Laboratoire Kastler Brossel
Physique quantique et applications

ENS cnrs SORBONNE UNIVERSITÉ

Continuous variable quantum networks -2

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Multimode quantum optics group

Continuous Variables Quantum Complex Networks team

European Research Council

Okinawa School in Physics: From quantum key distribution to the quantum internet (OSP2025)

September 21, 2025 - October 3, 2025

CV cluster states as quantum networks

Cluster states in
Quantum Information protocols

Multimode quantum optics

Good platform for

Quantum information

Continuous variables encoding

$$\{x_i\} \in \mathcal{R}$$

superposition

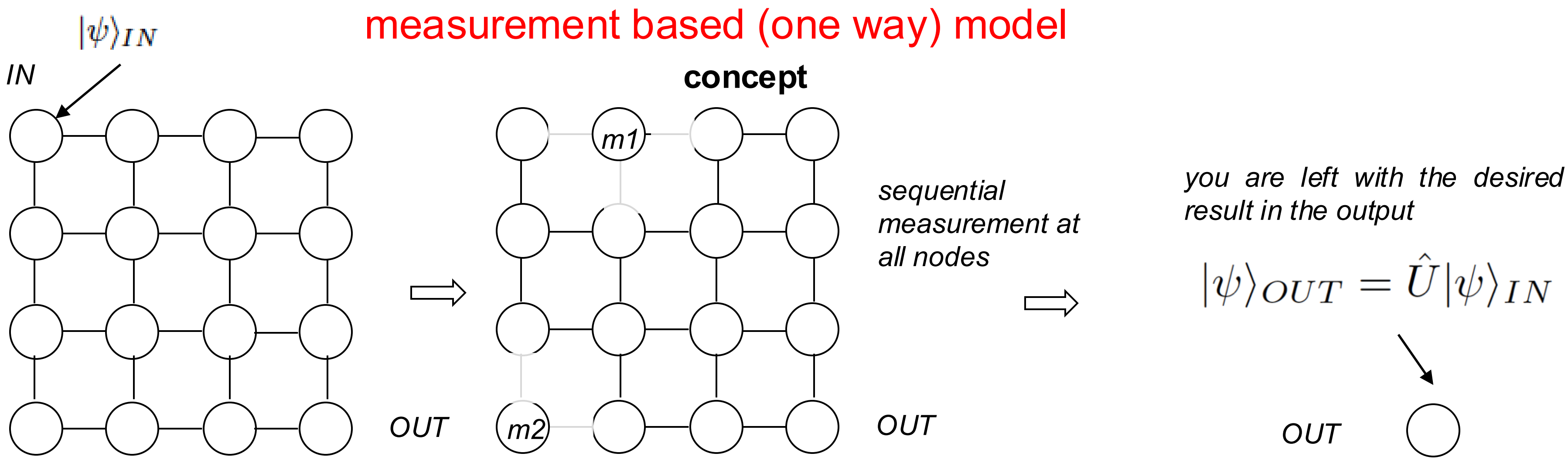
$$|\,\psi\,\rangle = \int f(x)|x\rangle dx$$

entanglement: quantum correlations

$$|\psi\rangle \sim \delta(q_s - q_i)\delta(p_s + p_i)$$

measurement based (one way) model

concept



Multimode quantum optics

Good platform for

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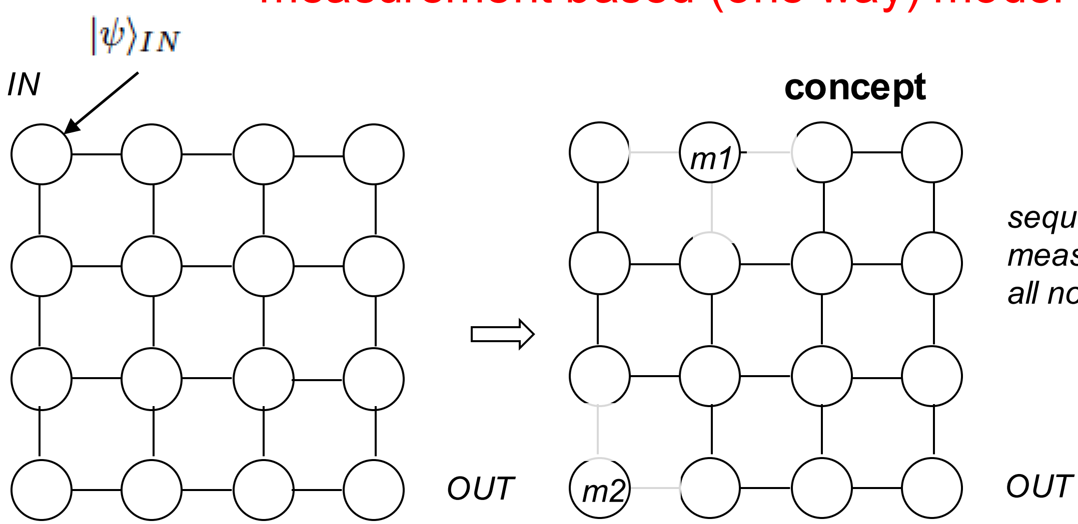
superposition $$|\psi\rangle = \int f(x)|x\rangle dx$$

entanglement: quantum correlations

$$|\psi\rangle \sim \delta(q_s - q_i)\delta(p_s + p_i)$$

measurement based (one way) model -> it is a generalized teleportation

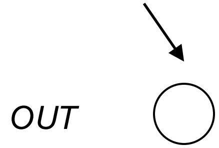
concept



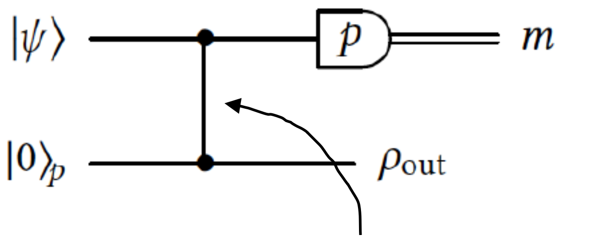
sequential measurement at all nodes

you are left with the desired result in the output

$$|\psi\rangle_{OUT} = \hat{U}|\psi\rangle_{IN}$$



The underlying paradigm : teleportation gate



$$\hat{C}_z = exp[\imath \hat{q}_1 \otimes \hat{q}_2]$$

The initial state in mode 1 is given by

$|\psi\rangle_1 = \int ds \psi(s) |s\rangle_q$ $\quad$ $|s\rangle_q$ Is the eigenstate of the quadrature q with eigenvalue s $\quad$ $\hat{q}|s\rangle_q = s|s\rangle_q$

In mode 2

$|0\rangle_p$ Is the eigenstate of the quadrature p with eigenvalue 0

The Cz operation is applied between the two modes, then the quadrature p is measured in the first mode and the value m is obtained. The action of the teleportation gate is then given by

$$|\psi_{out}\rangle_2 = \langle m|_{p1} e^{\imath \hat{q}_1 \otimes \hat{q}_2} |\psi\rangle_1 |0\rangle_{p2} = \langle m|_{p1} e^{\imath \hat{q}_1 \otimes \hat{q}_2} \int ds \psi(s) |s\rangle_{q1} |0\rangle_{p2}$$

By using

$e^{\imath \hat{q}_1} \psi(s) |s\rangle_{q1} = e^{\imath s} \psi(s) |s\rangle_{q1}$ $\quad$ as if $\hat{A}|\lambda\rangle = \lambda|\lambda\rangle$ then $f(\hat{A})|\lambda\rangle = f(\lambda)|\lambda\rangle$

$$|\psi_{out}\rangle_2 = \langle m|_{p1} \int ds e^{\imath s \hat{q}_2} \psi(s) |s\rangle_{q1} |0\rangle_{p2}$$

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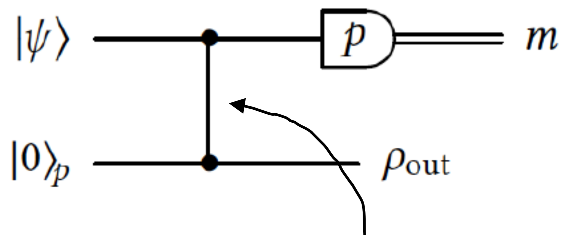


$$\hat{C}_z = exp[\imath \hat{q}_1 \otimes \hat{q}_2]$$

$$|\psi_{out}\rangle_2 = \langle m|_{p1} \int ds e^{\imath s \hat{q}_2} \psi(s) |s\rangle_{q1} |0\rangle_{p2}$$

$\hat{q}$ Is the generator of translation in p $e^{\imath \beta \hat{q}} |p\rangle_p = |p + \beta\rangle_p$

$$|\psi_{out}\rangle_2 = \langle m|_{p1} \int ds \psi(s) |s\rangle_{q1} |s\rangle_{p2}$$

The states of well defined quadratures q and p are linked by the Fourier transform

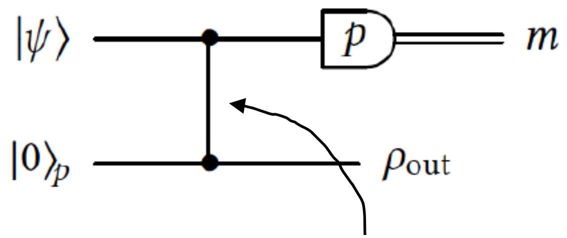
$$|s\rangle_{q1} = \frac{1}{\sqrt{2\pi}} \int dr e^{-\imath s r} |r\rangle_{p1}$$

$$|\psi_{out}\rangle_2 = \langle m|_{p1} \frac{1}{\sqrt{2\pi}} \int ds \psi(s) \int dr e^{-\imath s r} |r\rangle_{p1} |s\rangle_{p2}$$

$$\langle m|_{p1} e^{-\imath s r} |r\rangle_{p1} = e^{-\imath s m}$$

$$|\psi_{out}\rangle_2 = \frac{1}{\sqrt{2\pi}} \int ds \psi(s) e^{-\imath s m} |s\rangle_{p2}$$

The underlying paradigm : teleportation gate



$$\hat{C}_z = exp[\imath \hat{q}_1 \otimes \hat{q}_2]$$

$$|\psi_{out}\rangle_2 = \frac{1}{\sqrt{2\pi}} \int ds\psi(s) e^{-\imath s m} |s\rangle_{p2}$$

we can bring the exponential function outside the integral by considering that it can be generated by the operator $\hat{p}$

$$|\psi_{out}\rangle_2 = \frac{1}{\sqrt{2\pi}} e^{-\imath \hat{p}_2 m} \int ds\psi(s) |s\rangle_{p2}$$

$|s\rangle_{p2} = F|s\rangle_{q2}$ *Where F is the Fourier Transform* $\int ds\psi(s)|s\rangle_{p2} = F|\psi\rangle$

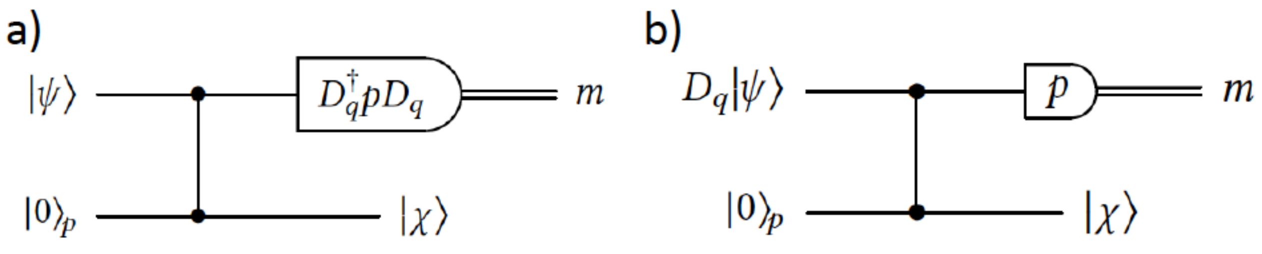
$$|\psi_{out}\rangle_2 = e^{-\imath \hat{p}_2 m} F|\psi\rangle$$

$e^{-\imath \hat{p}_2 m}$ *Is the translation in q,* *we call* $e^{-\imath \hat{p}_2 m} = X(m)$

$$\boxed{|\psi_{out}\rangle_2 = X(m)F|\psi\rangle}$$

so the teleportation gate teleports the state from mode 1 to mode 2 and it contingently applies a Fourier transform plus a displacement of the quadrature q by the value given by the measurement outcome m!

The underlying paradigm : teleportation gate



Consider now that it is possible to measure the observable $\hat{D}_q^\dagger \hat{p} \hat{D}_q$ for some unitary $\hat{D}_q = exp(\imath f(\hat{q}))$

$\hat{D}_q$ Commutes with the Cz so the final state is

$$\boxed{|\psi_{out}\rangle_2 = |\chi\rangle = X(m) F \hat{D}_q |\psi\rangle}$$

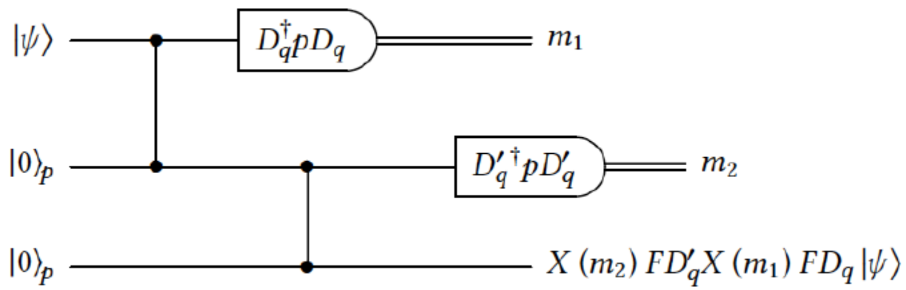
so that we can not only teleport the state but also apply the operation $\hat{D}_q$!

$$|\psi_{out}\rangle_2 = X(m) F |\psi\rangle$$

so the teleportation gate teleports the state from mode 1 to mode 2 and it contingently applies a Fourier transform plus a displacement of the quadrature q by the value given by the measurement outcome m!

The underlying paradigm : teleportation gate

Concatenating elements



$$|\psi_{out}\rangle_3 = X(m_2)F\hat{D}'_q X(m_1)F\hat{D}_q|\psi_{in}\rangle = X(m_2)FX(m_1)X^\dagger(m_1)\hat{D}'_q X(m_1)F\hat{D}_q|\psi_{in}\rangle$$

$$X(m_1)X^\dagger(m_1) = 1$$

$$X^\dagger(m_1)\hat{D}'_q X(m_1) = X^\dagger(m_1)exp(\imath f(\hat{q}))X(m_1) = exp(\imath f(\hat{q}+m_1))$$

$$\Longrightarrow \quad |\psi_{out}\rangle_3 = X(m_2)FX(m_1)\hat{D}'_{q+m1}F\hat{D}_q|\psi_{in}\rangle = X(m_2)FX(m_1)FF^\dagger\hat{D}'_{q+m1}F\hat{D}_q|\psi_{in}\rangle$$

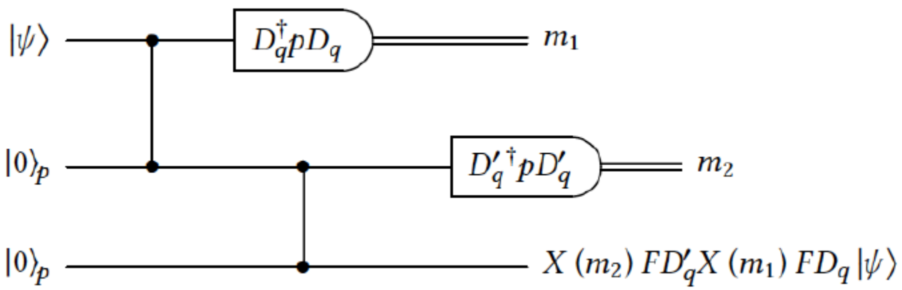
$$F^\dagger F = 1$$

$$F^\dagger\hat{D}'_{q+m1}F = \hat{D}'_{-p+m1}$$

$$\Longrightarrow \quad \boxed{|\psi_{out}\rangle_3 = X(m_2)FX(m_1)F\hat{D}'_{-p+m1}\hat{D}_q|\psi_{in}\rangle}$$

The underlying paradigm : teleportation gate

Concatenating elements



The result shows that at the second stage we can actively apply an operator that depends on a function of the quadrature p, i.e. $\hat{D}'_{-p+m1}$

To act with the desired transformation on the initial state we need to adapt the measured observable,

in order to apply $\hat{D}'_p$ and not $\hat{D}'_{-p+m1}$ we have to measure $\hat{D}'_{-q-m1}$

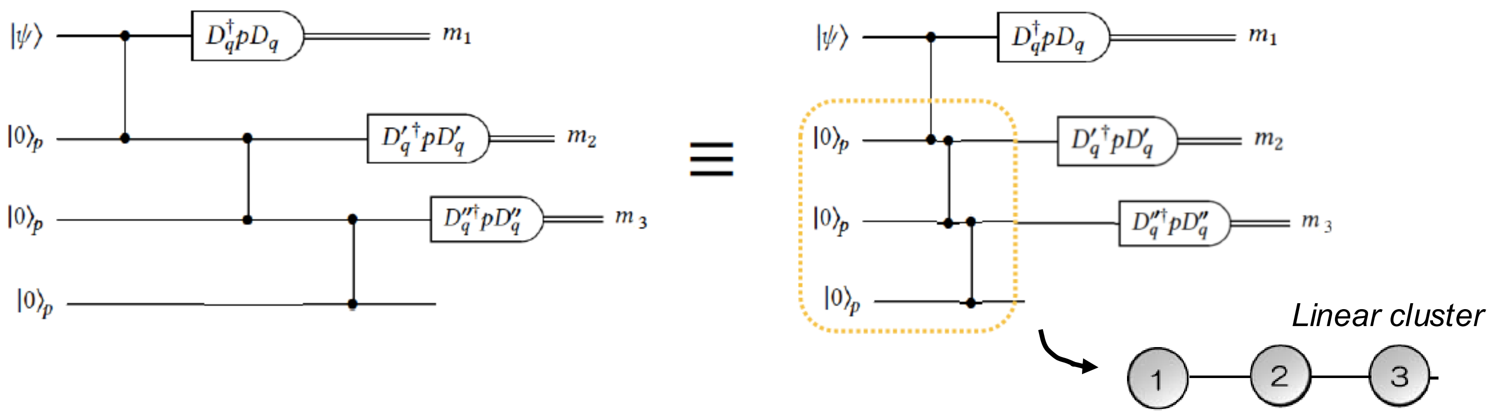
so at each step we have to adapt the new measurement setting according to the previous result.

$$|\psi_{out}\rangle_3 = X(m_2)FX(m_1)F\hat{D}'_{-p+m1}\hat{D}_q|\psi_{in}\rangle$$

The underlying paradigm : teleportation gate

Concatenating elements

From teleportation gate to cluster states



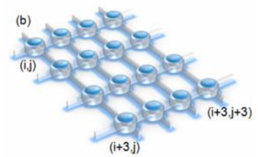
As the measurements and the Cz gates commute, the circuit on the left side of and the one on the right side are equivalent, all the Cz gates can operate at the begining between the modes occupied by the states $|0\rangle_p$

With linear cluster we can perform only single mode operation, we need at least grids for general quantum computing

CV MBQC - Summary

Continuous Variable Measurement Based-Quantum Computing

1) Build a cluster states



$$|\psi_V\rangle = \hat{C}_Z[V]|0\rangle_p^{\otimes N} = \prod_{j,k}^{N} e^{\frac{i}{2}V_{jk}\hat{q}_j\hat{q}_k}|0\rangle_p^{\otimes N} = e^{\frac{i}{2}\hat{q}^T V\hat{q}}|0\rangle_p^{\otimes N}$$

2) Define a set of input modes Vin and a set of output modes Vout

3) Encode $|\phi\rangle$ in Vin

4) Measure each vertex (except the ones belonging to Vout) in a basis of the form $M_i = e^{-if_i(\hat{q})}\hat{p}e^{if_i(\hat{q})}$ with $f_i(\hat{q})$ polynomials of $\hat{q}$ depending on the unitary we want to implement

5) The remaining unmeasured qumodes of Vout encode $U|\phi\rangle$

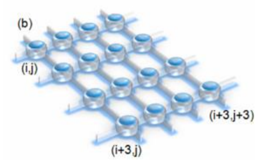
CV MBQC - Summary

LKB

Continuous Variable Measurement Based-Quantum Computing

1) Build a cluster states

Well…not normalized states with infinite energy



$$|\psi_V\rangle = \hat{C}_Z[V]|0\rangle_p^{\otimes N} = \prod_{j,k}^{N} e^{\frac{i}{2}V_{jk}\hat{q}_j\hat{q}_k}|0\rangle_p^{\otimes N} = e^{\frac{i}{2}\hat{q}^T V \hat{q}}|0\rangle_p^{\otimes N}$$

Collection of N infinitely p-squeezed states (modes)

We replace them with a collection of finite squeezed states

2) Define a set of input modes Vin and a set of output modes Vout

3) Encode $|\phi\rangle$ in Vin

4) Measure each vertex (except the ones belonging to Vout) in a basis of the form $M_i = e^{-if_i(\hat{q})}\hat{p}e^{if_i(\hat{q})}$ with $f_i(\hat{q})$ polynomials of $\hat{q}$ depending on the unitary we want to implement

5) The remaining unmeasured qumodes of Vout encode $U|\phi\rangle$

As in the teleportation this add (unavoidable) noise to the calculation

In order to get any polynomial you need non-Gaussian measurements (not-homodyne)

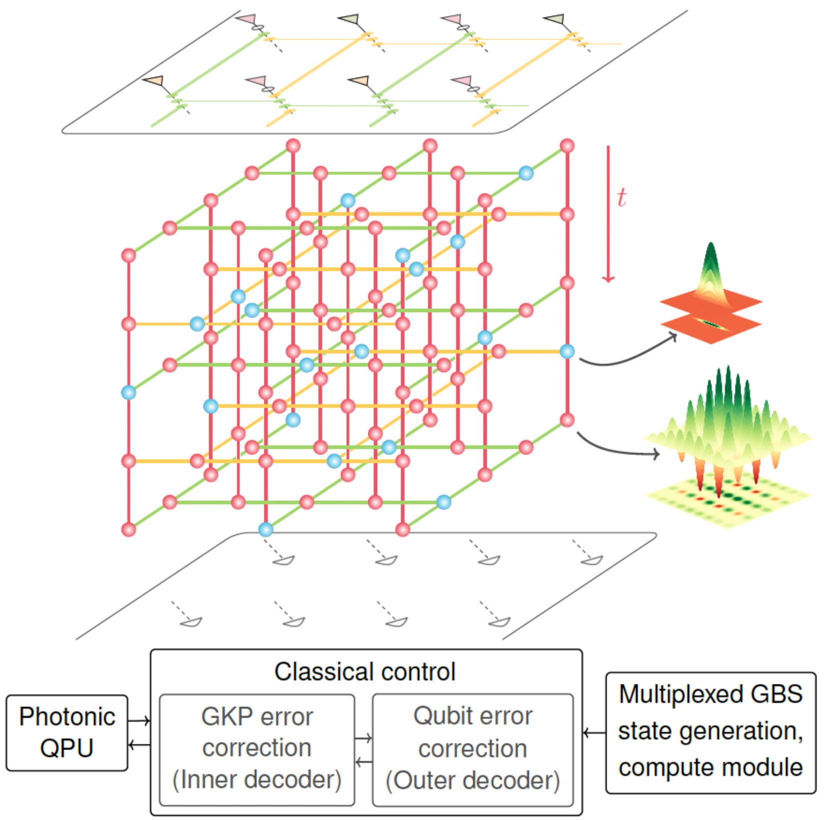
And not yet faul tolerant here!

CV- Photonic QC–state of the art

XANADU

Photonic quantum computing

A proposal for a fault-tolerant optical implementation



Bourassa J. E. *et al. Blueprint for a Scalable Photonic Fault-Tolerant Quantum Computer,* Quantum 5, 392 (2021)

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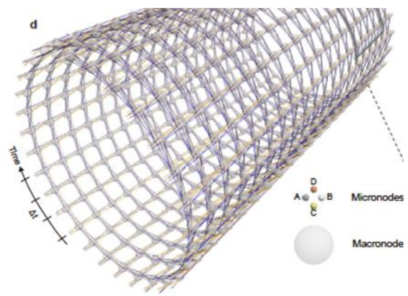
A proposal for a fault-tolerant optical implementation

- *Deterministic room-temperature generation of large number of Gaussian entangled states*



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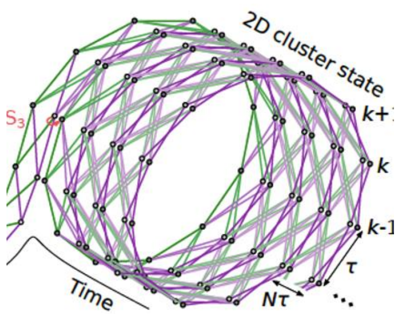

M. V. Larsen et al., Science 366, 369 (2019).

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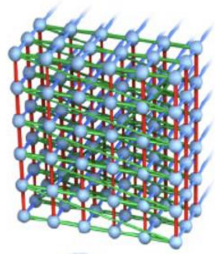
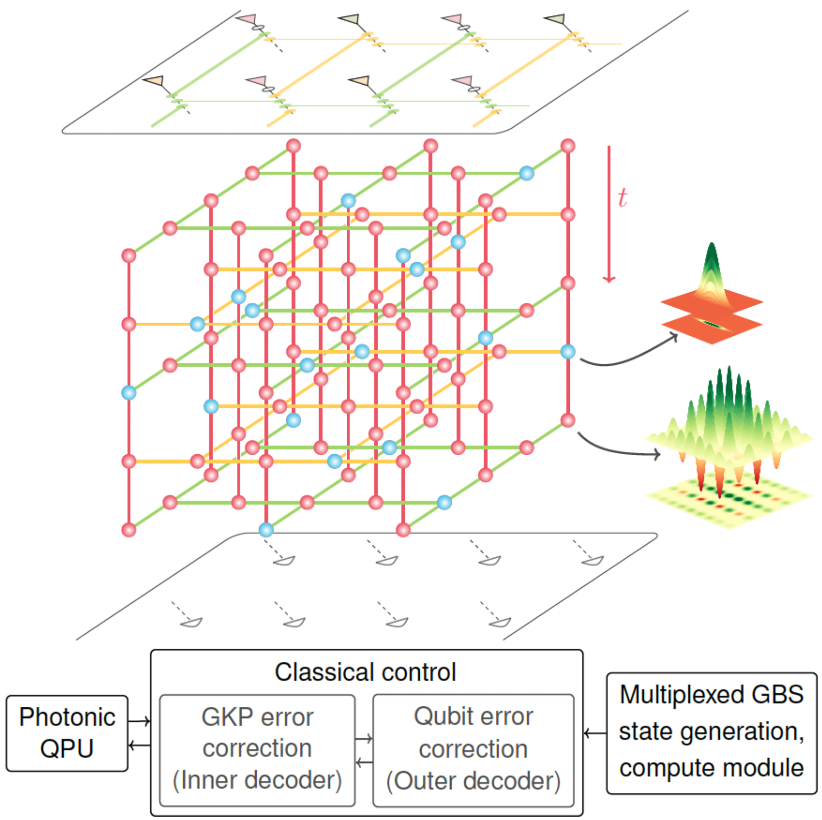


L. S. Madsen *et al.* Nature 606, 75 (2022)



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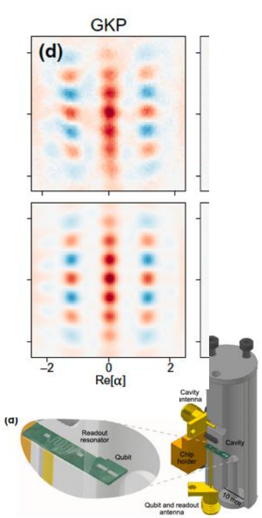
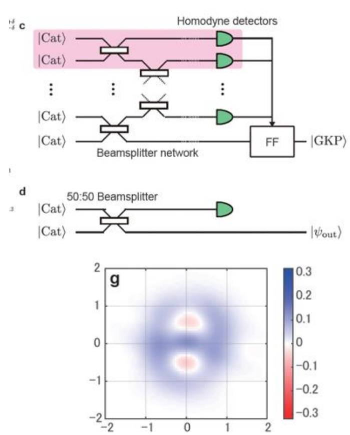
- *Probabilistic cryogenic generation of non-Gaussian GKP for error correction*

microwaves

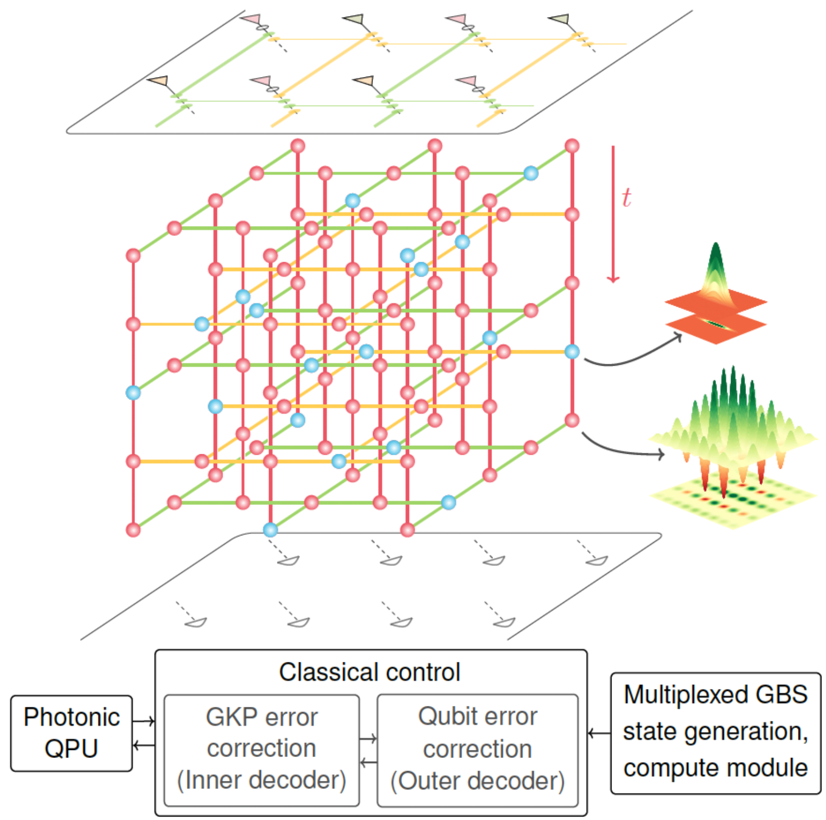


M. Kudra et al. PRX QUANTUM 3, 030301 (2022)

optics



S. Konno et al. Science 383, 6680 (2024)



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CV- Photonic QC–state of the art

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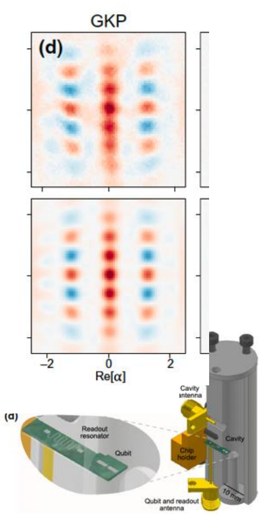

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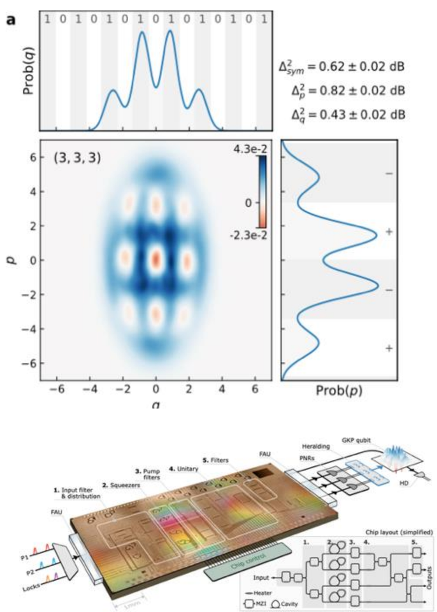

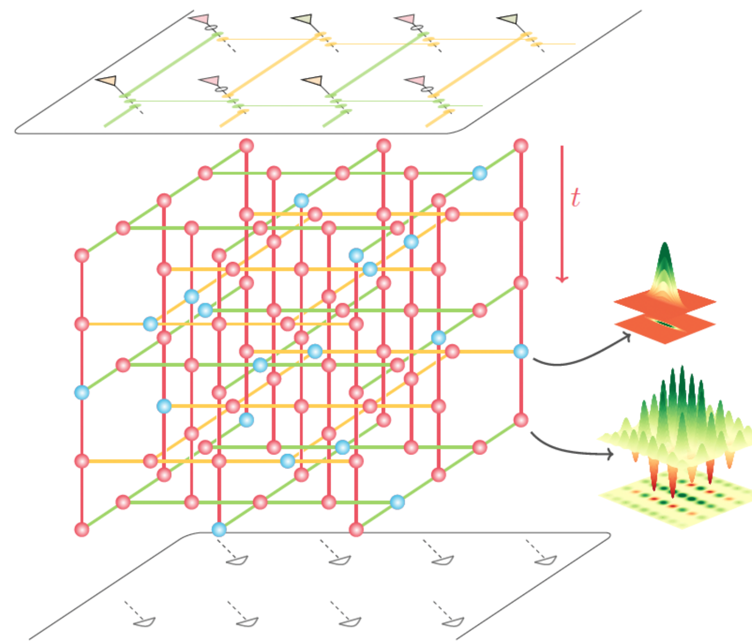

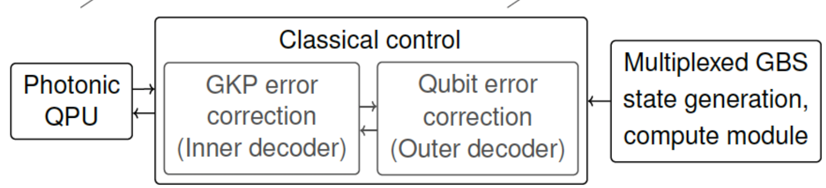

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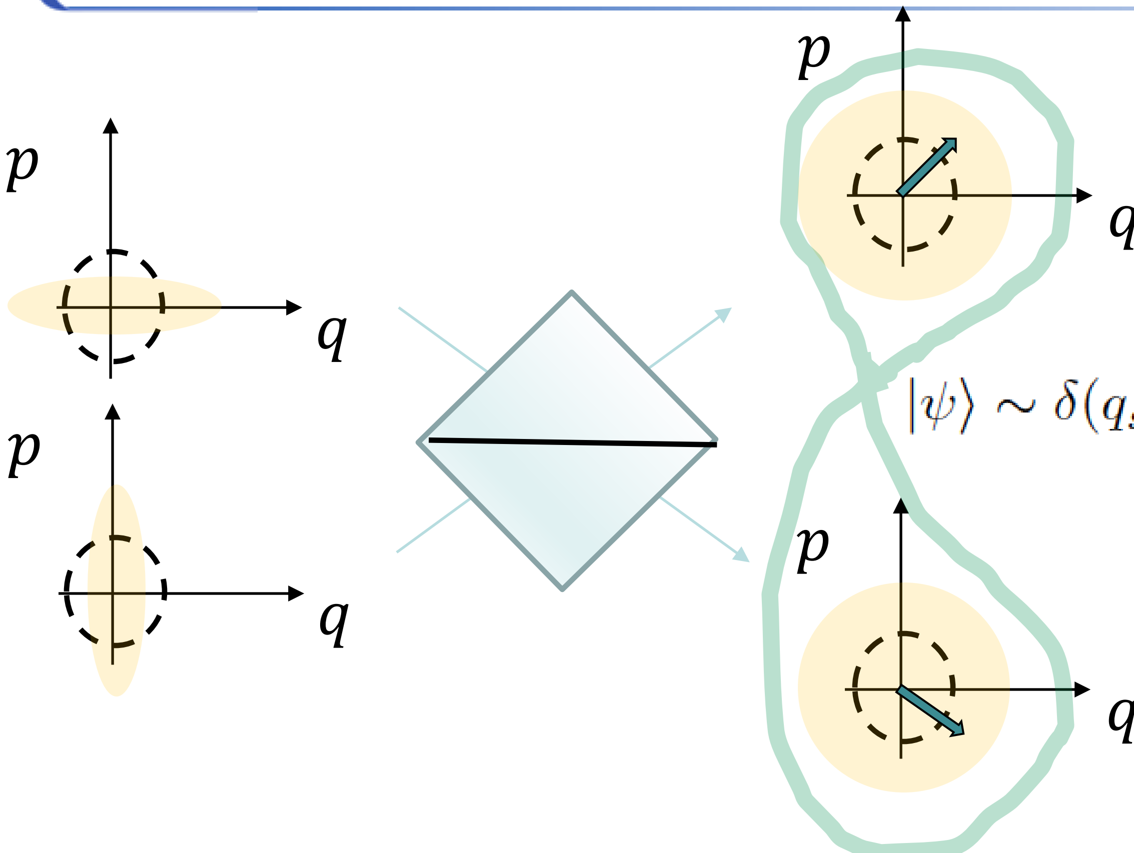
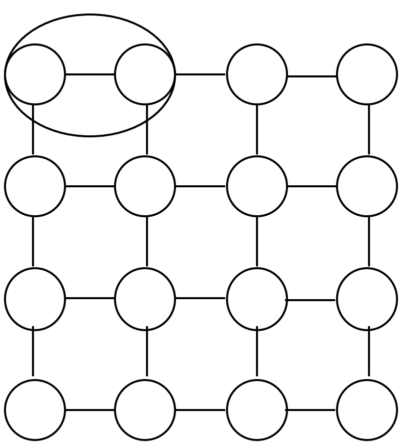
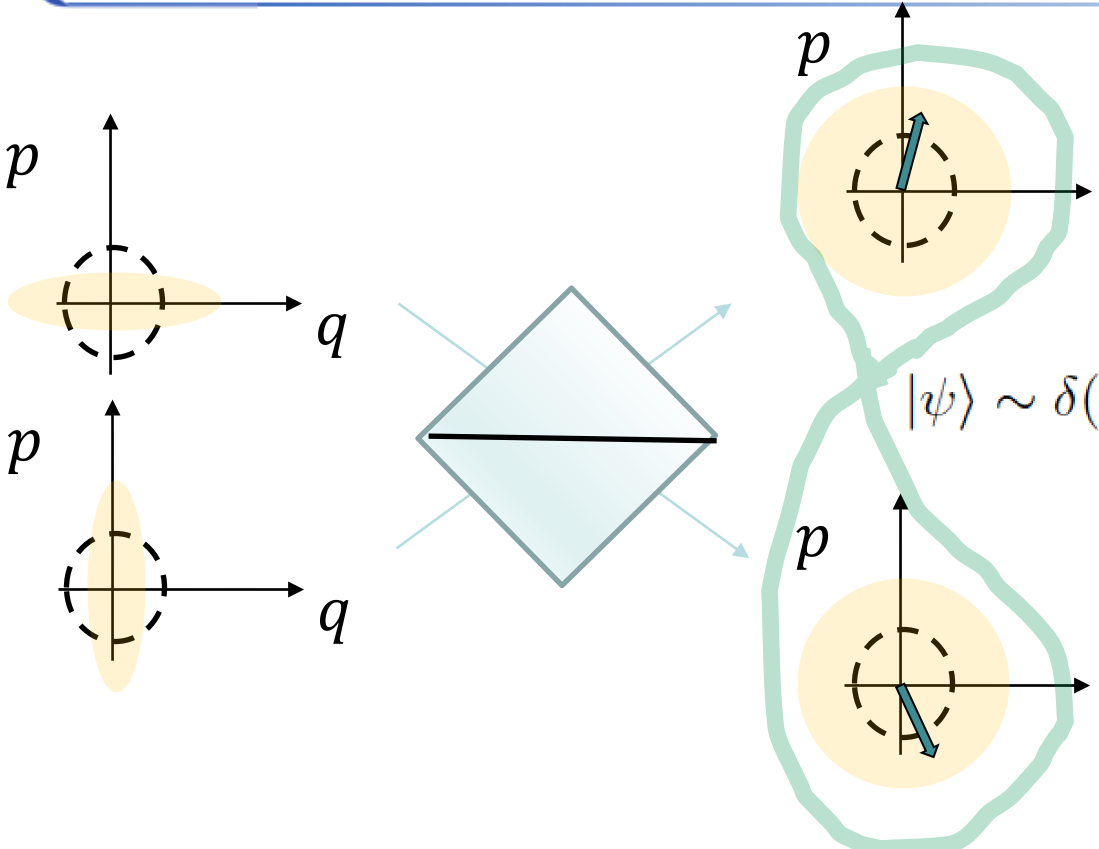
Generating CV Custer states

Multimode quantum optics

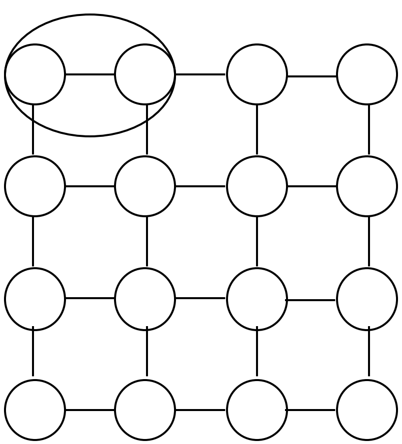


$$|\psi\rangle \sim \delta(q_s - q_i)\delta(p_s + p_i)$$



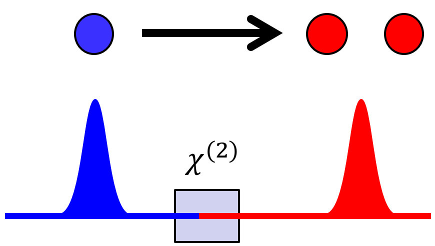


$|\psi\rangle \sim \delta(q_s - q_i)\delta(p_s + p_i)$



Generate the two nodes

Parametric process



$$H = g\,i\,(a_s^\dagger a_i^\dagger - a_s a_i)$$

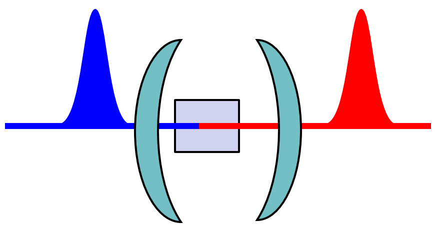
$$\hbar\omega_p = \hbar\omega_s + \hbar\omega_i$$

Generate the two nodes

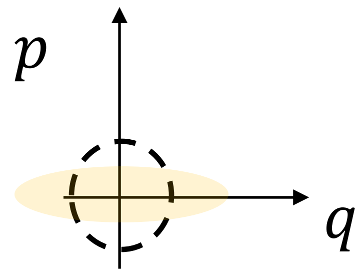
Degenerate case

Parametric process

$$\omega_s = \omega_i$$



$$\hbar\omega_p = \hbar\omega_s + \hbar\omega_i$$



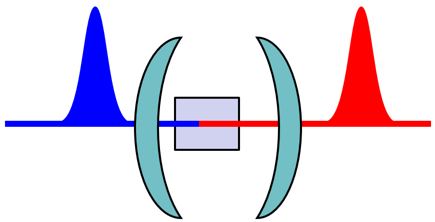
$$H = g\,i\left((a^+)^2 - (a)^2\right)$$

Generate the two nodes

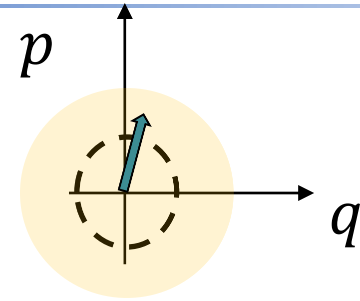
Non-Degenerate case

Parametric process

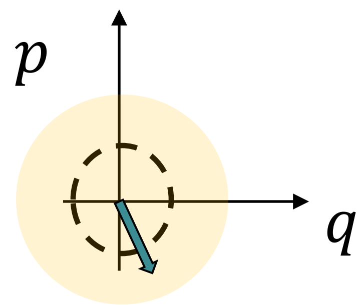
$$\omega_s \neq \omega_i$$



$$\hbar\omega_p = \hbar\omega_s + \hbar\omega_i$$



$$|\psi\rangle \sim \delta(q_s - q_i)\delta(p_s + p_i)$$



$$H = g\chi\left(a_s^\dagger a_i^\dagger - a_s a_i\right)$$

Interlude –CV and DV quantum states
In parametric processes

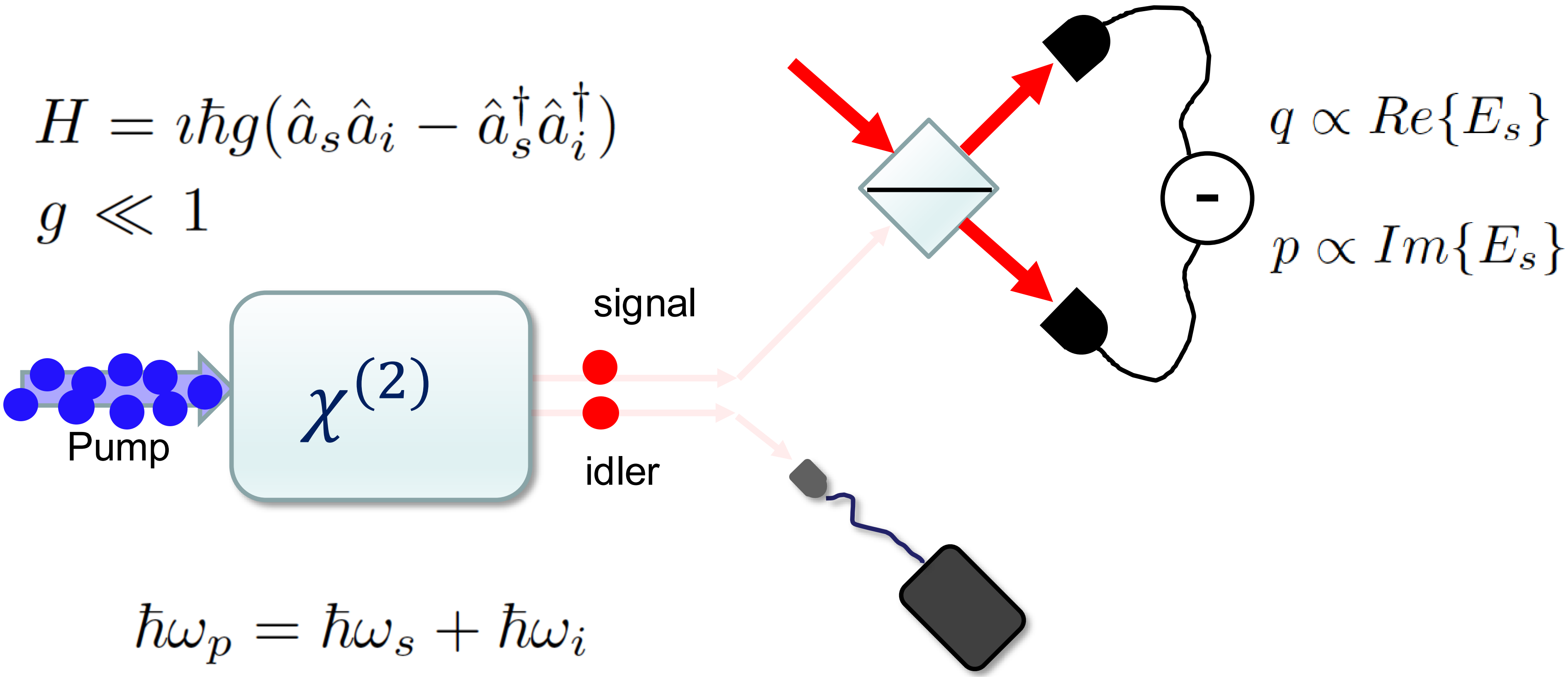
Linear and weak non-linear process ($\chi^{(2)}$)

…or the zoology of quantum states of light

Single-photon state

$$H = \imath\hbar g(\hat{a}_s\hat{a}_i - \hat{a}_s^\dagger\hat{a}_i^\dagger)$$

$$g \ll 1$$



$$\hbar\omega_p = \hbar\omega_s + \hbar\omega_i$$

$$\vec{k}_p = \vec{k}_s + \vec{k}_i$$

$$|\psi(t)\rangle \approx |0\rangle_s|0\rangle_i + \lambda|1\rangle_s|1\rangle_i$$

Linear and weak non-linear process ($\chi^{(2)}$)

…or the zoology of quantum states of light

Single-photon state

$$H = \imath\hbar g(\hat{a}_s\hat{a}_i - \hat{a}_s^\dagger\hat{a}_i^\dagger)$$

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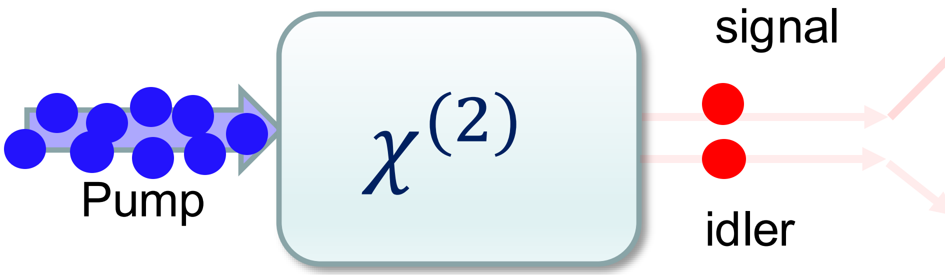
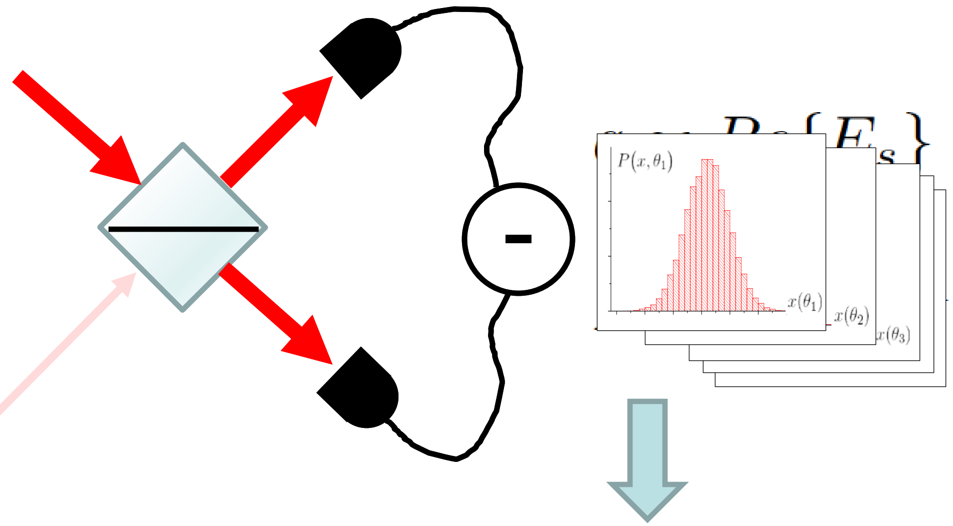


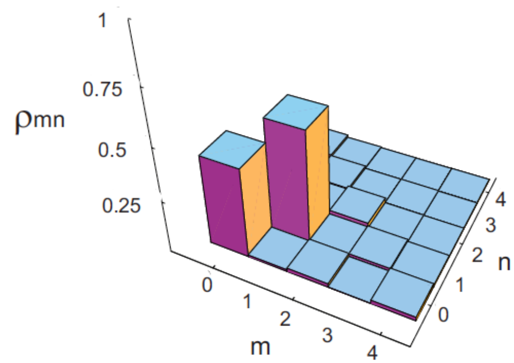


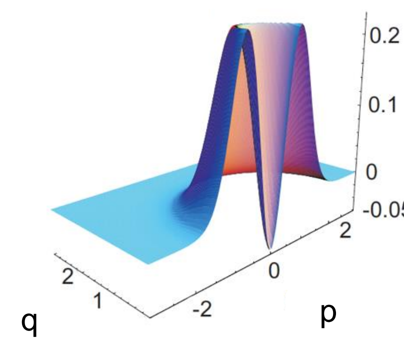
Tomographic reconstruction

$$\hbar\omega_p = \hbar\omega_s + \hbar\omega_i$$

$$\vec{k}_p = \vec{k}_s + \vec{k}_i$$

$$|\psi(t)\rangle \approx |0\rangle_s|0\rangle_i + \lambda|1\rangle_s|1\rangle_i$$



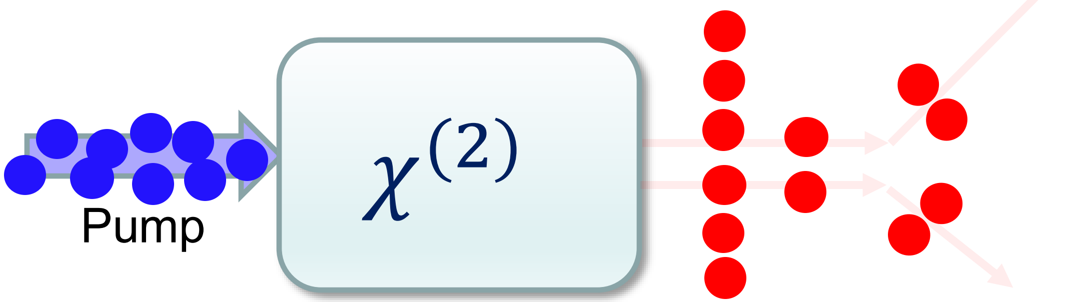


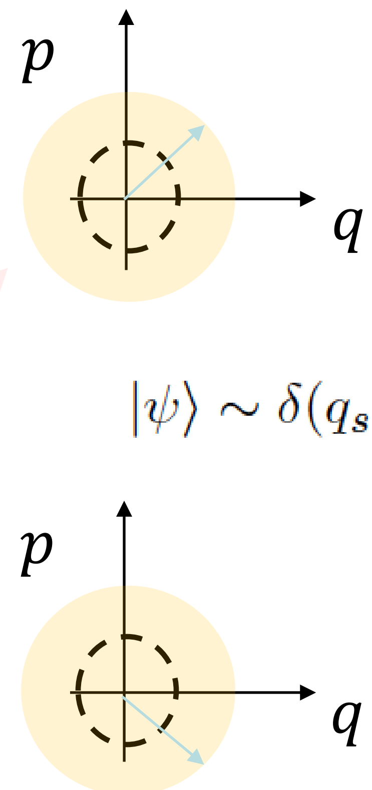
Experimental data!

…or the zoology of quantum states of light

Two-mode squeezed states ~ EPR

$$H = \imath\hbar g(\hat{a}_s\hat{a}_i - \hat{a}_s^\dagger\hat{a}_i^\dagger)$$





$$|\psi\rangle \sim \delta(q_s - q_i)\delta(p_s + p_i)$$

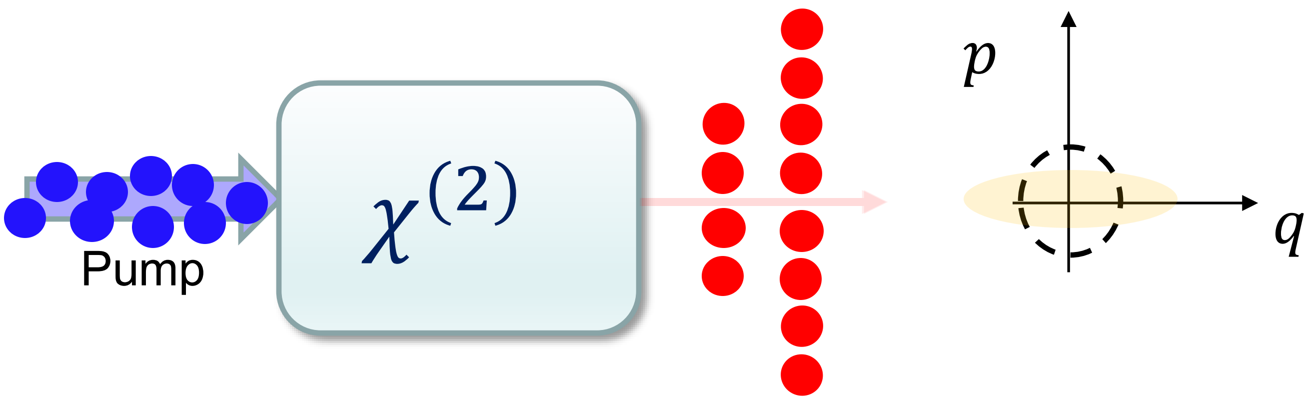
$$\omega_s \neq \omega_i$$

$$|\psi\rangle = (1-\lambda^2)^{1/2}\sum_{n=0}^{\infty}\lambda^n|n\rangle_s|n\rangle_i$$

Linear and weak non-linear process ($\chi^{(2)}$)

…or the zoology of quantum states of light **Squeezed vacuum**

$$H = \imath\hbar g(\hat{a}_s\hat{a}_i - \hat{a}_s^{\dagger}\hat{a}_i^{\dagger})$$



$$\omega_s = \omega_i$$

$$|\psi\rangle = (1-\lambda^2)^{1/4}\sum_{n=0}^{\infty}\binom{2n}{n}\left(\frac{\lambda}{2}\right)^n|2n\rangle$$

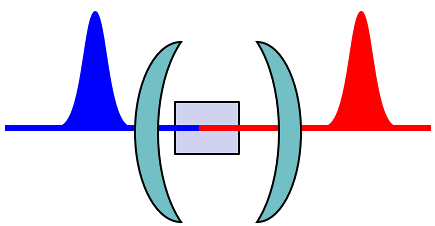
End of the Interlude

Generate the two nodes

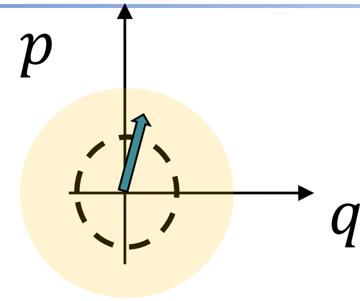
Non-Degenerate case

Parametric process

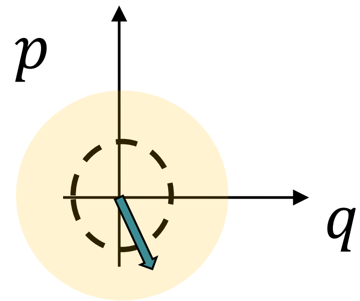
$$\omega_s \neq \omega_i$$



$$\hbar\omega_p = \hbar\omega_s + \hbar\omega_i$$



$$|\psi\rangle \sim \delta(q_s - q_i)\delta(p_s + p_i)$$

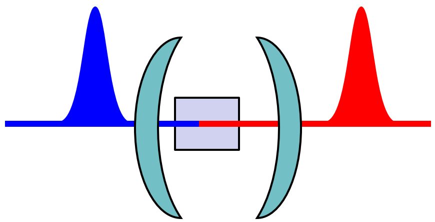


$$H = g_i \left(a_s^\dagger a_i^\dagger - a_s a_i \right)$$

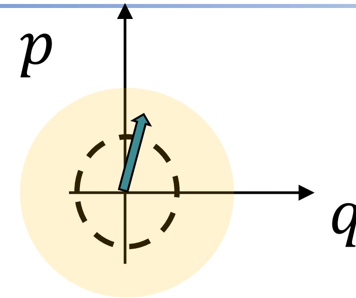
Multimode quantum optics

Parametric process

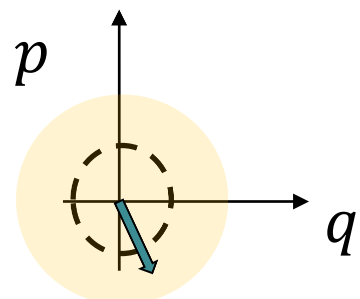
$$\omega_s \neq \omega_i$$

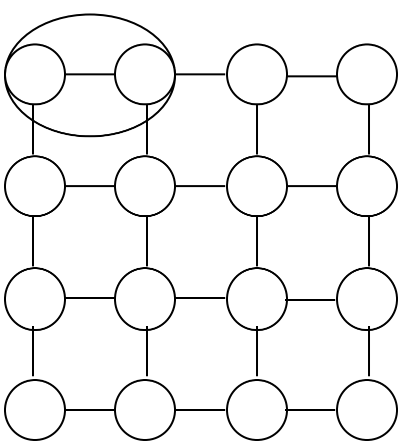


$$\hbar\omega_p = \hbar\omega_s + \hbar\omega_i$$



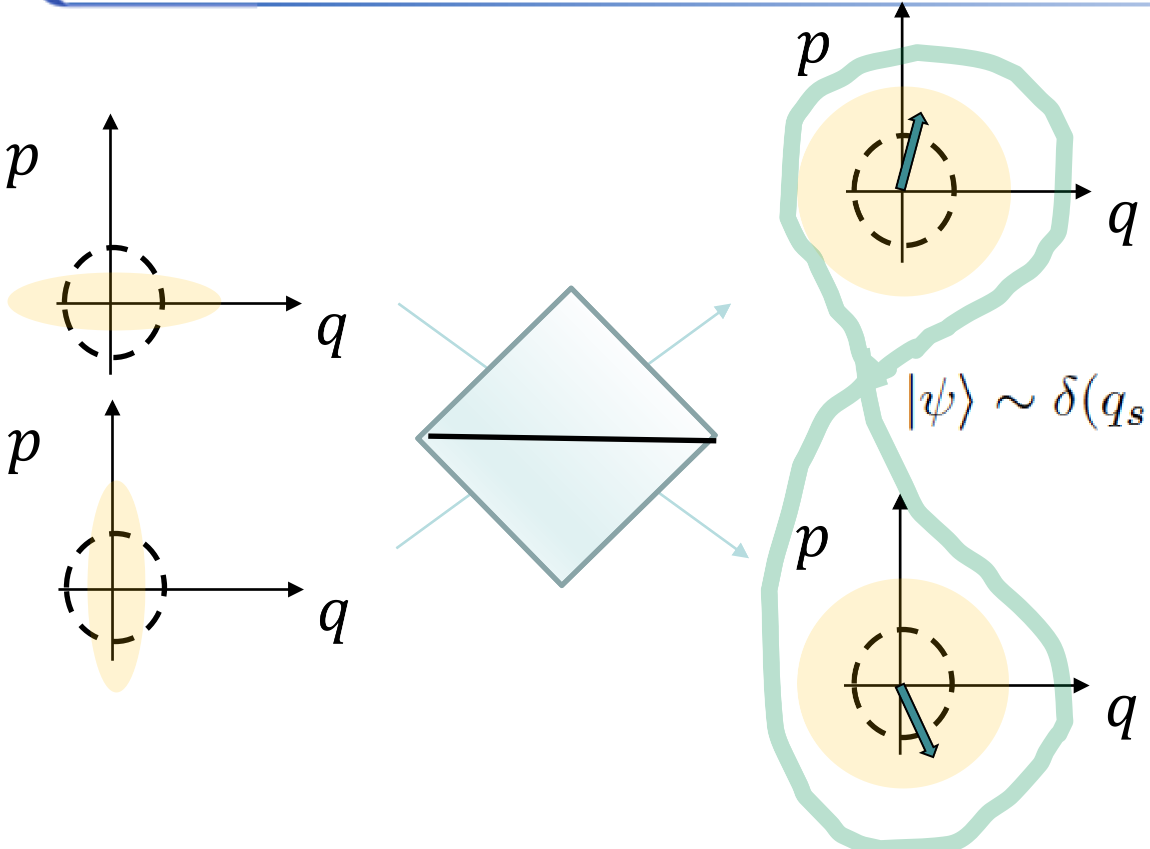
$$|\psi\rangle \sim \delta(q_s - q_i)\delta(p_s + p_i)$$



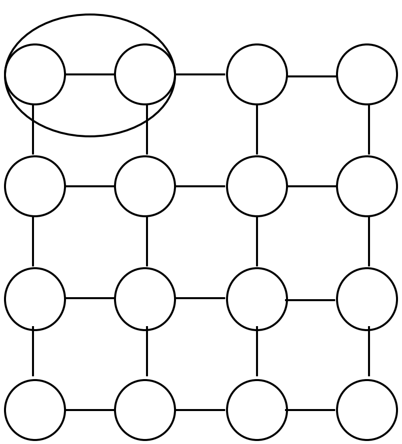


But only two entangled mode how to do many??

Multimode quantum optics

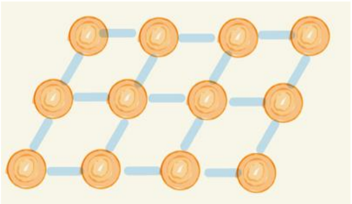


$$|\psi\rangle \sim \delta(q_s - q_i)\delta(p_s + p_i)$$



Multimode for cluster

Deterministic implementation ***CV Cluster states***



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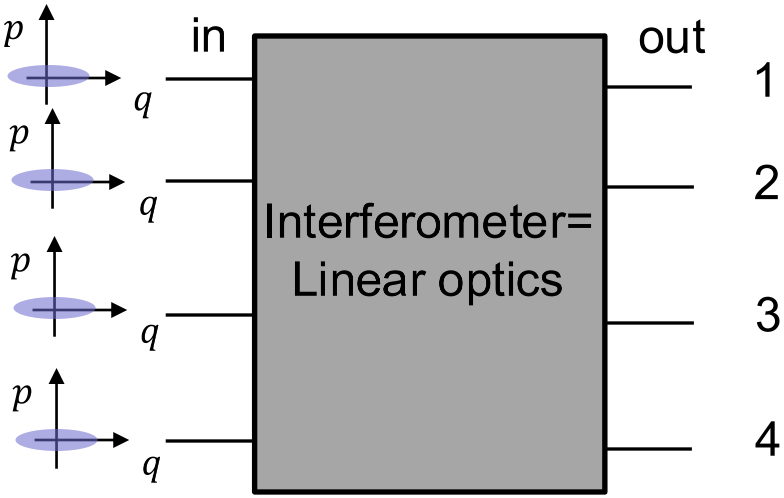
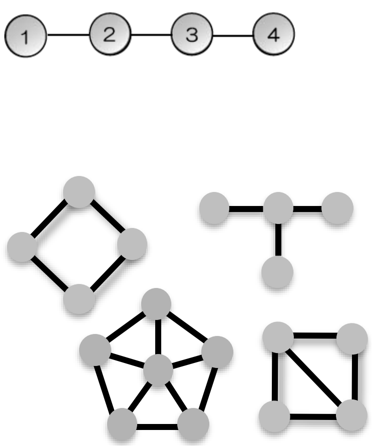
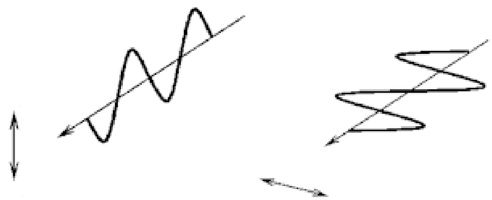




By controlling U_{lin}

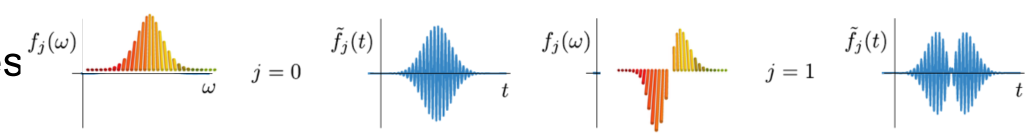
Light propagates

with different polarizations

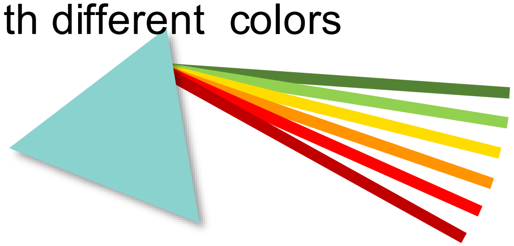


with different spatial shapes

with different spectral-temporal shapes



with different colors

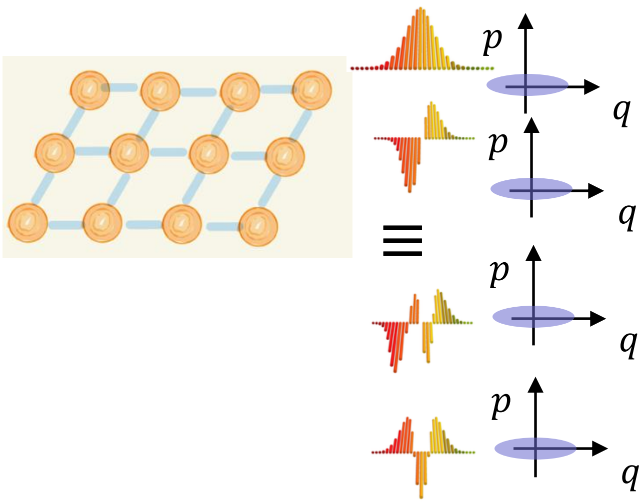


Our experimental approach
Spectro-temporal modes

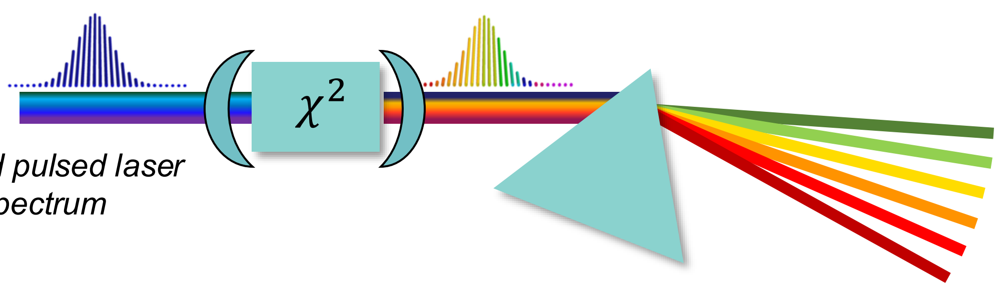
Bidimensional layer: optical spectra

LKB

CV Cluster states



Multi-color(mode) parametric process



femtosecond pulsed laser
large spectrum

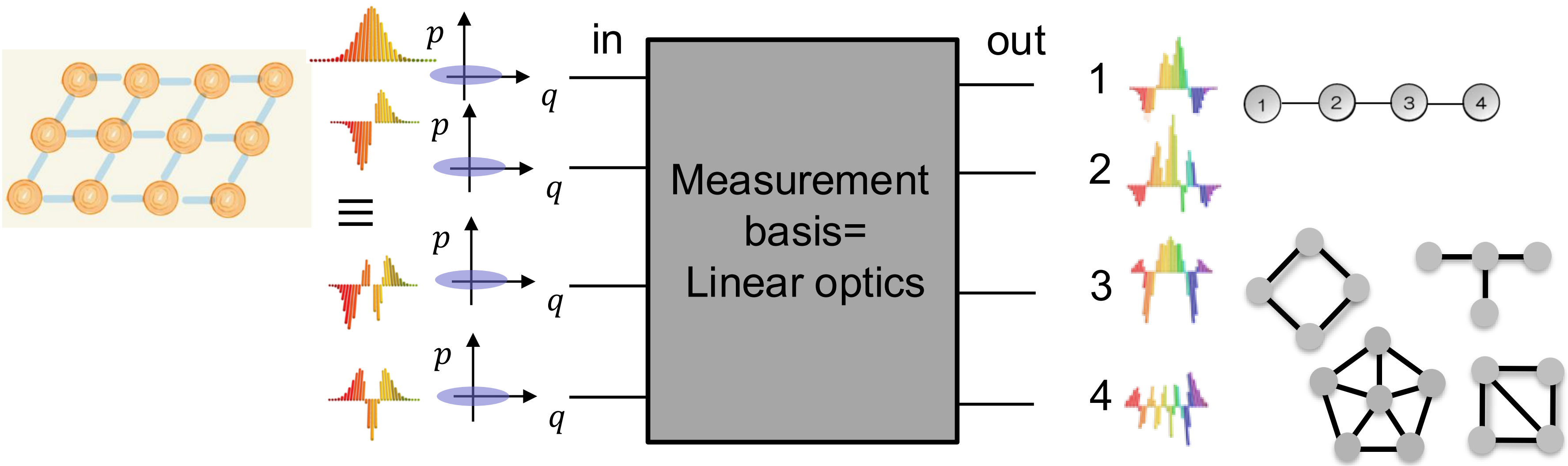
$$H = i\hbar \sum_{m,n} L_{-m,n}\, \hat{a}^{\dagger}_{-m}\, \hat{a}^{\dagger}_{n} \quad + h.c.$$

$$\hat{H}^{m}_{\text{int}} = \mathcal{K} \sum_{j} \lambda_j \left(\hat{s}^{\dagger}_{j}\right)^2 + h.c.$$

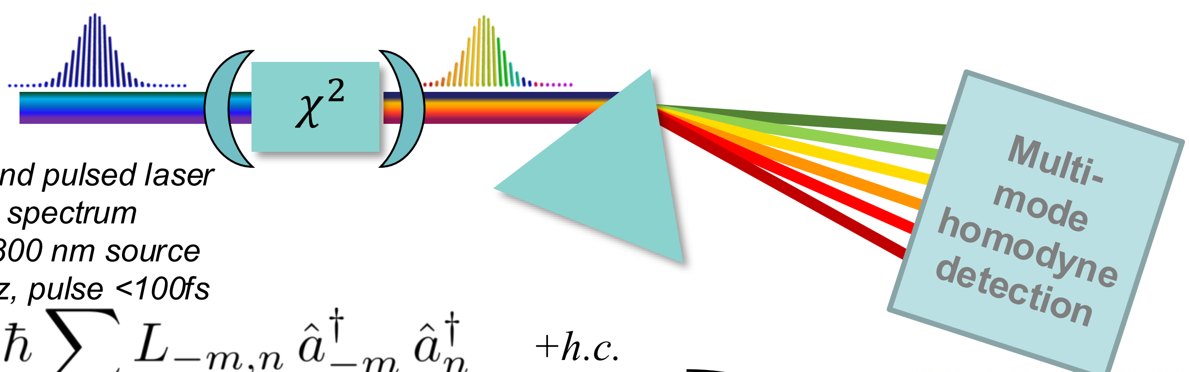
Bidimensional layer: optical spectra

Deterministic implementation

CV Cluster states



Multi-color(mode) parametric process



femtosecond pulsed laser
large spectrum
SHG of 800 nm source
RR 80MHz, pulse <100fs

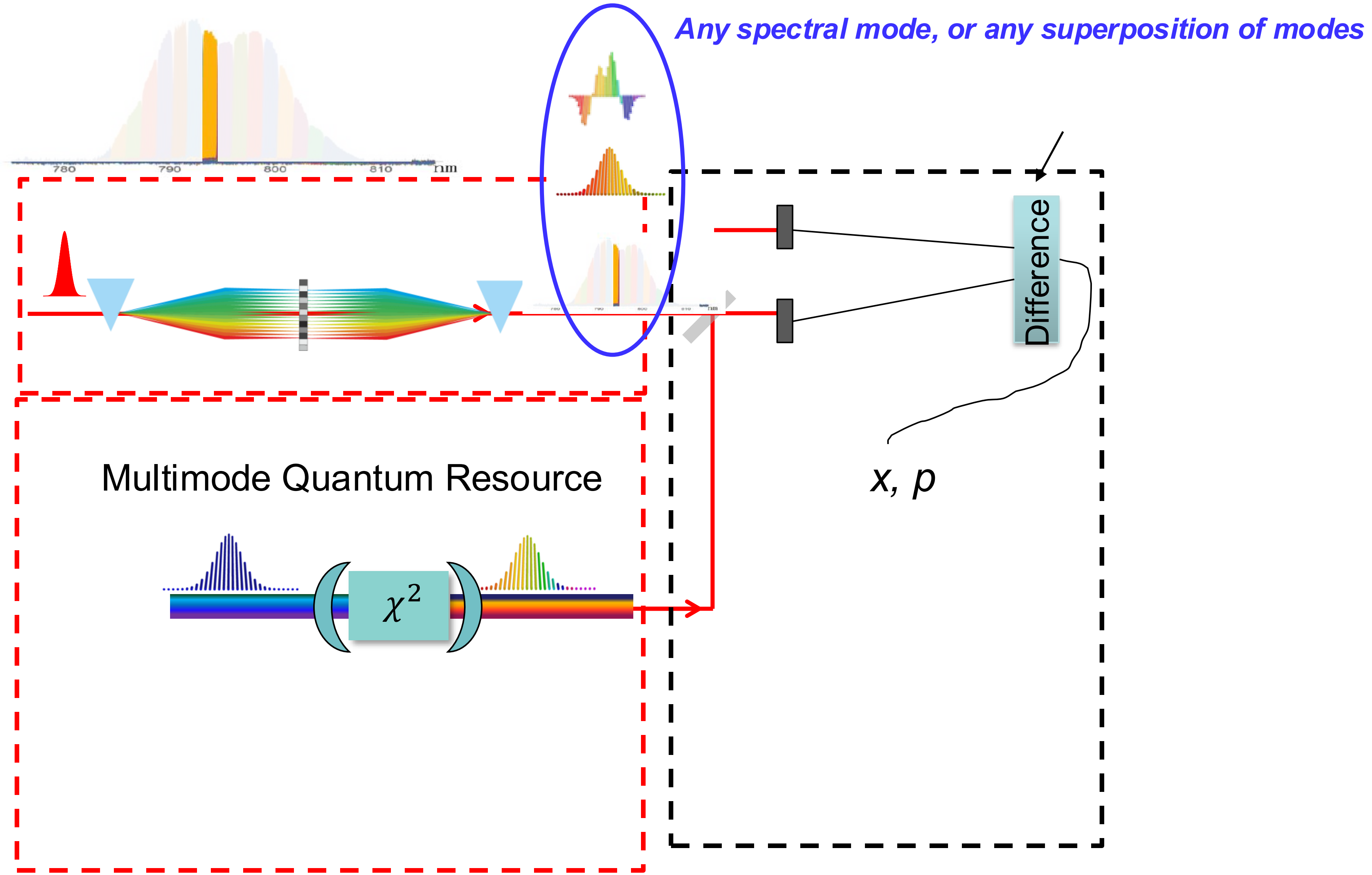
$$H = i\hbar \sum_{m,n} L_{-m,n}\, \hat{a}^{\dagger}_{-m}\, \hat{a}^{\dagger}_{n} \quad + h.c.$$

$$\hat{H}^{m}_{\mathrm{int}} = \mathcal{K} \sum_{j} \lambda_j \left(\hat{s}^{\dagger}_{j}\right)^2 + h.c.$$

N. Treps

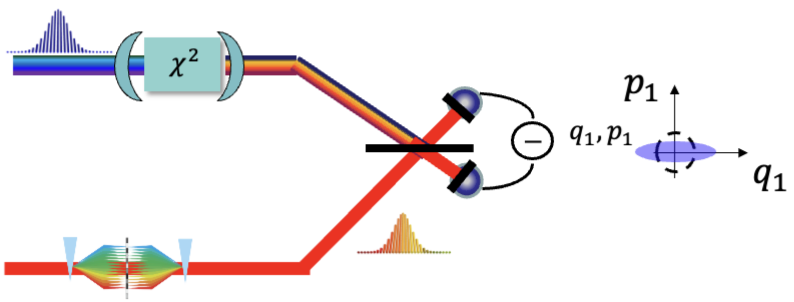
Homodyne: pulse shaping

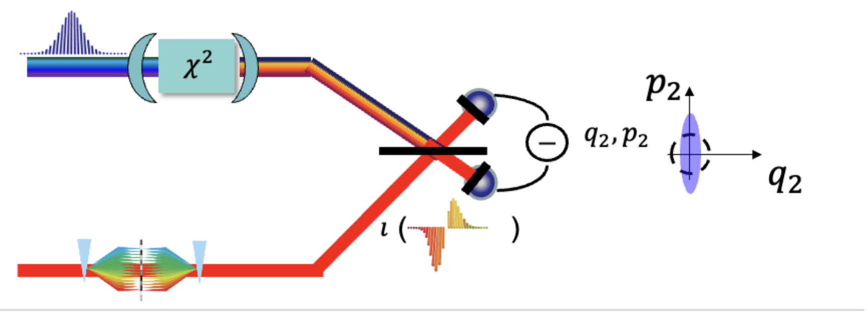
Mode-selective homodyne detection



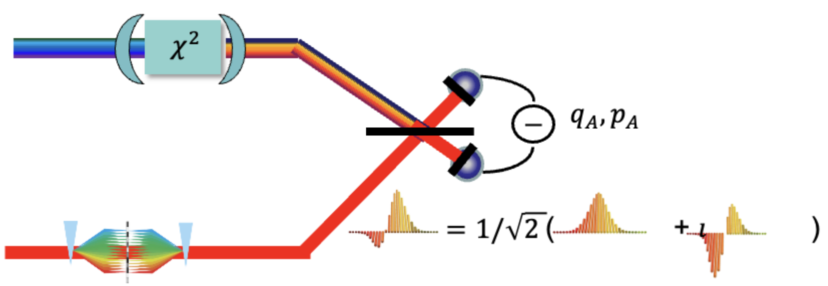
Homodyne: pulse shaping

Homodyne is mode-selective: the mode of the local oscillator select the measured mode





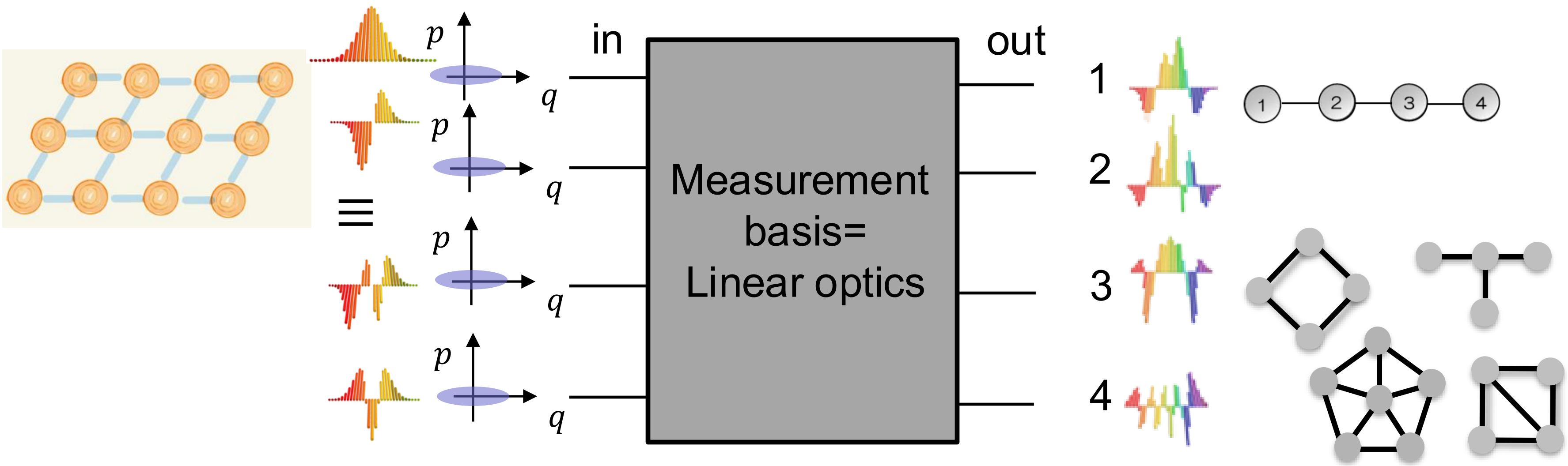
Any mode can be chosen, any mode superposition -> equivalent to basis change (i. e. interferometer)

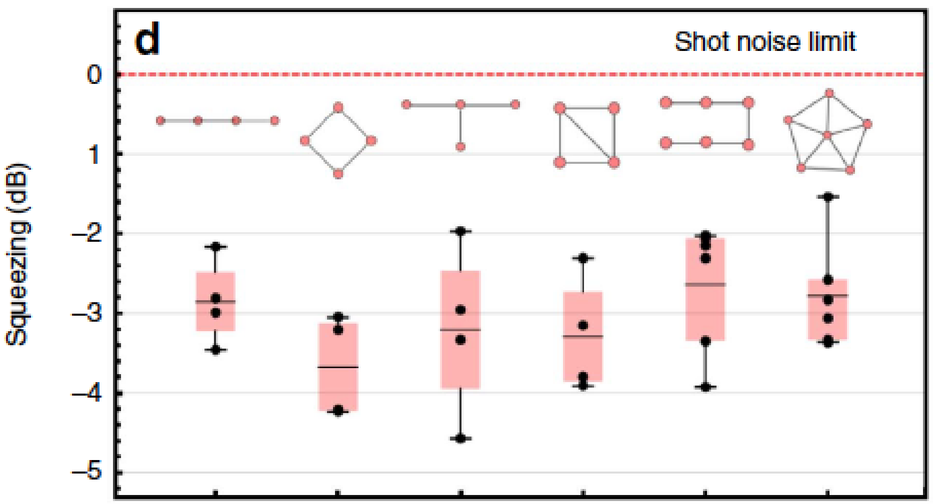


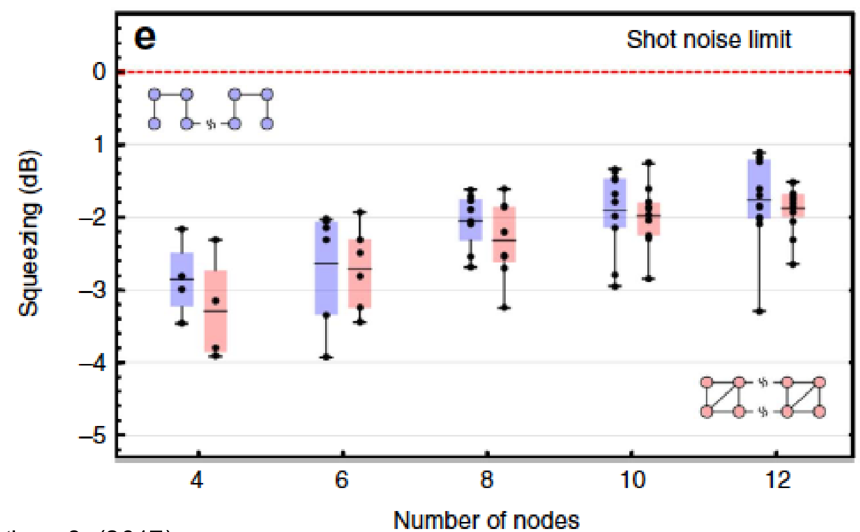
Bidimensional layer: optical spectra

Deterministic implementation

CV Cluster states

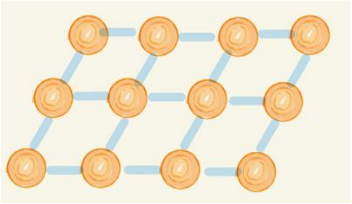


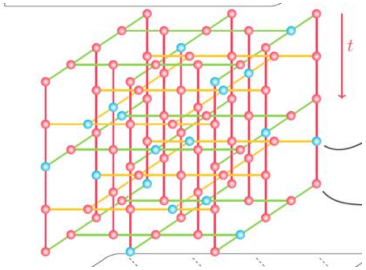




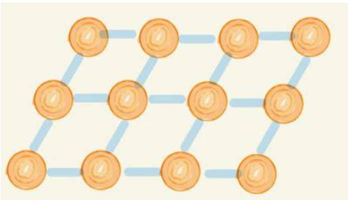
Y Cai, J Roslund, G Ferrini, F Arzani, X Xu, C Fabre, N Treps Nature Communications 8, (2017)

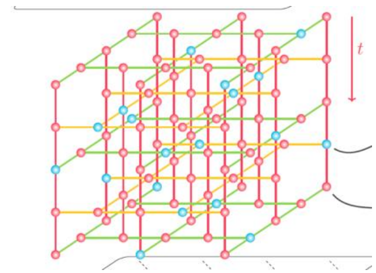
Towards 3D structures





Towards 3D structures

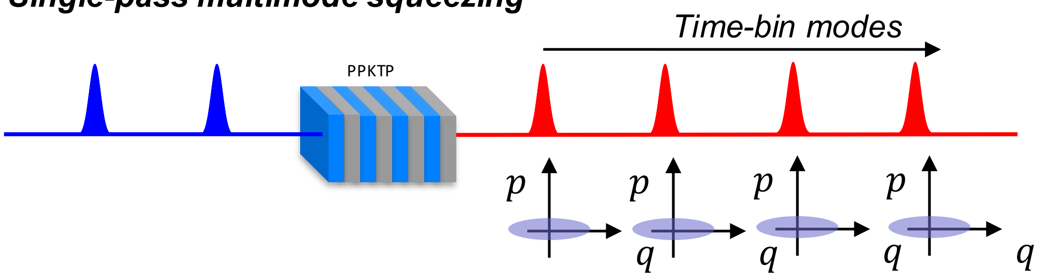




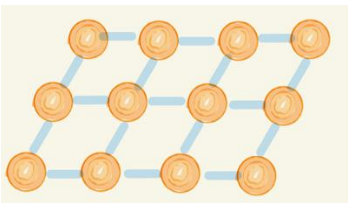
Building block

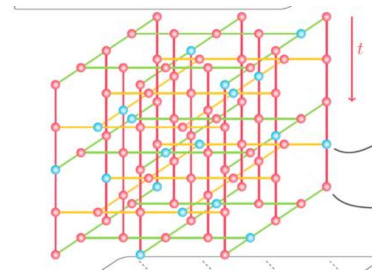
Large number of involved modes:
merging strategy based on optical spectral shape with the one based on time-bin (pulse based in our case)

Single-pass multimode squeezing



Towards 3D structures

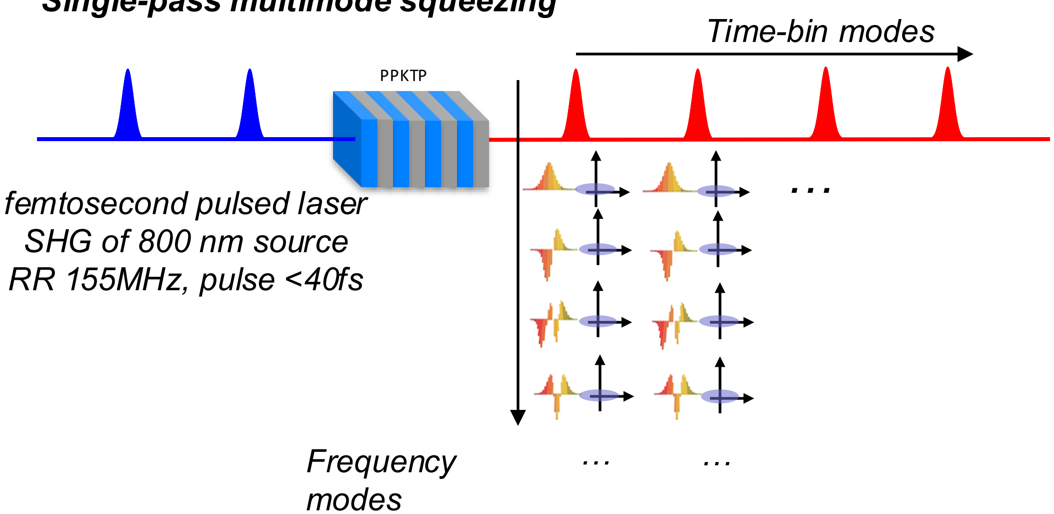


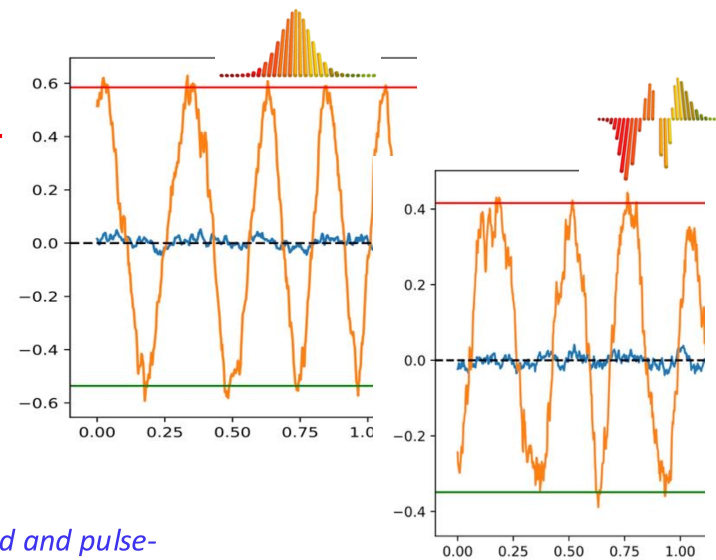


Building block

Large number of involved modes:
merging strategy based on optical spectral shape with the one based on time-bin (pulse based in our case)

Single-pass multimode squeezing

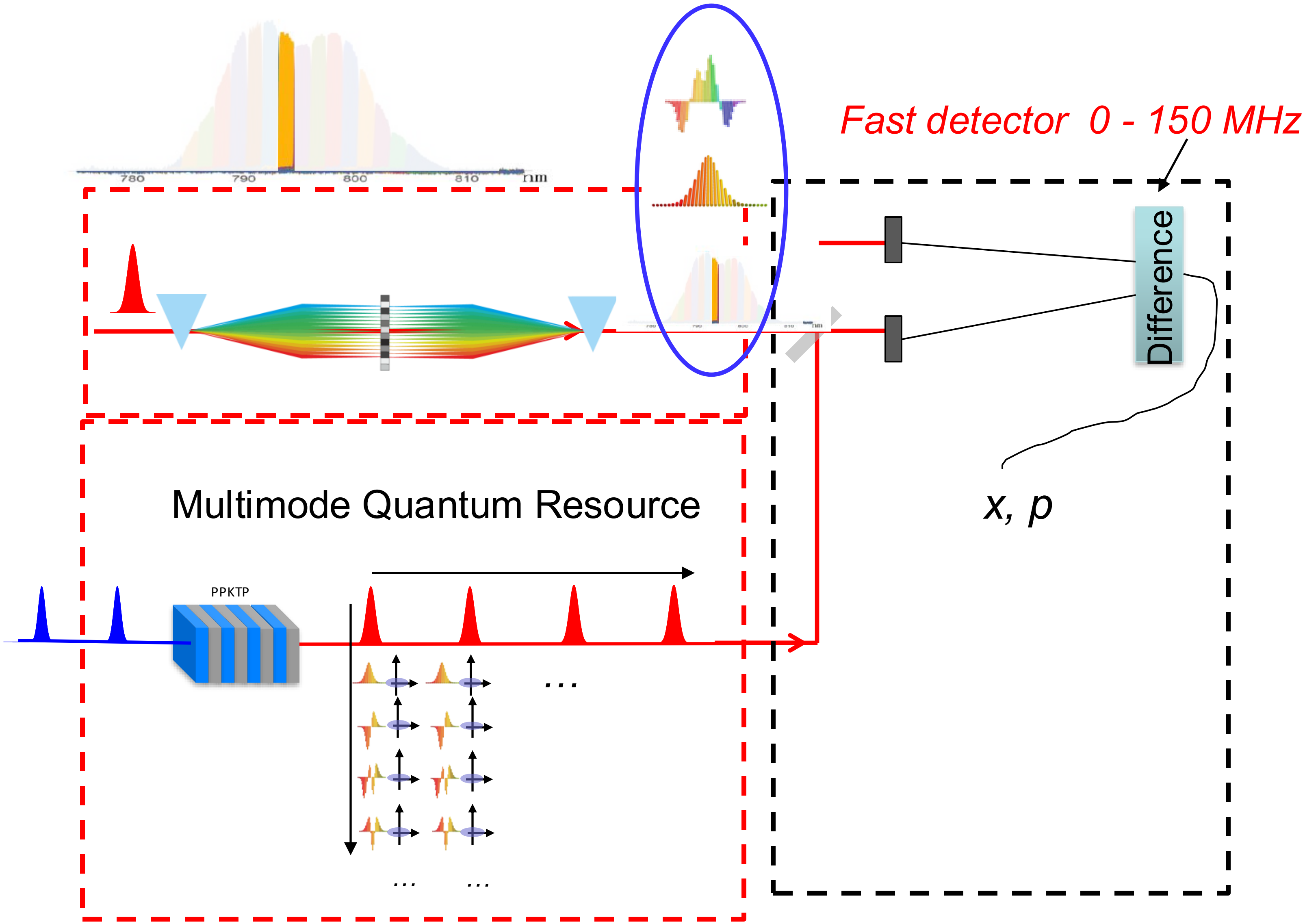




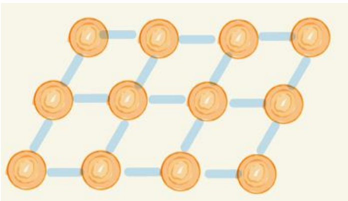
T. Kouadou, F. Sansavini, M. Ansquer, J. Henaff, N. Treps, V. Parigi, *Spectrally shaped and pulse-by pulse multiplexed multimode squeezed states of light*, APL Photonics 8, 086113 (2023)

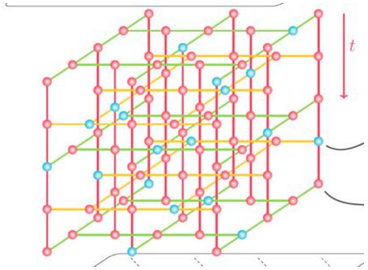
Homodyne: pulse shaping

<u>*Characterization : mode-selective and fast homodyne detection*</u>



Towards 3D structures



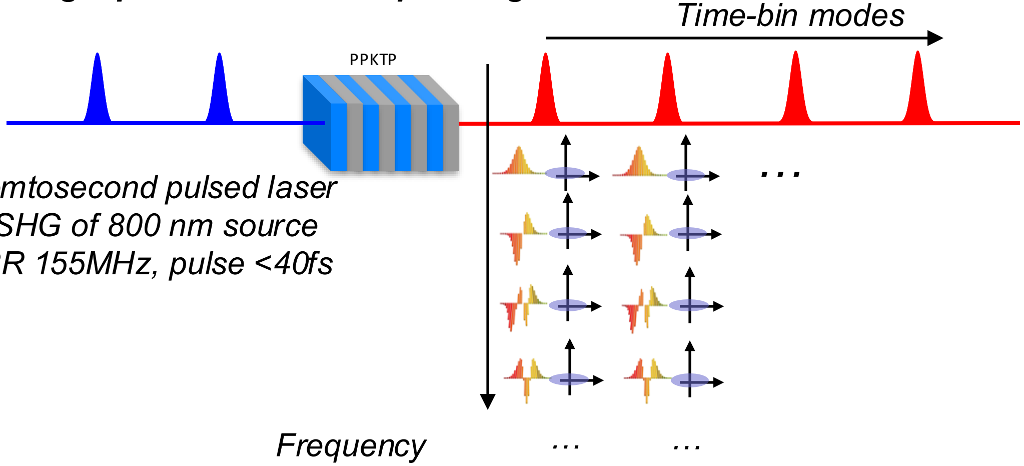


Building block

Simultaneous generation of 21 squeezed spectral modes at 156 MHz

Large number of involved modes:
merging strategy based on optical spectral shape with the one based on time-bin (pulse based in our case)

Single-pass multimode squeezing



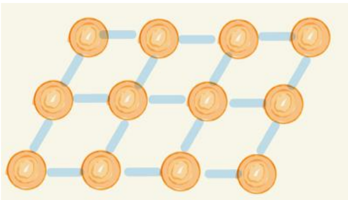
femtosecond pulsed laser
SHG of 800 nm source
RR 155MHz, pulse <40fs

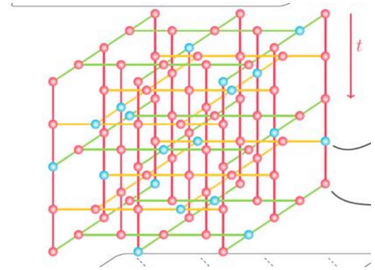
Frequency modes

Mode	Sqz (dB)	Asqz (dB)
HG0	-0.47	0.55
HG1	-0.33	0.42
HG2	-0.23	0.35
HG3	-0.20	0.28
HG4	-0.17	0.30
HG5	-0.18	0.30
…		
HG15	-0.09	0.17
HG20	-0.08	0.16

T. Kouadou, F. Sansavini, M. Ansquer, J. Henaff, N. Treps, V. Parigi, *Spectrally shaped and pulse-by pulse multiplexed multimode squeezed states of light*, APL Photonics 8, 086113 (2023)

Towards 3D structures



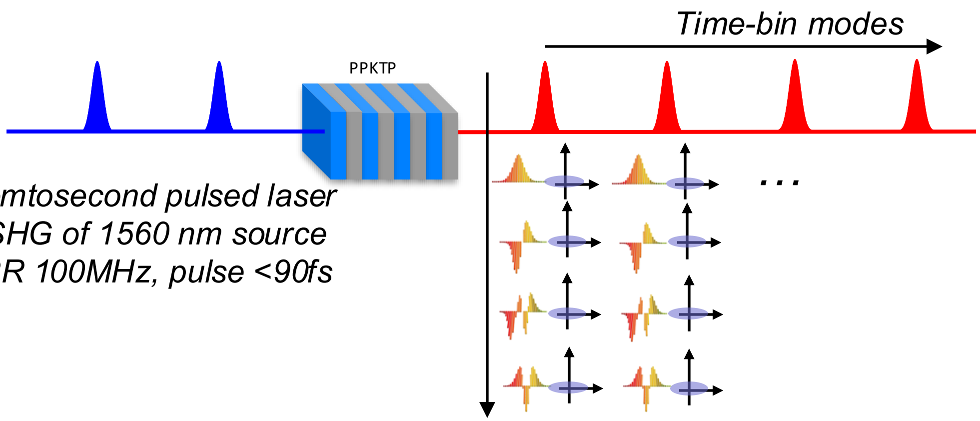


@telecom!

21 modes with more than 2.5 dB of squeezing

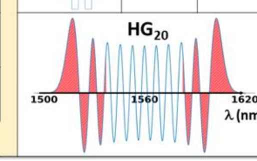
Building block

Large number of involved modes:
merging strategy based on optical spectral shape with the one based on time-bin



femtosecond pulsed laser
SHG of 1560 nm source
RR 100MHz, pulse <90fs

Hermite-Gauss	Sqz	ASqz		Sqz	ASqz	Flat modes	Sqz	ASqz
0	-1.03	1.39	6	-0.73	1.45	0	-2.66	6.99
1	-0.68	1.31	7	-0.74	1.27	1	-2.43	6.49
2	-0.62	1.16	8	-0.54	1.16	2	-2.32	6.83
3	-0.61	1.27	12	-0.55	1.15	3	-2.01	6.47
4	-0.57	1.41	15	-0.60	1.36			
5	-0.58	1.46	20	-0.53	0.85			



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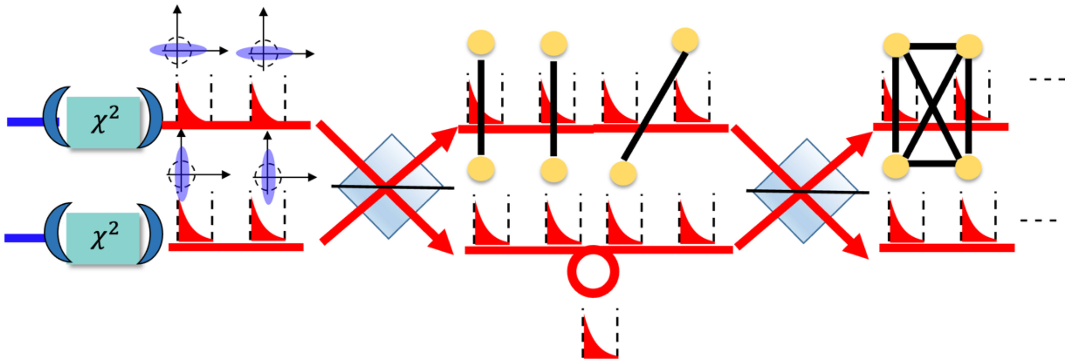
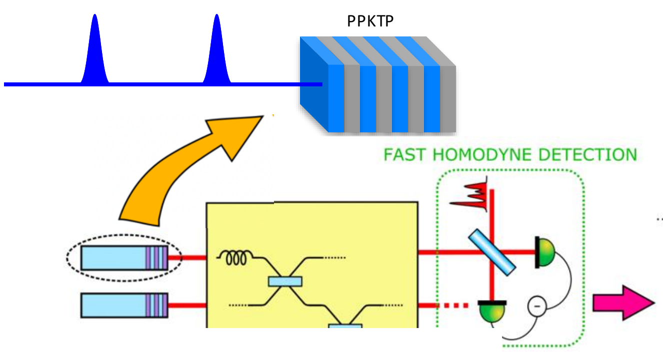
V. Roman-Rodriguez, B. Brecht, K. Srinivasan, C. Silberhorn, N. Treps, E. Diamanti, V. Parigi, *New J. Phys.* 23 043012 (2021)

V. Roman-Rodriguez, D. Fainsin, G. L. Zanin, N. Treps, E. Diamanti, and V. Parigi Physical Review Research 6, 043113 (2024)

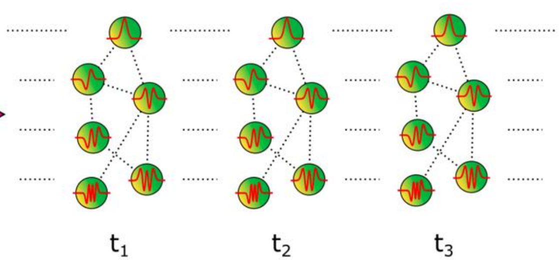
Towards 3D structures

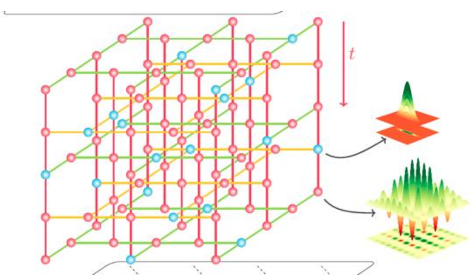


Building blocks + linear optics and delay lines



Three-dimensional structure!





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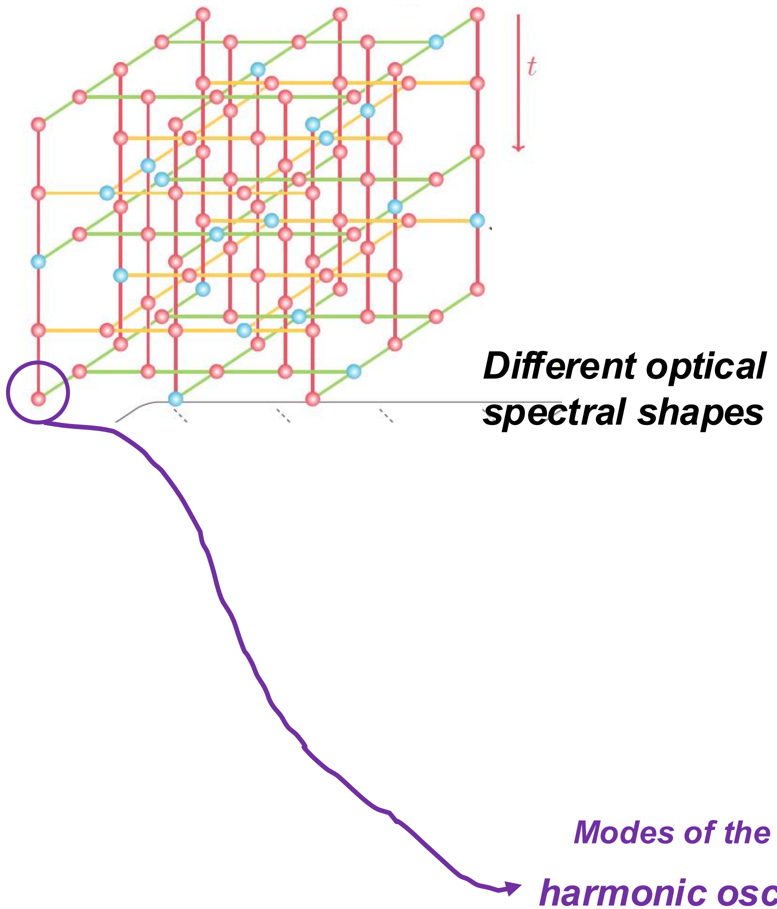
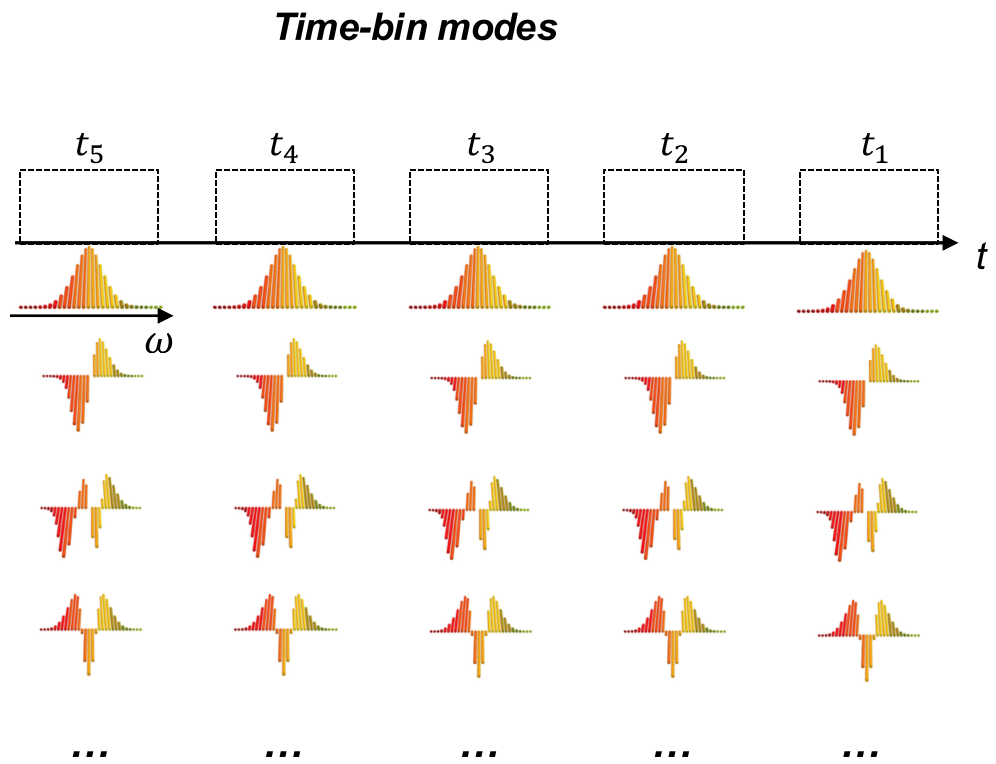
Spectral and time multiplexing

Our strategy

- *Deterministic room-temperature* generation of *large number* of Gaussian entangled states

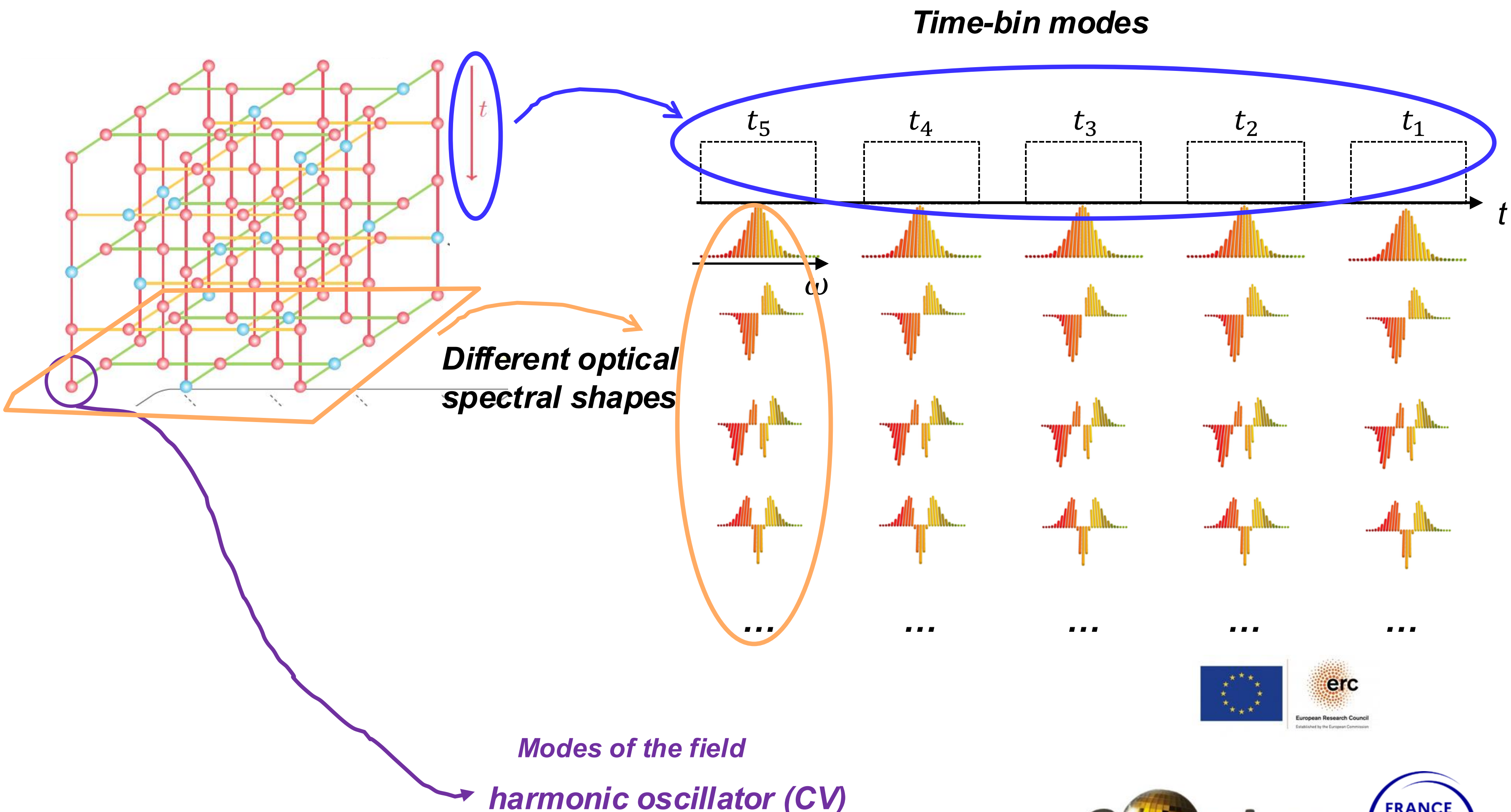




Spectral and time multiplexing

Our strategy

- *Deterministic room-temperature* *generation of large number of Gaussian entangled states*



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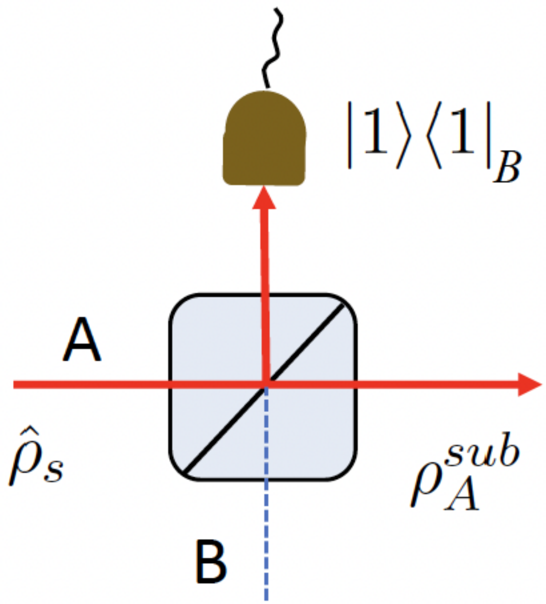
You need a BS

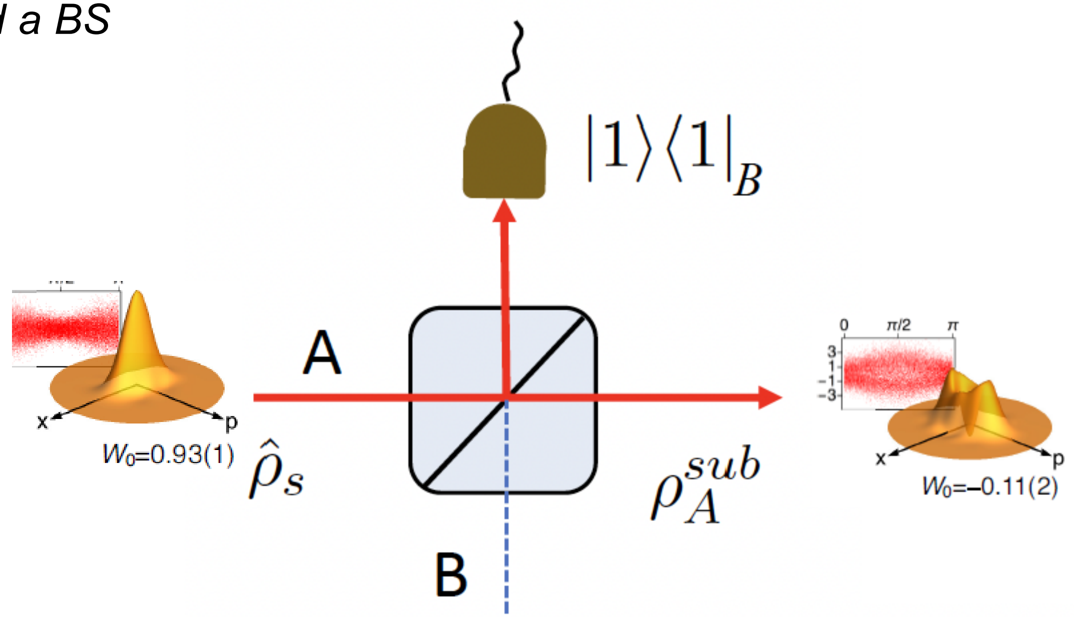


$$\rho_A^{sub} = \frac{\theta^2 \hat{a}\rho_A\hat{a}^\dagger}{Tr\{\theta^2\hat{a}\rho_A\hat{a}^\dagger\}} = \frac{\hat{a}\rho_A\hat{a}^\dagger}{Tr\{\hat{a}\rho_A\hat{a}^\dagger\}}$$

$$U(\theta) = Exp(\theta(\hat{b}^\dagger\hat{a} - \hat{b}\hat{a}^\dagger)) \approx \mathbb{1} + \theta(\hat{b}^\dagger\hat{a} - \hat{b}\hat{a}^\dagger)$$

Mode-selective single-photon subtraction

You need a BS

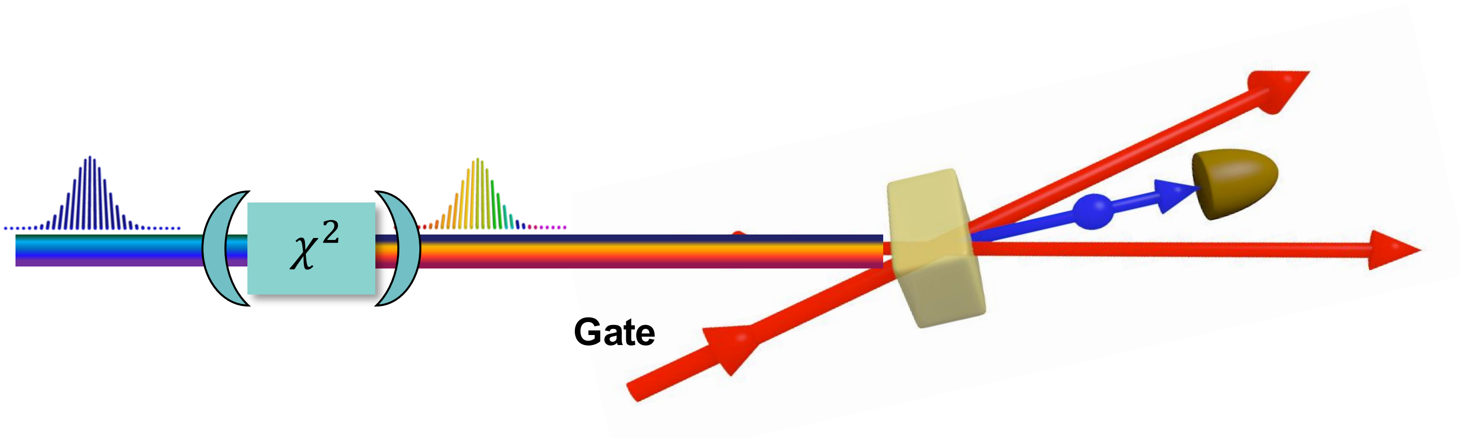


$$\rho_A^{sub} = \frac{\theta^2 \hat{a}\rho_A\hat{a}^\dagger}{Tr\{\theta^2\hat{a}\rho_A\hat{a}^\dagger\}} = \frac{\hat{a}\rho_A\hat{a}^\dagger}{Tr\{\hat{a}\rho_A\hat{a}^\dagger\}}$$

$$U(\theta) = Exp(\theta(\hat{b}^\dagger\hat{a} - \hat{b}\hat{a}^\dagger)) \approx \mathbb{1} + \theta(\hat{b}^\dagger\hat{a} - \hat{b}\hat{a}^\dagger)$$

Mode-selective single-photon subtraction

You need a mode-selective BS



Sum frequency generation

You want the gate shape to control the mode from which the photon is subtracted

$$\hat{H} = \int\int d\omega_s d\omega_{\rm up} T(\omega_s, \omega_{\rm up}) \hat{a}(\omega_s) \hat{c}^\dagger(\omega_{\rm up}) + \text{h.c.},$$

Gate

Transfer function

$$T(\omega_s, \omega_{\rm up}) = \alpha_g(\omega_{\rm up} - \omega_s)\phi(\omega_s, \omega_{\rm up}) = \sum_l \sqrt{\lambda_l} m_l(\omega_s) n_l(\omega_{\rm up})$$

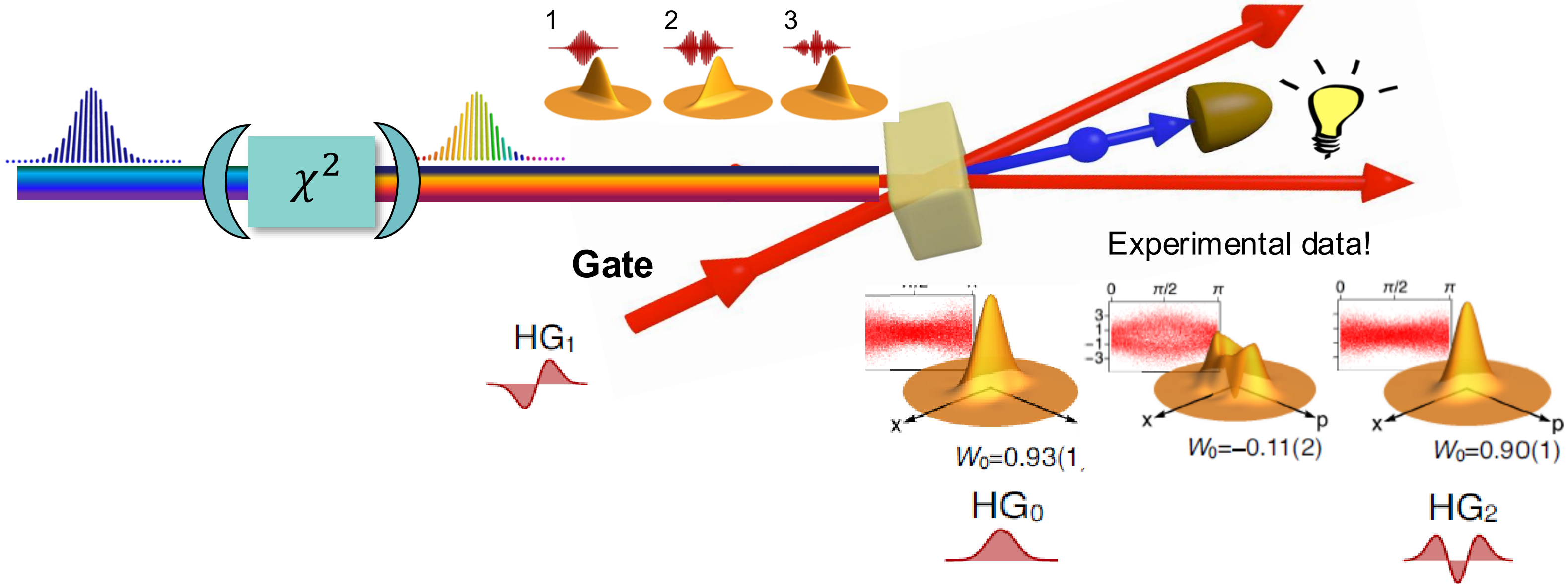
$$K = \frac{\left(\sum_n \lambda_n\right)^2}{\sum_n \lambda_n^2}$$

To get a pure state the process should be single-mode in the sense of Schmidt decomposition

Y.-S. Ra, et al. Nature Physics 16, 144 (2020).

Mode-selective single-photon subtraction

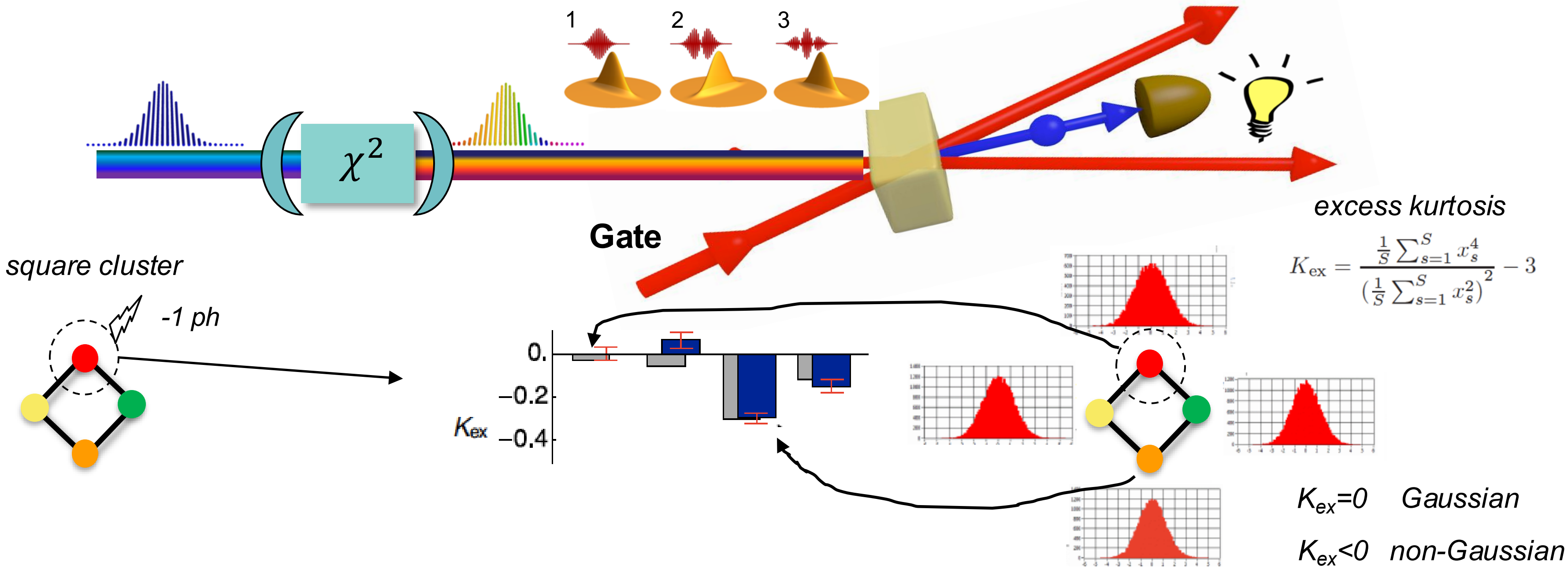
You need a mode-selective BS



Y.-S. Ra, et al. Nature Physics 16, 144 (2020);

Mode-selective single-photon subtraction

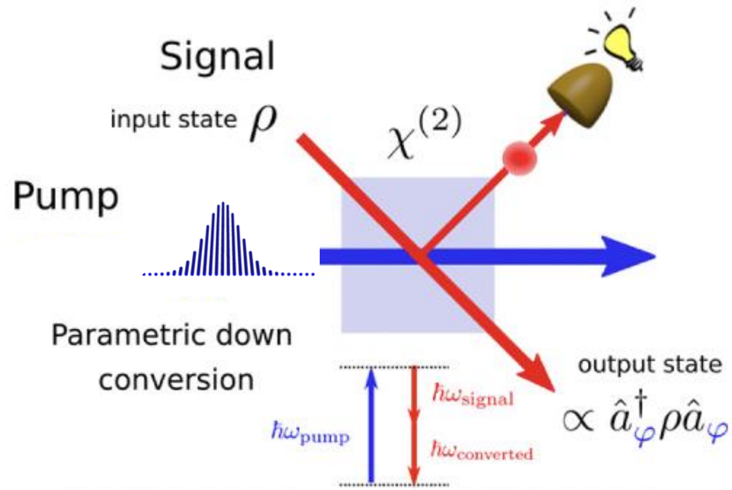
You need a mode-selective BS



Y.-S. Ra, et al. Nature Physics 16, 144 (2020);

Mode-selective single-photon addition

You need a parametric process



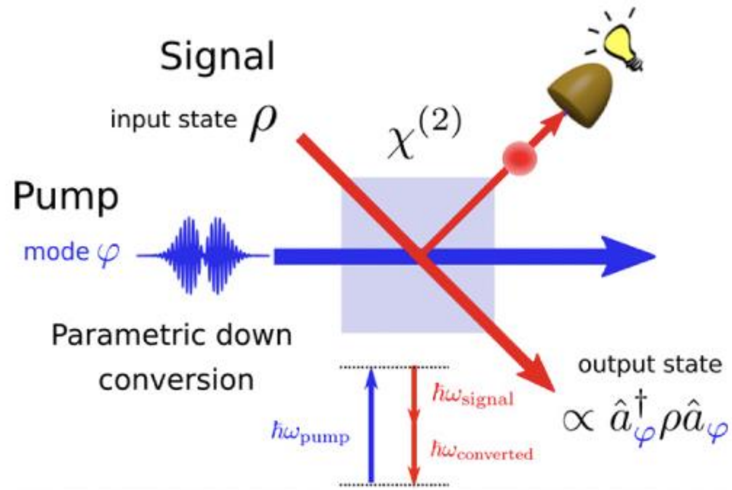
$$\rho_s^{add} = \frac{\lambda^2 \hat{a}^\dagger \rho_s \hat{a}}{Tr\{\lambda^2 \hat{a}^\dagger \rho_s \hat{a}\}} = \frac{\hat{a}^\dagger \rho_s \hat{a}}{Tr\{\hat{a}^\dagger \rho_s \hat{a}\}}$$

$$U(t) = Exp(-\frac{\imath H t}{\hbar}) \approx \mathbb{1} - \lambda(\hat{a}_s \hat{a}_i - \hat{a}_s^\dagger \hat{a}_i^\dagger)$$

G. Roeland et al New J. Phys. *24 043031 (2022), P Namdar et al, in preparation*

Mode-selective single-photon addition

You need a mode selective parametric process



You want the pump shape to control the mode to which the photon is added

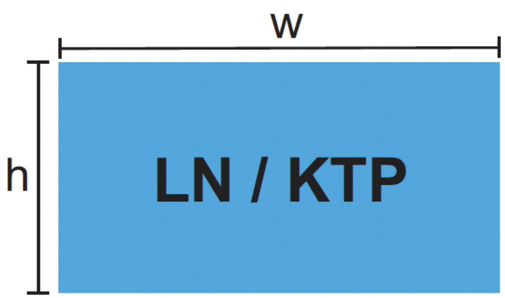
$$\hat{H} = \int\int d\omega_s d\omega_i \, J(\omega_s, \omega_i)\hat{a}^\dagger(\omega_s)\hat{b}^\dagger(\omega_i) + \text{h.c.}$$

$$J(\omega_s, \omega_i) = \alpha(\omega_s + \omega_i)\phi(\omega_s, \omega_i) = \sum_l \sqrt{\lambda_l} h_l(\omega_s) g_l(\omega_i)$$

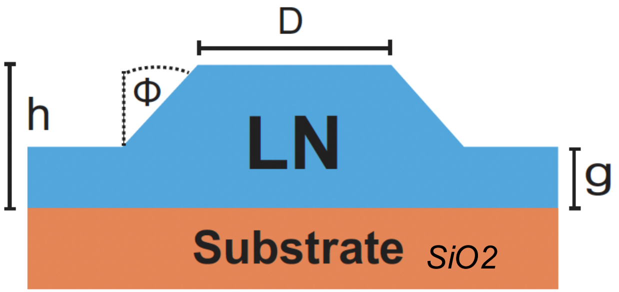
To get a pure state the process should be single-mode in the sense of Schmidt decomposition

Reverse engineering in wave-guides

Task: get the operations at telecom wavelength via diffusive or thin film waveguides



(a) Metallic waveguide geometry



(b) Thin-film waveguide geometry

1. *Precise modelling of the process*
2. *Run Evolutionary algorithm to get waveguide parameters. Fitness function= get K as close to 1 as possible !*

Peter Namdar, Sorbonne University

Patrick F. Folge, Paderborn Uiversity

P Namdar et al, in preparation

Reverse engineering in wave-guides

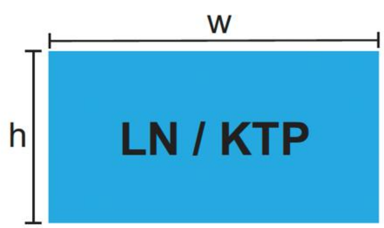
Task: get the operations at telecom wavelength via diffusive or thin film waveguides

Results

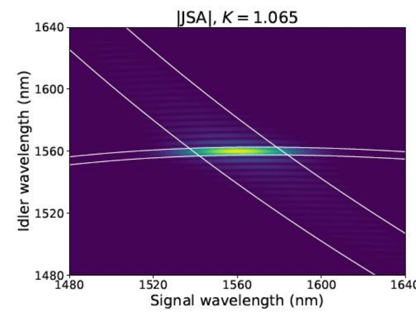
Single-Photon Addition

11

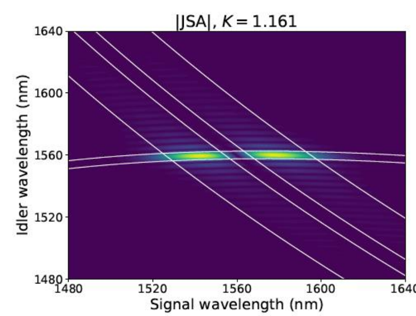
Parameter	Value
Length	7 mm
Width	2.8 μm
Height	2.3 μm
Crystal type	pp:KTP
Pump width	7.5 nm
Pump mode	HG 0/1/2
Type	II



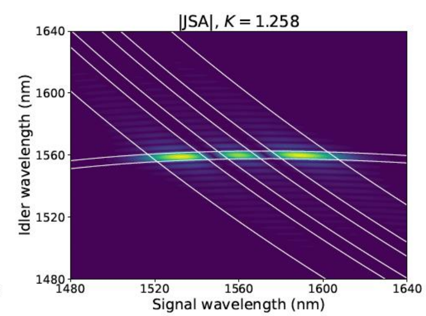
(a) Metallic waveguide geometry



(a) Pump mode: HG0



(b) Pump mode: HG1



(c) Pump mode: HG2

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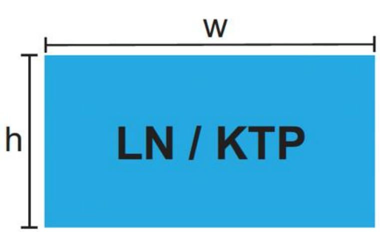
Reverse engineering in wave-guides

Task: get the operations at telecom wavelength via diffusive or thin film waveguides

Results

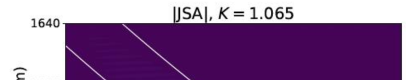
Single-Photon Addition

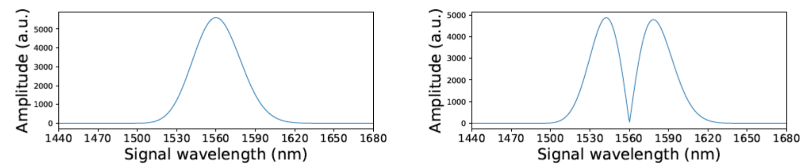
Parameter	Value
Length	7 mm
Width	2.8 μm
Height	2.3 μm
Crystal type	pp:KTP
Pump width	7.5 nm
Pump mode	HG 0/1/2
Type	II



(a) Metallic waveguide geometry

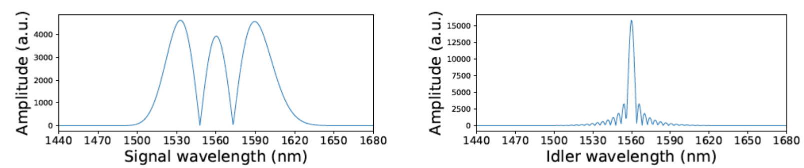
11





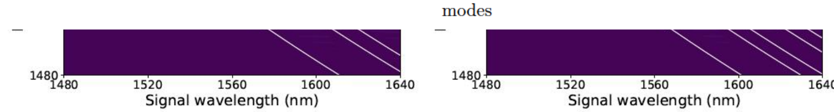
(a) Obtained signal mode with pump: HG0

(b) Obtained signal mode with pump: HG1



(c) Obtained signal mode with pump: HG2

(d) Obtained idler mode. Obtained with HG0-mode as pump. Representative for all pump-modes



(b) Pump mode: HG1

(c) Pump mode: HG2

P Namdar et al, in preparation

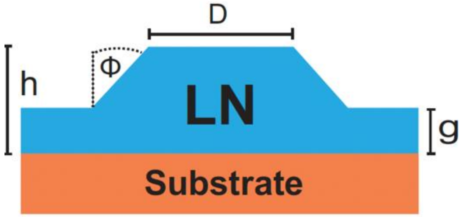
Reverse engineering in wave-guides

Task: get the operations at telecom wavelength via diffusive or thin film waveguides

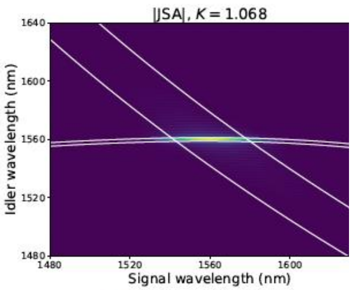
Results

Single-Photon Addition

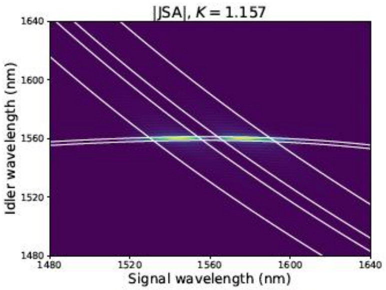
Parameter	Value
Length	7 mm
Width / D	1274 nm
Height / h	570 nm
Etching angle / ϕ	53.6°
Layer width / h - g	600 nm
Material	LN
Pump mode	HG 0/1/2
Type	II



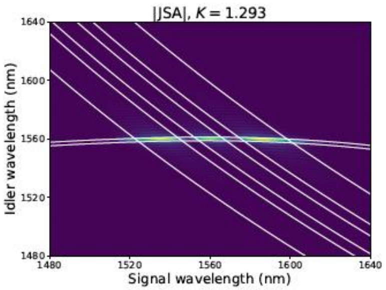
(b) Thin-film waveguide geometry



(a) Pump mode: HG0



(b) Pump mode: HG1



(c) Pump mode: HG2

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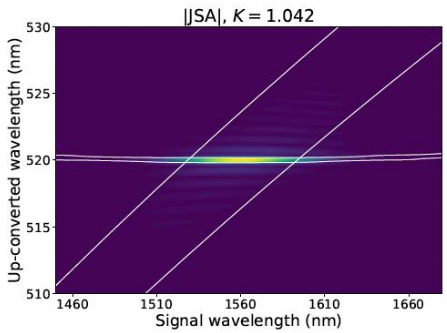
Reverse engineering in wave-guides

Task: get the operations at telecom wavelength via diffusive or thin film waveguides

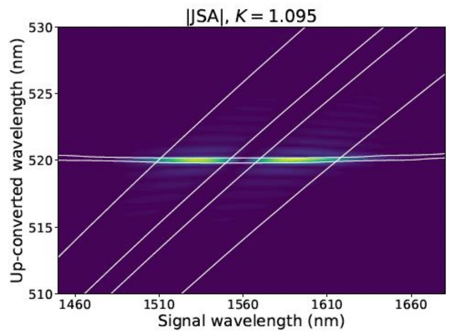
Results

Single-Photon Subtraction

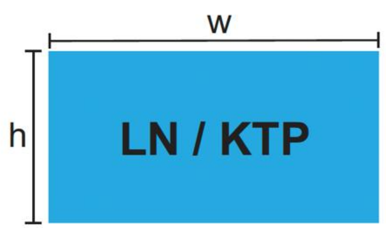
Parameter	Value
Length	2.0 mm
Width	2.5 μm
Height	1.8 μm
Material	KTP
Pump width	11.5 nm
Pump mode	HG 0/1/2
Type	0



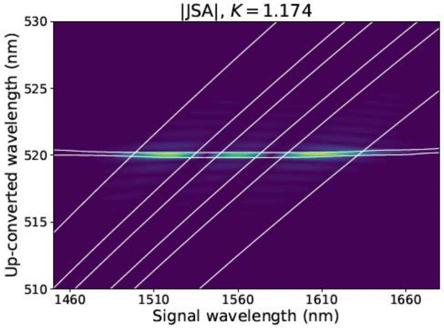
(a) Pump mode: HG0



(b) Pump mode: HG1



(a) Metallic waveguide geometry



(c) Pump mode: HG2

P Namdar et al, in preparation

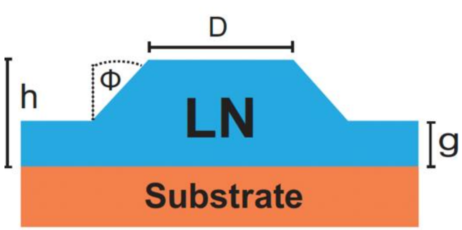
Reverse engineering in wave-guides

Task: get the operations at telecom wavelength via diffusive or thin film waveguides

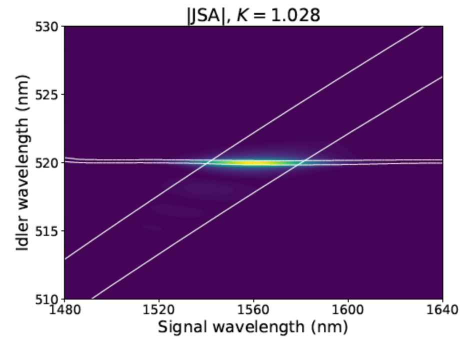
Results

Single-Photon Subtraction

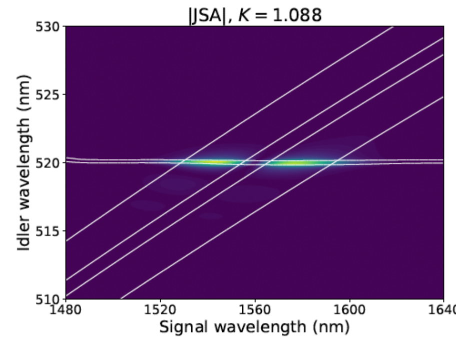
Parameter	Value
Length	7 mm
Width / D	883 nm
Height / h	774 nm
Etching angle / ϕ	75.2°
Layer width / h - g	788 nm
Material	LN
Pump width	7 mm
Pump mode	HG 0/1/2
Type	II



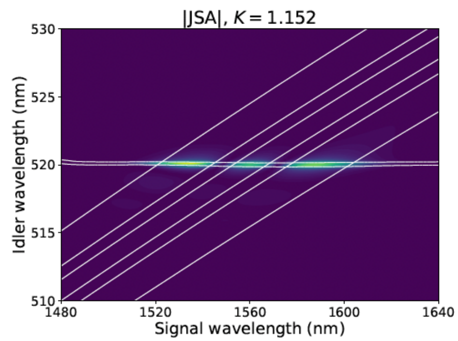
(b) Thin-film waveguide geometry



(a) Pump mode: HG0



(b) Pump mode: HG1



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Thank you!

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M. C Soriano,
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S. Maniscalco
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J. Piilo

F. Grosshans
F. Centrone
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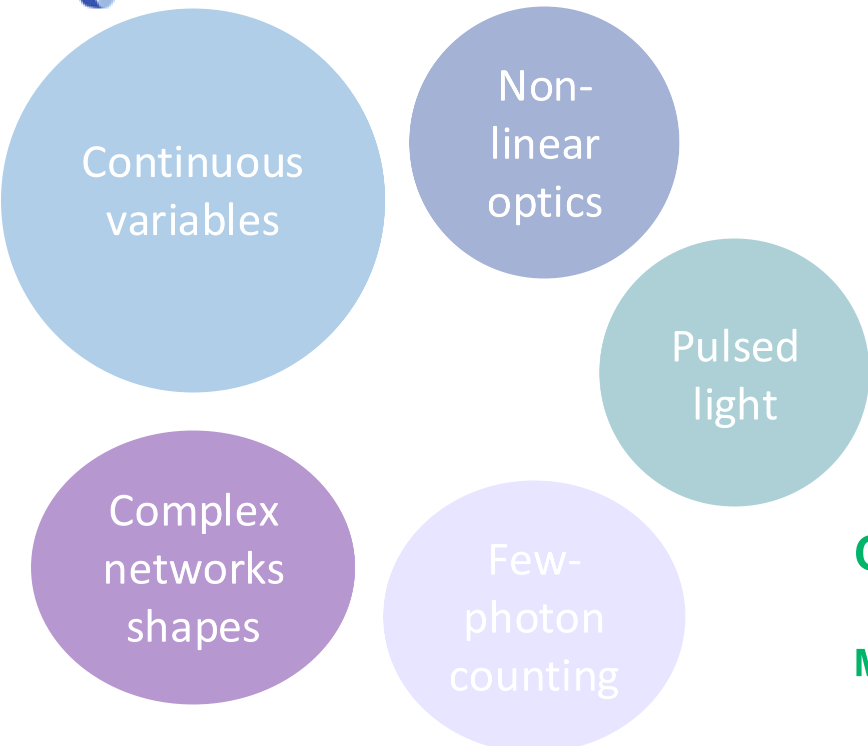
C. Silberhorn
B. Brecht
P. F. Folge

LKB

INTRO - *We play with - What for*



Photonic quantum computing

Continuous Variable cluster states for measurement-based protocols

Reservoir Computing,
Variational Quantum algorithms

CV quantum communication networks

Multiparty quantum protocols and routing

Simulating and probing complex quantum structure

Simulating quantum environment
Probing non-Gaussian features

Thank you!