Sequential Parametric Amplification: Quantum Technology with Multimode Light

Squeezing is a valuable quantum resource, which enables sensitive optical measurements by overcoming the shot noise – the noise stemming from the photon structure of light. At the same time, squeezing is susceptible to optical loss and inefficient detection, which limits its use in technology. SPARQL will apply multimode parametric amplification to make this resource loss-tolerant. This step will open practical applications for sub-shot-noise quantum imaging, microscopy, and spectroscopy. It will also protect from loss extremely fragile multimode non-Gaussian states. Moreover, by implementing two stages of parametric amplification in sequence, SPARQL will apply multimode squeezing to wide-field Raman spectroscopy and quantum key distribution.

Teams

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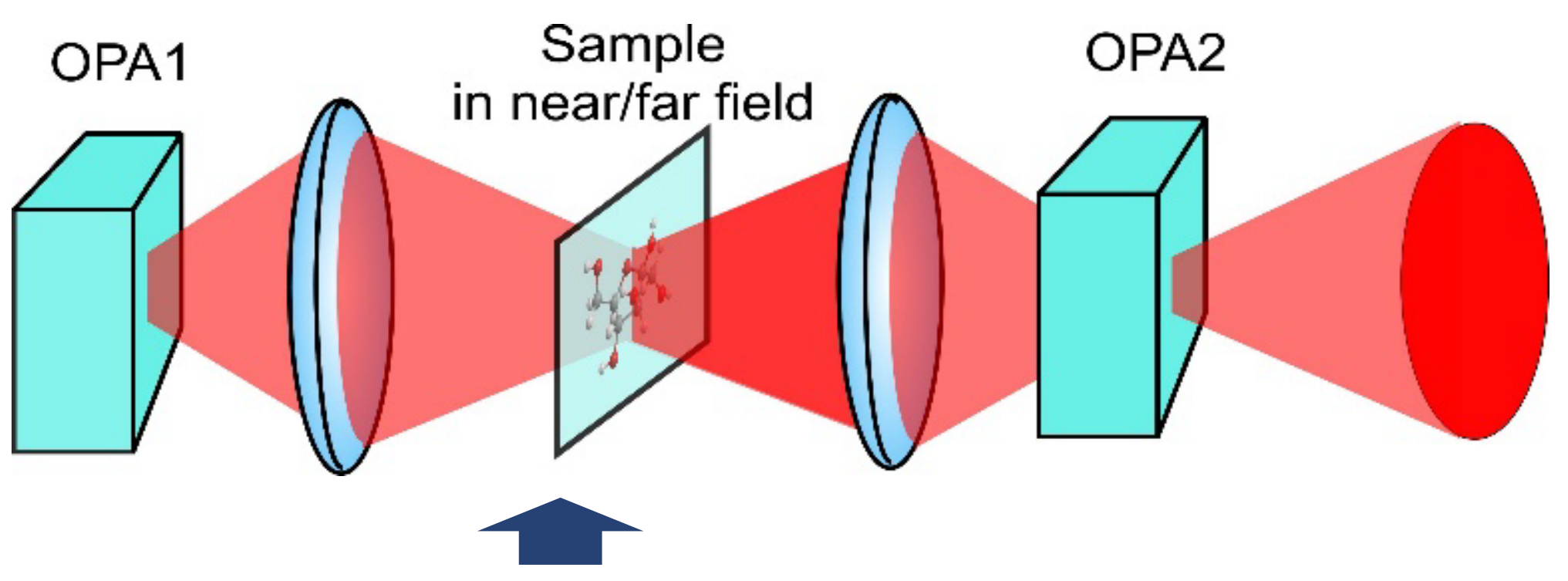
Objectives

O1. Sub-shot-noise imaging and spectroscopy tolerant to inefficient detection.
O2. Squeezing-enhanced Raman spectroscopy.
O3. Wide-field squeezing-enhanced Raman microscopy.
O4. Quantum sensing and communication with multimode light..
O5. Generation and measurement of multimode non-Gaussian states for quantum sensing.

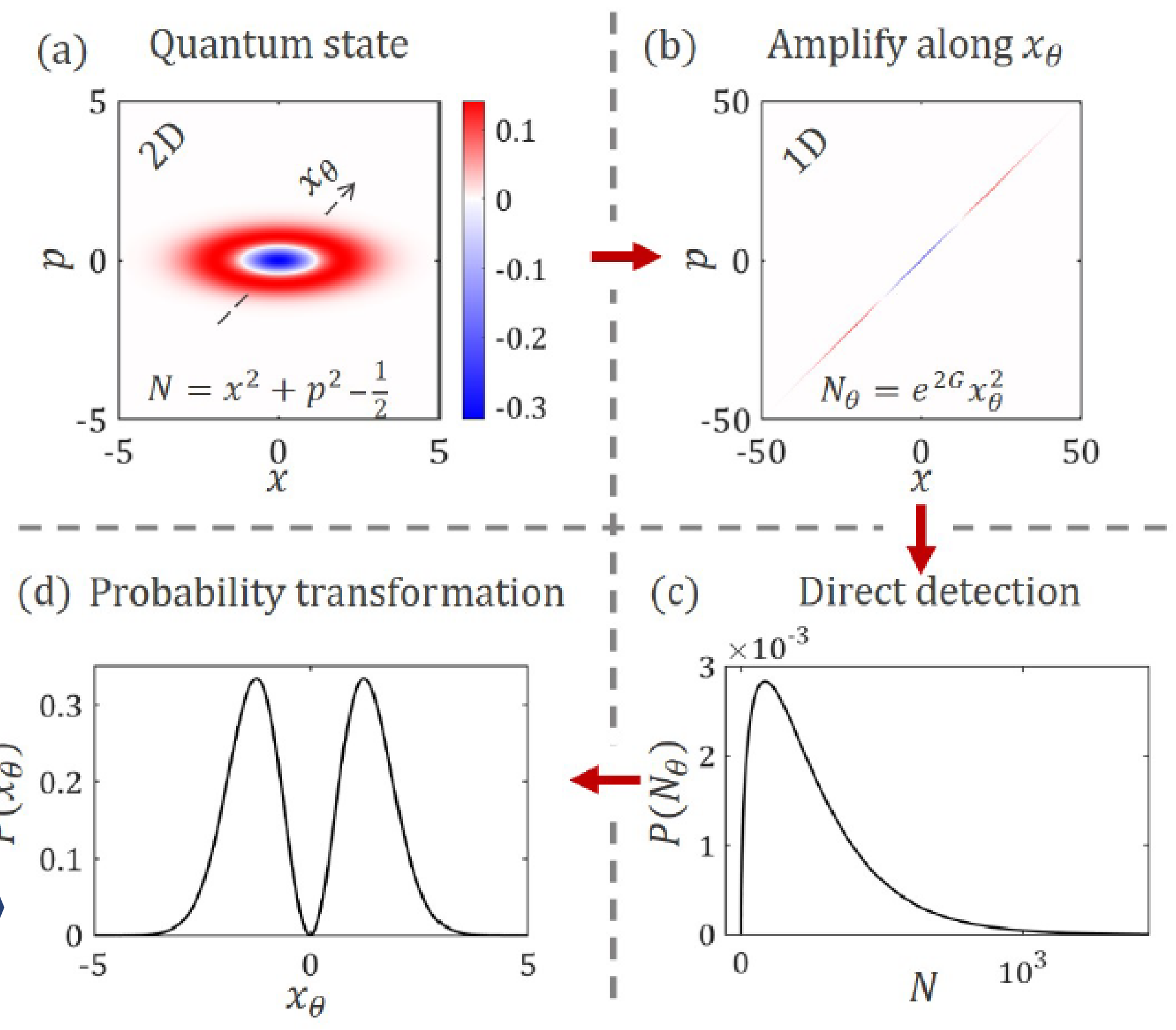
Expected results

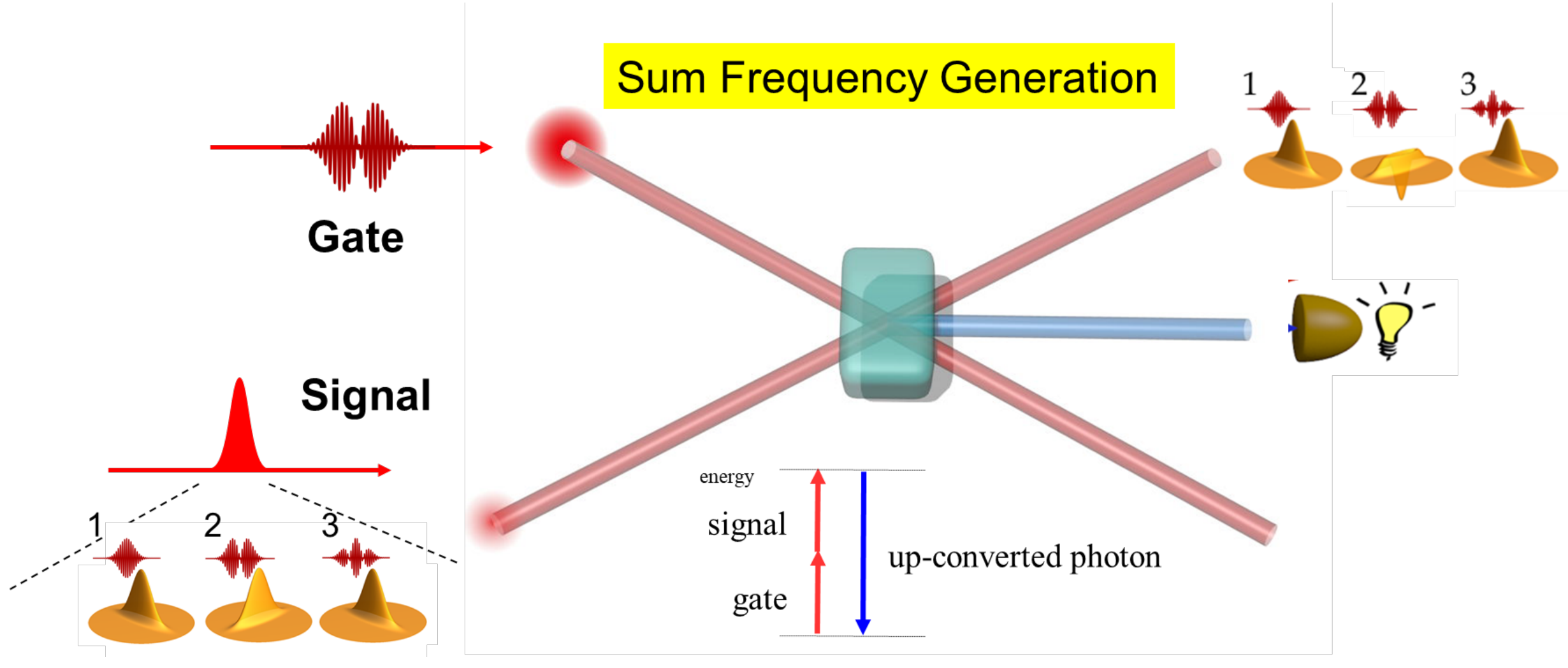


The workhorse of the project: the first optical parametric amplifier (OPA1) generates nonclassical light. After sensing the sample but before detection, the second optical parametric amplifier (OPA2) amplifies the quadrature carrying the useful information. Such a system is known as the SU(1,1) interferometer.

MPL and BIU will apply an SU(1,1) interferometer to Raman spectroscopy: a Raman sample will be placed between two OPAs and work like a weak OPA whose phase depends on the Raman shift [1]. Raicol, together with MPL and BIU, will develop crystals with optical properties supporting broadband spontaneous parametric down-conversion (SPDC) for the use in such an interferometer. In particular, we will shape the SPDC spectrum by engineering custom-poled KTP crystals for different quantum applications.

MPL will take advantage of an OPA in the role of a homodyne detector ('parametric homodyne') [2], with tolerance to loss and noise. We will use it to characterize non-Gaussian states, including bright ones, such as a squeezed single photon [3].





To generate non-Gaussian states, LKB will apply several single-photon operations, using sum-frequency generation, to multimode squeezed beams. LKB and UP will study their relations with the Fisher Information [4]

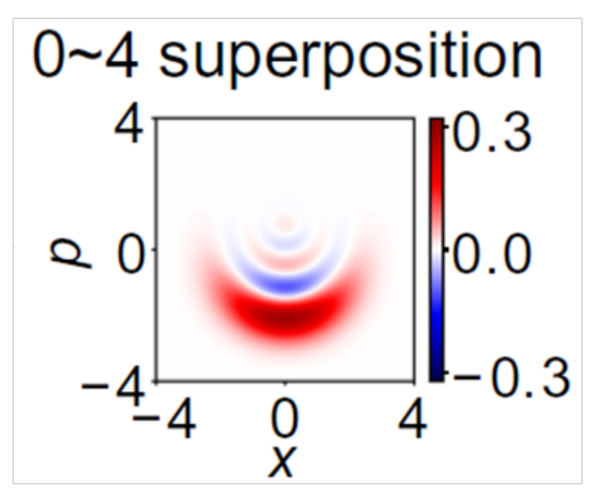
RESOURCES

Fock-state superposition

$$|\psi\rangle = \sum_{n=0}^{n_{max}} c_n |n\rangle$$

$$c_n = e^{i\varphi_n}$$

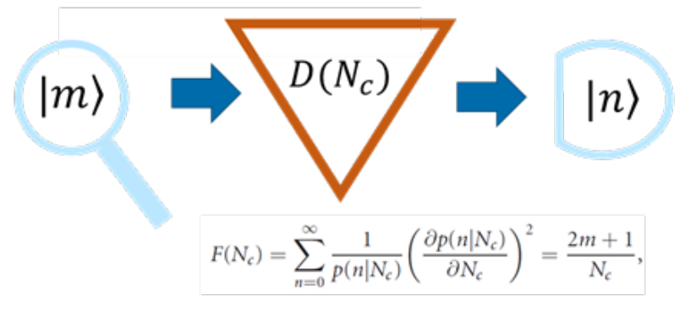
UP, LKB, and other teams will then turn available quantum non-Gaussian resources into sensing, communication and computing applications, which UP is already developing.



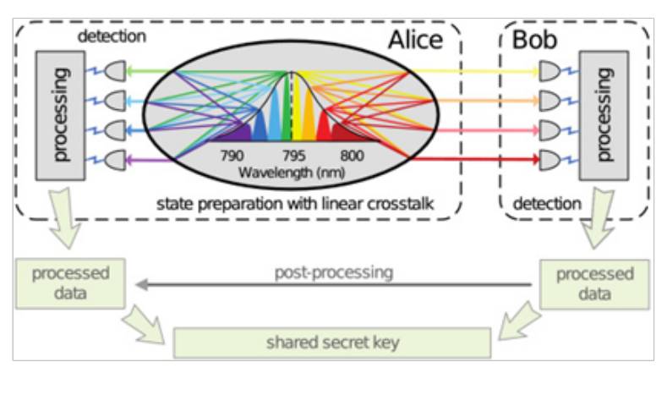
SPARQL

APPLICATIONS

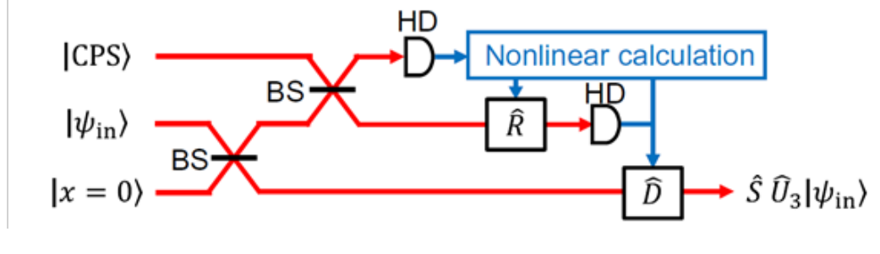
Quantum sensing



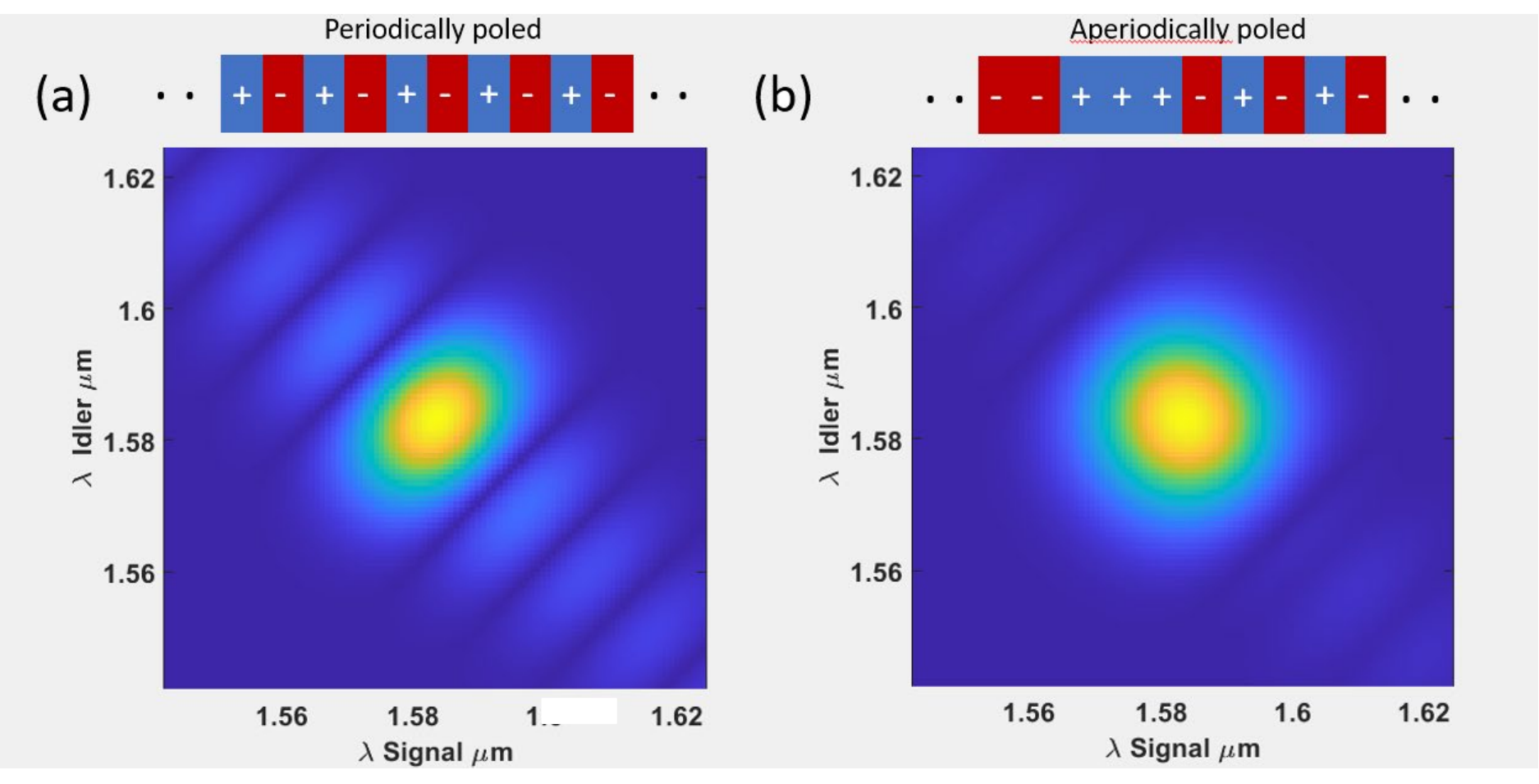
Quantum communication



Quantum gates and computing

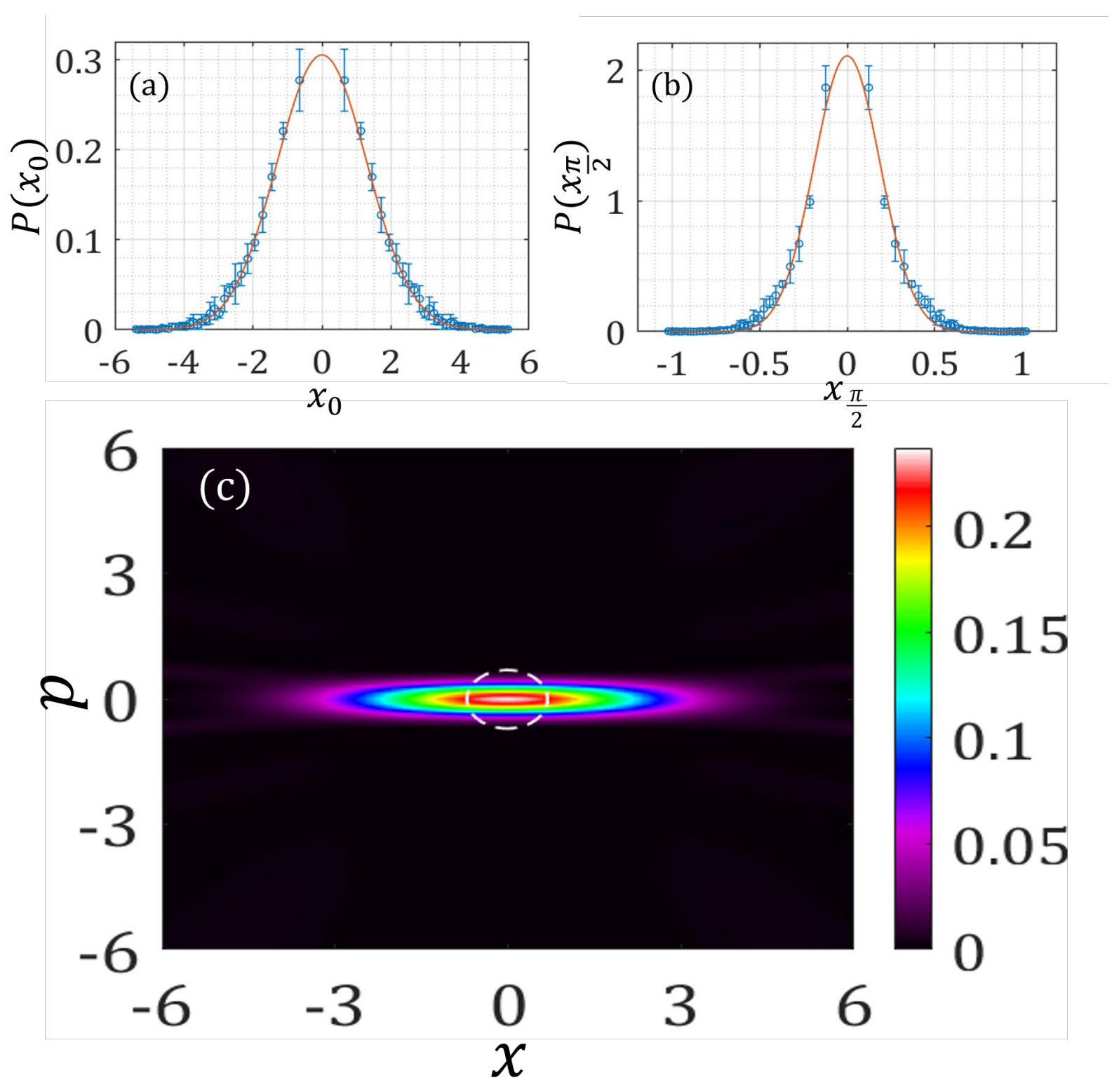


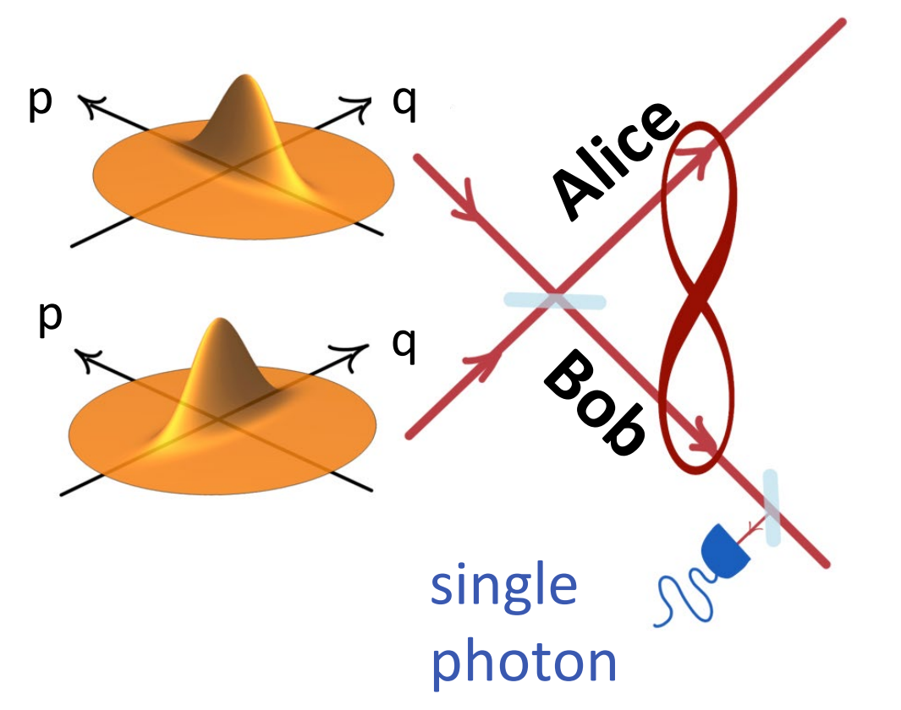
First results



Raicol: The joint spectrum of (a) type-II periodically poled KTP and (b) aperiodically poled KTP. The aperiodic design was engineered for side-lobe removal and maximizing the spectral purity for applications of heralded single photons.

MPL: proof-of-principle Wigner-function tomography of a squeezed vacuum state using the 'parametric homodyne' method: (a,b) the probability distributions for the anti-squeezed and squeezed quadratures and (c) the reconstructed Wigner function measured with detection loss >90% [3]. White dashed circle shows the vacuum state Wigner function at 1/e level. The squeezing is 7.7 dB and the purity is 93%.

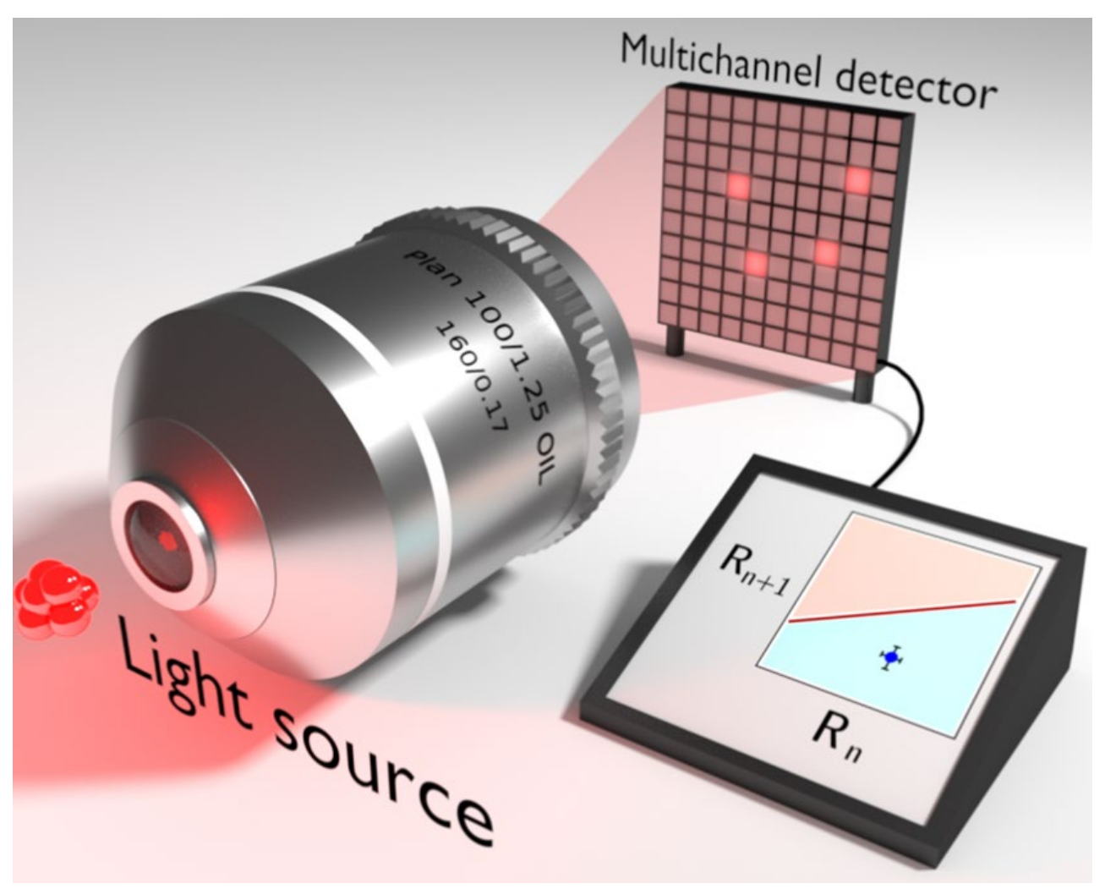




LKB: Detecting non-Gaussian states with Fisher information. Using inequalities based on the Fisher information associated with quadrature measurement, one can derive a steering criterion [5]. This criterion allows to detect entanglement in a non-Gaussian scenario, where usual Gaussian steering criteria, such as Reid's and Drummond's, fail to detect entanglement.

$$\mathrm{Var}[\hat{p}_B|\hat{p}_A] \underset{\text{steering}}{<} \mathcal{F}_\theta[\hat{q}_B|\hat{q}_A] = \sum_q P(\hat{q}_A = q)\mathcal{F}_\theta[\hat{q}_B|\hat{q}_A = q]$$

UP: detection and faithful identification of quantum non-Gaussian states of light for applications, using multiphoton detectors or homodyne detection based on the criteria we develop further [6].



BIU: Augmenting the Sensing Performance of Entangled Photon Pairs through Asymmetry: We show that the visibility of the SU(1,1) interference directly discerns between loss on the measured mode (signal) and the conjugated mode (idler). This asymmetry also affects the phase sensitivity of the interferometer [7].

References

[1] Y. Michael, L. Bello, M. Rosenbluh, and A. Pe'er, npj Quantum Information **5**:81 (2019).
[2] Y. Shaked et al., Nature Comm. **9**:609 (2018).
[3] M. Kalash and M. V. Chekhova, arxiv:2207.10030 [quant-ph] (2022).
[4] Y.-S. Ra et al., Nature Physics **11**, 1 (2019).
[5] C. E. Lopetegui, M. Gessner, M. Fadel, N. Treps, and M. Walschaers, arXiv:2201.11439. (2022), to be published in PRX Quantum.
[6] L. Lachman and R. Filip, Progress in Quantum Electronics **83**, 100395 (2022).
[7] Y. Michael et al., PRL **127**, 173603 (2021).