Laboratoire Kastler Brossel
Physique quantique et applications

Measurement Based Quantum Information with Optical Frequency Combs

Francesco Arzani

My mission

Devising quantum information processing tasks to perform with available experimental resources, or minimal modifications thereof.

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« Resourceful and possessing an encyclopedic knowledge of the physical sciences, he solves complex problems by making things out of ordinary objects, along with his ever-present Swiss Army knife. »

See "MacGyver", Wikipedia

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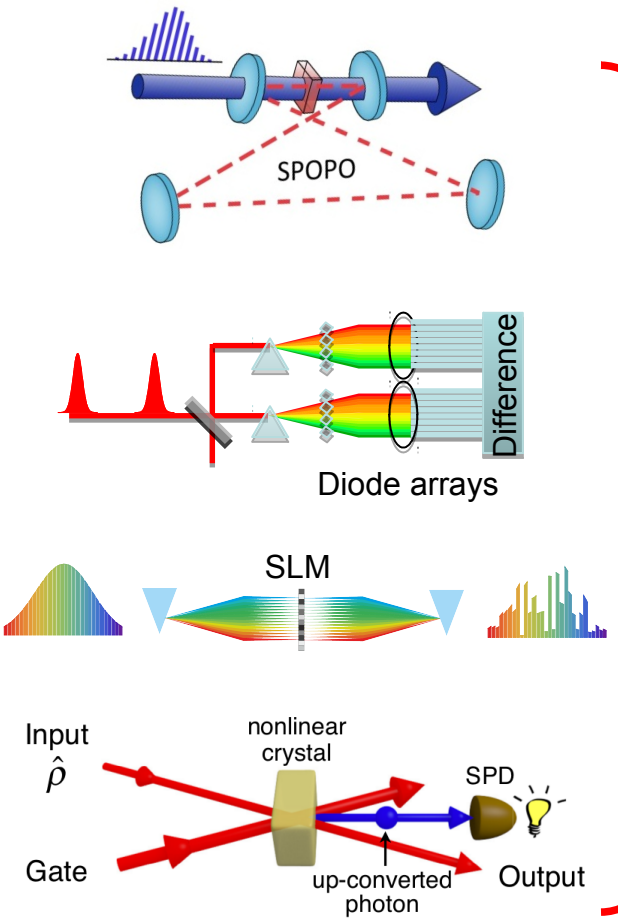

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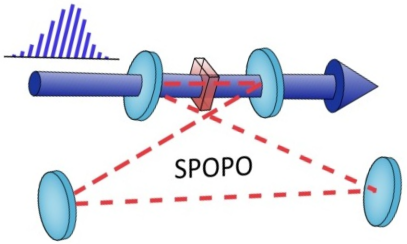
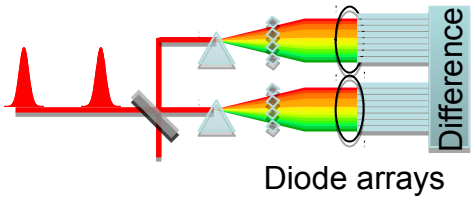
Outline

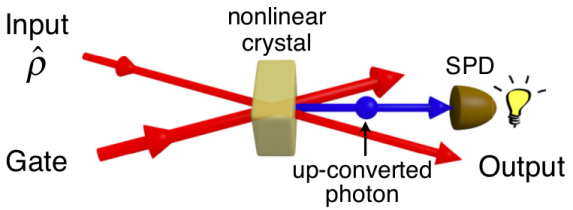


- Squeeze many modes



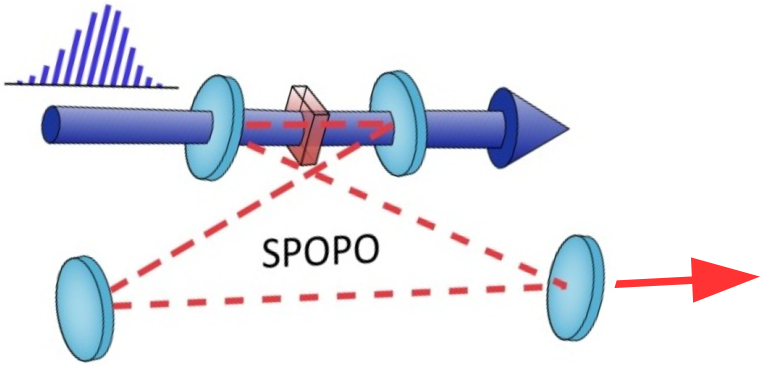
- Multi pixel homodyne detection

- Shape the pump for better clusters



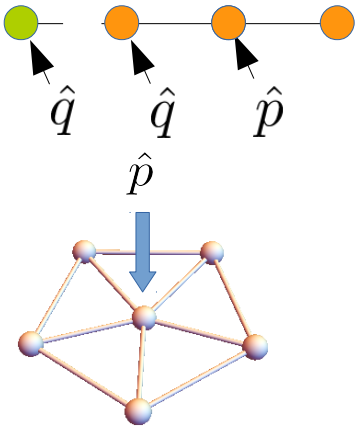
- Introduce non-Gaussianity: subtract photons

Motivation: CV cluster states



Multi-mode squeezed vacuum

- CV One way QC



- CV Secret Sharing

G. Patera et al, EPJD 56, 123-140 (2010)

P. Van Loock, D. Markham, AIP Conf. Proc. 1363, 256, (2011)

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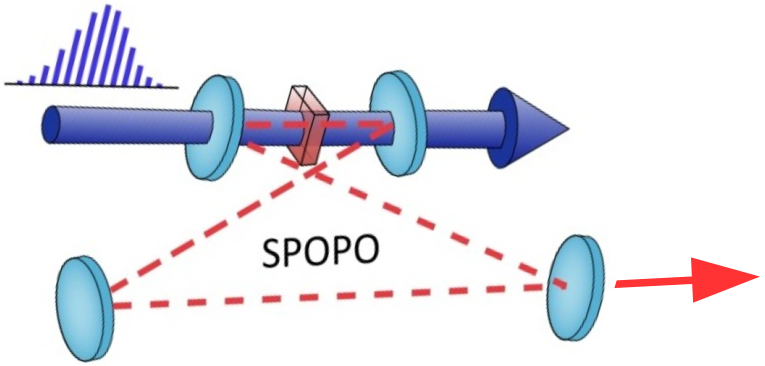

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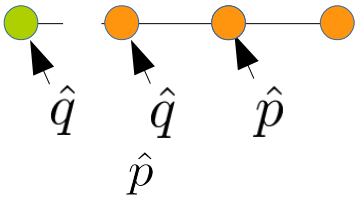

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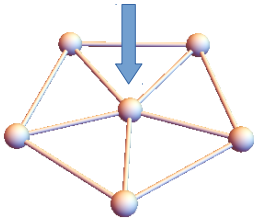

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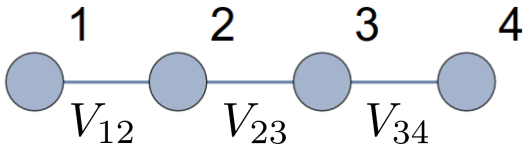

$$\begin{aligned}\hat{\delta}_1 &= \hat{p}_1 - \hat{q}_2 \\ \hat{\delta}_2 &= \hat{p}_2 - \hat{q}_1 - \hat{q}_3 \\ \hat{\delta}_3 &= \hat{p}_3 - \hat{q}_2 - \hat{q}_4 \\ \hat{\delta}_4 &= \hat{p}_4 - \hat{q}_3\end{aligned}$$

$$\exp\left(i\sum_{i>j} V_{ij}\hat{q}_i \otimes \hat{q}_j\right)|0\rangle_p^{\otimes N}$$

- Can be represented as graphs
- Characterized by **nullifier operators**
- Approximated by Gaussian states

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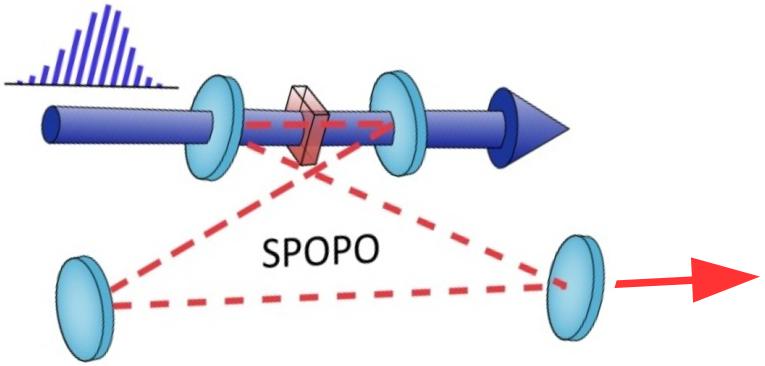

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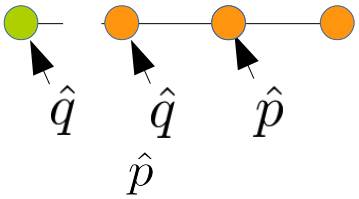

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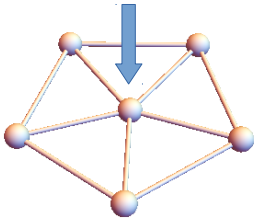

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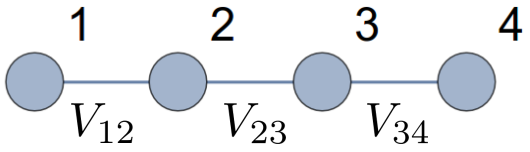

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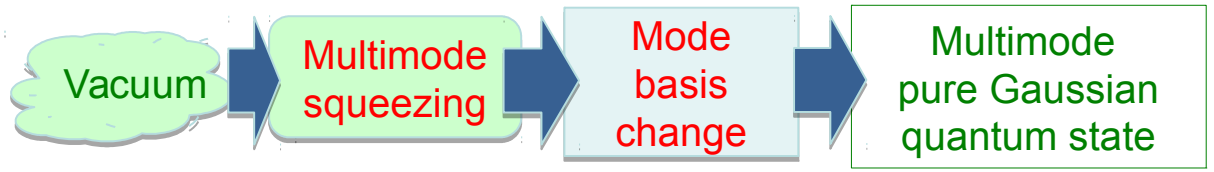
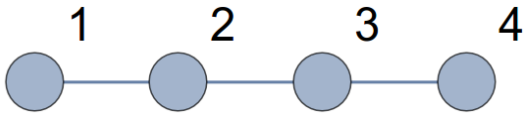


S. Braunstein, PRA 71, 055801 (2005)

CV Cluster States



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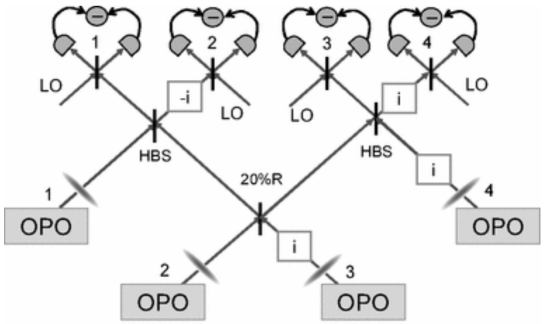
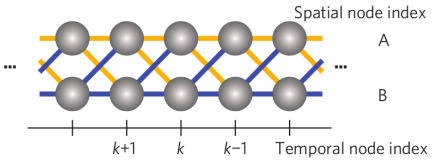
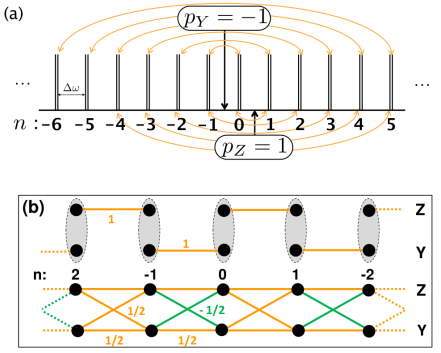


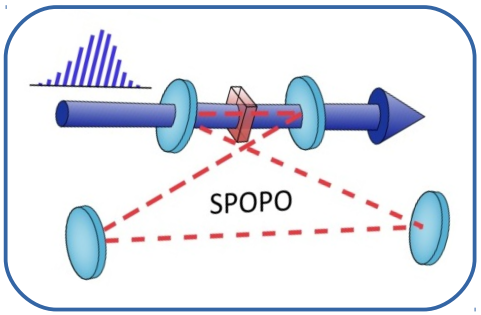
X. Su et al, PRL 98, 070502 (2007)



S. Yokoyama et al, Nat. Photon. 7, 982–986 (2013)



M. Chen et al, PRL 112, 120505 (2014)



G. Patera et al, EPJD 56, 123-140 (2010)

What exactly is a mode?

A normalized solution $f_i(\mathbf{r},t)$ of Maxwell's equations

MODE BASIS

$$\int f_n(\vec{r},t)\cdot f_m^*(\vec{r},t)d^3rdt = \delta_n^m$$

QUANTUM HILBERT SPACE(S)

$$L^2(\mathbb{R},\mathbb{C})\otimes L^2(\mathbb{R},\mathbb{C})\otimes ...$$

$$|\Psi\rangle = \sum_{n1,n2,...} A_{n1n2...}\,|n1:f_1\rangle\otimes|n2:f_2\rangle\otimes...$$

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$$\hat{E}^+(\vec{r},t)=E_0\sum_n\hat{a}_n f_n(\vec{r},t)=E_0\sum_k\hat{b}_k g_k(\vec{r},t)$$

Change of modes ⟷ **Linear optics**

$$g_k(\vec{r},t)=\sum_m U_{km}f_m(\vec{r},t)$$

$$\hat{b}_k=\sum_m\left(U^\dagger\right)_{km}\hat{a}_m$$

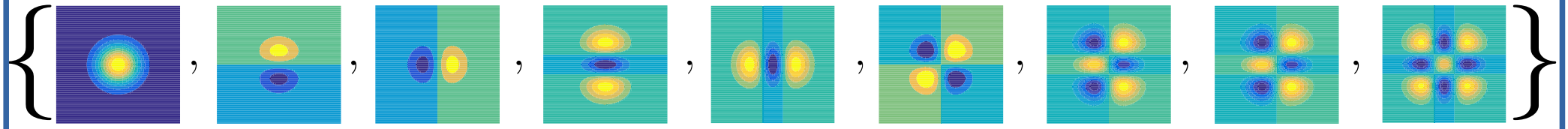
$$|\Psi\rangle=\sum_{n1,n2,\ldots}A_{n1n2\ldots}|n1:f_1\rangle\otimes|n2:f_2\rangle\otimes\ldots$$

What exactly is a mode?

Polarization modes

$\{V, H\}$ or $\{+, -\}$ or $\{\mathcal{R}, \mathcal{L}\}$

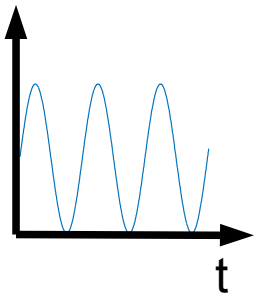
Spatial modes, TEMs



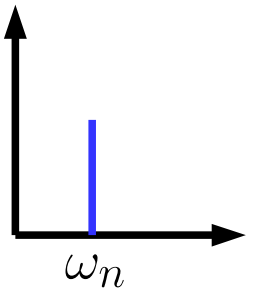
Temporal modes

The ones I will talk about !

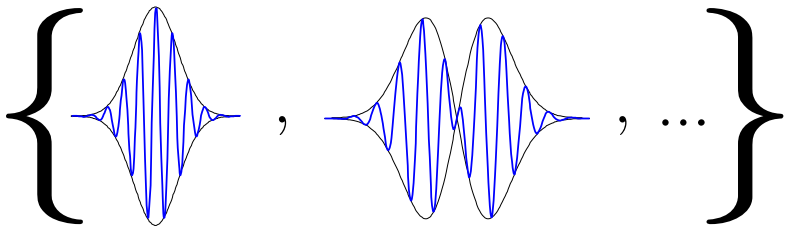
Plane waves $\{e^{i\omega_n t}\}$



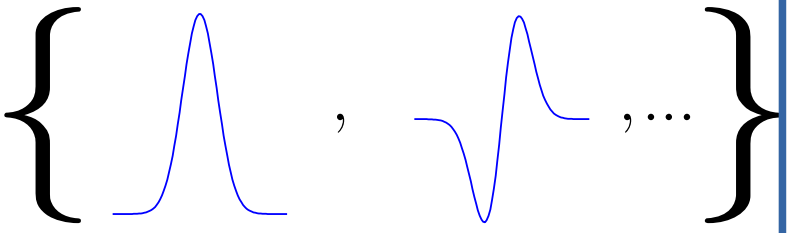
Fourier Transform



HG modes



FT



(Quantum) Computing and continuous variables

Discrete encoding $\vec{x} = 1001111010101001...$

bits $\vec{x} \mapsto b(\vec{x})$ For any boolean function

qubits $|\vec{x}\rangle|\phi\rangle \mapsto U_b|\vec{x}\rangle|\phi\rangle = |\vec{x}\rangle|b(\vec{x})\rangle$

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Continuous Variables

qu**modes** $|\psi\rangle \in \left(L^2(\mathbb{R},\mathbb{C})\right)^{\otimes n} \mapsto e^{-itH\left(\hat{\vec{a}},\hat{\vec{a}}^\dagger\right)}|\psi\rangle$

General polynomial

Computation with arbitrary encoding

(Quantum) Computing and continuous variables

LKB

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Continuous Variables

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General polynomial

Universal set:

$$\left\{\underbrace{e^{i\hat{q}s}, e^{i\hat{q}^2 s}, e^{i\frac{\pi}{4}(\hat{q}^2+\hat{p}^2)}}, e^{i\hat{q}_1\otimes\hat{q}_2}, e^{i\hat{q}^3 s}\right\}$$

Single-mode, Gaussian

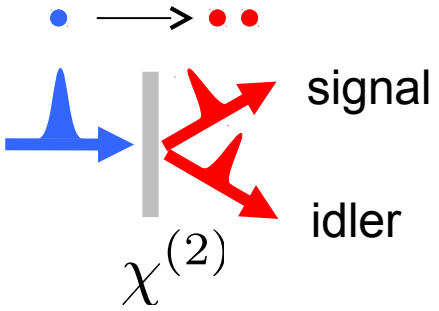
Two-modes C_Z

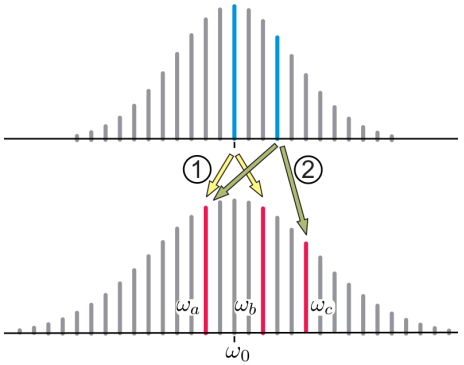
Non-Gaussian

Computation with arbitrary encoding

S. Lloyd and S. L. Braunstein
PRL 82, 1784 (1999)

Multimode squeezing: Parametric Interaction



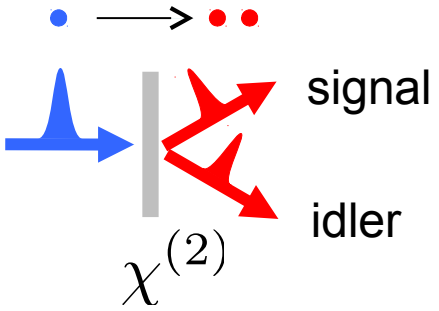


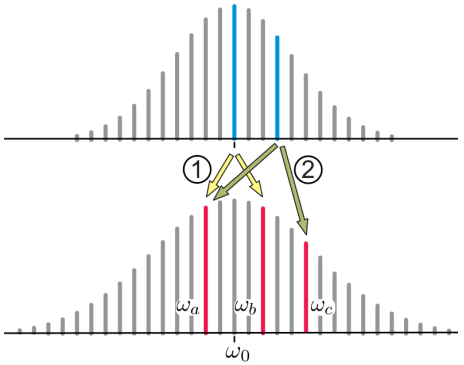
Interaction Hamiltonian

$$H = i \sum_{m,q} \mathcal{L}_{m,q} \hat{a}^{\dagger}_{\omega_m} \hat{a}^{\dagger}_{\omega_q} + \text{h.c.}$$

$$\mathcal{L}_{m,q} = \underbrace{\text{sinc}\left(\Delta k_{m,q} \frac{l}{2}\right)}_{\text{Crystal}} \times \underbrace{\alpha\left(\omega_m + \omega_q\right)}_{\text{Pump}}$$

Multimode squeezing: Parametric Interaction





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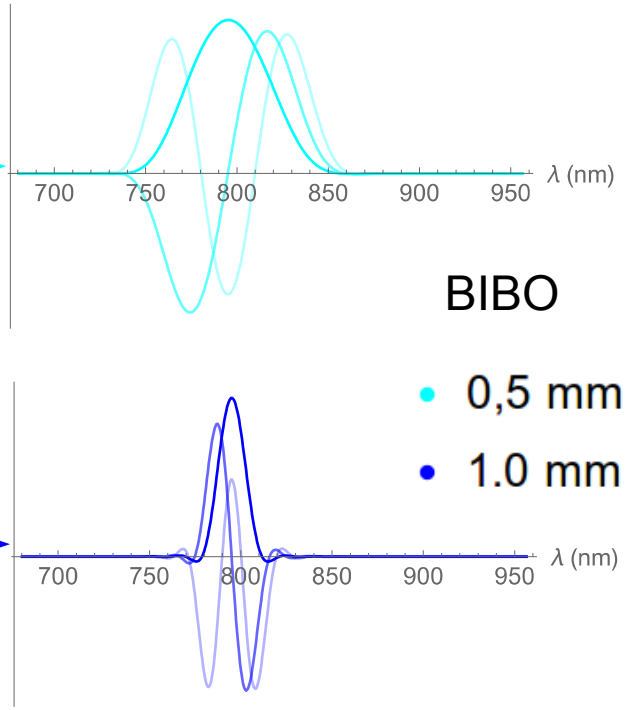
$$U \mathcal{L} U^T = \Lambda$$

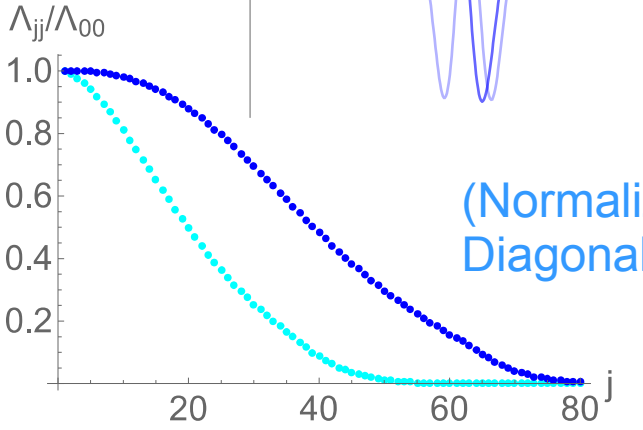
Symmetric SVD

Rows of U

Supermodes



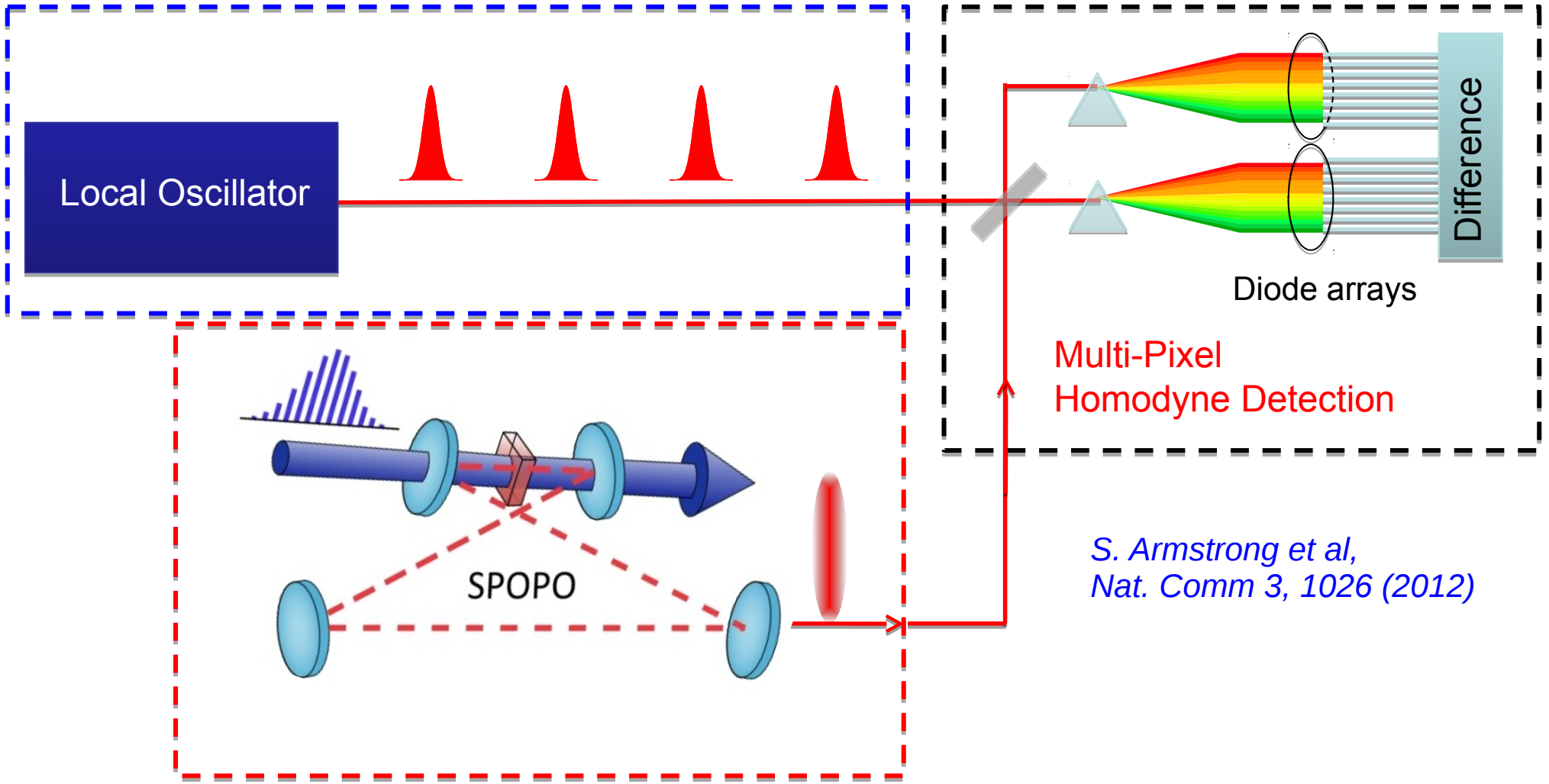
$$H = i \sum_{j} \Lambda_{jj} \left(\hat{S}^{\dagger}_{j}\right)^2 + \text{h.c.}$$



(Normalized)
Diagonal of Λ

Change of mode basis ? Homodyne !

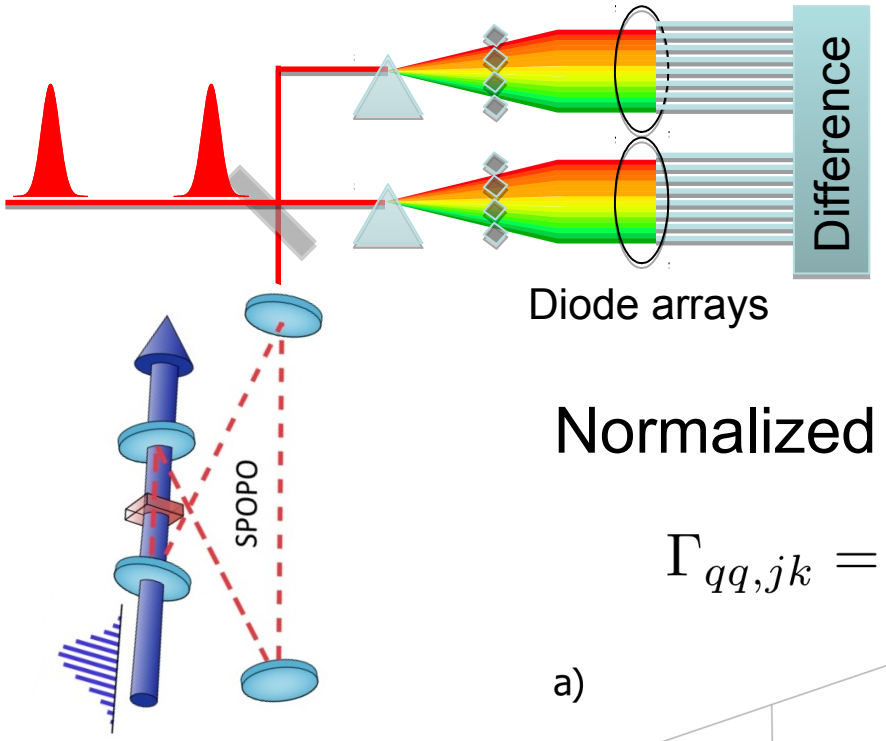
Multi-Pixel Homodyne Detection

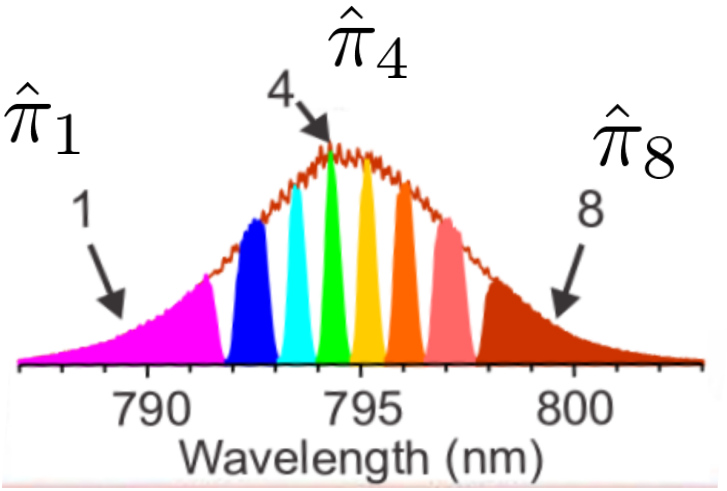


S. Armstrong et al,
Nat. Comm 3, 1026 (2012)

- Modes can be separated easily
- Measurement of one mode does not destroy the rest of the system

State of the System: Covariance Matrix



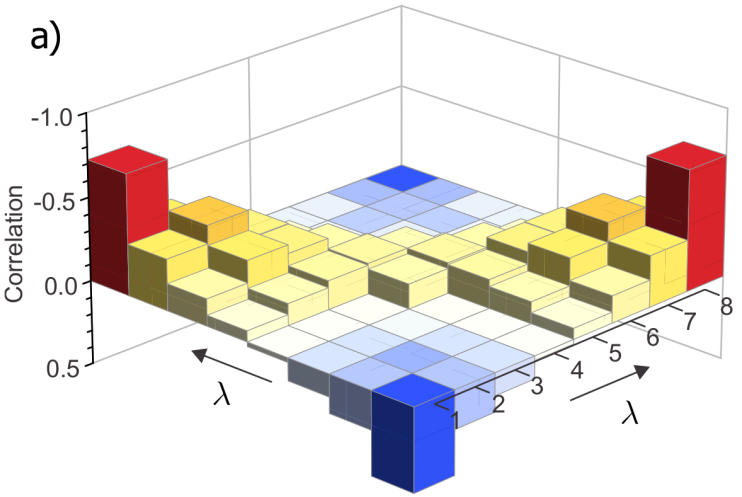


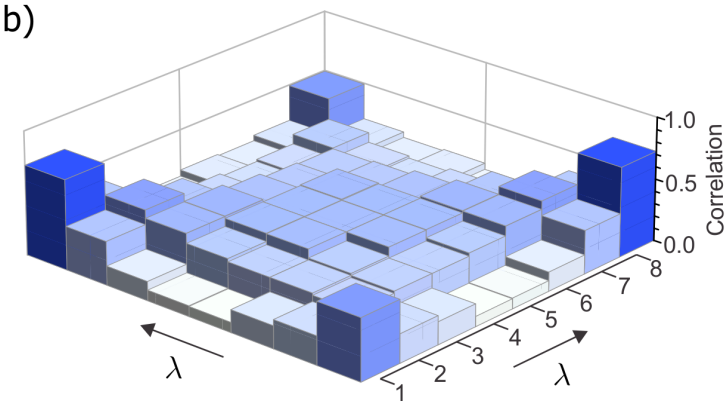
Normalized correlations between frequency bands

$$\Gamma_{qq,jk} = \frac{1}{2}\langle\{\hat{q}_j, \hat{q}_k\}\rangle$$

$$\Gamma_{pp,jk} = \frac{1}{2}\langle\{\hat{p}_j, \hat{p}_k\}\rangle$$

$$\Gamma_{qp,jk} = \frac{1}{2}\langle\{\hat{q}_j, \hat{p}_k\}\rangle$$





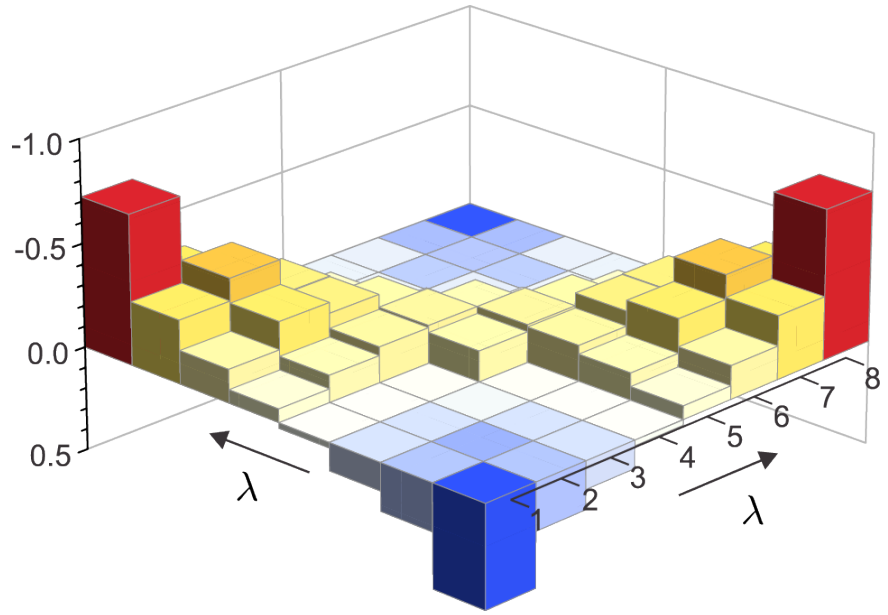
Highly entangled state!

S. Gerke et al,
PRL 114, 050501 (2015)

Reconstructing the squeezed modes

Diagonalization

- Independent Squeezers
- Transition matrix to measured modes



R. Madeiros de Araújo et al, PRA 89, 053828 (2014)

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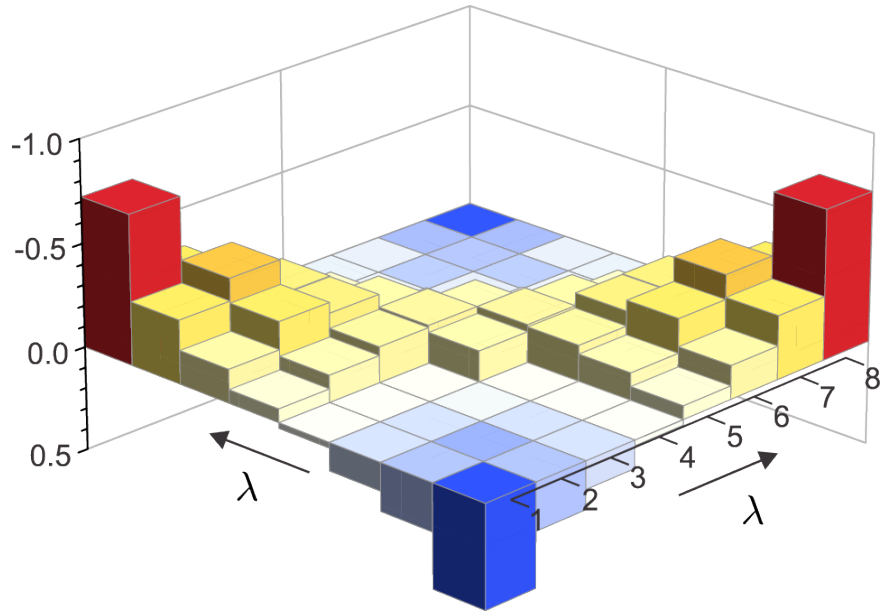
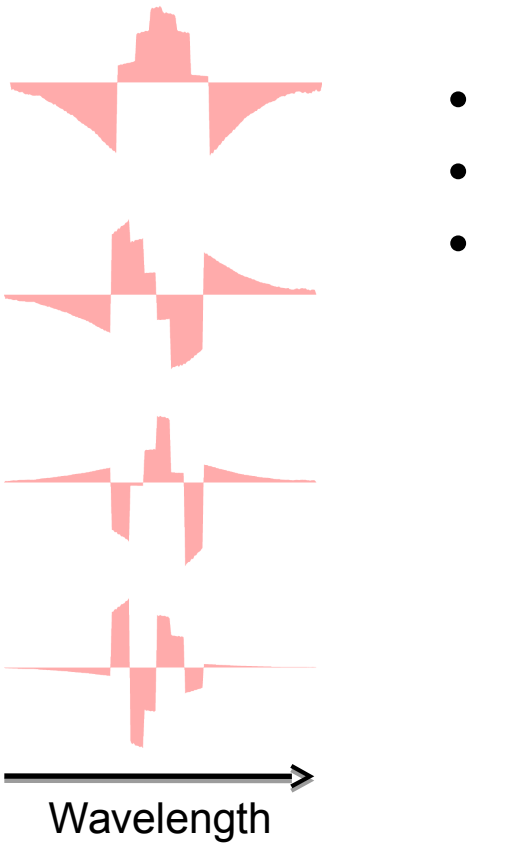


R. Madeiros de Araújo et al, PRA 89, 053828 (2014)

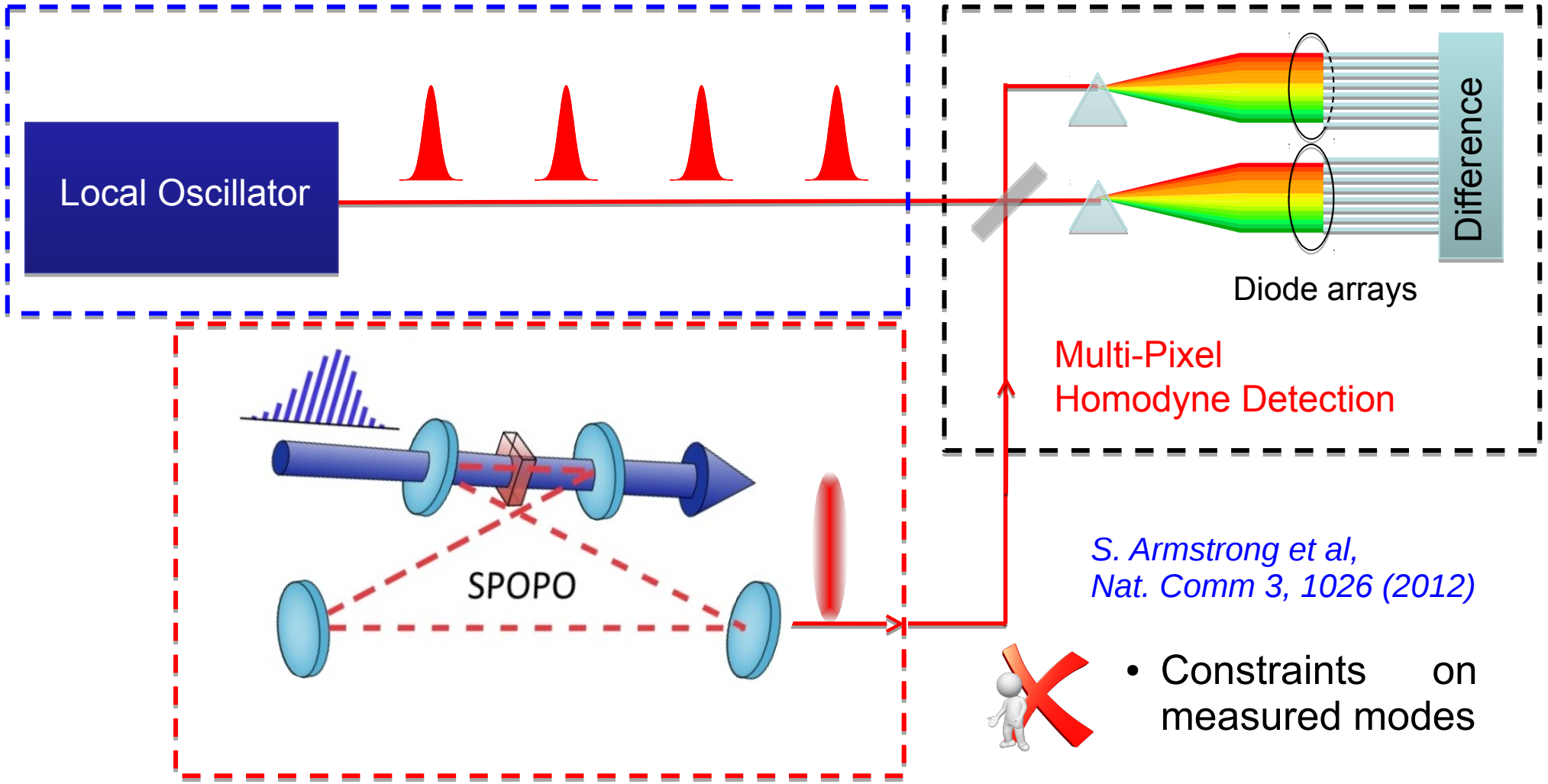
Shape Noise level

$$\hat{S}_1 = \sum_k \left(U_{\mathrm{T}}^{\dagger}\right)_{1k} \hat{\pi}_k$$

$$\hat{S}_2 = \sum_k \left(U_{\mathrm{T}}^{\dagger}\right)_{2k} \hat{\pi}_k$$



Multi-Pixel Homodyne Detection



S. Armstrong et al,
Nat. Comm 3, 1026 (2012)

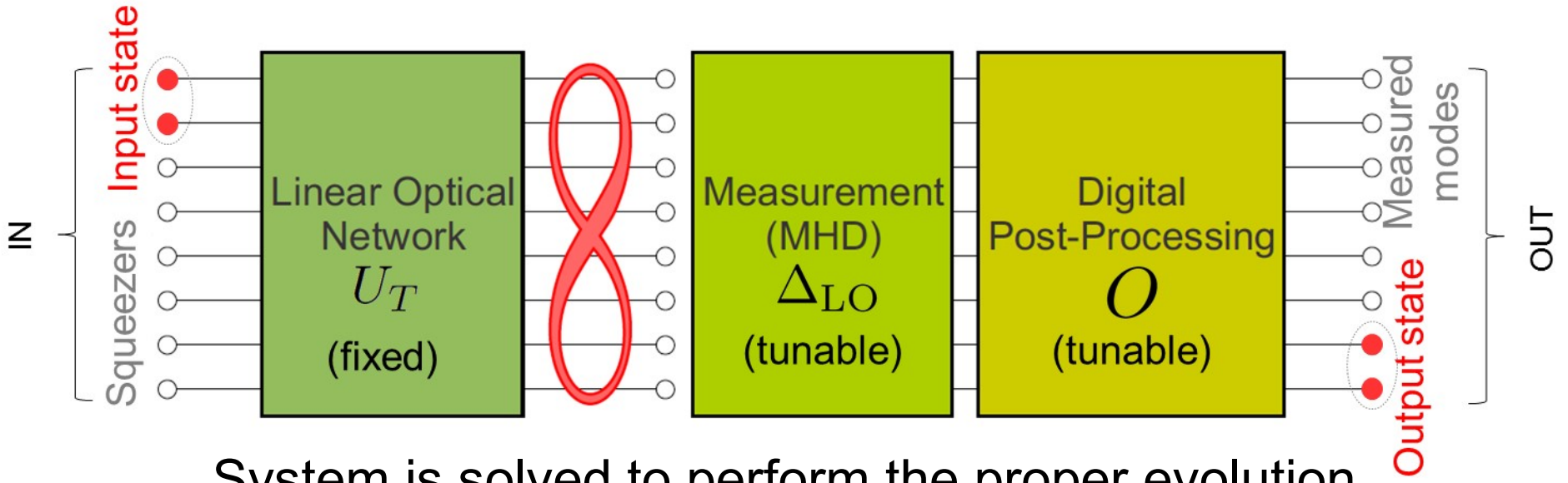
- Constraints on measured modes

- Modes can be separated easily
- Measurement of one mode does not destroy the rest of the system

1)Can we use the state anyway ?

2)Can we engineer correlations given such constraints ?

Direct Measurement-Based QC



System is solved to perform the proper evolution and eliminate "anti-squeezed" quadratures

$$\begin{pmatrix} \hat{\vec{q}}_{\mathrm{out}} \\ \hat{\vec{p}}_{\mathrm{out}} \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} \hat{\vec{q}}_{\mathrm{in}} \\ \hat{\vec{p}}_{\mathrm{in}} \end{pmatrix} + \begin{pmatrix} \hat{\vec{\delta}}_q \\ \hat{\vec{\delta}}_p \end{pmatrix} + \begin{pmatrix} \vec{\eta}_q \\ \vec{\eta}_p \end{pmatrix}$$

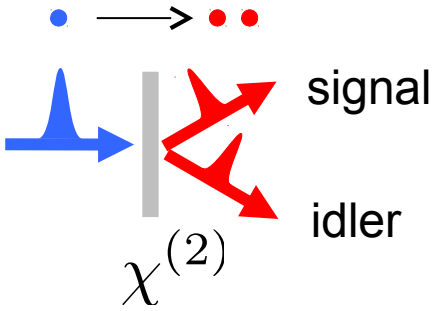
G. Ferrini et al, PRA 94, 062332 (2016)

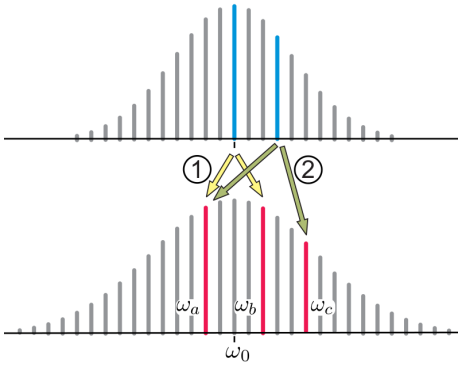
Excess noise due to finite squeezing

Correction factors from post processing

- Perform Gaussian gates
- Works for non-Gaussian inputs

Pump Shaping: Experimental Setup



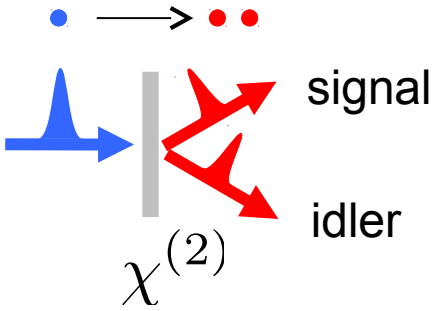


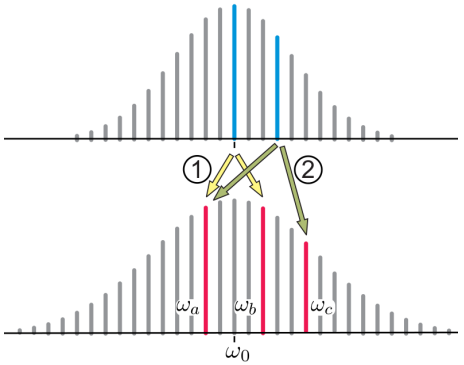
Interaction Hamiltonian

$$H = i \sum_{m,q} \mathcal{L}_{m,q} \hat{a}^{\dagger}_{\omega_m} \hat{a}^{\dagger}_{\omega_q} + \text{h.c.}$$

$$\mathcal{L}_{m,q} = \underbrace{\text{sinc}\left(\Delta k_{m,q} \frac{l}{2}\right)}_{\text{Crystal}} \times \underbrace{\alpha\left(\omega_m + \omega_q\right)}_{\text{Pump}}$$

Pump Shaping: Experimental Setup





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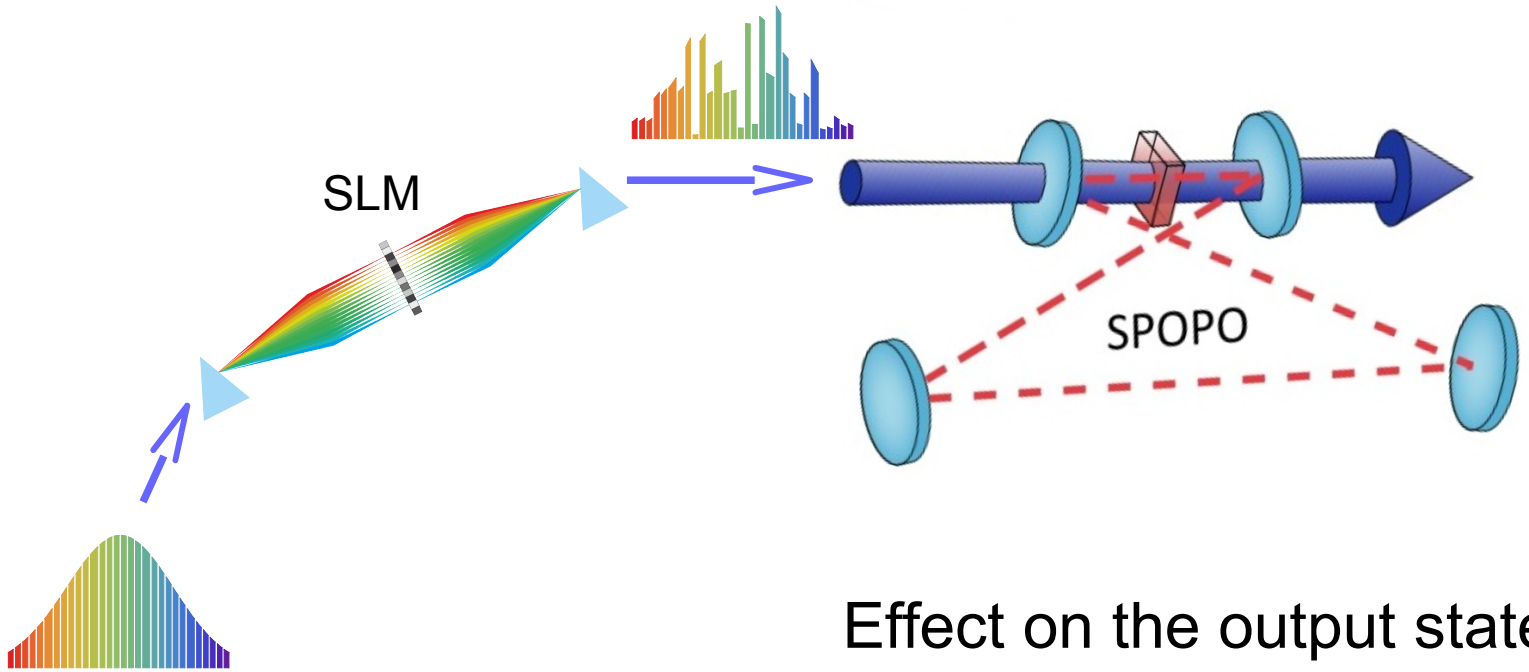

Effect on the output state ?

Tweaking the Squeezing

Complex relation between pump and squeezing/supermodes :

Use **numerical optimization**

To flatten the squeezing spectrum : $f_{\mathrm{Fl}}\left(\vec{\theta}\right) = \sum_{j=0}^{100} \Lambda_{jj}\left(\vec{\theta}\right) / \Lambda_{00}\left(\vec{\theta}\right)$

To concentrate the squeezing in one mode : $f_{\mathrm{Conc}}\left(\vec{\theta}\right) = \Lambda_{00}\left(\vec{\theta}\right) / \Lambda_{11}\left(\vec{\theta}\right)$

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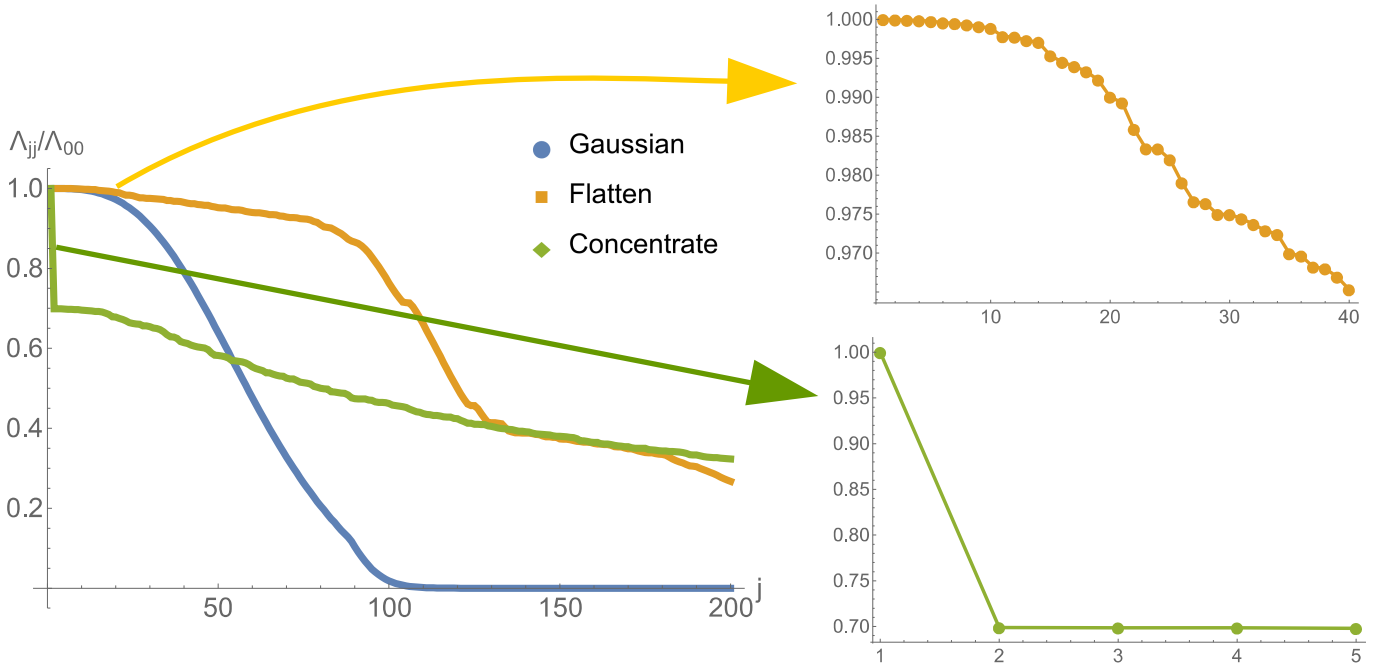

Tweaking the Squeezing

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F. Arzani et al,
In preparation...I should be writing.

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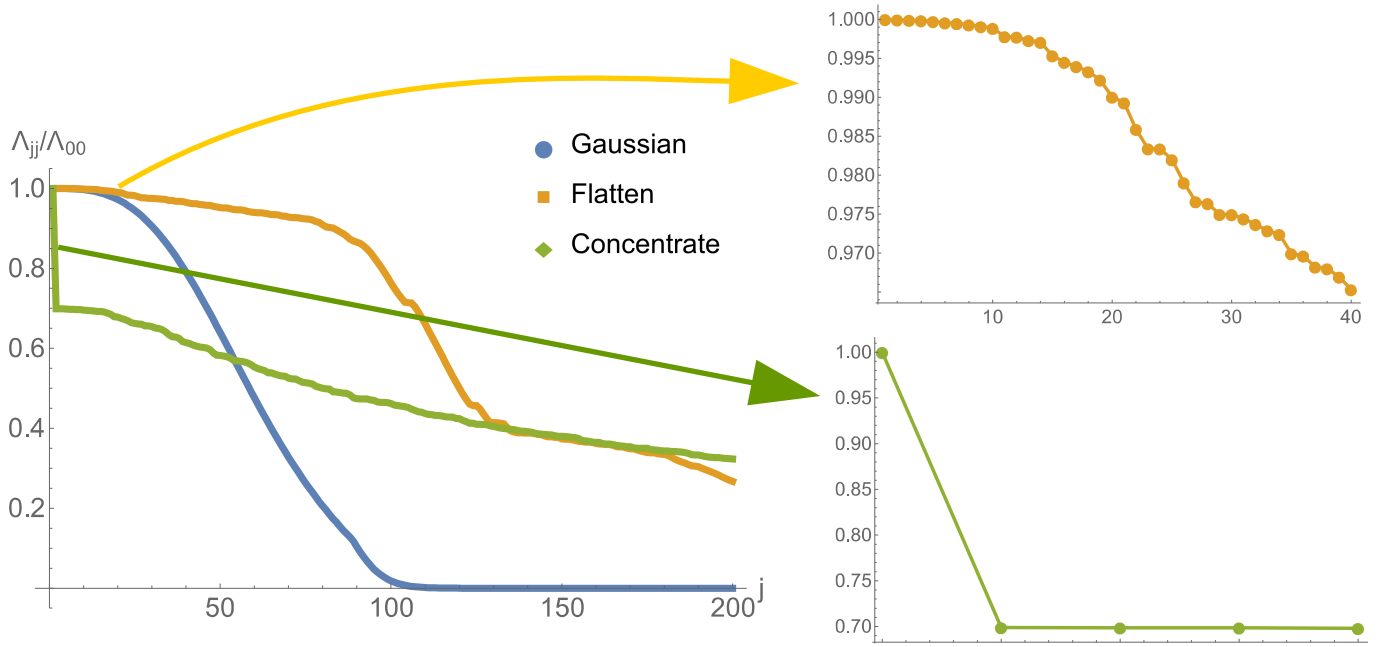
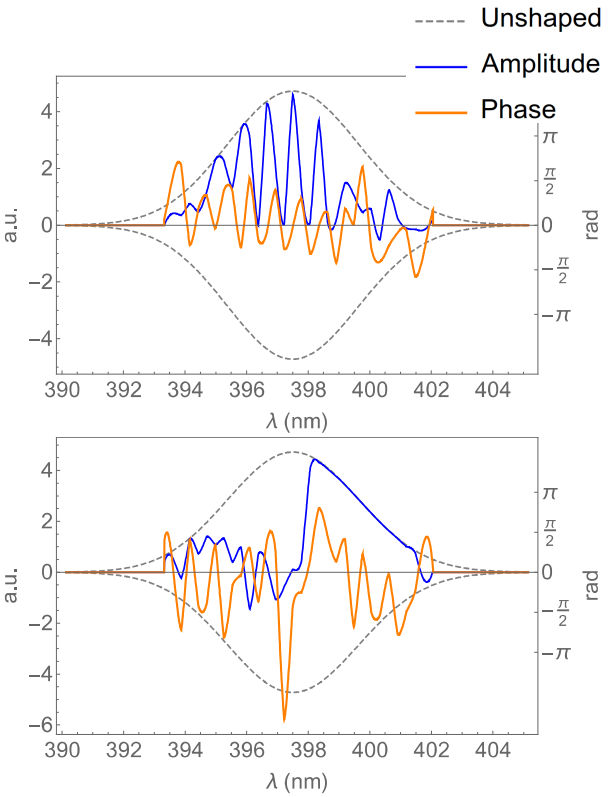


Optimal Pump



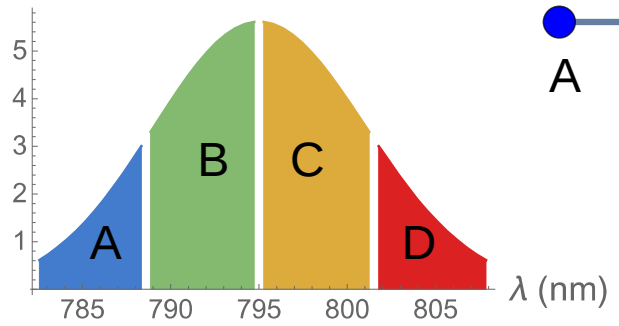
Adjust the squeezing spectrum : Quantum simulation of oscillator networks

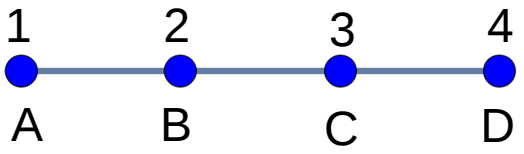
With V. Parigi

J. Nokkala et al,
Sci. Rep. 6, 26861 (2016)

Optimizing CV Cluster States - QC

LKB

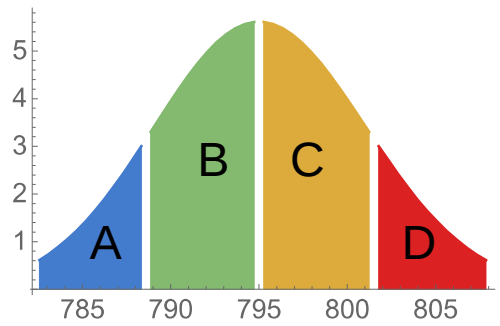


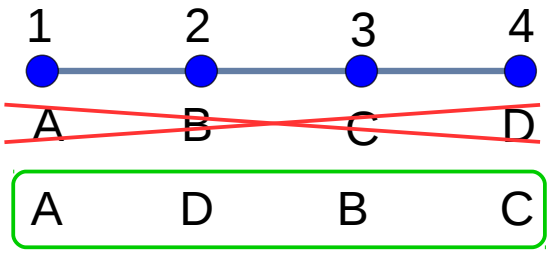


Mean nullifiers' squeezing :

$\langle \Delta\delta_i \rangle$ = - 0.18 dB

Optimizing CV Cluster States - QC





$$\hat{\delta}_1 = \hat{p}_A - \hat{q}_D$$

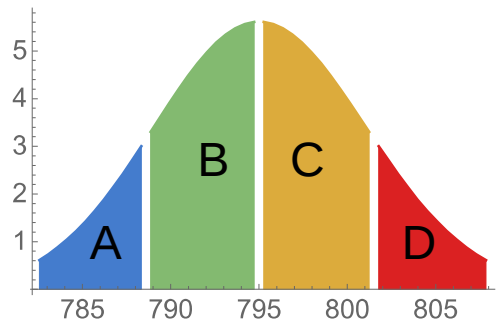
Mean nullifiers' squeezing :

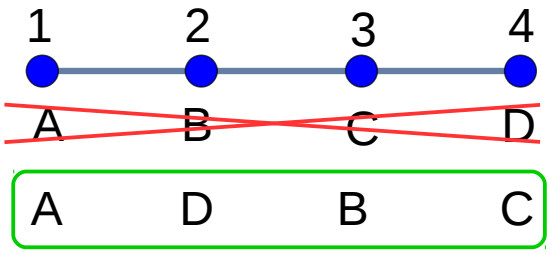
$\langle \Delta\delta_i \rangle$ = - 0.18 dB

$\langle \Delta\delta_i \rangle$ = - 2.31 dB

Fully inseparable (PPT)

Optimizing CV Cluster States - QC





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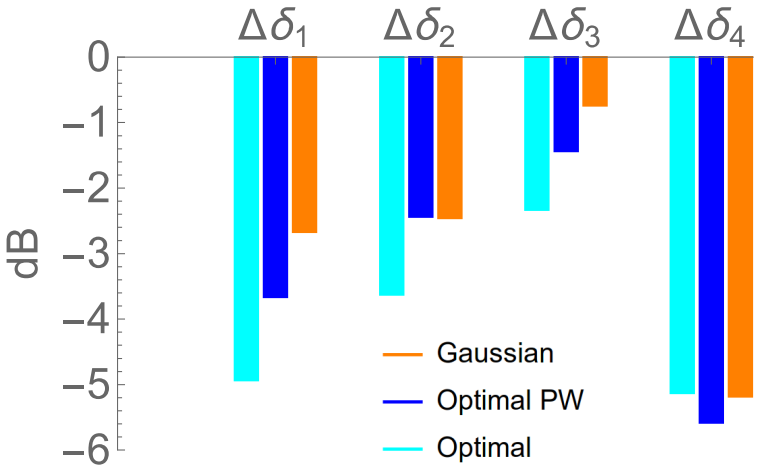
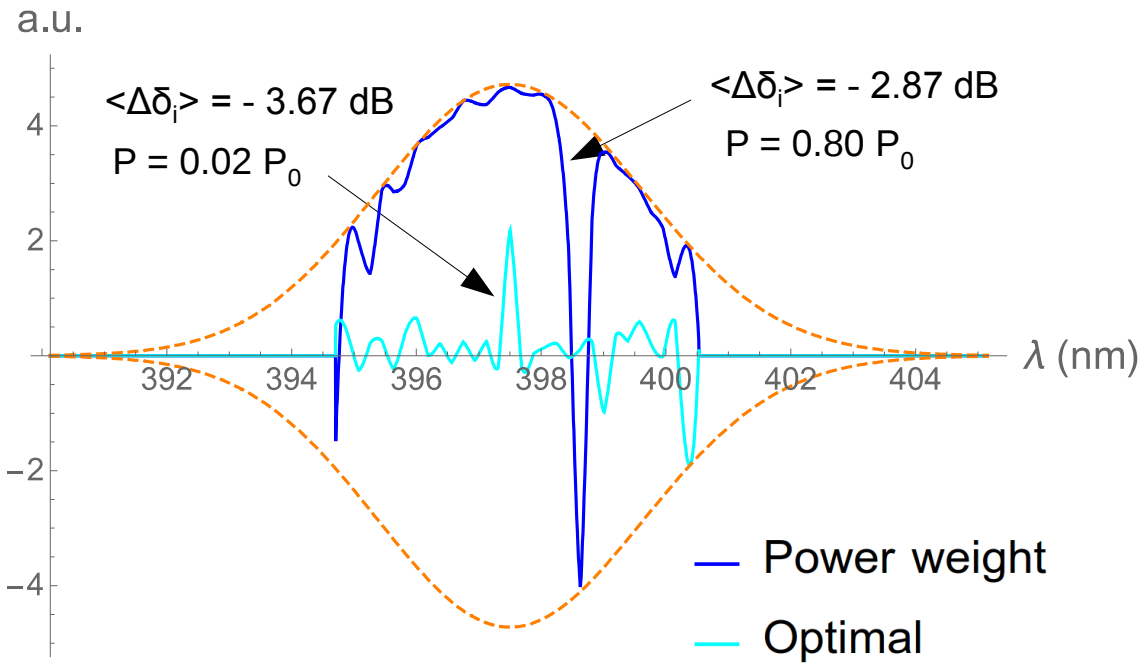


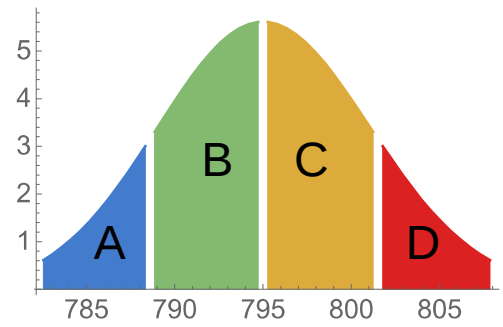
Pump optimizing average nullifiers' noise

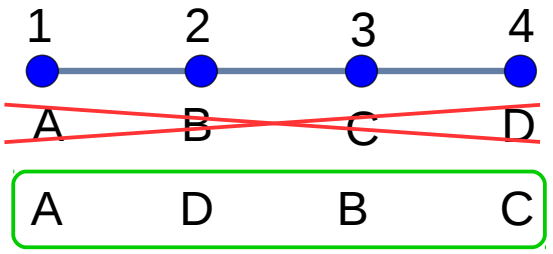
(fixed maximum squeezing = 7 dB)



Non trivial spectral phase as well...

Optimizing CV Cluster States - QC





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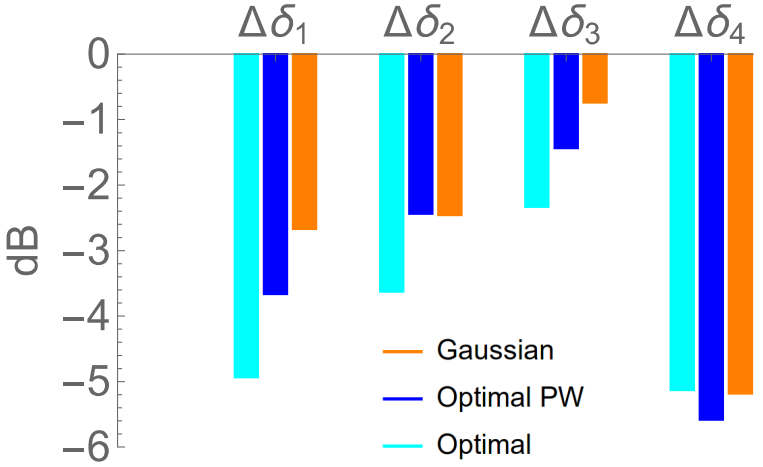

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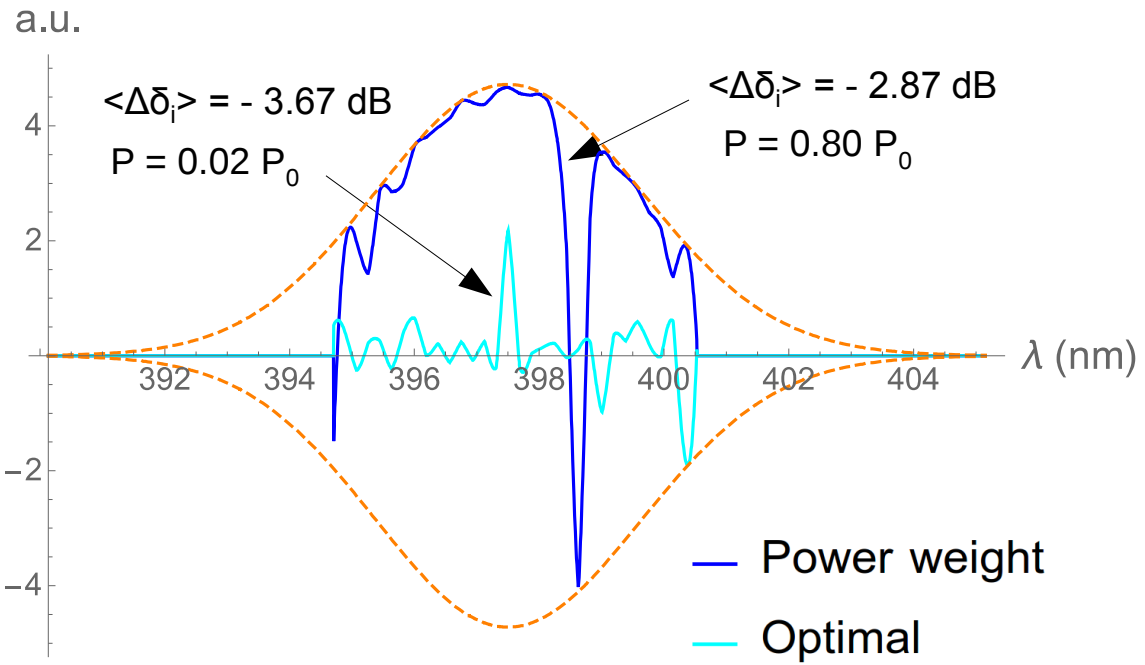
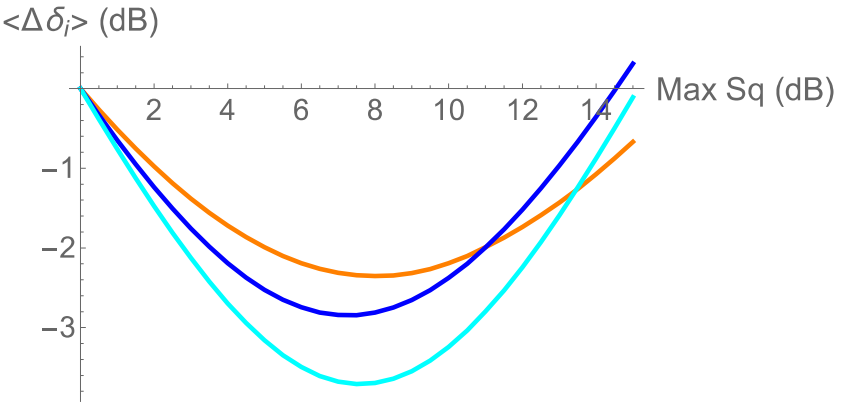
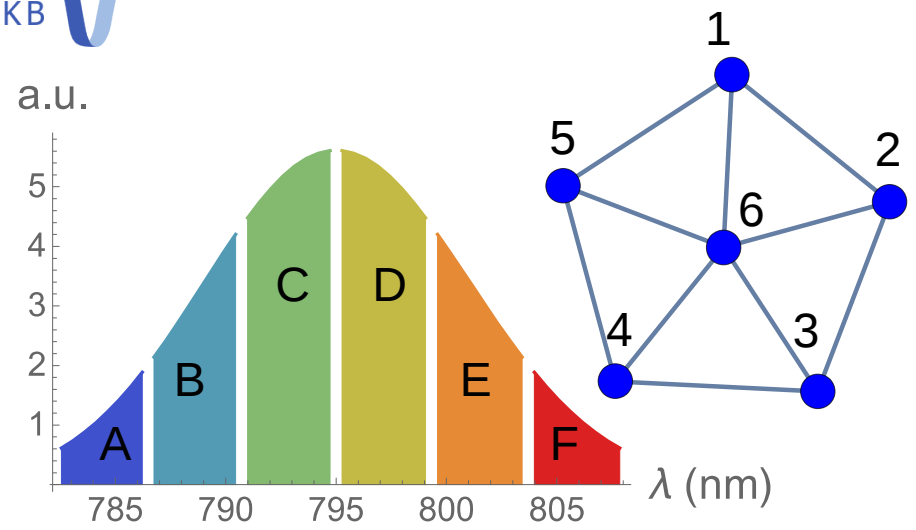


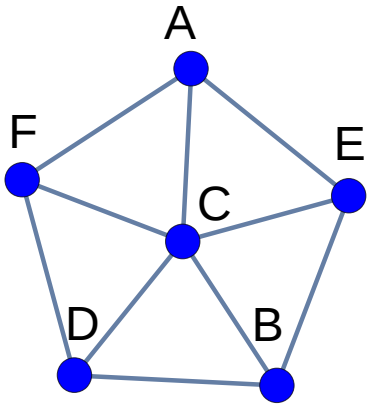
More squeezing ≠ Better nullifiers



Non trivial spectral phase as well...

Optimizing CV Cluster States - SS





Mean nullifiers' squeezing :

$\langle \Delta\delta_i \rangle$ = - 1.57 dB

Fully inseparable (PPT)

Pump optimizing average nullifiers' noise
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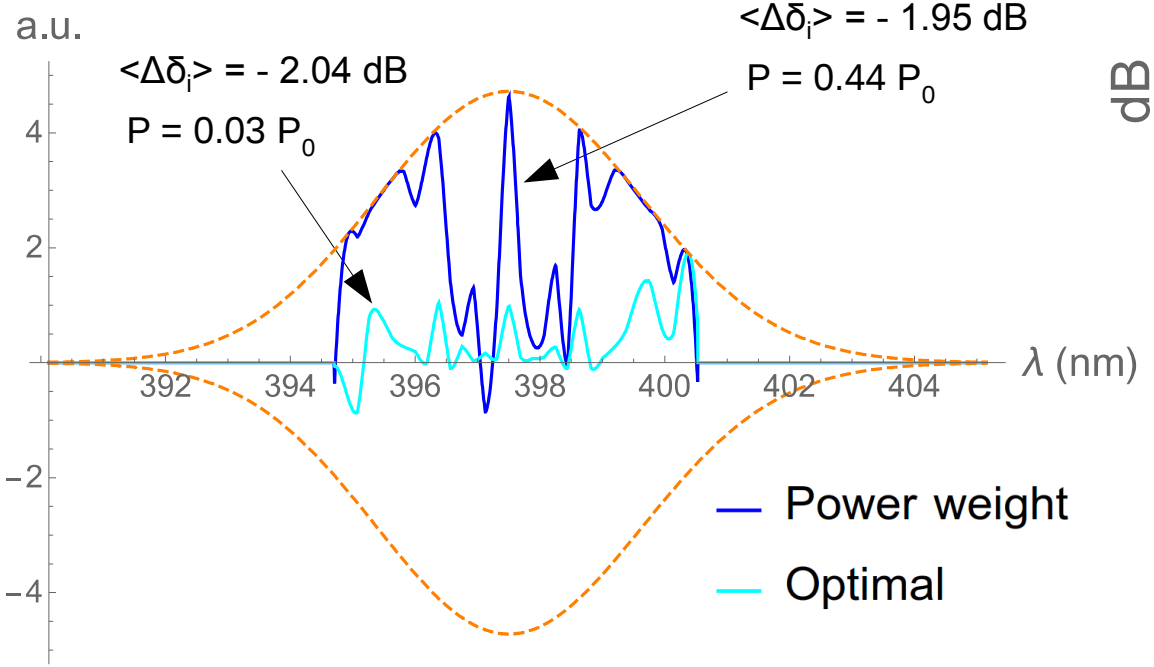
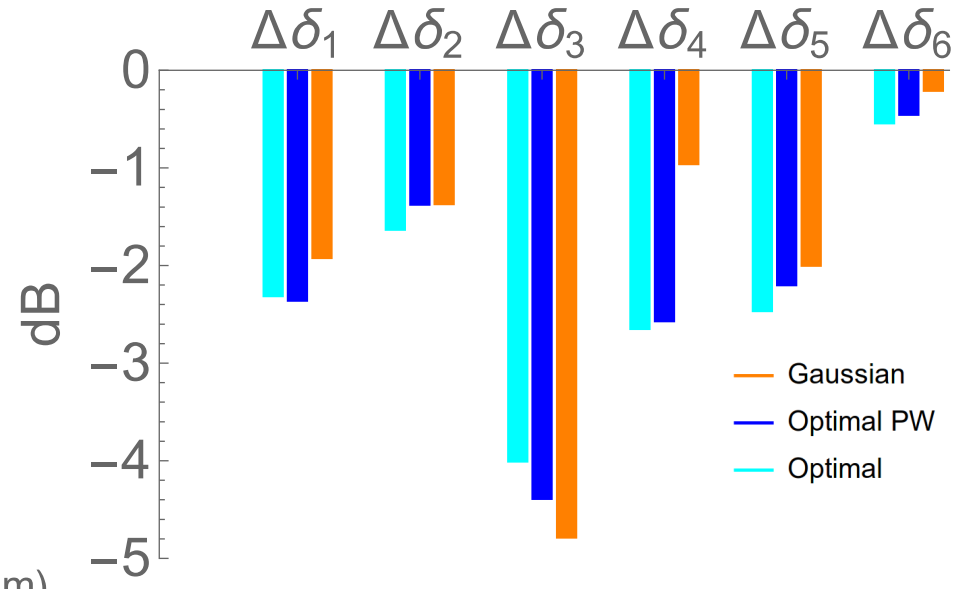
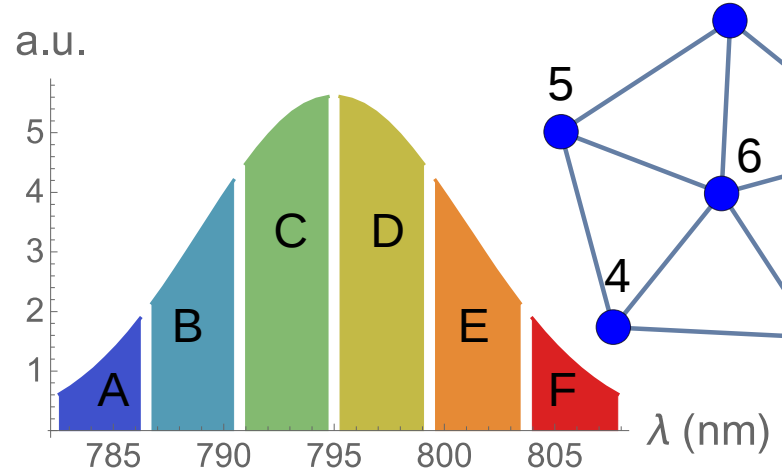
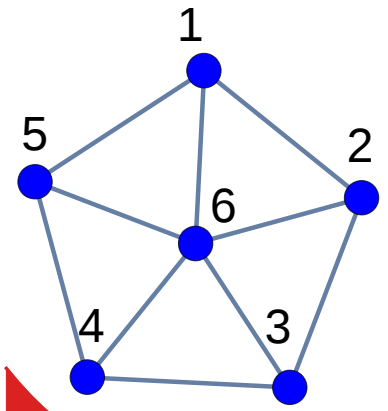


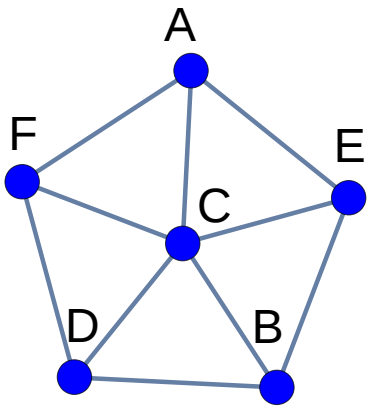
Nullifiers' squeezing



Optimizing CV Cluster States - SS







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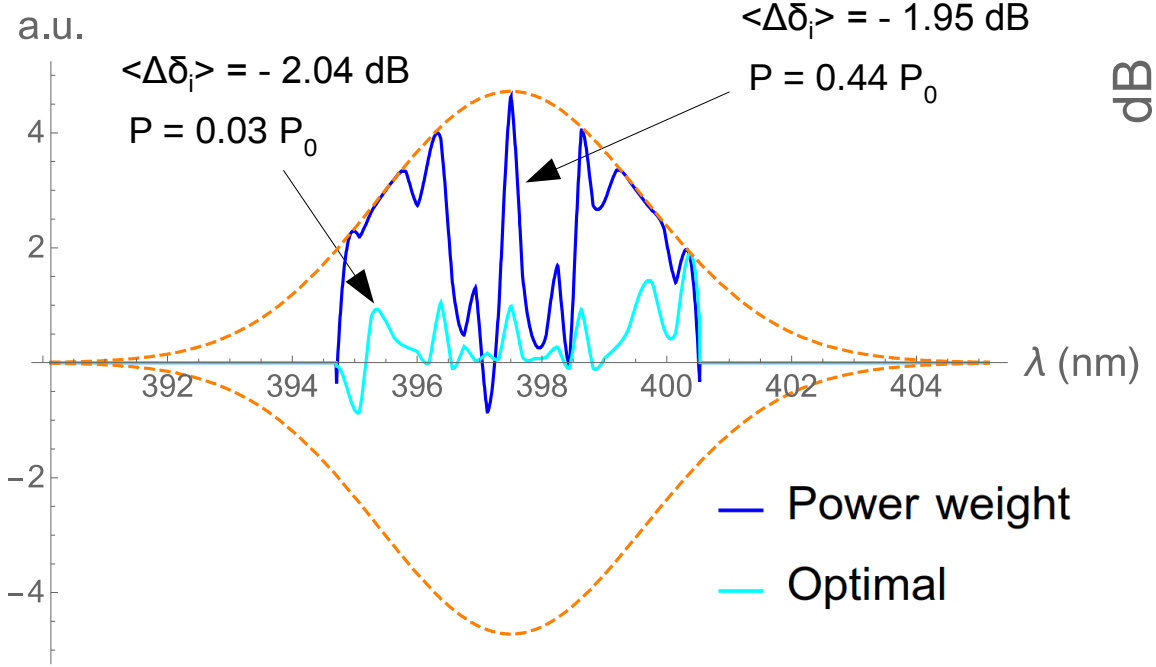

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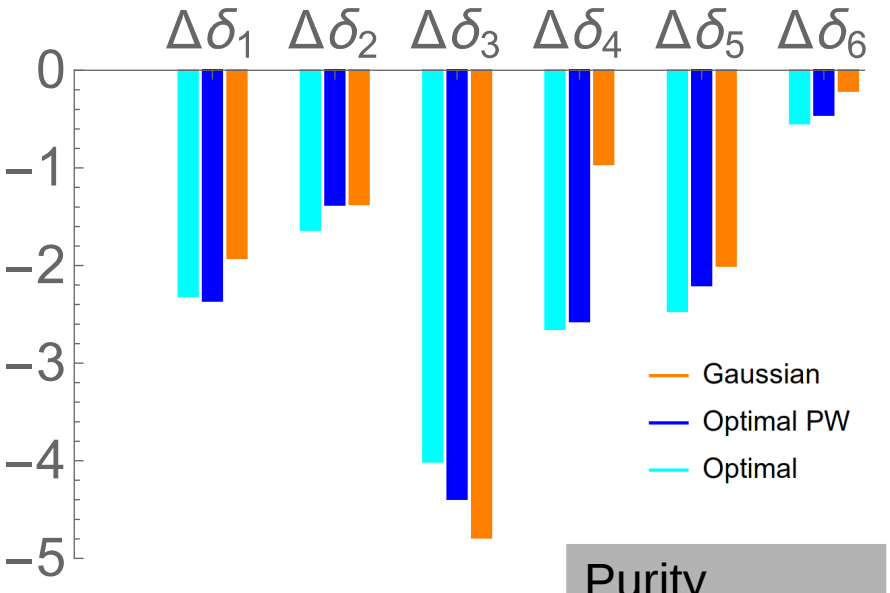


	Purity
Gaussian	0.73
Optimal PW	0.84
Optimal	0.91

The Need for Non-Gaussian Gates

Universal set for any evolution with **polynomial hamiltonians in the quadratures**

S. Lloyd and S. L. Braunstein
PRL 82, 1784 (1999)

$$\left\{ \underbrace{e^{i\hat{q}s}, e^{i\hat{q}^2 s}, e^{i\frac{\pi}{4}(\hat{q}^2+\hat{p}^2)}}, e^{i\hat{q}_1\otimes\hat{q}_2}, e^{i\hat{q}^3 s} \right\}$$

Single-mode, Gaussian

Two-mode C_Z

Non-Gaussian

Universality:

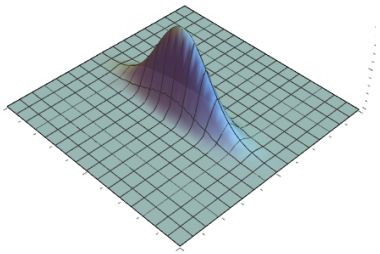
$$e^{i\hat{A}\delta t}e^{i\hat{B}\delta t}e^{-i\hat{A}\delta t}e^{-i\hat{B}\delta t} = e^{\left(\hat{A}\hat{B}-\hat{B}\hat{A}\right)\delta t^2} + O(\delta t^3)$$

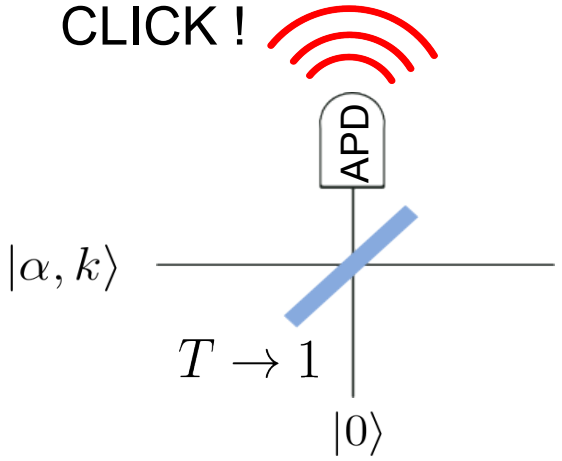
No quantum advantage without non-Gaussianity !

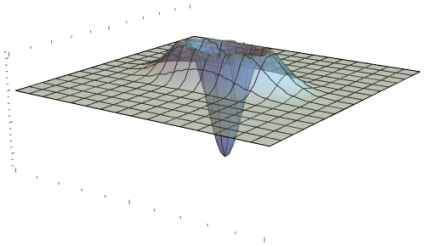
A. Mari and J. Eisert
PRL 109, 230503 (2012)

Actually, it's negativity of the WF...

Introducing Negativity: Photon Subtraction







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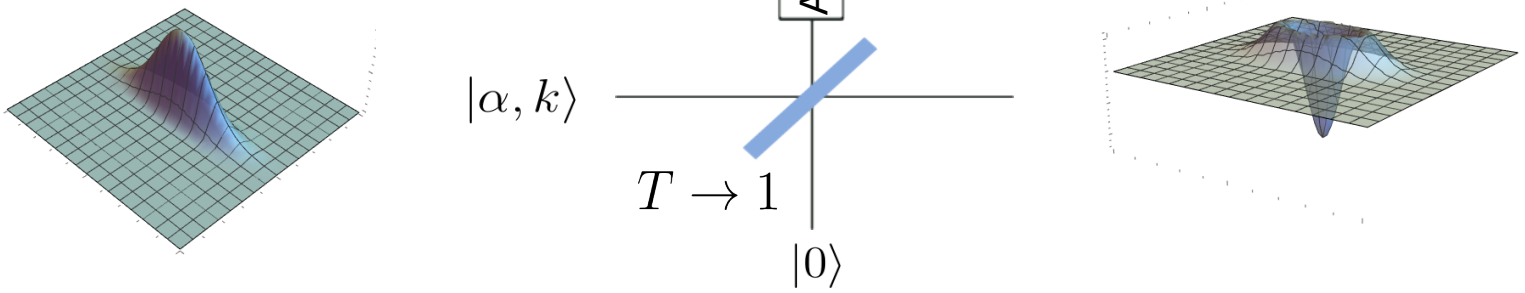
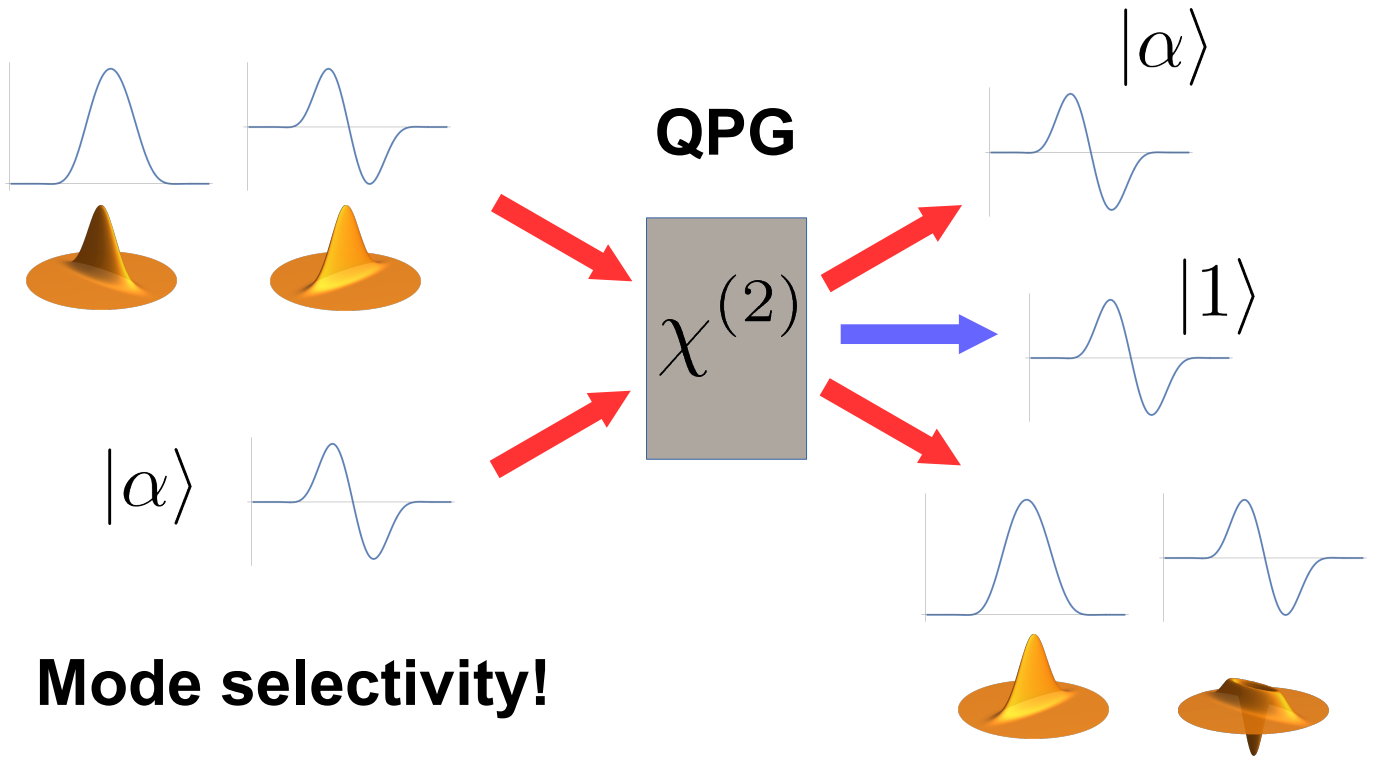


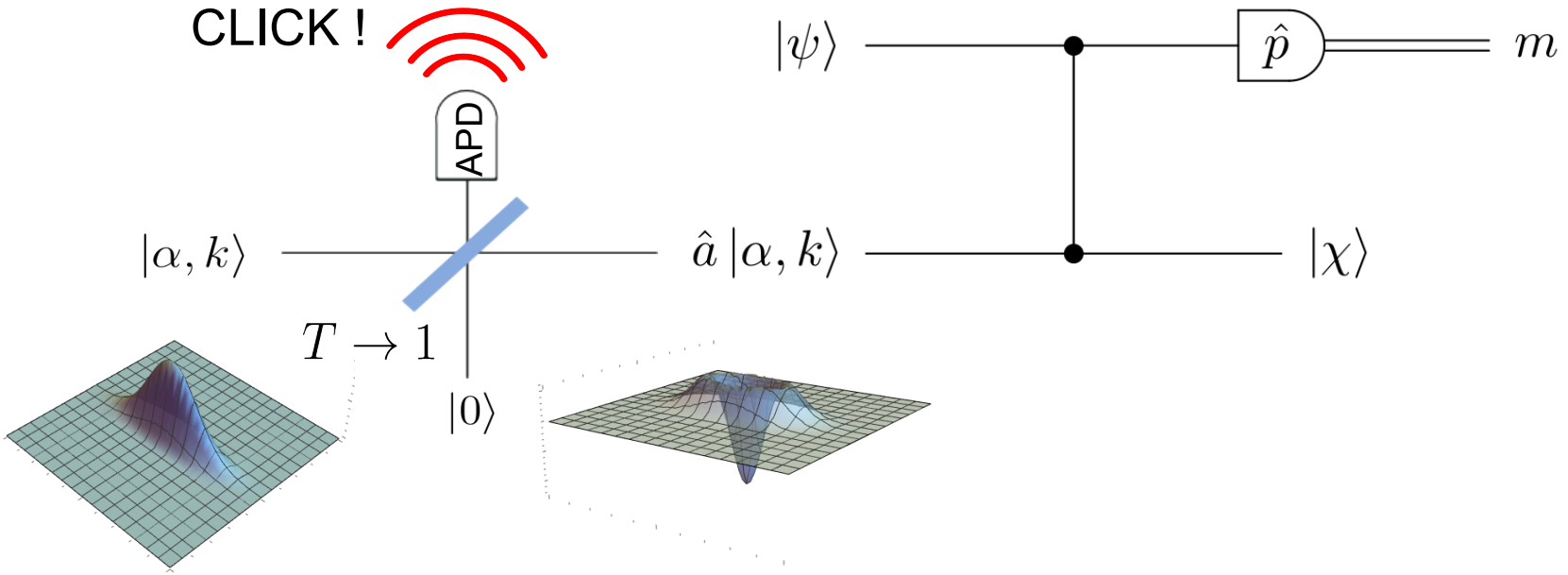


Mode selectivity!

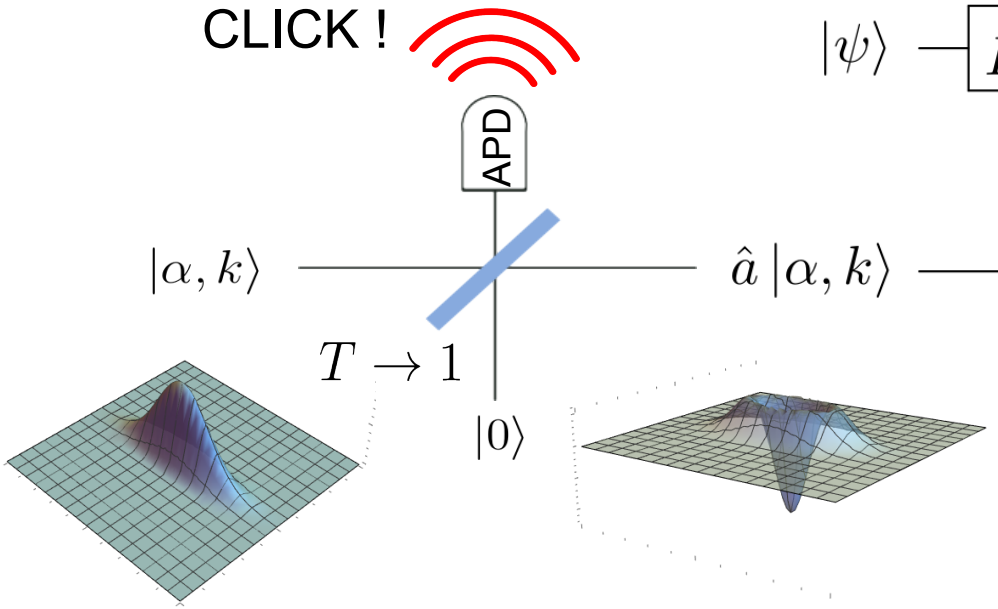
A. Eckstein et al, Opt. Expr. 19;15 (2011)

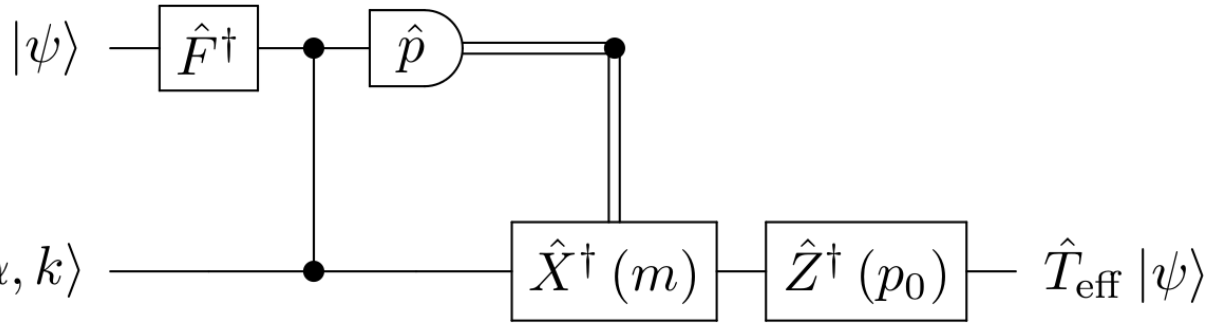
J. S. Ra et al, arXiv:1702.02082

Introducing Negativity: Photon Subtraction



Polynomials through Photon-Subtracted Ancillae





F. Arzani et al, arXiv:1703.06693

$$\hat{T}_{\text{eff}} = \mathcal{N} \exp\left\{-\frac{(\hat{q} - q_0 + m)^2}{k^2}\right\} \left(\hat{q} - \lambda(\alpha, k, m)\right)$$

Normalization ~ attenuation Monomial in *q*

$$\lambda(\alpha, k, m) = -\left(\frac{2}{k^2 - 2}\right) q_0 - i\left(\frac{k^2}{k^2 - 2}\right) p_0 - m$$

Depends on

- Experimental parameters
- Measurement (!!!)

Approximating Unitaries

Repeated application: **polynomial** in the quadratures

P. Marek et al
PRA 84(5), 053802 (2011)

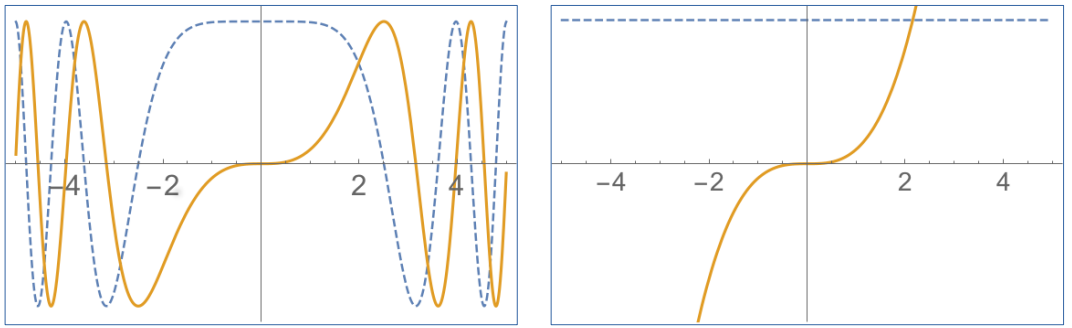
K. Marshall et al
PRA 91, 032321 (2015)

es.

$$e^{i\nu\hat{q}^3} \approx \mathbb{I} + i\nu\hat{q}^3 = (\hat{q} - \lambda_1)(\hat{q} - \lambda_2)(\hat{q} - \lambda_3)$$

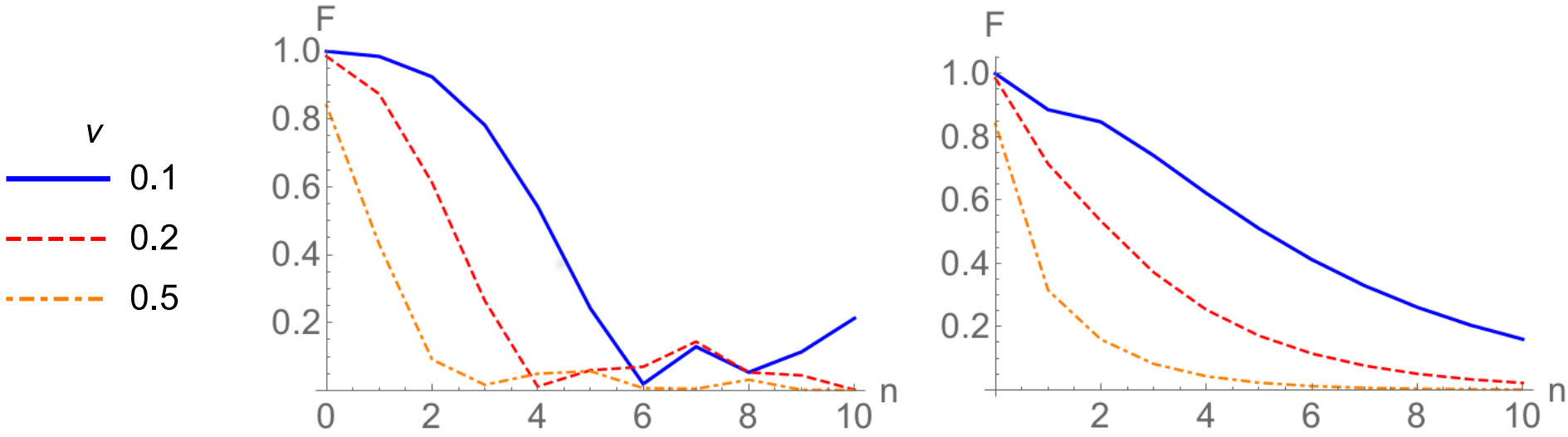
Benchmarking: Fidelity of the Bare Polynomial

$e^{0.1ix^3}$ $\quad$ $1+0.1ix^3$



$$\mathcal{F} = \left| \langle \psi | \, \hat{U}^\dagger \hat{\mathcal{T}} | \psi \rangle \right|$$

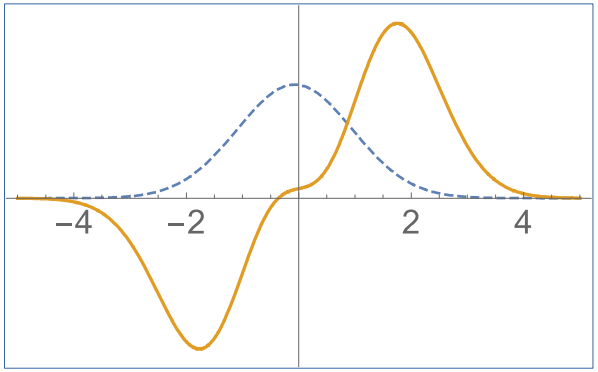
$\hat{U} = e^{i\nu\hat{q}^3}$ $\qquad$ $\hat{\mathcal{T}} = \mathcal{N}_\psi \left(\mathbb{I} + i\nu\hat{q}^3 \right)$ $\qquad$ Non unitary: ψ-dependent normalization



Input: Fock states Coherent states

Photon-Subtracted Ancillae

$$\mathcal{T}_{\text{eff}}\left(x,\vec{m}\right) \propto \prod_{i=1}^{3}\left[\mathcal{G}\left(x,\alpha_i,k,m_i\right)\left(x-\lambda\left(\alpha_i,k,m_i\right)\right)\right]$$



- Finite squeezing: envelope
- Imperfect measurement: deformation
- Finite **success probability**: acceptance region Ω

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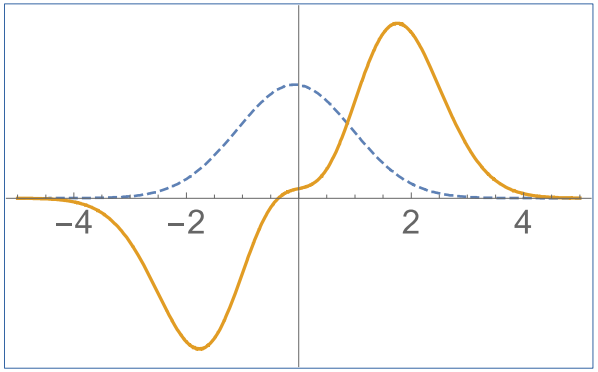

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≈ 10^{-9} - 10^{-12}

Average output state

$$\rho_{\Omega}=\int_{\Omega}\mathrm{d}^{n}m\frac{p\left(\vec{m}\right)}{p_{\Omega}}\hat{\mathcal{T}}_{\text{eff}}\left(\vec{m}\right)\left|\psi\right\rangle\left\langle\psi\right|\hat{\mathcal{T}}_{\text{eff}}^{\dagger}\left(\vec{m}\right)$$

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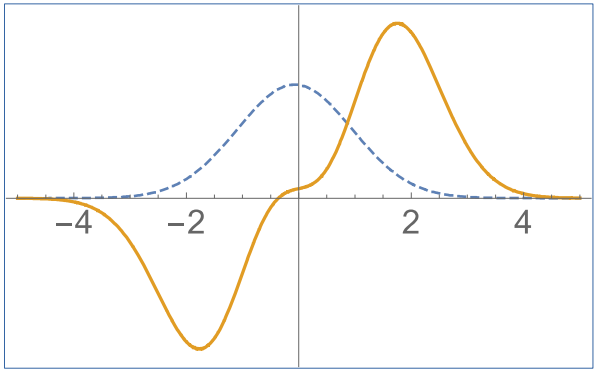

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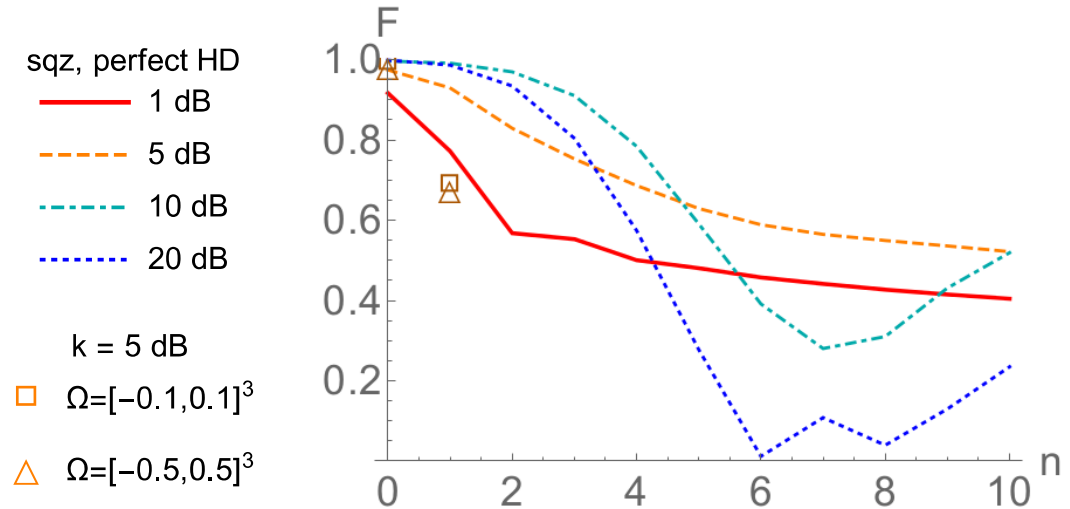
$$\mathcal{F} = \sqrt{\langle\psi|\hat{U}^\dagger\rho\hat{U}|\psi\rangle}$$



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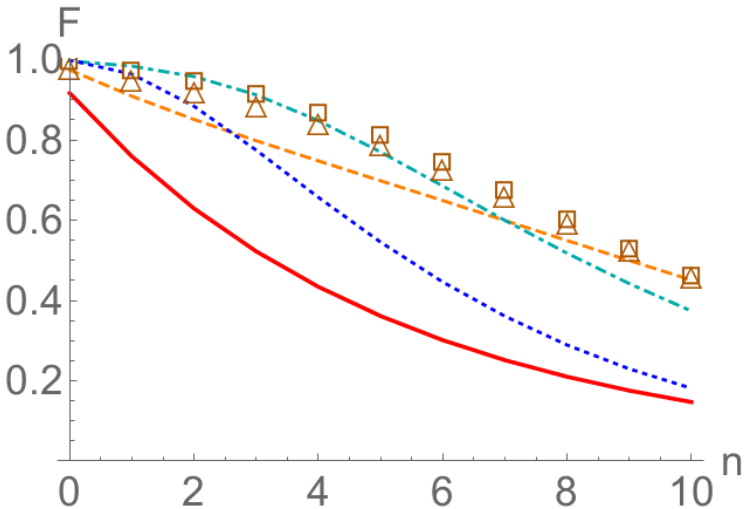
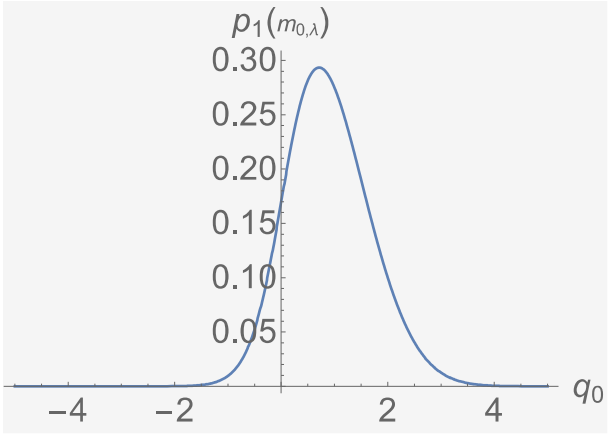


Coherent states

State Preparation

Know the input: optimize displacements to increase success probability

$$\left(\hat{q}-\lambda(\alpha,k,m)\right) \rightsquigarrow \lambda(\alpha,k,m) = -\left(\frac{2}{k^2-2}\right) q_0 - i\left(\frac{k^2}{k^2-2}\right) p_0 - m$$



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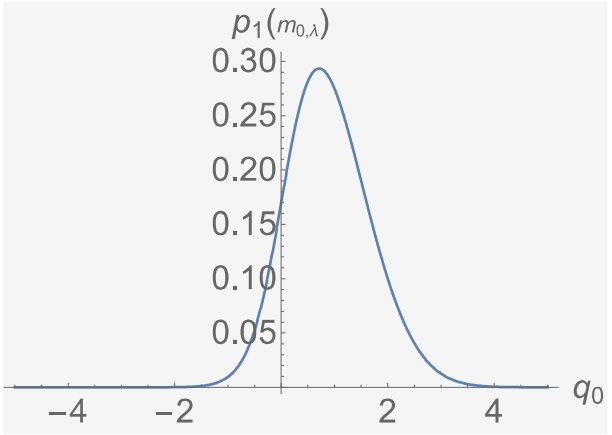
Cubic phase state

$$|\gamma(\nu)\rangle = \hat{\gamma}(\nu)\,|0\rangle_p \rightarrow \hat{\gamma}_{\text{appr}}(\nu)\,|k_{in}\rangle_p$$



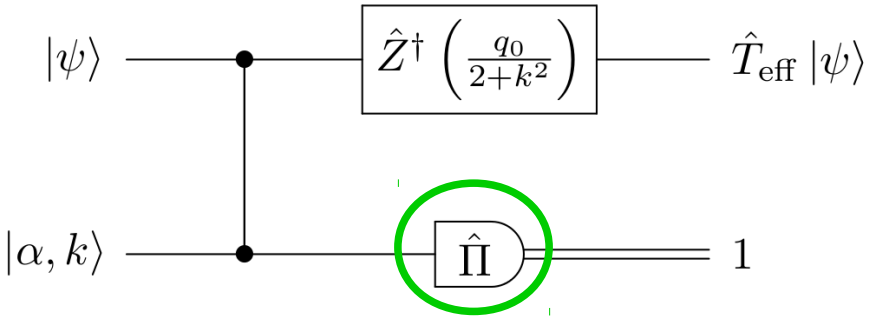
Fidelity = 0.9 with

$$\hat{\gamma}(\nu)\,|k_{in}\rangle_p = e^{i\nu\hat{q}^3}\,|k_{in}\rangle_p$$

for k = 5 dB, k_{in} = 5 dB, v = 0.1

Success probability ~ 10^{-4}

Alternative Scheme: Single-Photon Counter



Projects on **single photon**

Still post-selection but no binning of HD outcomes

~ Conjugate process of

K. Park et al
PRA 90, 013804 (2014)

$$\hat{T}_{\rm eff} = \tilde{\mathcal{N}} \exp\left\{-\left(\frac{k^2}{4+2k^2}\right)(\hat{q}+p_0)^2\right\}\left(\hat{q}-\lambda(\alpha,k)\right)$$

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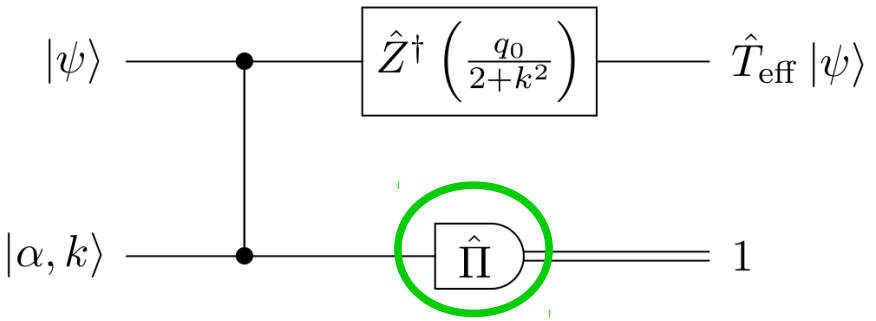

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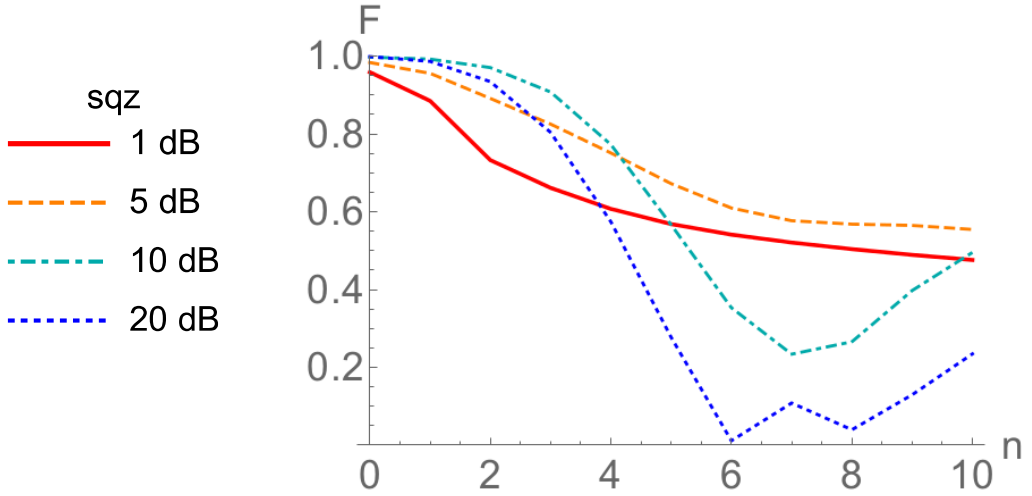
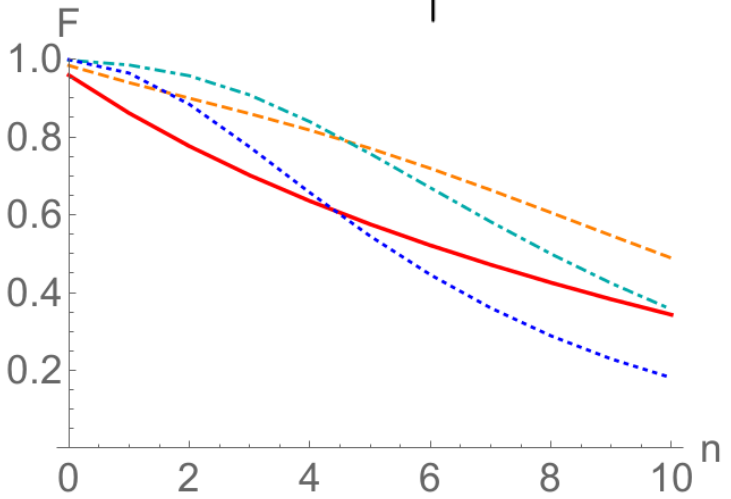


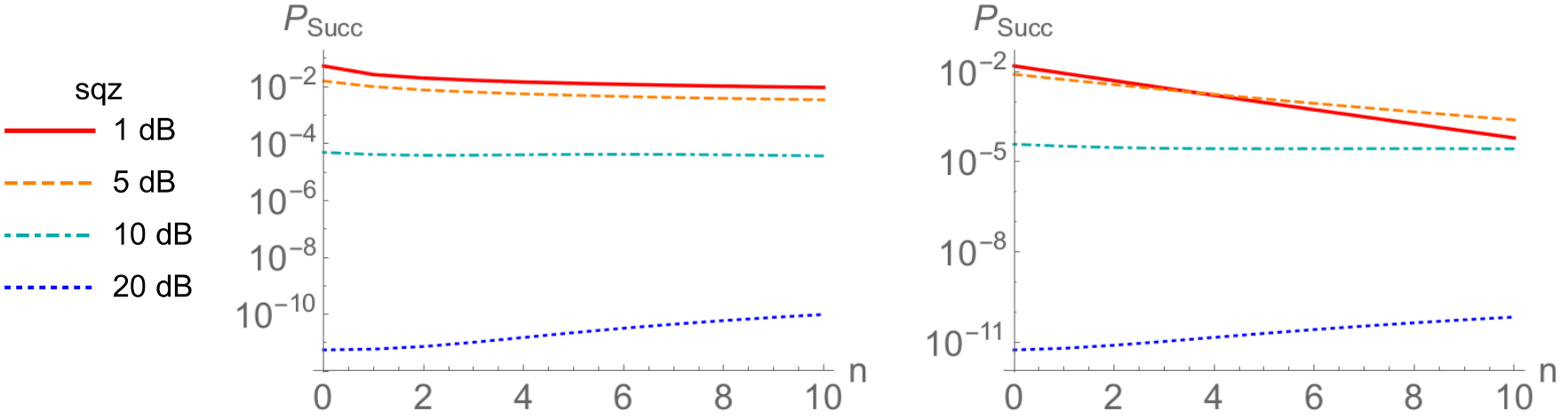
Fock states



Coherent states

Input:

Success Probability



Input: Fock states Coherent states

- Probability of detecting exactly one photon in each step
- Lower for high squeezing: many photons in the ancilla

Summary

- Modes, infinite dimensions for QIP
- Multi-pixel homodyne for MBQC
- Shaping the pump for better cluster states
- Non-Gaussianity subtracting photons, counting one photon at a time

Thank you !