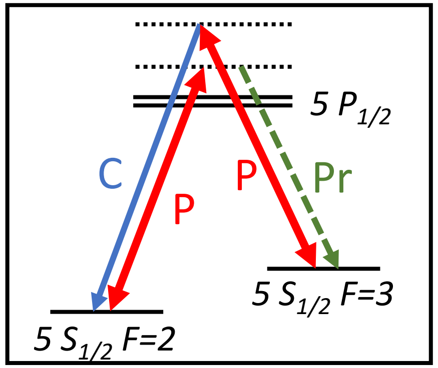
Nonlocal phase modulation of continuous-variable twin beams

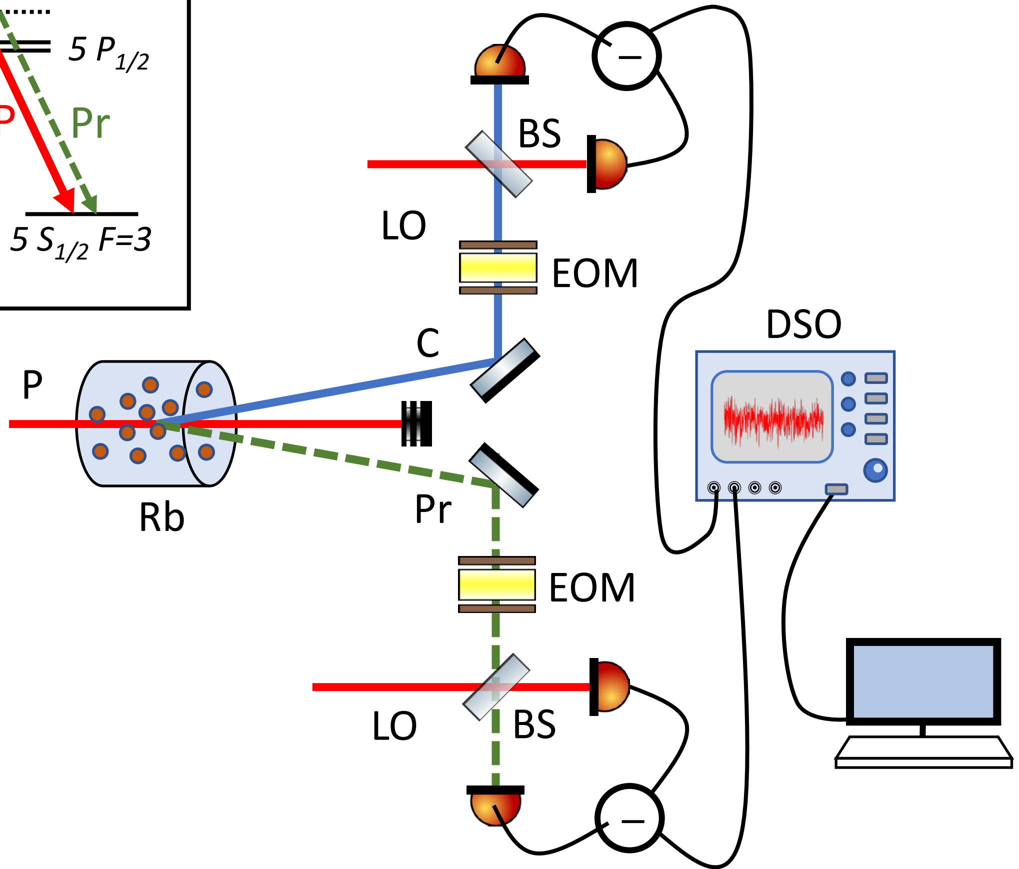
Zhifan Zhou[1], Luis E. E. Araujo[1,2], Matthew DiMario[1], Jie Zhao[1], B. E. Anderson[3], Kevin M. Jones[4], Paul D. Lett[1]

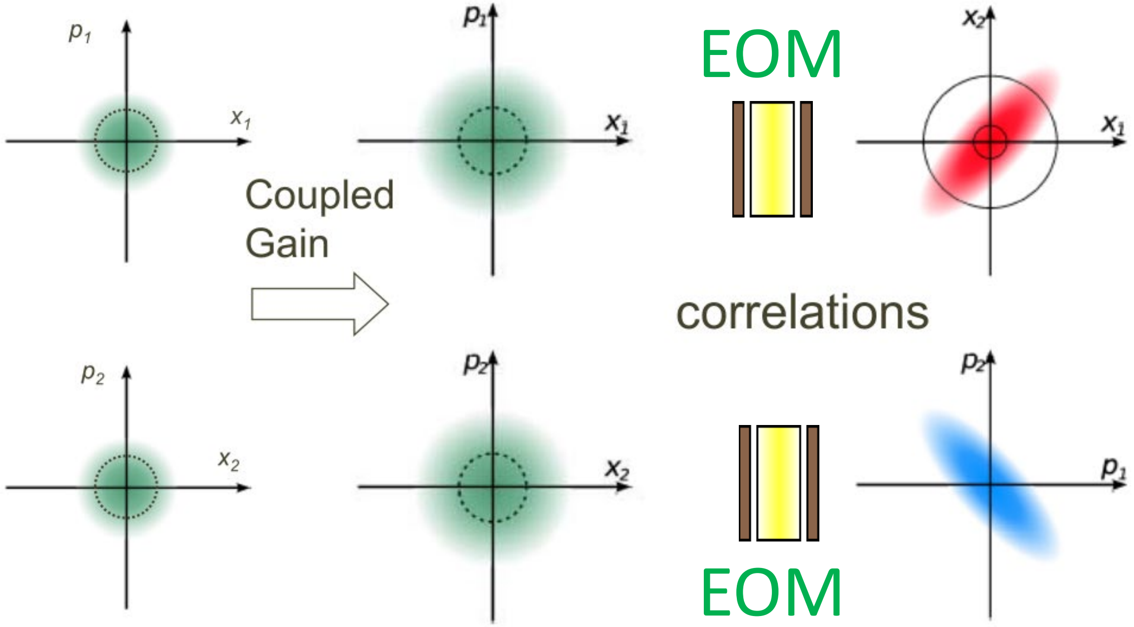
1. Joint Quantum Institute, NIST and the University of Maryland, College Park, MD 20742, USA
2. Institute of Physics "Gleb Wataghin," University of Campinas (UNICAMP), 13083-859 Campinas, São Paulo, Brazil

2. Department of Physics, American University, DC 20016, USA

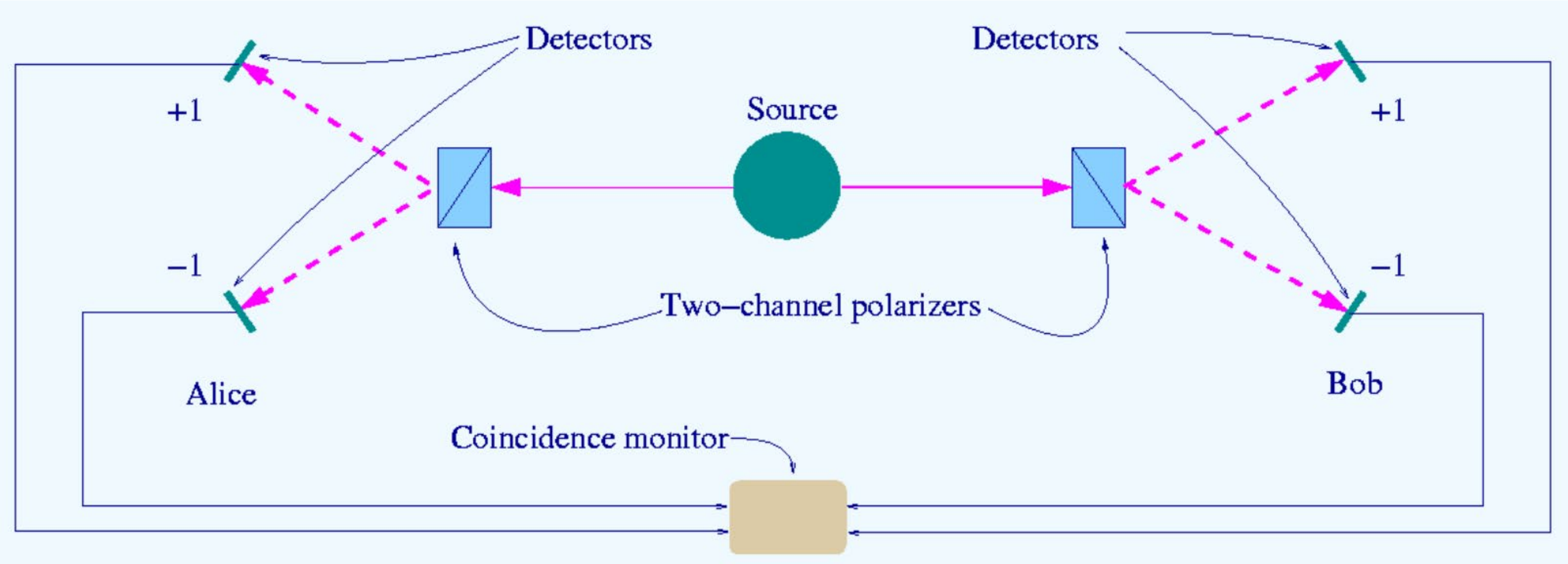
3. Department of Physics, Williams College, Williamstown, MA 01267, USA







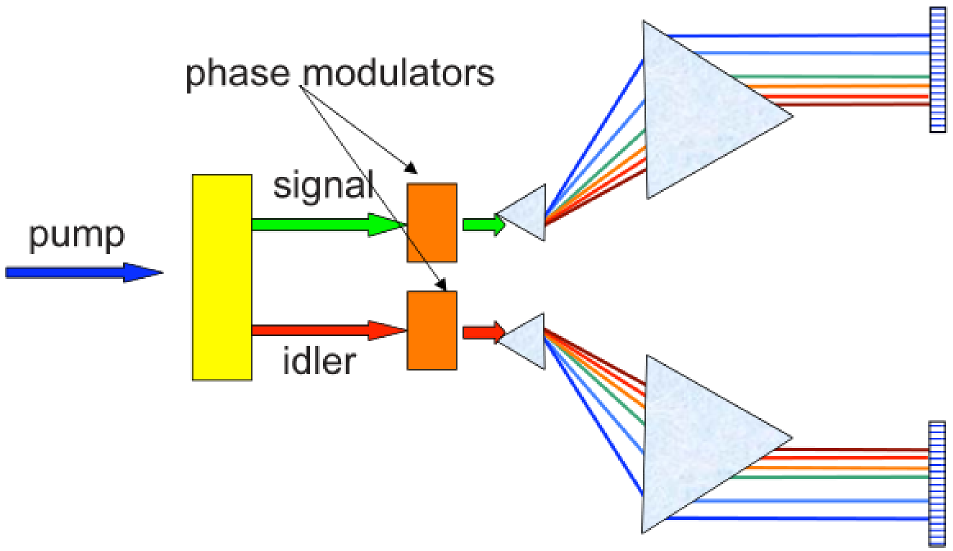
Quantum nonlocality

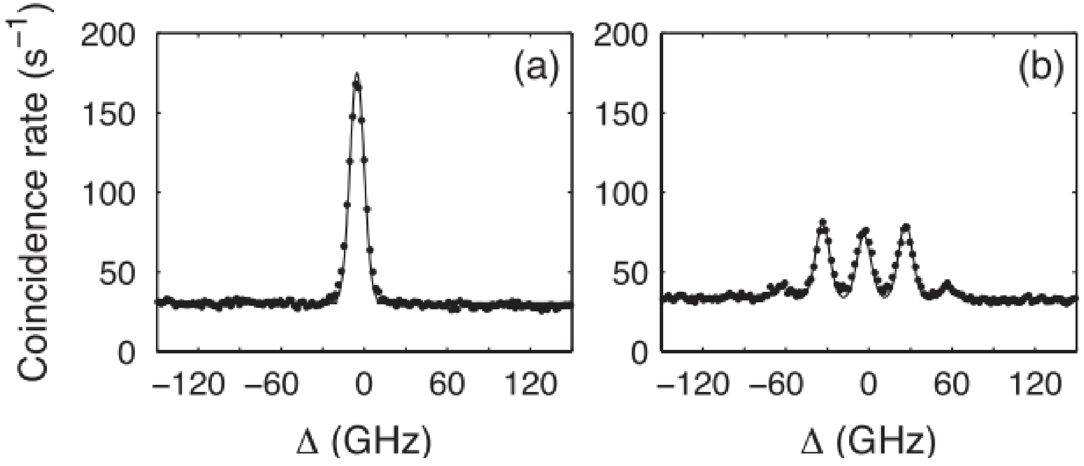


- Particles don't know their own polarizations until the measurements.
- Once one particle is measured, the other is automatically projected into the corresponding correlated state, no matter how far apart.

Confirmed by the Bell test experiments!

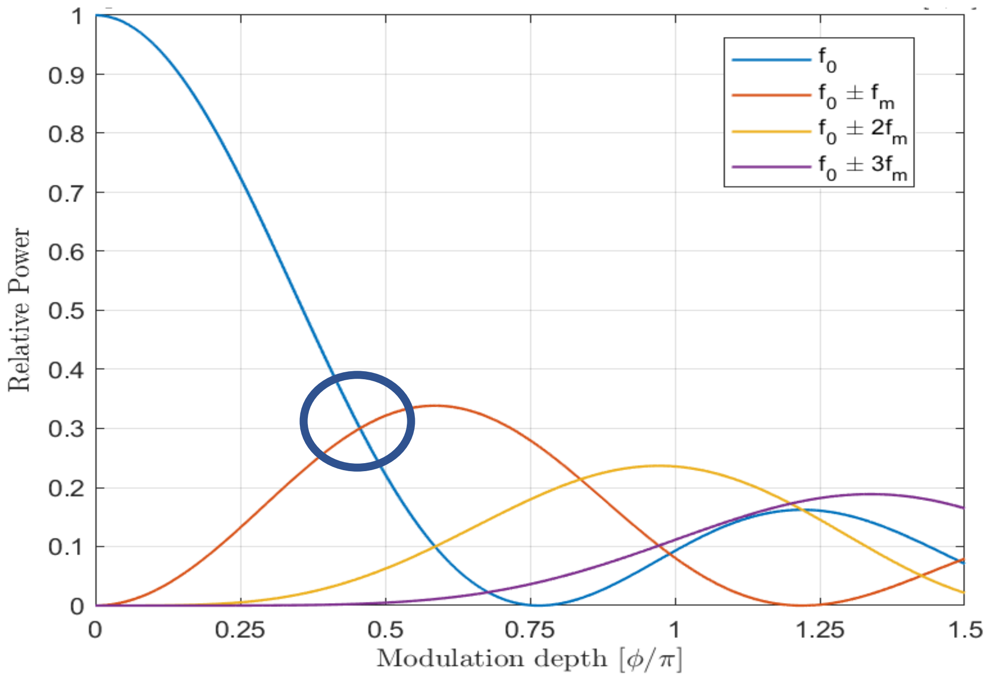
Nonlocal phase modulation in discrete variable (DV) regime





Frequency correlation measurements (a) with both modulators turned off and (b) with the modulator in channel 1 running at a modulation depth of 1.5.

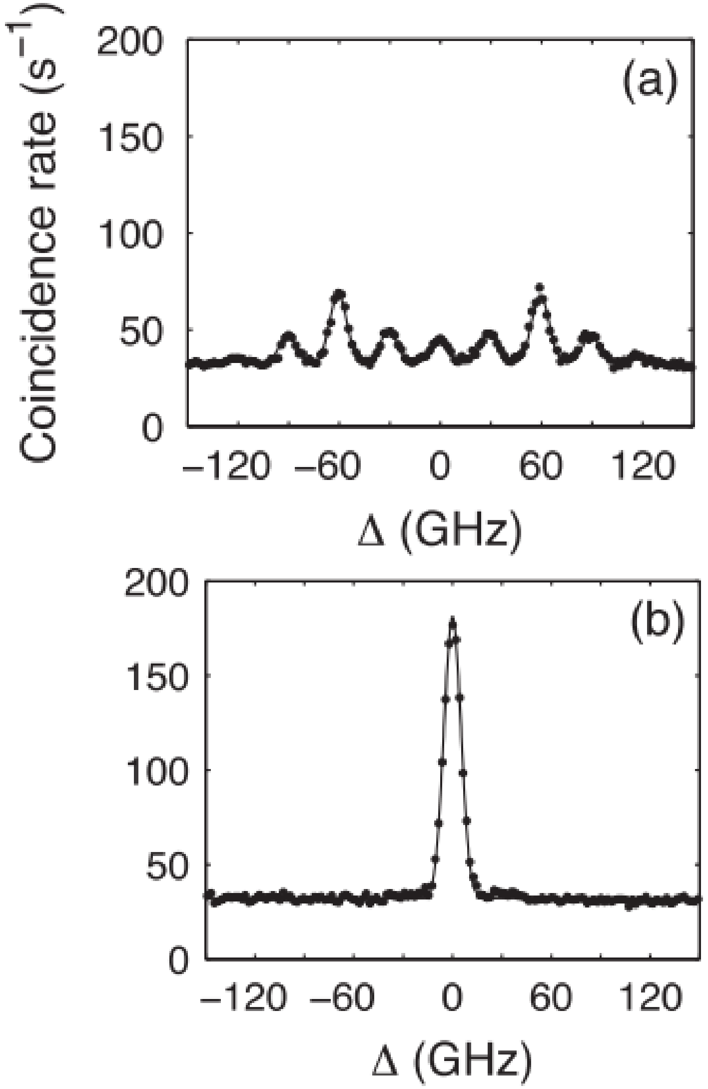
Modulation frequency: 30GHz. Following the modulators are identical monochromators, each having a linear dispersion of 210 GHz=mm and a Gaussian instrument response function with a FWHM bandwidth of 8.5 GHz.



Nonlocal modulation of entangled photons, S. E. Harris, PRA(R) 78,021807 (2008).

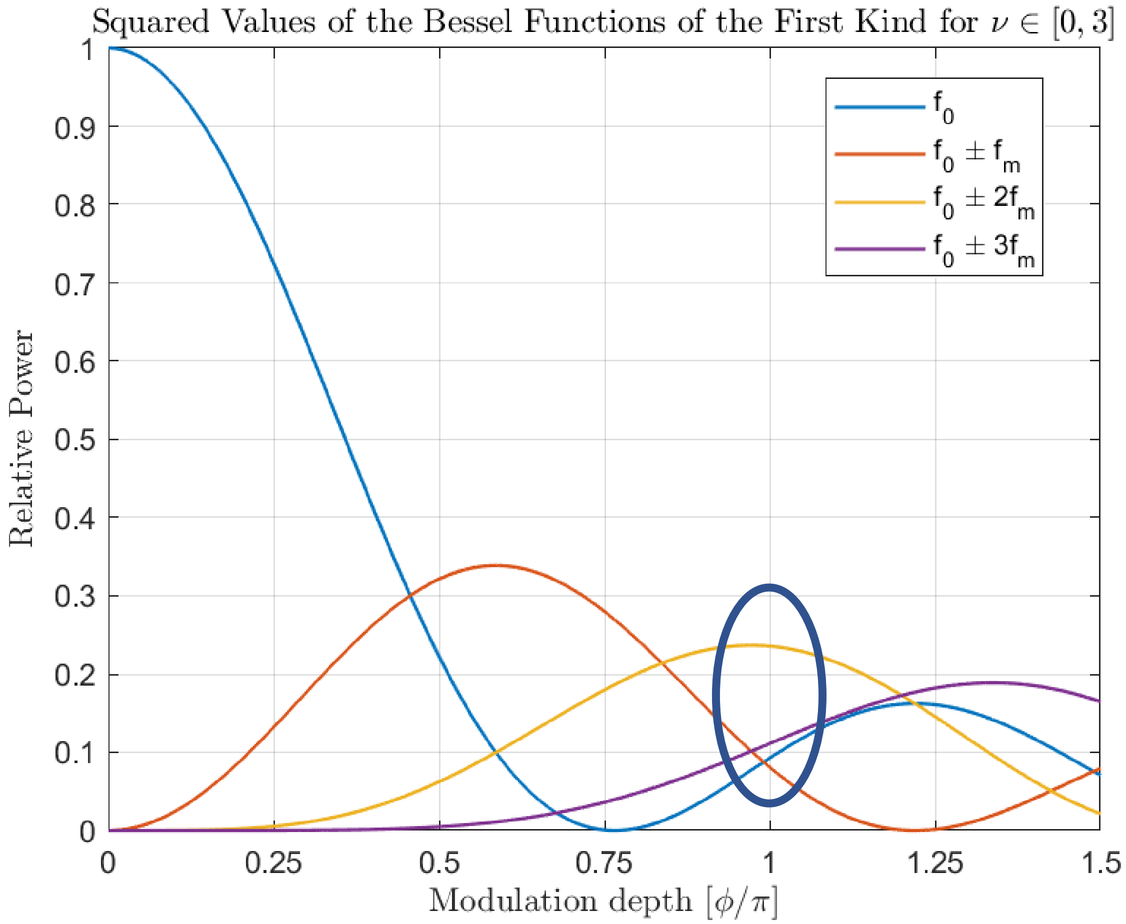
Observation of Nonlocal Modulation with Entangled Photons, S. Sensarn, G. Y. Yin, and S. E. Harris, PRL 103, 163601 (2009).

EOMs with the same phase and the opposite phase



Both modulators running (a) with the same phase, at a modulation depth of 1.5.

(b) with the opposite phase.



Observation of Nonlocal Modulation with Entangled Photons, S. Sensarn, G. Y. Yin, and S. E. Harris, PRL 103, 163601 (2009).

Nonlocal modulation of the probability wave!

Motivation: continuous-variable quantum computing

Quantum optics provides a scalable platform for continuous-variable (CV) universal quantum computing (QC), based on qumodes (e.g., quantum optical fields) rather than qubits.

Xuan Zhu, Chun-Hung Chang, Carlos Gonz´alez-Arciniegas, Avi Pe'er, Jacob Higgins, and Olivier Pfister, "Hypercubic cluster states in the phase modulated quantum optical frequency comb," Optica 8,281 (2021).

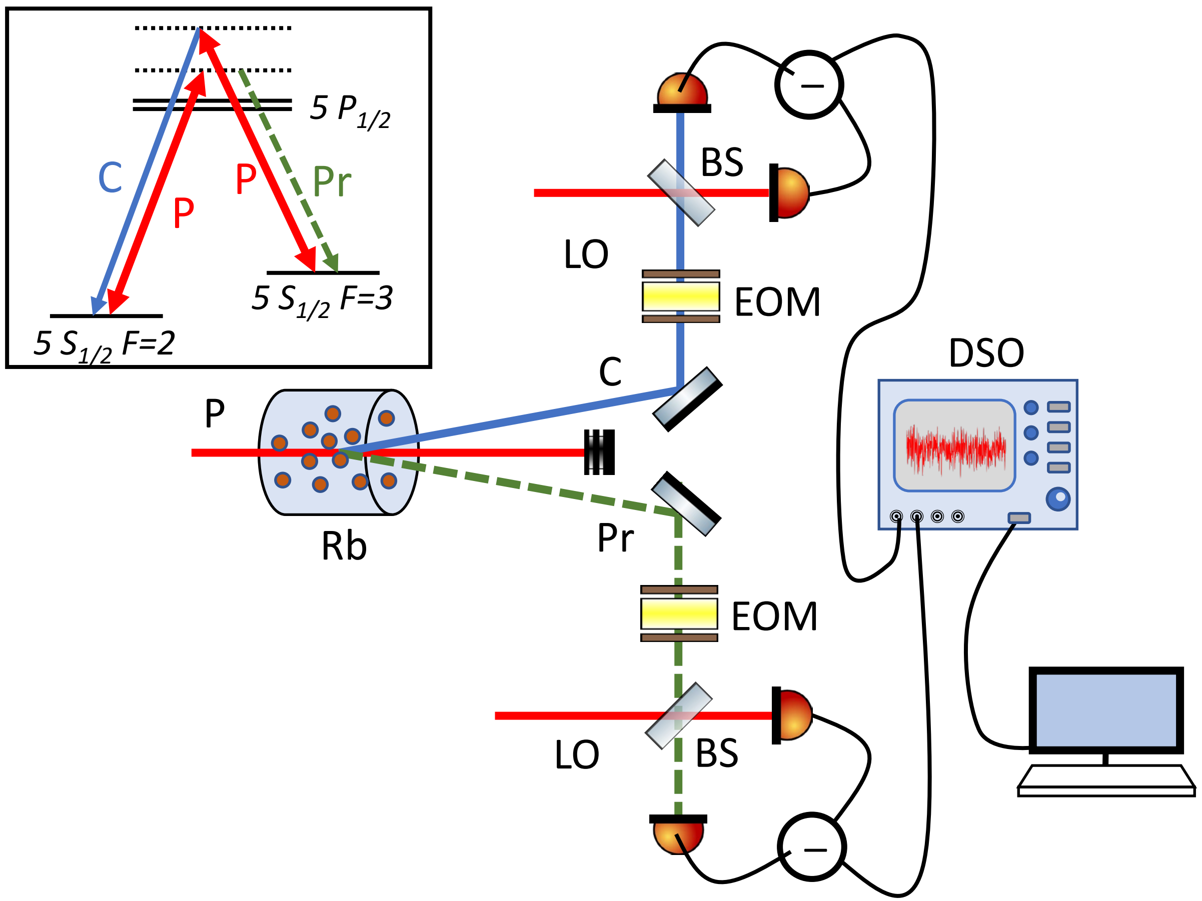
CVQC can be made fault tolerant at reachable squeezing levels.

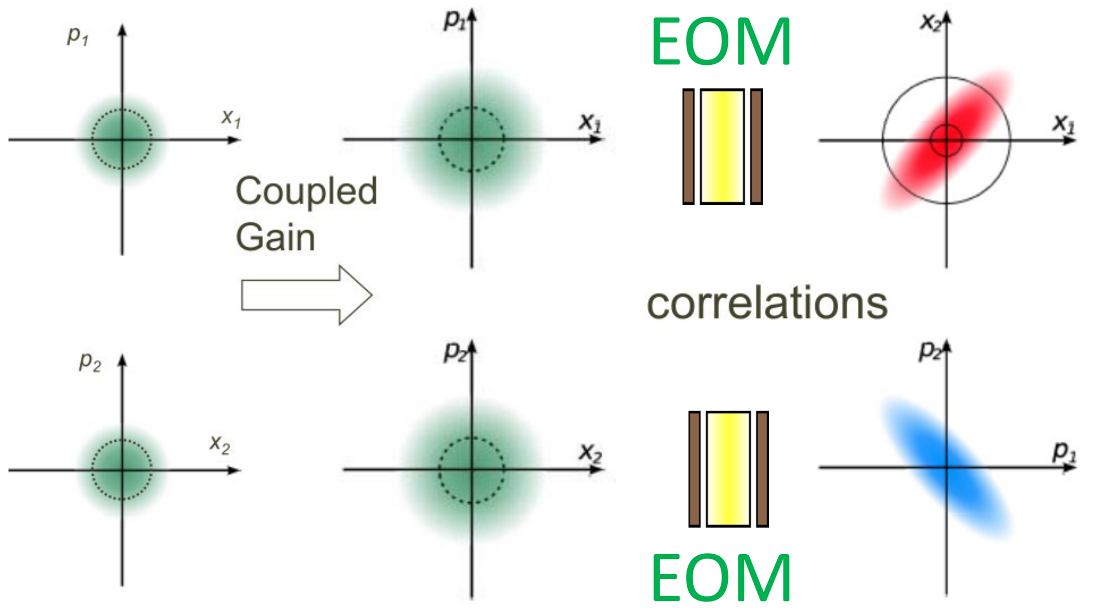
- N. C. Menicucci, "Fault-tolerant measurement-based quantum computing with continuous-variable cluster states," Phys. Rev. Lett. 112, 120504 (2014).

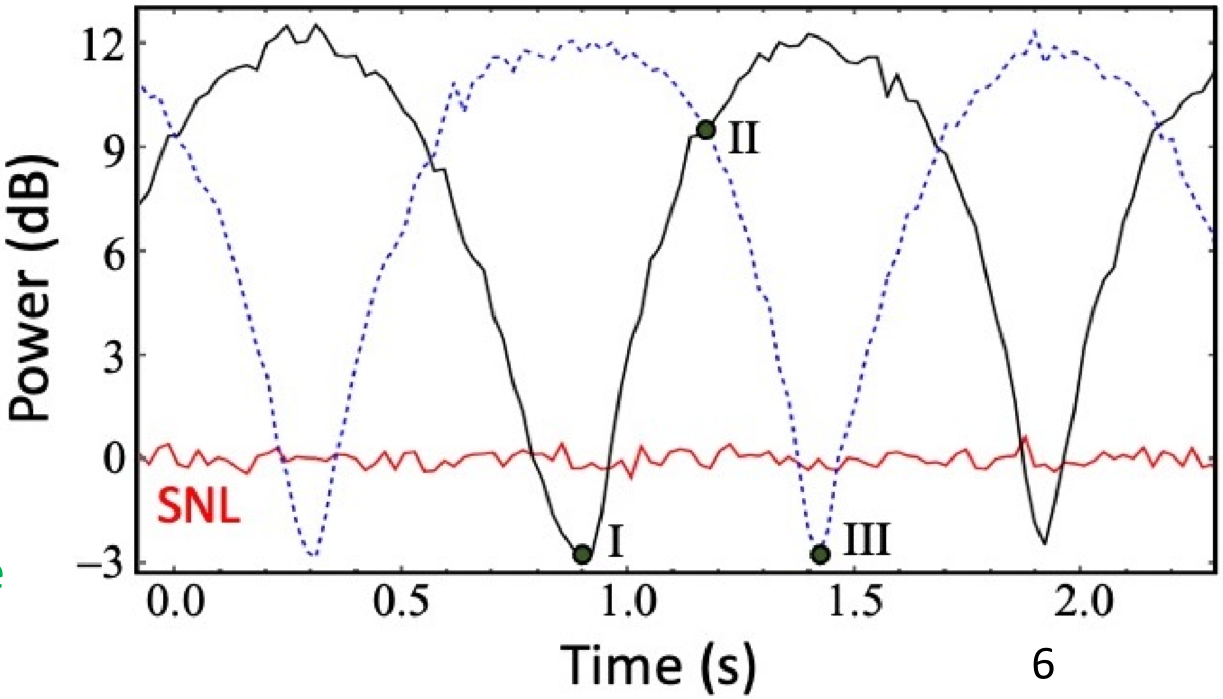
Quantum error correction topological encoding.

R. Raussendorf, J. Harrington, and K. Goyal, "A fault-tolerant one-way quantum computer," Ann. Phys. 321, 2242–2270 (2006).

Continuous-variable (CV) nonlocal phase modulation

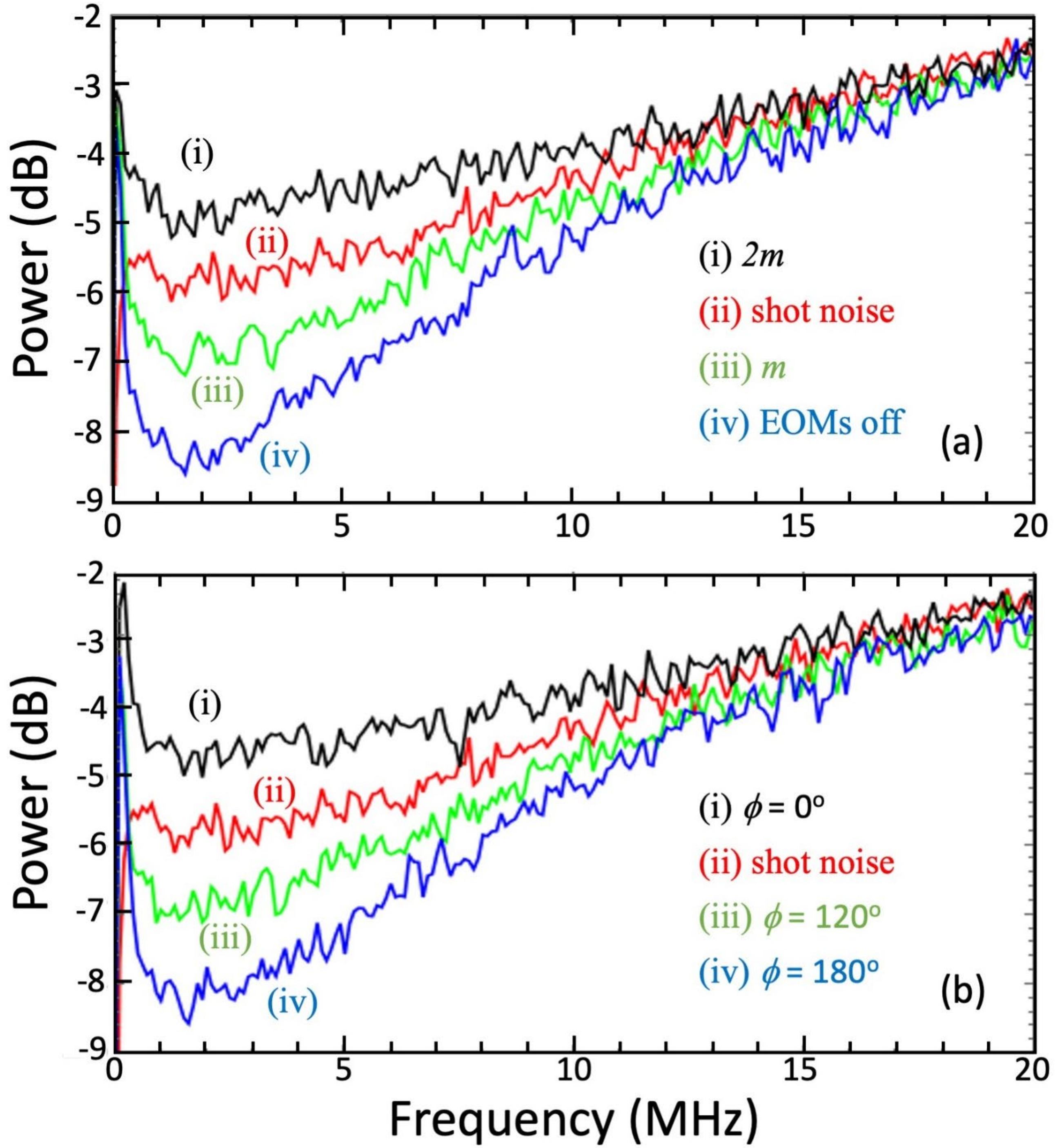




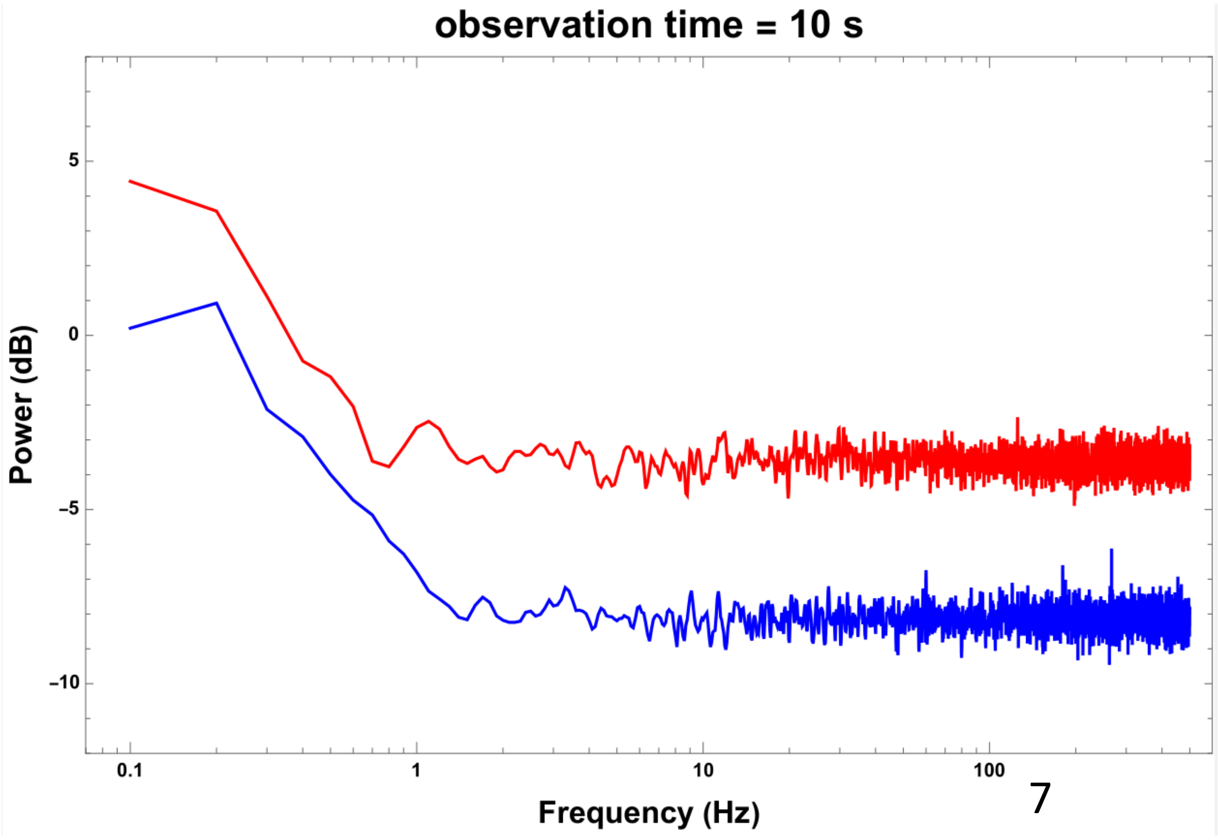


Noise power of the sum (dashed blue) and difference (solid black) of the quadratures measured by the homodyne detectors as the phase θ is varied. In both cases, the noise is analysed at a frequency of 1 MHz.

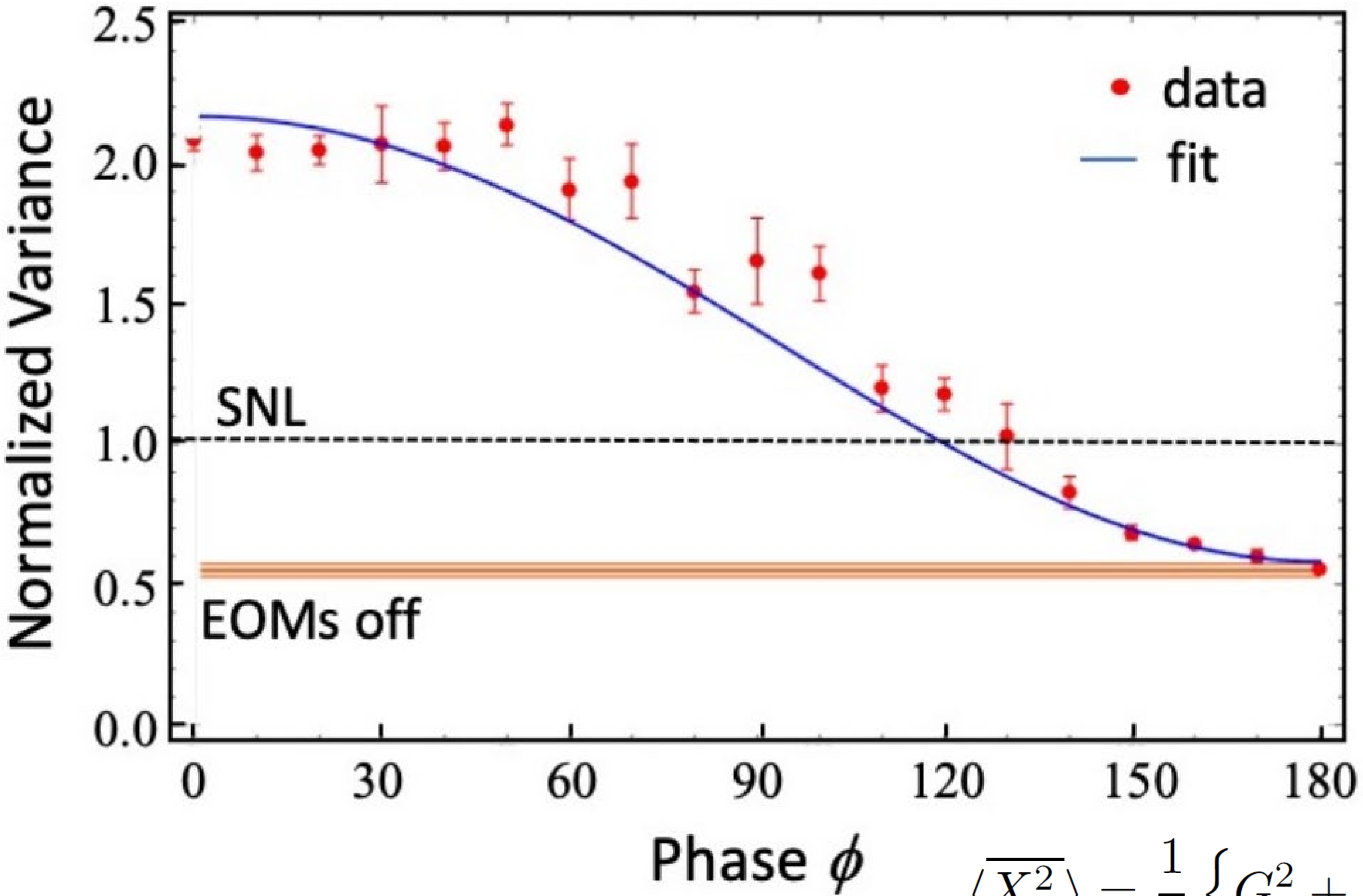
Squeezing spectra



Quantum noise locking, Kirk McKenzie et, al., J. Opt. B: Quantum Semiclass. Opt. 7, S421 (2005).



Phase dependent

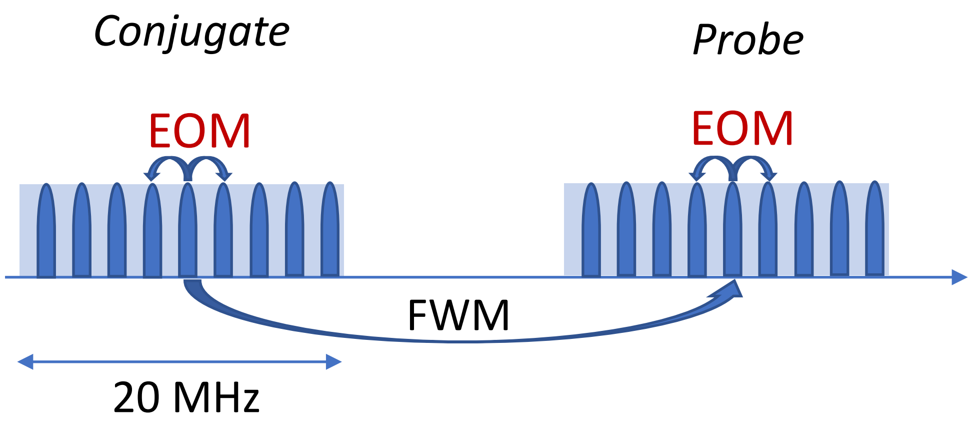


Joint quadrature variance $\langle X_-^2 \rangle$ normalized by the shot noise variance as a function of the phase difference φ between the EOMs.

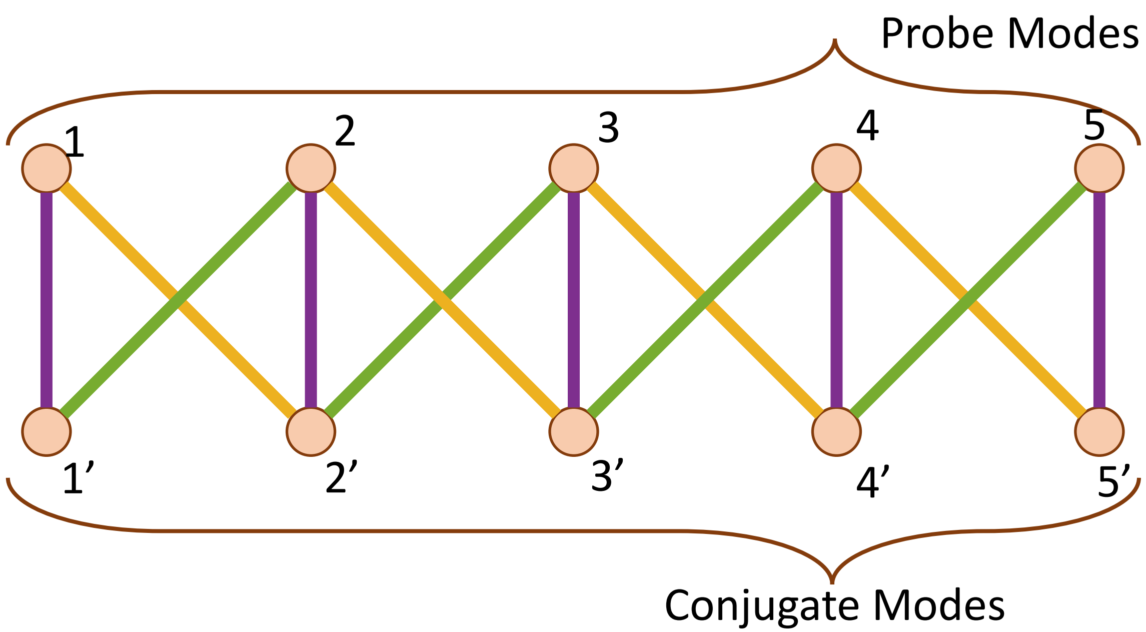
$$\langle \overline{X_-^2} \rangle = \frac{1}{2}\left\{ G^2 + g^2 - 2gGJ_0\left(\pi m\sqrt{2+2\cos\phi}\right)\right\}$$

Variance of 100kHz window measured at 1MHz.

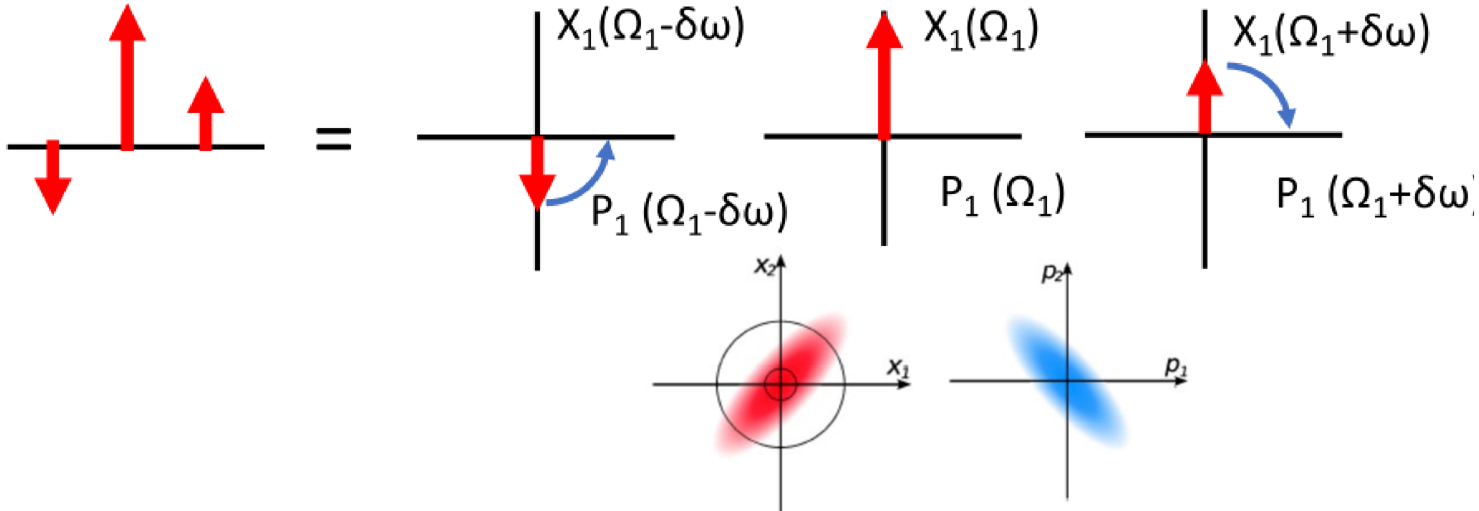
Correlation structure via phase modulation

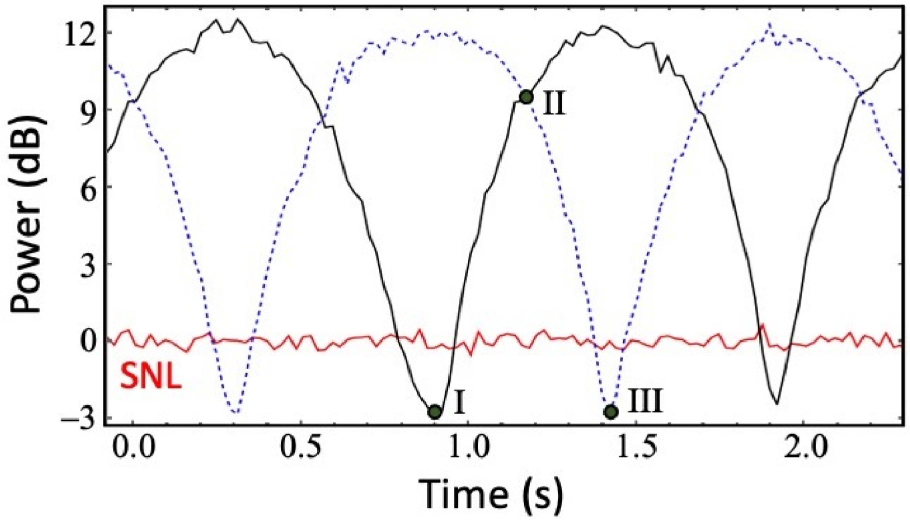


Optical spectrum

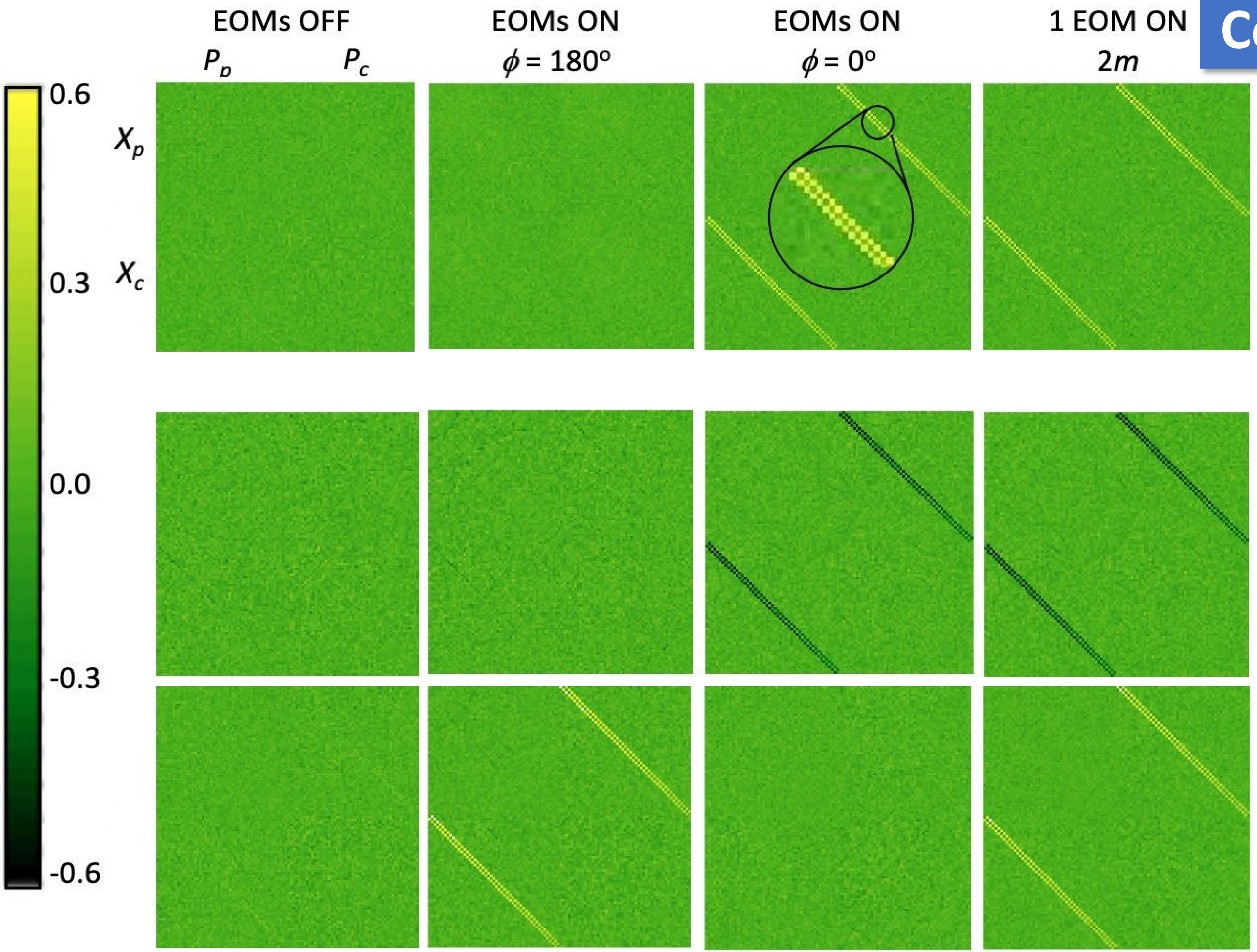


In phase modulation:





Correlation structure



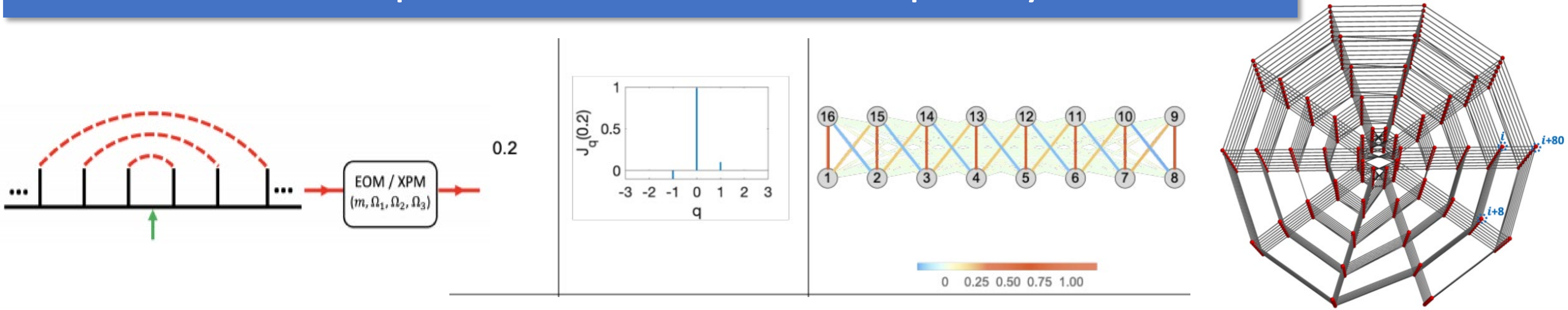
EOMs in Squeezing Signal path.

EOMs in Local Oscillator path.

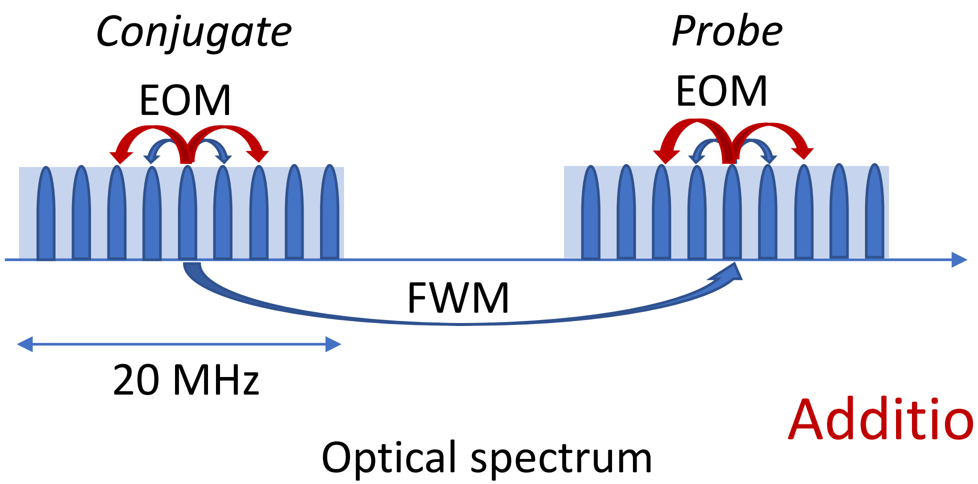
Hybrid

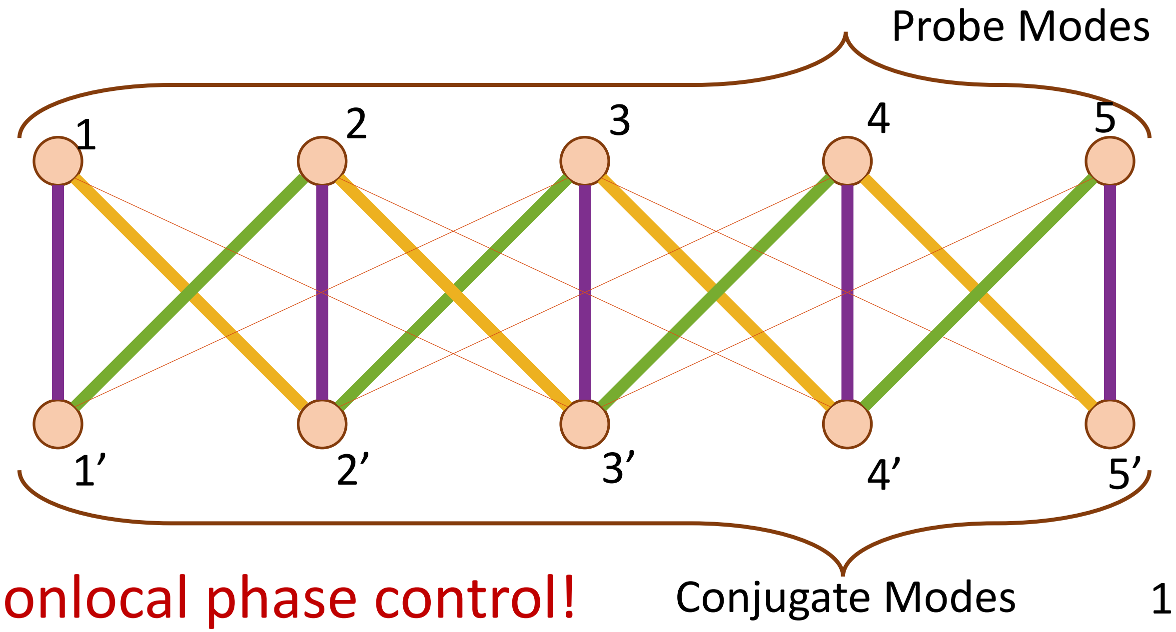
Non-local modulation happens for each mode in covariance matrix!

Cluster state with phase modulation in frequency domain



Xuan Zhu, Chun-Hung Chang, Carlos Gonz´alez-Arciniegas, Avi Pe'er, Jacob Higgins, and Olivier Pfister, "Hypercubic cluster states in the phase modulated quantum optical frequency comb," Optica 8,281 (2021).

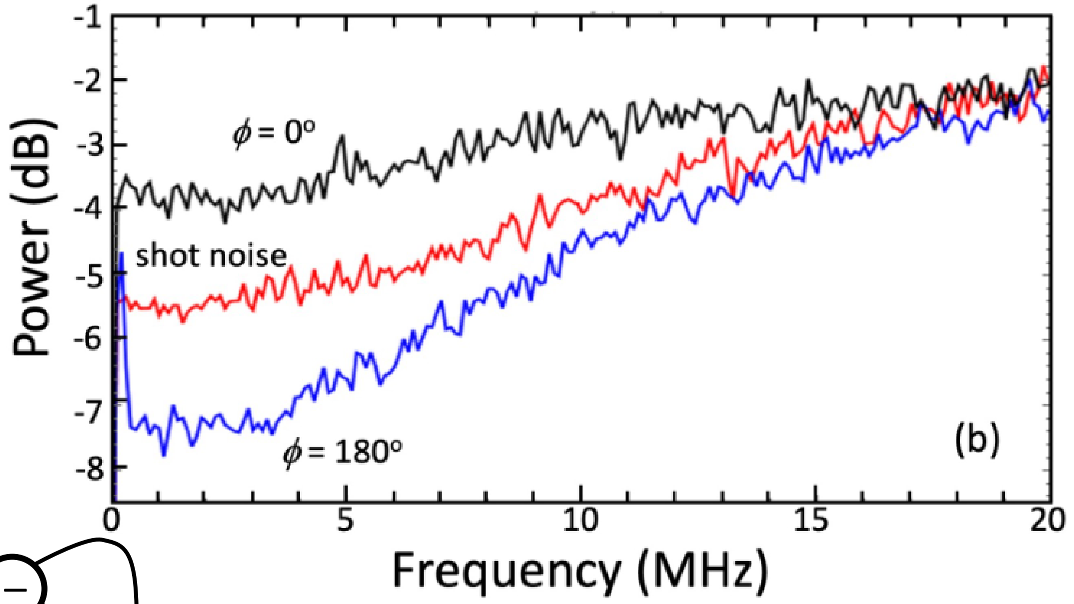


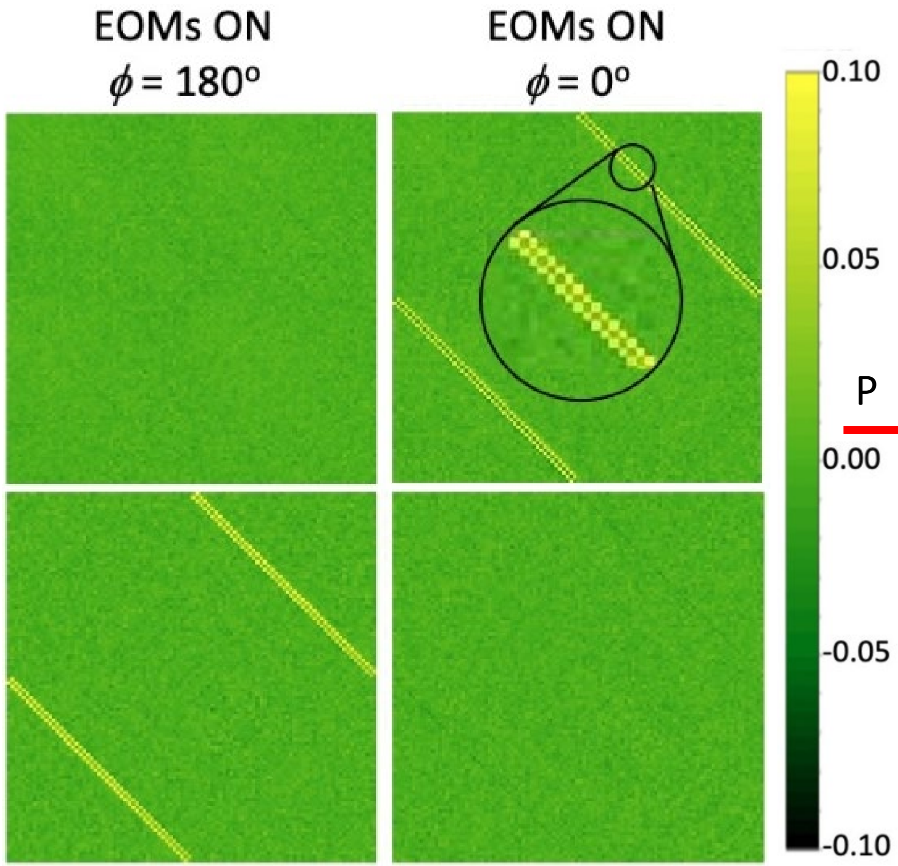


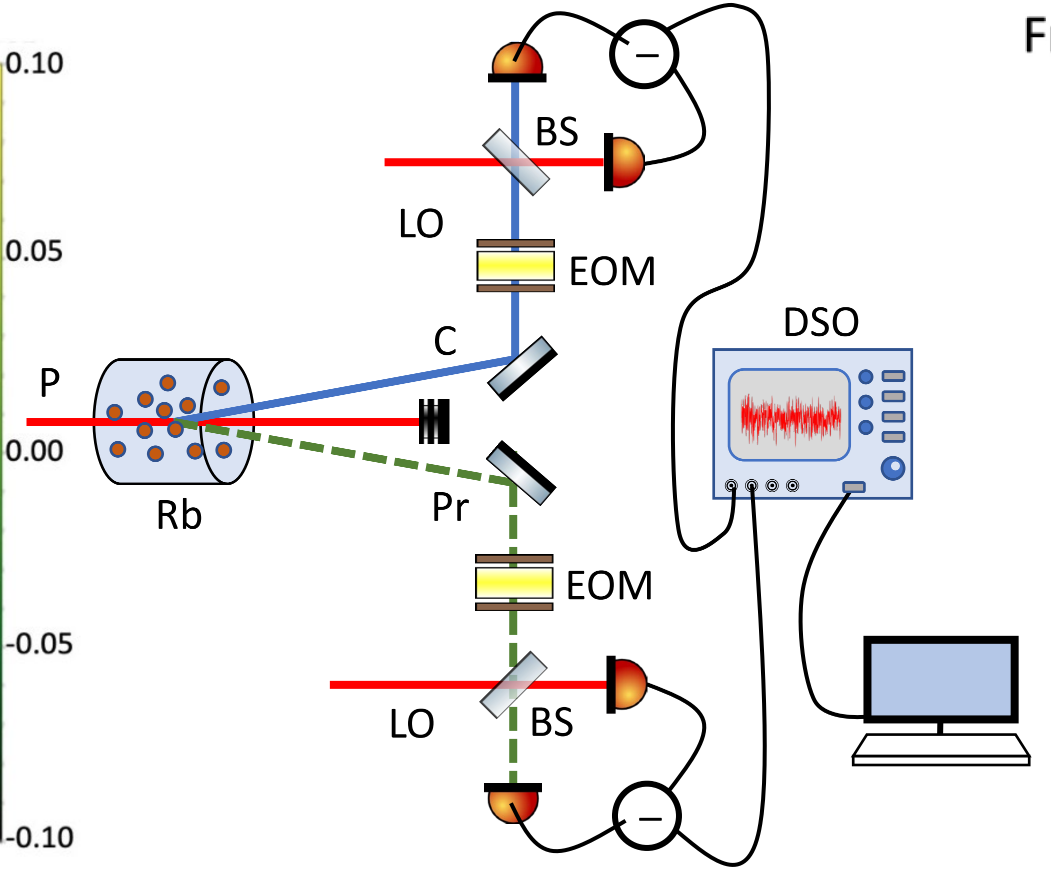
Addition: nonlocal phase control!

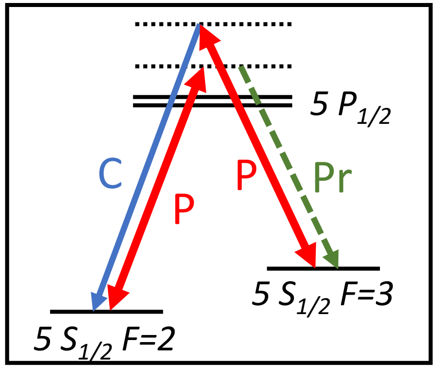
Summary & outlook

- Nonlocal phase modulation of continuous-variable twin beams .
- Individual mode, covariance matrix
- Hypercubic cluster state, frequency domain.

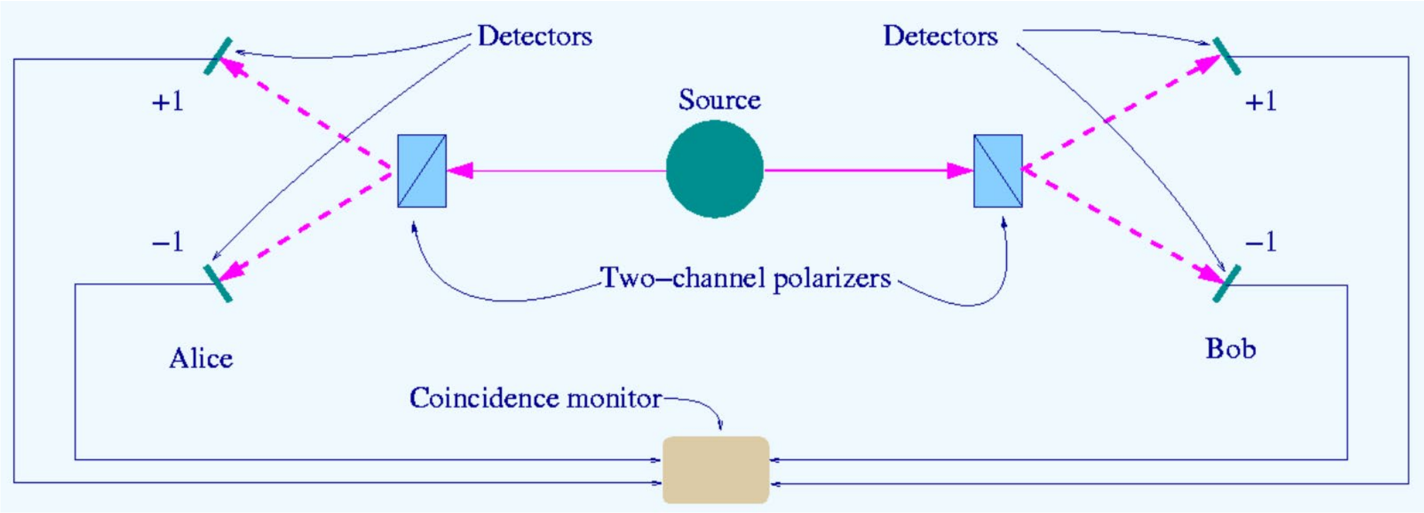


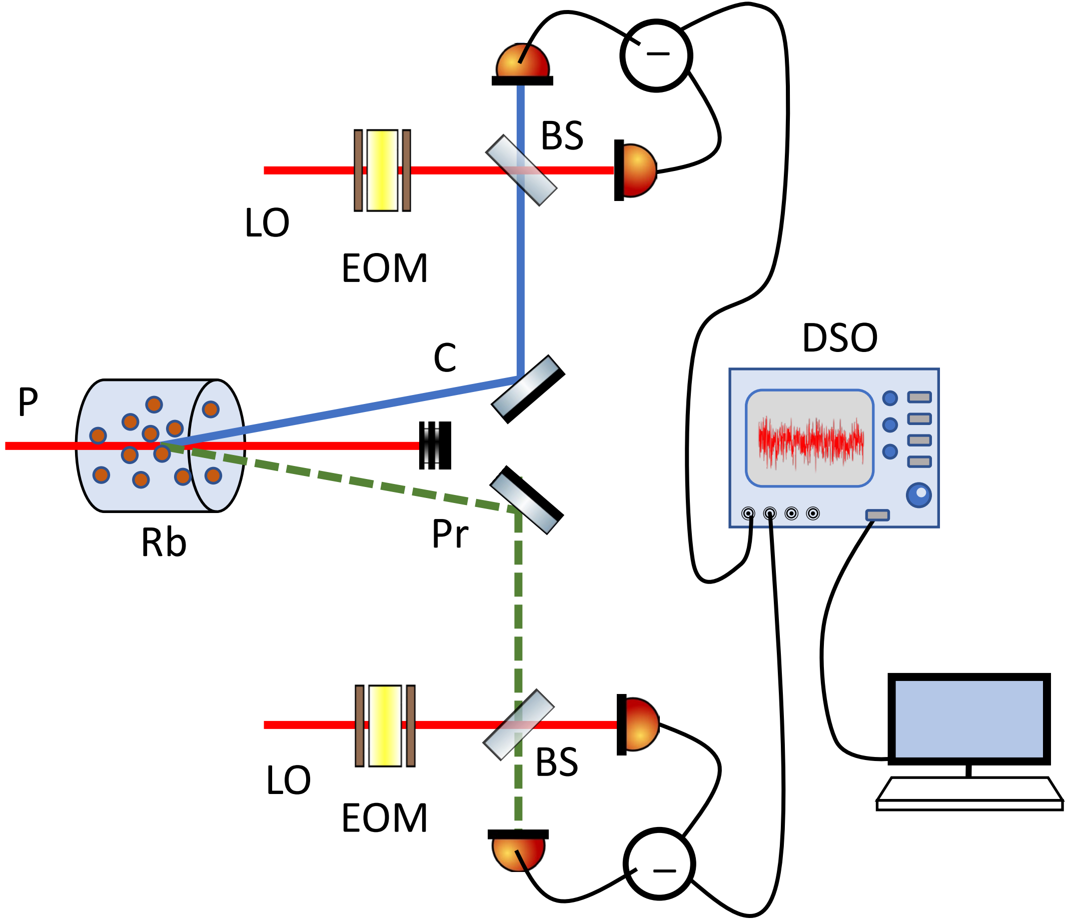






Test of Bell’s nonlocality in CV





Evidence for Bell’s nonlocality is so far mainly restricted to microscopic systems, where the elements of reality that are negated predetermine results of measurements to within one spin unit. Any observed nonlocal effect (or lack of classical predetermination) is then limited to no more than the difference of a single photon or electron being detected or not (at a given detector).

Quantifying the Mesoscopic Nature of Einstein-Podolsky-Rosen Nonlocality, M. D. Reid and Q. Y. He, *PRL 123, 120402 (2019).*

See also: Proposal for a Loophole-Free Bell Test Using Homodyne Detection, R. Garcıa Patron, J. Fiurasek, N. J. Cerf, J. Wenger, R. Tualle-Brouri, and Ph. Grangier, *PRL 93, 130409(2004).*