Laboratoire Kastler Brossel
Physique quantique et applications

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SORBONNE UNIVERSITÉ
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# Réseaux quantiques multimodes à variables continues


Valentina Parigi

Multimode quantum optics group

**Continuous Variables Quantum Complex Networks team**


European Research Council

OQuLus
FRANCE 2030

**Séminaire – cours Pascale Senellart – Chaire annuelle Innovation Technologique Liliane Bettencourt**

# Intro : CV quantum optics & information

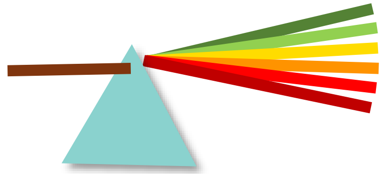
# Multimode quantum optics

**Light propagates**

with different polarizations

with different spatial shapes


with different spectral-temporal shapes

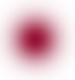


C.Fabre & N. Treps Modes and states in quantum optics, Rev. Mod. Phys. 92, 35005 (2020)

# Multimode quantum optics

**Light propagates**

with different polarizations 

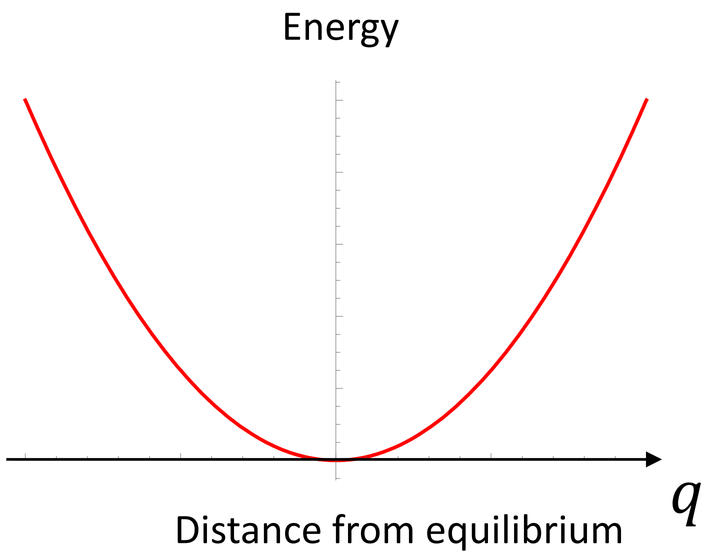
with different spatial shapes 

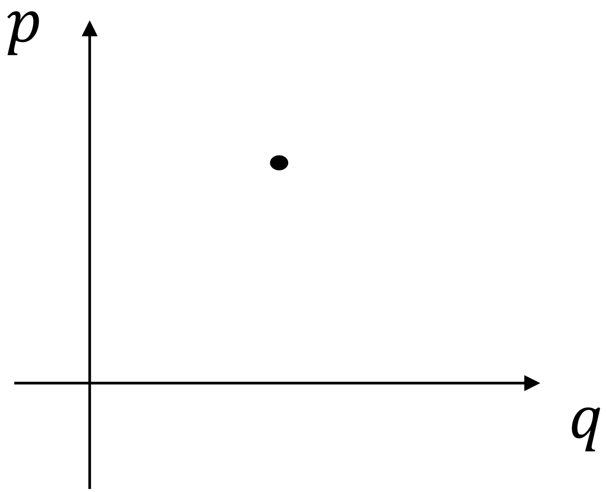

with different spectral-temporal shapes

each mode of light can be described by a

quantum harmonic oscillator $$H = \frac{p^2}{2m} + m\omega^2 \frac{q^2}{2}$$

# quantum optics



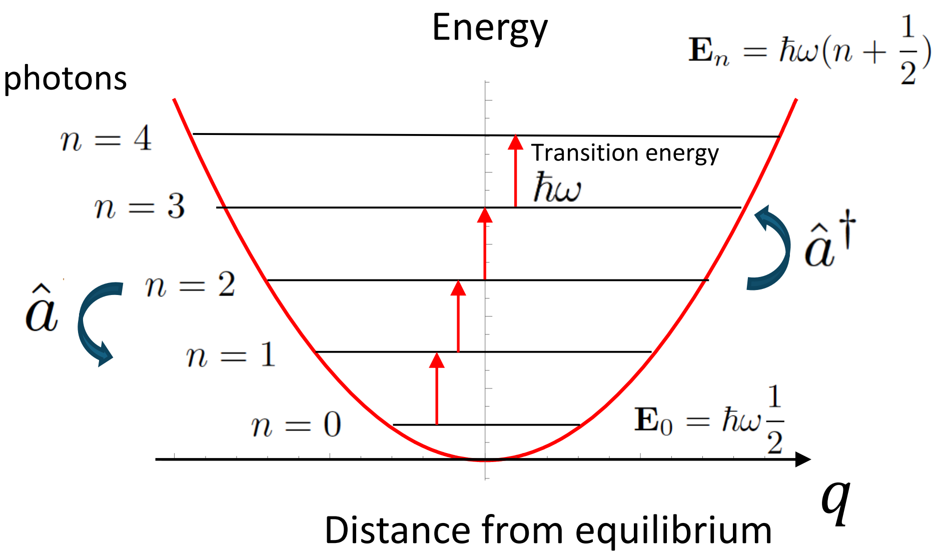



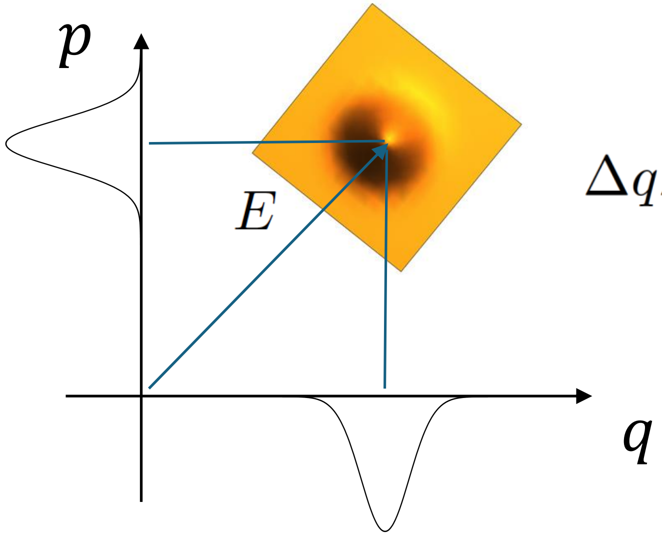

⇨ each mode of light can be described by a

quantum harmonic oscillator

$$H = \frac{p^2}{2m} + m\omega^2 \frac{q^2}{2}$$

# quantum optics




$$\Delta q \Delta p \geq \frac{\hbar}{2}$$

***Discrete variables description***

$$\hat{\rho} = \sum_{n,m} \varrho_{n,m} |n\rangle\langle m|$$

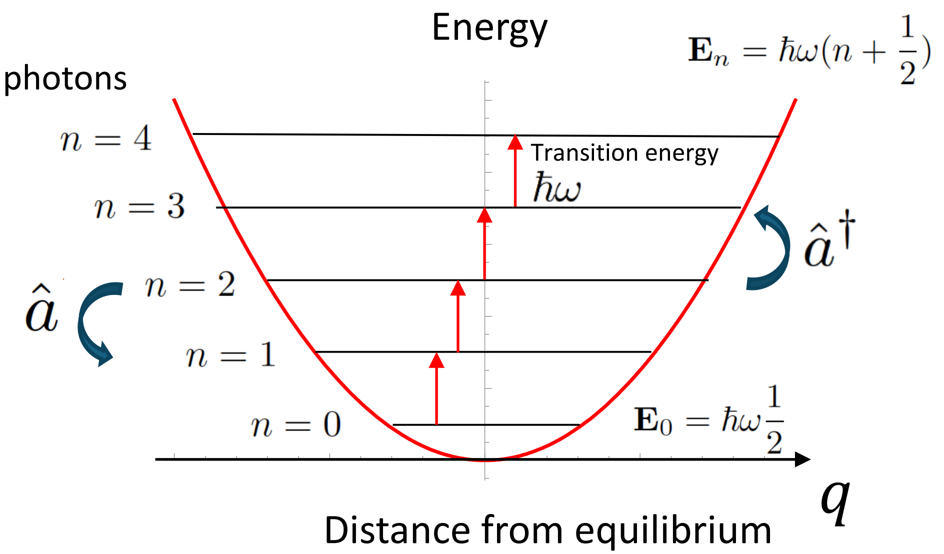
***Continuous variables description***

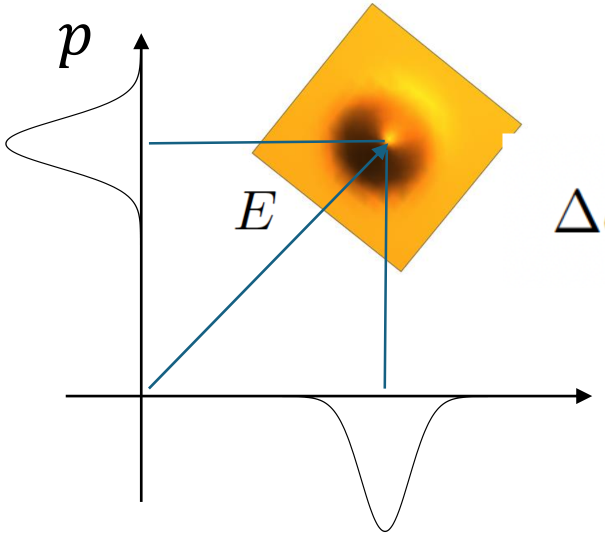
$$W(q,p)$$

each mode of light can be described by a

quantum harmonic oscillator $\hat{H} = \frac{\hat{p}^2}{2m} + m\omega^2\frac{\hat{q}^2}{2}$ $\hat{H} = \hbar\omega(\frac{1}{2} + \hat{a}^\dagger \hat{a})$

# quantum optics




$$\Delta q \Delta p \geq 1$$

***Discrete variables description***

$$\hat{\rho} = \sum_{n,m} \varrho_{n,m} |n\rangle\langle m|$$

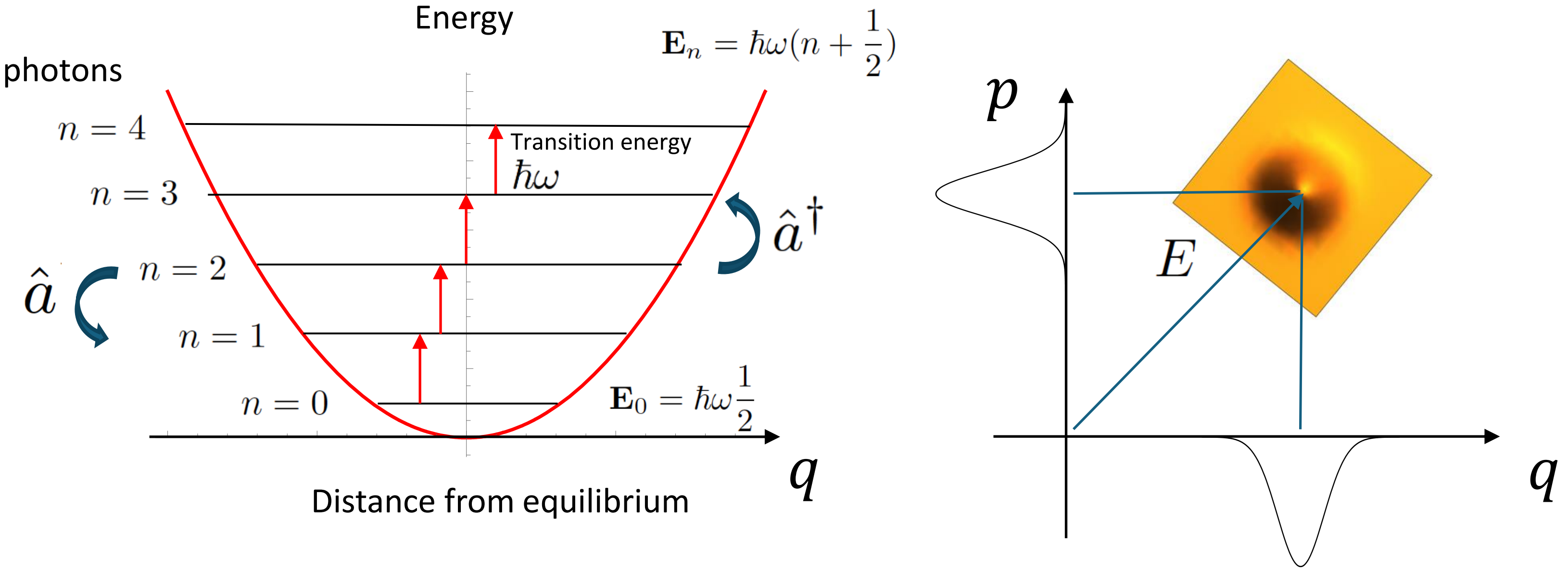
***Continuous variables description***

$$W(q,p)$$

each mode of light can be described by a $E^{(+)} = E_0 f(\vec{r},t)(\hat{q} + i\hat{p})$

quantum harmonic oscillator $\hat{H} = \frac{\hbar\omega}{2}(\hat{p}^2 + \hat{q}^2)$ $\hat{H} = \hbar\omega(\frac{1}{2} + \hat{a}^\dagger\hat{a})$

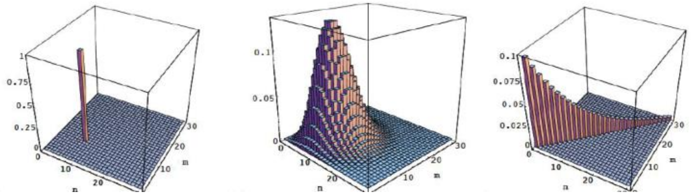
# quantum optics



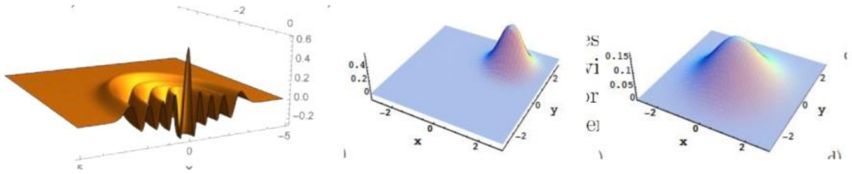

***Discrete variables description*** ↔ ***Continuous variables description***

$$\hat{\rho} = \sum_{n,m} \varrho_{n,m} |n\rangle\langle m|$$

$$W(q,p)$$



Fock Coherent Thermal



Fock Coherent Thermal

Fully equivalent (sometimes one is more practical than the other..)

# Experimental quantum optics

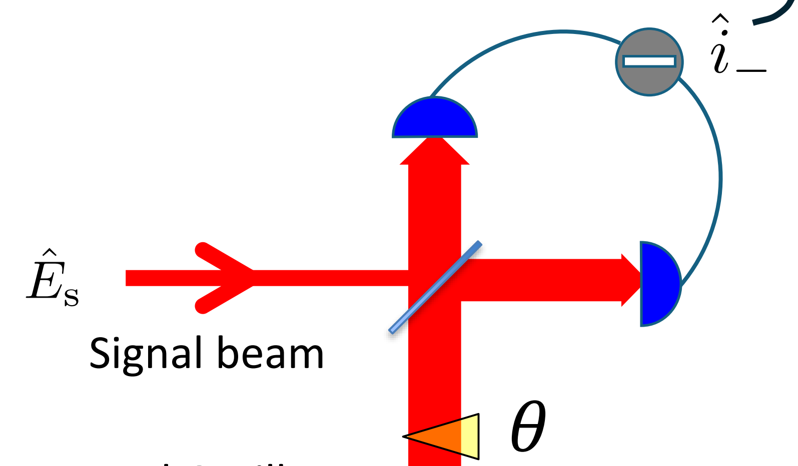
***Choice of Homodyne Detection***

Experimental measurement of quadratures

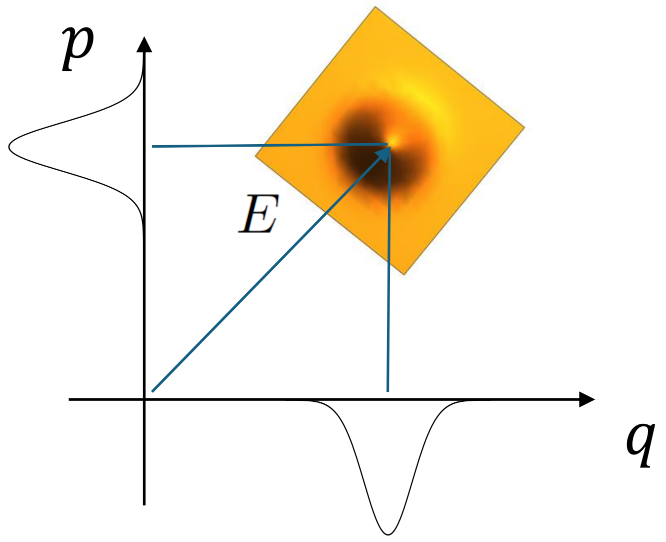
$$\hat{q} = \hat{a}^\dagger + \hat{a}$$

$$\hat{p} = i(\hat{a}^\dagger - \hat{a})$$

$$\hat{q}(\theta) = \hat{q}\cos(\theta) + \hat{p}\sin(\theta)$$

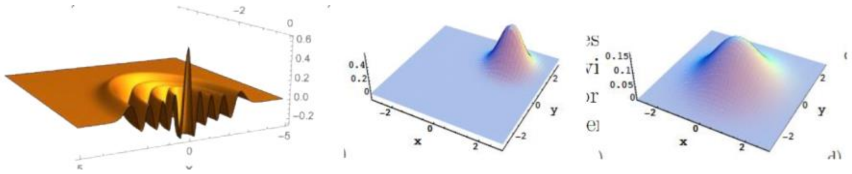



**Room temperature!**




***Continuous variables description!***

$$W(q,p)$$



Fock Coherent Thermal

# Information

***Discrete variables encoding***

0 1 0 0 0 1 1 1 0 1

***Continuous variables encoding***

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

# Quantum Information

**Discrete variables encoding**

0 1 0 0 0 1 1 1 0 1

$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$

**Continuous variables encoding**

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

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

*superposition*

*entanglement: quantum correlations*

$|\psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle_S|1\rangle_I + |1\rangle_S|0\rangle_I)$

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

# Quantum Information

LKB

***Discrete variables encoding***

***Continuous variables encoding***

0 1 0 0 0 1 1 1 0 1

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

*superposition*

$$| \psi \rangle = \alpha|0\rangle + \beta|1\rangle$$

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

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

**Quantum technologies based on CV encoding and measurement via homodyne!**

CV quantum communication ( ex. E. Diamanti)
CV quantum metrology ( ex. N. Treps)
CV quantum computing

# Photonics: entangled networks

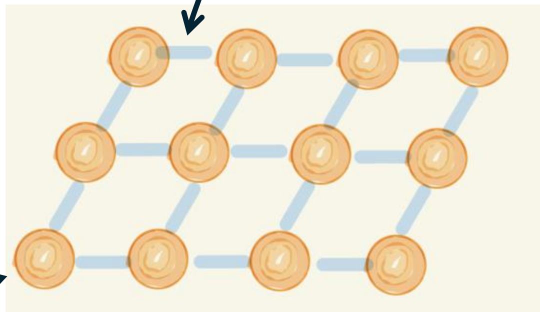
LKB

***Discrete variables encoding***

***Continuous variables encoding***

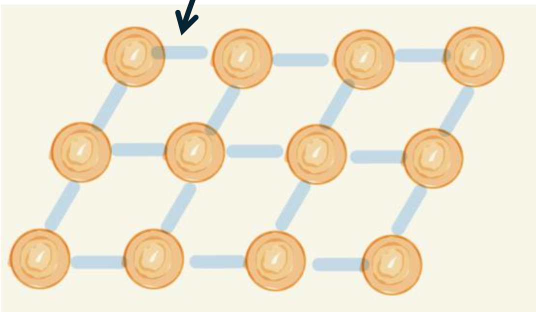
***entanglement: quantum correlations***

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle_S|1\rangle_I + |1\rangle_S|0\rangle_I\right)$$



Photons
Qubits

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



Modes of the field
Qumodes

# Photonics: entangled networks

***Discrete variables encoding***

P. Senellart group, …

QUANDELA

See class and seminar of G. Rempe - 03 February !

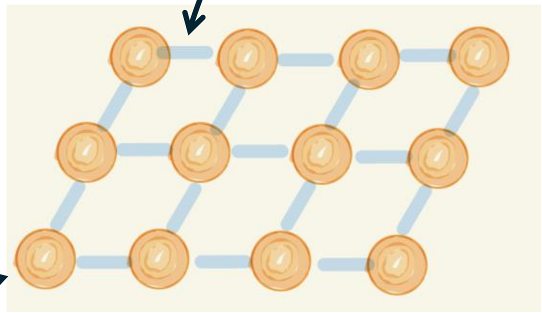
***Continuous variables encoding***

U. Andersen group, A. Furusawa, O. Pfister, our group,

XANADU

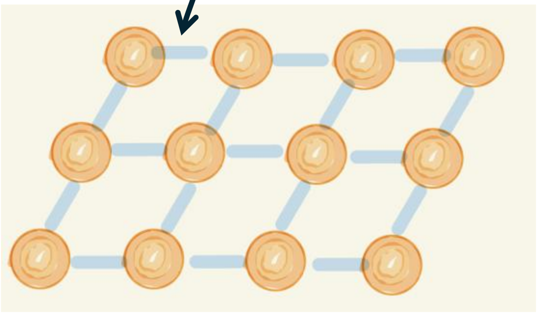
***entanglement: quantum correlations***

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|0\rangle_S|1\rangle_I + |1\rangle_S|0\rangle_I)$$



Photons
Qubits

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



Modes of the field
Qumodes

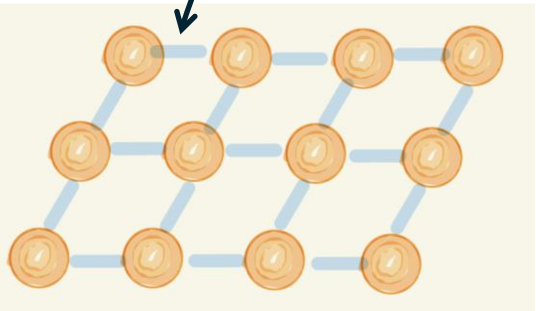
# What I do : CV entangled networks

*Continuous variables encoding*

**Quantum technologies based on CV encoding and measurement via homodyne!**

**CV quantum communication**
**CV quantum computing**

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



Modes of the field
Qumodes

# What I do : CV entangled networks

## Photonic quantum computing

**Continuous Variable cluster states for measurement-based protocols**

**Quantum Reservoir Computing**

## Quantum communication networks

**Multiparty quantum protocols and routing**

## Simulating and probing complex quantum structure

**Simulating quantum environment, open quantum systems quantum thermodynamics**

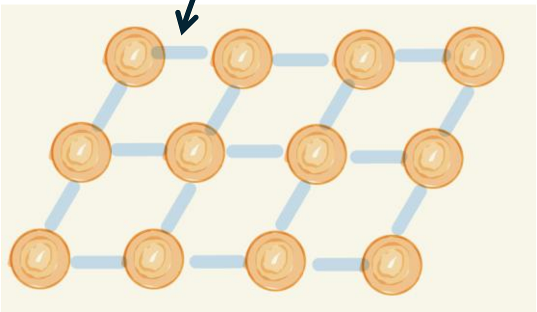
**Probing non-Gaussian features**

***Continuous variables encoding***

**Quantum technologies based on CV encoding and measurement via homodyne!**

**CV quantum communication**
**CV quantum computing**

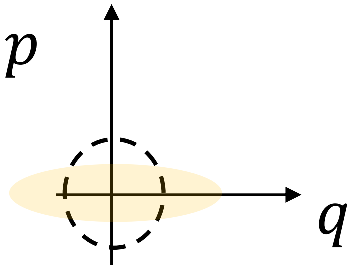
$$|\psi\rangle \sim \delta(q_s - q_i)\delta(p_s + p_i)$$



Modes of the field
Qumodes

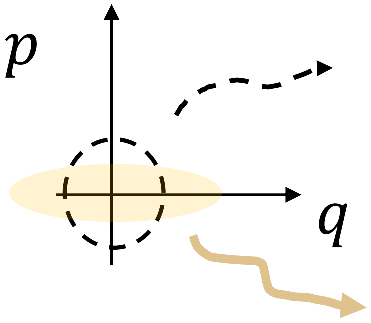
# Building CV entangled newtorks

# Squeezing: building block of CV entangled states




*squeezed state of light*

# Squeezing: building block of CV entangled states



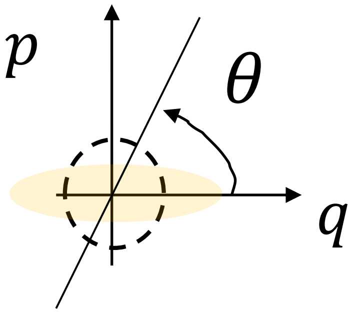

*vacuum*

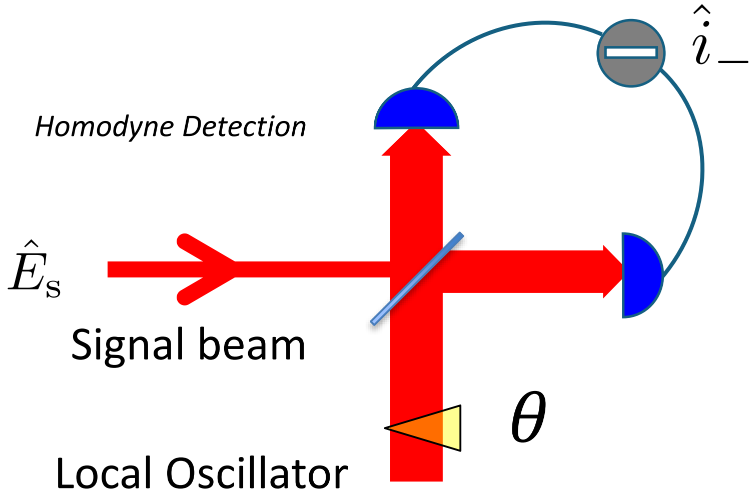
$\Delta q \Delta p = 1 \qquad \Delta q = \Delta p = 1$

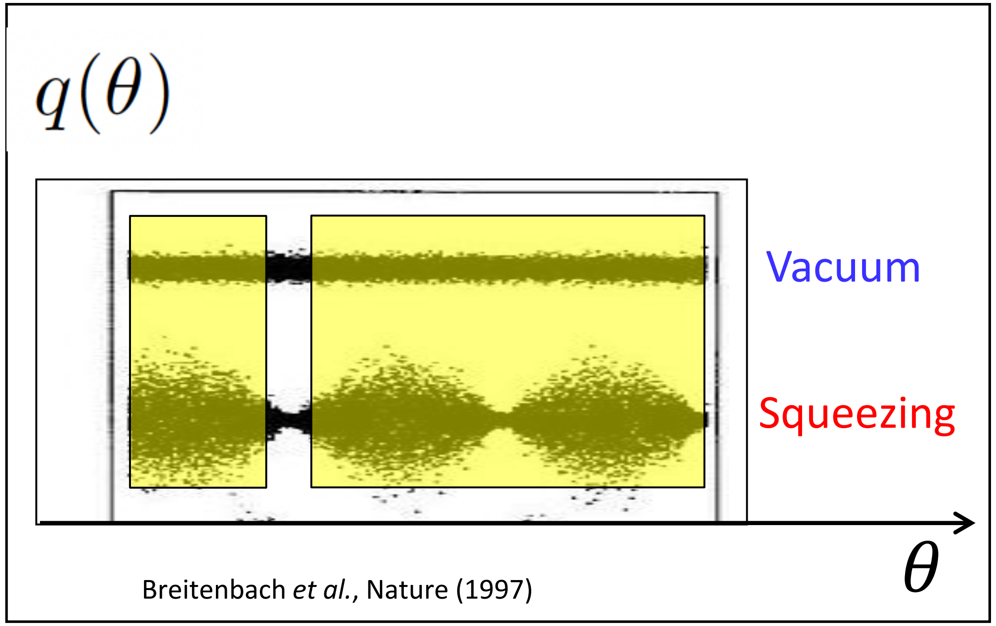
*squeezed state of light*

$\Delta q \Delta p = 1 \qquad \Delta q < 1 \quad \Delta p > 1$

# Squeezing: building block of CV entangled states



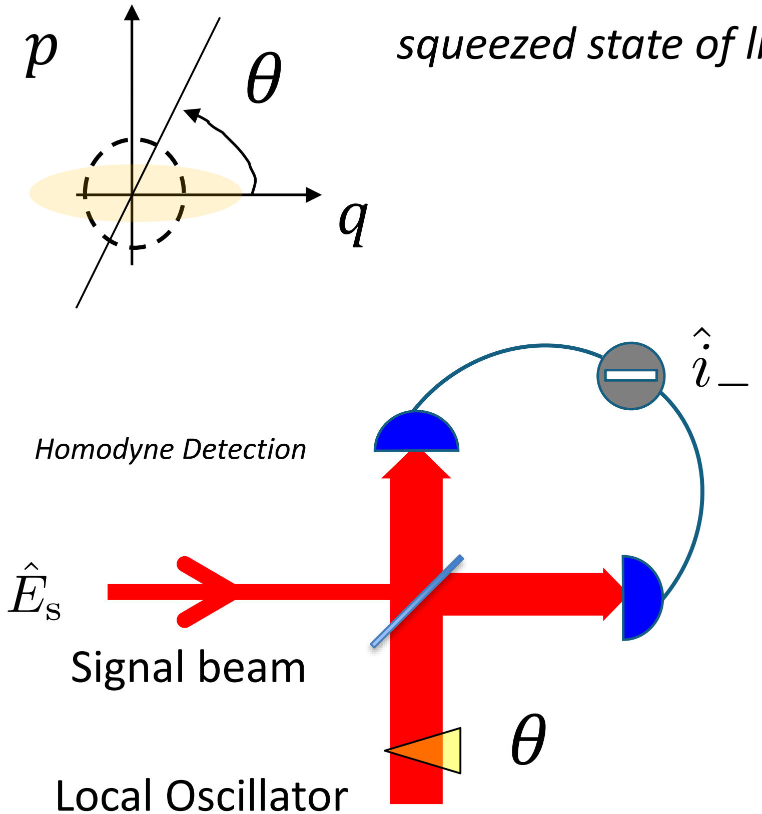



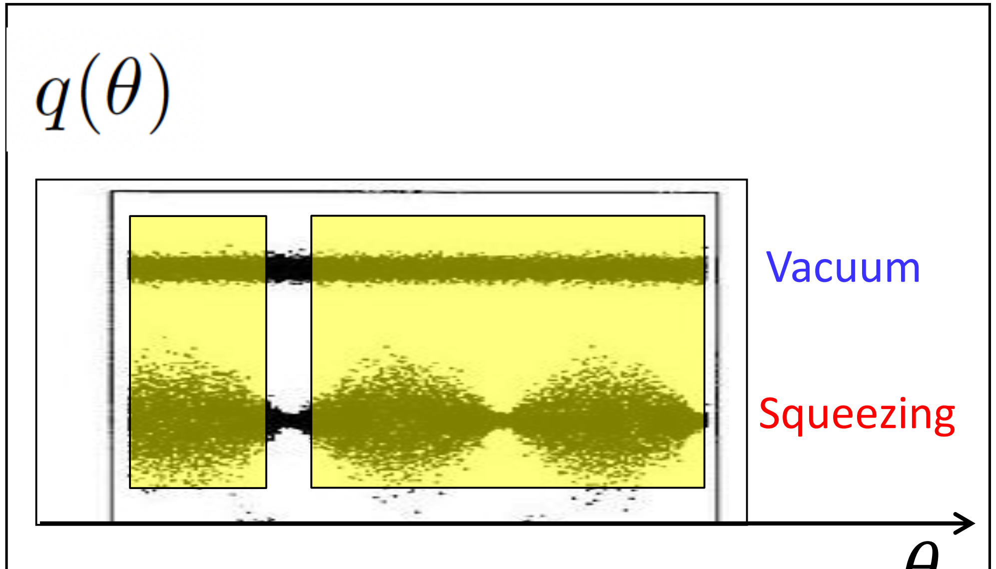

$$\hat{q}(\theta) = \hat{q}\cos(\theta) + \hat{p}\sin(\theta)$$

Squeezing = measured noise smaller than the vacuum noise

Squeezing usually expressed in dB

# Squeezing: building block of CV entangled states




Breitenbach *et al.*, Nature (1997)

$$\hat{q}(\theta) = \hat{q}\cos(\theta) + \hat{p}\sin(\theta)$$

LKB - > pioneer in the generation and measurement of squeezing ( C. Fabre, E. Giacobino, A. Heidmann,..)

P.-F. Cohadon

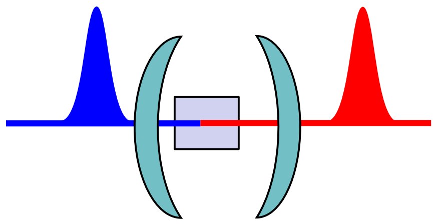
**Squeezed state of light used to improve sensitivity In gravitational wave detectors ( LIGO-VIRGO)**

# Squeezing: building block of CV entangled states

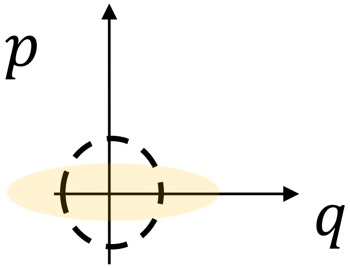
*Generation: Spontaneous parametric down conversion process*

*Degenerate case*

$$\omega_s = \omega_i$$

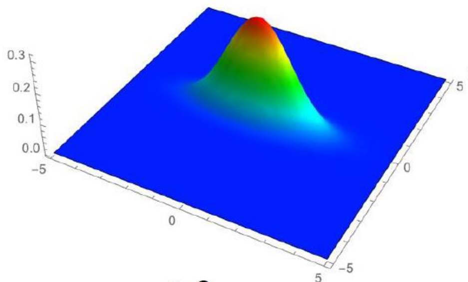


$$\hbar\omega_p = \hbar\omega_s + \hbar\omega_i$$

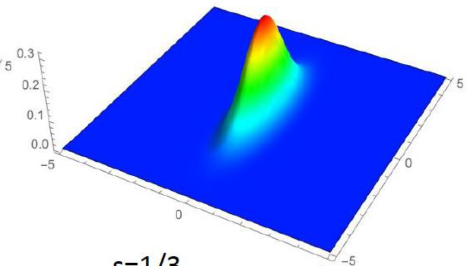



$$H = g\chi\left((a^{\dagger})^2 - (a)^2\right)$$

$$W_s(x,p) = \frac{1}{\pi} e^{-\frac{(x-\langle x\rangle)^2}{s} - \frac{(p-\langle p\rangle)^2}{1/s}}$$

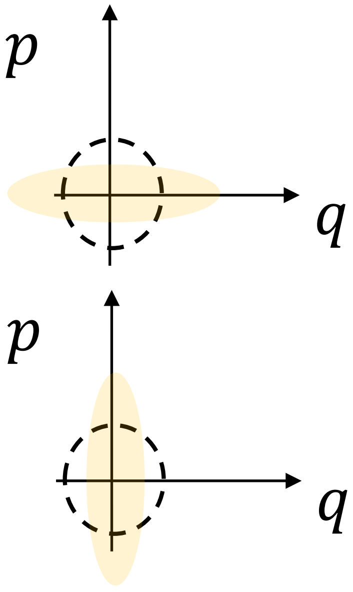


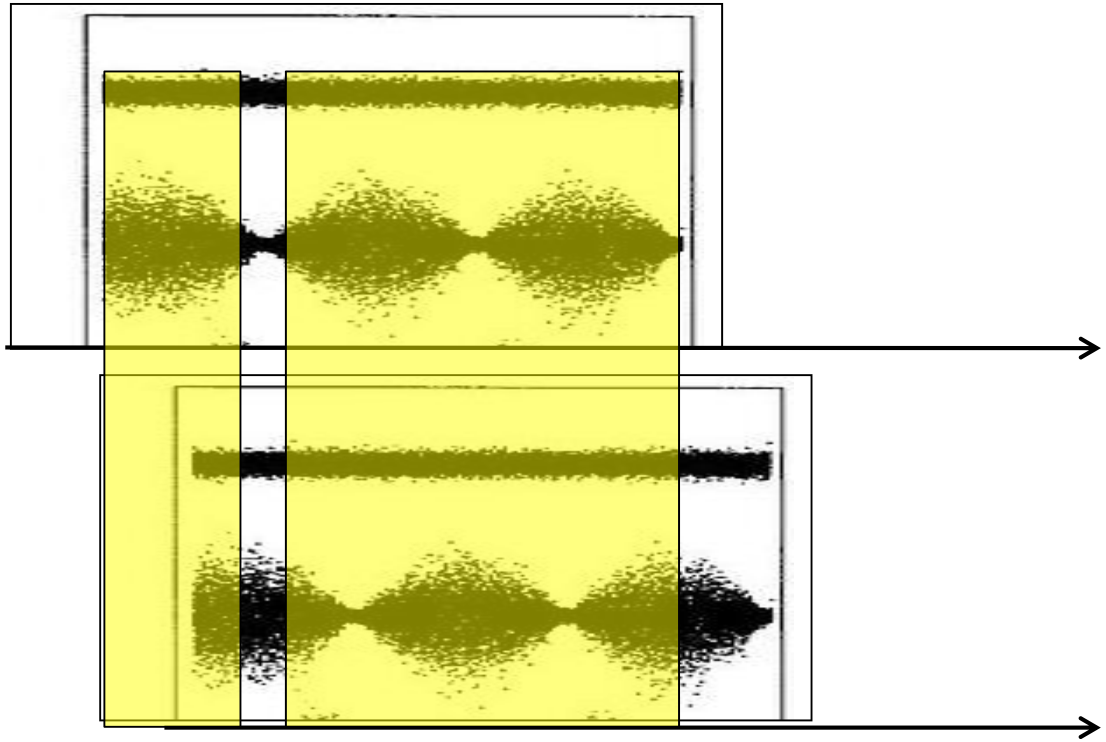

s=3



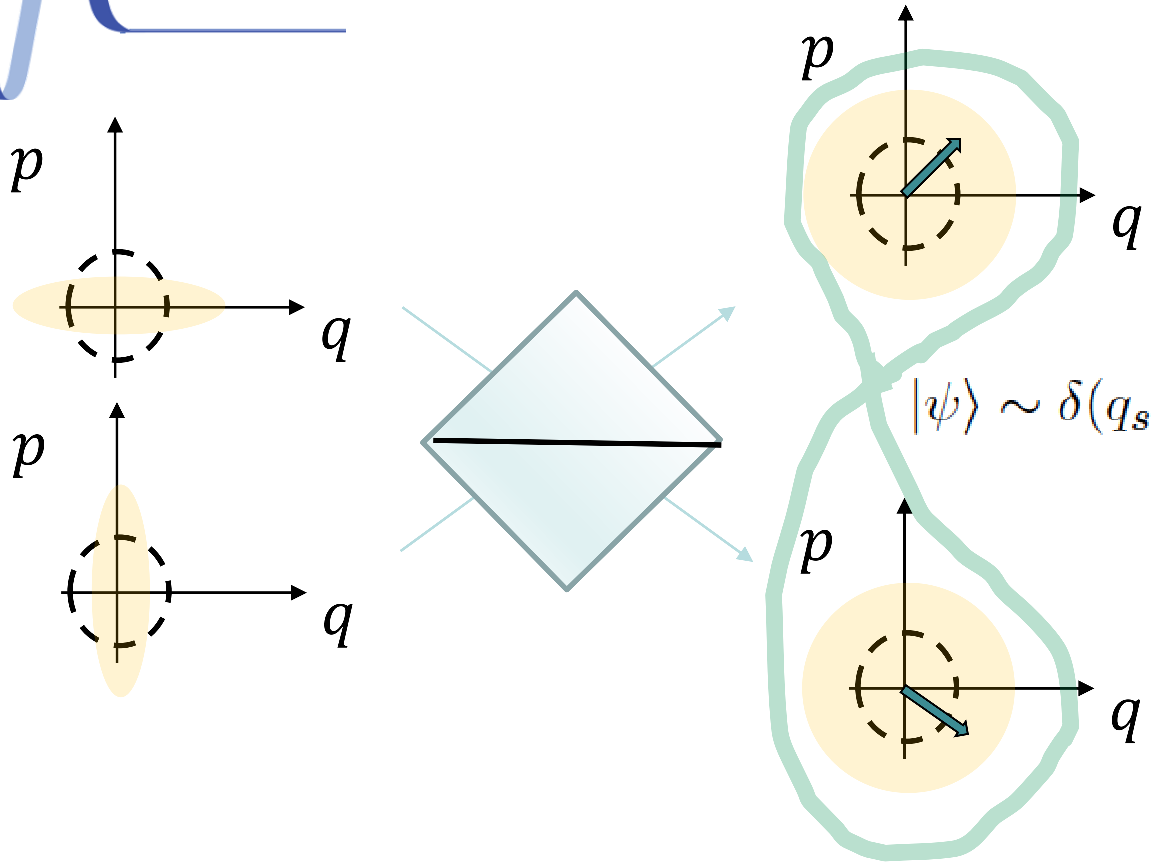

s=1/3

# Two nodes of the network

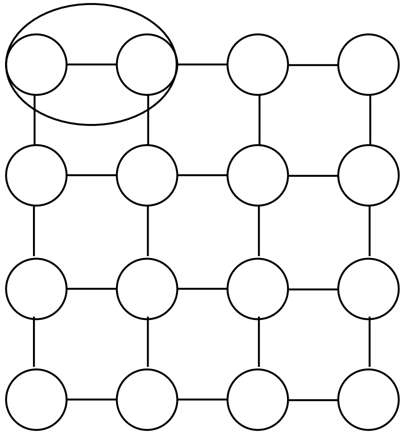


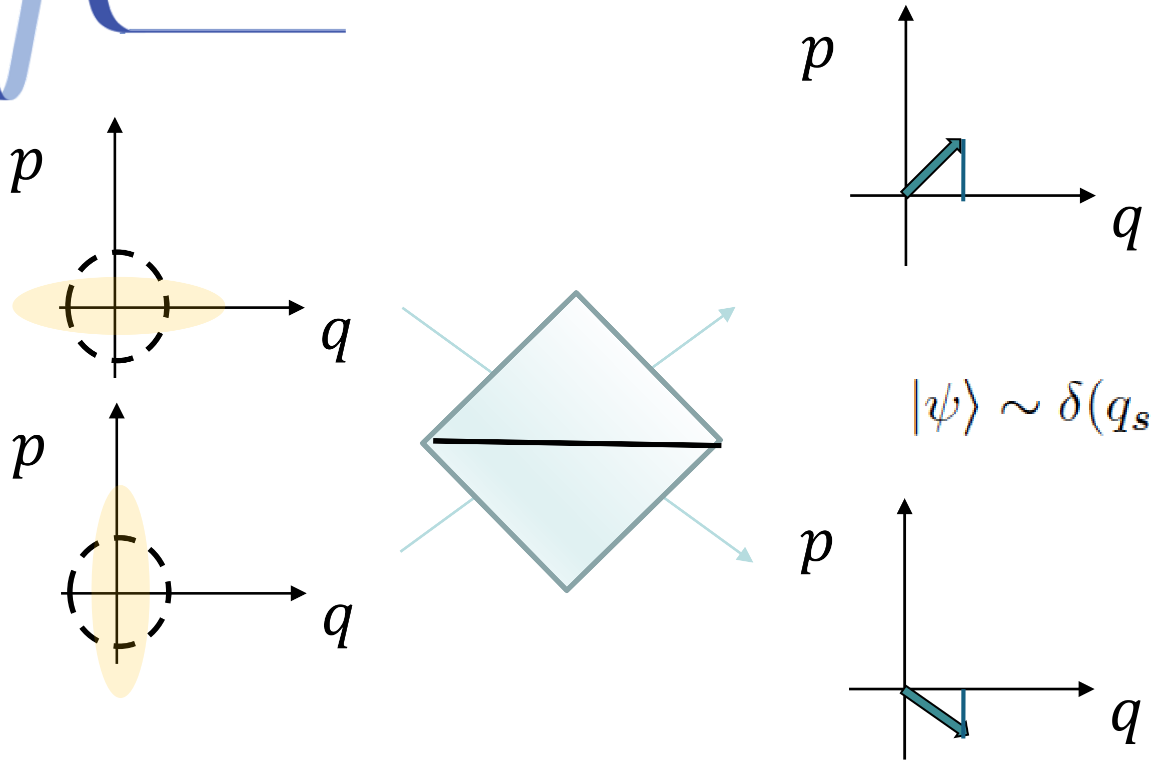
# Two nodes of the network




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



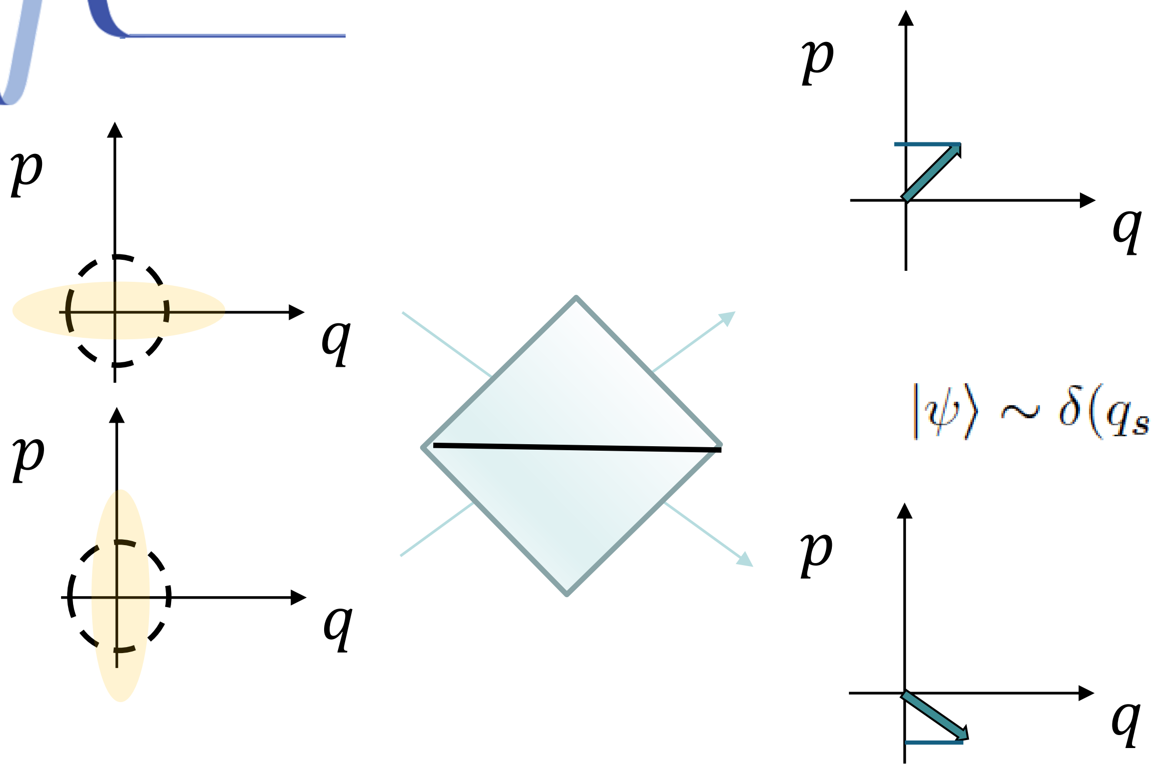
# Two nodes of the network




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

Simultaneous homodyne measurement of either q or p on both outputs !

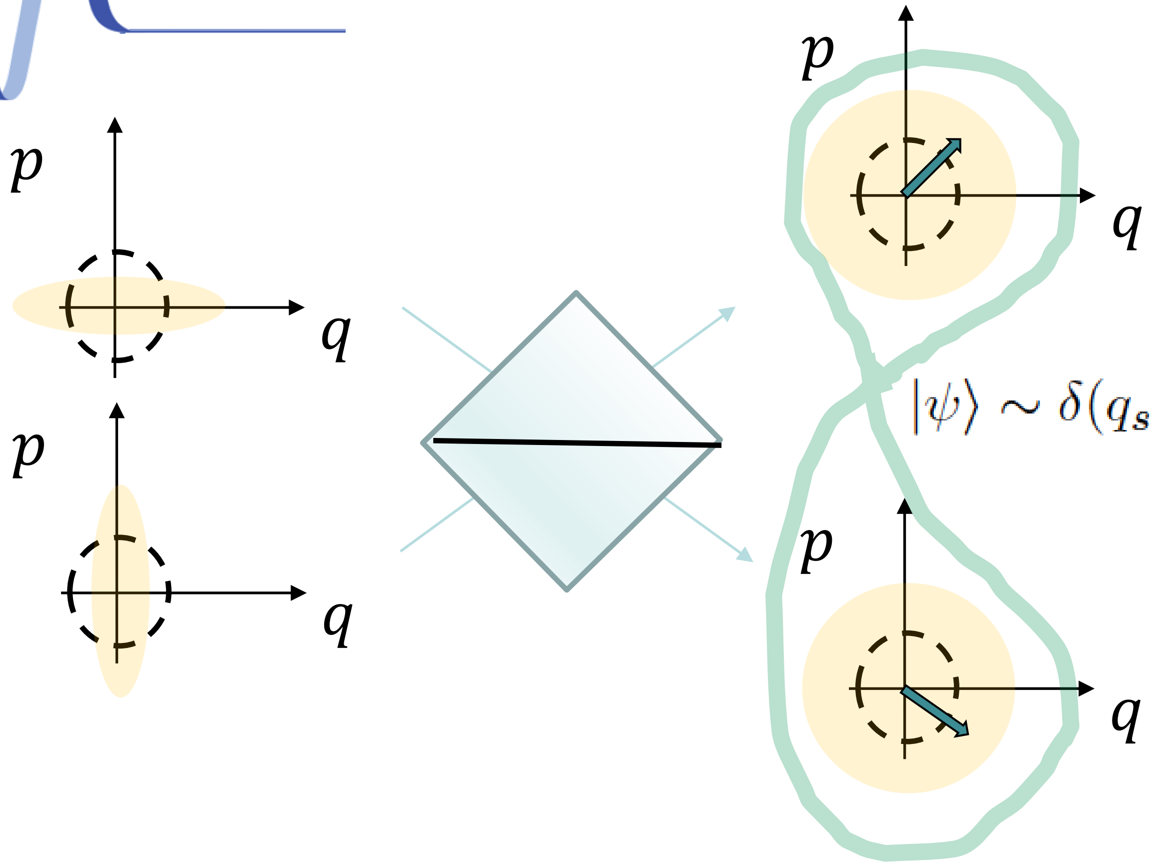
# Two nodes of the network




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

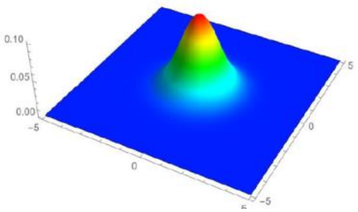
Simultaneous homodyne measurement of either q or p on both outputs !

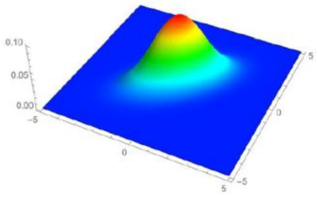
# Two nodes of the network




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

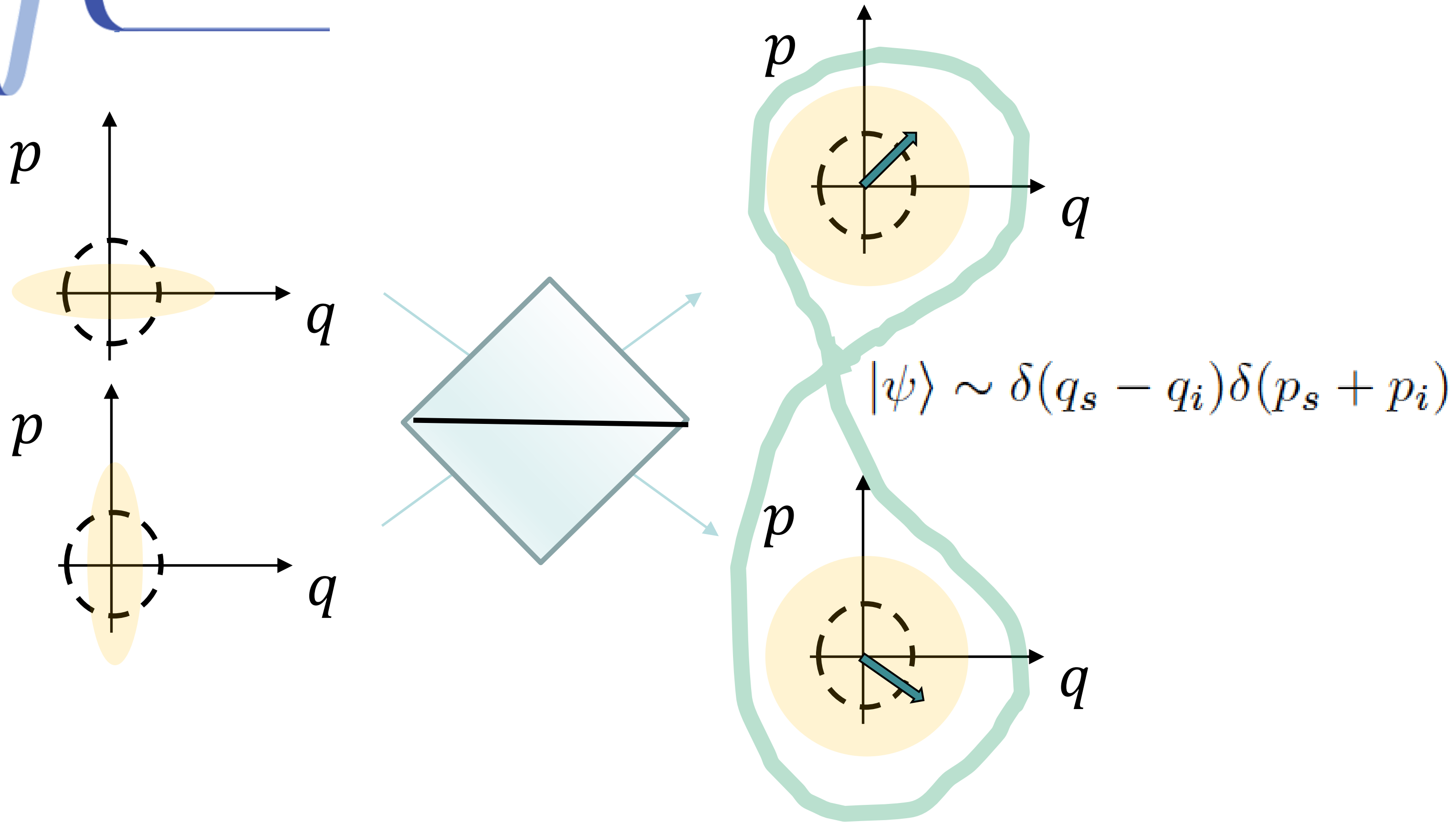
Two-mode squeezed vacuum

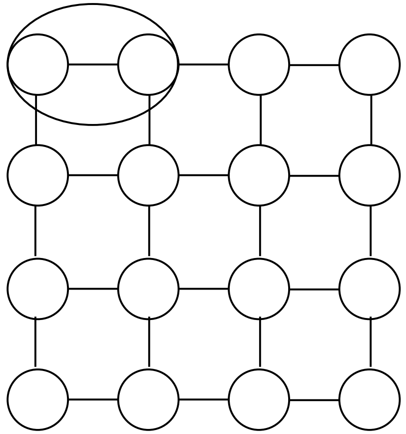




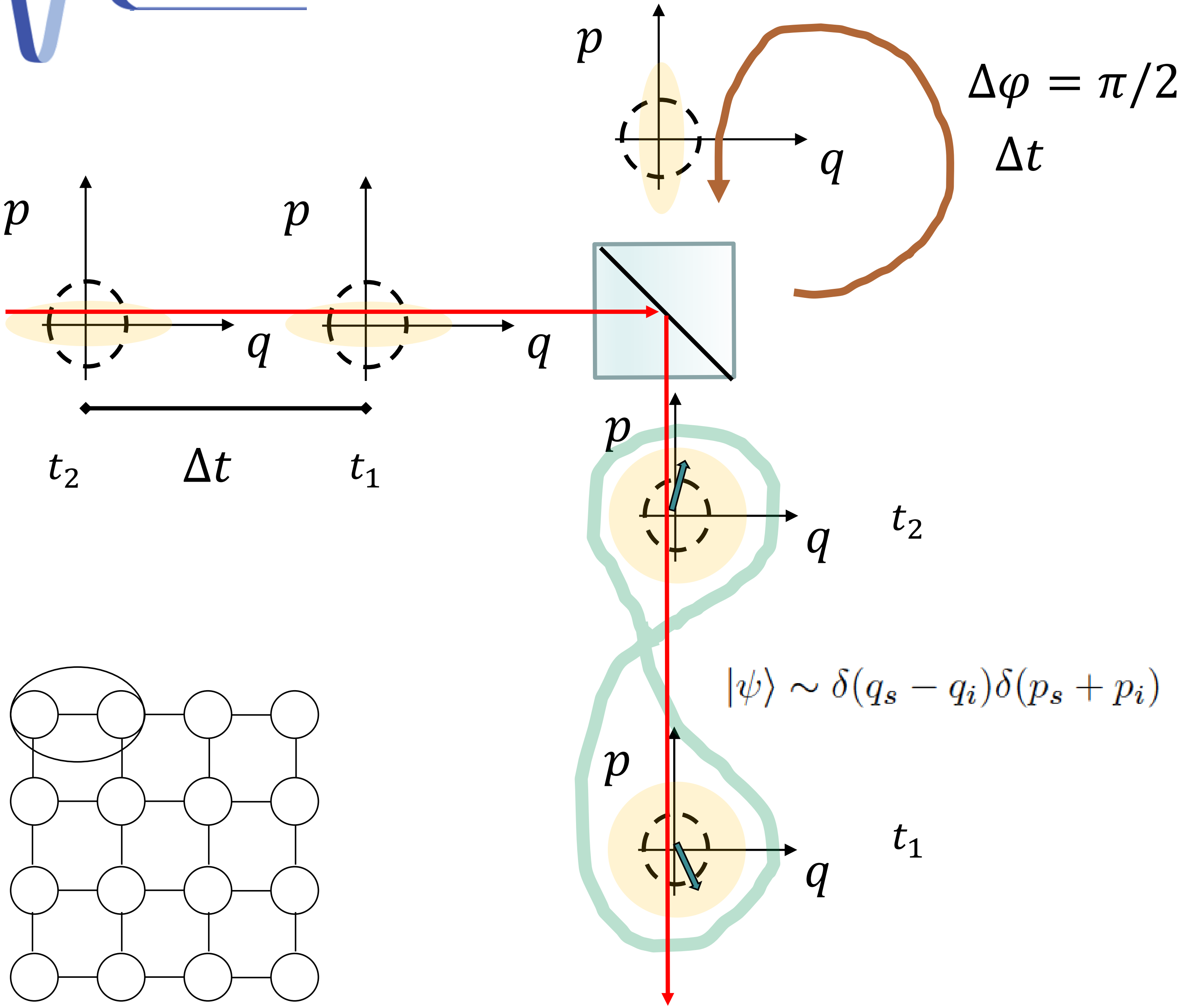
$$W_{EPR}(x_1,p_1,x_2,p_2) = \frac{1}{\pi^2} e^{-\frac{(x_1-x_2)^2}{2s} - \frac{(p_1-p_2)^2}{2/s} - \frac{(x_1+x_2)^2}{2/s} - \frac{(p_1+p_2)^2}{2s}}.$$

# Two nodes of the network



# Two nodes of the network

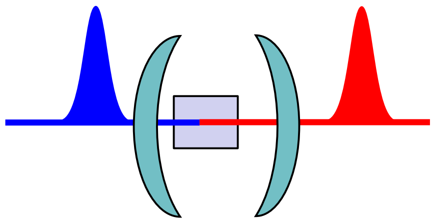


# Two nodes of the network

*Generation: Spontaneous parametric down conversion process*

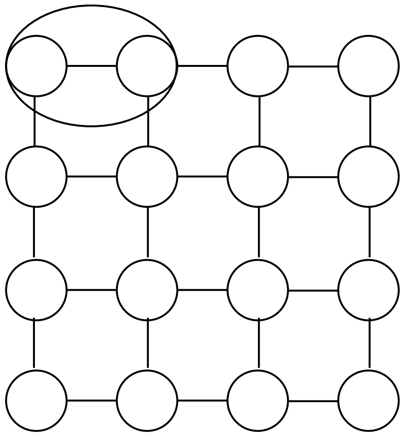
*Non- Degenerate case*

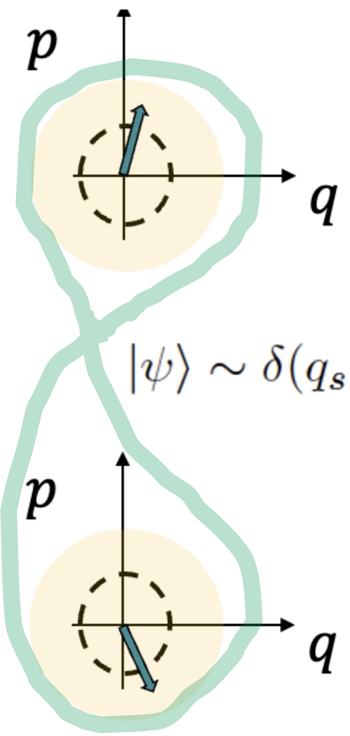
$$\omega_s \neq \omega_i$$



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

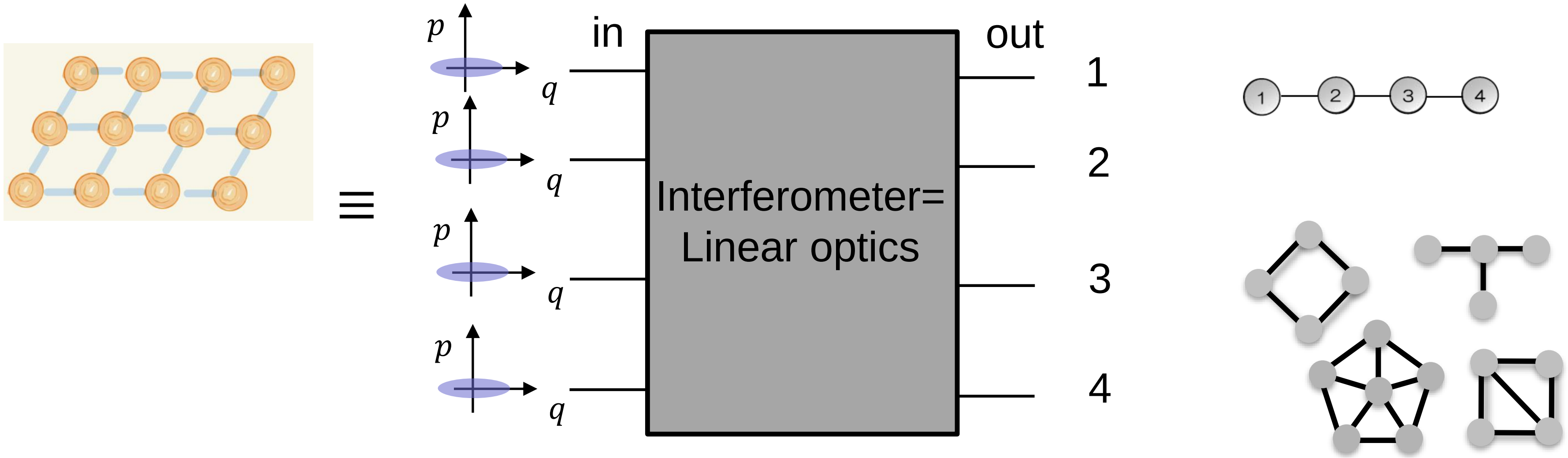
$$H = g\,i\left(a_s^\dagger a_i^\dagger - a_s a_i\right)$$






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

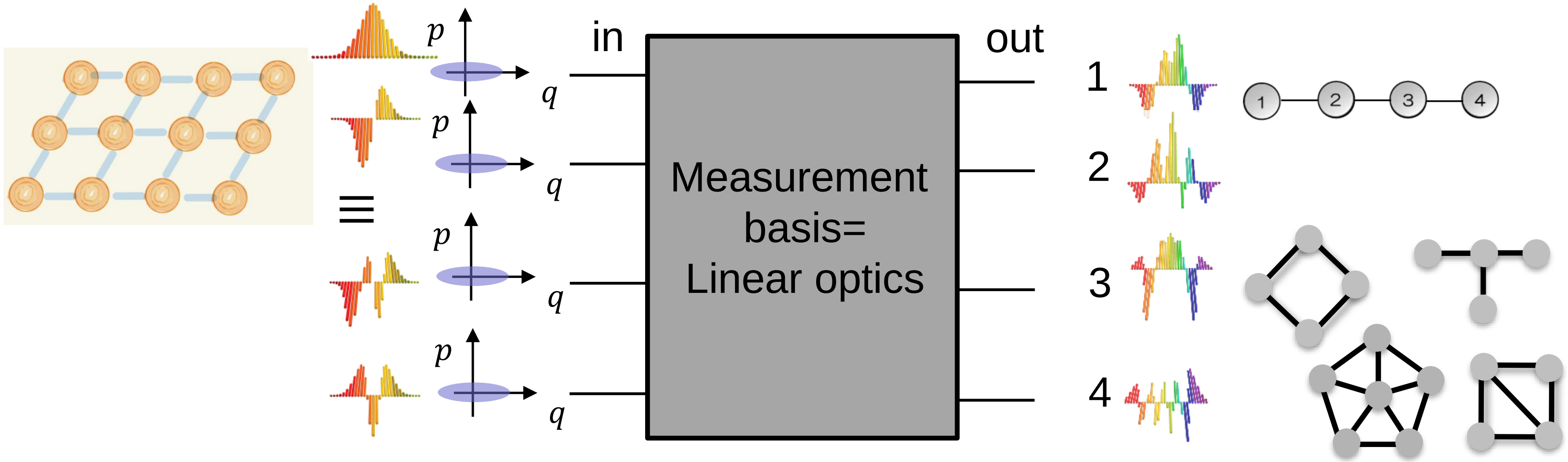
# Building a large network : spatial modes




*By controlling* $U_{lin}$

# Building a large network : spectral modes

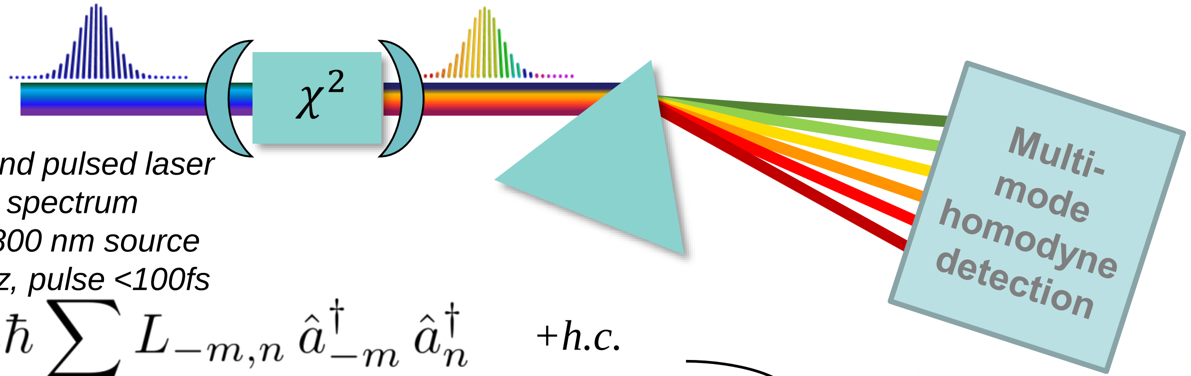
***Deterministic implementation***




Multi-color(mode) parametric process

*C. Fabre*

*N. Treps*




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

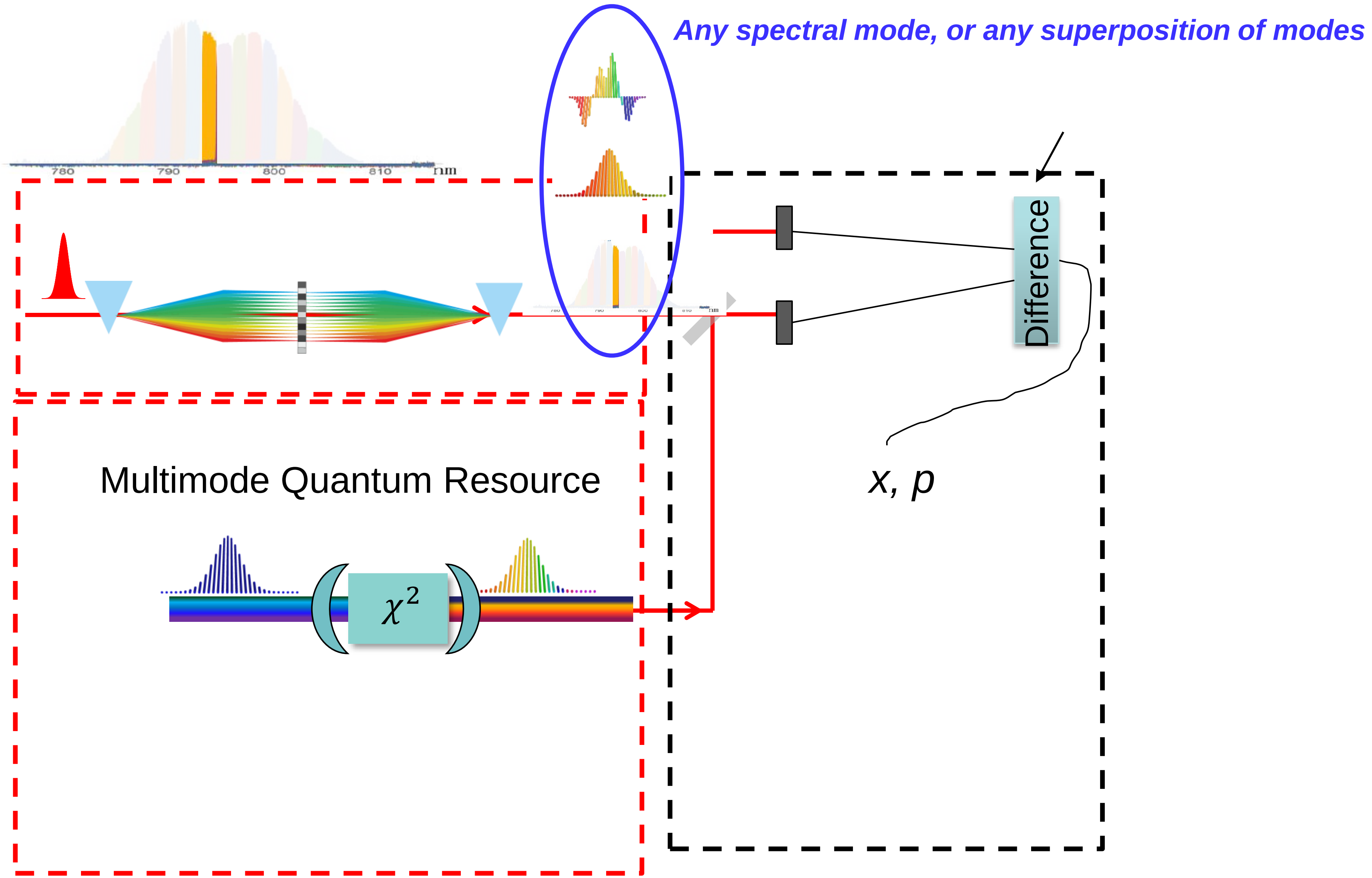
$$H = i\hbar \sum_{m,n} L_{-m,n}\, \hat{a}^{\dagger}_{-m}\, \hat{a}^{\dagger}_{n} \quad + h.c.$$

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

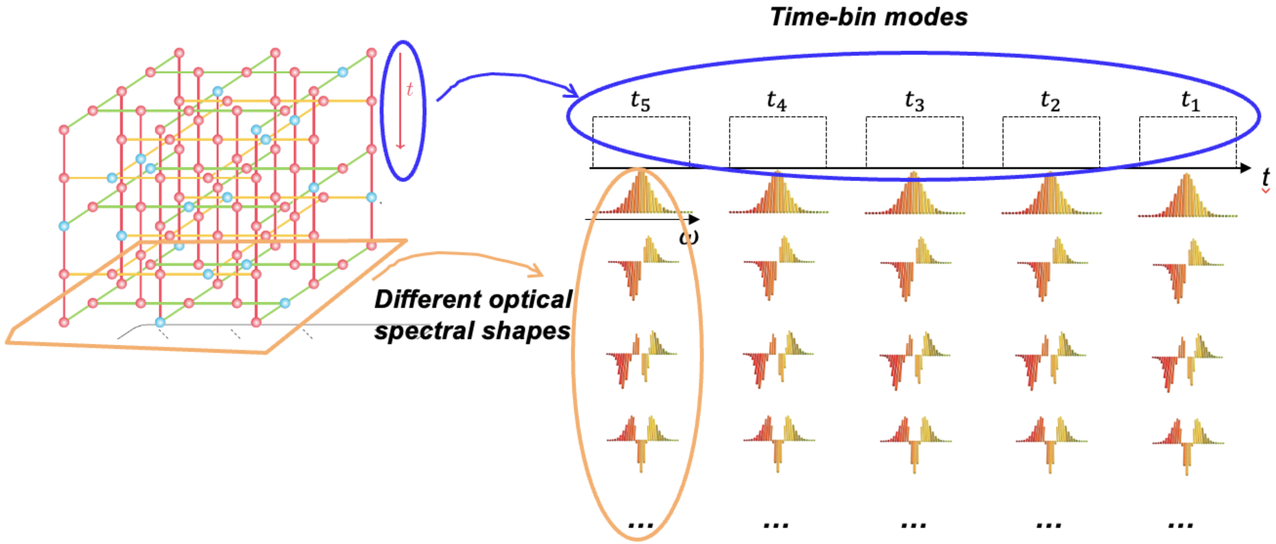
Y Cai, J Roslund, G Ferrini, F Arzani, X Xu, C Fabre, N Treps Nature Communications 8, (2017)

# Building a large network : spectral modes

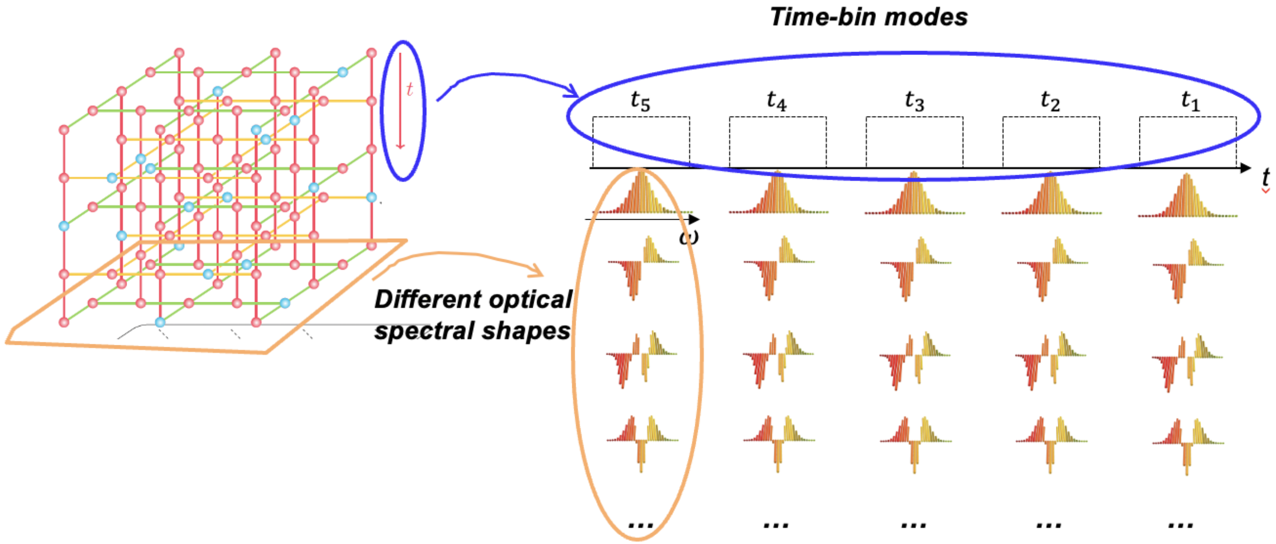
*Mode-selective homodyne detection*

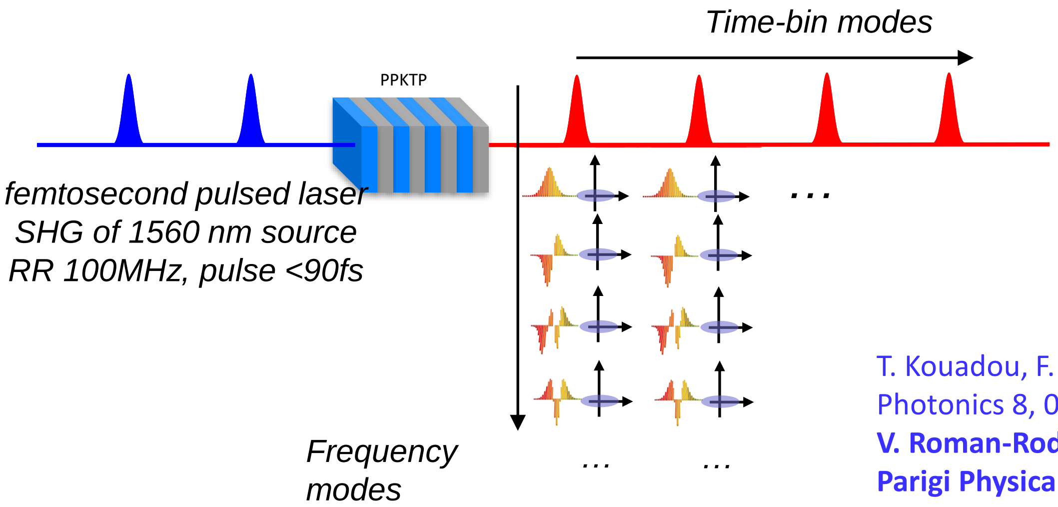


# Building a large network: spectral & time modes

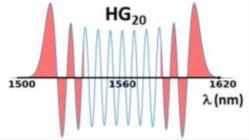


# Building a large network: spectral & time modes



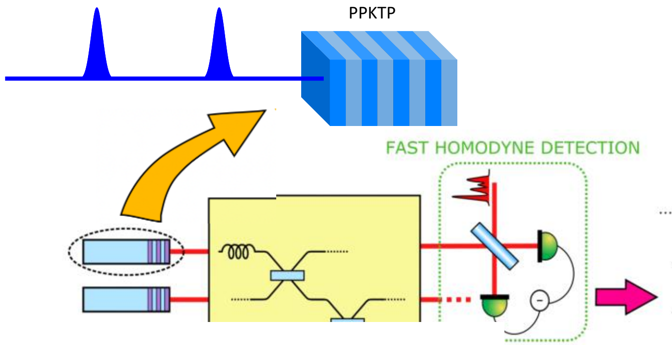

| Hermite-Gauss | Sqz | ASqz | | Sqz | ASqz | Flat modes | Sqz | ASqz |
|---|---|---|---|---|---|---|---|---|
| 0 | -1.03 | 1.39 | 6 | -0.73 | 1.45 | 0 | -2.66 | 6.99 |
| 1 | -0.68 | 1.31 | 7 | -0.74 | 1.27 | 1 | -2.43 | 6.49 |
| 2 | -0.62 | 1.16 | 8 | -0.54 | 1.16 | 2 | -2.32 | 6.83 |
| 3 | -0.61 | 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 | | | |




T. Kouadou, F. Sansavini, M. Ansquer, J. Henaff, N. Treps, V. Parigi,, APL Photonics 8, 086113 (2023)

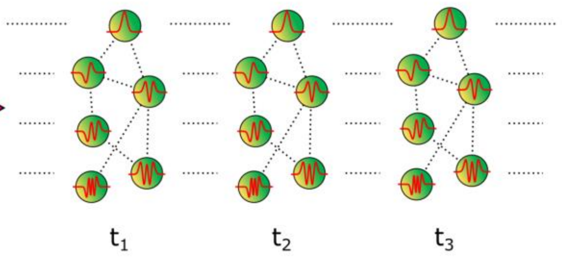
**V. Roman-Rodriguez, D. Fainsin, G. L. Zanin, N. Treps, E. Diamanti, and V. Parigi Physical Review Research 6, 043113 (2024**

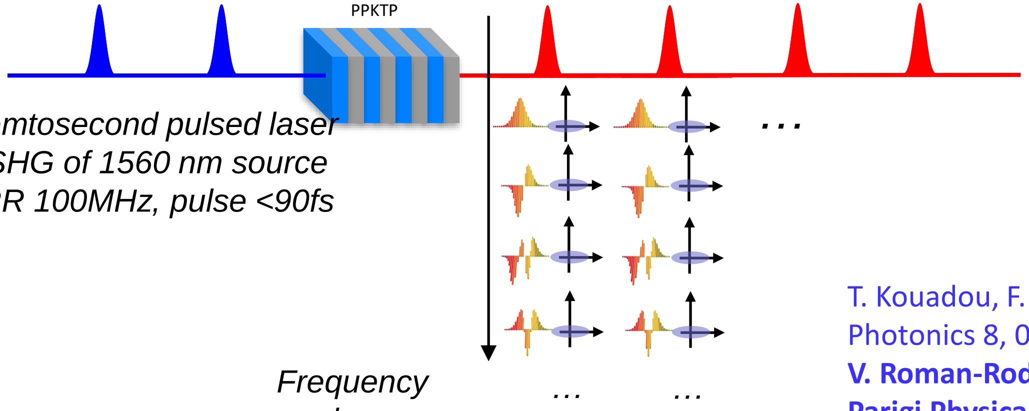
# Building a large network: spectral & time modes




Building block

*Three-dimensional structure!*




*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 |
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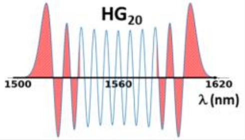
| 4 | -0.57 | 1.41 | 15 | -0.60 | 1.36 |  | | |
| 5 | -0.58 | 1.46 | 20 | -0.53 | 0.85 | | | |




T. Kouadou, F. Sansavini, M. Ansquer, J. Henaff, N. Treps, V. Parigi,, APL Photonics 8, 086113 (2023)

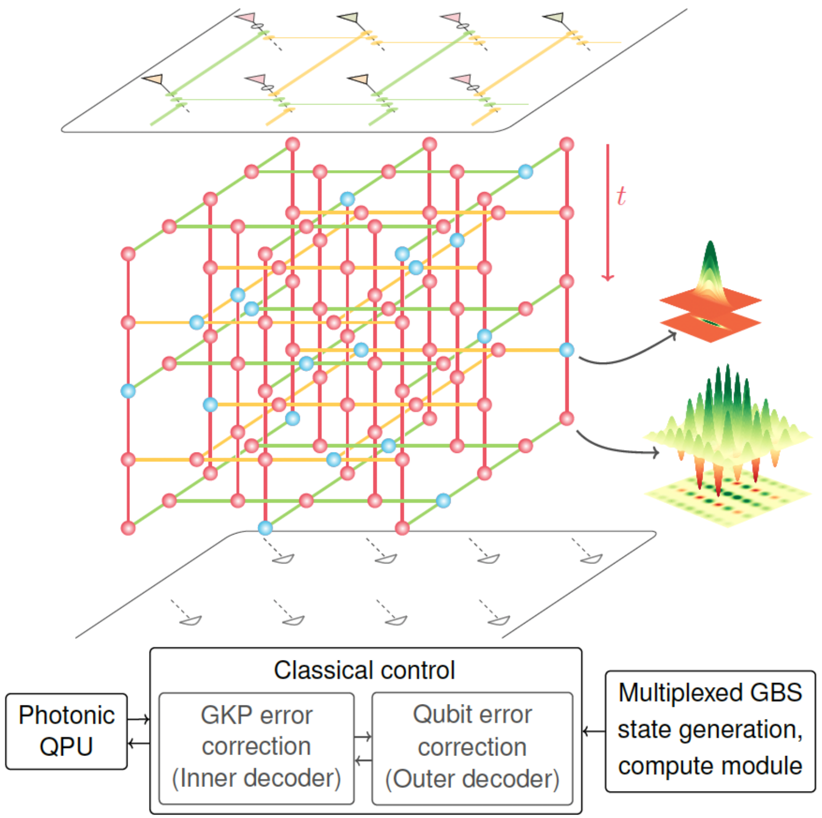
**V. Roman-Rodriguez, D. Fainsin, G. L. Zanin, N. Treps, E. Diamanti, and V. Parigi Physical Review Research 6, 043113 (2024**

# Photonic entangled newtorks for quantum Information protocols

# CV –photonic quantum computing

## Photonic quantum computing

*A proposal for a fault-tolerant optical implementation*



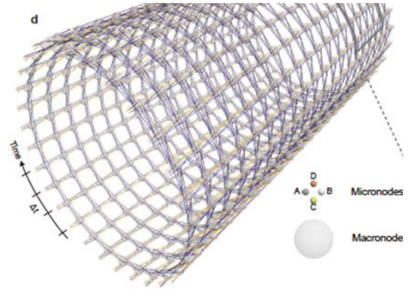

Bourassa J. E. *et al. Blueprint for a Scalable Photonic Fault-Tolerant Quantum Computer,* Quantum 5, 392 (2021)

# CV –photonic quantum computing

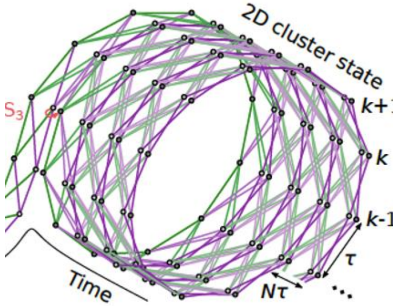
## Photonic quantum computing

***A proposal for a fault-tolerant optical implementation***

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

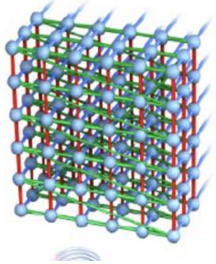



W. Asavanant *et al.* Science 366, 373 (2019).

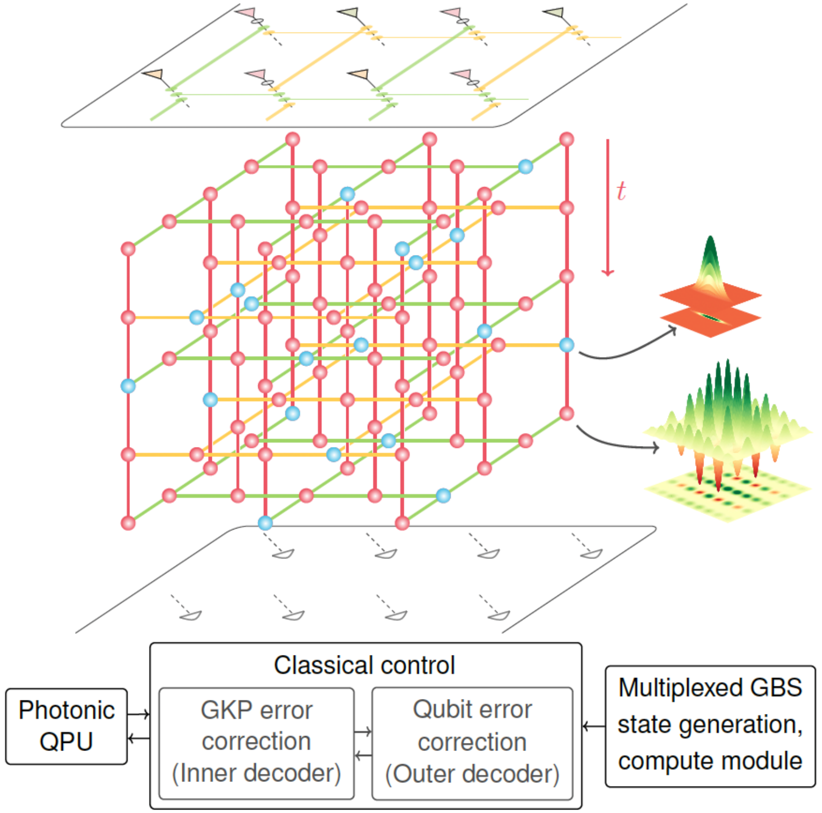



M. V. Larsen et al., Science 366, 369 (2019).

XANADU

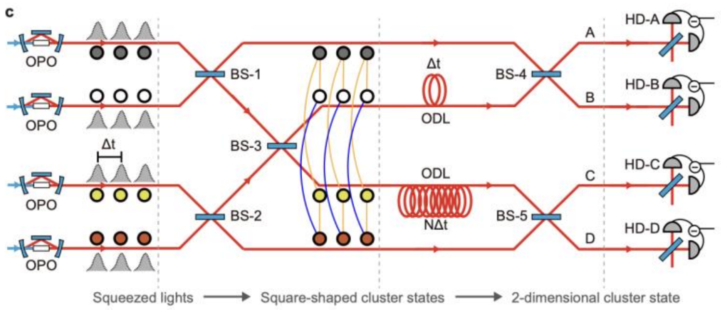


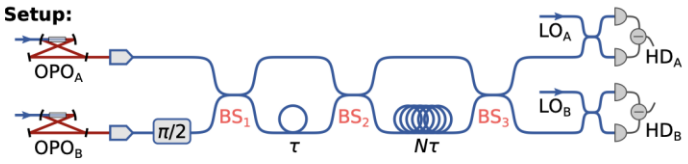
L. S. Madsen *et al.* Nature 606, 75 (2022)

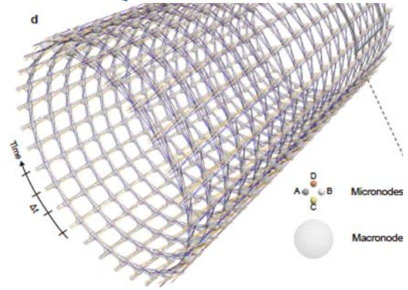



Bourassa J. E. *et al. Blueprint for a Scalable Photonic Fault-Tolerant Quantum Computer,* Quantum 5, 392 (2021)

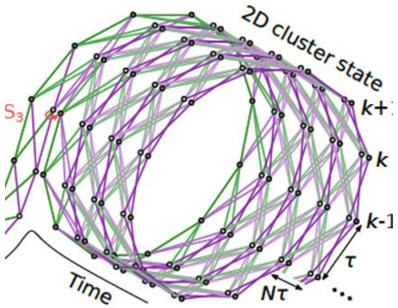
# CV –photonic quantum computing




W. Asavanant *et al.*
Science 366, 373
(2019).




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

# CV –photonic quantum computing

LKB

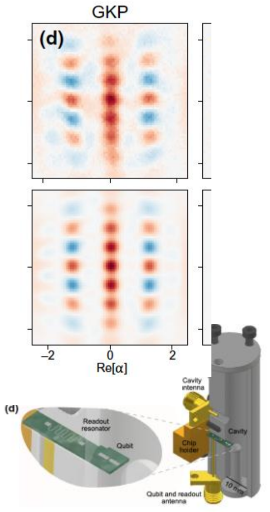
## Photonic quantum computing

*A proposal for a fault-tolerant optical implementation*

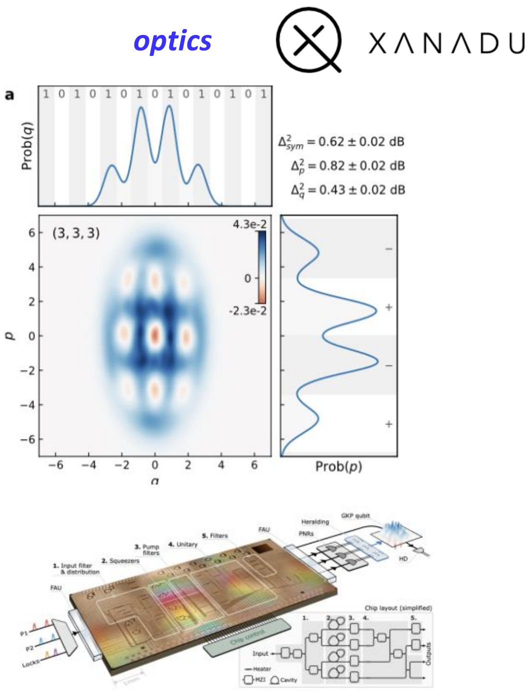
- *Deterministic room-temperature generation of large number of Gaussian entangled states*

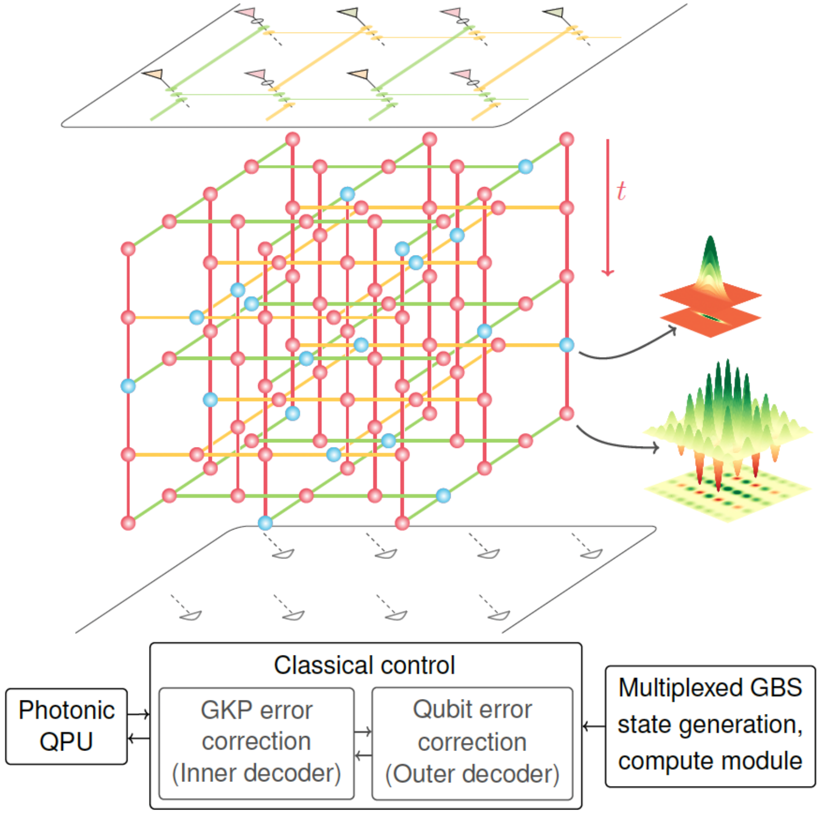
- *Probabilistic cryogenic generation of non-Gaussian GKP for error correction*

***microwaves*** ***optics***



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



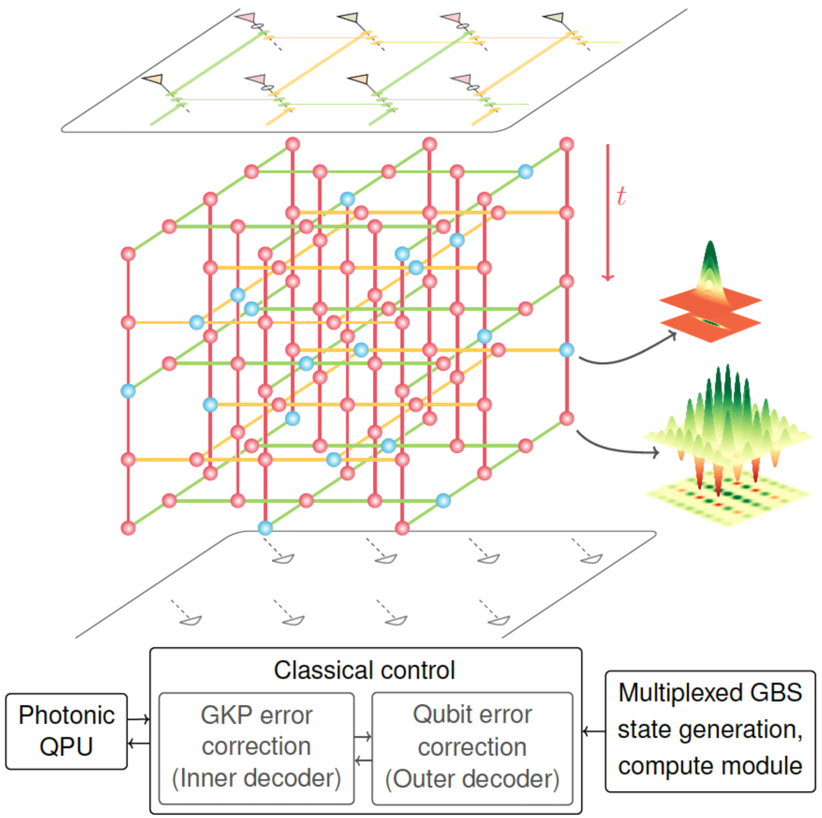

Bourassa J. E. *et al. Blueprint for a Scalable Photonic Fault-Tolerant Quantum Computer,* Quantum 5, 392 (2021)

# CV –photonic quantum computing

*NISQ protocols*
*(Noisy intermidiate scale quantum protocols)*

## 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)

# CV –photonic quantum computing

Collaboration with

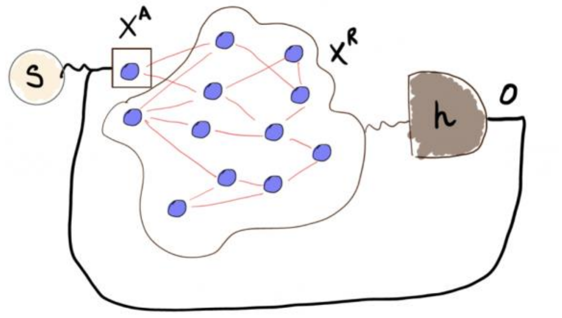
*R. Zambrini*

## Photonic quantum computing

*A proposal for a fault-tolerant optical implementation*

***NISQ protocols***

*Quantum reservoir Computing*

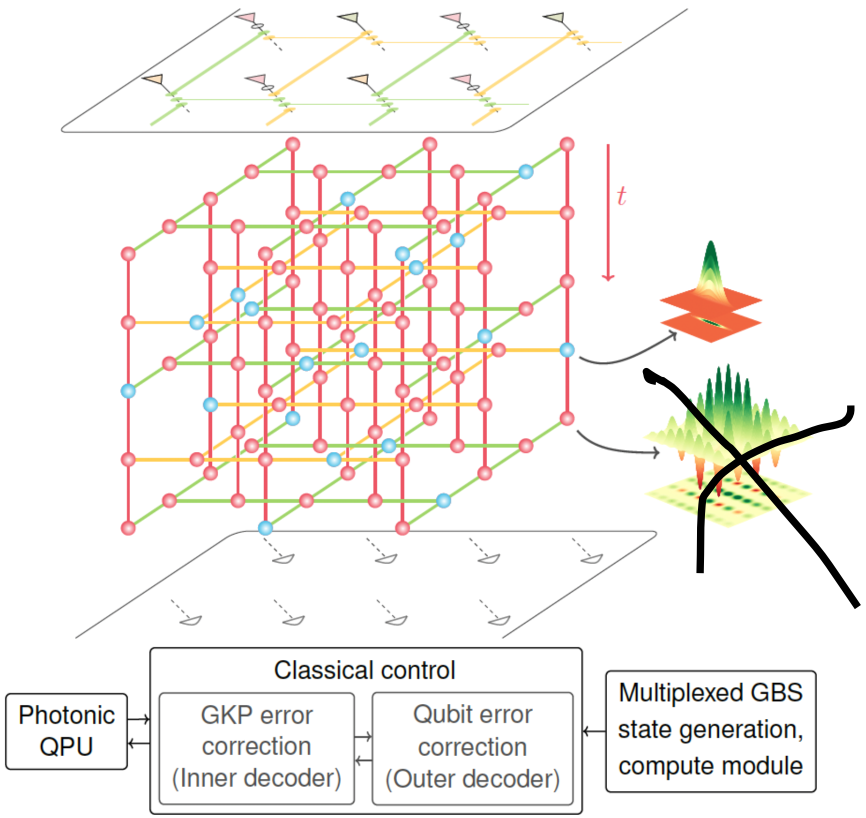



J. Nokkala, R. Martínez-Peña, G. L. Giorgi, V. Parigi, M. C Soriano, R. Zambrini, Communications Physics volume 4, Article number: 53 (2021)

J Henaff, M Ansquer, MC Soriano, R Zambrini, N Treps, V Parigi arXiv:2401.14073 (2024), Optics Lett. Optics Letters 49, 2097 (2024)

J García-Beni, I Paparelle, V Parigi, GL Giorgi, MC Soriano, R Zambrini, EPJ Quantum Technology 12 (1), 1-14 (2025)

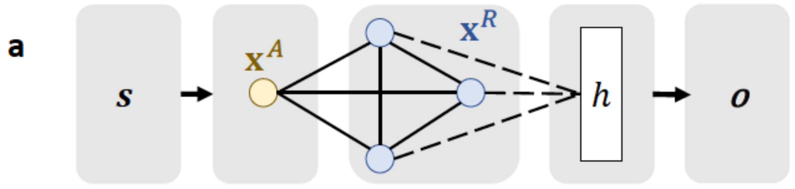
I. Paparelle, J. Henaff, J. Garcia-Beni, E. Gillet, D. Montesinos, G. L. Giorgi, M. C Soriano, R. Zambrini, V. Parigi arXiv:2506.07279 (2025), Accepted Nature Photonics




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

# Reservoir computing

RC universal = when it can approximate any so-called fading memory function (continuous function of a finite number of past inputs)




*Netwok, fixed, not trained =* ***reservoir***

*only connections leading to the final output layer are trained* ***( linear regression****)*

$$\begin{cases} \mathbf{x}_k = T(\mathbf{x}_{k-1}, \mathbf{s}_k) \\ o_k = h(\mathbf{x}_k), \end{cases}$$

***Temporal task, like time-series forecasting***

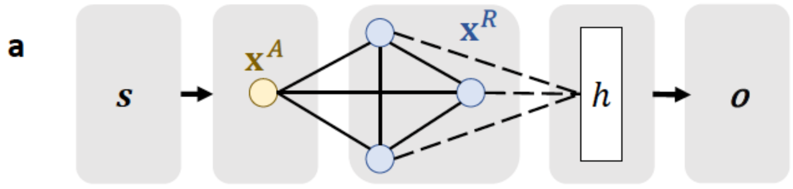
J. Nokkala, R. Martínez-Peña, G. L. Giorgi, V. Parigi, M. C Soriano, R. Zambrini, ***Gaussian states of continuous-variable quantum systems provide universal and versatile reservoir computing*** Communications Physics volume 4, 53 (2021)

# Reservoir computing via quantum states

**Multimode Gaussian resources**
**+**
**Continuous Variable measurements**

RC universal = when it can approximate any so-called fading memory function (continuous function of a finite number of past inputs)

*quantum harmonic oscillators*

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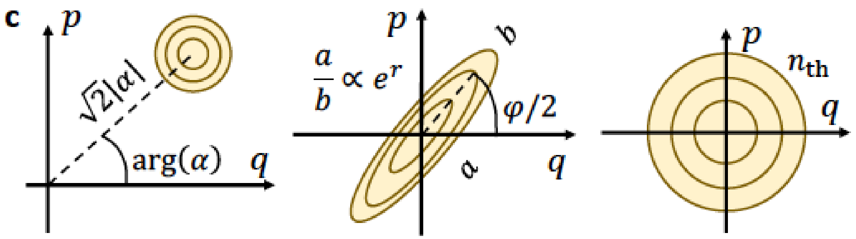


*coherent states* *squeezed states* *thermal states*

J. Nokkala, R. Martínez-Peña, G. L. Giorgi, V. Parigi, M. C Soriano, R. Zambrini, ***Gaussian states of continuous-variable quantum systems provide universal and versatile reservoir computing*** Communications Physics volume 4, 53 (2021)

# Reservoir computing via quantum states

LKB

**Multimode Gaussian resources**
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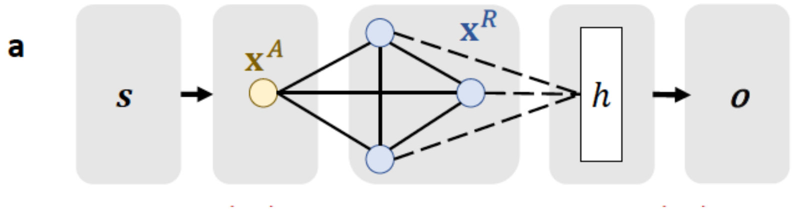
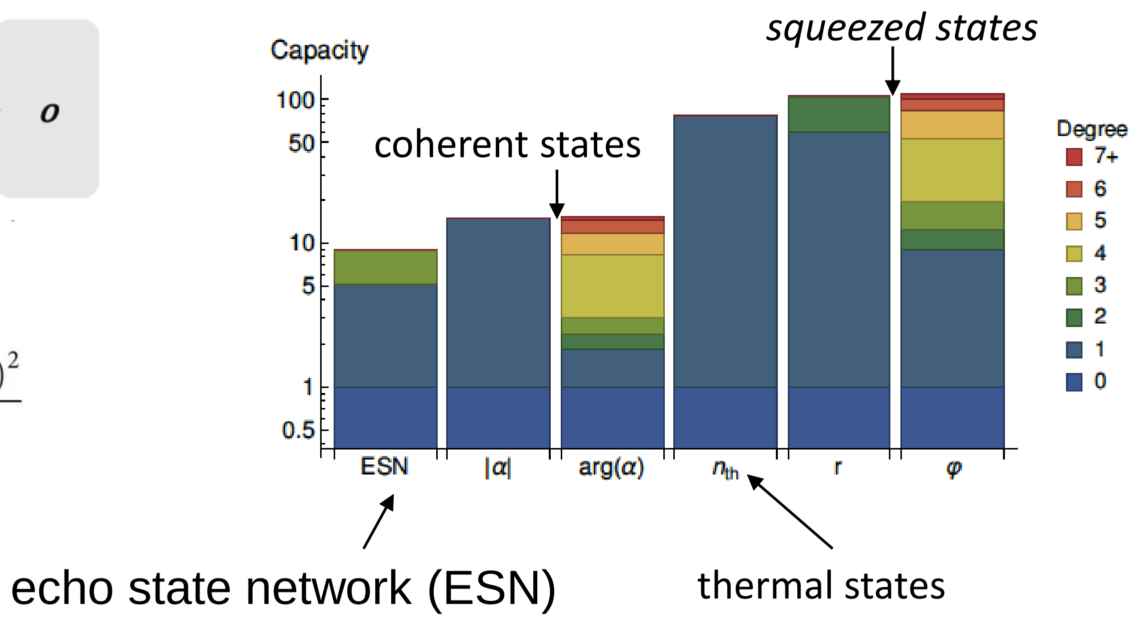


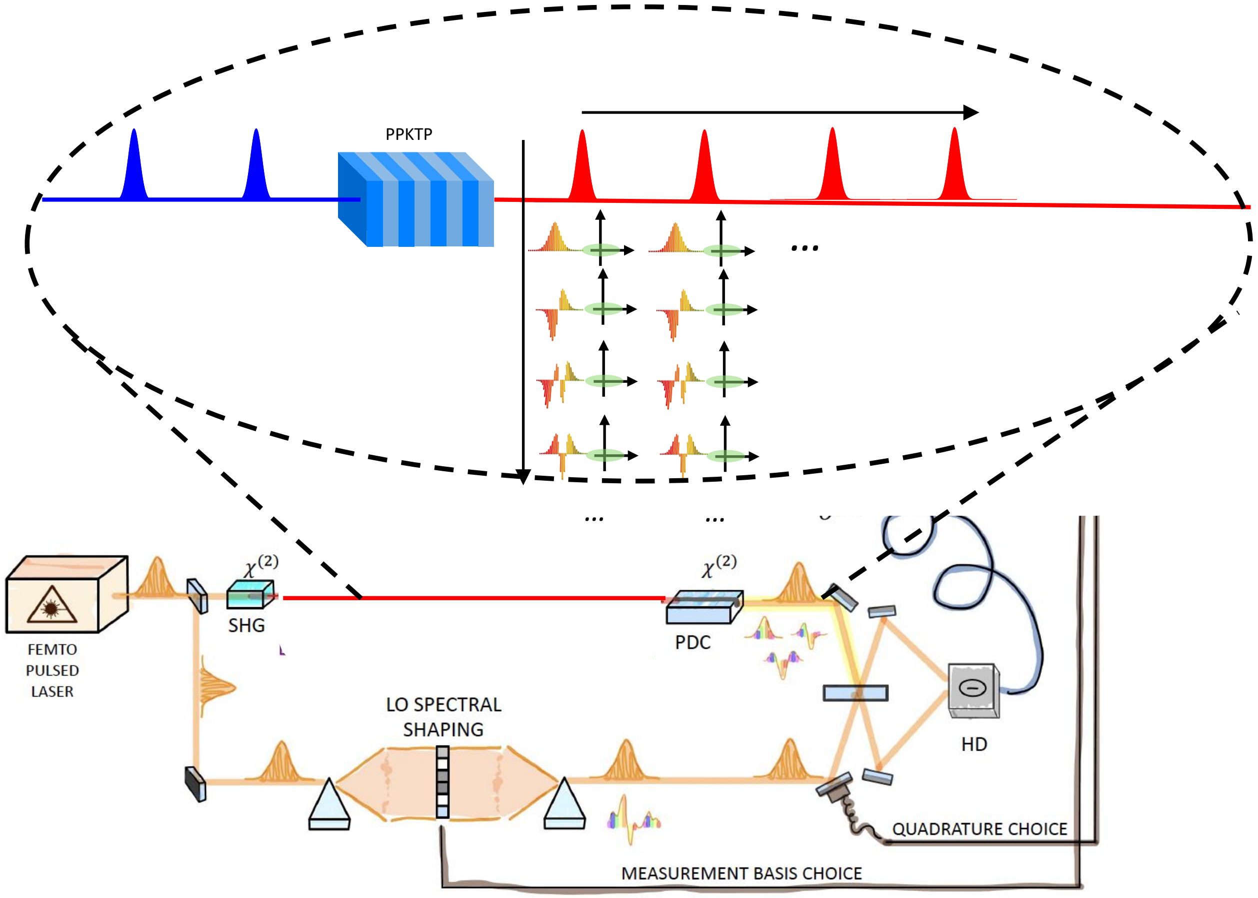

$$C_{s',s}(X,z) = 1 - \frac{\min_h \sum_k (z_k - o_k)^2}{\sum_k z_k^2}$$



# Experimental CV quantum Reservoir Computing

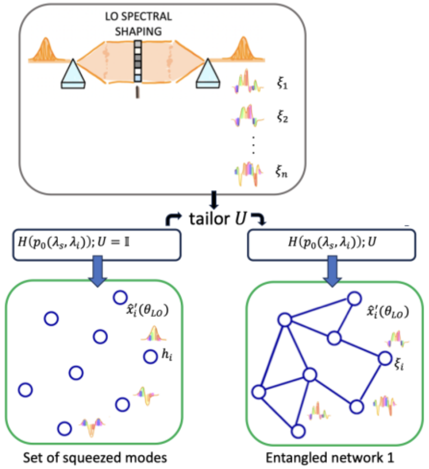
$$H = i\hbar \sum_{m,n} L_{-m,n}\, \hat{a}^\dagger_{-m}\, \hat{a}^\dagger_n \quad + h.c.$$

$$\hat{H}^m_{\text{int}} = \mathcal{K} \sum_j \lambda_j \left(\hat{s}^\dagger_j\right)^2 + h.c.$$

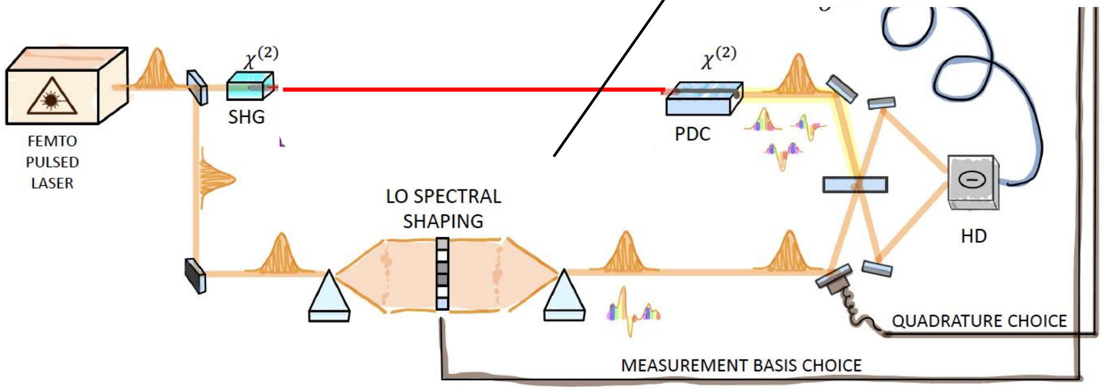



I. Paparelle, J. Henaff, J. Garcia-Beni, E. Gillet, D. Montesinos, G. L. Giorgi, M. C Soriano, R. Zambrini, V. Parigi arXiv arXiv:2506.07279 (2025)

# Experimental CV quantum Reservoir Computing




*Choice of netwok (entanglement structure)*

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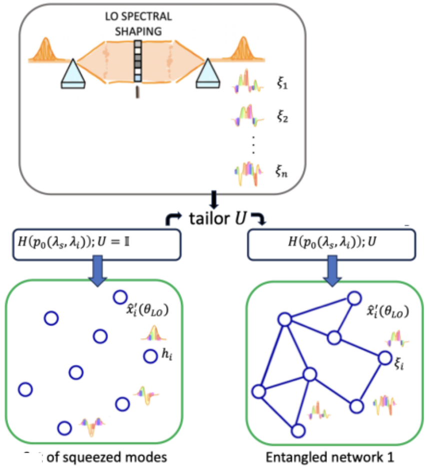
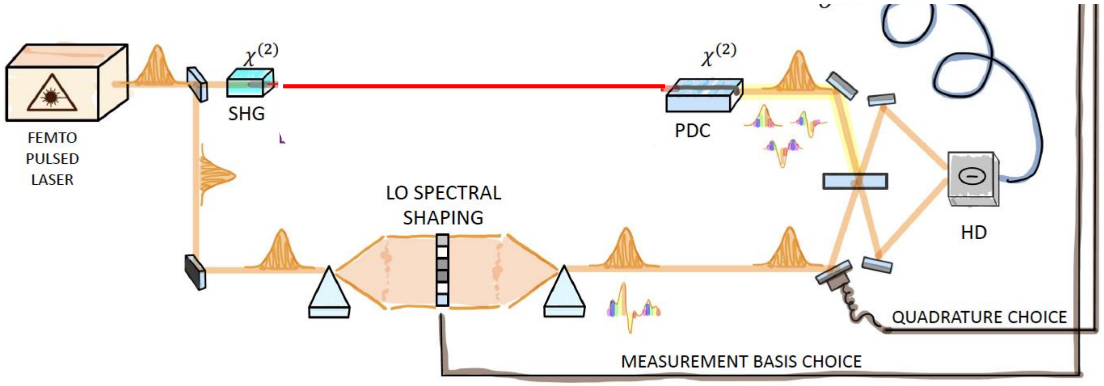
# Experimental CV quantum Reservoir Computing




*Covariance Matrix*

$$S_U^T\ \sigma(H( \quad )S_U$$

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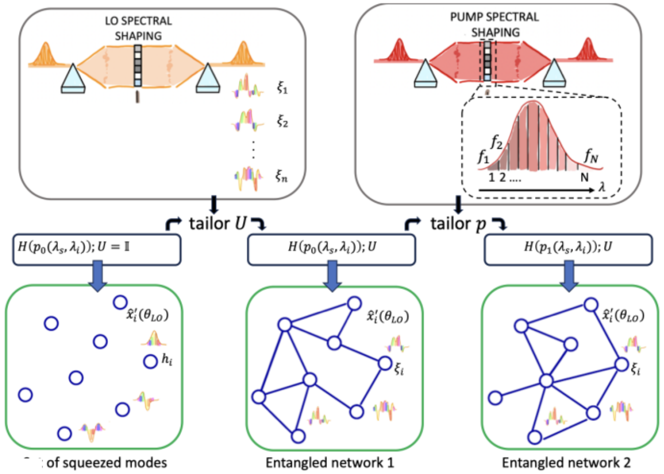
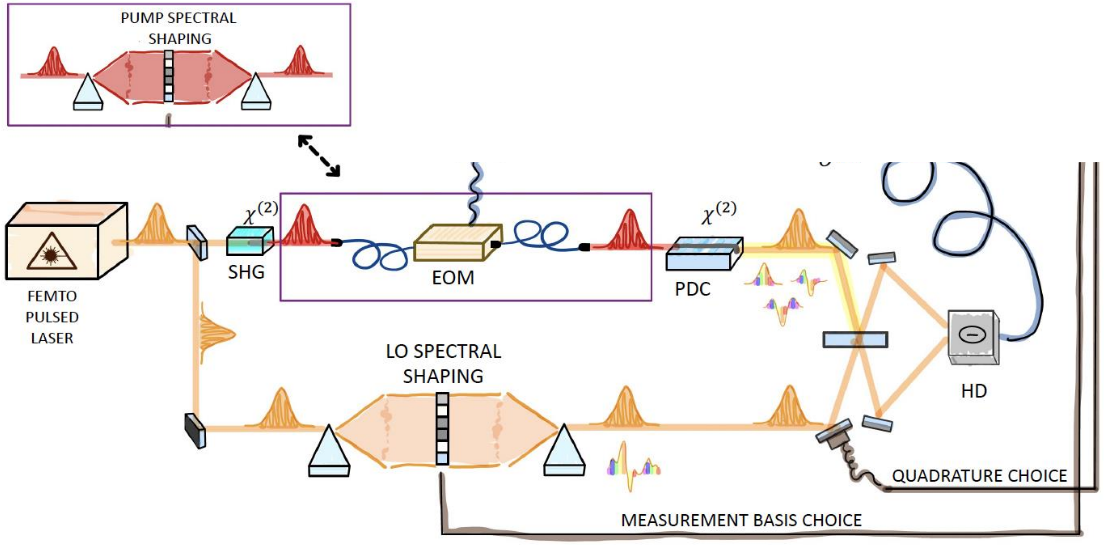



*Covariance Matrix*

*pump*

$$S_U^{\,T}\,\sigma(H(p( \qquad )\,S_U$$

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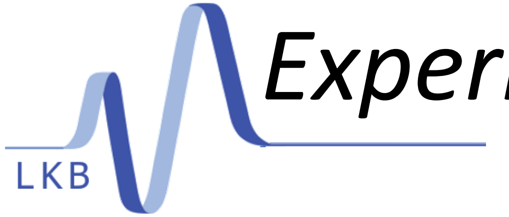


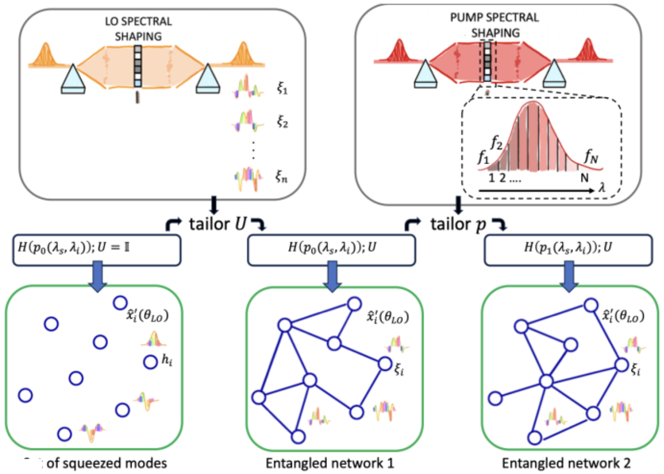
**Experimental memory control in continuous variable optical quantum reservoir computing**

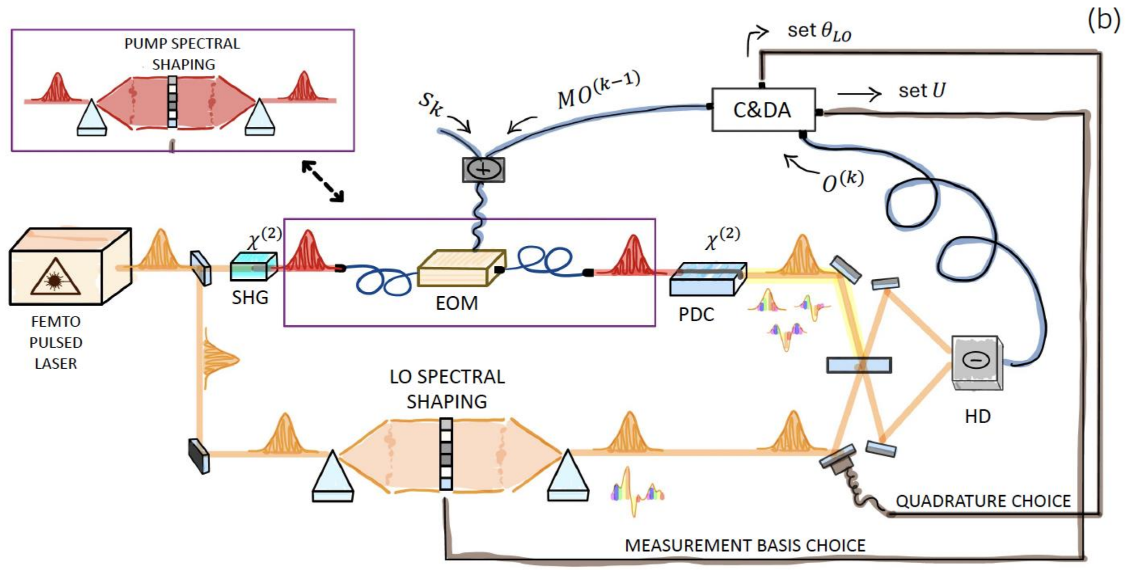
Iris Paparelle,[1] Johan Henaff,[1] Jorge García-Beni,[2] Émilie Gillet,[1] Daniel Montesinos,[2] Gian Luca Giorgi,[2] Miguel C. Soriano,[2] Roberta Zambrini,[2] and Valentina Parigi[1,*]

*Covariance Matrix*

*pump*

$$S_U{}^T\,\sigma(H(p(s_k, O^{(k-1)})))\,S_U$$

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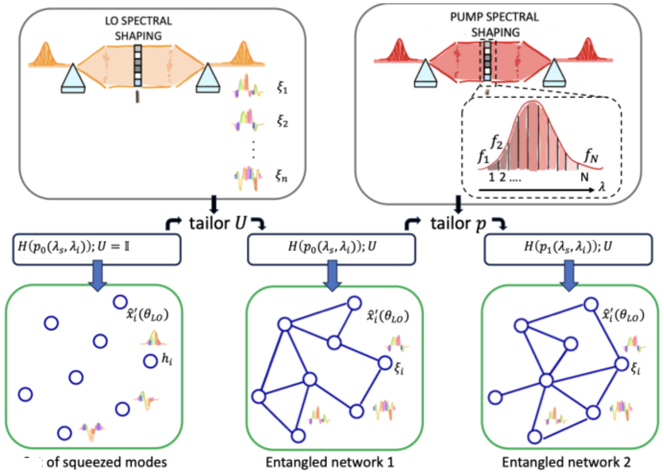



$$\begin{cases} \mathbf{x}_k = T(\mathbf{x}_{k-1}, \mathbf{s}_k) \\ o_k = h(\mathbf{x}_k), \end{cases}$$

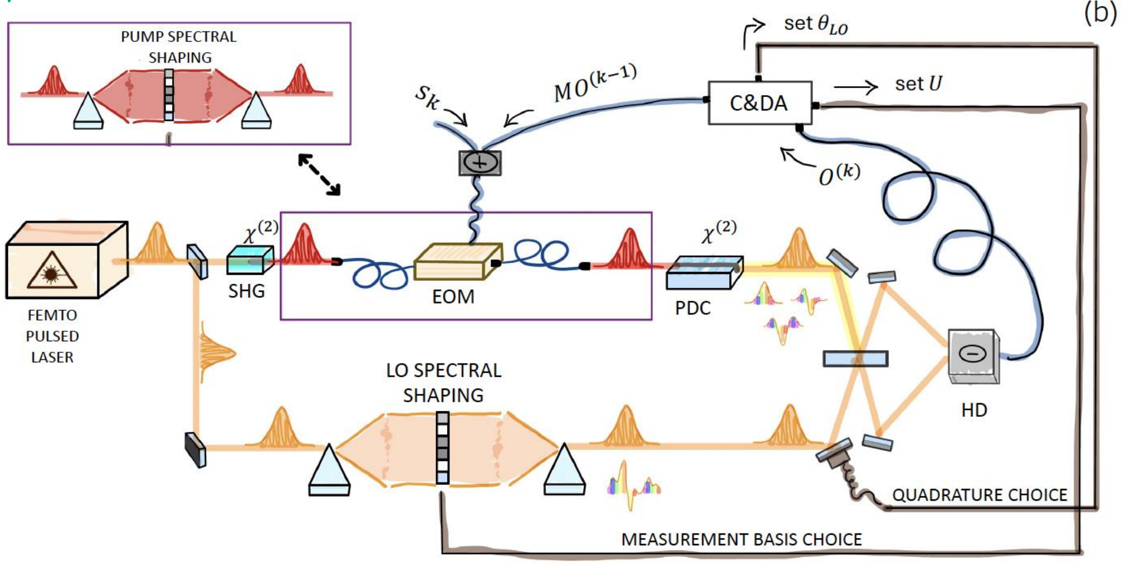
Covariance Matrix

pump

$$\begin{cases} O_m^{(k)} \propto \sigma'^{(k)}_{ij} \mid \sigma'^{(k)} = S_U{}^T\, \sigma(H(p(s_k, O^{(k-1)})))\, S_U \\ y_k = \mathbf{w}^T \mathbf{O}^{(k)} + b \end{cases}$$

Observables

Result

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# *Experimental CV quantum Reservoir Computing*

***Results***

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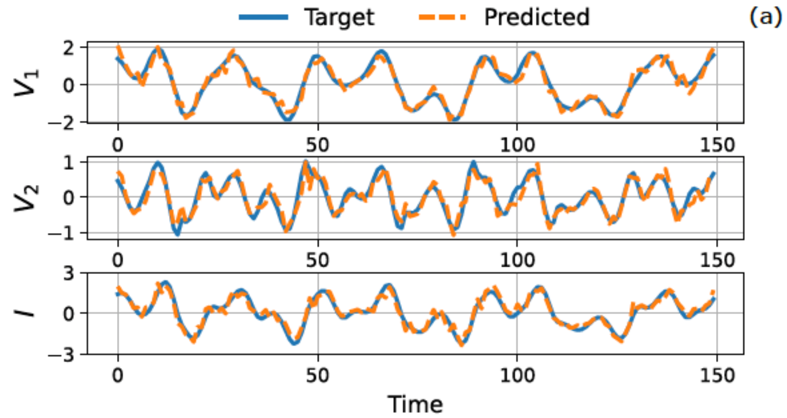


*Forecasting of chaotic time-series:*
*the double-scroll electronic circuit*

I. Paparelle, J. Henaff, J. Garcia-Beni, E. Gillet, D. Montesinos, G. L. Giorgi, M. C Soriano, R. Zambrini, V. Parigi arXiv:2506.07279 (2025) Accepted Nature Photonics

# Experimental CV quantum Reservoir Computing

**Results**

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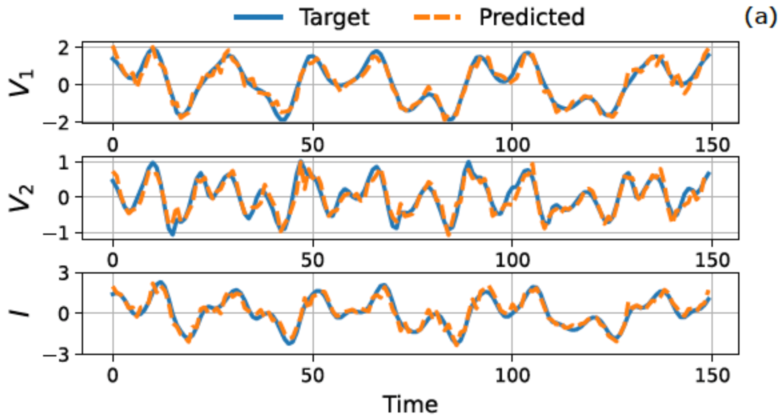
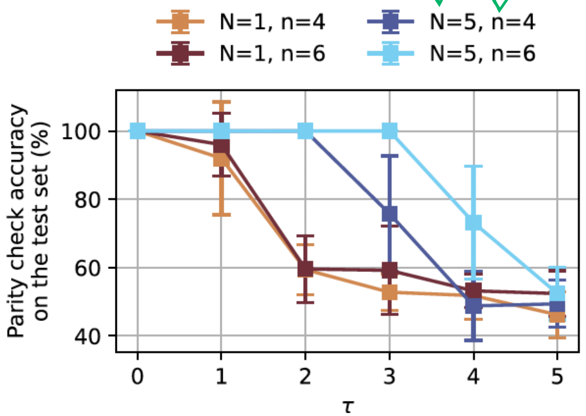



*Forecasting of chaotic time-series: the double-scroll electronic circuit*

*Controlled elements of the pump*

*measured modes*




*A task with memory*

I. Paparelle, J. Henaff, J. Garcia-Beni, E. Gillet, D. Montesinos, G. L. Giorgi, M. C Soriano, R. Zambrini, V. Parigi arXiv:2506.07279 (2025) Accepted Nature Photonics

# Experimental CV quantum Reservoir Computing

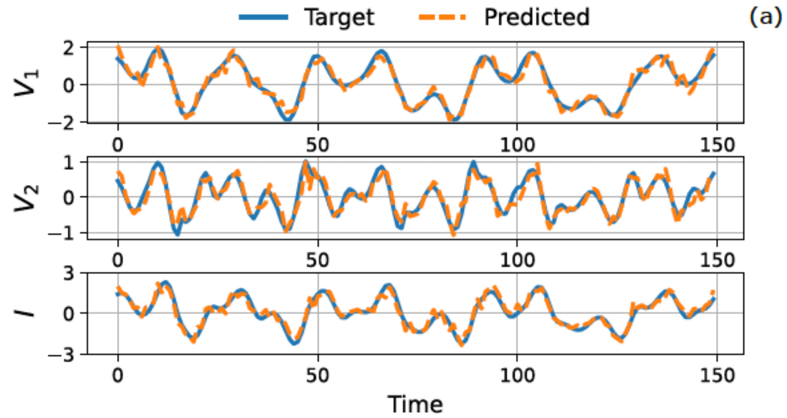
***Results***

**Experimental memory control in continuous variable optical quantum reservoir computing**

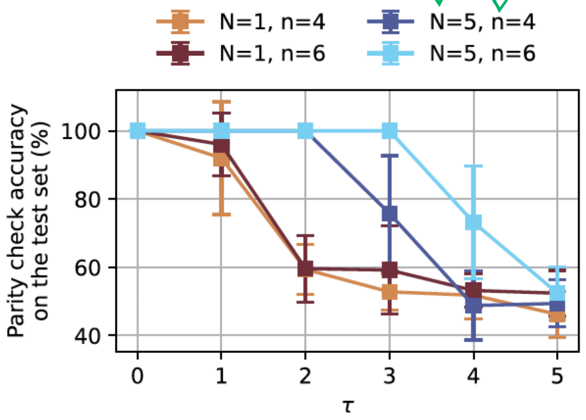
Iris Paparelle,[1] Johan Henaff,[1] Jorge García-Beni,[2] Émilie Gillet,[1] Daniel Montesinos,[2] Gian Luca Giorgi,[2] Miguel C. Soriano,[2] Roberta Zambrini,[2] and Valentina Parigi[1,*]

*Controlled elements of the pump*

*measured modes*



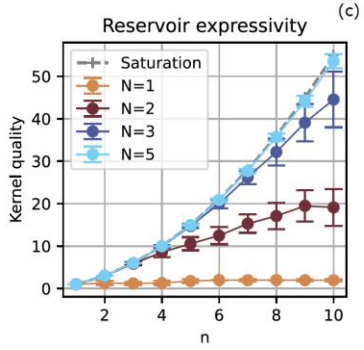

*Forecasting of chaotic time-series: the double-scroll electronic circuit*

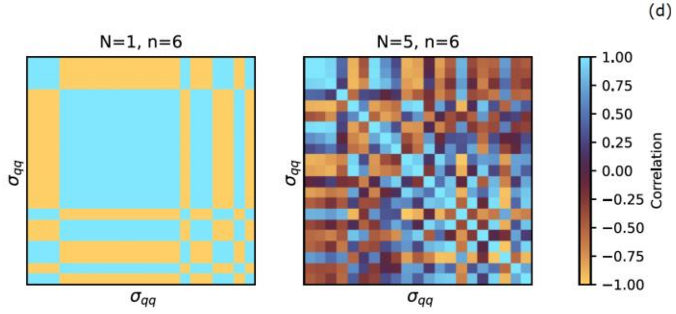



*A task with memory*

*Saturation of a quadratic scaling with n(n + 1)/2 if N large enough*

*(**15 non entangled reservoirs compare with N, n = 9, 9**)*

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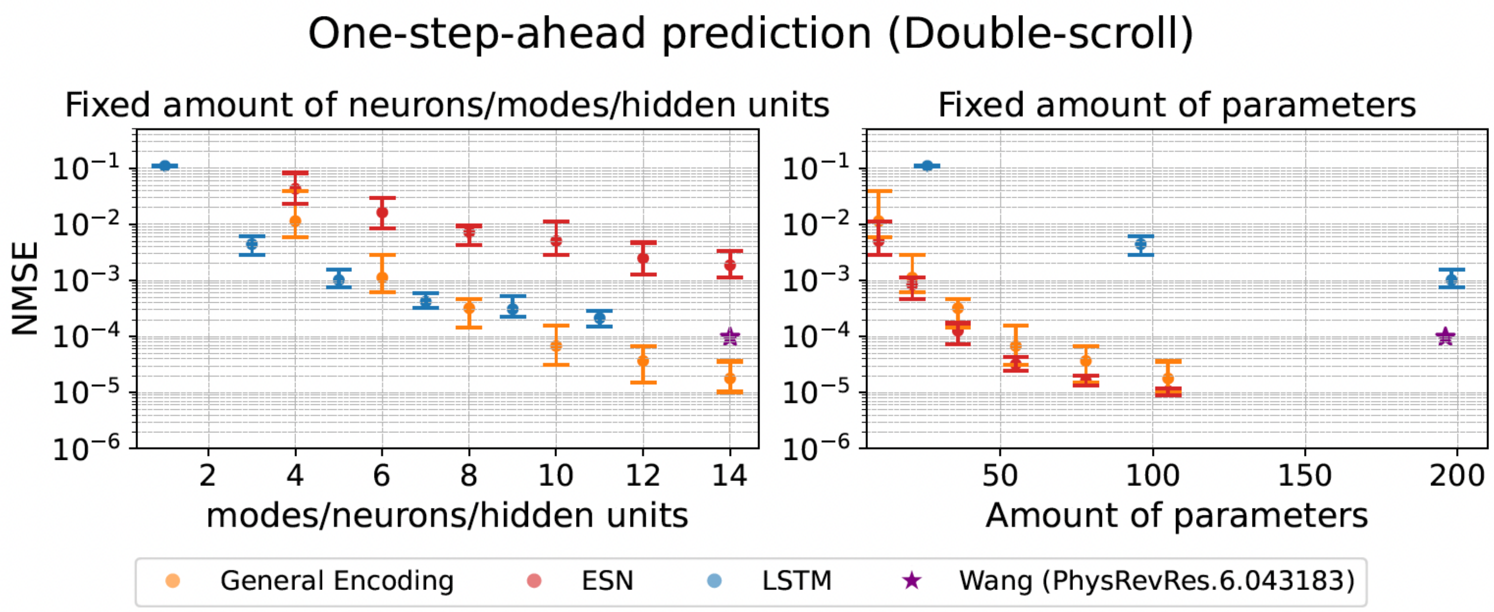
# Experimental CV quantum Reservoir Computing

***Results***

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*Saturation of a quadratic scaling with n(n + 1)/2 if N large enough*

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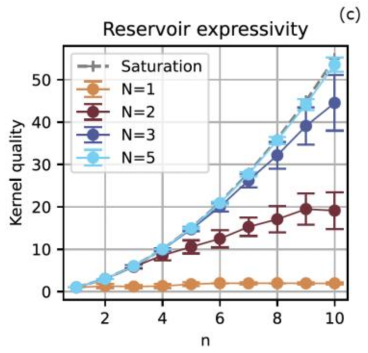



***Detailed comparison with classical machine learning approaches***

*(Echo State Networks and Long Short-Term Memory networks)*
*and with other QRC model.*

***Our approach compares favourably with state-of-the-art time-series processing techniques !***

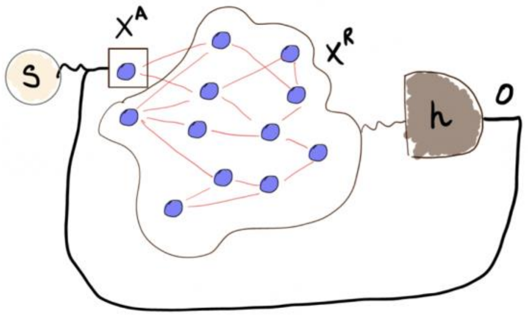
# CV –photonic quantum computing

LKB

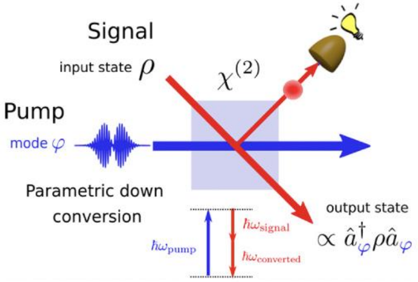
R. Zambrini

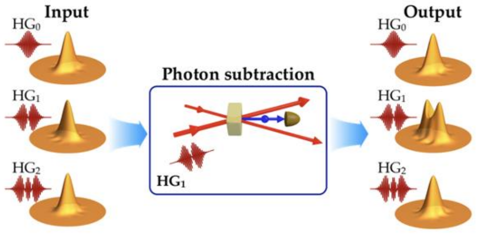
**_NISQ protocols_**

*Quantum reservoir Computing*



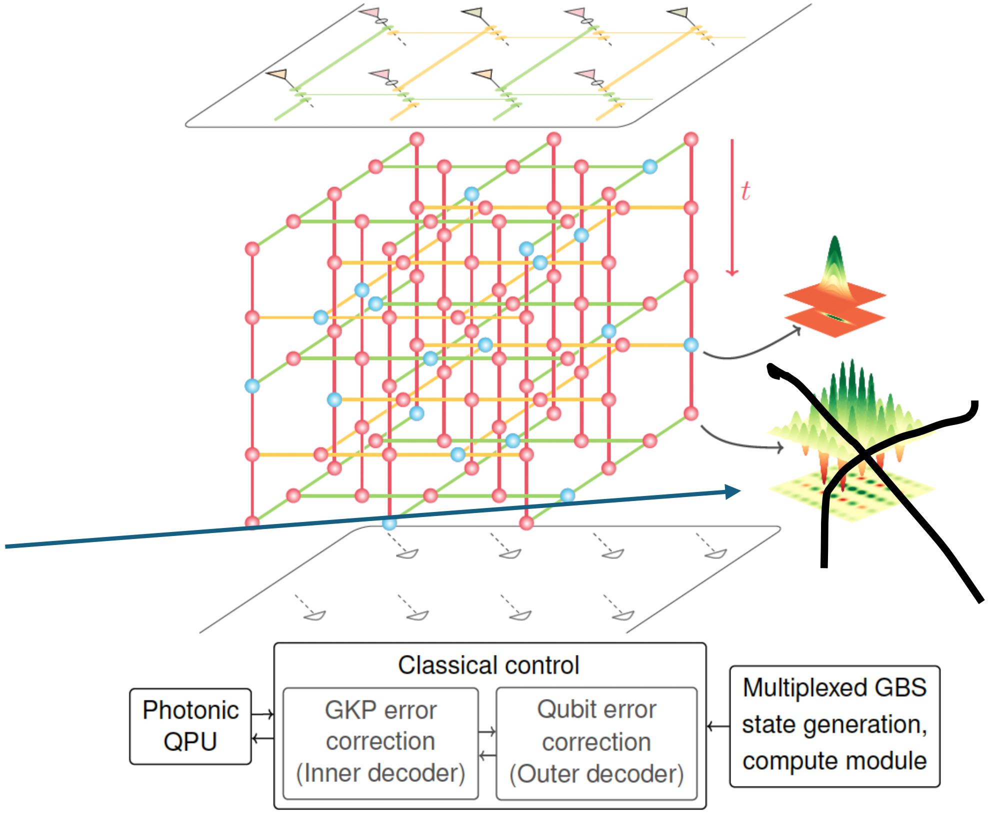

Outlook : set some non-Gaussian operation




## 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)

# Thank you!

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