L3 – Quantum Technologies for GW detection

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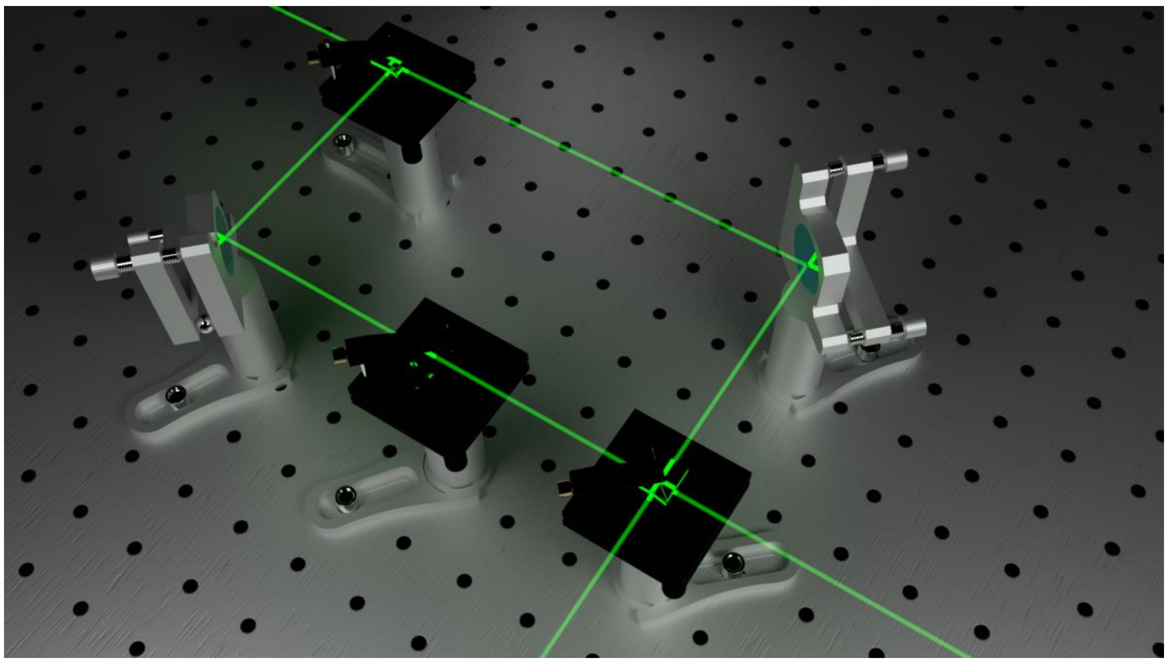
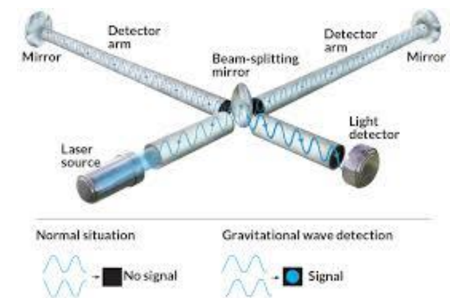
Quantum technologies for quantum sensing

Aim: improved precision in the estimation of an unknown physical quantity by adopting quantum resources

Optical phase estimation: → Unknown parameter ϕ phase difference between interferometer arms



Applications:

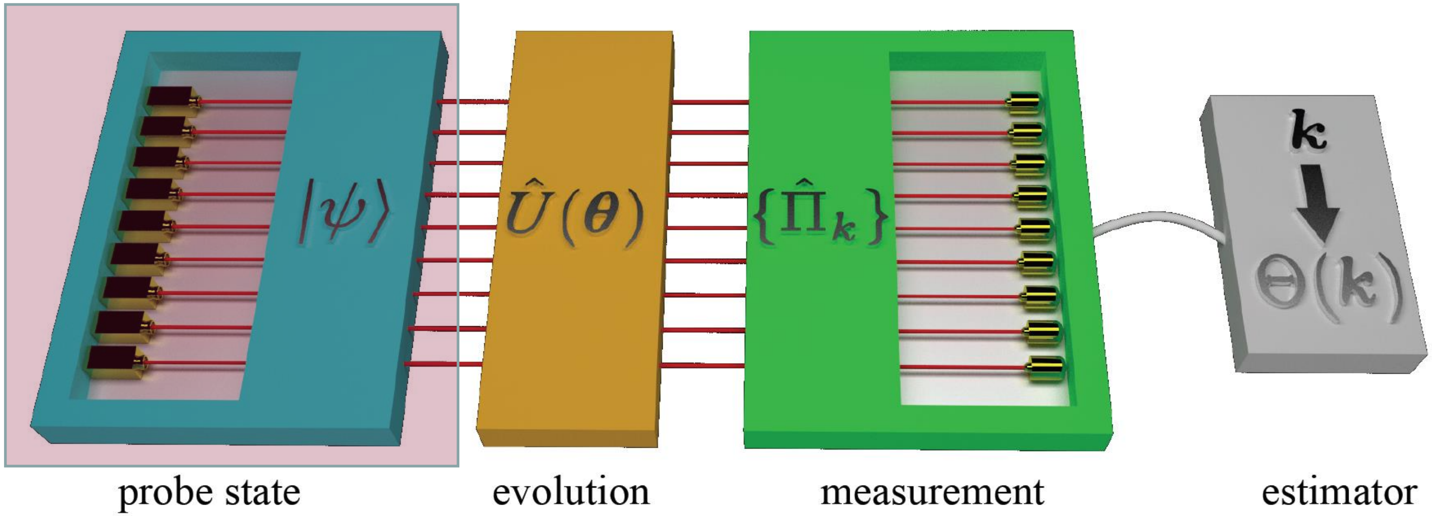


-) Gravitational wave detection
-) Imaging
-) Quantum communications
-) Biological systems measurements

E. Polino, M. Valeri, N. Spagnolo, F. Sciarrino, AVS Quantum Science **2**, 024703 (2020)

Quantum metrology

General quantum framework for estimation problems



Key element: preparation of the probe state

<u>Ultimate limits for optical phase estimation</u>

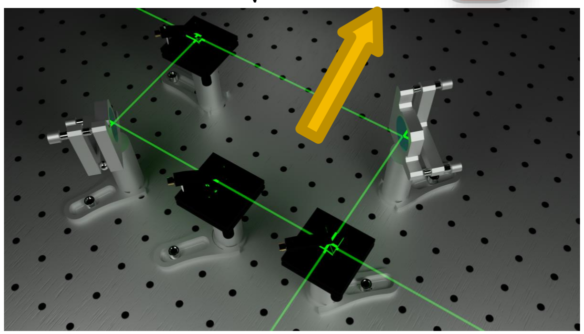
$$\Delta\phi \geq \frac{1}{\sqrt{\nu N}}$$ Standard quantum limit (SQL), achievable with classical resources

$$\Delta\phi \geq \frac{1}{\nu\sqrt{N}}$$ Heisenberg limit (HL), achievable with quantum resources (entangled states, squeezed states)

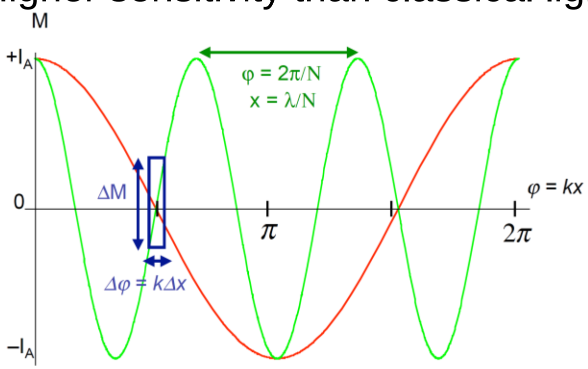
Optical phase estimation and quantum approach

Maximally entangled states

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|2\rangle|0\rangle + \boxed{e^{i2\phi}}|0\rangle|2\rangle)$$



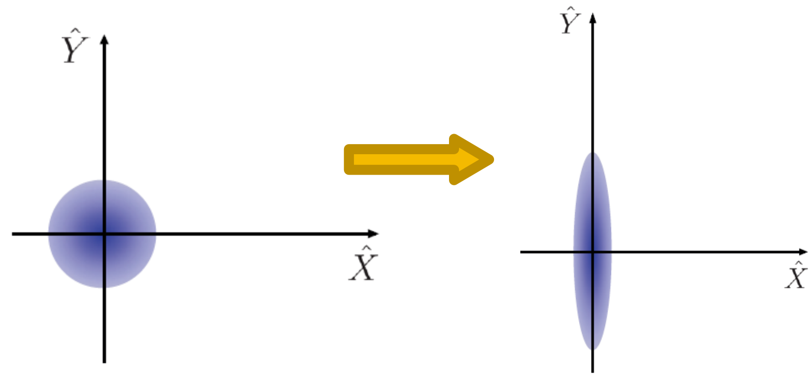
Higher sensitivity than classical light



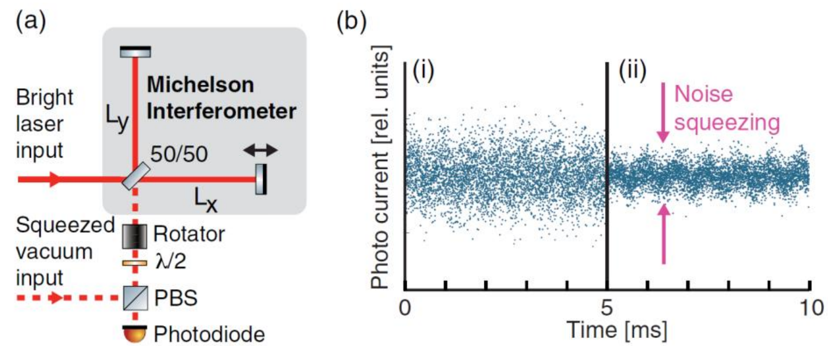
First unconditional violation of the standard quantum limit:
S. Slussarenko, et al., Nature Photonics **11**, 700-703 (2017)

Squeezed light

Reduced noise in one phase quadrature



Application for GW detection



Recent review:
L. Barsotti, et al., Rep. Prog. Phys. **82**, 016905 (2019)

Quantum estimation: open issues

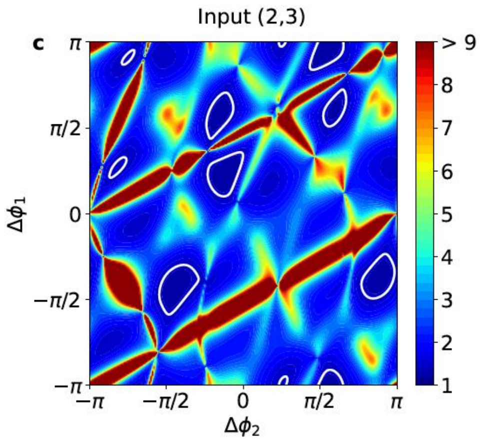
1. Estimation with limited data

Can we improve convergence rate to SQL or HL with limited data?

Robustness to noise in the estimation process?

Sensitivity may depend on the parameters value

Same precision is required



2. Calibration of large scale quantum sensors

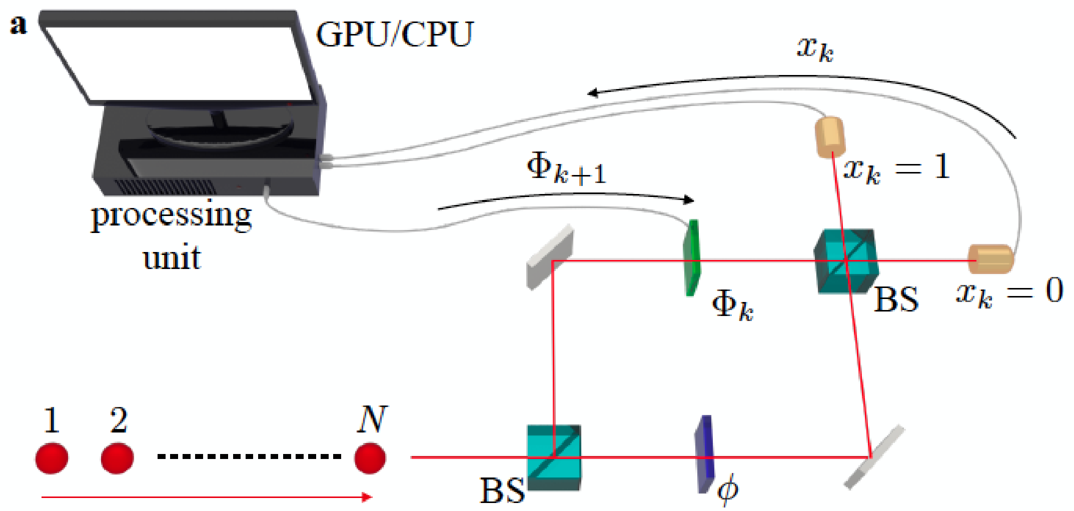
Precise calibration of the system response function

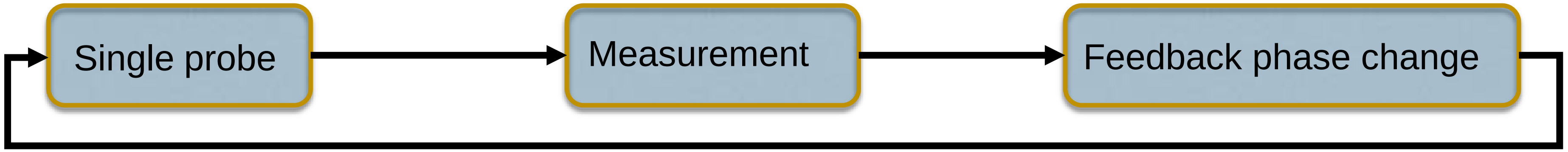
can we reduce the number of measurements?

can we soften the need for system modeling?

our approach: devising algorithms based on machine learning

Adaptive estimation with limited data





-) **Online approaches**: feedback phase is evaluated at each run by the processing unit

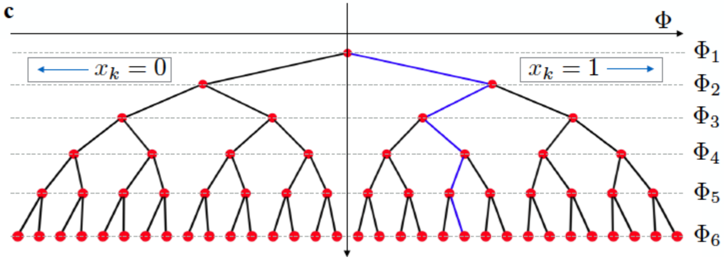
-) **Offline approaches**: feedback phase is changed from a list of pre-calculated rules

Machine learning techniques can be employed

Adaptive estimation with limited data

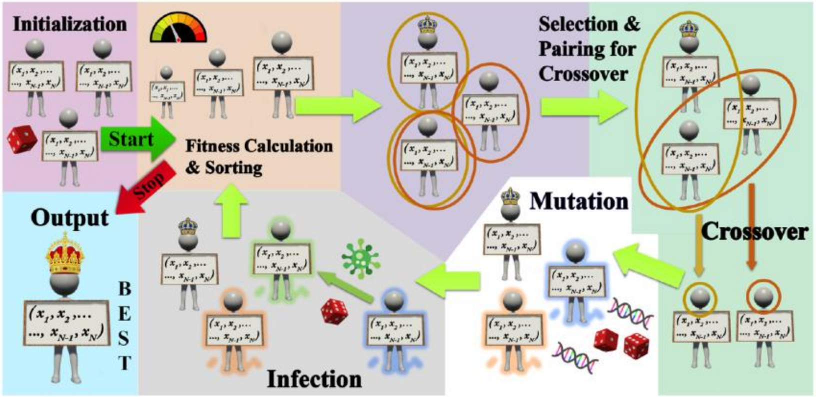
OFFLINE APPROACHES

Particle Swarm Optimization



maps the problem to particle evolution

Genetic Algorithm

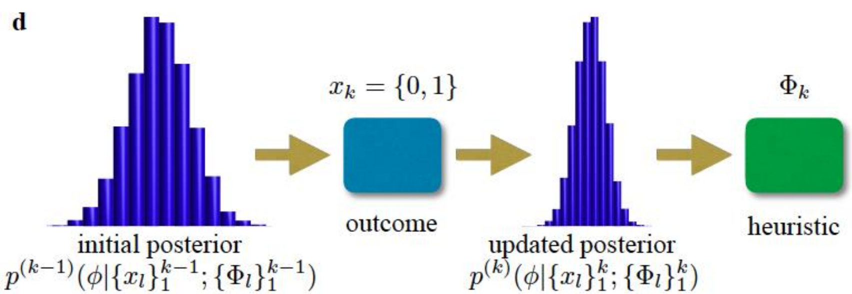


inspired by the principles of natural selection

A. Lumino, et al., Phys. Rev. Applied **10**, 064028 (2018)
K. Rambhatla, et al., Phys. Rev. Research **2**, 033078 (2020)

ONLINE APPROACHES

Optimized adaptive Bayesian approach

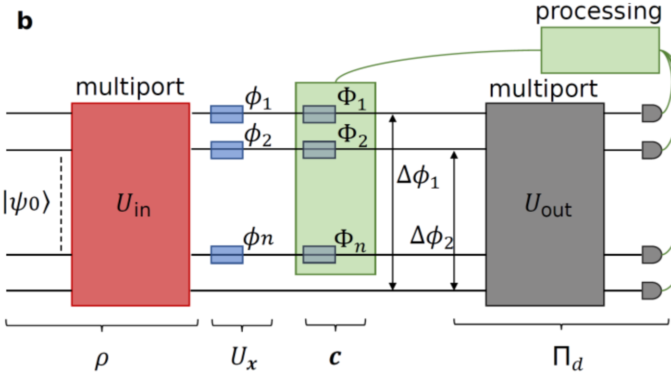


At each step the feedback is applied to minimize the variance of the posterior distribution

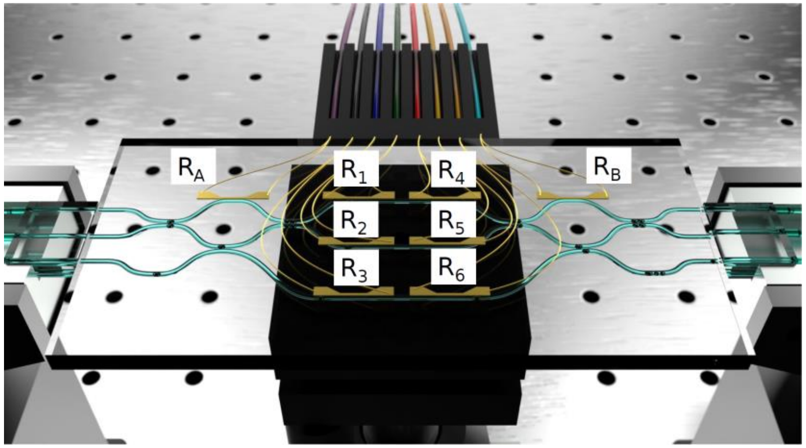
A. Lumino, et al., Phys. Rev. Applied **10**, 064028 (2018)
M. Valeri, at al., npj Quantum Information **6**, 92 (2020)

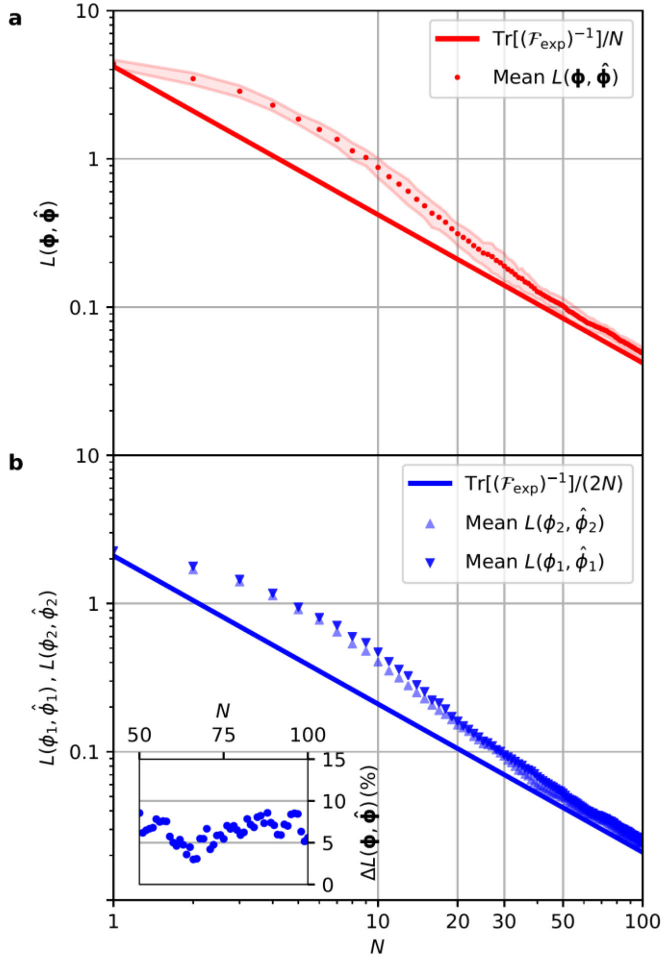
Extension to multiparameter estimation

Optimized adaptive Bayesian approach



Requires multiple feedback phases:



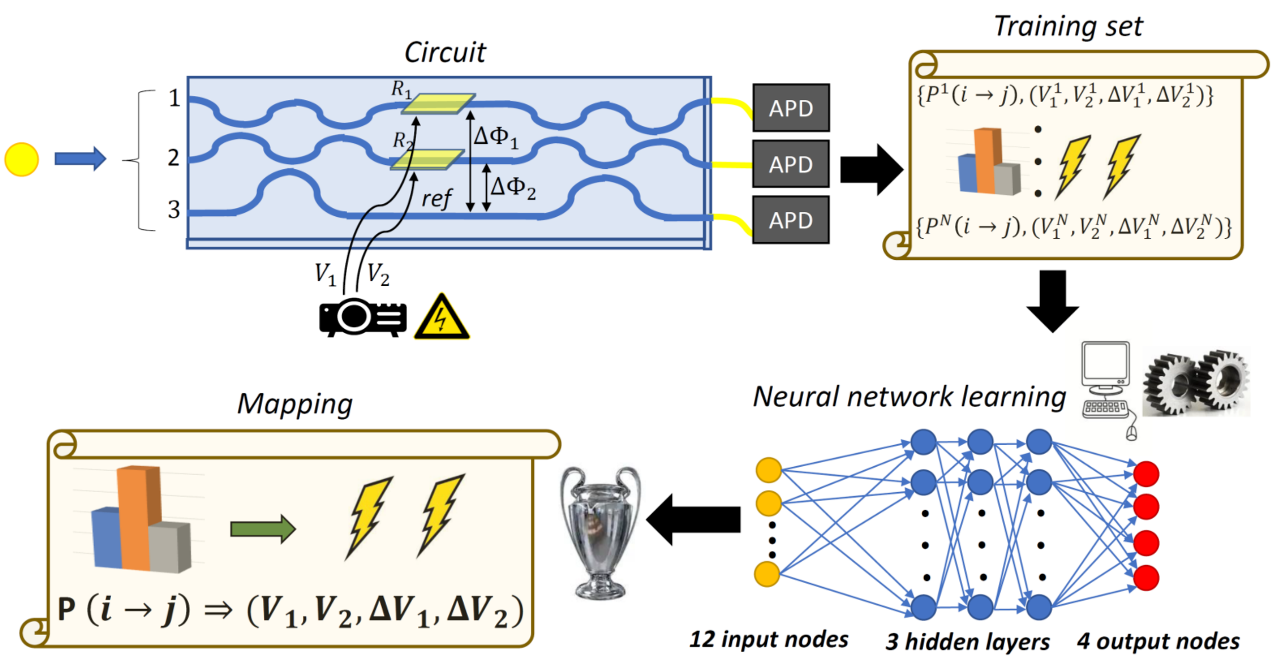


M. Valeri, et al., npj Quantum Information **6**, 92 (2020)

Calibration of quantum sensors via neural networks

New approach for calibration - machine learning for quantum sensors

Advantage: Neural networks do not rely on knowledge of the device model

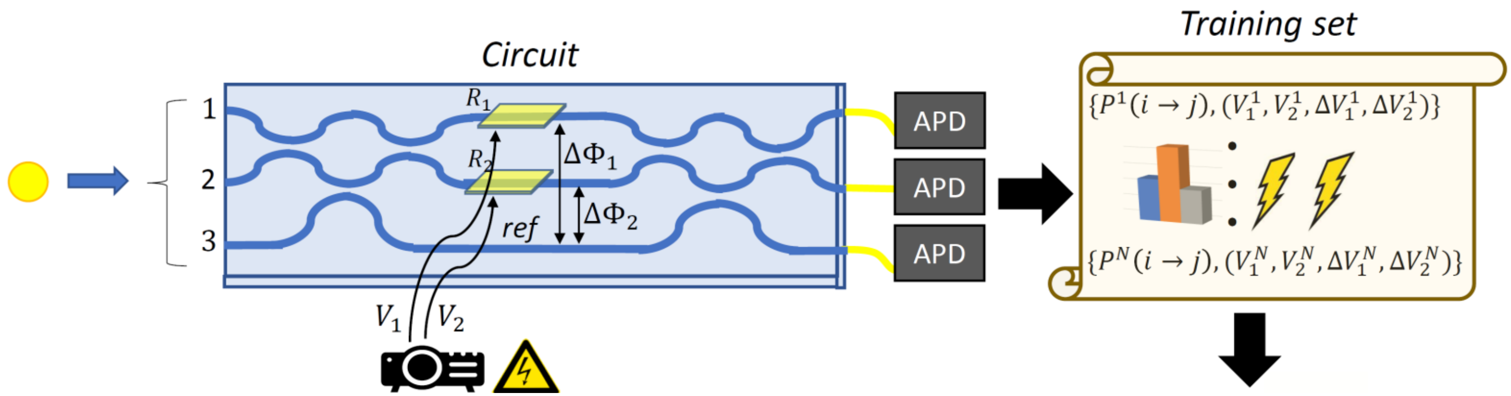


Neural networks learns the model directly from training data (very limited a priori knowledge is required)

V. Cimini, et al., Phys. Rev. Lett. **123**, 230502 (2019)
V. Cimini, et al., Phys. Rev. Appl. **15**, 044003 (2020)

Calibration of quantum sensors via neural networks

Concept of the approach



(1) A series of input-output data are generated from the apparatus

$$\{\vec{x}, \vec{y}\}_k = \{P(i \to j), (V_1, V_2)\}_k \text{ for } i, j = 1, 2, 3.$$

input parameters tuned by the user

$$\Delta\phi_i = \sum_{j=1}^{2} \left(\alpha_{ij} P_{R_j} + \alpha_{ij}^{\mathrm{NL}} P_{R_j}^2 \right)$$

output probabilities

V. Cimini, et al., Phys. Rev. Lett. **123**, 230502 (2019)
V. Cimini, et al., Phys. Rev. Appl. **15**, 044003 (2020)

Requires additional calibration of $(V_1, V_2) \leftrightarrow (\Delta\phi_1, \Delta\phi_2)$

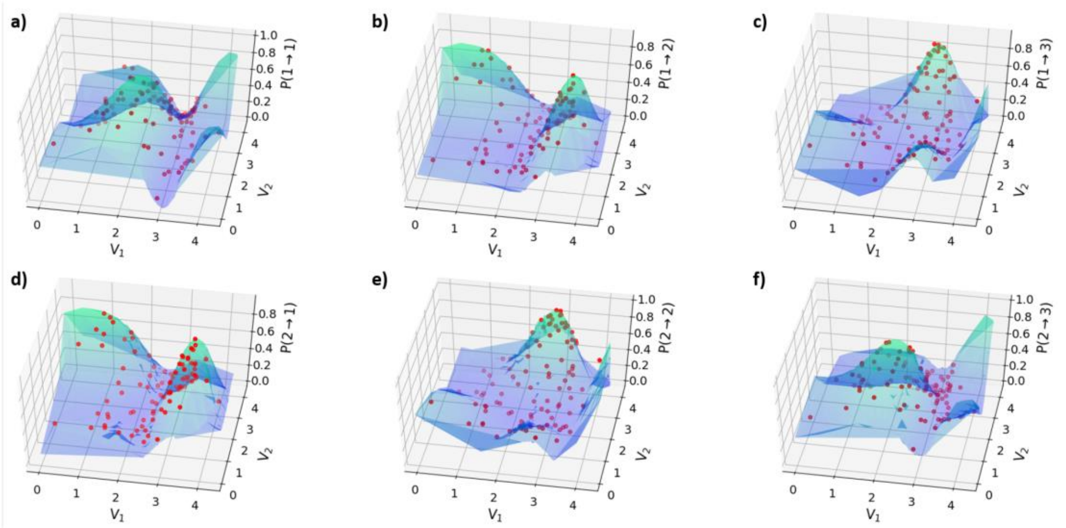
Calibration of quantum sensors via neural networks

Concept of the approach

(2) The training set is used to train a neural network to learn the mapping between $P(i \rightarrow j)$ and (V_1, V_2)

No a priori knowledge on the functional form of the model/mapping is generally required, including noise

(3) After training, the network is capable of predicting the correspondence between $P(i \rightarrow j)$ and (V_1, V_2) on new sets of data



V. Cimini, et al., Phys. Rev. Lett. **123**, 230502 (2019)
V. Cimini, et al., Phys. Rev. Appl. **15**, 044003 (2020)

Results and Perspectives

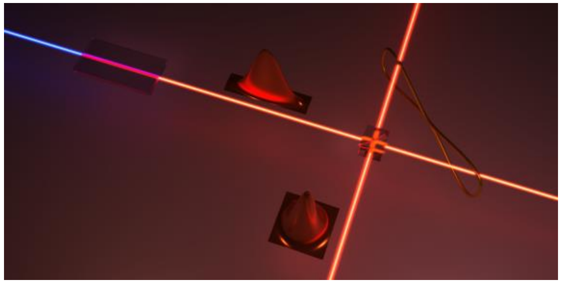
Other results
A. Z. Goldberg, et al., Phys. Rev. A **102**, 022230 (2020)
V. Cimini, et al., Phys. Rev. Applied **13**, 024048 (2020)
V. Cimini, at al., arXiv:2110.02908 (2021)

ML for adaptive estimation

ML for sensors calibration

ongoing and future work

Quantum phase estimation with squeezed light



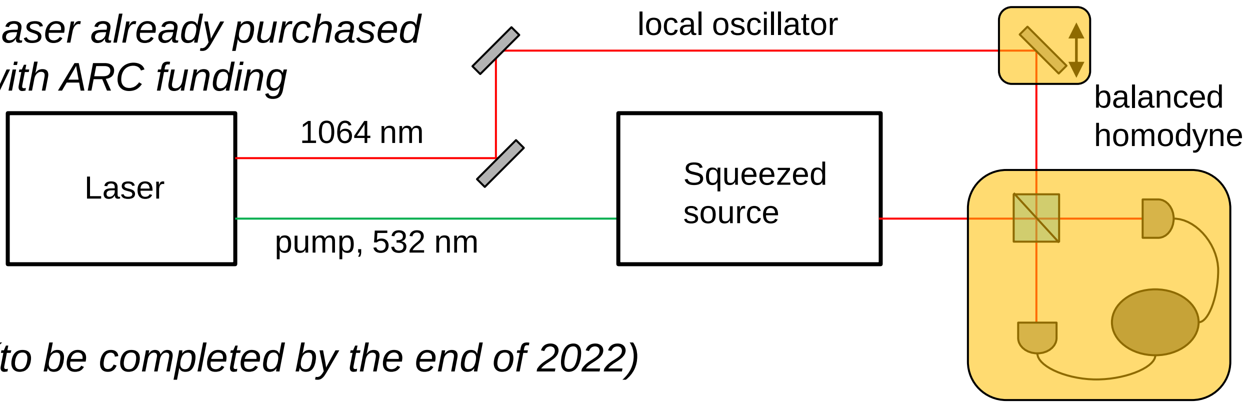
Development in progress of a squeezing apparatus

Testing of protocols for phase estimation with squeezed light for GW detection

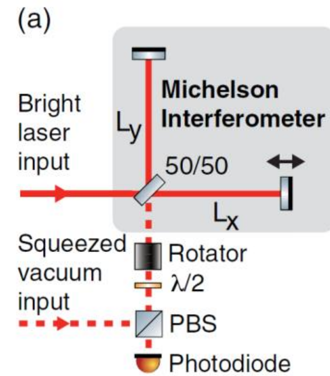
Results and Perspectives

Development of a squeezed single-mode light source

Laser already purchased with ARC funding

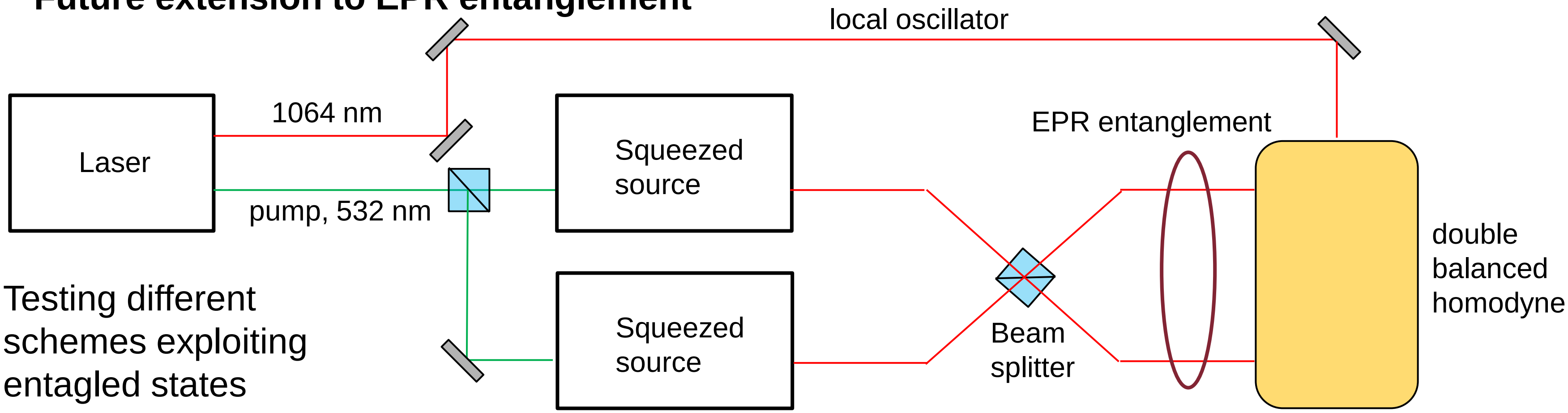


(to be completed by the end of 2022)



Testing protocols for phase noise reduction in GW interferometers

Future extension to EPR entanglement



Testing different schemes exploiting entagled states

People

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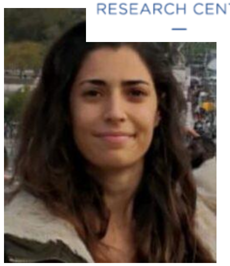

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