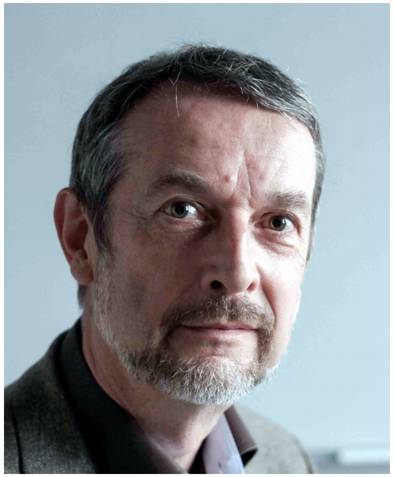
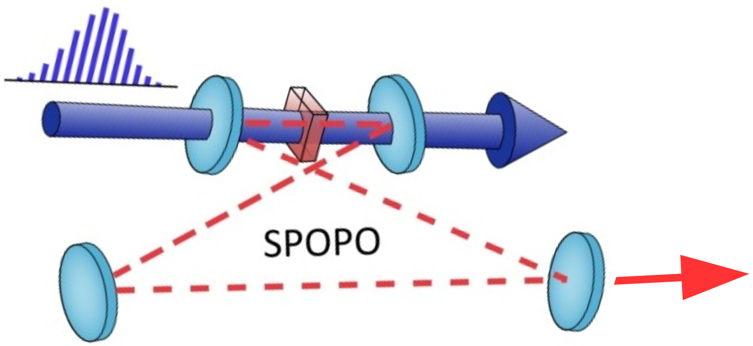
Versatile engineering of multimode squeezed states by optimizing the pump spectral profile in spontaneous parametric down-conversion

Francesco Arzani, Claude Fabre, Nicolas Treps

Phys. Rev. A 97, 033808 (2018)



Motivation: CV cluster states



Multi-mode squeezed vacuum

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

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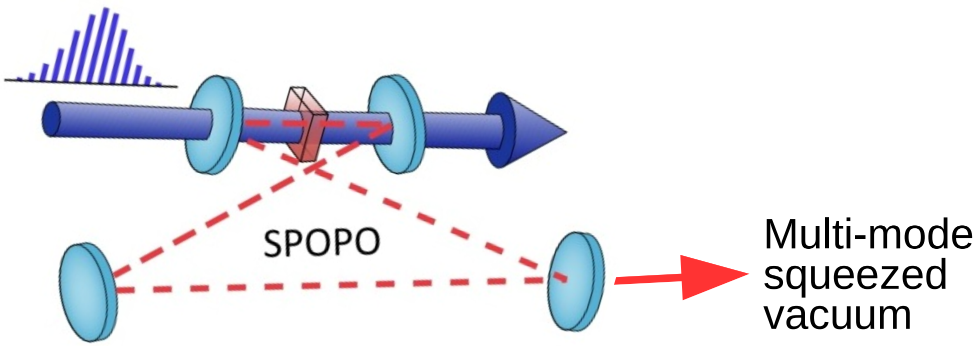

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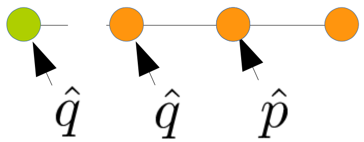
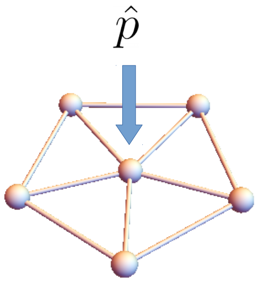
- CV One way QC



N. C. Menicucci et al, PRL 97, 110501 (2006)

- CV Secret Sharing



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

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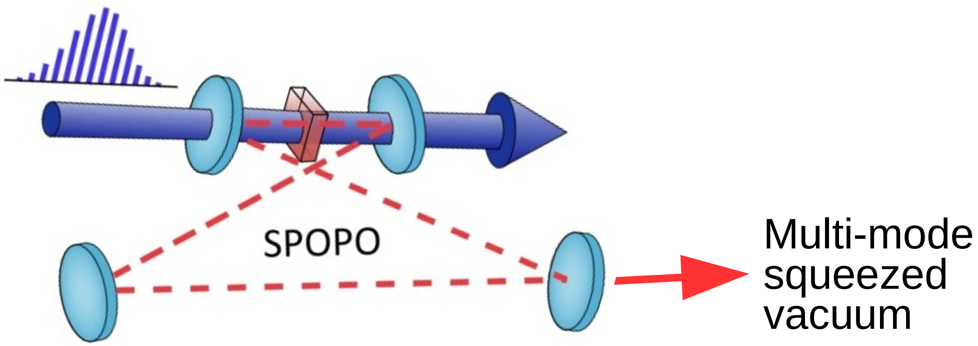

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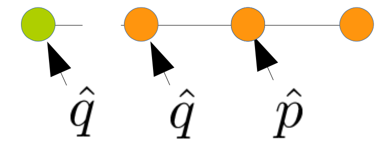

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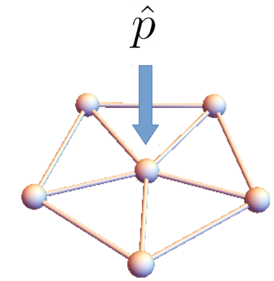

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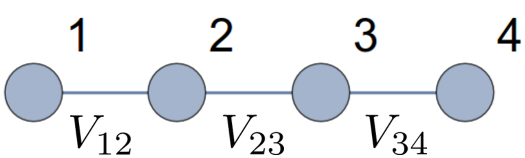


$$\begin{aligned}
\hat{\delta}_1 &= \hat{p}_1 - \hat{q}_2 \\
\hat{\delta}_2 &= \hat{p}_2 - \hat{q}_1 - \hat{q}_3 \\
\hat{\delta}_3 &= \hat{p}_3 - \hat{q}_2 - \hat{q}_4 \\
\hat{\delta}_4 &= \hat{p}_4 - \hat{q}_3
\end{aligned}$$

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

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

Producing Gaussian cluster states

For pure Gaussian states:

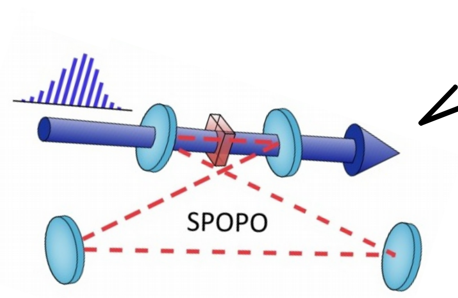
S. Braunstein, PRA 71, 055801 (2005)

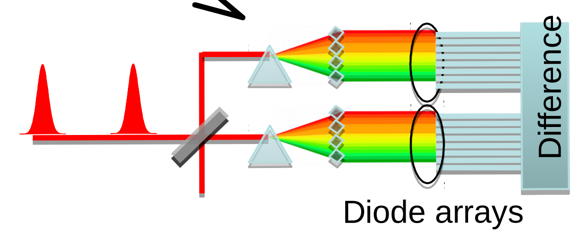
Vacuum → Multimode squeezing → Mode basis change → Multimode pure Gaussian quantum state

(Linear optics)

These operations are **deterministic**!

⇨ Approximate cluster states with squeezing + mode basis change

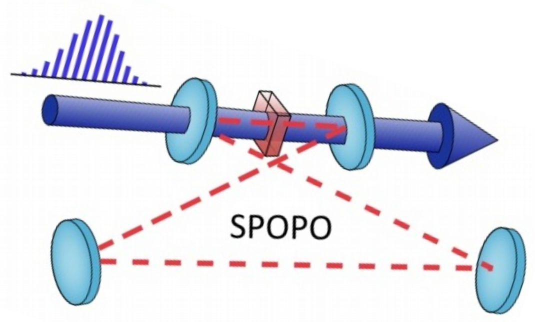


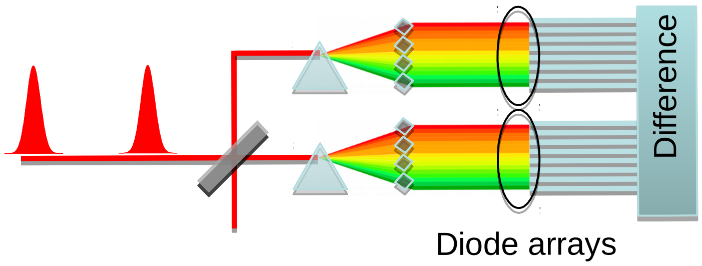


1

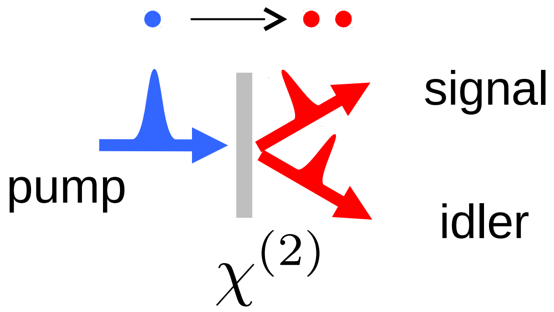
Spontaneous parametric down-conversion of optical frequency combs

(And how to measure it)





Multimode squeezing: Parametric Interaction



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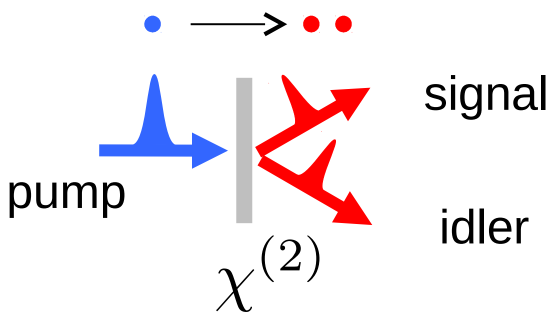

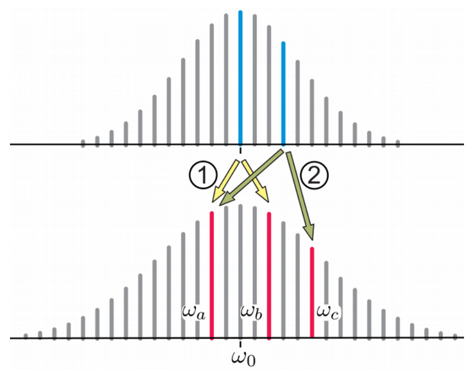

Interaction Hamiltonian

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

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

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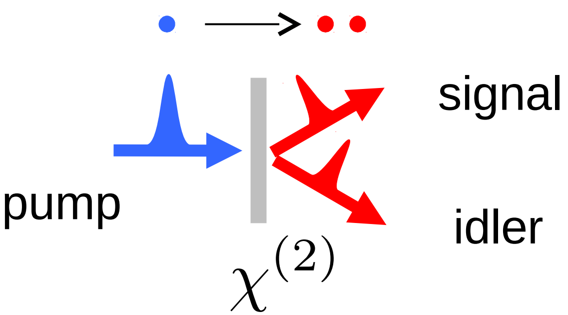

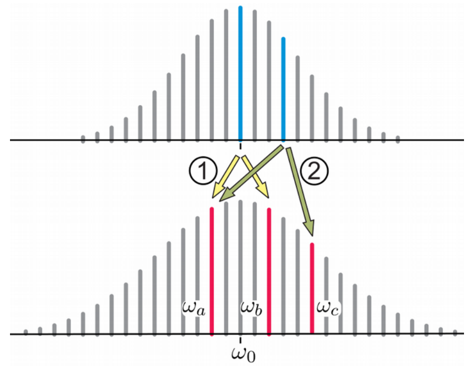

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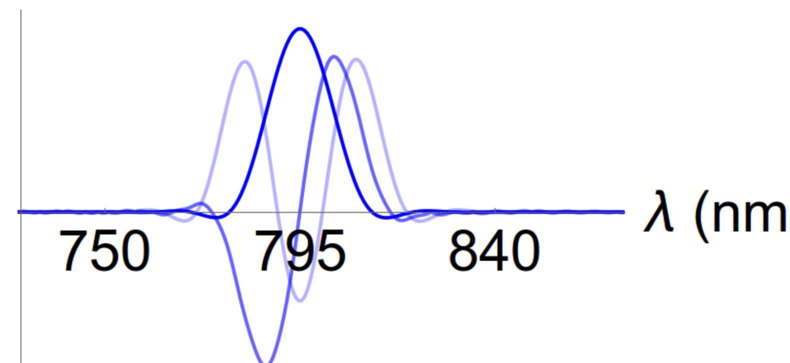
$$U \mathcal{L} U^T = \Lambda$$

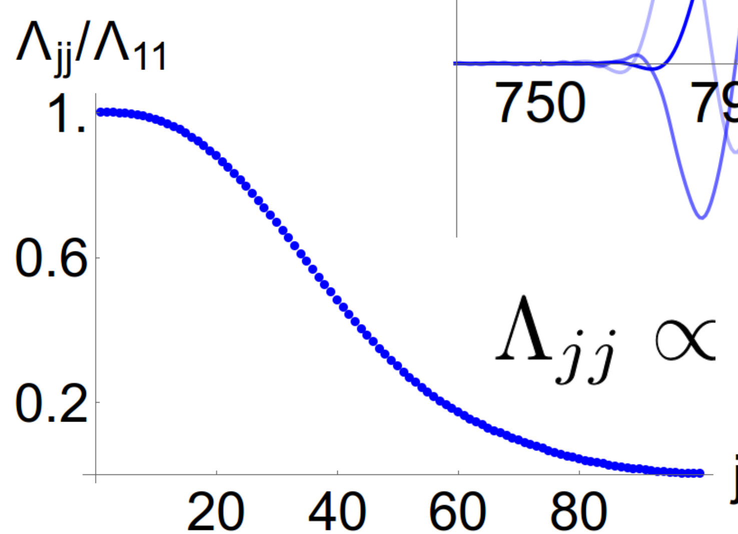
Symmetric SVD

$$H = i \sum_j \Lambda_{jj} \left(\hat{S}^\dagger_j\right)^2 + \text{h.c.}$$

Independent squeezers

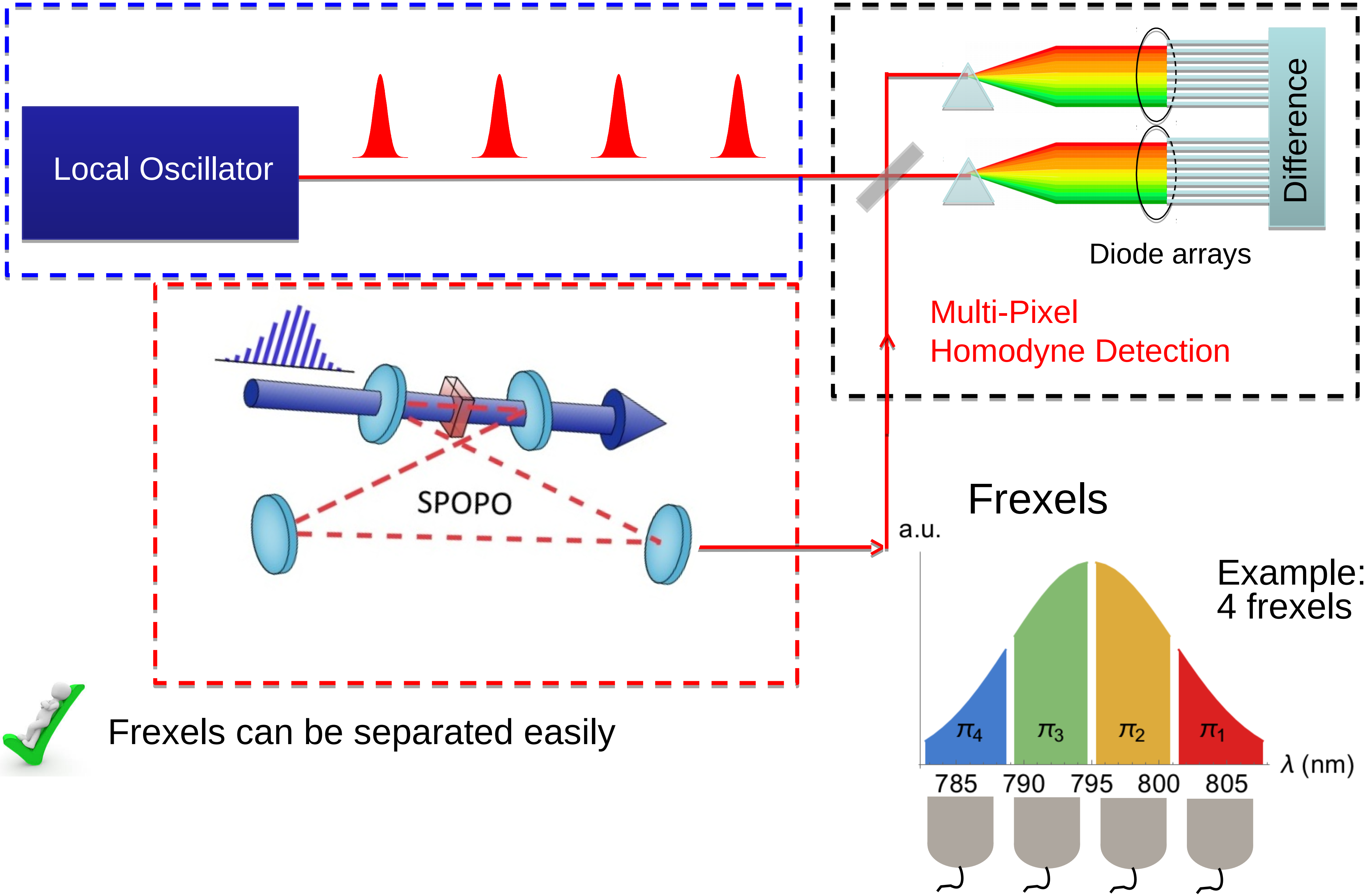
Rows of *U*:
Spectra of squeezed modes





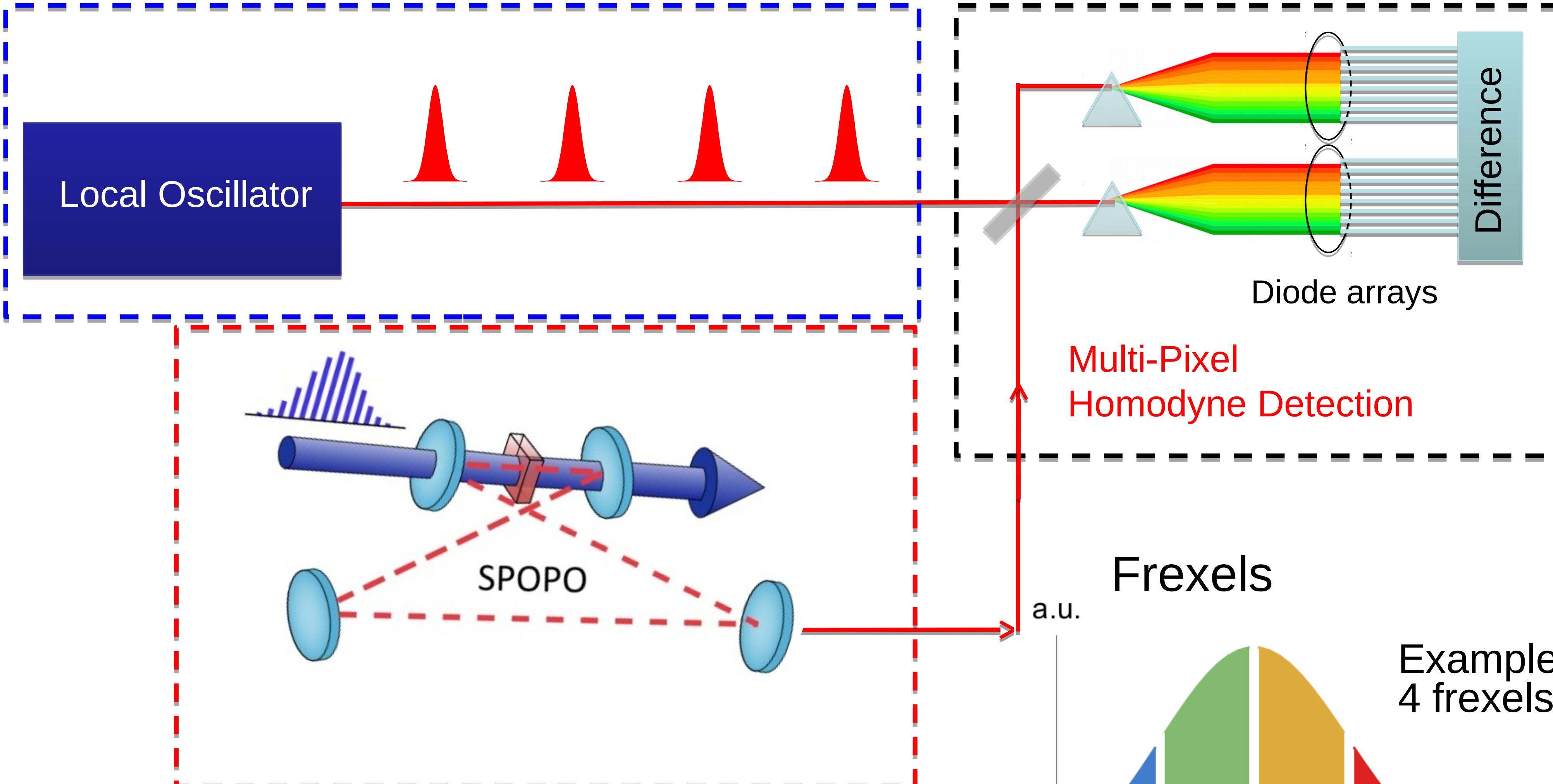
$$\Lambda_{jj} \propto$$ Squeezing parameters

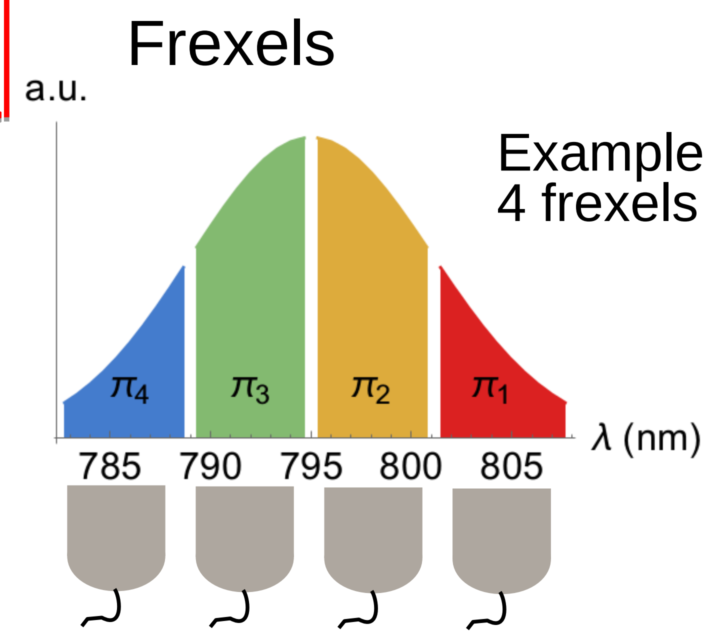
Multi-Pixel Homodyne Detection



Frexels can be separated easily

Multi-Pixel Homodyne Detection





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Not a cluster on frexels

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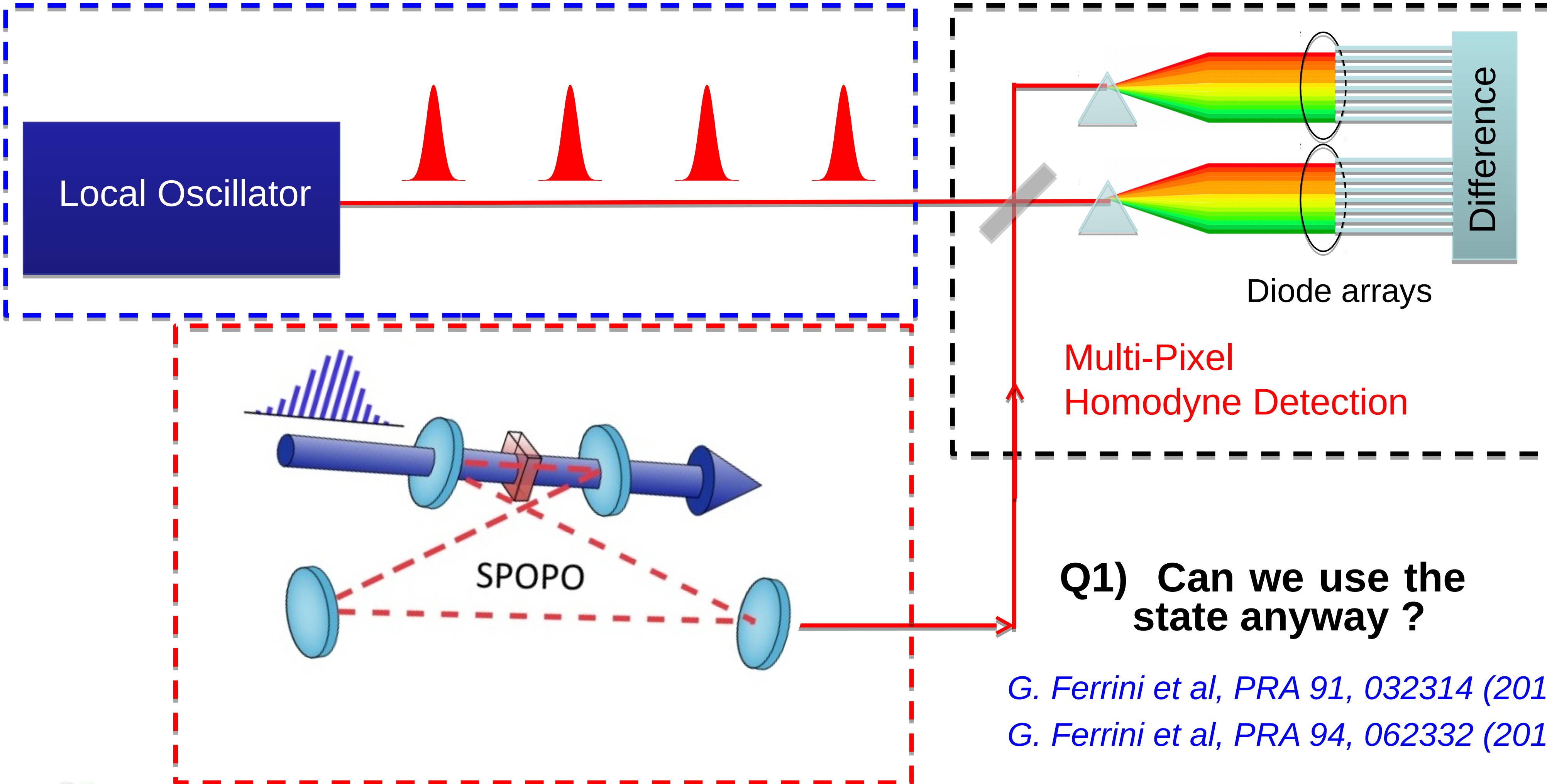

Q1) Can we use the state anyway ?

G. Ferrini et al, PRA 91, 032314 (2016)
G. Ferrini et al, PRA 94, 062332 (2016)

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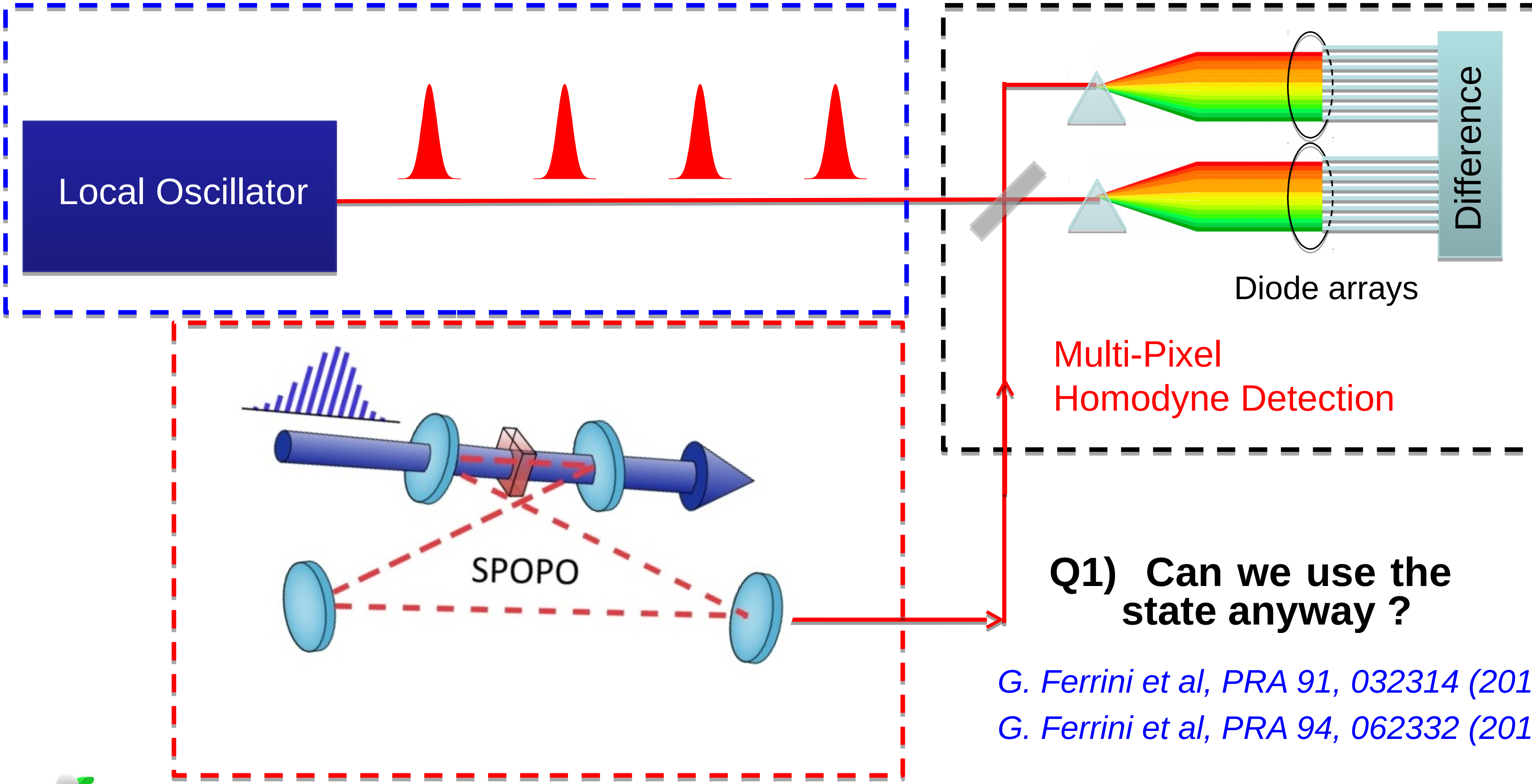

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G. Ferrini et al, PRA 91, 032314 (2015)
G. Ferrini et al, PRA 94, 062332 (2016)

Frexels can be separated easily

Not a cluster on frexels

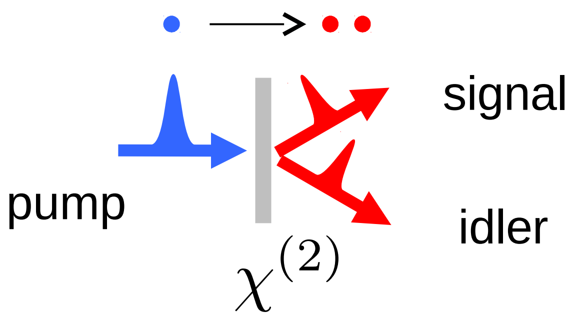
Q2) Can we engineer correlations given the measurement modes ?

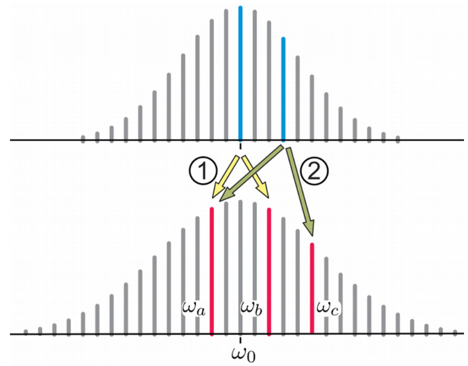
2

Shaping the pump spectrum

F. Arzani, C. Fabre, N. Treps. Phys. Rev. A 97, 033808 (2018)

Pump Shaping: Experimental Setup





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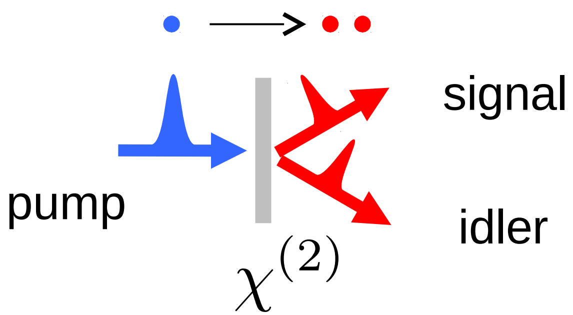

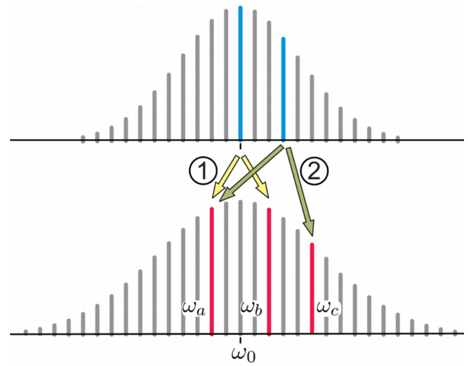

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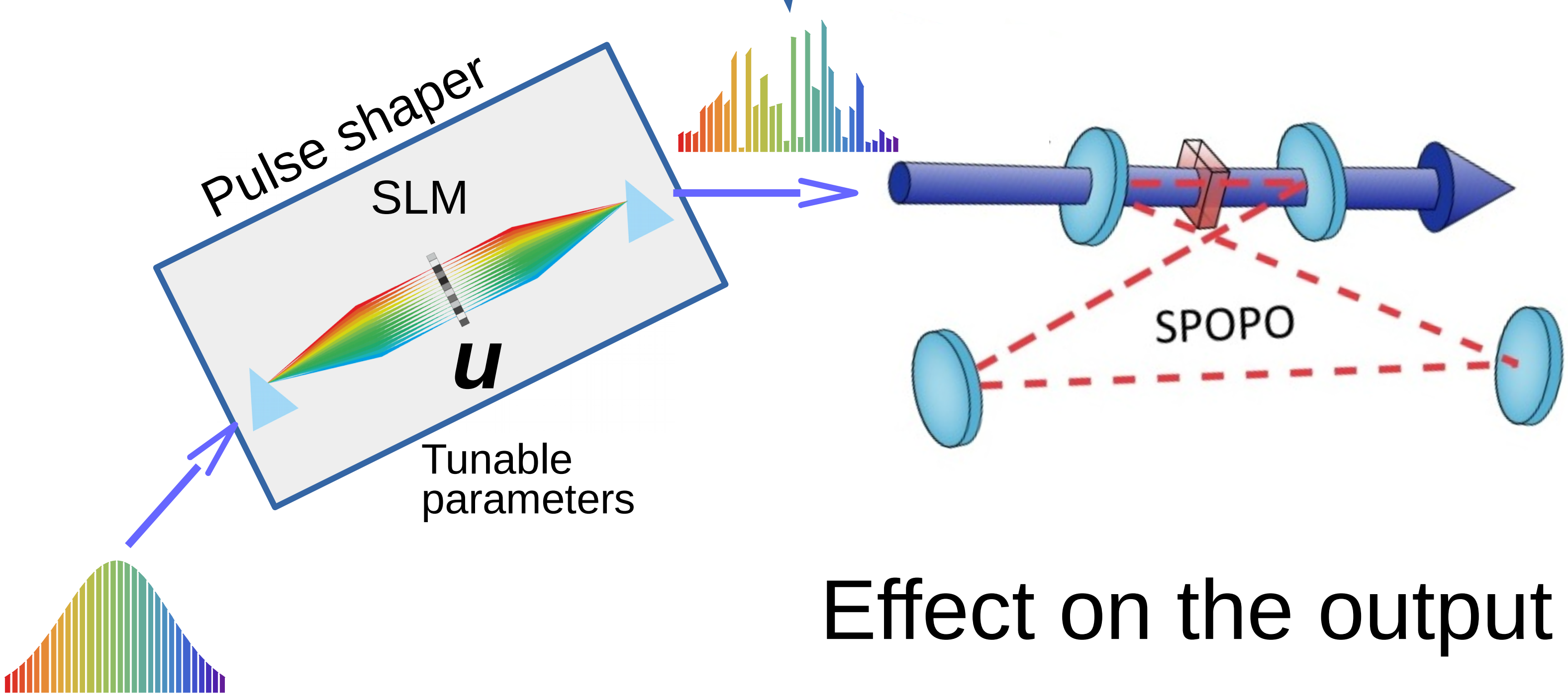

Effect on the output state ?

Tweaking the Squeezing

Complex relation between pump and squeezing/supermodes :
Use **numerical optimization**:

Tweaking the Squeezing

Complex relation between pump and squeezing/supermodes :
Use **numerical optimization**:

Maximize $\bar{f}_1$: flatten squeezing spectrum

Maximize $\bar{f}_2$: introduce gap between 1st and 2nd squeezing

+ Penalty for unfeasible shapes

Tweaking the Squeezing

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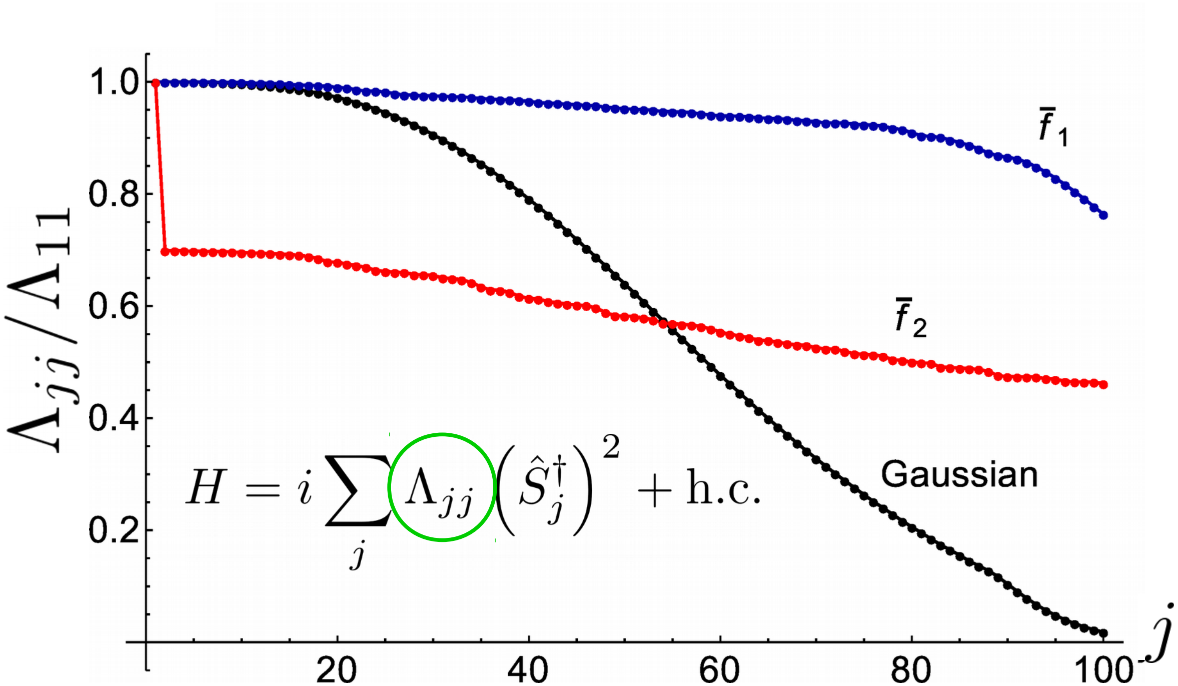
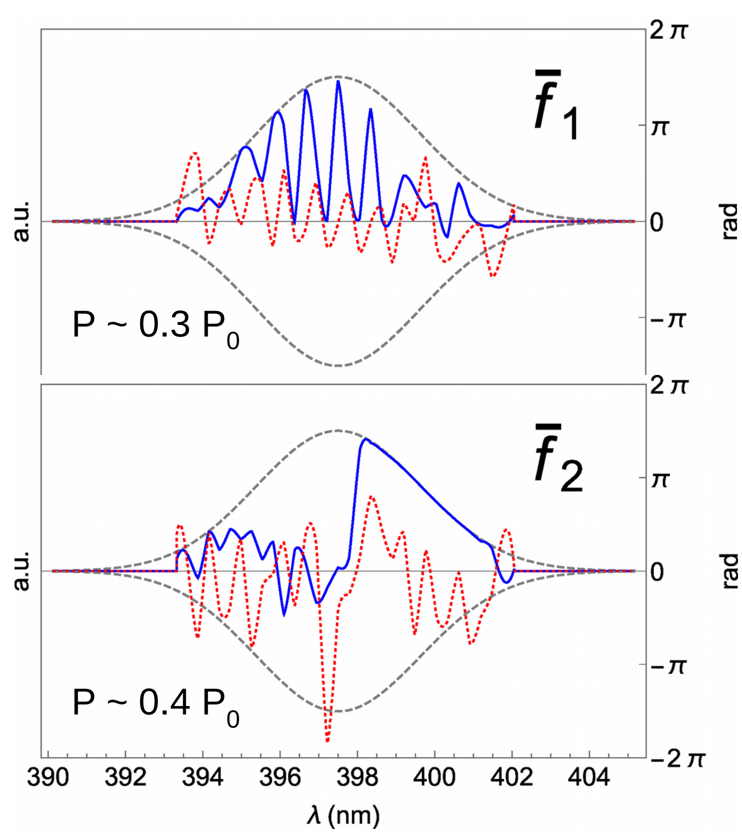


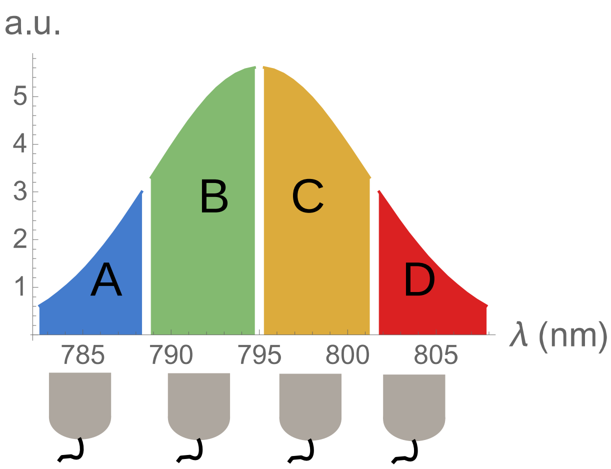
Optimal pump shapes

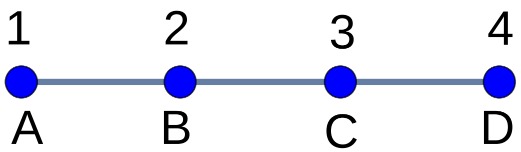


Adjust the squeezing spectrum :
Study collective behavior of quantum oscillators

J. Nokkala et al, NJP 20, 053024 (2018)

Optimizing CV Cluster States

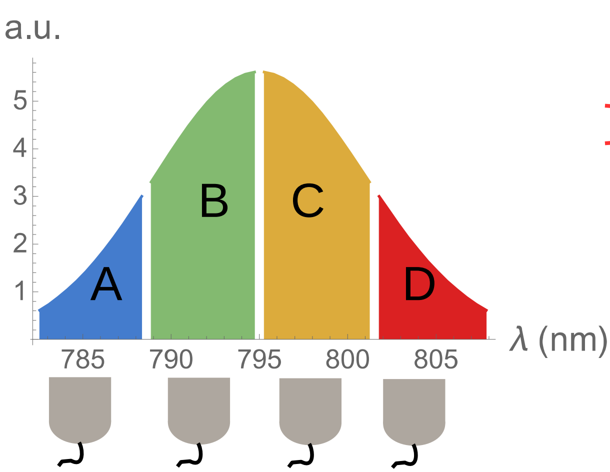


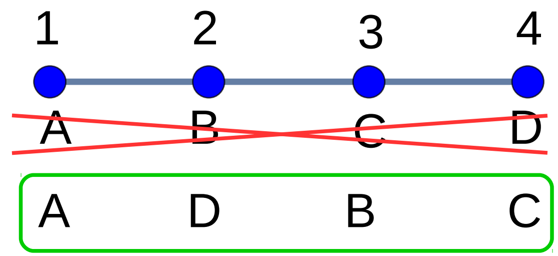


Mean nullifiers' squeezing :

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

Optimizing CV Cluster States





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

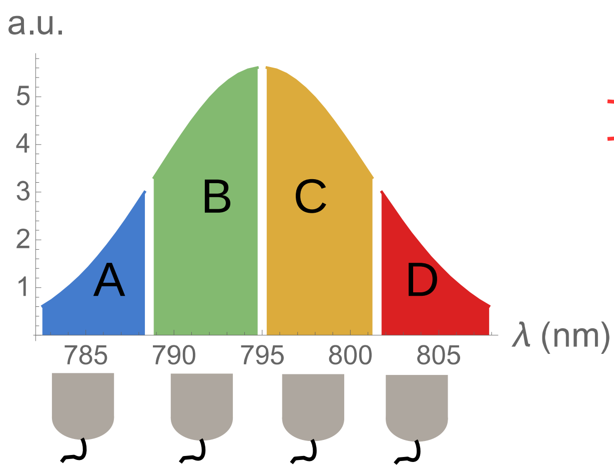
Mean nullifiers' squeezing :

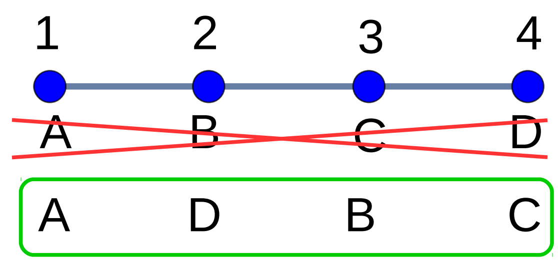
$\langle\Delta\delta_i\rangle$ = - 0.18 dB

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

Fully inseparable

Optimizing CV Cluster States





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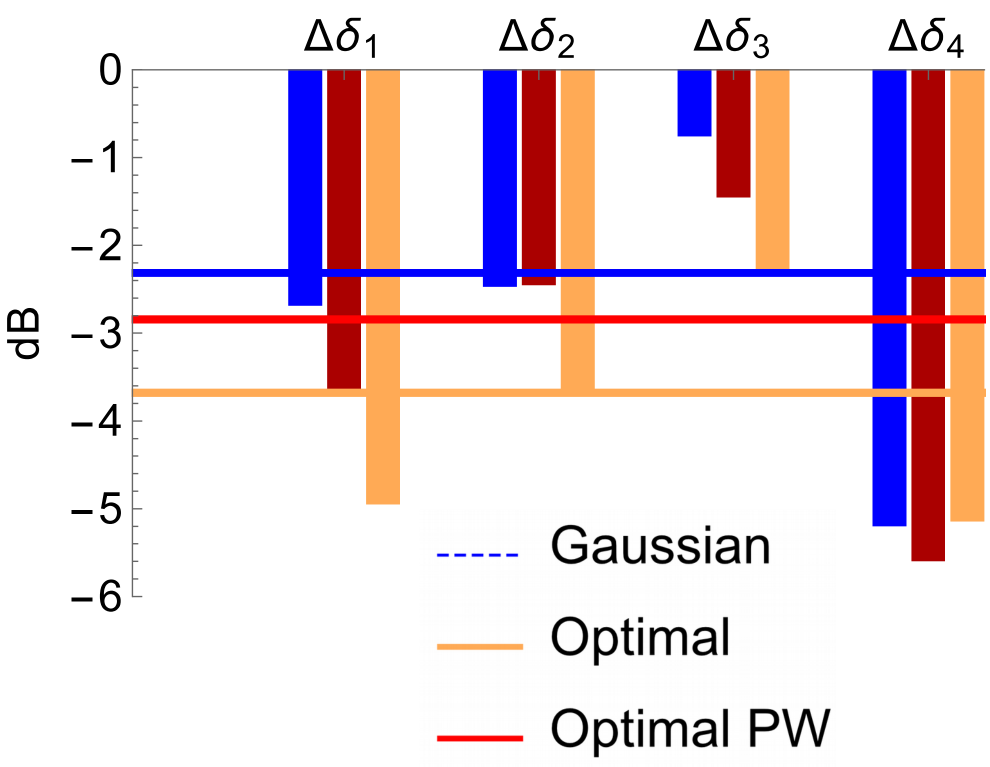
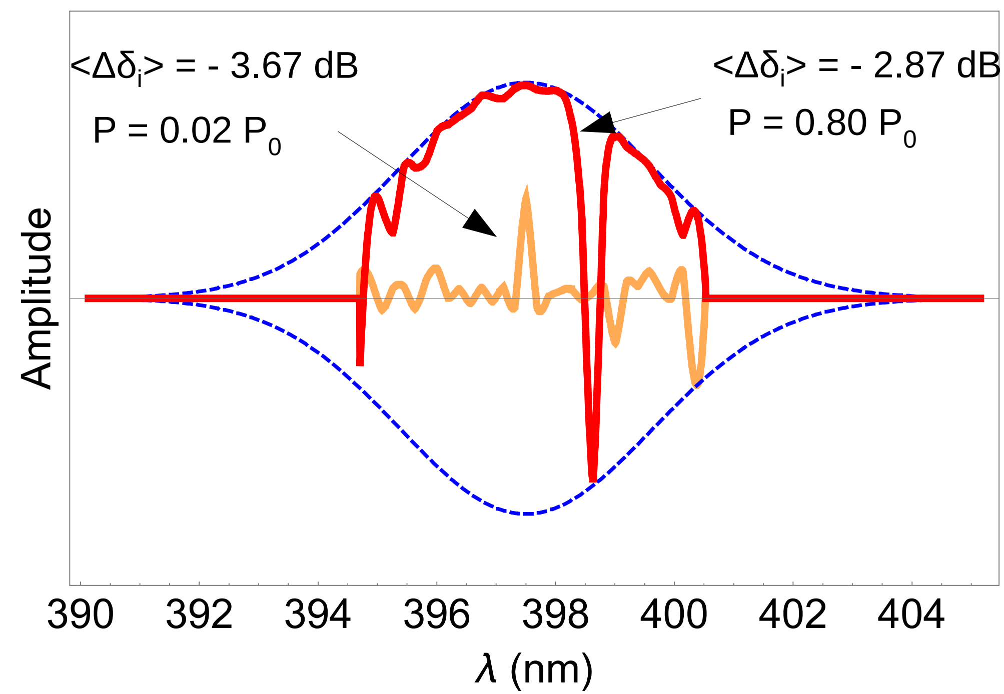
Mean nullifiers' squeezing :

$$\left.\begin{array}{l} \langle\Delta\delta_i\rangle = -\ 0.18 \text{ dB} \\ \langle\Delta\delta_i\rangle = -\ 2.31 \text{ dB} \end{array}\right\} \text{Fully inseparable}$$

Nullifiers' squeezing



Optimal pump profiles



(Non trivial spectral phase as well, not shown)

Summary

- SPOPOs can generate CV entangled states
- Spectrum of the pump has macroscopic effect
- Optimization effectively improves CV cluster states
- The method is versatile

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Johannes Nokkala


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Giulia Ferrini


Valentina Parigi


Jyrki Piilo

Thank you !