Nonlocal phase modulation of multi-frequency-mode, continuous-variable twin beams

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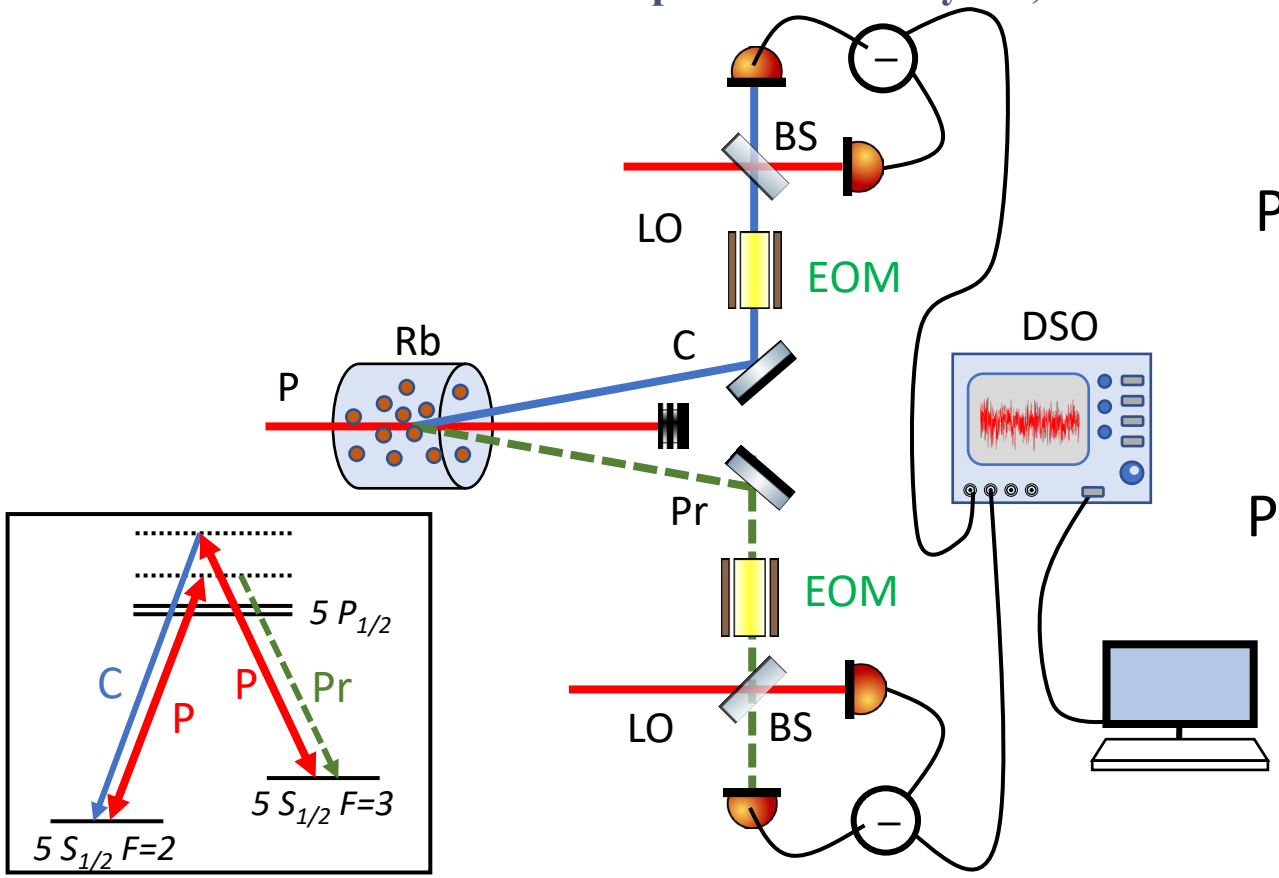
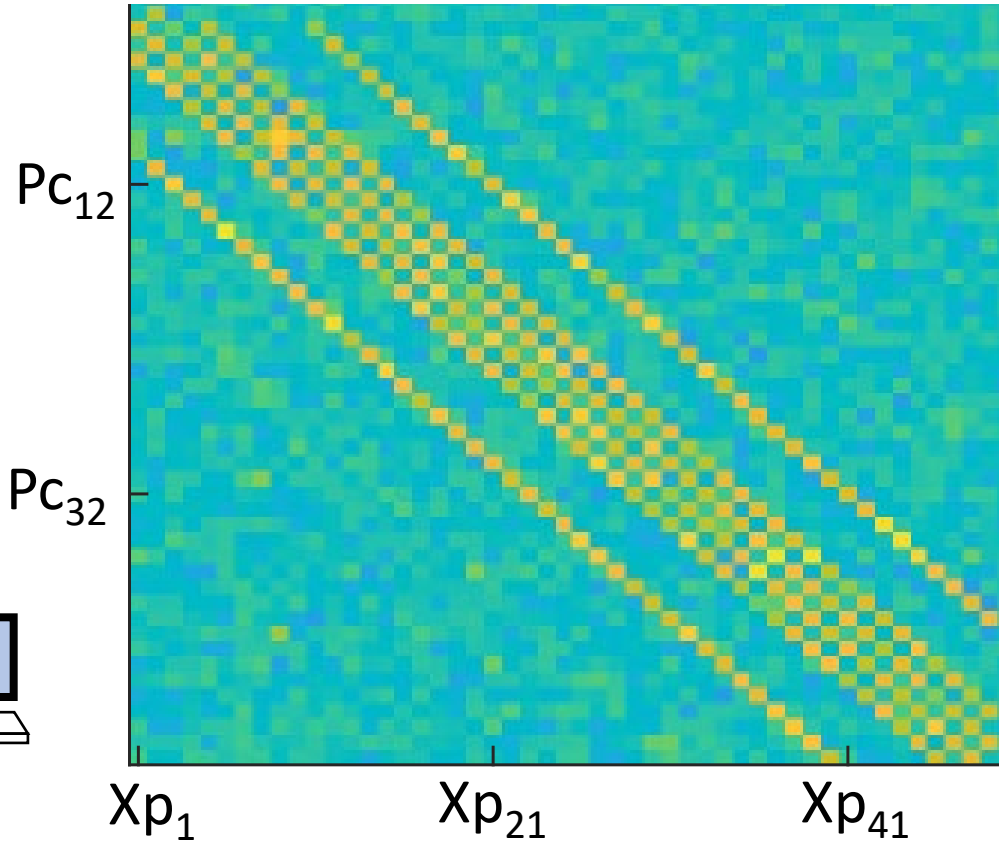
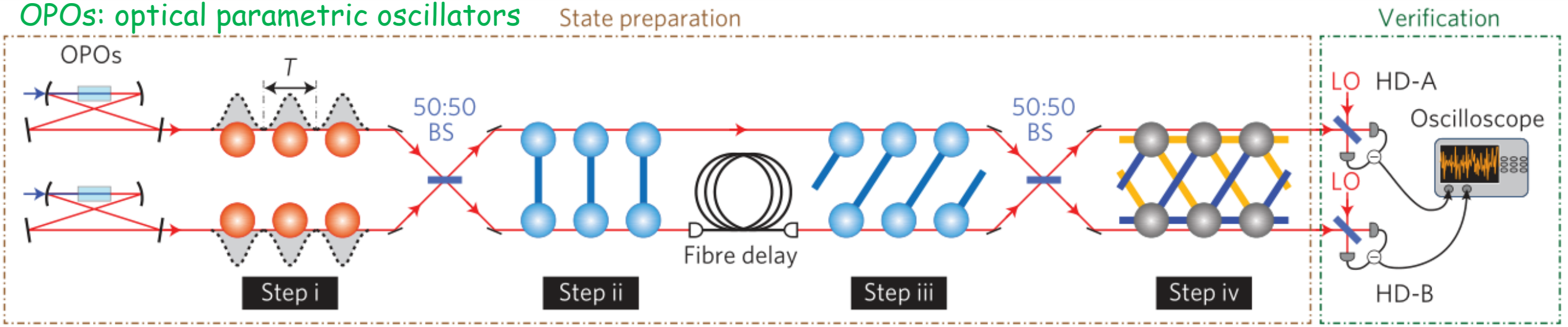




3D graph states!

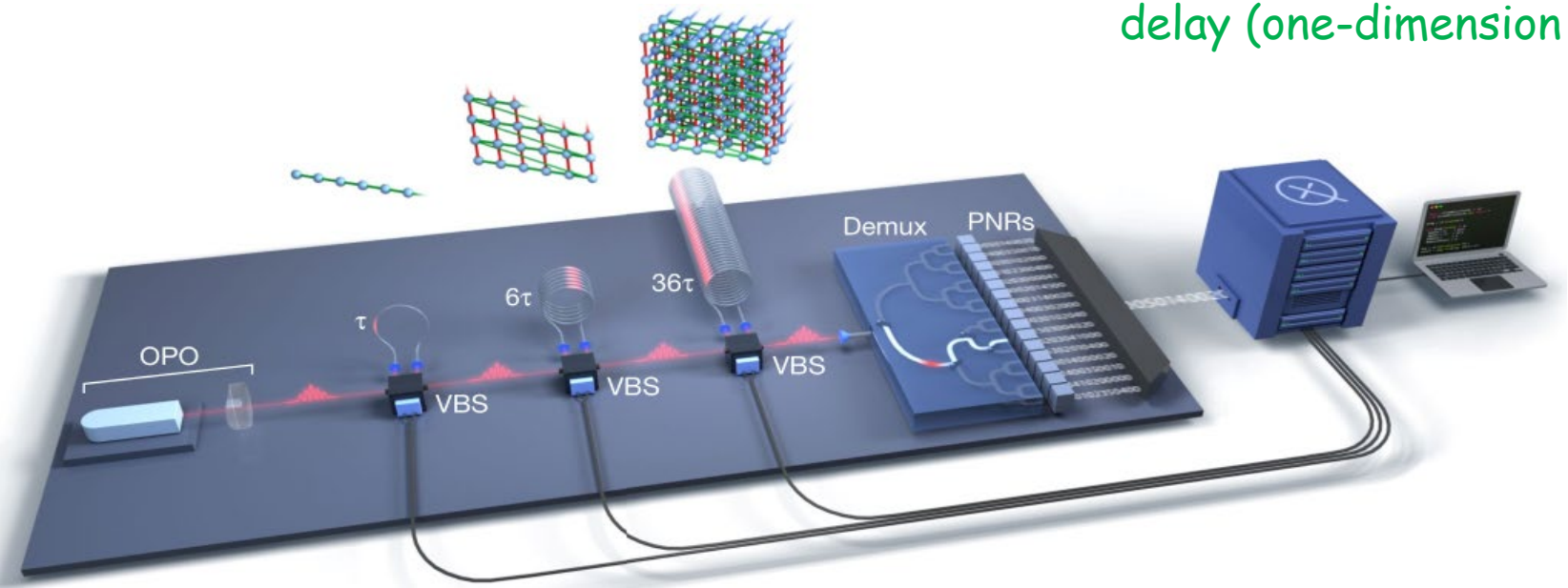
Cluster state: multipartite entangled resource states

OPOs: optical parametric oscillators



Ultra-large-scale continuous-variable cluster states multiplexed in the time domain, S. Yokoyama, et al. Nature Photonics 7, 982-986 (2013).

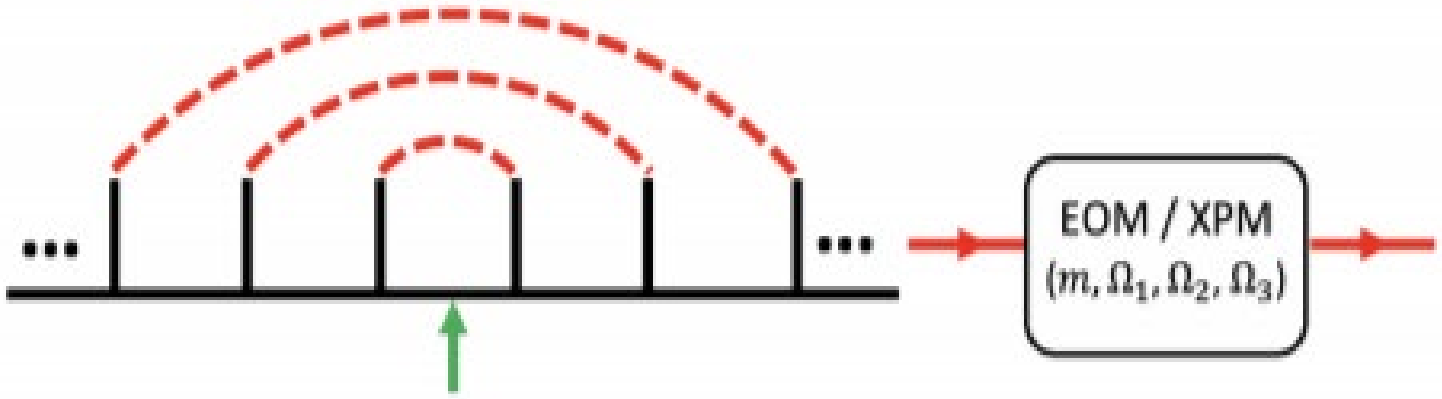
multiplexed time bins (10,000 entangled modes) & fiber delay (one-dimension cluster states)

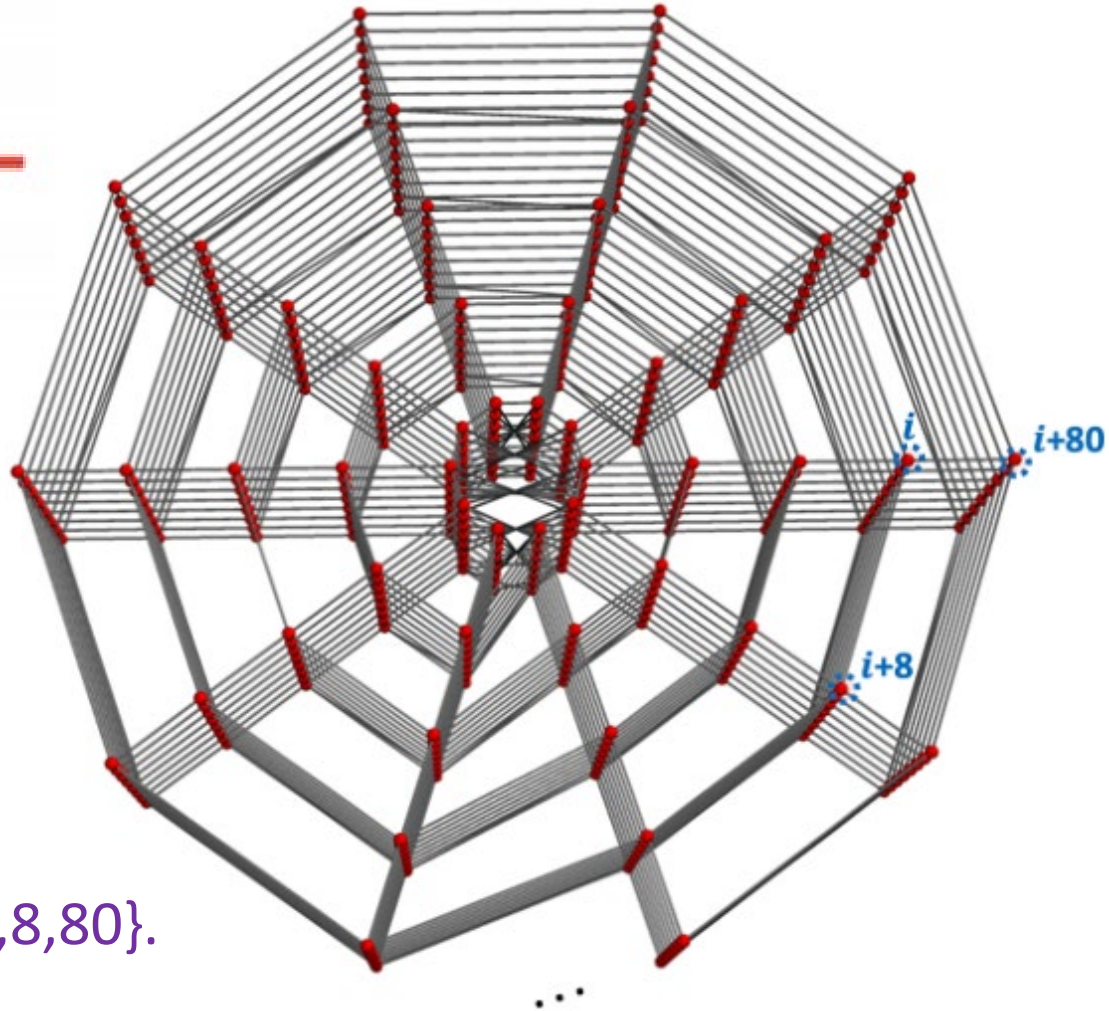


Quantum computational advantage with a programmable photonic processor, L. Madsen, et al. (Xanadu) Nature 606, 75-81, (2022).

Scalability and flexibility!

Cluster state with phase modulation: compact and scalable





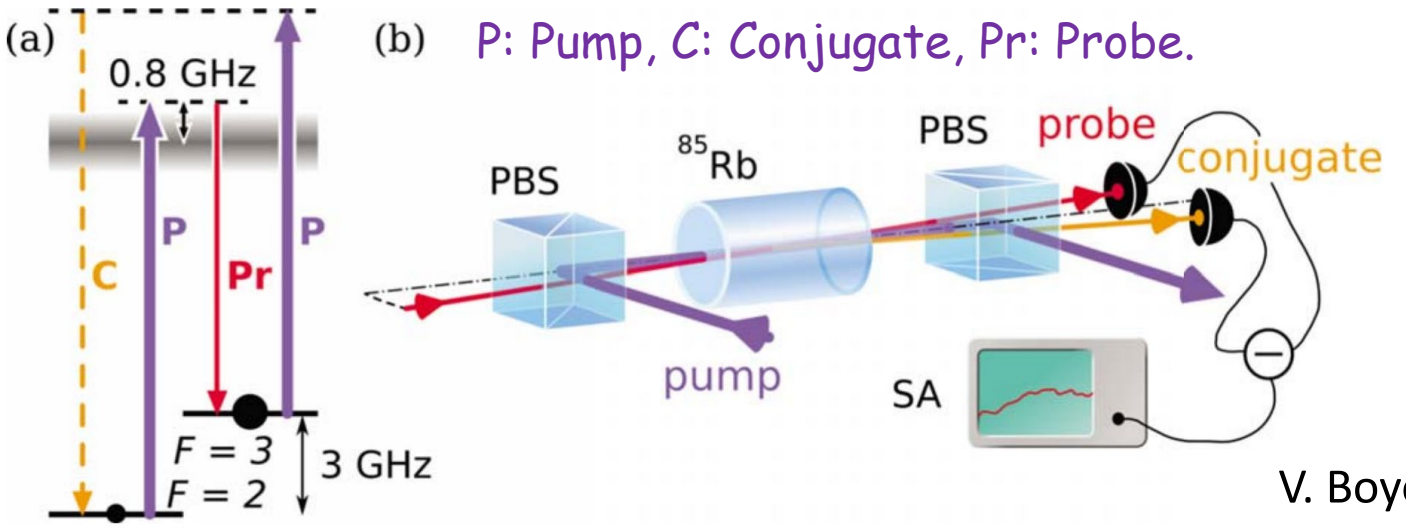
EOM: electro-optic modulator;
XPM: cross-phase modulation
(alternative phase modulation).

m: modulation index;
$\Omega_{1,2,3}$: modulation frequency.

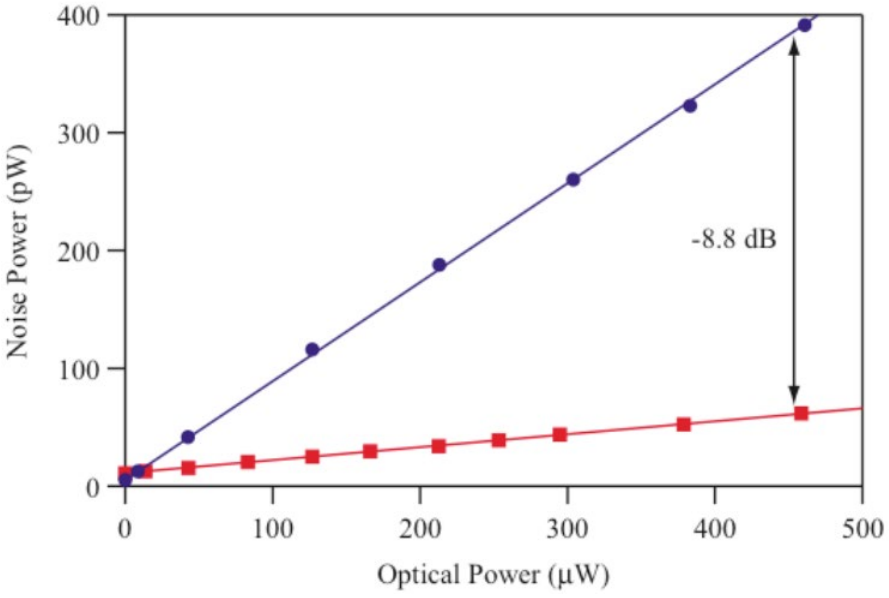
$\{\Omega_1, \Omega_2, \Omega_3\}=\{1,8,80\}$.

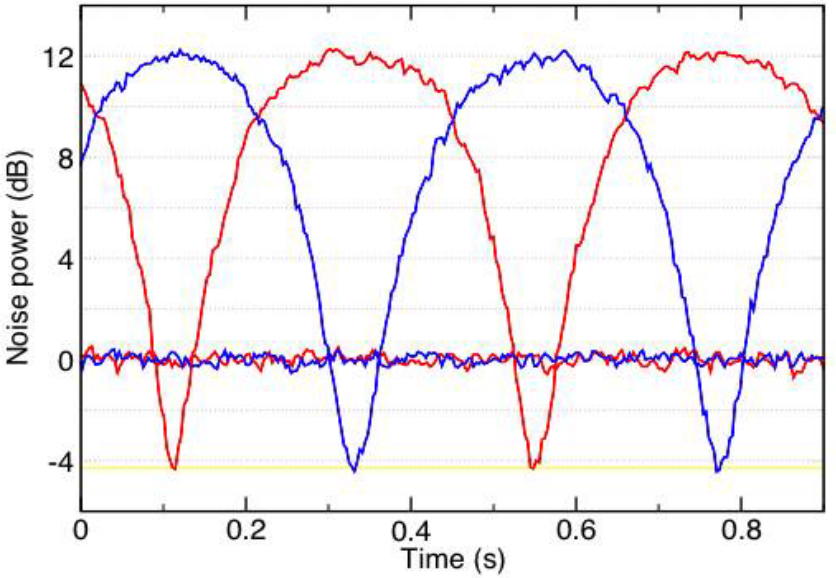
Xuan Zhu, Chun-Hung Chang, Carlos González-Arciniegas, Avi Pe'er, Jacob Higgins, and Olivier Pfister, "Hypercubic cluster states in the phase modulated quantum optical frequency comb," Optica 8,281 (2021).

Four-wave mixing in warm rubidium

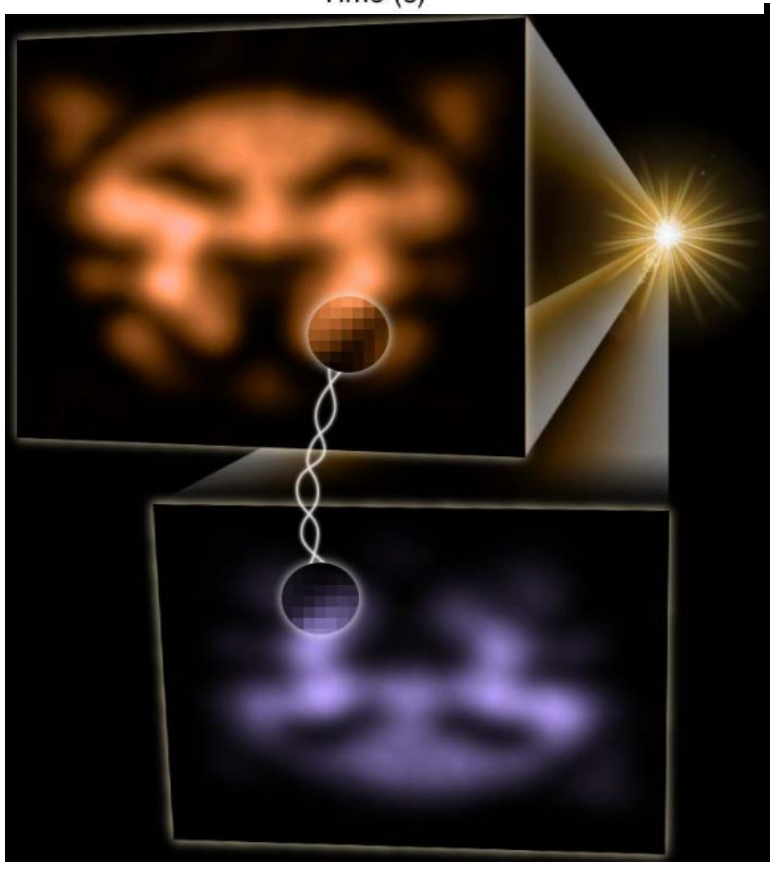


C. McCormick, et al., Phys Rev A 78, 043816 (2008).



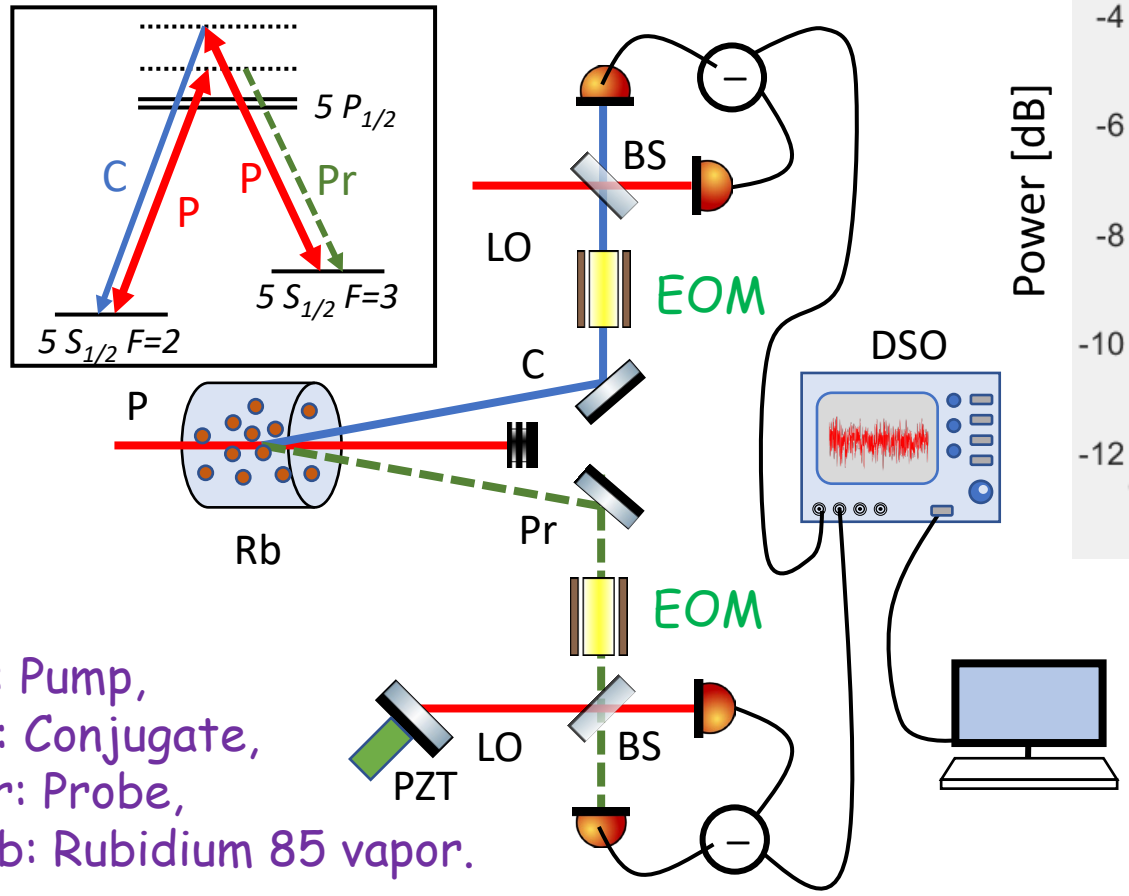


V. Boyer, et al. Science, 321, 547 (2008).



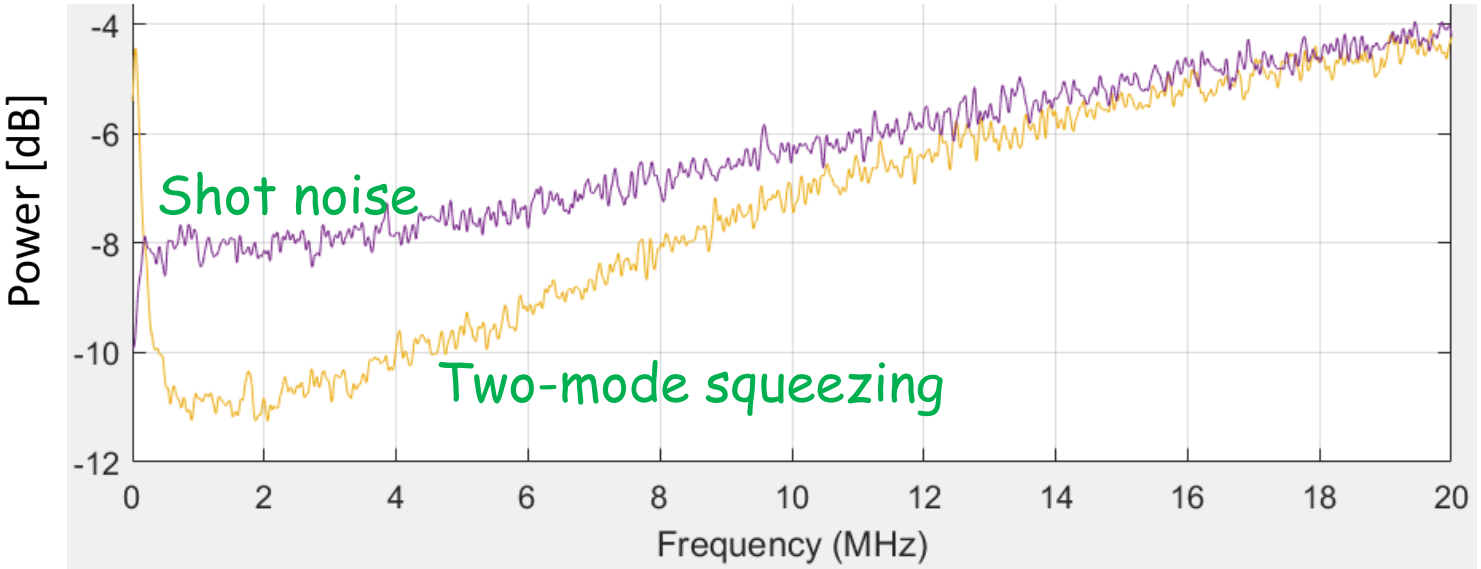
Good resources of quantum entanglement with independent modes!

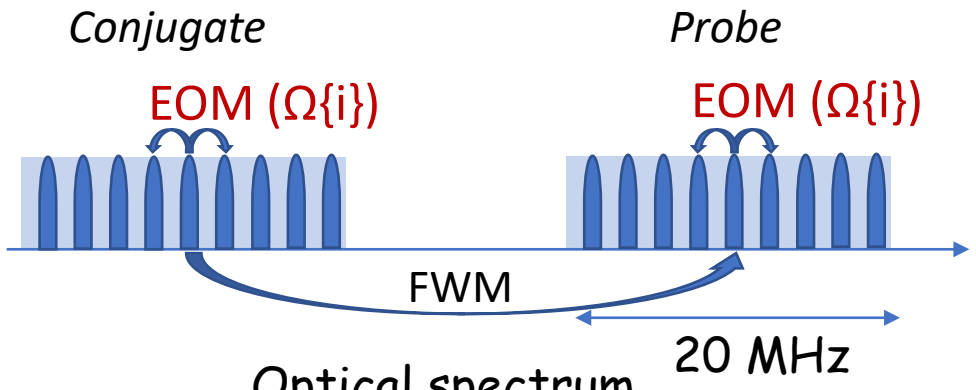
Multi-frequency-mode with nonlocal phase modulation



P: Pump,
C: Conjugate,
Pr: Probe,
Rb: Rubidium 85 vapor.

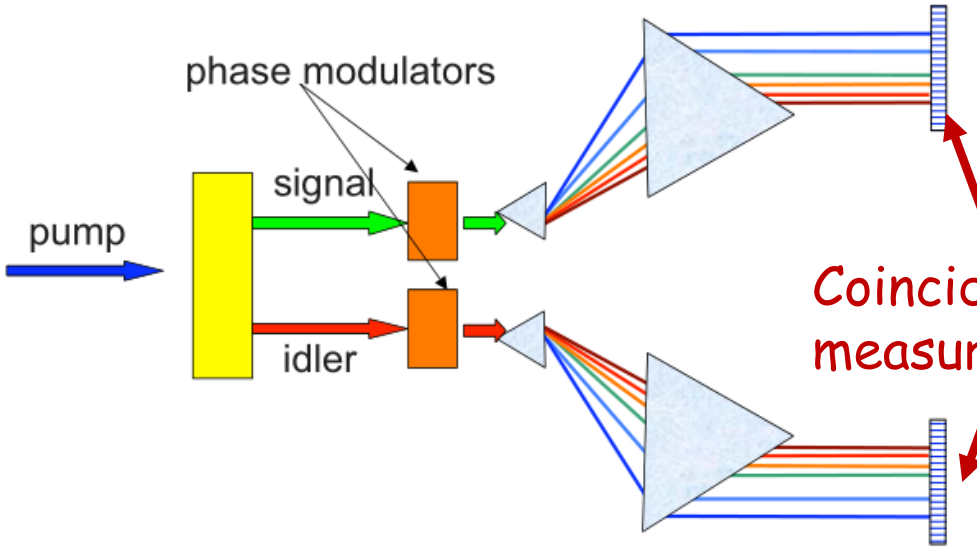
LO: Local oscillator,
BS: Beam splitter,
DSO: Digital Storage Oscilloscope.





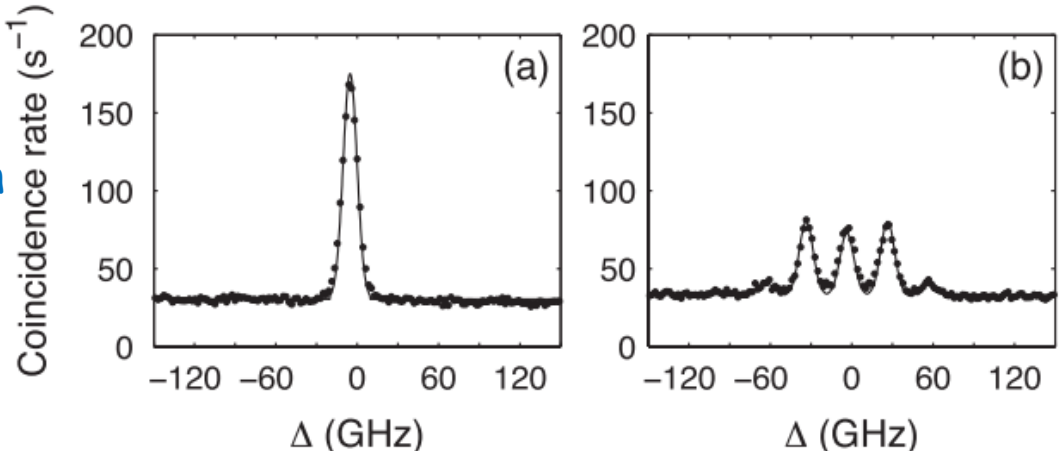
FWM: four-wave mixing

Nonlocal phase modulation



Δ: the coincidence rate of photon detection.

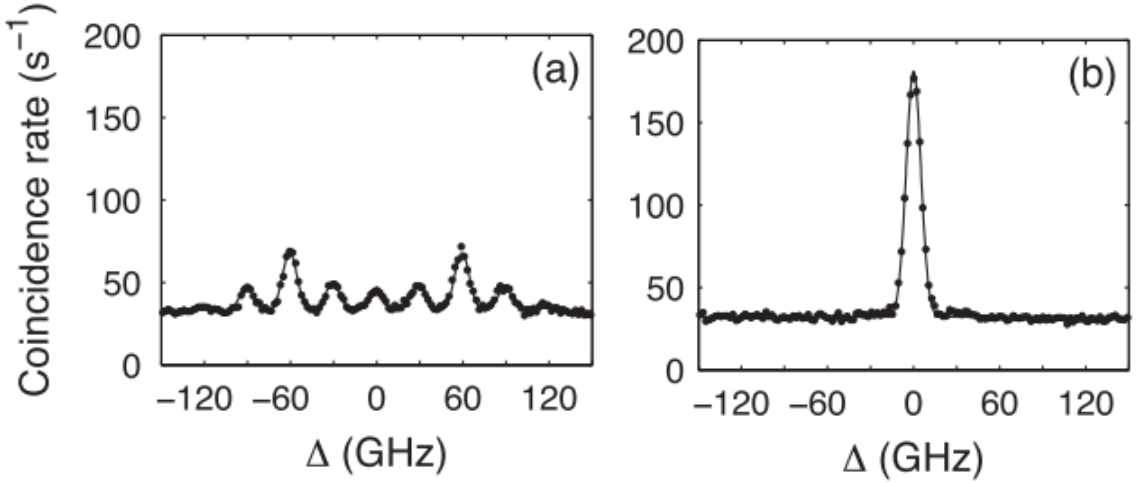
Coincidence measurement.



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.

It is the coincidence rate is influenced by the opposite phase, not the phase modulation itself!

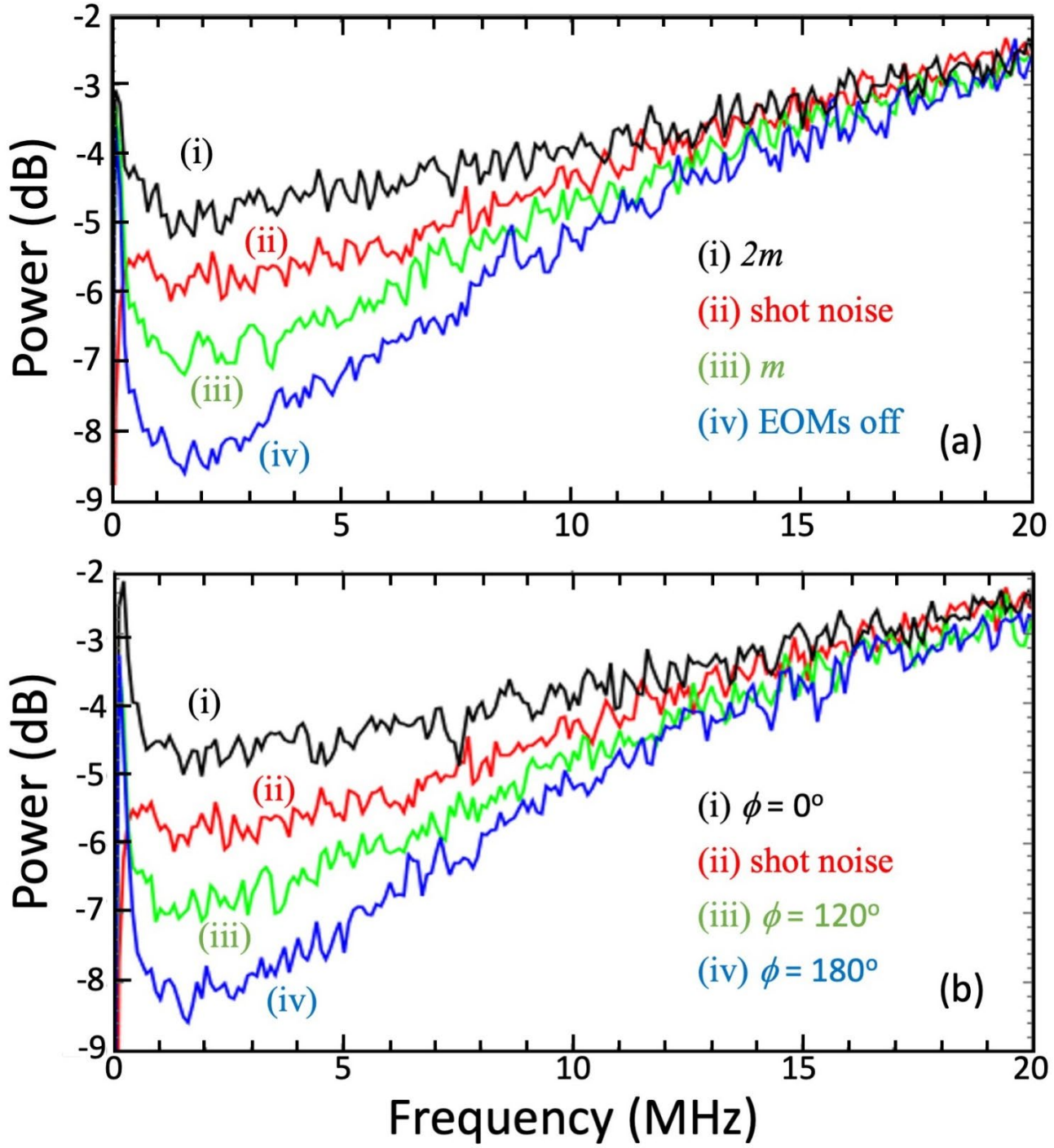


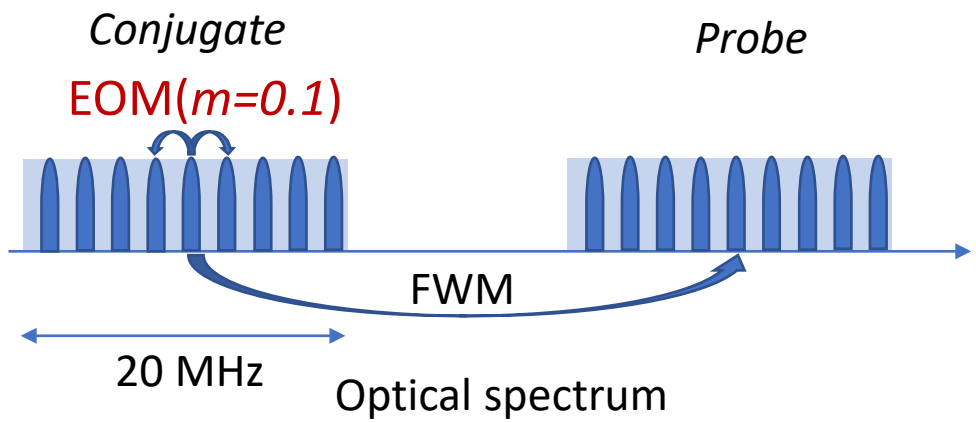
(a) both modulators running with the same phase.

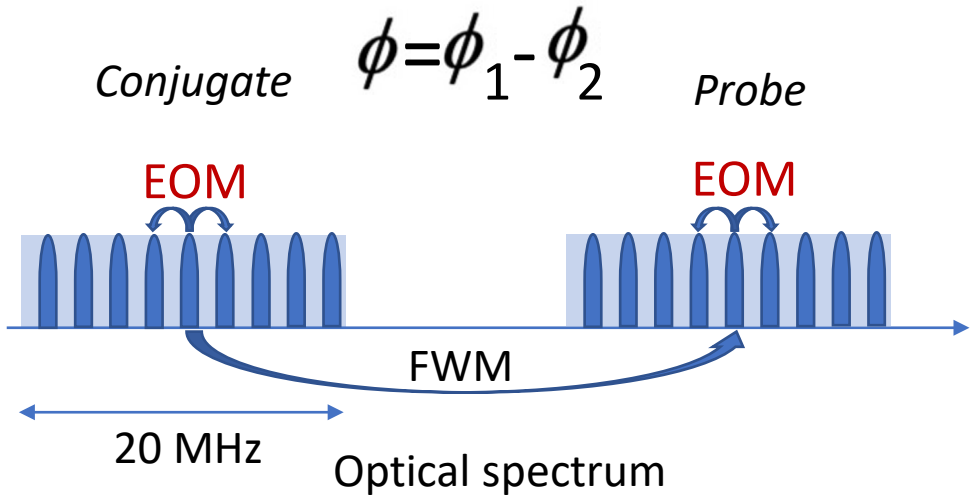
(b) with the opposite phase.

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

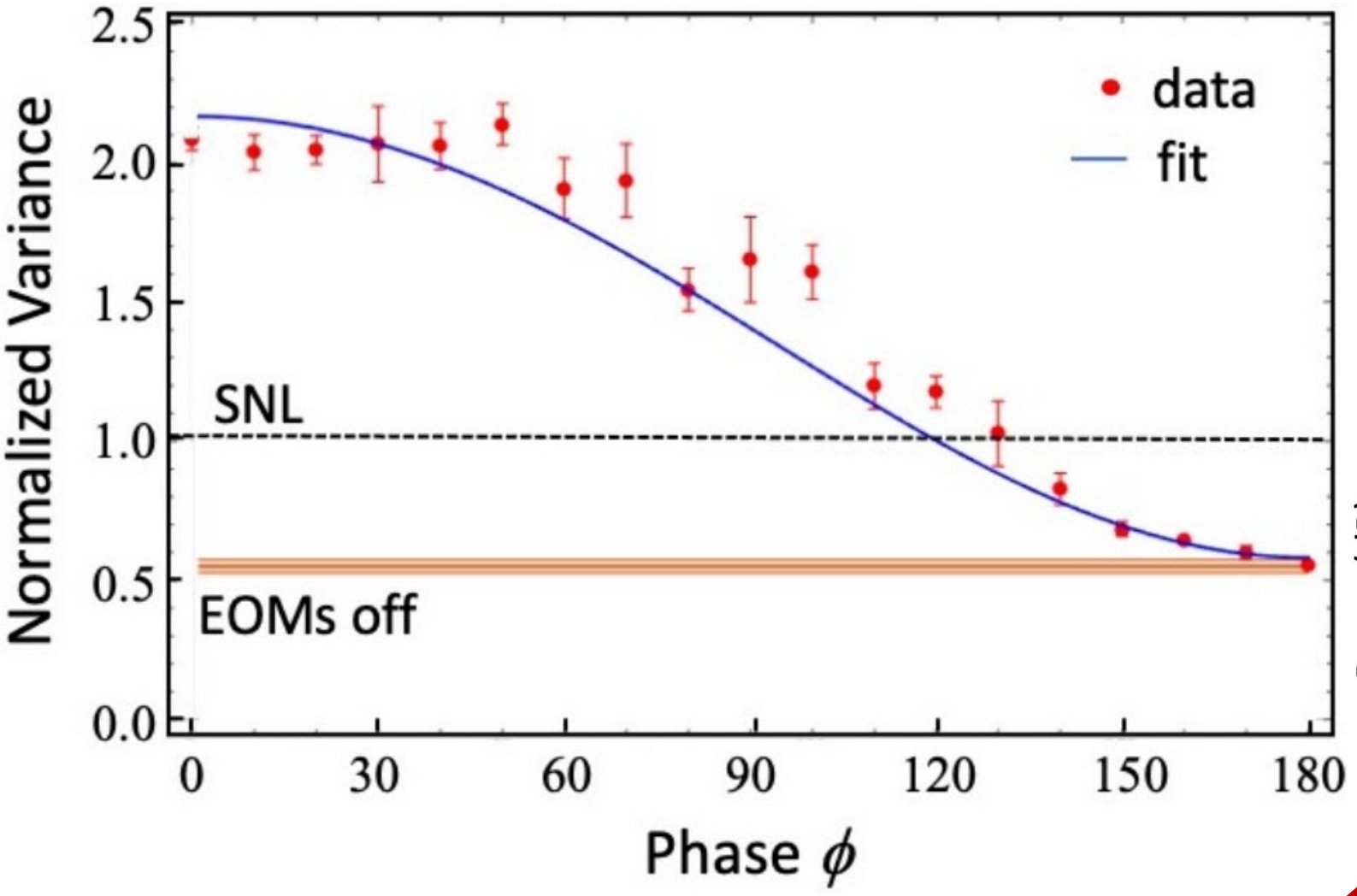
Nonlocal phase modulation in continuous variable regime



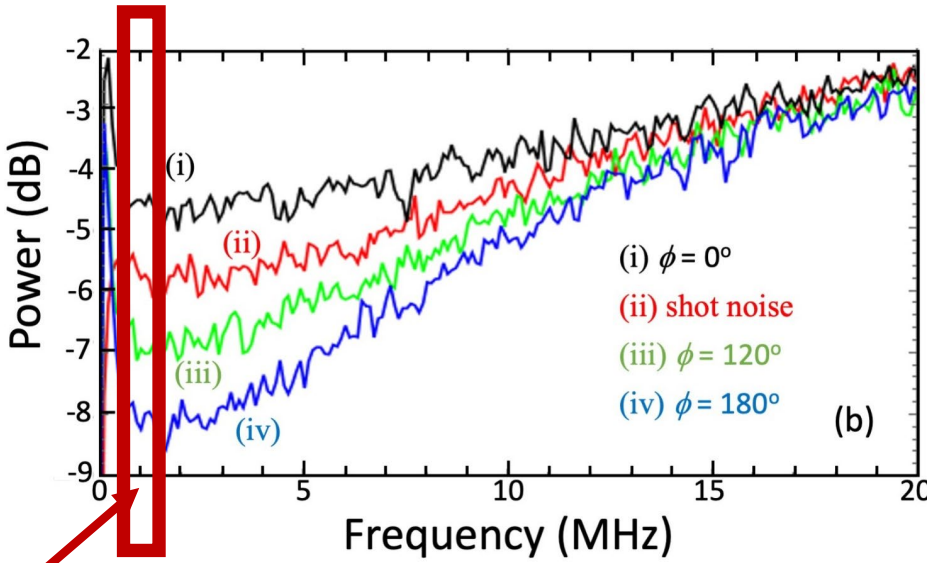




Scanning phase dependent modulation

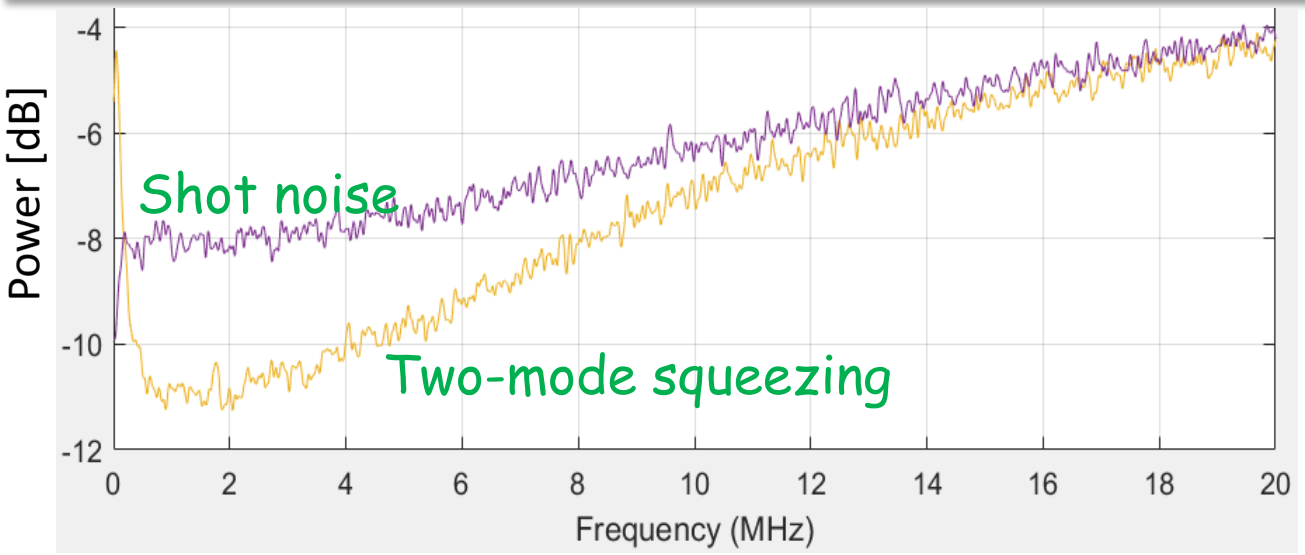


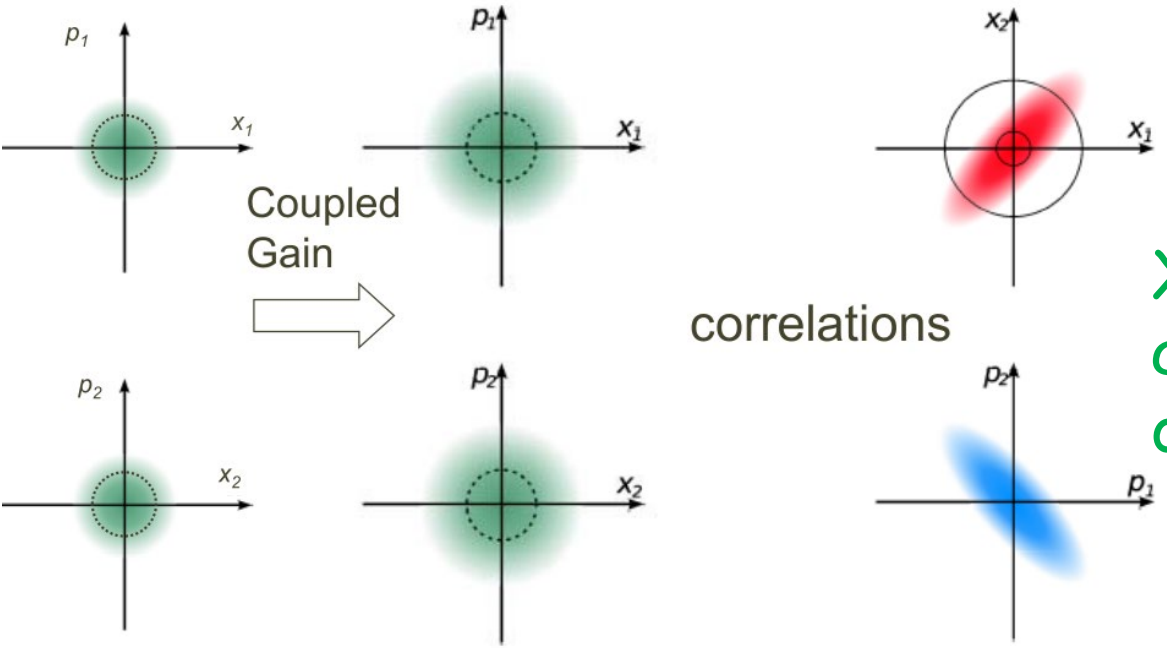
Joint quadrature variance $\langle X_-^2 \rangle$ normalized by the shot noise variance as a function of the phase difference ϕ between the EOMs.



Variance of 100kHz window measured at 1MHz.

Two-mode squeezing measurement and covariance matrix

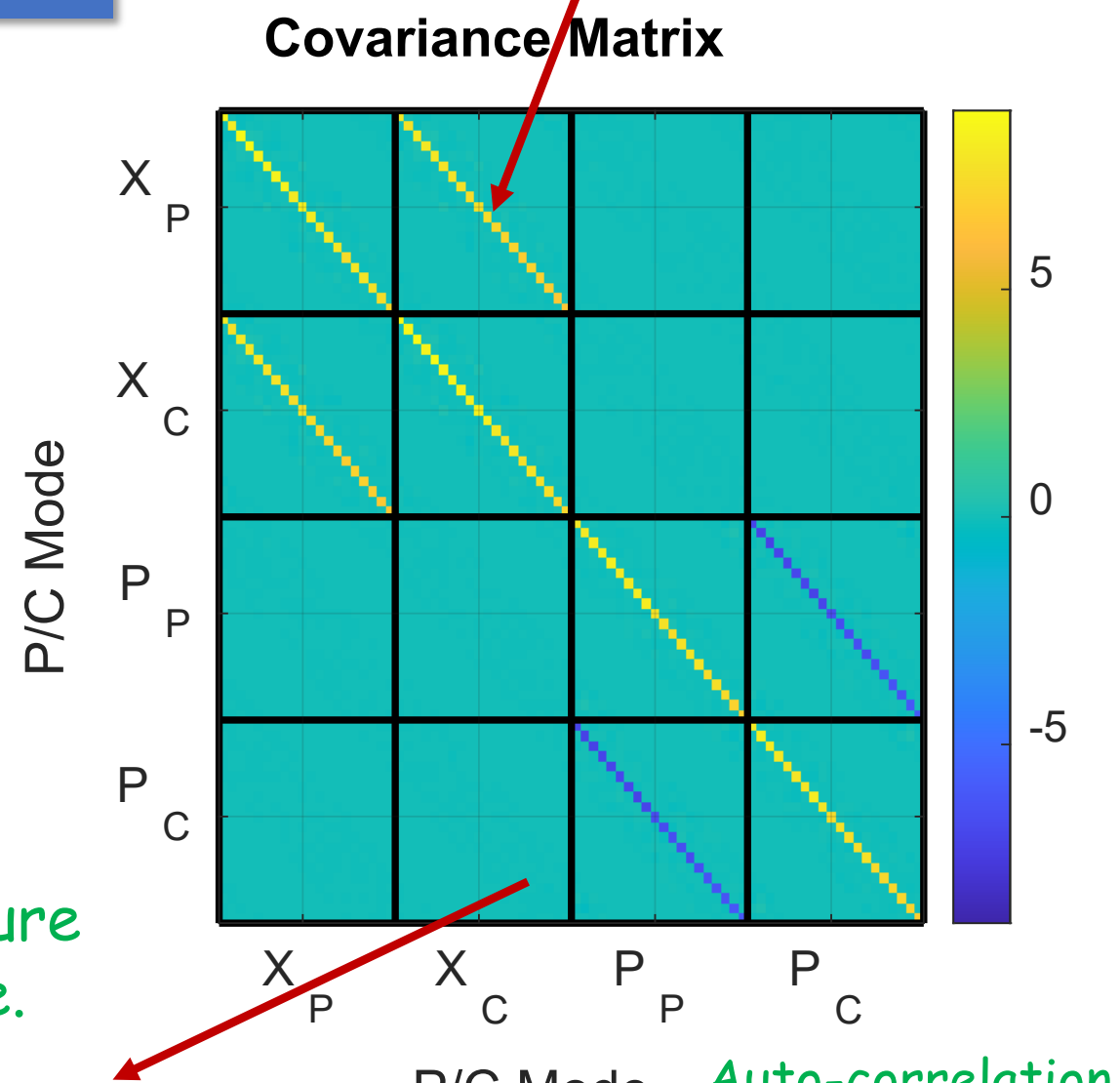




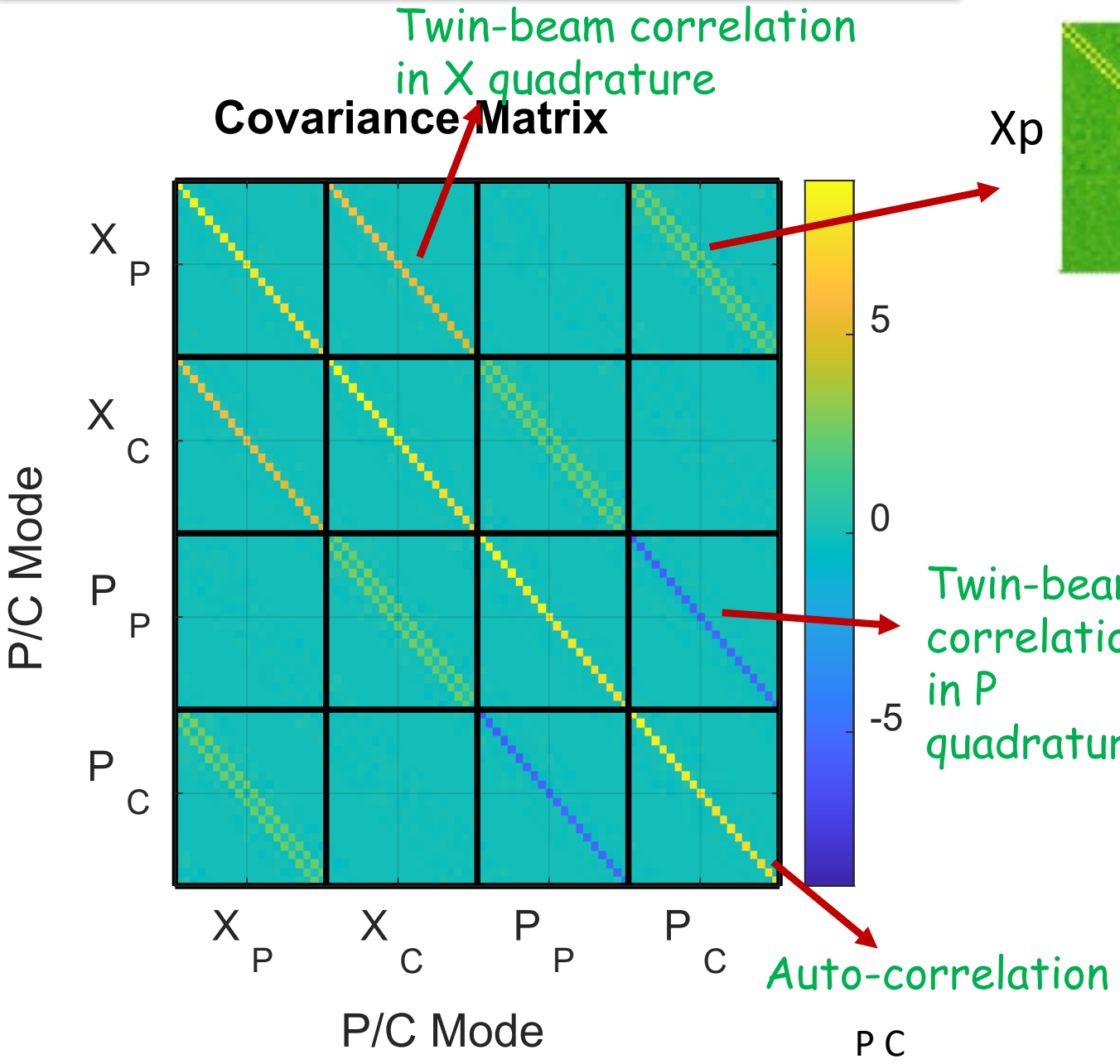
X_P: X quadrature of probe.

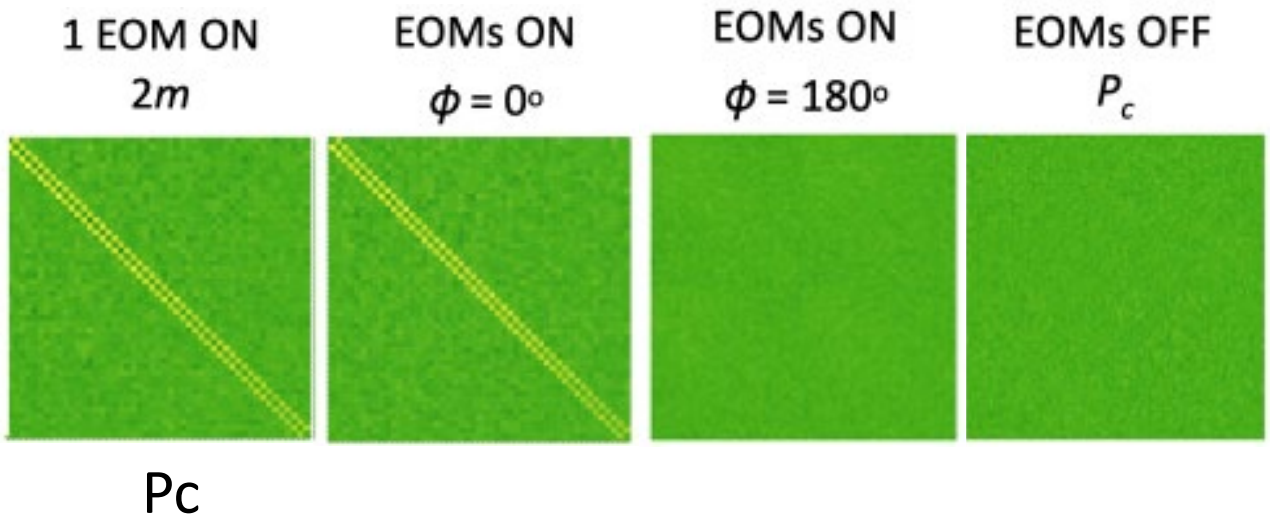
Twin-beam correlation in P quadrature

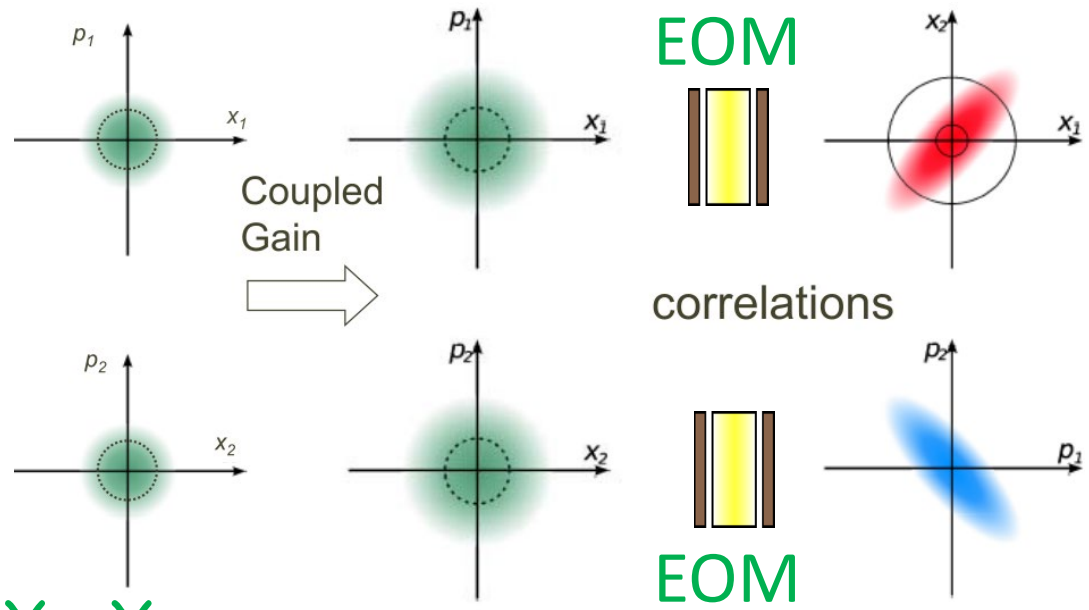
Twin-beam correlation in X quadrature



Covariance matrix with EOMS

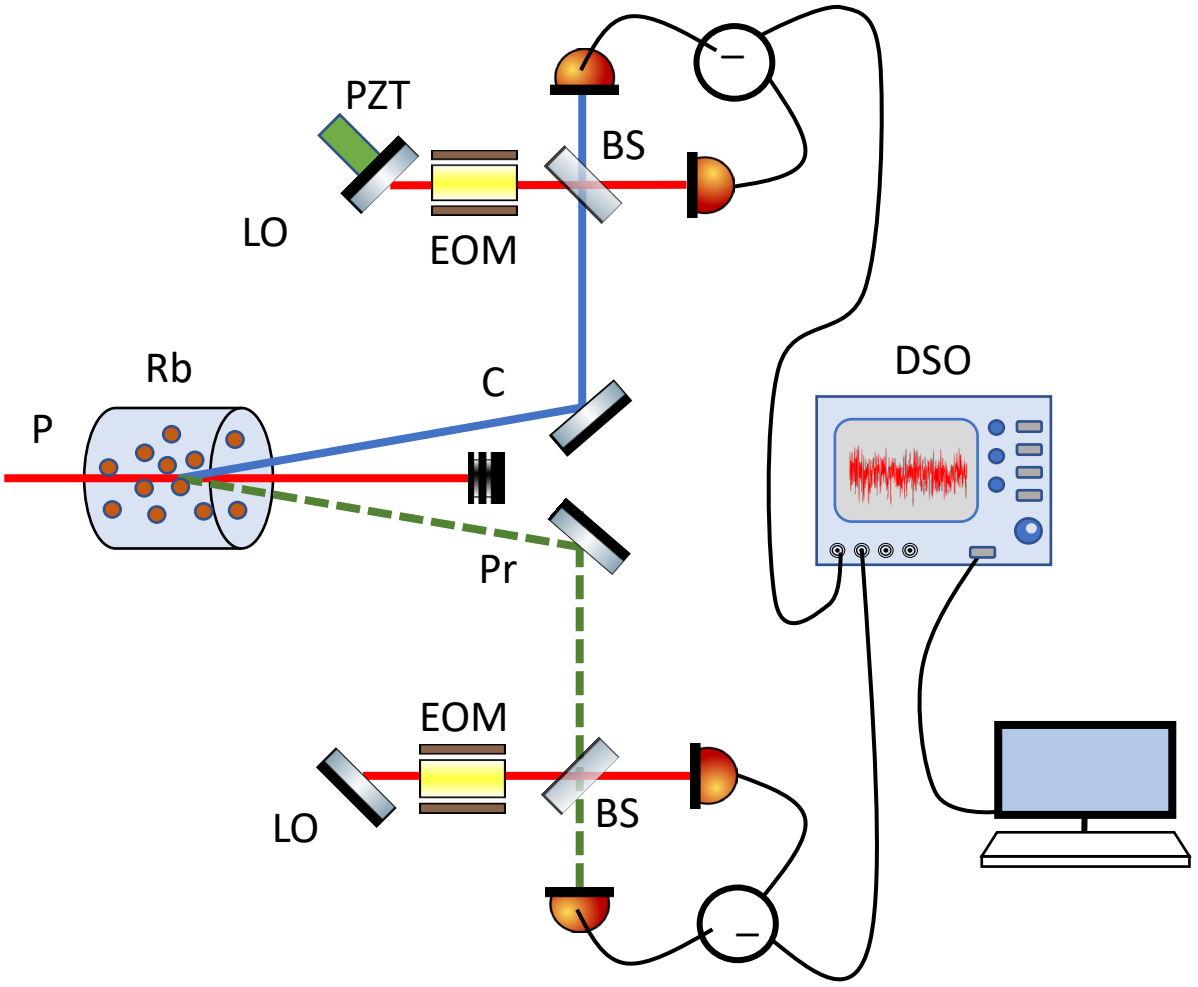






X_P: X quadrature of probe.

EOMs in local oscillators & quantum nonlocality



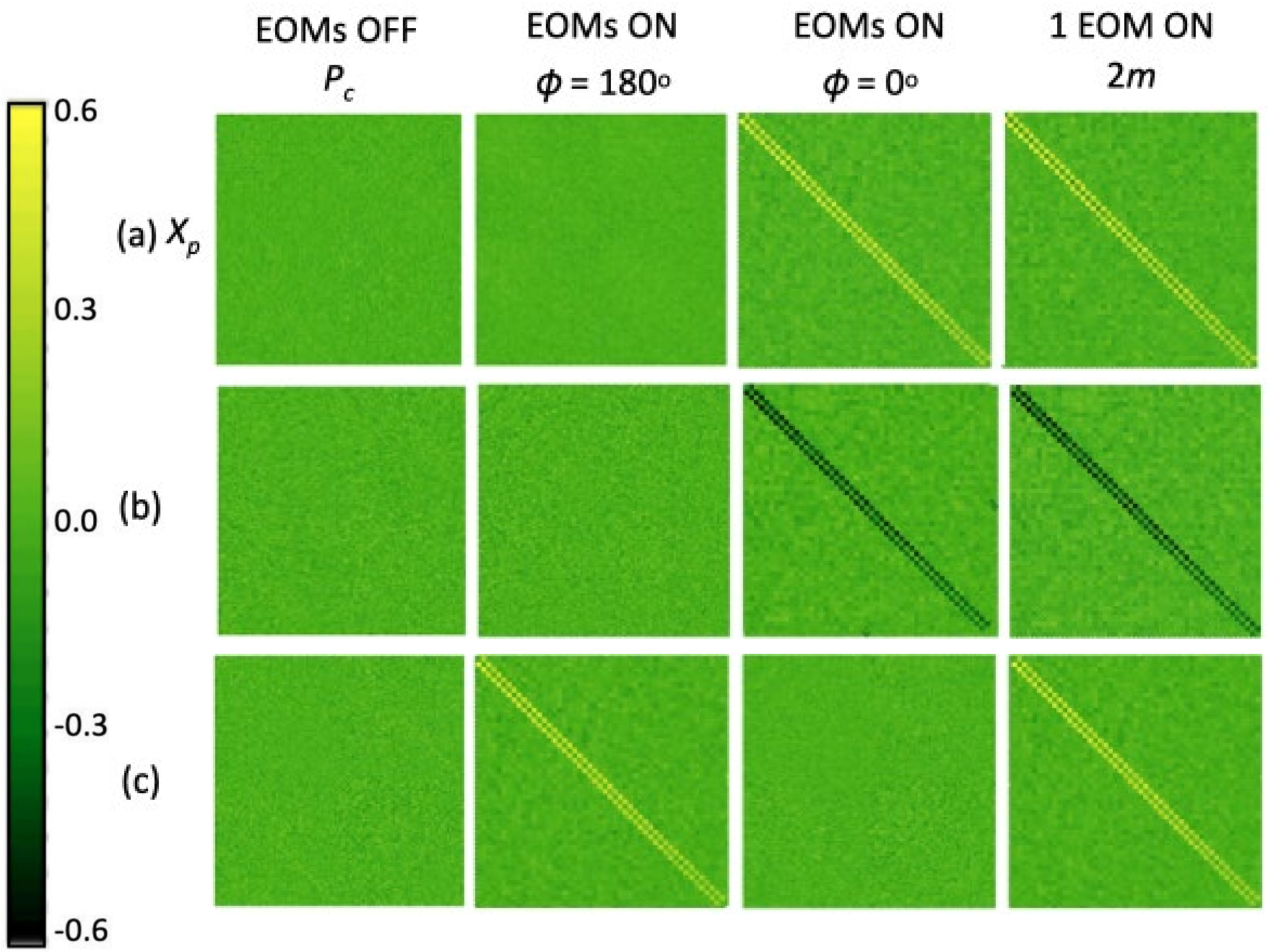
Positive shift of signal is equivalent to shifting LO's phase down.

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. G.Patron, et al., Ph. Grangier, *PRL 93, 130409(2004).*

Correlation structure



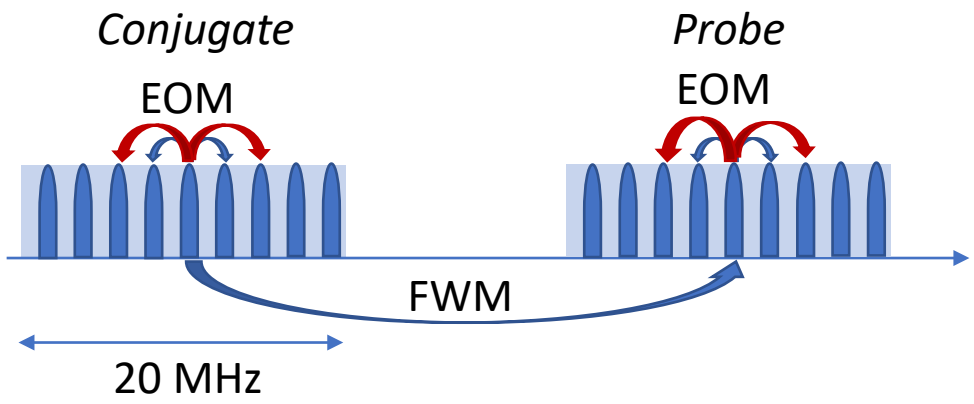
EOMs in Squeezing Signal path.

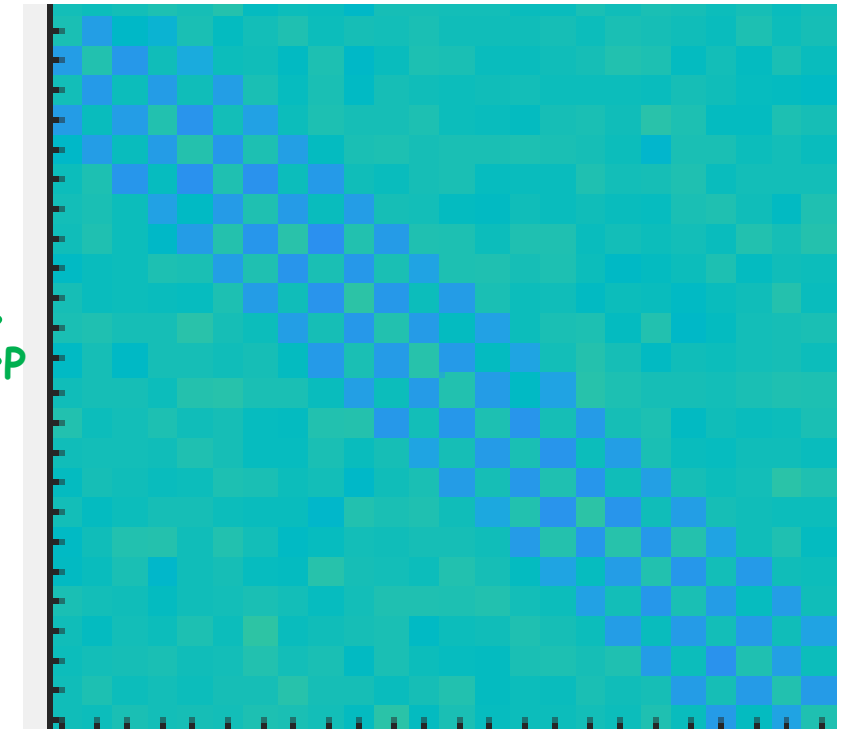
EOMs in Local Oscillator path.

Hybrid

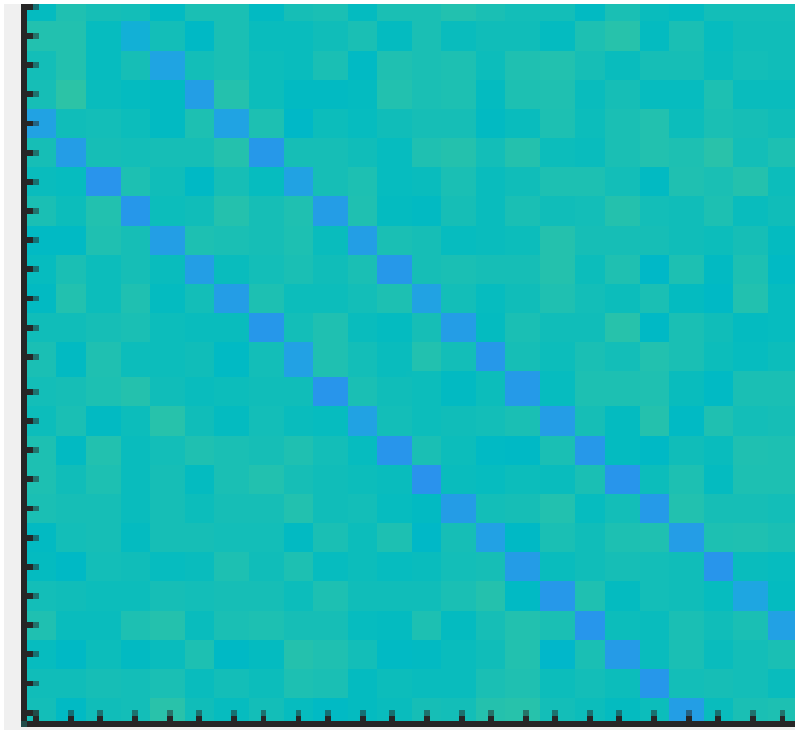
Non-local modulation happens for each mode in covariance matrix!

Complicated covariance structure

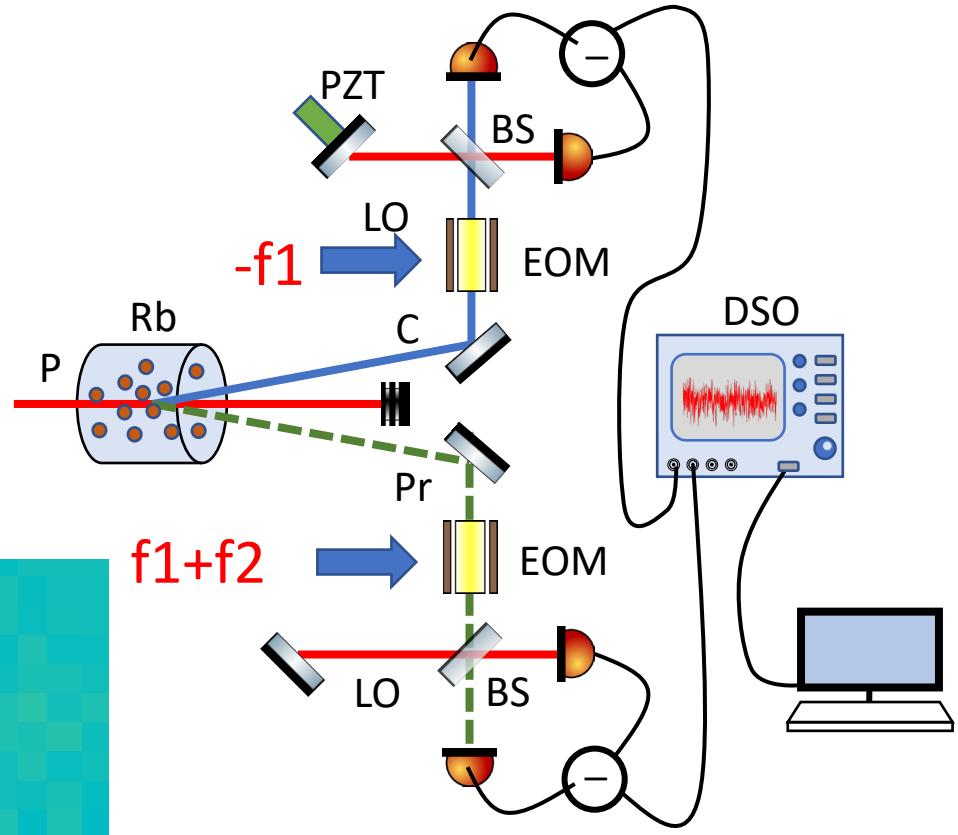




X_P

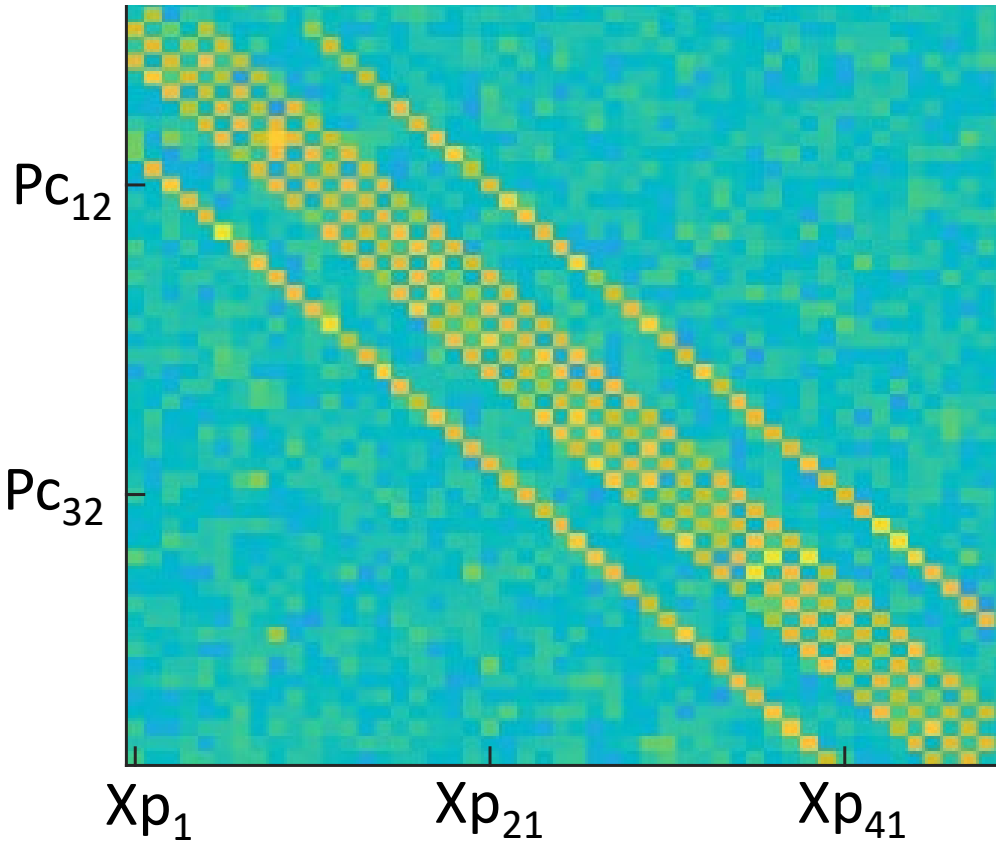


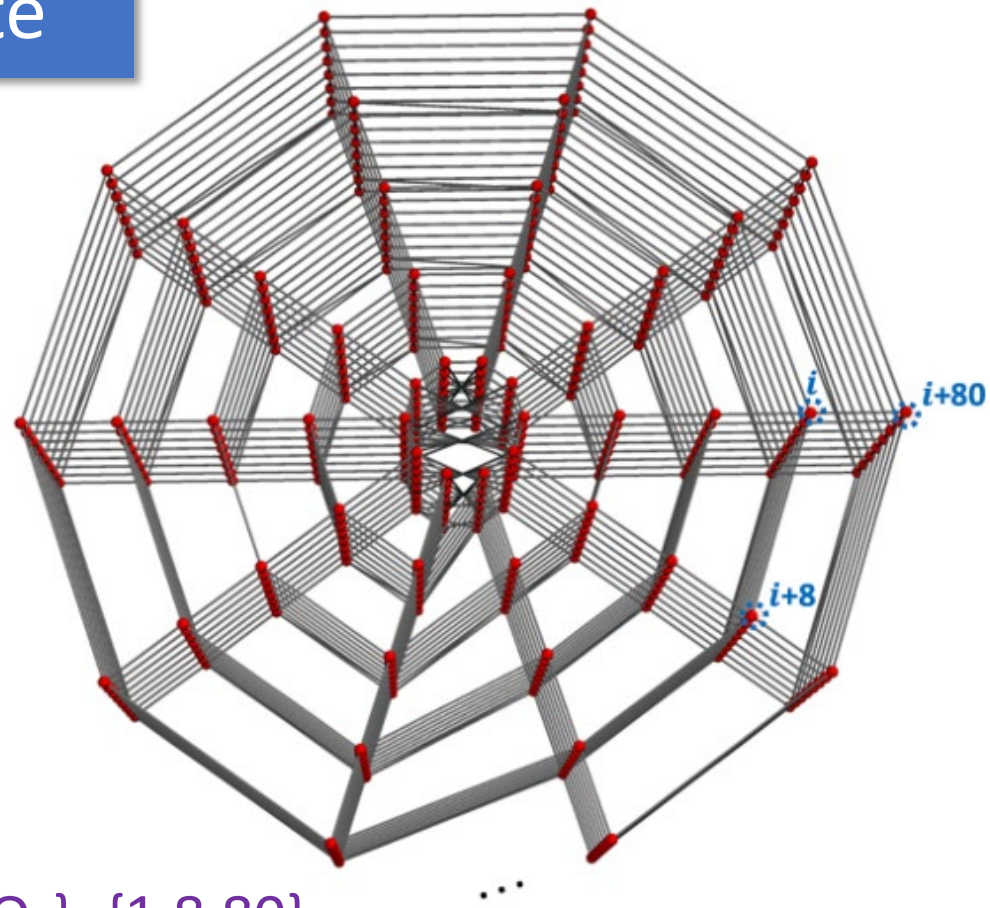
P_c



f1:100kHz, f2: 300kHz,
bin frequency: 100kHz

High-dimensional modulation and graph state





Proposal: $\{\Omega_1, \Omega_2, \Omega_3\}=\{1,8,80\}$.

Our results: $\{\Omega_1, \Omega_2, \Omega_3\}=\{1,3,9\}$.

f1:100kHz, f2: 300kHz, f3: 900kHz,
bin frequency: 100kHz

3D graph states!

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

Summary & outlook

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