Heralded quantum states characterized by homodyne detection

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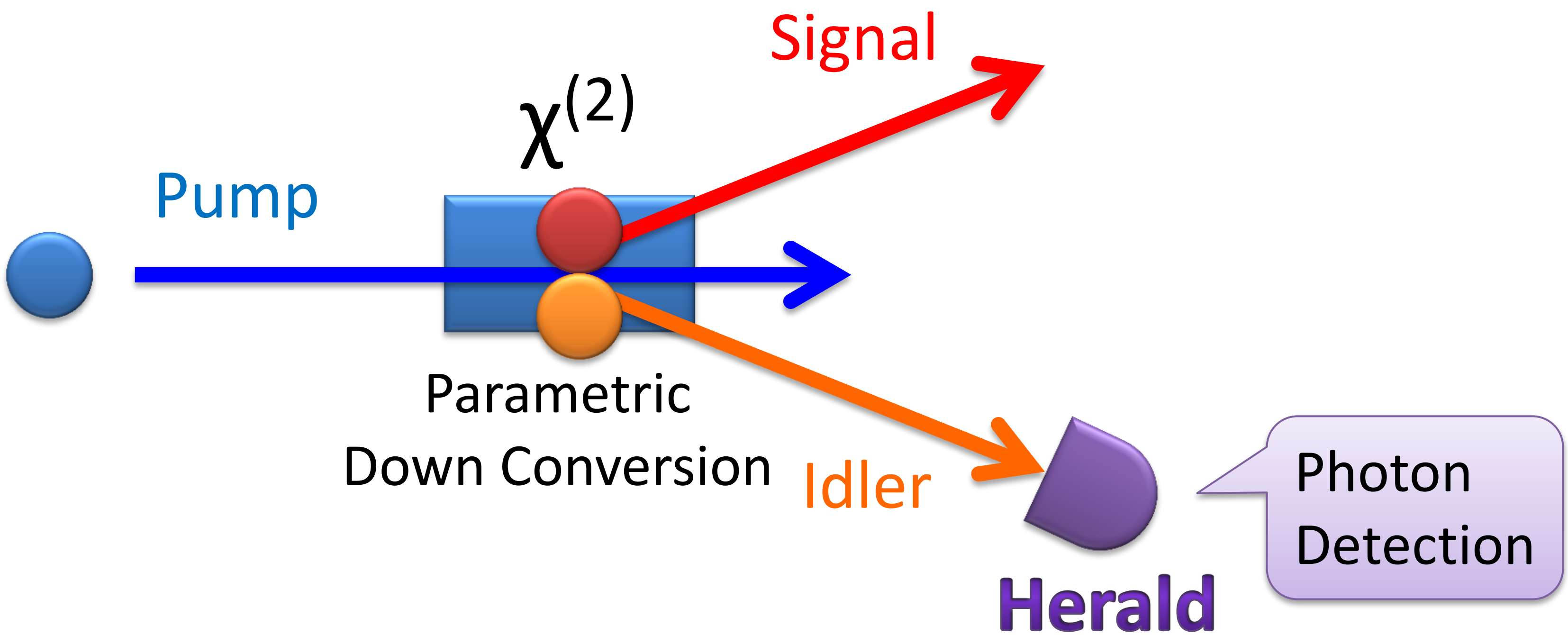
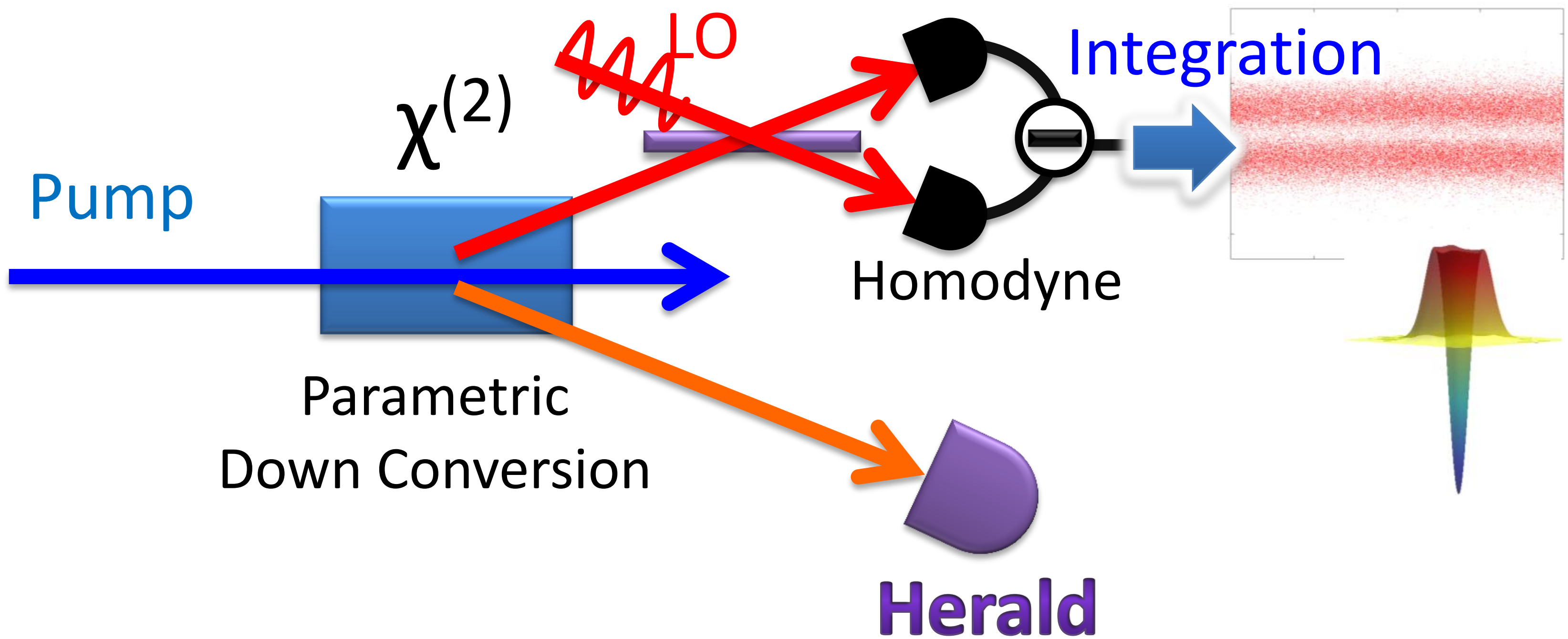
The University of Tokyo

Heralding Scheme



① Probabilistic

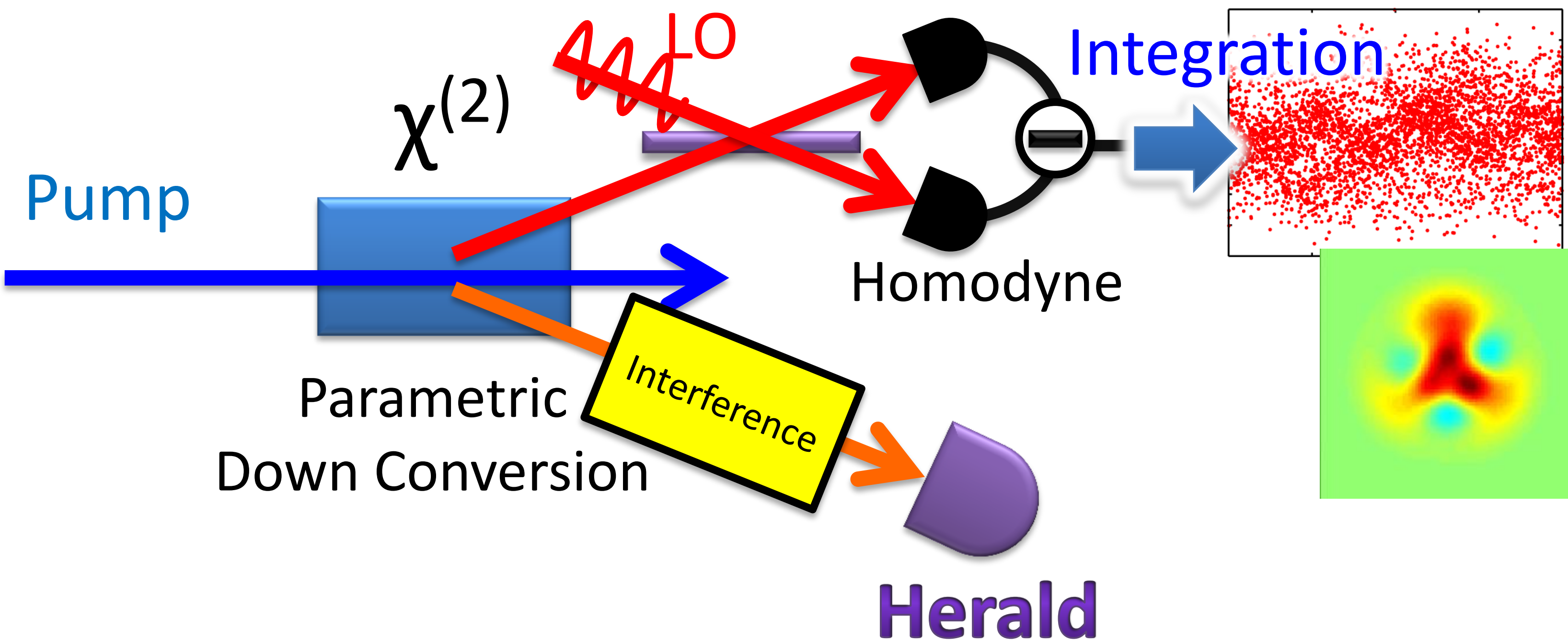
Homodyne Characterization



① Probabilistic

② Post Processing (Homodyne Integration)

Generalization

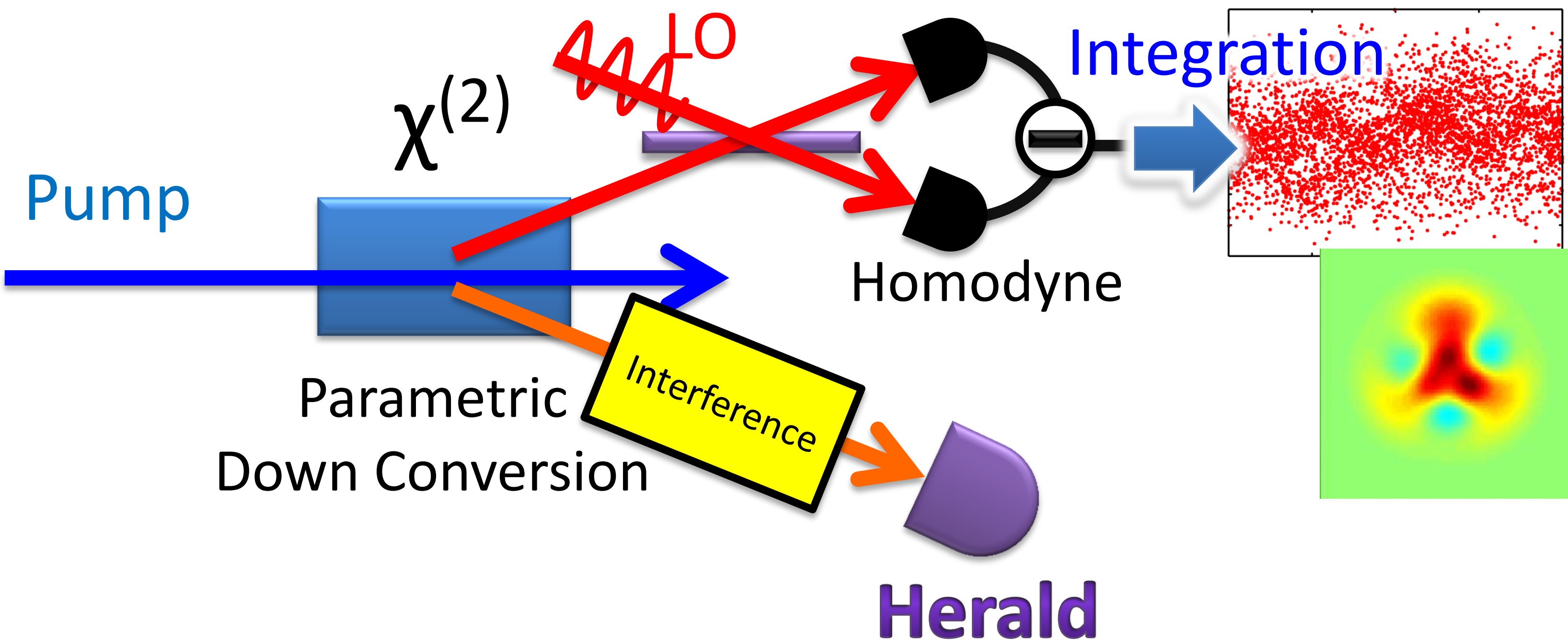


① Probabilistic

② Post Processing (Homodyne Integration)

③ Projection onto Various States

Three Topics



① Probabilistic ➡ Synchronization by Cavity Quantum Memories

② Post Processing (Homodyne Integration)

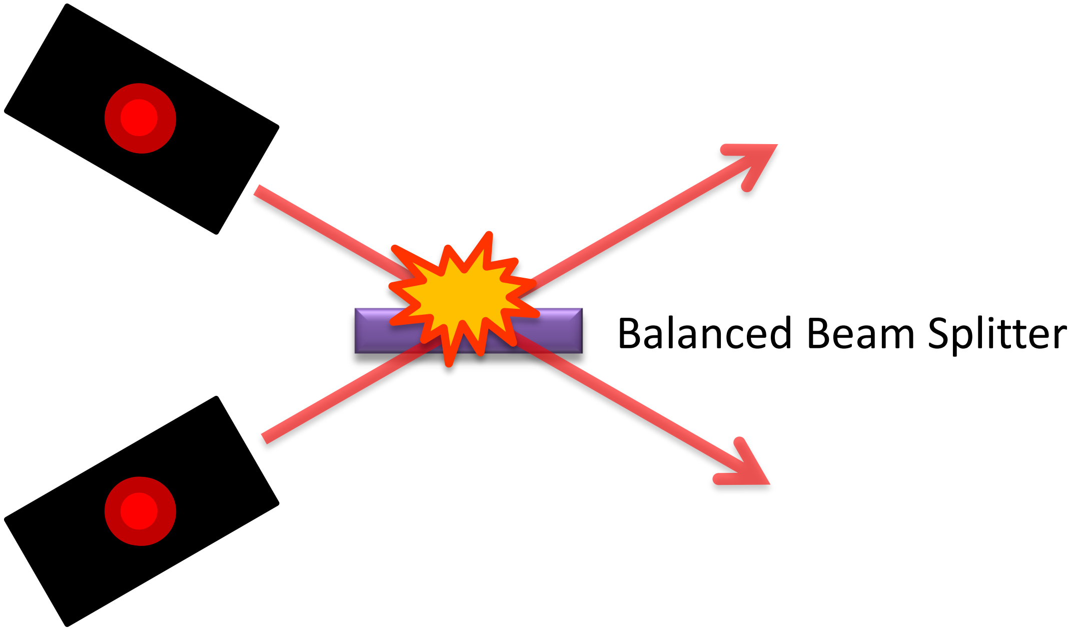
➡ Real-Time Acquisition of Non-Gaussian Quadratures

③ Projection onto Various States

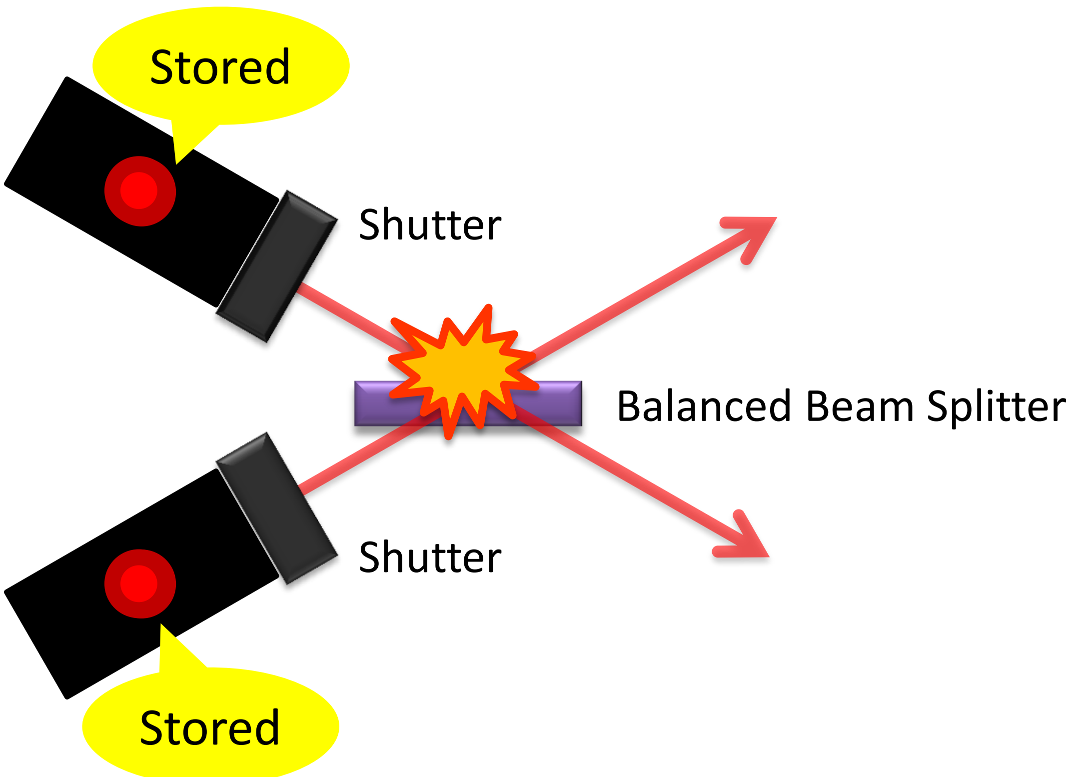
➡ Multi-Mode Multi-Photon Heralded States

I) SYNCHRONIZATION OF HERALDED SINGLE PHOTONS

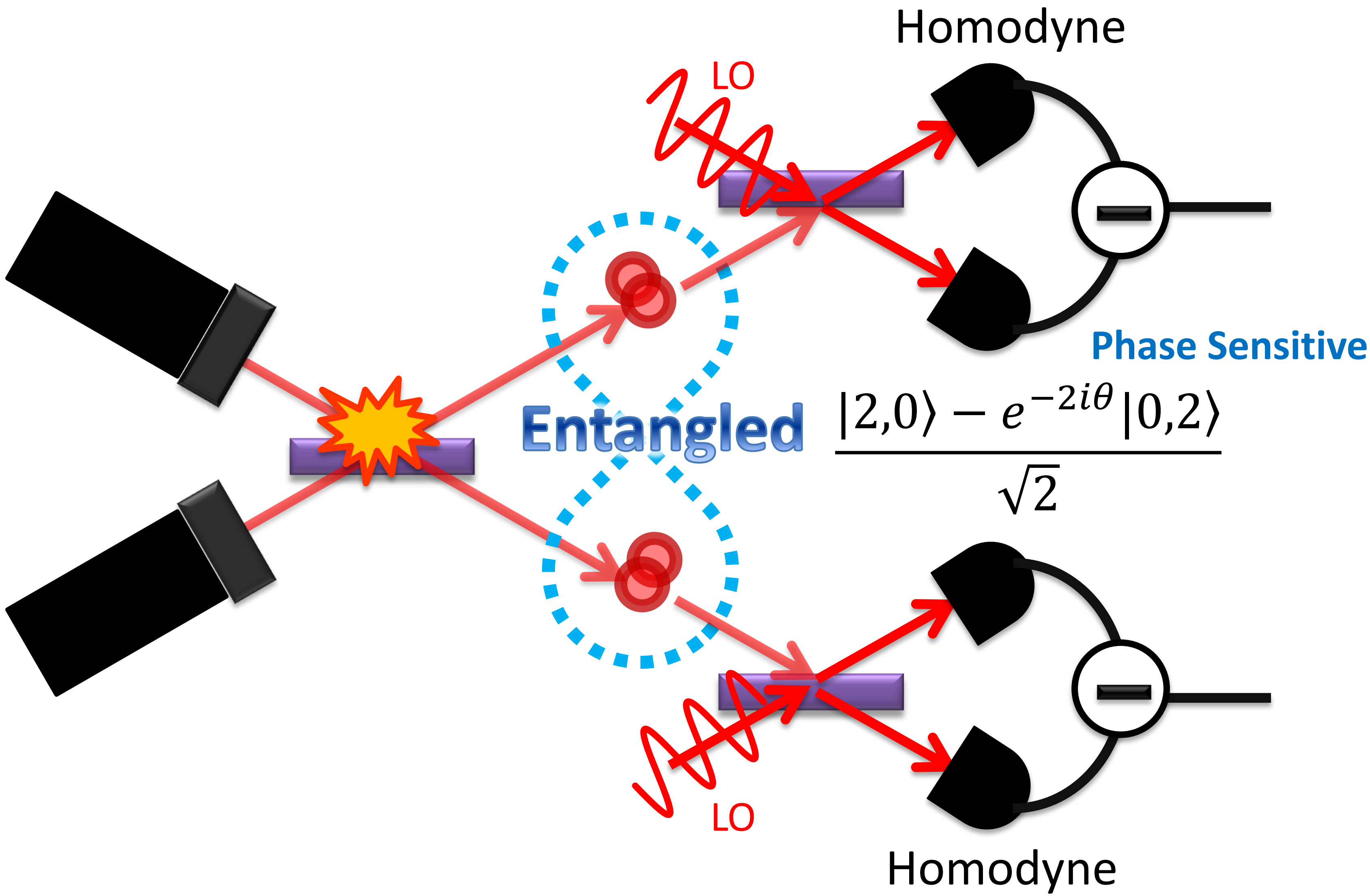
Two-Photon (HOM) Interference



Controlled HOM Interference

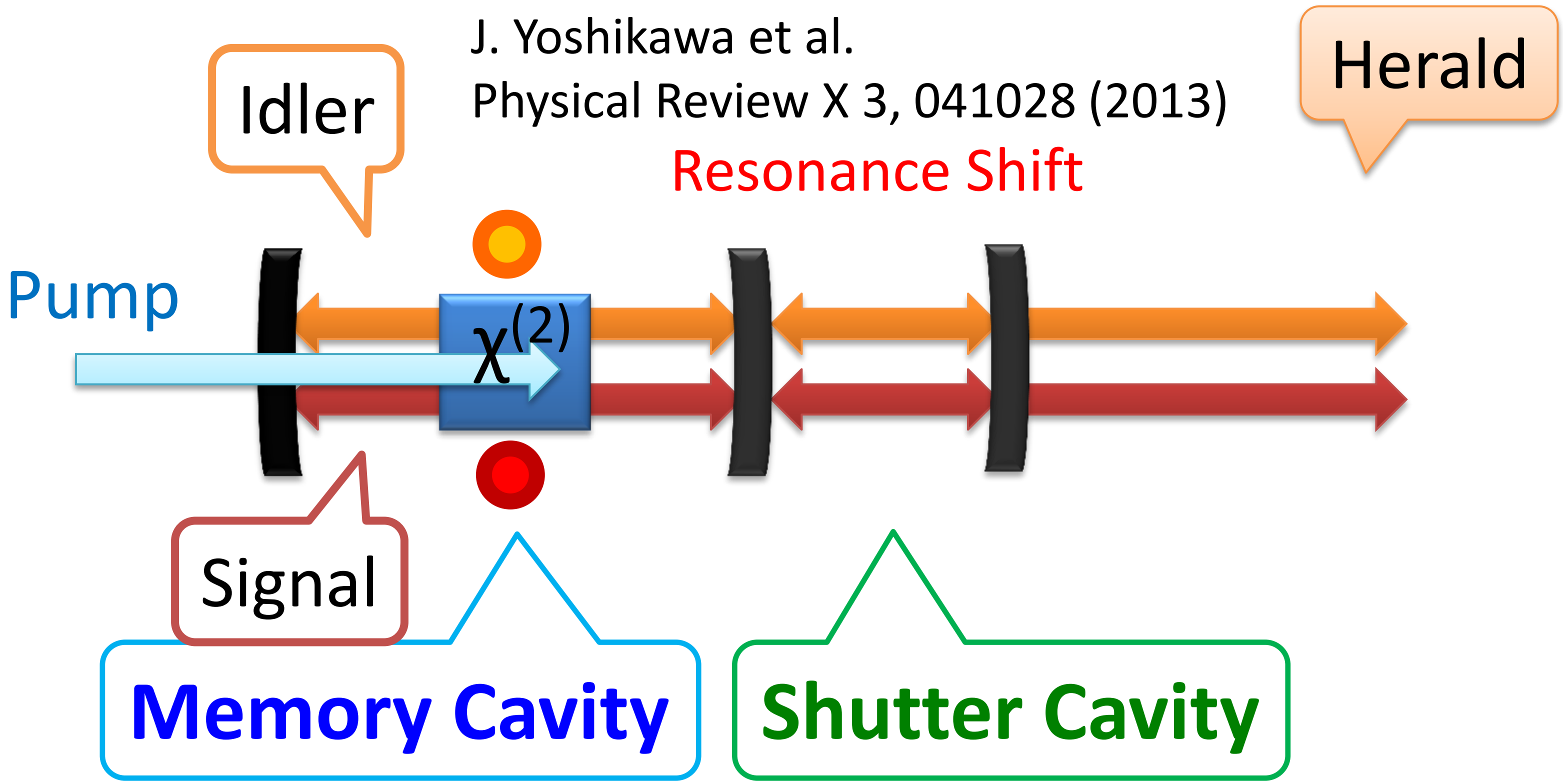


Controlled HOM Interference



Storage of Heralded Photons

J. Yoshikawa et al.
Physical Review X 3, 041028 (2013)

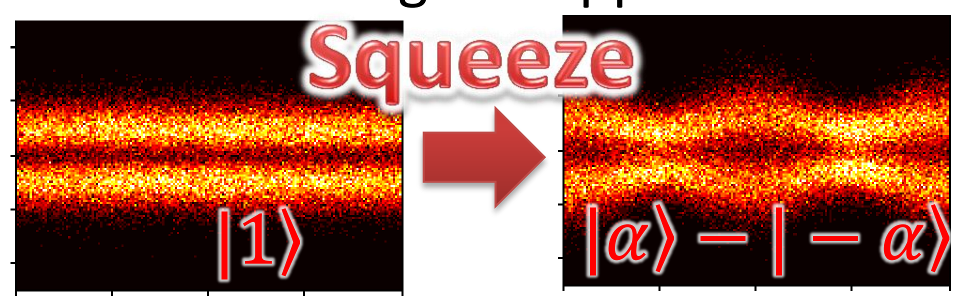


* Optical Frequency Not Limited by the Memory System

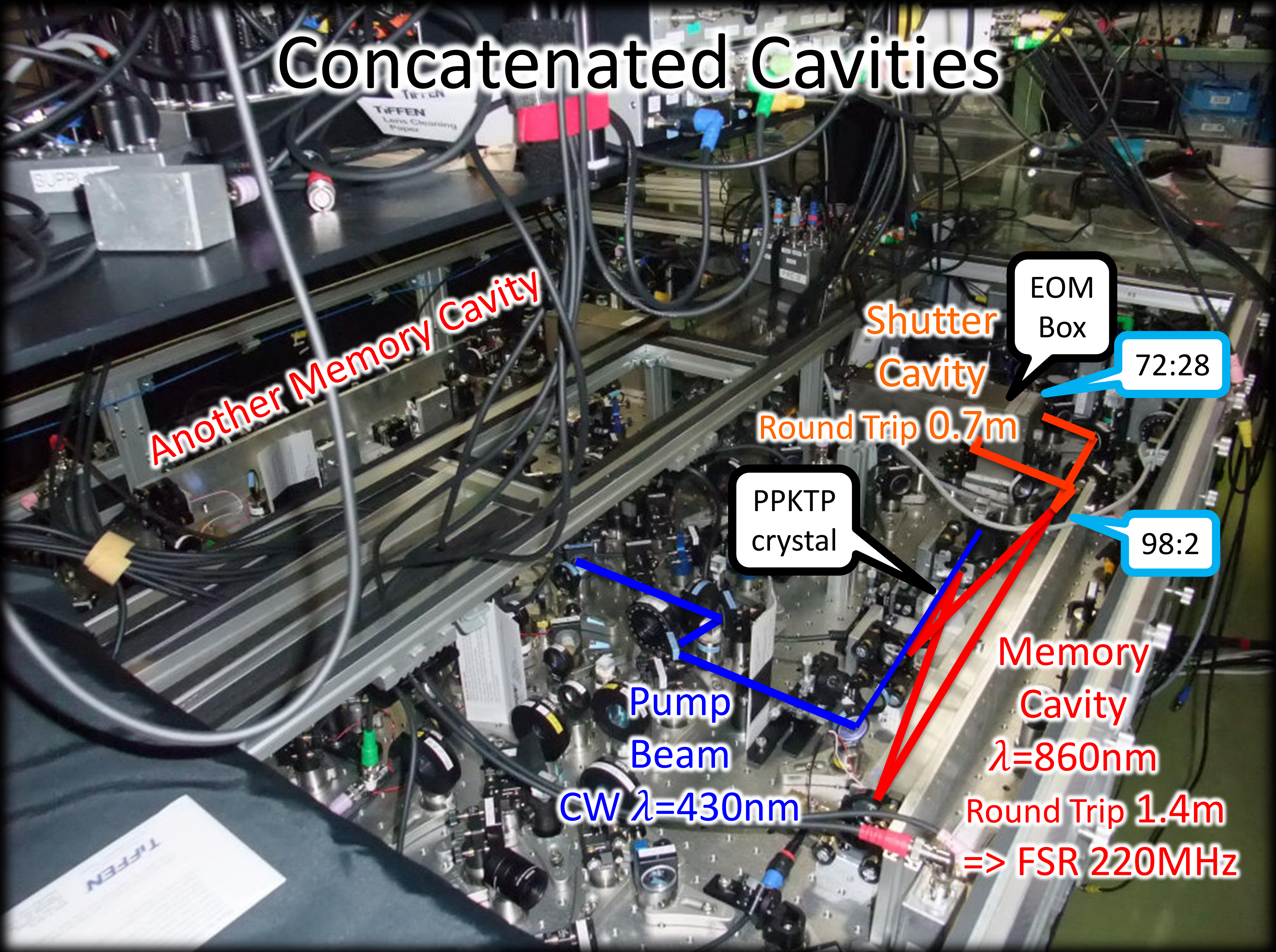
* Quantum Post-Processing may Extend the Range of Application

E.g. Squeezing => Minus Kitten

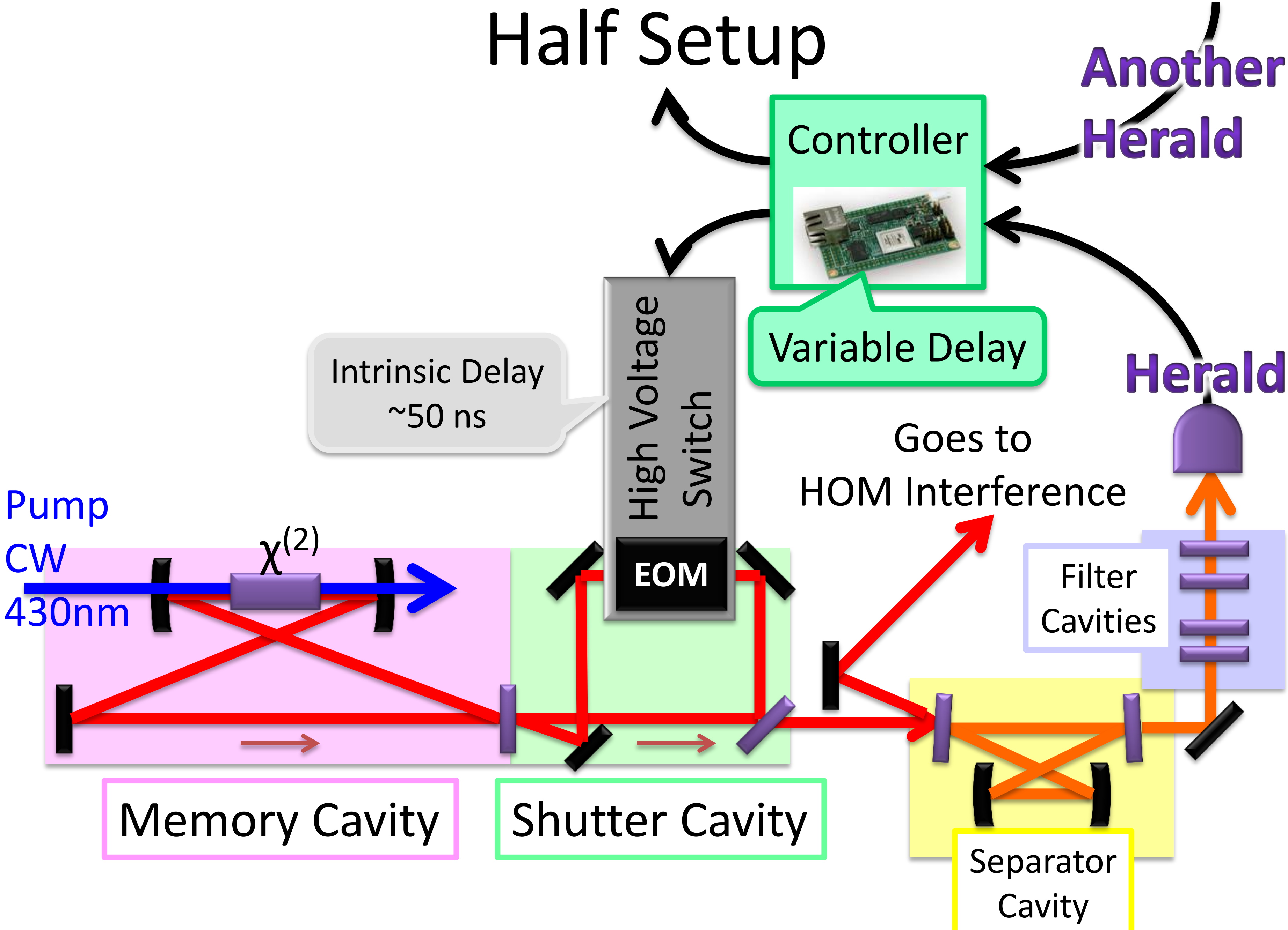
Y. Miwa *et al.*,
Phys. Rev. Lett. 113, 013601 (2014)



Concatenated Cavities

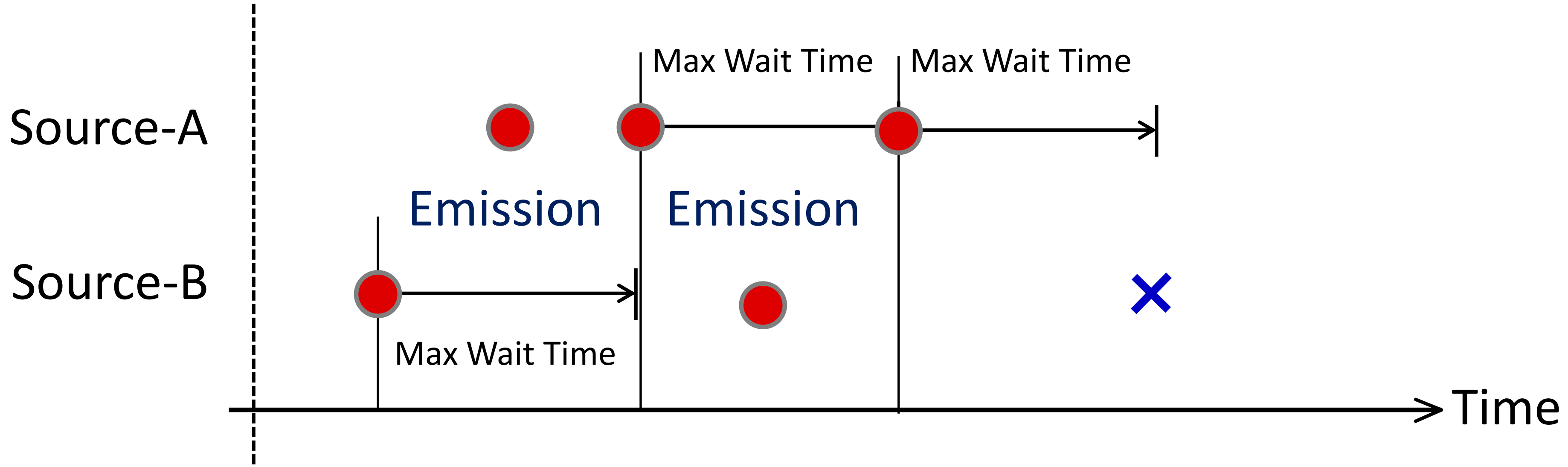


Half Setup

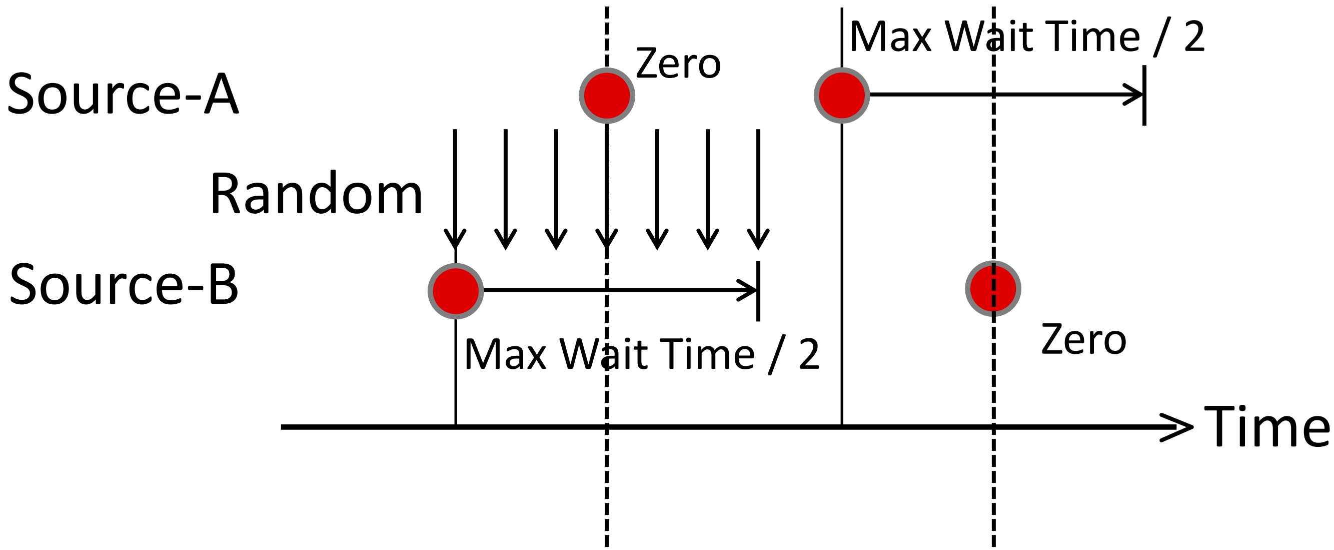


Another Herald
Controller
Variable Delay
Herald
Intrinsic Delay
~50 ns
High Voltage Switch
EOM
Goes to
HOM Interference
Pump
CW
430nm
χ(2)
Filter
Cavities
Memory Cavity
Shutter Cavity
Separator
Cavity

Synchronization



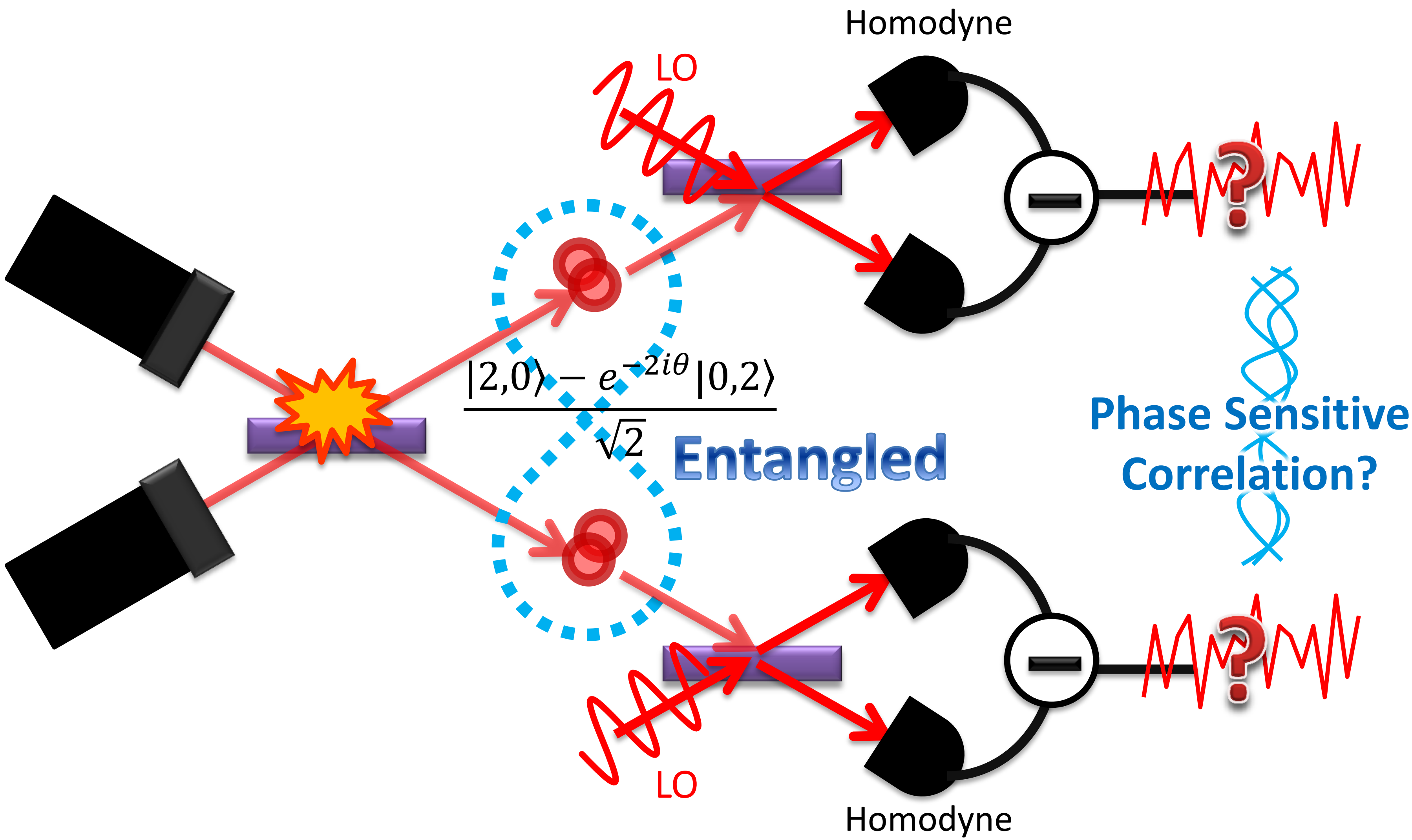
Average Waiting Time



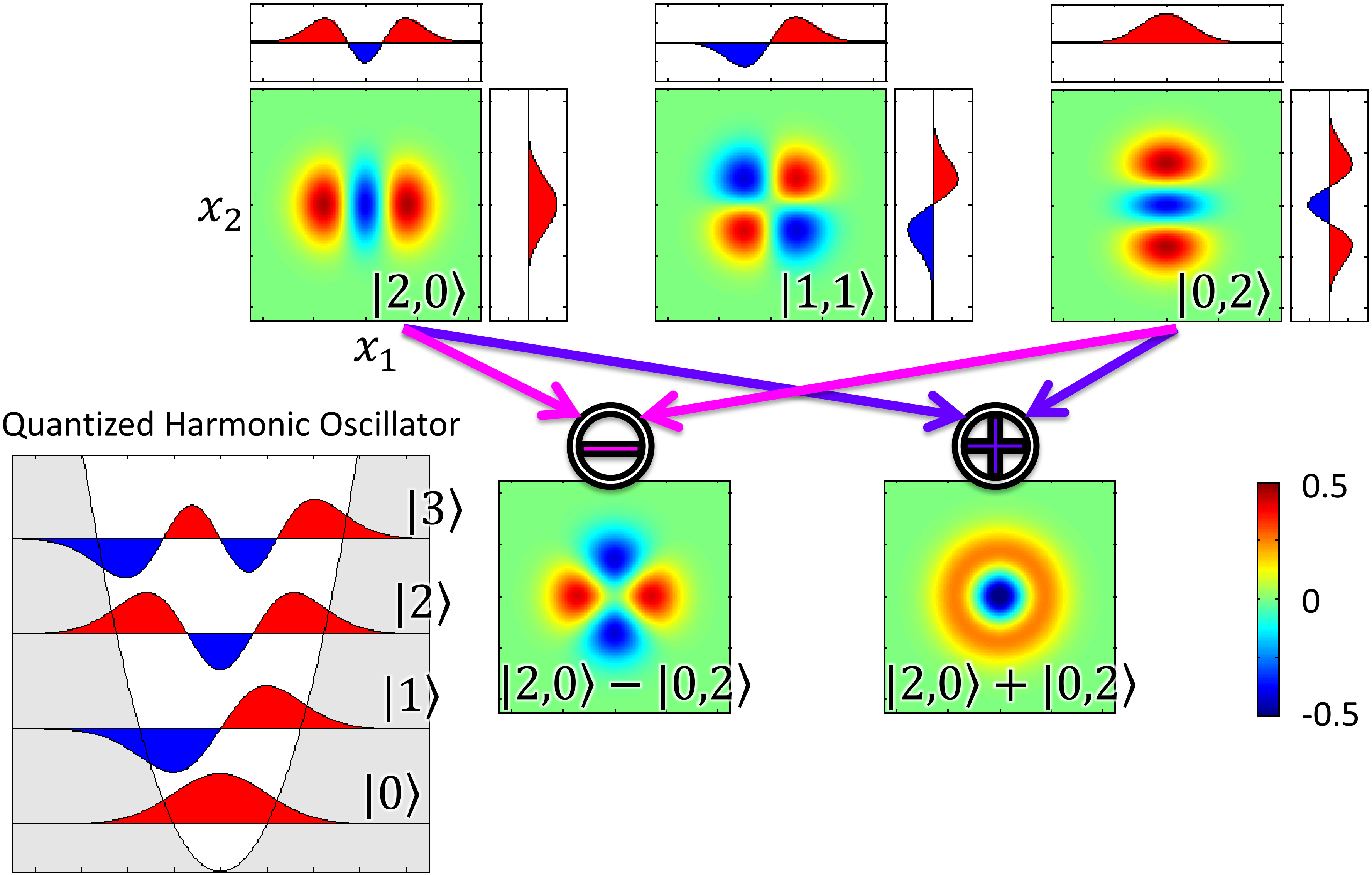
$$\text{Average Waiting Time} = \frac{(\text{Maximum Waiting Time}/2) + 0}{2}$$
$$= \frac{\text{Maximum Waiting Time}}{4}$$

Explanation of 4-fold Increase

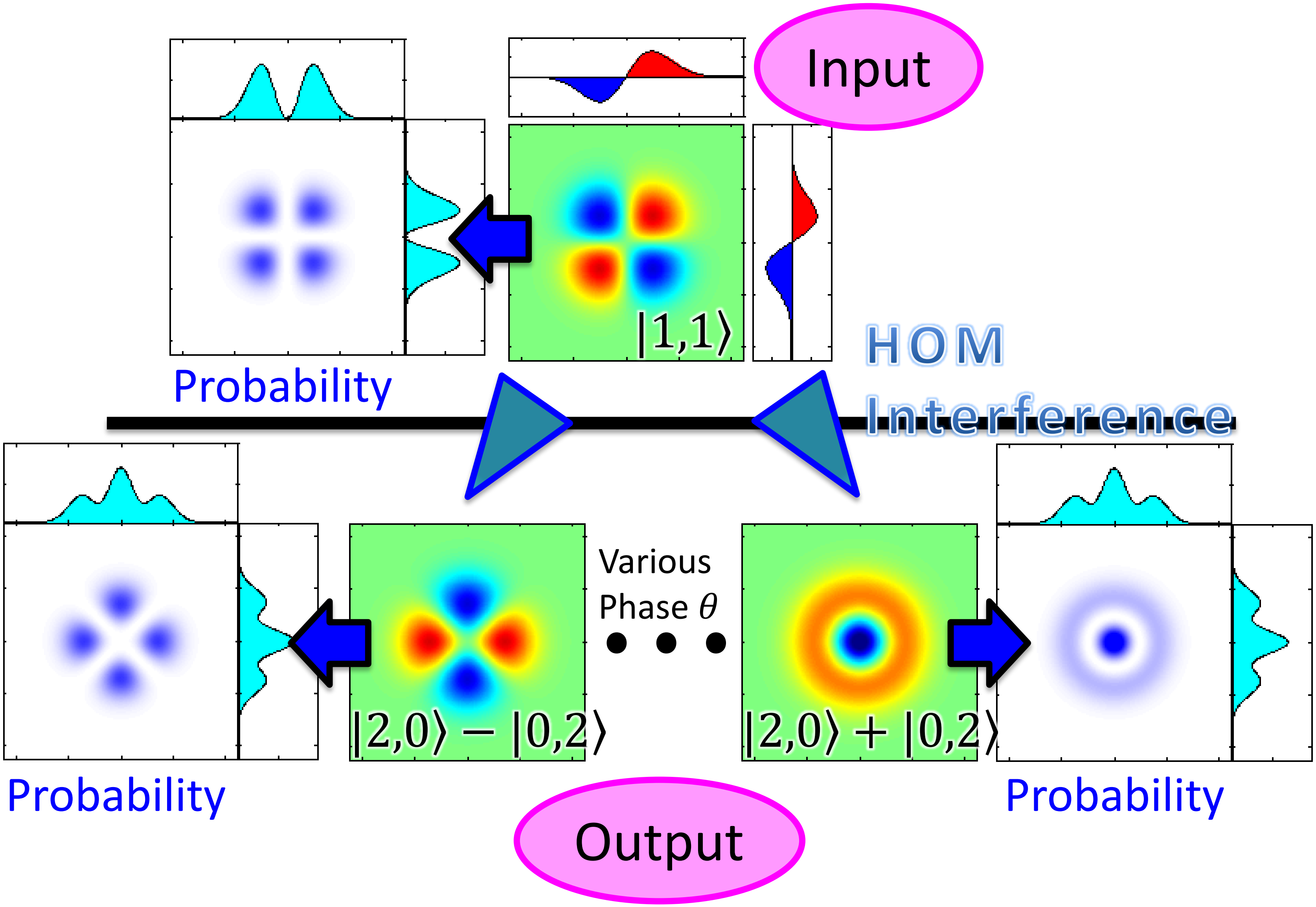
Wave Picture of a HOM State?



Two-Mode Wave Functions



HOM in a Wave Picture



Density Matrix in Number Basis

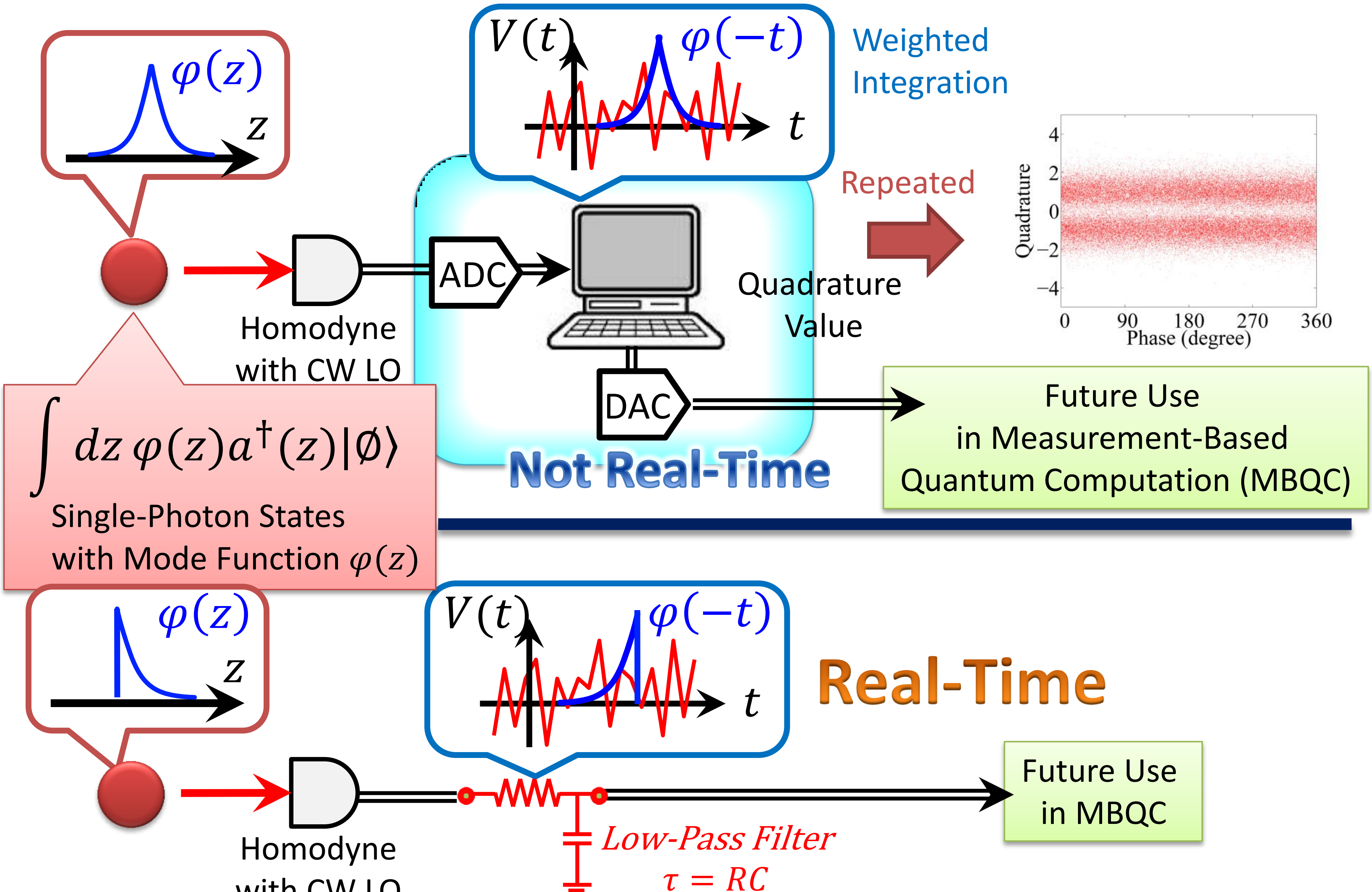
$$|\mathrm{HOM}(-\theta)\rangle = \frac{|2{,}0\rangle - e^{-2i\theta}|0{,}2\rangle}{\sqrt{2}}$$

Rotation of Measurement Basis
=> **Quantum Tomography** of $|\mathrm{HOM}(0)\rangle$

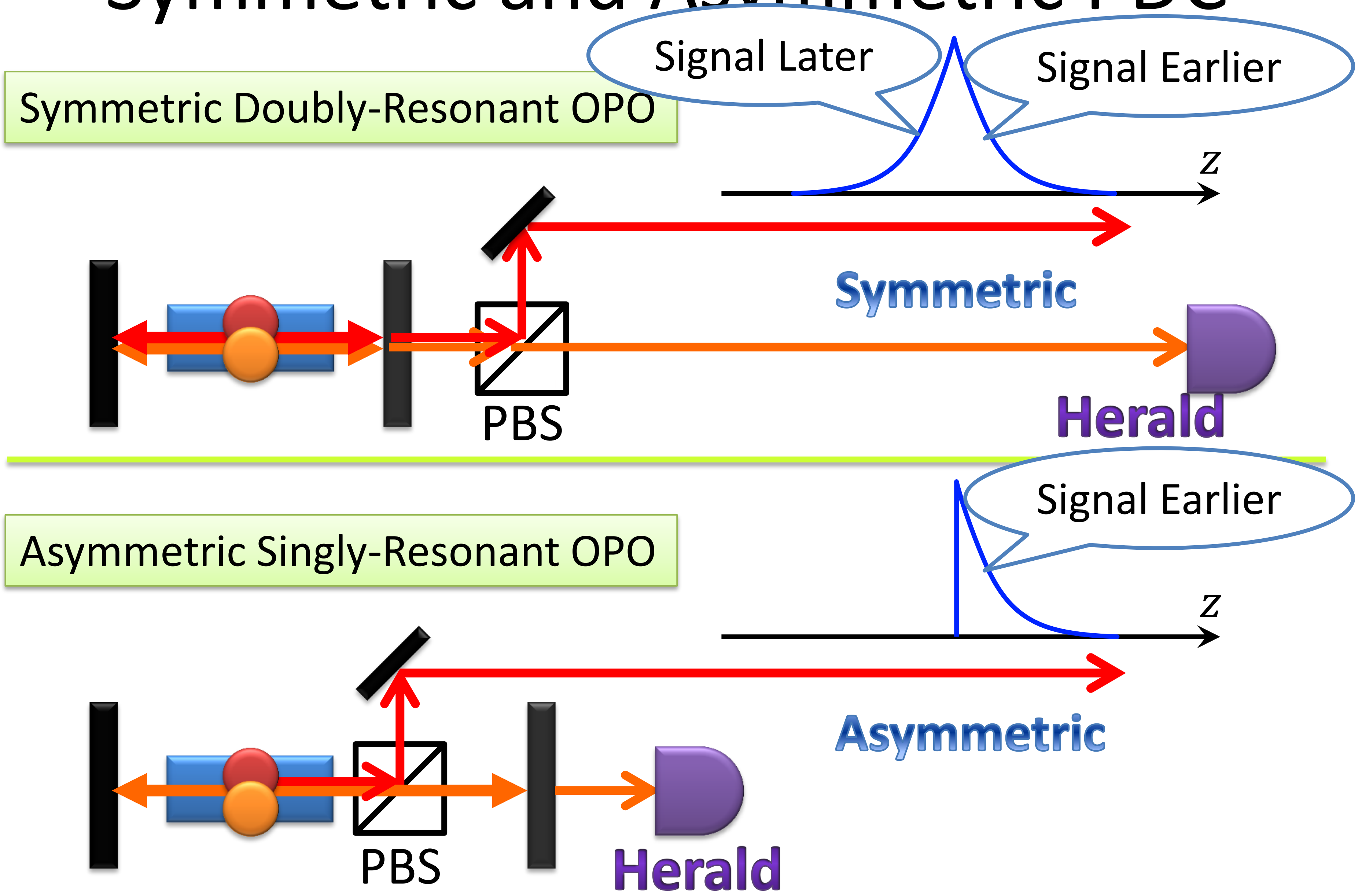
$$\Pr(x_1, x_2) = |\langle x_1, x_2|\mathrm{HOM}(-\theta)\rangle|^2 = \left|\langle x_1, x_2|\underbrace{\hat{U}^\dagger(\theta)}|\mathrm{HOM}(0)\rangle\right|^2$$

II) REAL-TIME ACQUISITION OF QUADRATURE VALUES

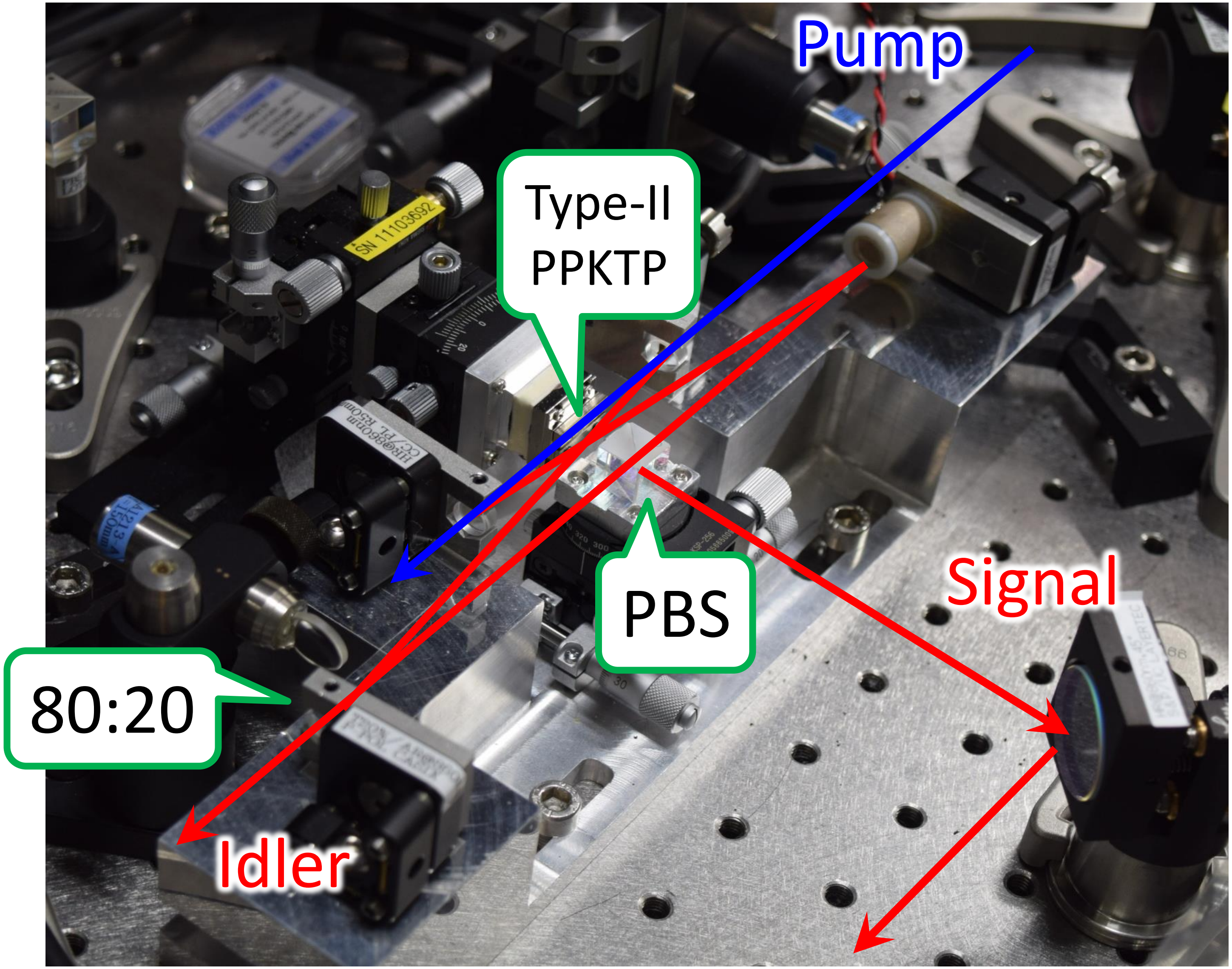
Weighted Integration for Quadratures



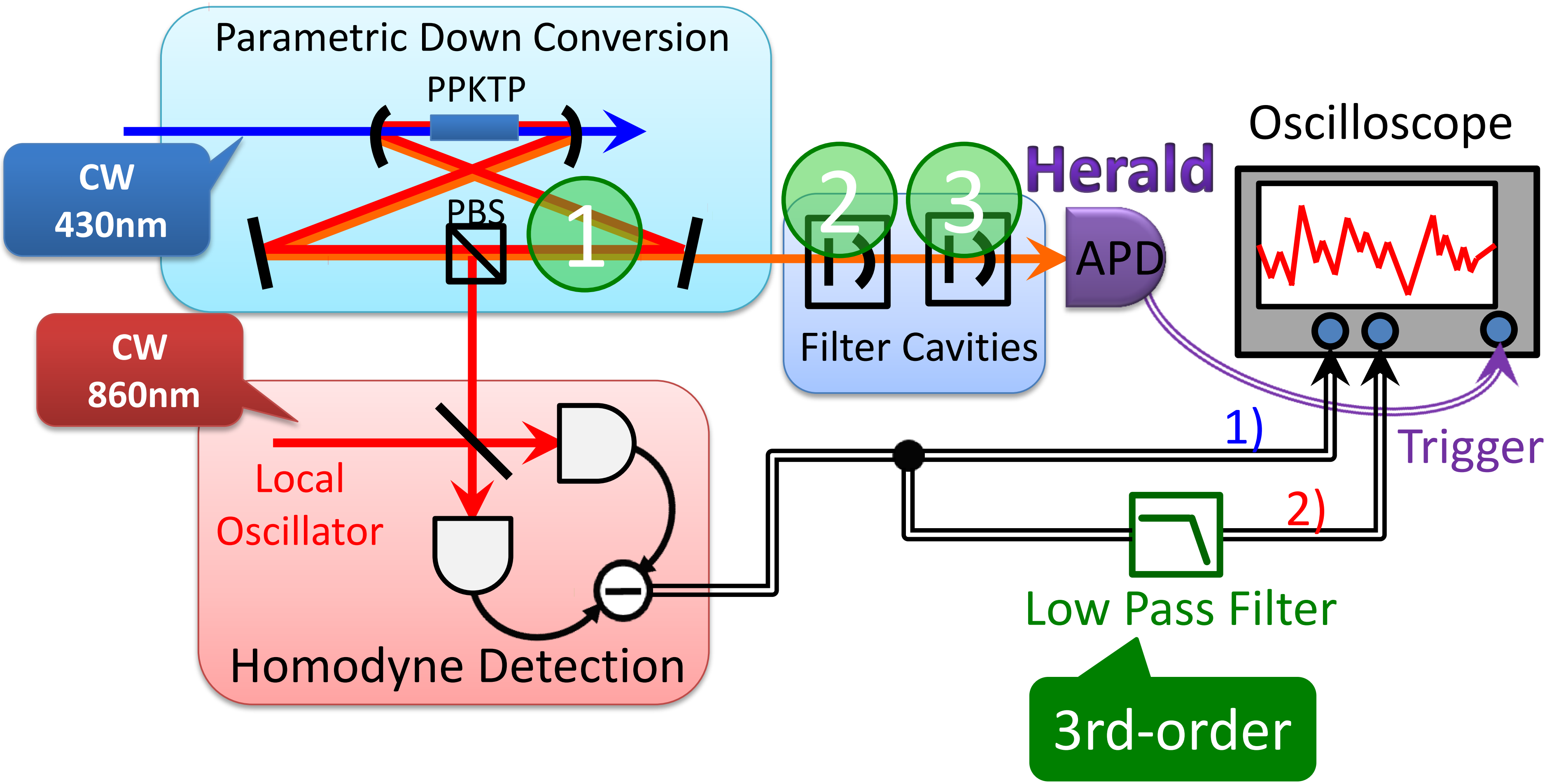
Symmetric and Asymmetric PDC



Singly-Resonant OPO



Experimental Setup

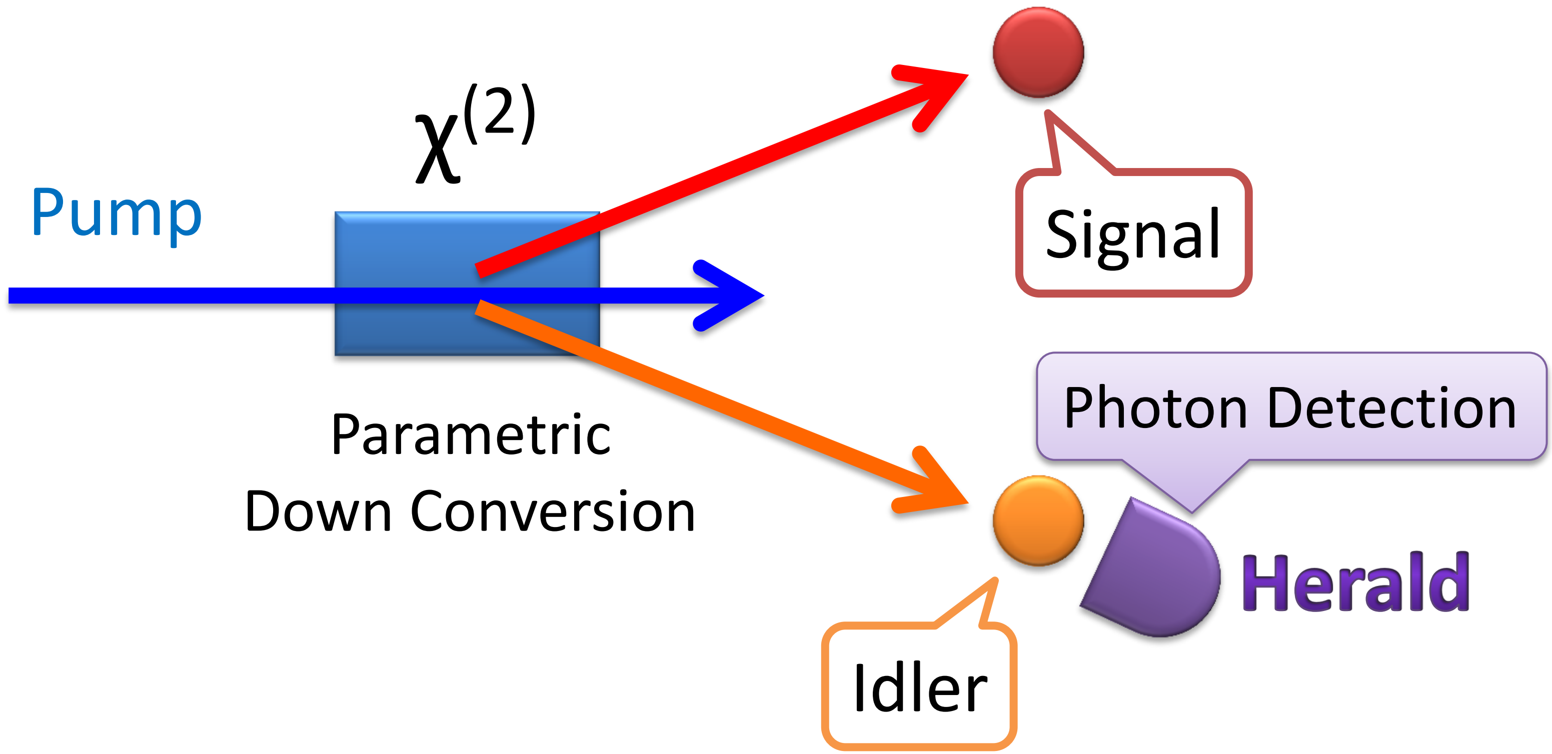


1) Unfiltered Original Signal => Integration by Post Processing

2) Filtered Signal

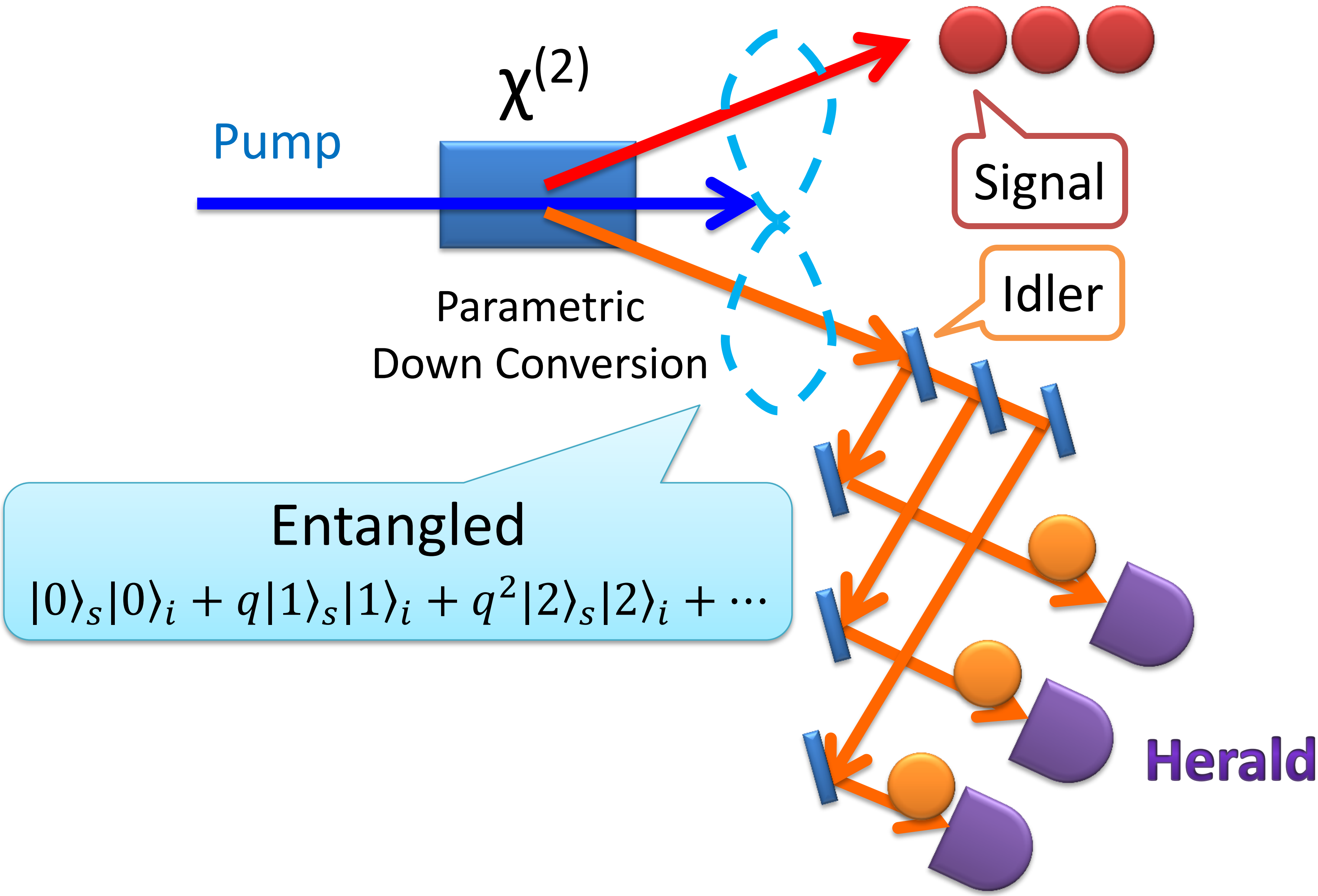
III) BI-PHOTON BI-MODE QUTRIT GENERATION

Heralding Scheme

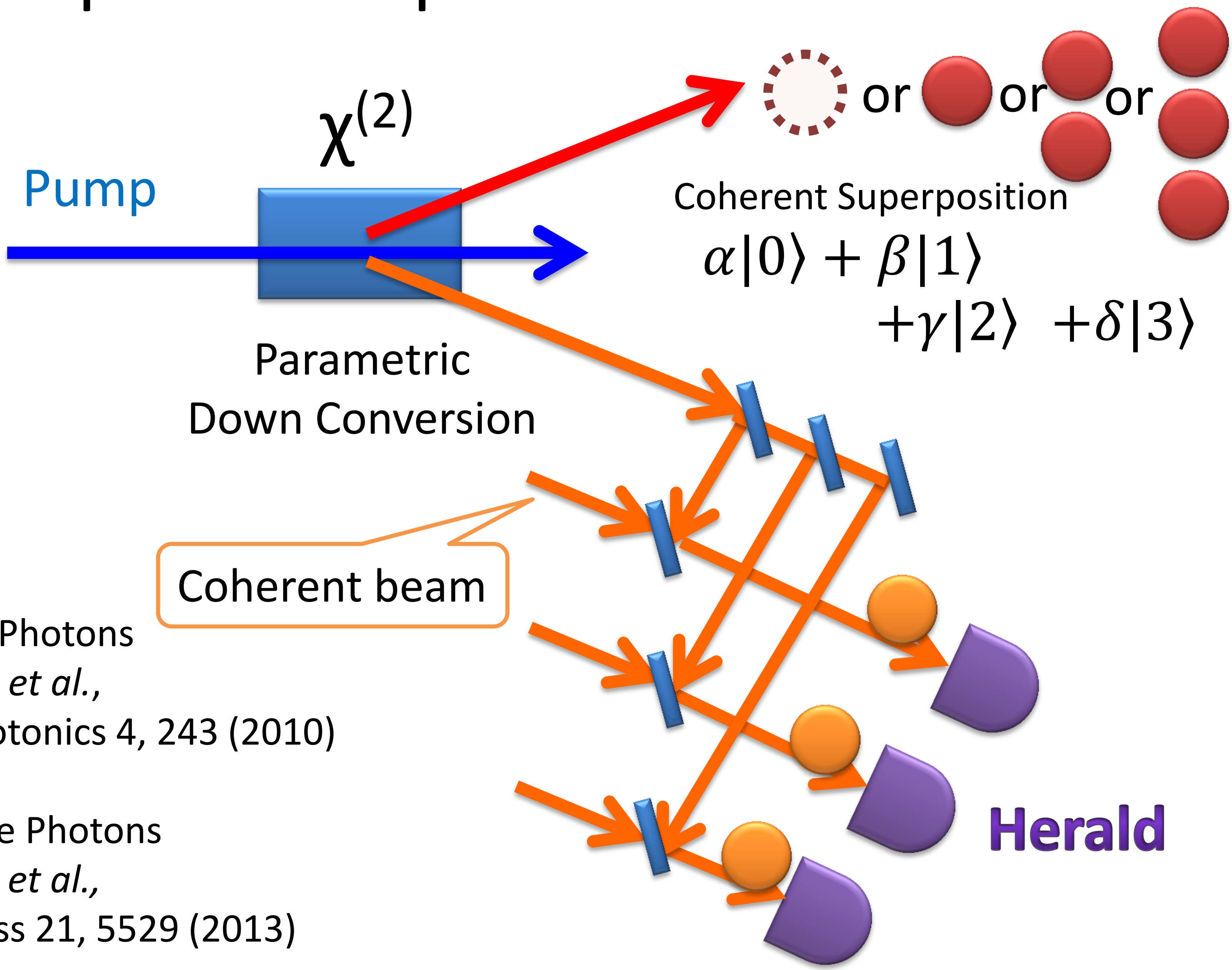


Extendable to a Variety of Non-Classical Quantum States

Multi-photon & phase-sensitive states



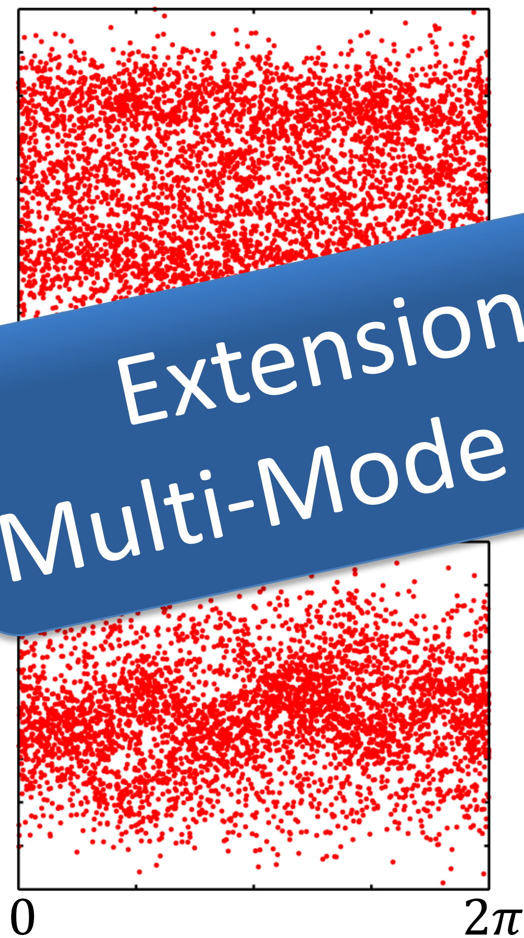
Multi-photon & phase-sensitive states

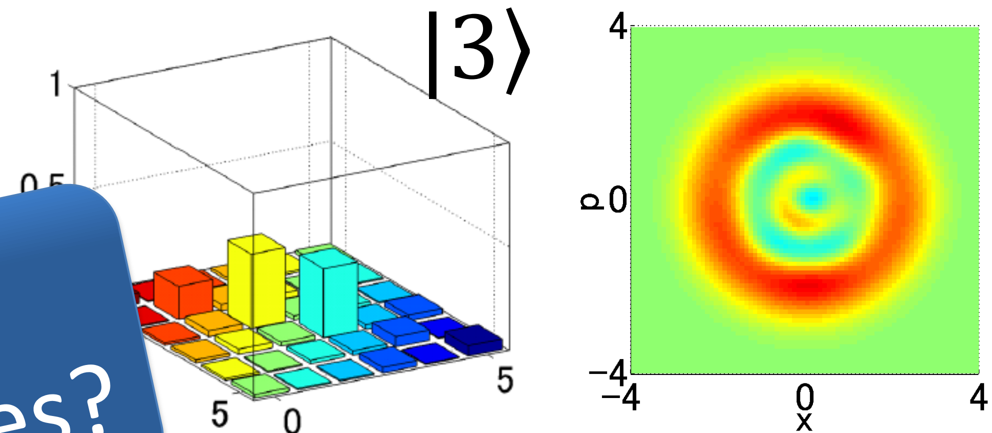


Up to Two Photons
E. Bimbard *et al.*,
Nature Photonics 4, 243 (2010)

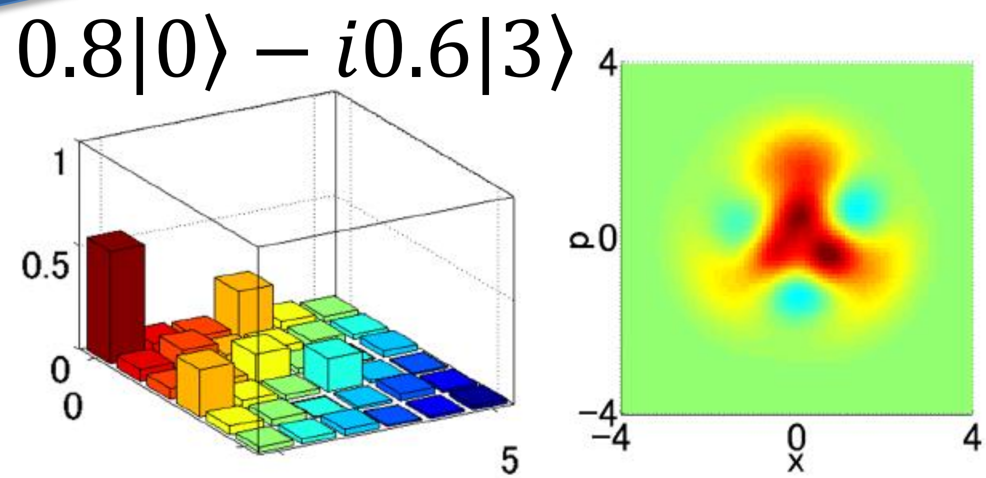
Up to Three Photons
M. Yukawa *et al.*,
Opt. Express 21, 5529 (2013)

Non-Gaussian State Generation





Extension to Multi-Mode States?



M. Yukawa *et al.*,
"Generating superposition of up-to three photons
for continuous variable quantum information processing"
Opt. Express 21, 5529 (2013)

Multi-Mode States for QEC

$$|0_L\rangle = \frac{1}{\sqrt{2}}(|4,0\rangle + |0,4\rangle)$$
$$|1_L\rangle = |2,2\rangle$$

Error Correction Code against a Photon Loss

I.L. Chuang et al., "Bosonic quantum codes for amplitude damping" Phys. Rev. A 56, 1114 (1997).

1) No-Error Case

$$\alpha|0_L\rangle + \beta|1_L\rangle$$

2)Photon Loss in the 1st Mode

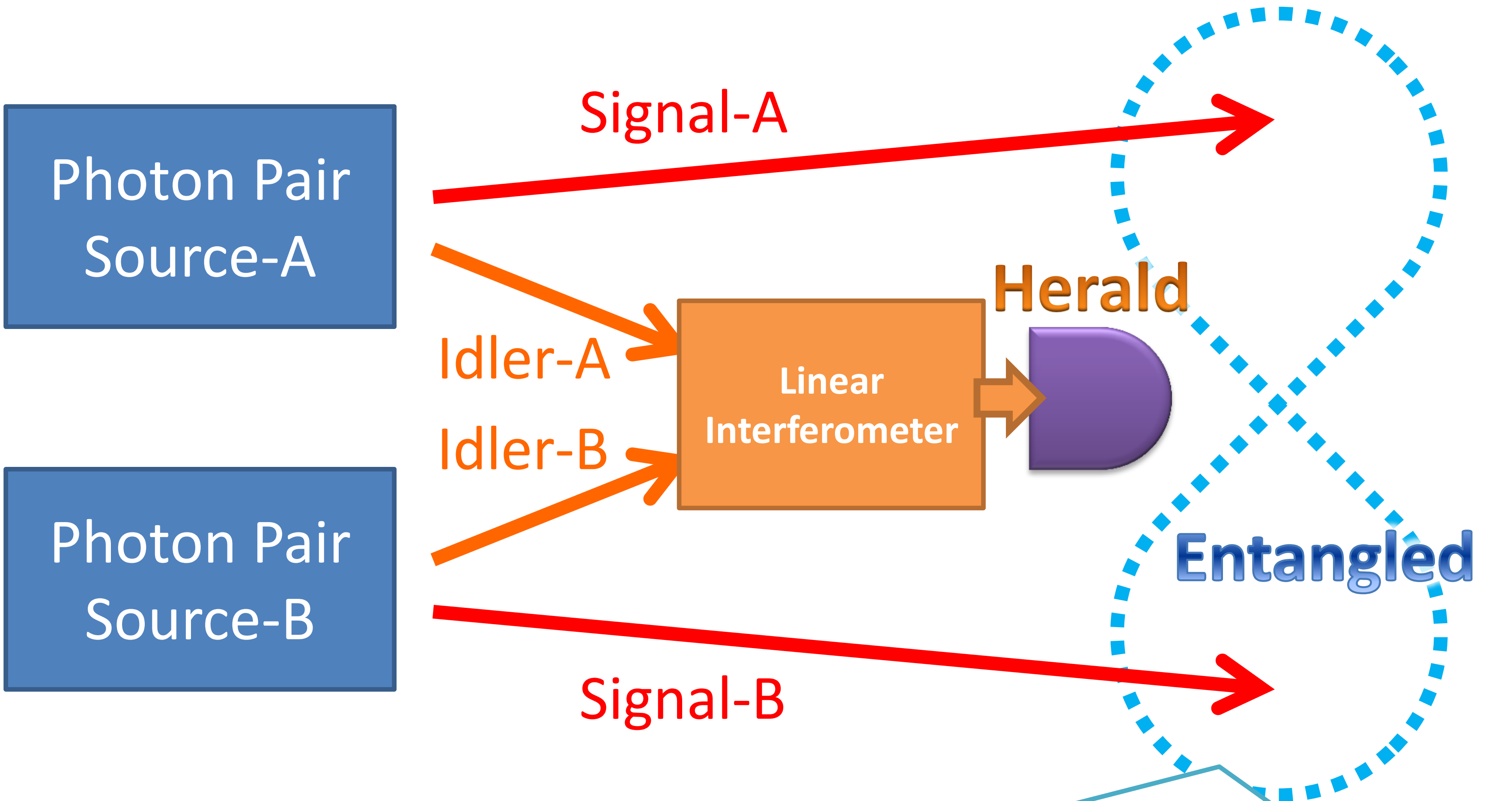
$$\hat{a}_A(\alpha|0_L\rangle + \beta|1_L\rangle) = \sqrt{2}(\alpha|3,0\rangle + \beta|1,2\rangle)$$

3) Photon Loss in the 2nd Mode

$$\hat{a}_B(\alpha|0_L\rangle + \beta|1_L\rangle) = \sqrt{2}(\alpha|0,3\rangle + \beta|2,1\rangle)$$

Mutually Orthogonal & Undeformed Superposition

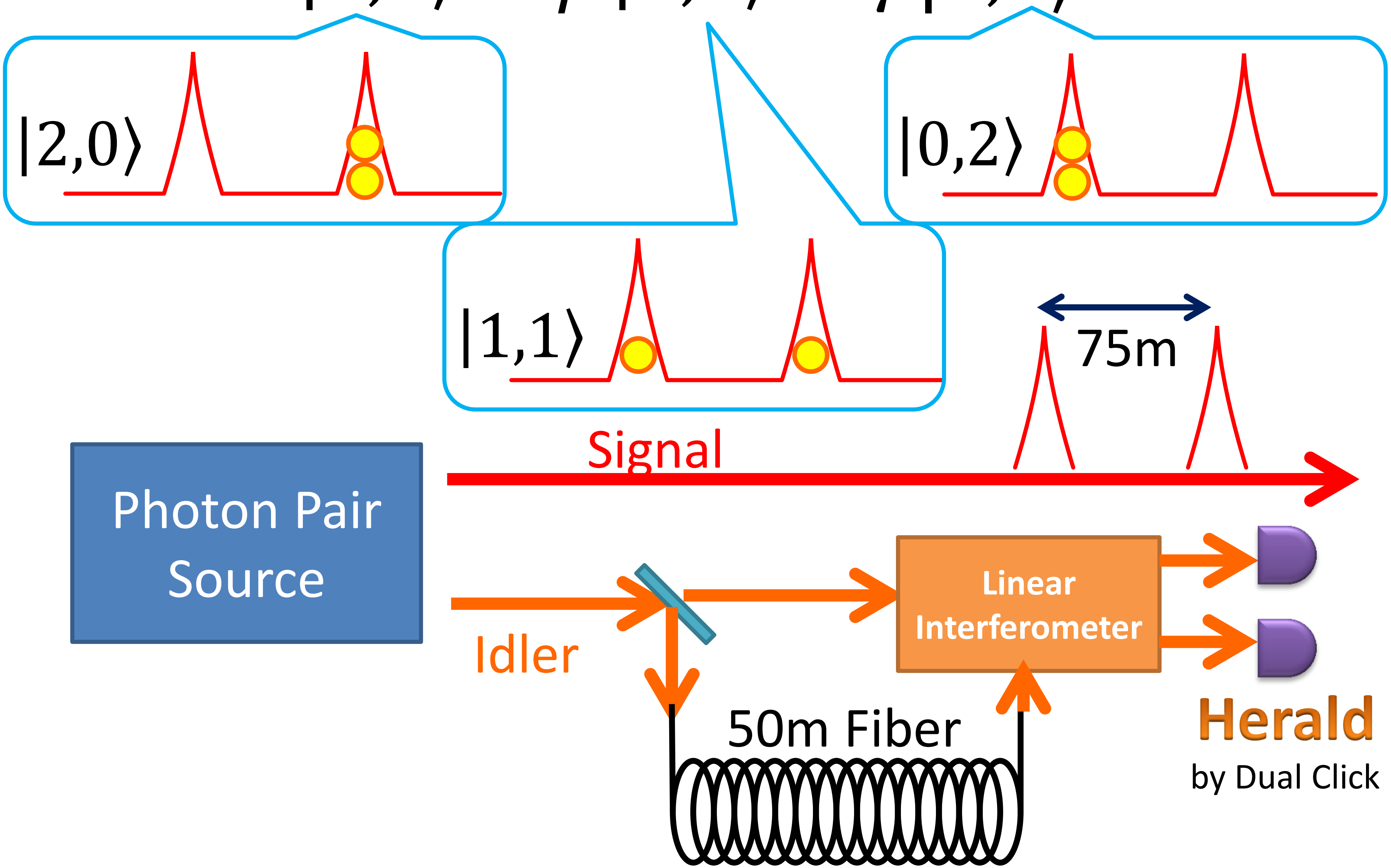
Heralded Multi-Mode States



$$\alpha_0|0,m\rangle + \cdots + \alpha_k|k,m-k\rangle + \cdots + \alpha_m|m,0\rangle$$

Time-bin Bi-Photon Qutrit Generation

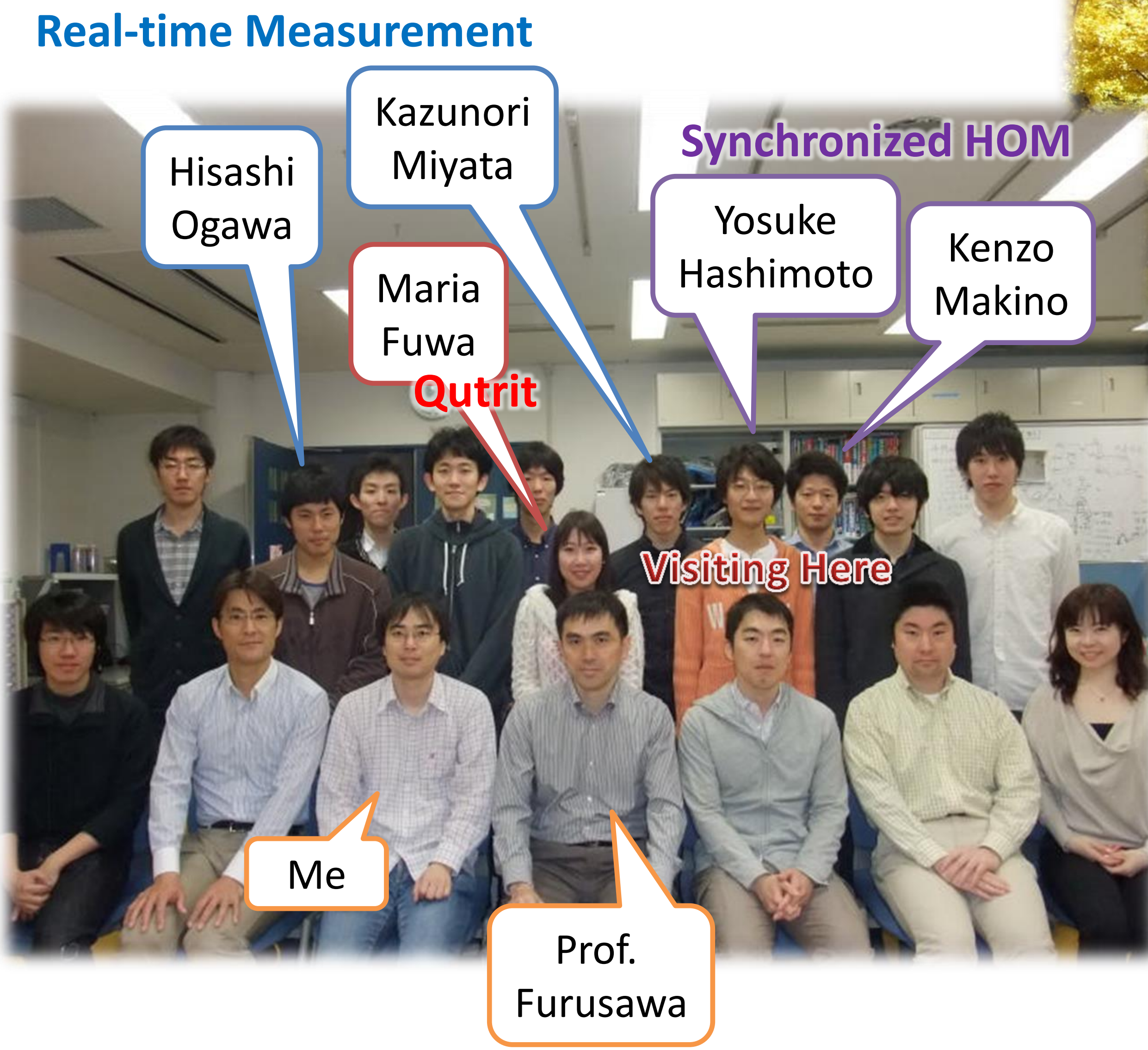
$$\alpha|2,0\rangle + \beta|1,1\rangle + \gamma|0,2\rangle$$



Summary

- We made use of optical cavities as memories to synchronize photons, and characterized the resulting HOM state by wave-basis homodyne.
- We realized real-time acquisition of quadrature values by utilizing exponentially rising photon pulses.
- We extended the heralding scheme to bi-mode, bi-photon qutrit states.

Thanks to Colleagues



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