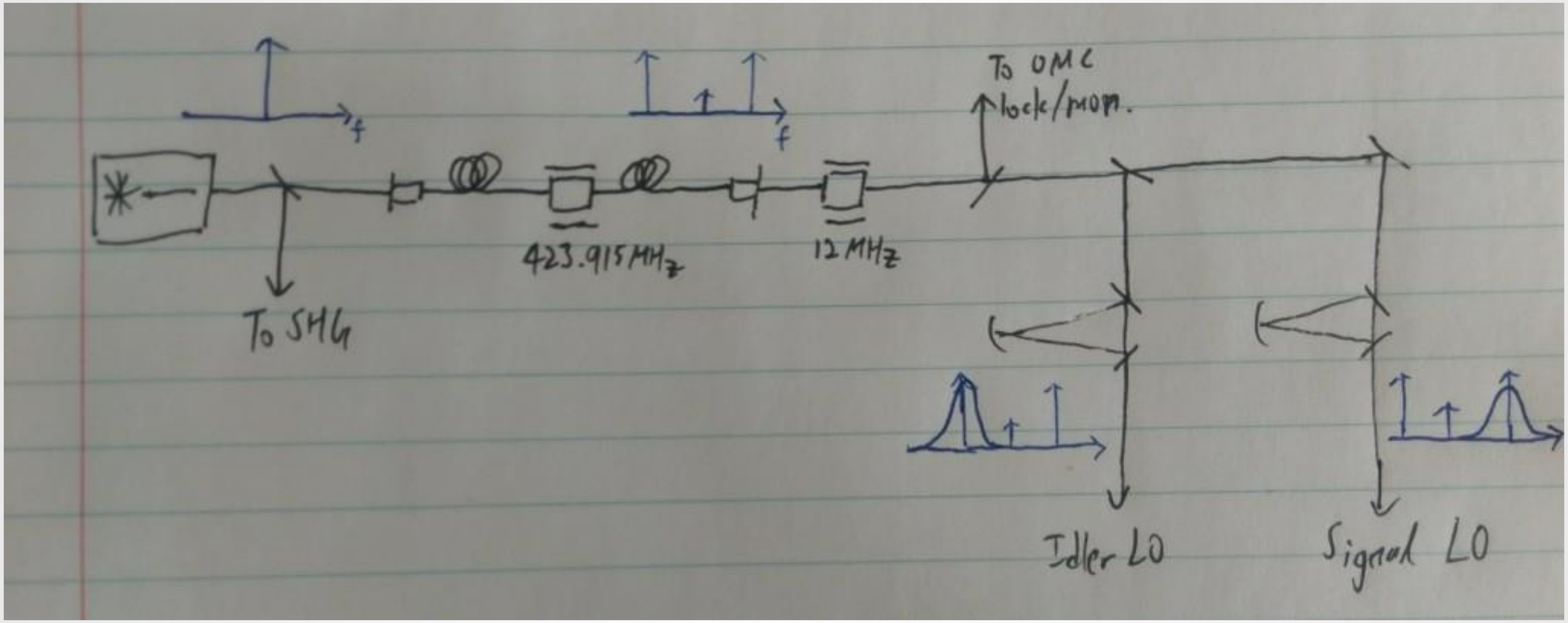
Acknowledgements

- ANU group: Terry McRae, Paul Altin, Robert Ward, Bram Slagmolen, and David McClelland

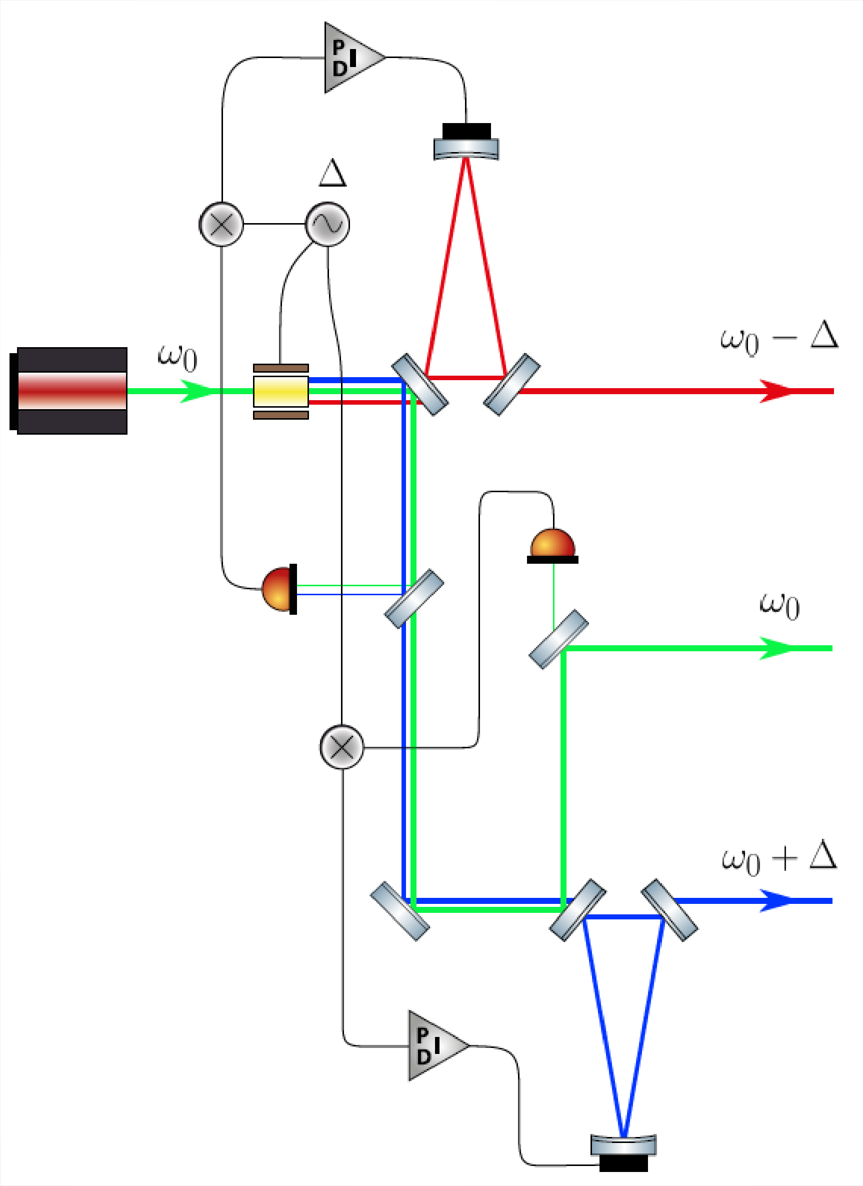
- Hamburg group: Mikhail Korobko, Sebastian Steinlechner, and Roman Schnabel

Extra slides

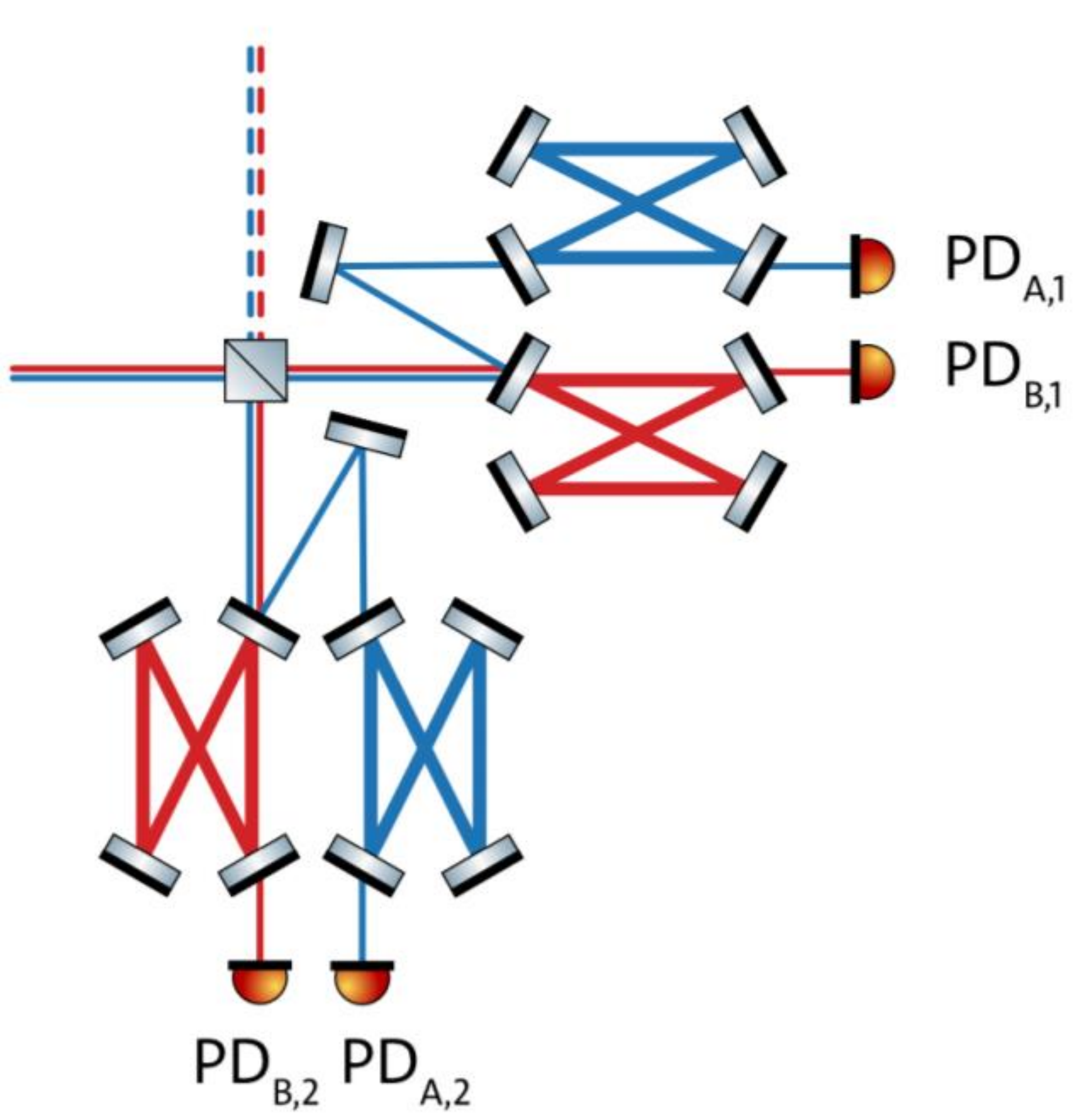
Generation of LOs ANU



Generation of Los Hamburg



Realistic Filter-Cavity Configuration



Based on Adv Ligo BHD study

Theoretical Model Hamburg

$$
\begin{aligned}
S_{\mathrm{yy}} =& 1 - \eta + \eta\cosh(2r) + 2\alpha\beta\eta\sinh(2r)\cdot \\
& \Big[\Big(\gamma^4 + (\delta_1^2 - \Omega^2)(\delta_2^2 - \Omega^2) - \gamma^2(\delta_1^2 + \delta_2^2 - 2\Omega^2 + 4\delta_1\delta_2)\Big)\cos(\xi) \\
& \quad + 2\gamma(\delta_1 + \delta_2)(\gamma^2 - \delta_1\delta_2 + \Omega^2)\sin(\xi)\Big]\cdot \\
& \frac{\left[\gamma^4 + (\delta_1^2 - \Omega^2)(\delta_2^2 - \Omega^2) + \gamma^2(\delta_1^2 + \delta_2^2 + 2\Omega^2)\right]}{(\alpha^2 + \beta^2)(\gamma^2 + (\delta_1 - \Omega)^2)(\gamma^2 + (\delta_2 - \Omega)^2)(\gamma^2 + (\delta_1 + \Omega)^2)(\gamma^2 + (\delta_2 + \Omega)^2)}.
\end{aligned}
$$