Laboratoire Kastler Brossel
Physique quantique et applications

# Quantum multimode resources based on optical frequency combs and implementation of quantum complex networks

Valentina Parigi

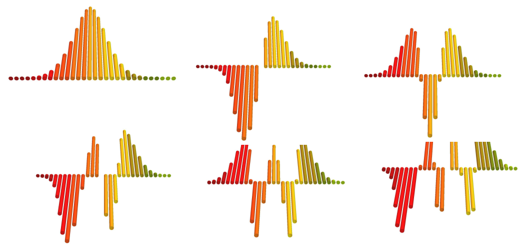
Nicolas Treps, Claude Fabre

Multimode quantum optics group

20 October 2017

# Outline

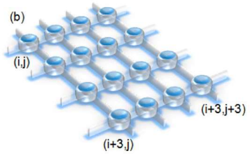
**Multimode quantum optics**



**mutipartite entanglement**

**Study of quantum network**

**cluster  states**

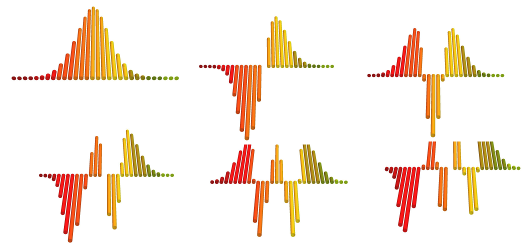



**quantum complex networks**

# Outline

**Multimode quantum optics**

**mutipartite entanglement**



**Study of quantum network**

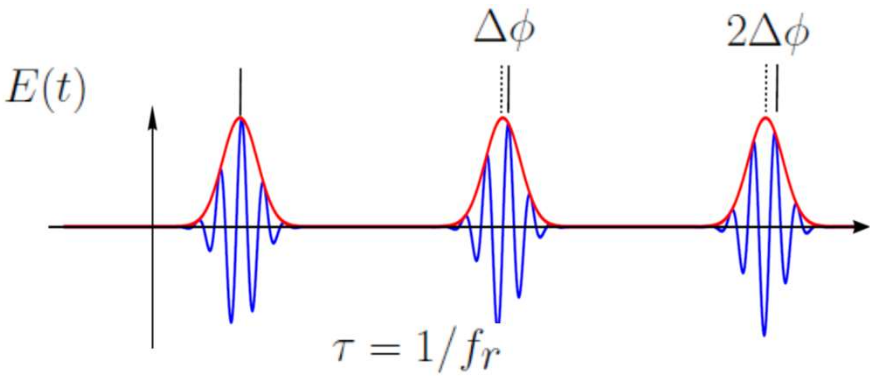
**cluster states**



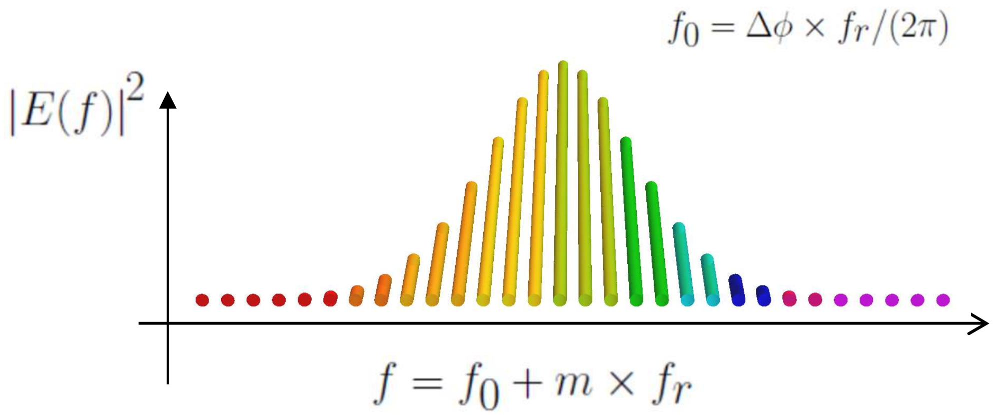

**quantum complex networks**

# Multimode quantum optics

**Optical frequency comb** + quantum optics




time

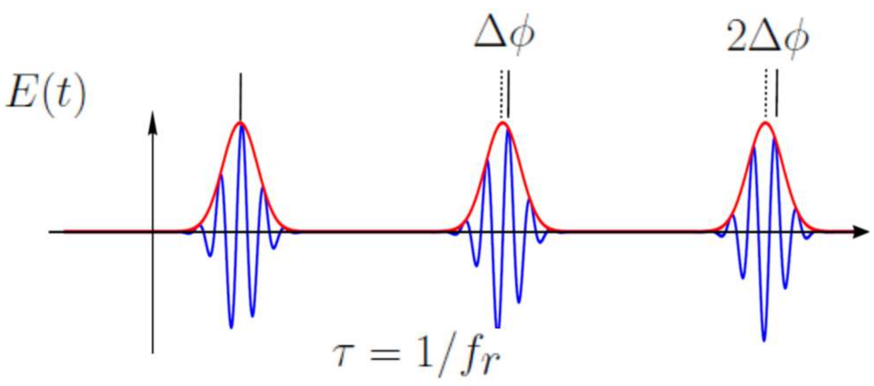



frequency

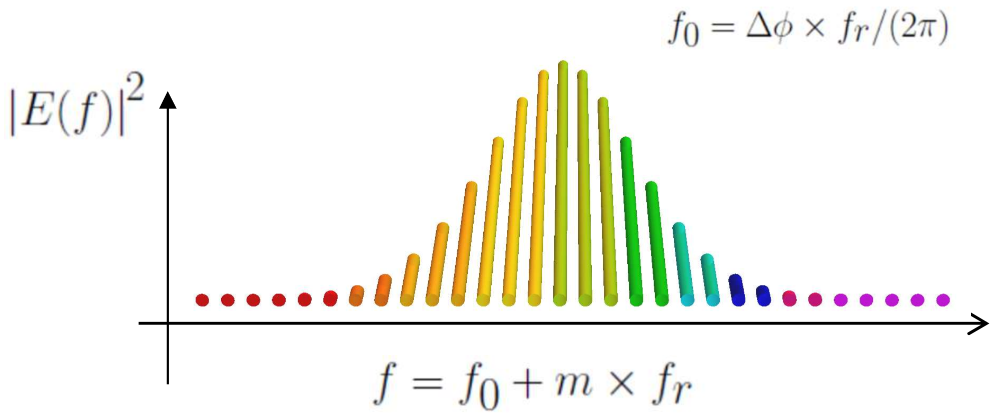
Femtosecond mode-locked laser -> Huge number of modes (~ $10^6$ frequencies)

# Multimode quantum optics

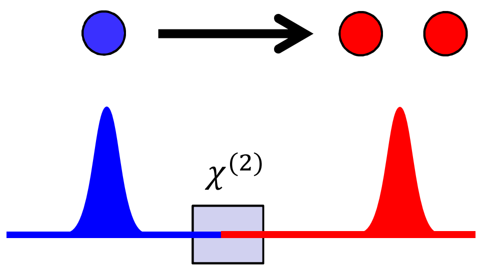
Optical frequency comb + **quantum optics**




time




frequency

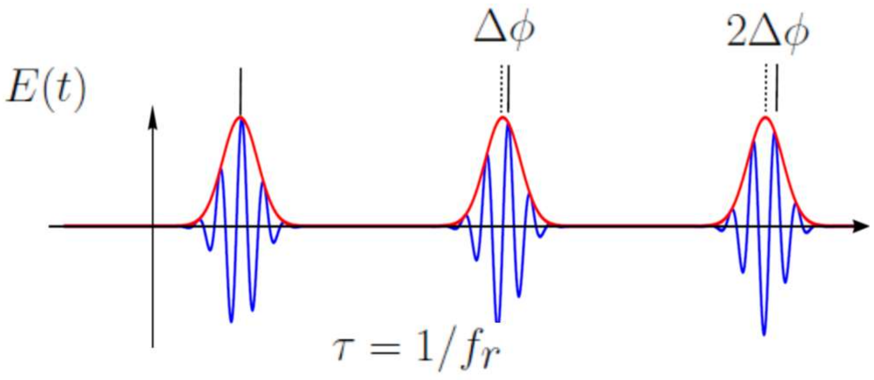



$$\hbar\omega_p = \hbar\omega_s + \hbar\omega_i$$

Parametric process

# Multimode quantum optics

Optical frequency comb + **quantum optics**

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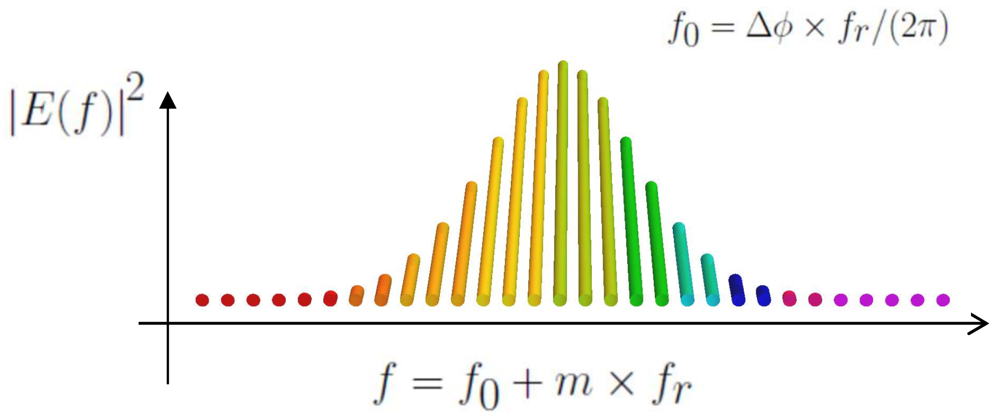
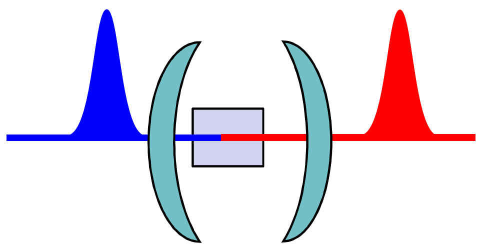
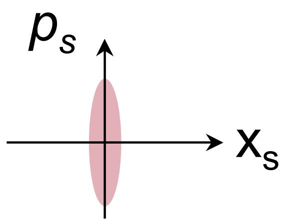



frequency

$$\omega_s = \omega_i$$






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

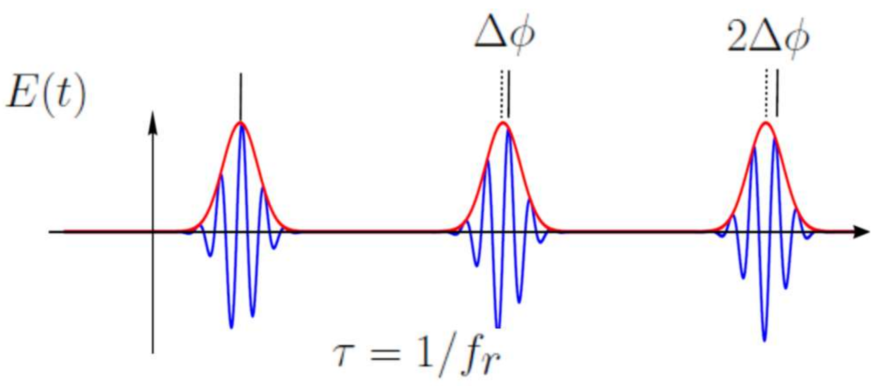
Parametric process

*squeezed states*

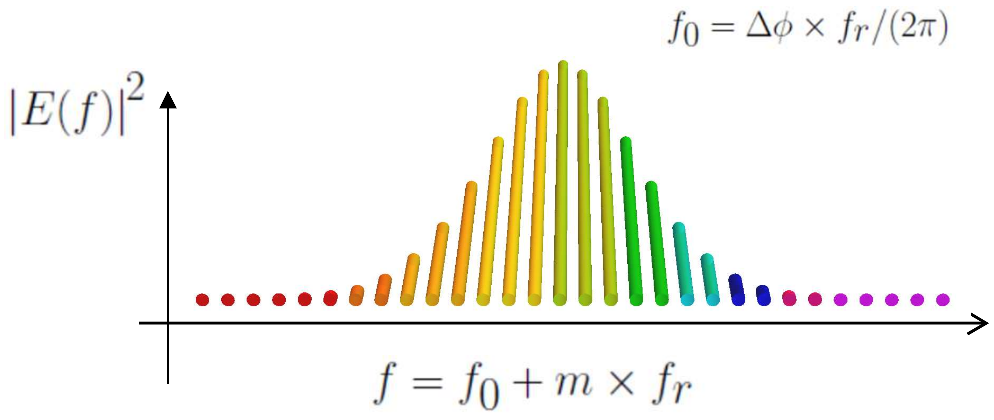
Variance of p < shot noise

# Multimode quantum optics

Optical frequency comb + **quantum optics**

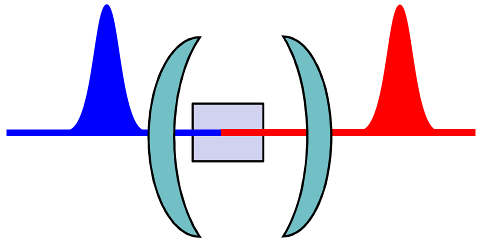



time



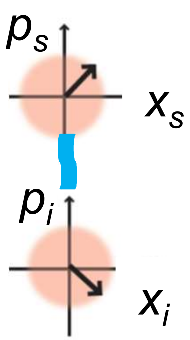

frequency

$\omega_s \neq \omega_i$



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

Parametric process



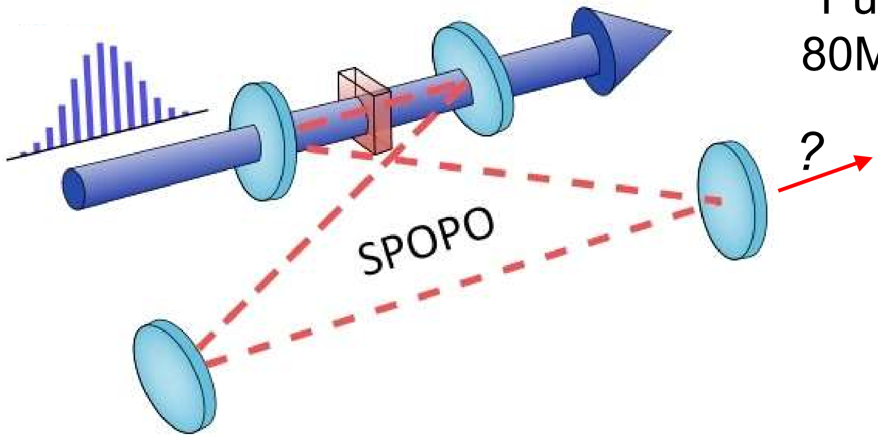

Quadrature entangled states

$x_s$ et $x_i$ correlated
$p_s$ et $p_i$ anti-correlated

# Multimode quantum optics

**Optical frequency comb + quantum optics**

Synchronously pumped OPO

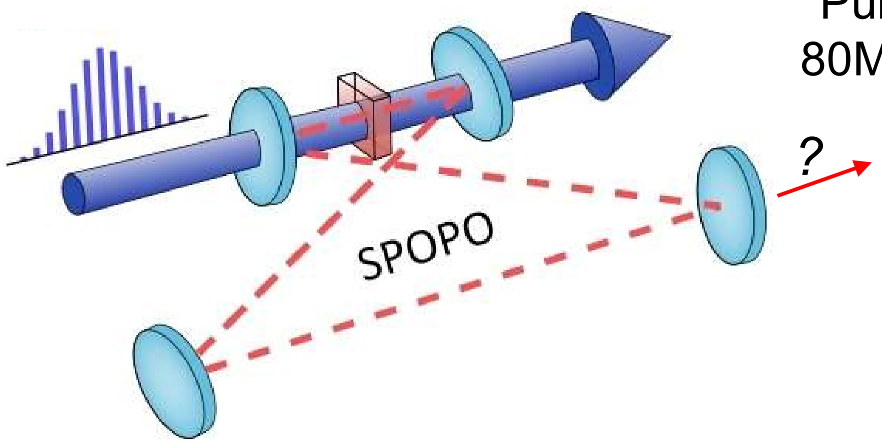



Pump : 200fs
80Mhz rep rate
400nm

# Multimode quantum optics

## Optical frequency comb + quantum optics

Synchronously pumped OPO




Pump : 200fs
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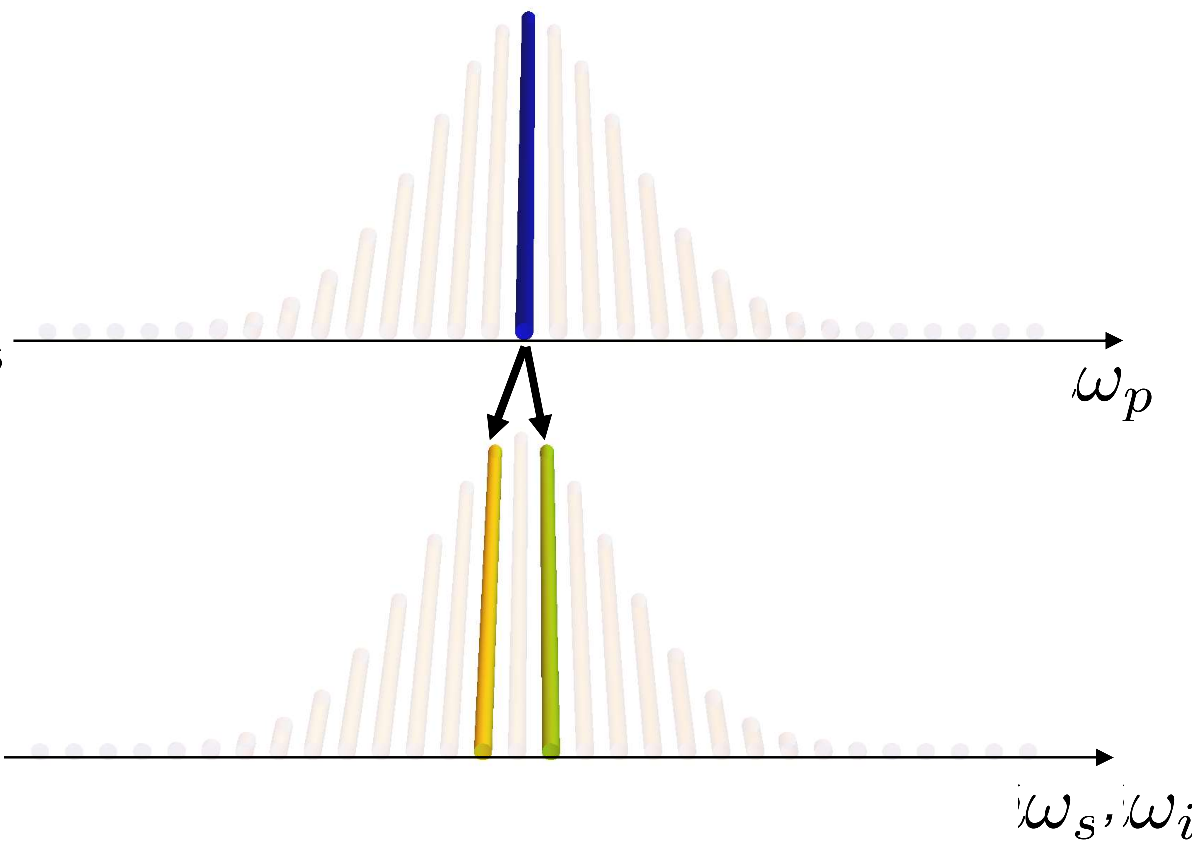
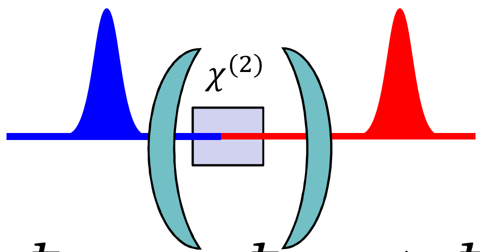
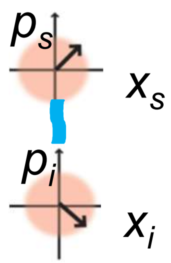
400nm

$$H = i\hbar \sum_{m,n} L_{-m,n}\, \hat{a}^{\dagger}_{-m}\, \hat{a}^{\dagger}_{n}$$




**Symmetric** Frequency Correlations
(quadratures entanglement)



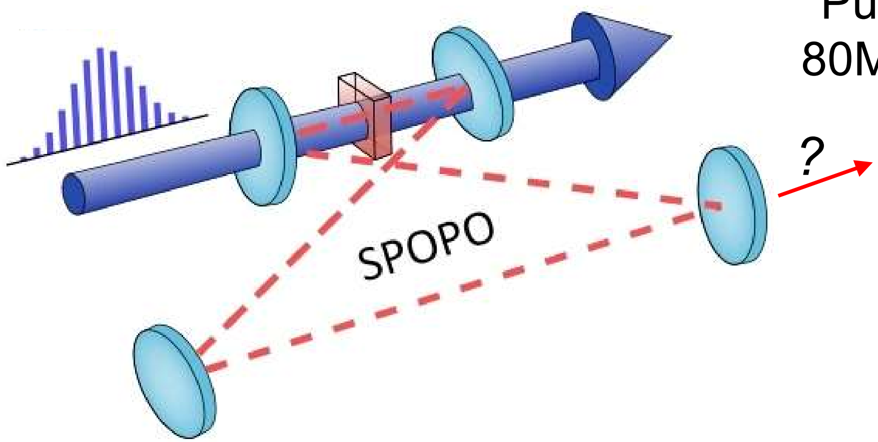

$$\hbar\omega_p = \hbar\omega_s + \hbar\omega_i$$

Parametric process

# Multimode quantum optics

## Optical frequency comb + quantum optics

Synchronously pumped OPO

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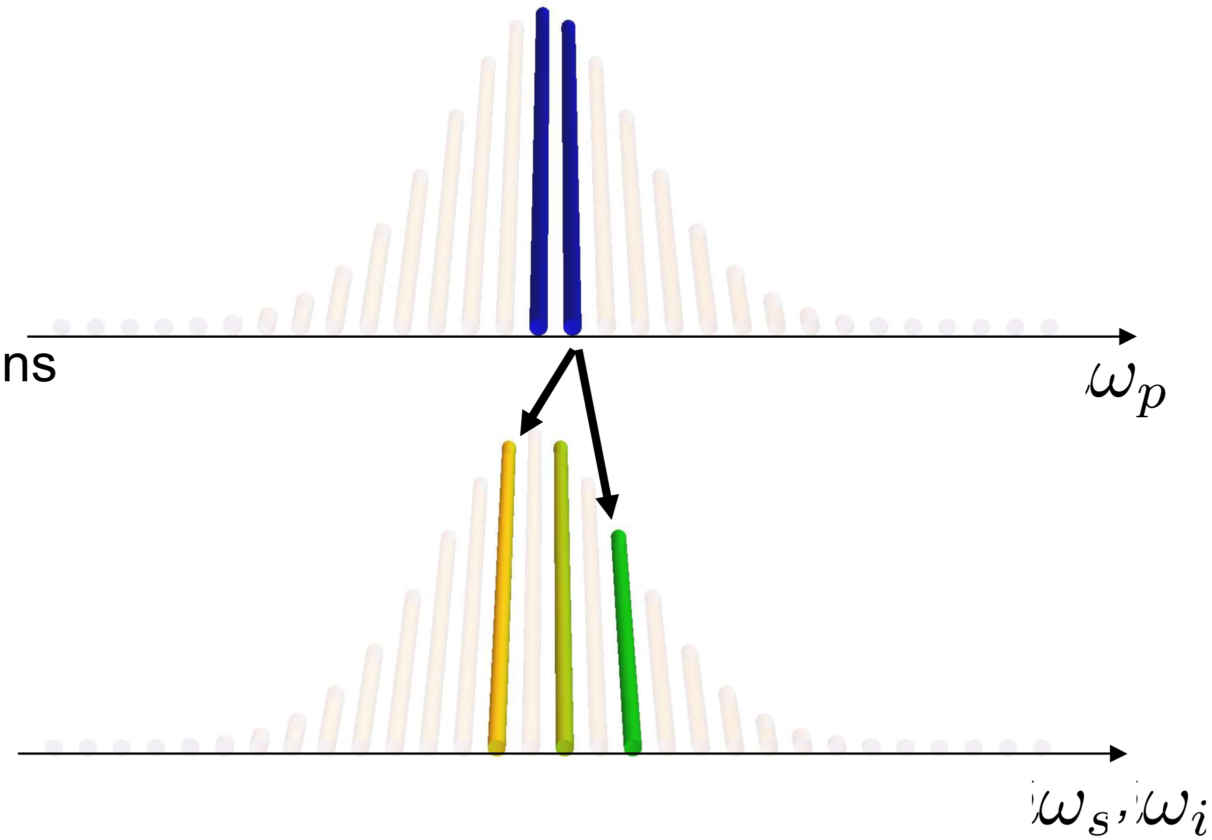
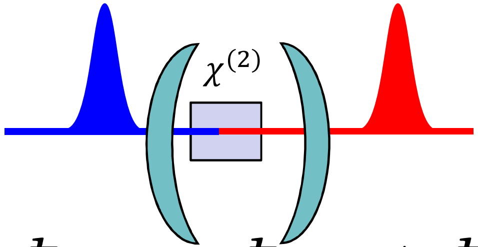



**Asymmetric** Frequency Correlations
(quadratures entanglement)



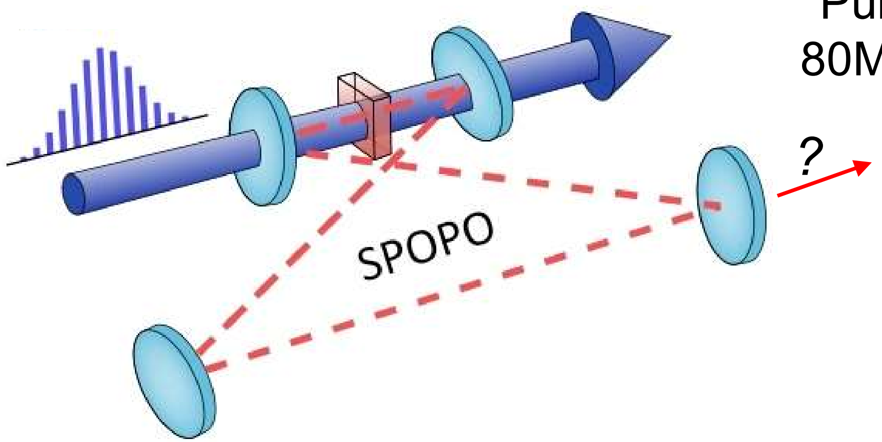

$$\hbar\omega_p = \hbar\omega_s + \hbar\omega_i$$

Parametric process

# Multimode quantum optics

## Optical frequency comb + quantum optics

Synchronously pumped OPO

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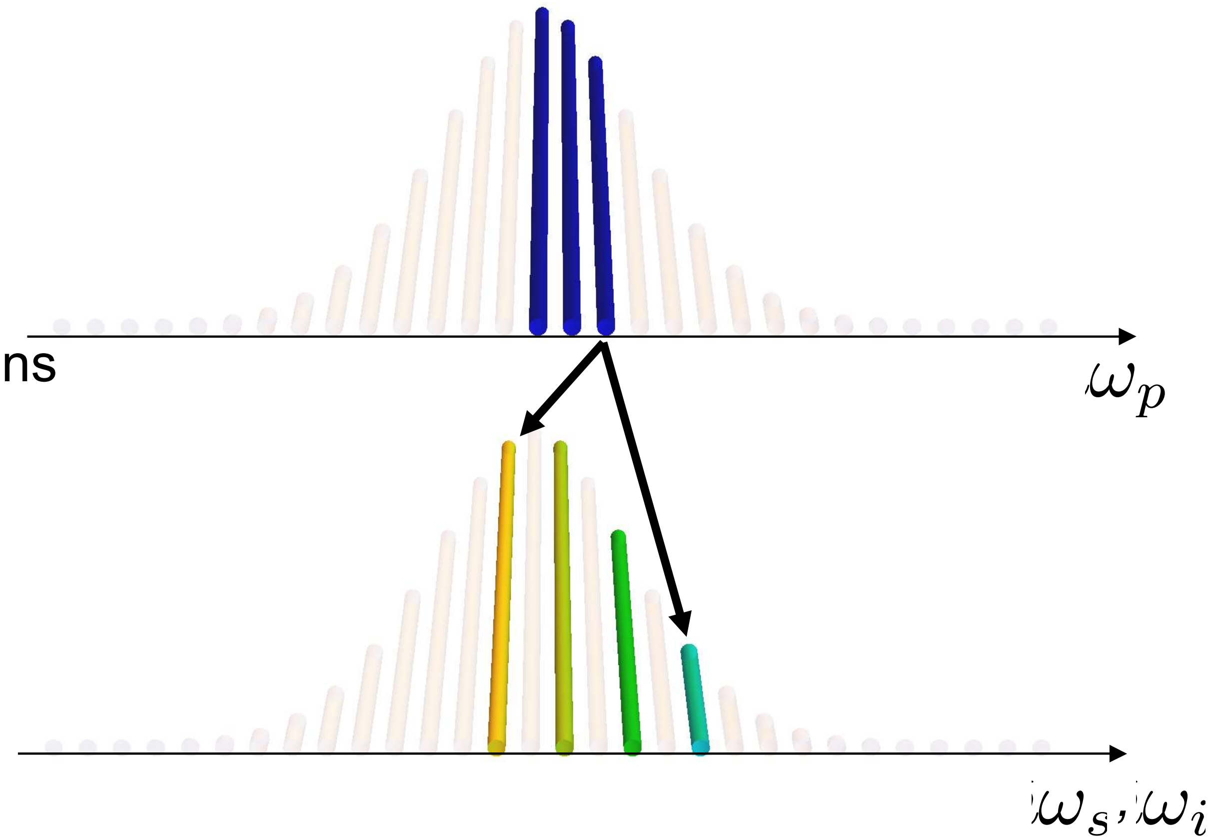


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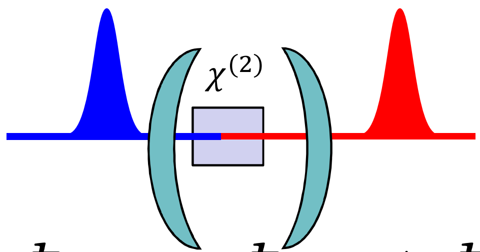


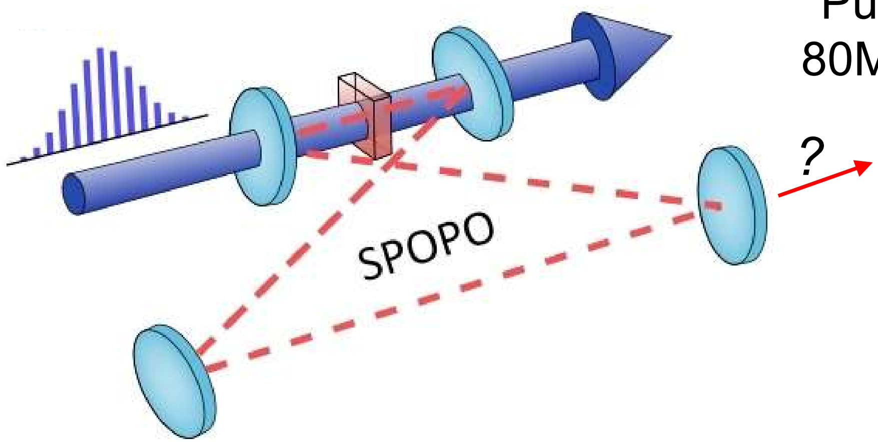

$$\hbar\omega_p = \hbar\omega_s + \hbar\omega_i$$

Parametric process

# Multimode quantum optics

## **Optical frequency comb + quantum optics**

Synchronously pumped OPO

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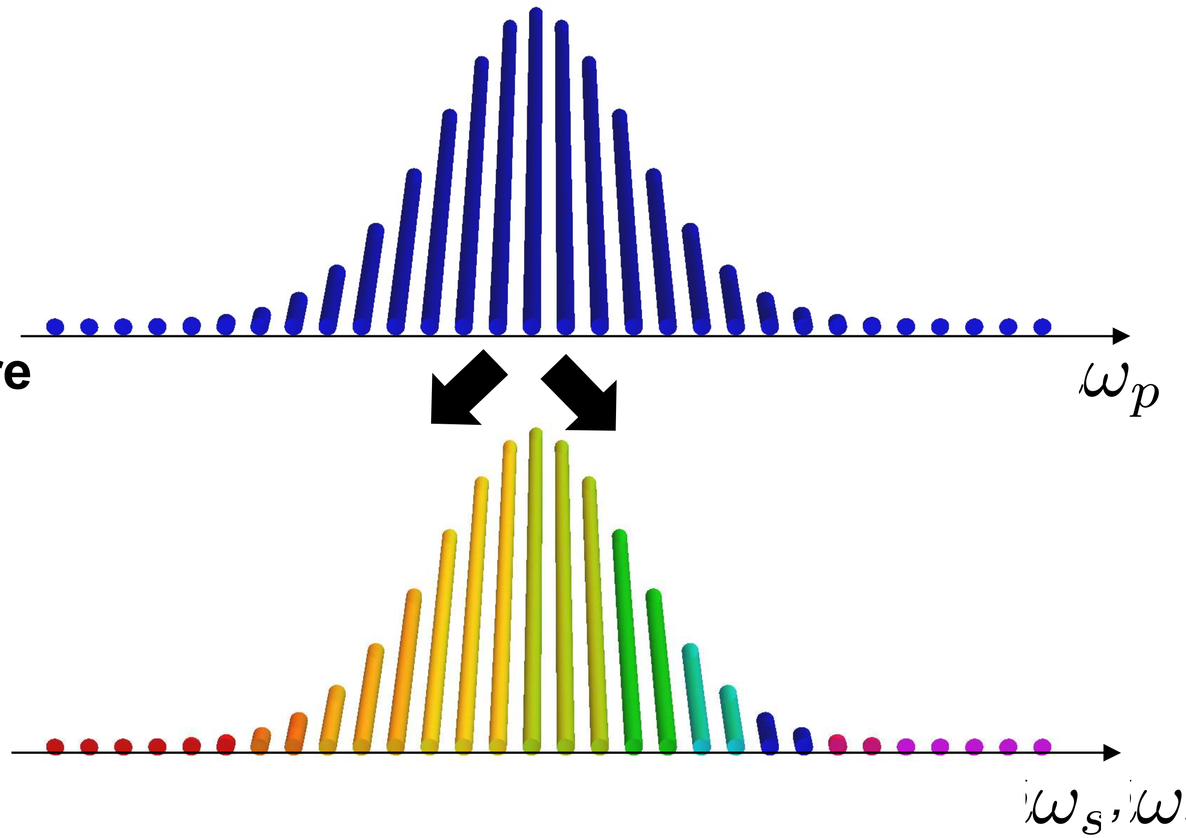
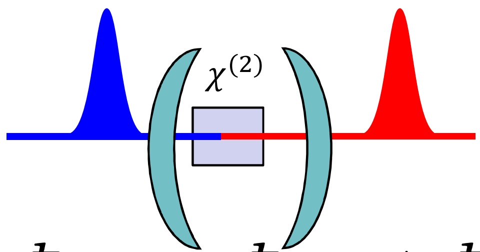
$$H = i\hbar \sum_{m,n} L_{-m,n}\, \hat{a}^{\dagger}_{-m}\, \hat{a}^{\dagger}_{n}$$




**Non-trivial entanglement structure**
(quadratures entanglement)



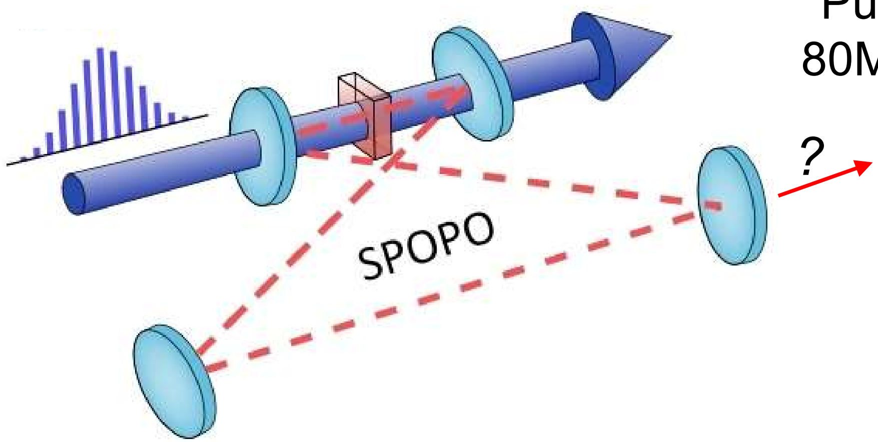

$$\hbar\omega_p = \hbar\omega_s + \hbar\omega_i$$

Parametric process

# Multimode quantum optics

**Optical frequency comb + quantum optics**

Synchronously pumped OPO

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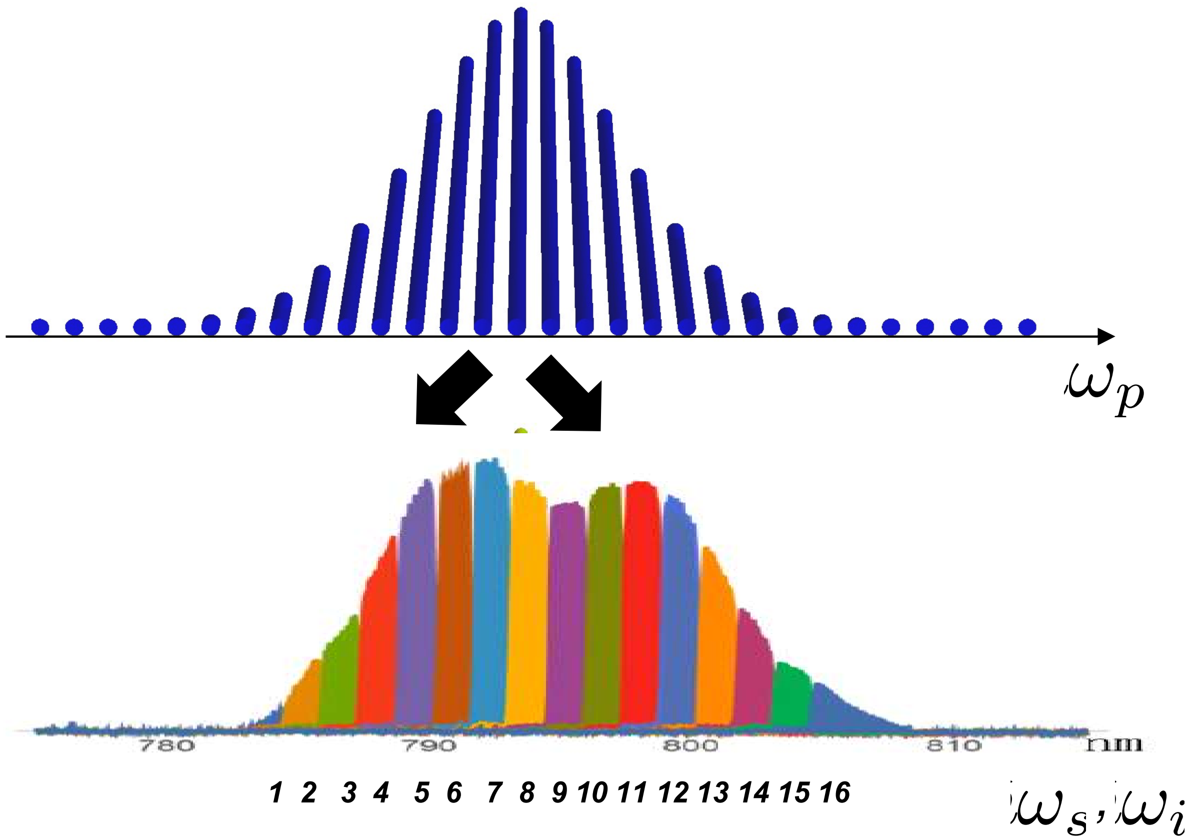
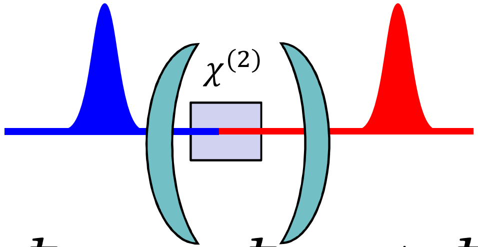
$$H = i\hbar \sum_{m,n} L_{-m,n}\, \hat{a}^\dagger_{-m}\, \hat{a}^\dagger_n$$




**Complex entanglement structure**
(quadratures entanglement)

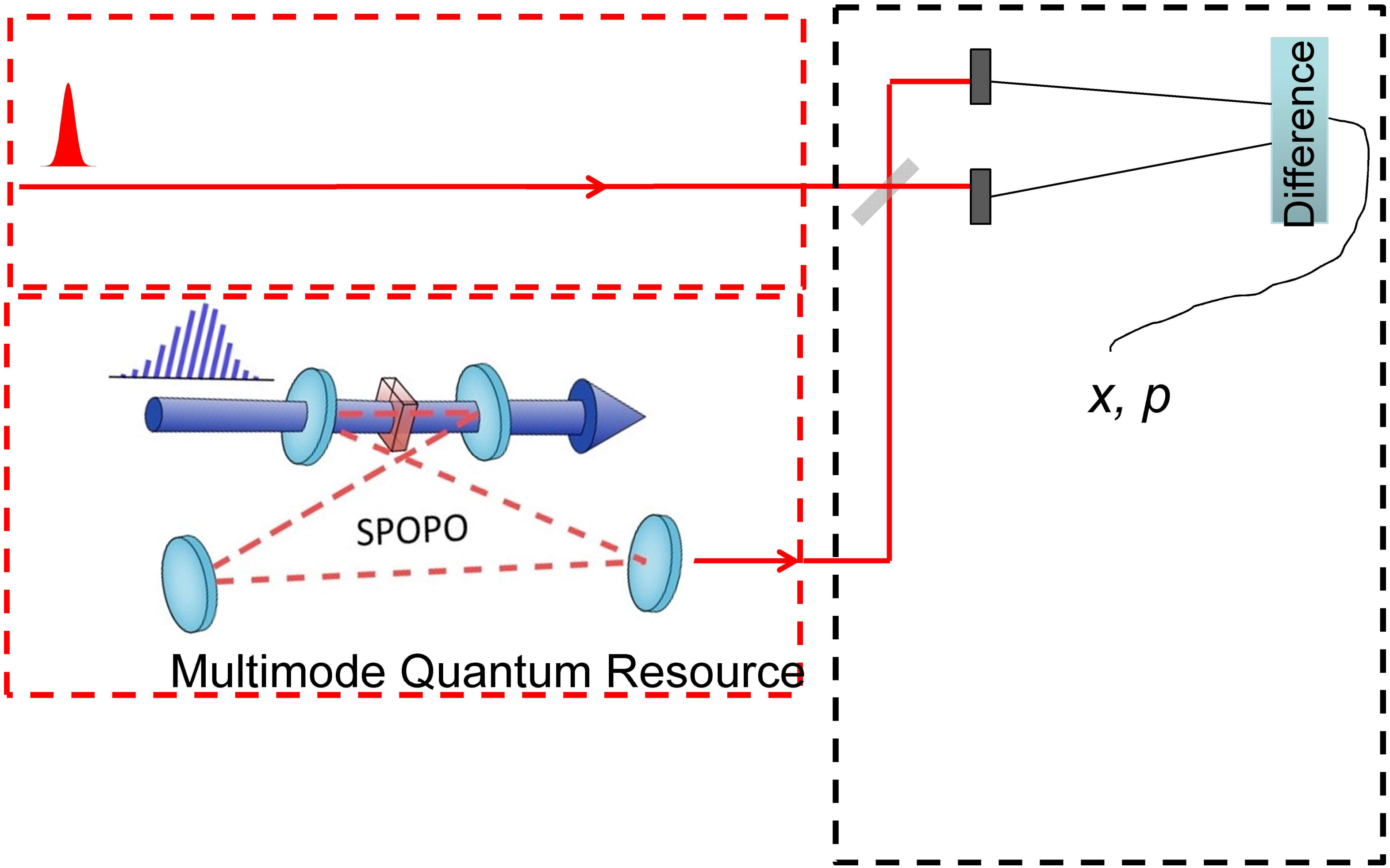



$$\hbar\omega_p = \hbar\omega_s + \hbar\omega_i$$

Parametric process

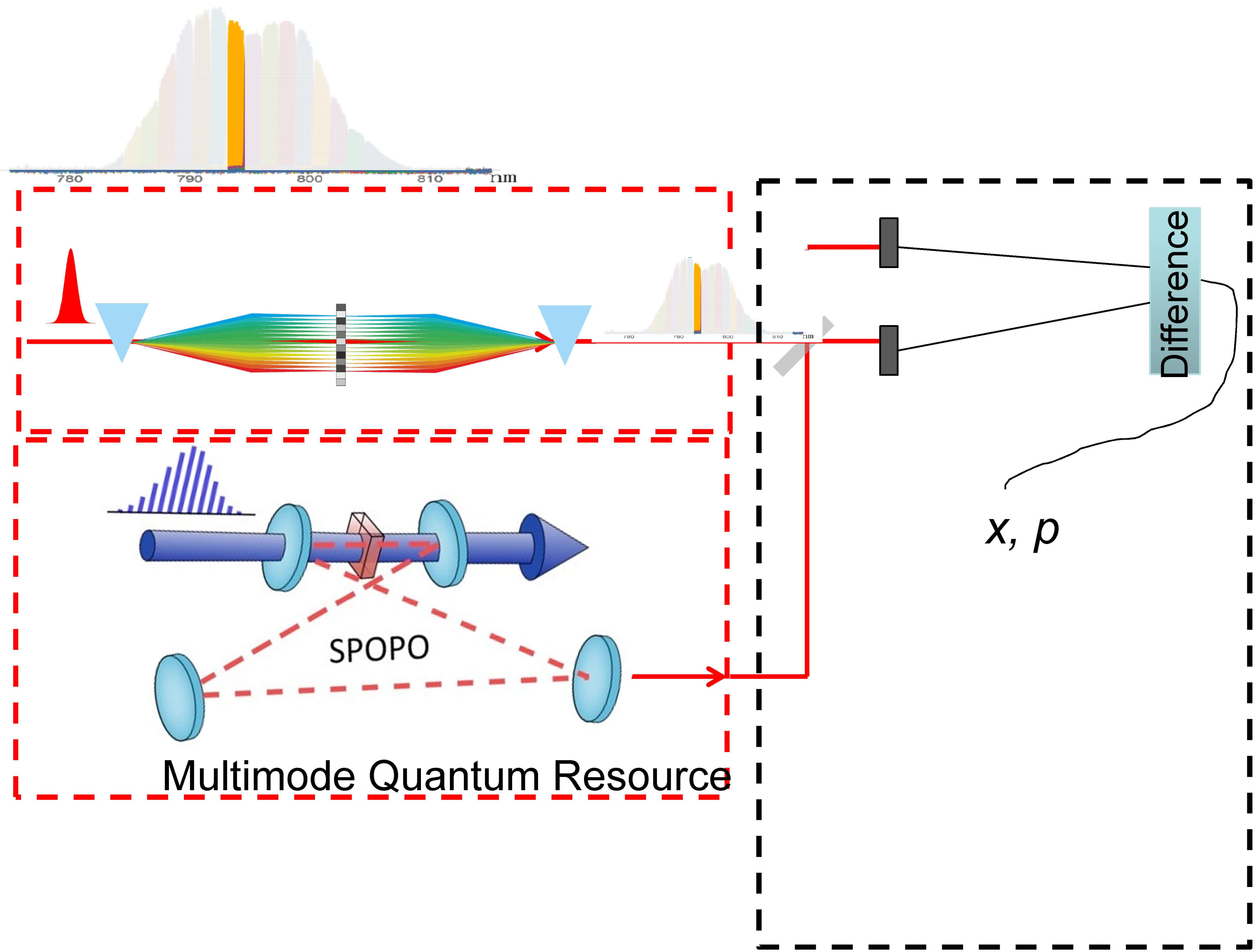
# Characterization

*Characterization :* *homodyne detection*



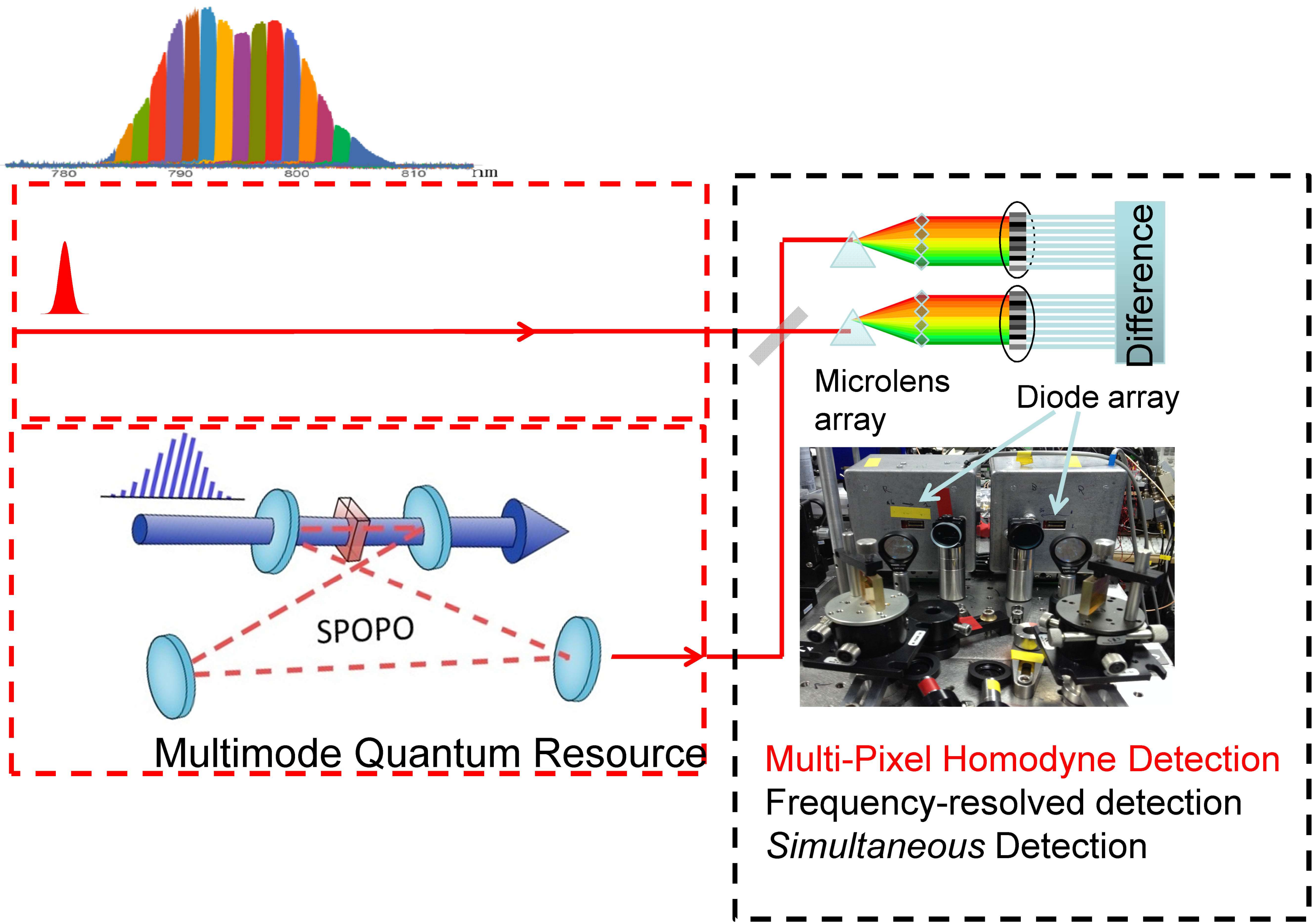
# Characterization 1: pulse shaping

Characterization : mode-selective homodyne detection

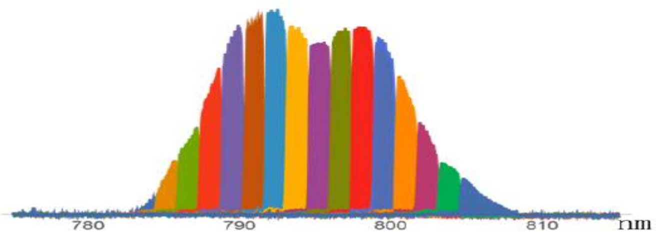


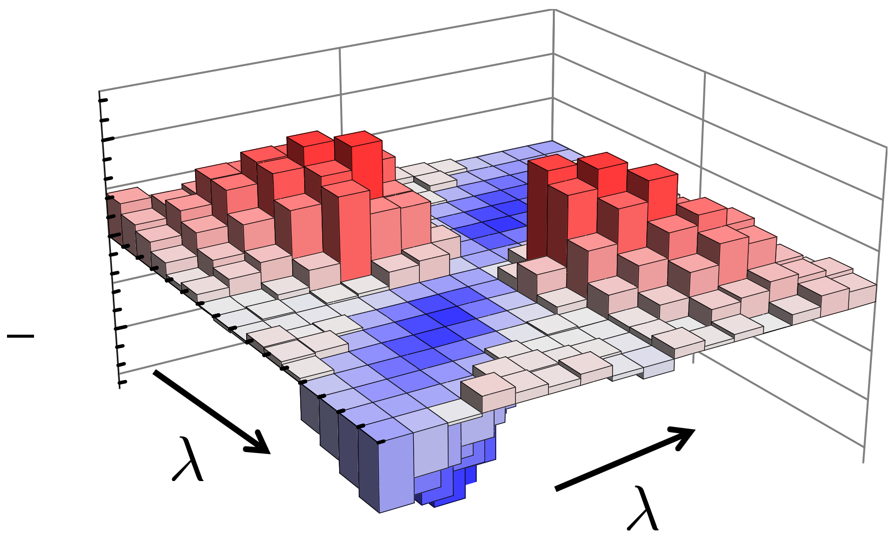
# Characterization 2: multi-pixel

## *Characterization : multi-mode homodyne detection*

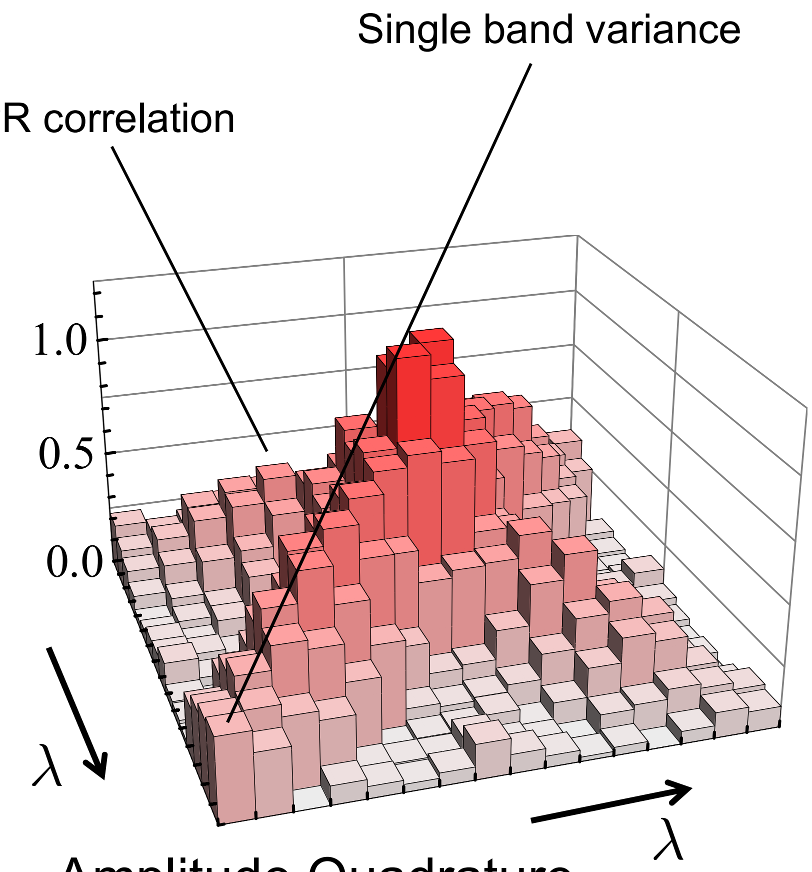


# Characterization: covariance matrix




16-mode Covariance matrix
of Phase Quadrature



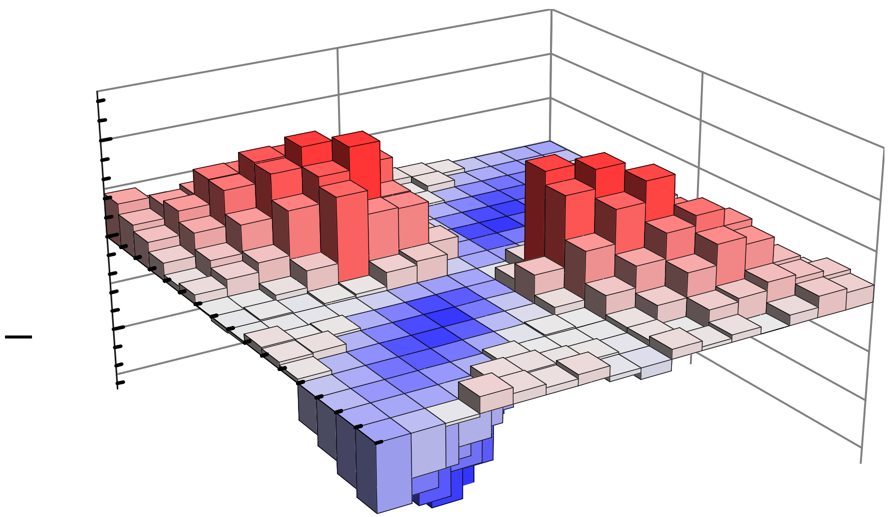

Amplitude Quadrature

$$\frac{\langle \delta\hat{q}_i \delta\hat{q}_j \rangle + \langle \delta\hat{q}_j \delta\hat{q}_i \rangle}{2}$$

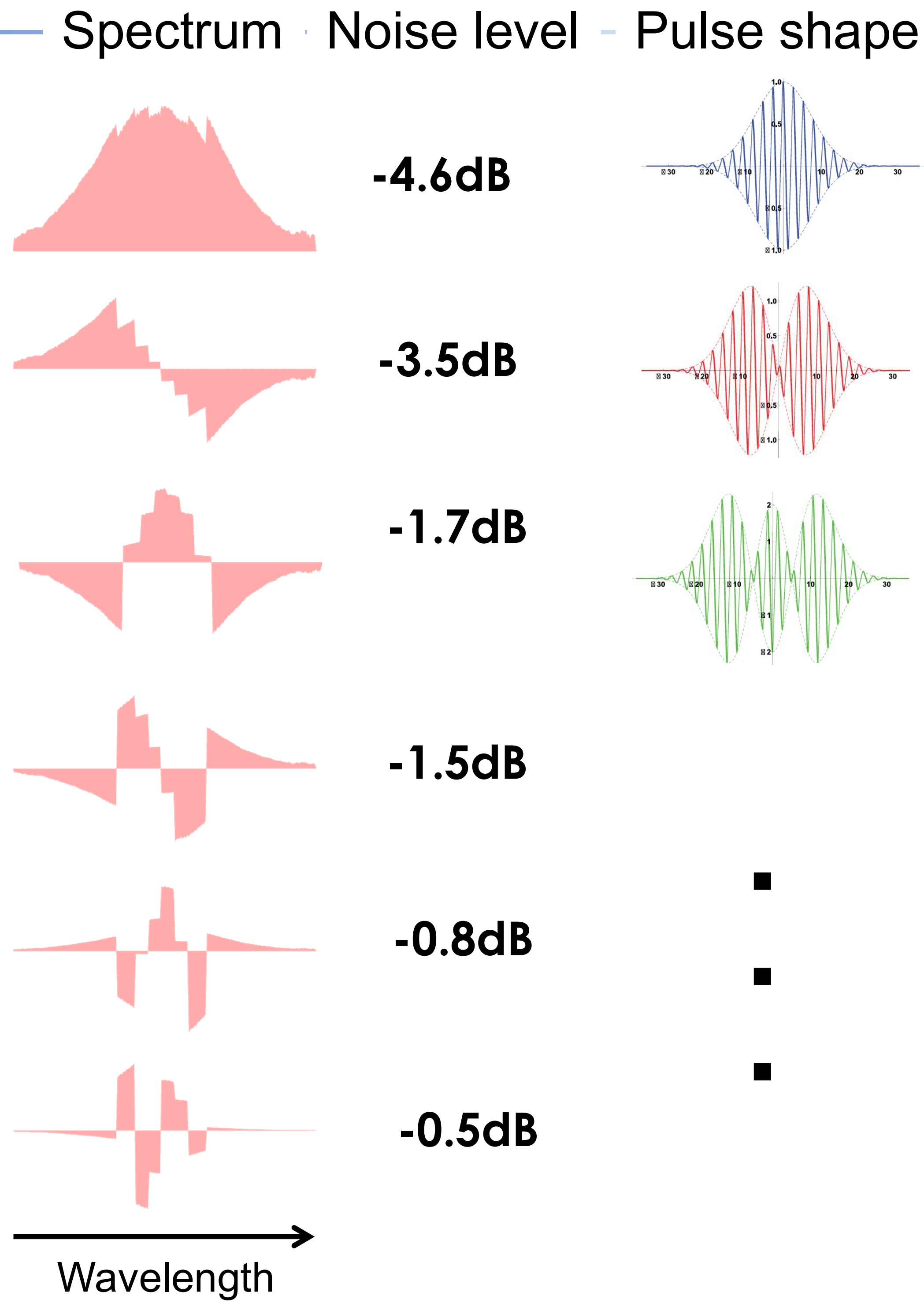
# Eigenmodes

## Diagonalization

- Independent Squeezers
- Unique temporal / spectral pulse shapes



J. Roslund, R. Medeiros, S. Jiang, C. Fabre and N. Treps, Nature Photonics 8, 109–112 (2014)



# Eigenmodes

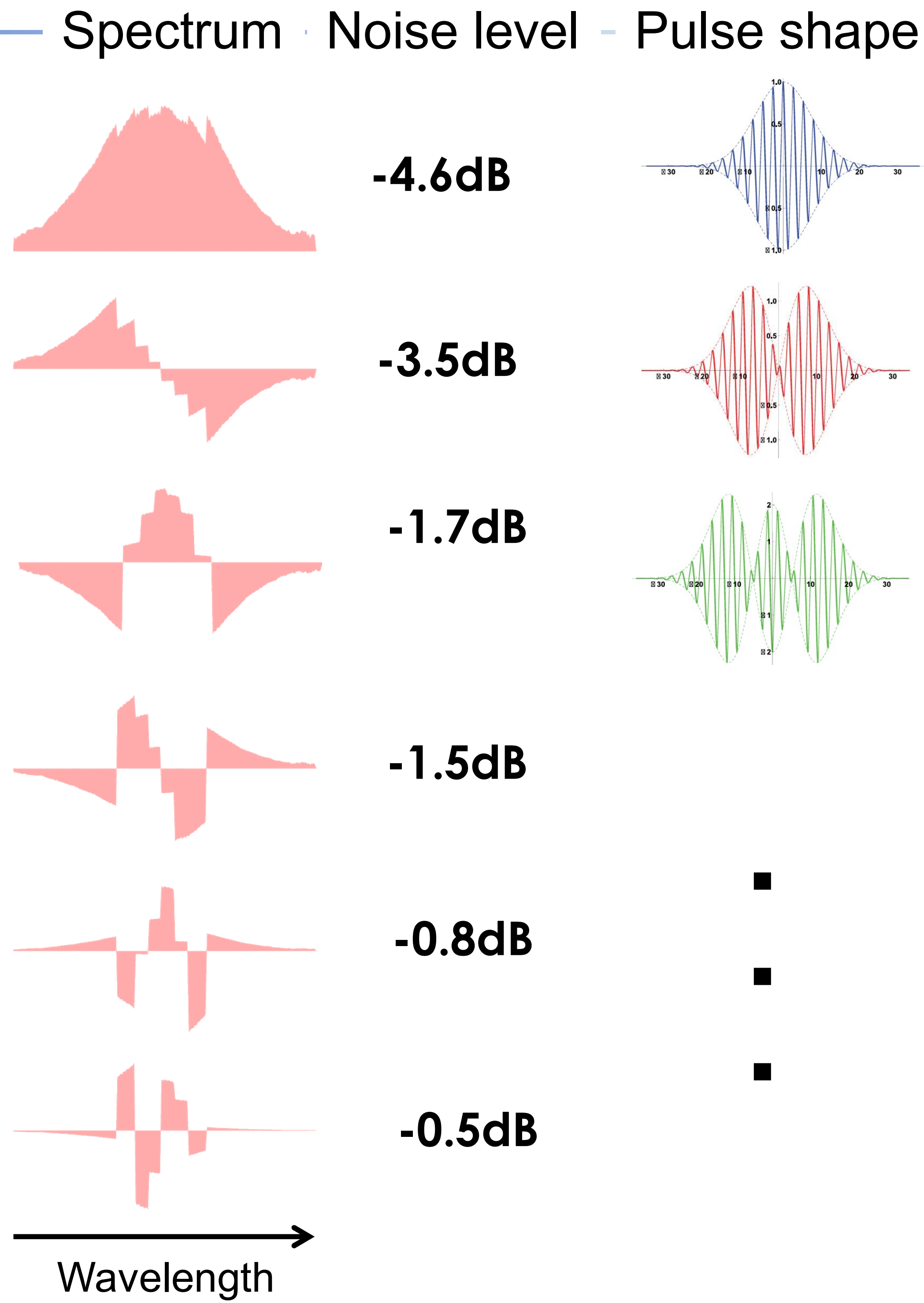
## Diagonalization

- Independent Squeezers
- Unique temporal / spectral pulse shapes = «supermodes»

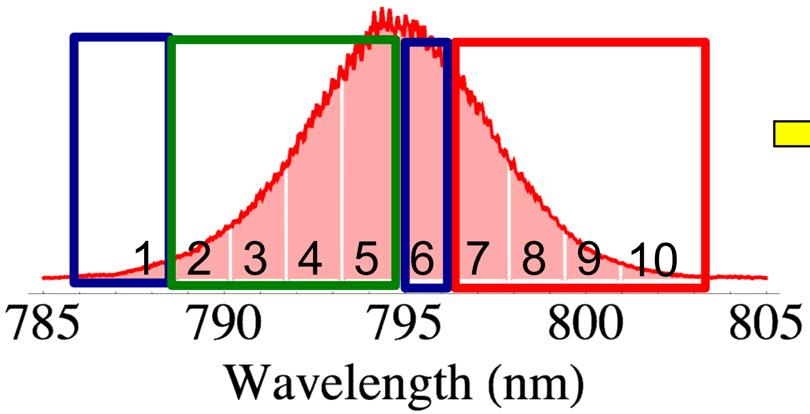
It corresponds to

$$H = i\hbar \sum_{m,n} L_{-m,n}\, \hat{a}^{\dagger}_{-m}\, \hat{a}^{\dagger}_{n}$$

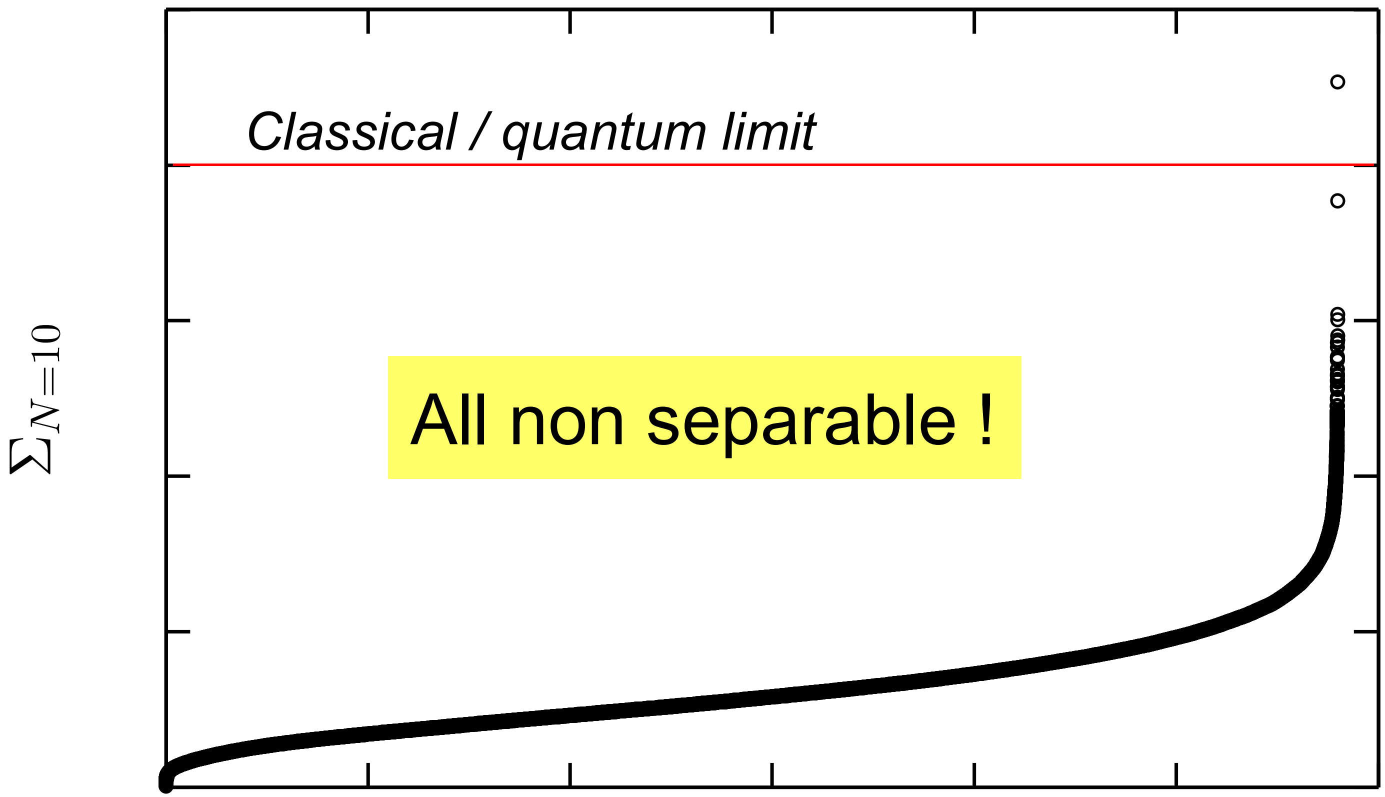
$$H = i\hbar \sum_{k} \Lambda_k \hat{S}_k^{\dagger 2}$$



# Multimode entangled state




10 frequency bands
115 974 possible partitions

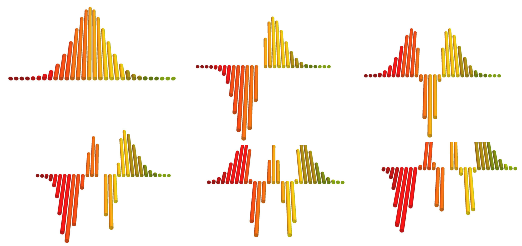



S. Gerke, J. Sperling, W. Vogel, Y. Cai, J. Roslund, N. Treps, and C. Fabre, Phys Rev Lett **114**, 050501 (2015).

# Outline

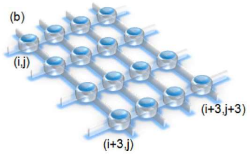
## Multimode quantum optics

### mutipartite entanglement



## Study of quantum network

### cluster  states



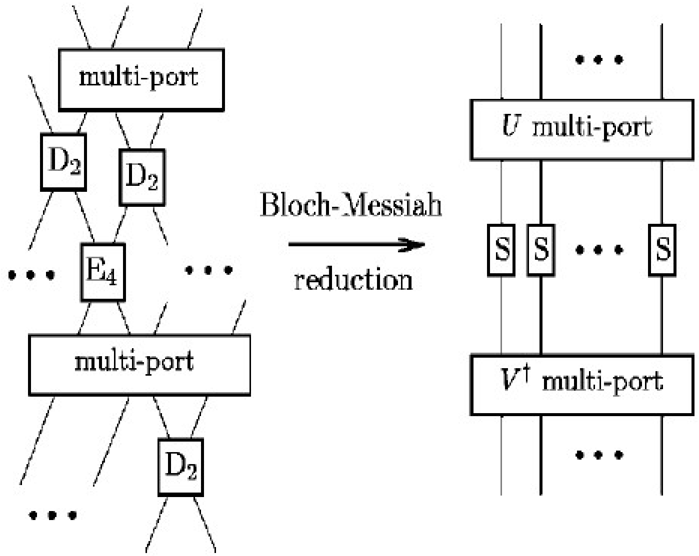

### quantum complex networks

# Bloch-Messiah decomposition

PHYSICAL REVIEW A **71**, 055801 (2005)

**Squeezing as an irreducible resource**

Samuel L. Braunstein
*Computer Science, University of York, York YO10 5DD, United Kingdom*
(Received 6 March 2005; published 31 May 2005)




multimode quantum Gaussian ressource = Squeezed modes + basis change

$$\vec{a} = (a_1, a_2, \dots, a_N).$$

*collection of input modes*

$$\{\boldsymbol{q}, \boldsymbol{p}\} = (q_1, q_2, \dots, q_N, p_1, p_2, \dots p_N).$$

$$\begin{pmatrix} \boldsymbol{q}_{out} \\ \boldsymbol{p}_{out} \end{pmatrix} = \boldsymbol{S} \begin{pmatrix} \boldsymbol{q}_{in} \\ \boldsymbol{p}_{in} \end{pmatrix}$$

$$\boldsymbol{S} = R_1^T \Delta R_2$$

squeezing ($\Delta$)

basis change ($R_1^T$, $R_2$)

***Bloch-Messiah reduction***

# Bloch-Messiah decomposition

PHYSICAL REVIEW A **71**, 055801 (2005)

## Squeezing as an irreducible resource

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*Computer Science, University of York, York YO10 5DD, United Kingdom*
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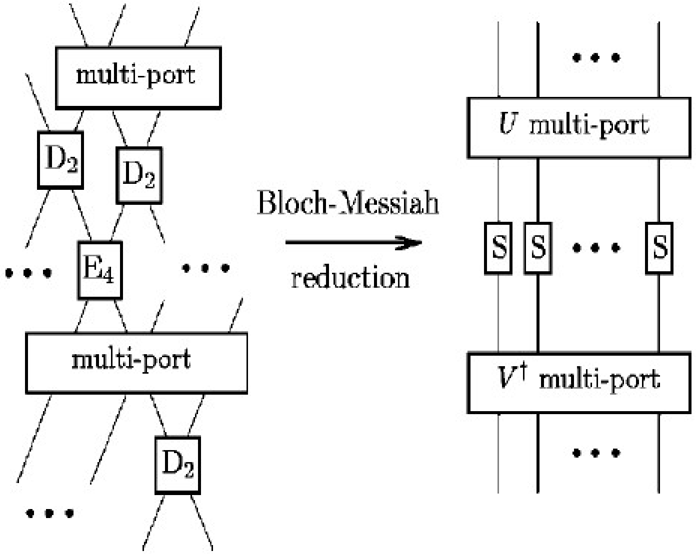
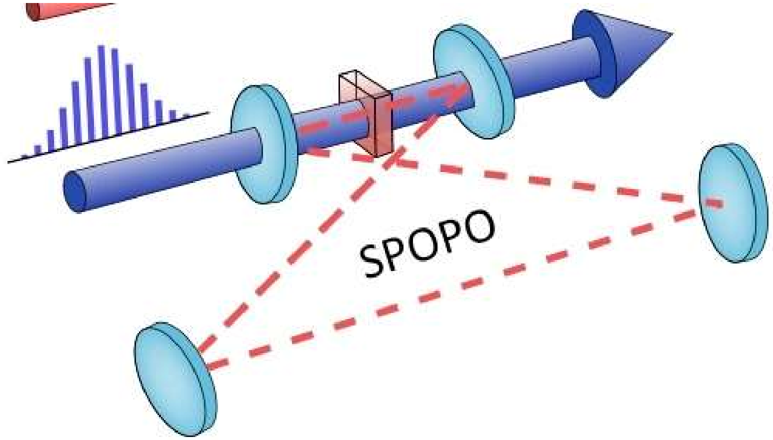



$$\vec{a} = (a_1, a_2, \dots, a_N).$$

*collection of input modes*

$$\{\boldsymbol{q}, \boldsymbol{p}\} = (q_1, q_2, \dots, q_N, p_1, p_2, \dots p_N).$$

***input modes in vacuum -> discard*** $R_2$

$$\begin{pmatrix} \boldsymbol{q}_{out} \\ \boldsymbol{p}_{out} \end{pmatrix} = \boldsymbol{S} \begin{pmatrix} \boldsymbol{q}_{in} \\ \boldsymbol{p}_{in} \end{pmatrix}$$

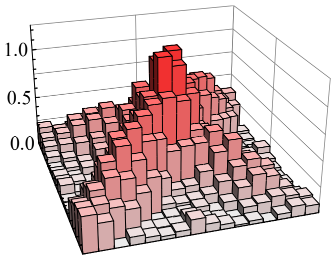
squeezing

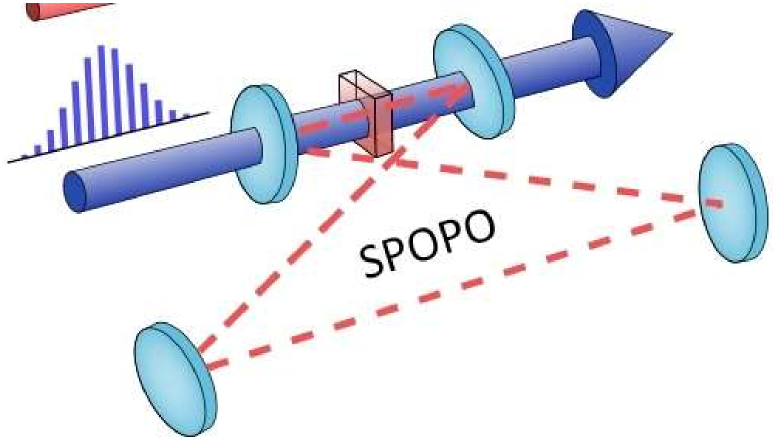
$$\boldsymbol{S} = R_1^T \Delta R_2$$

basis change

***Bloch-Messiah reduction***

# Bloch-Messiah decomposition

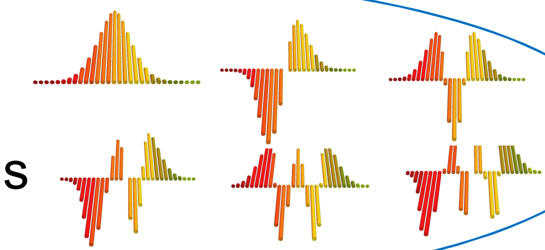



multipartite entanglement
in frequency-pixel basis

$$\begin{pmatrix} \boldsymbol{q}_{out} \\ \boldsymbol{p}_{out} \end{pmatrix} = R_1^T \Delta \begin{pmatrix} \boldsymbol{q}_{in} \\ \boldsymbol{p}_{in} \end{pmatrix}$$

squeezing in the
supermodes basis



$$\begin{pmatrix} \boldsymbol{q}_{out} \\ \boldsymbol{p}_{out} \end{pmatrix} = \boldsymbol{S} \begin{pmatrix} \boldsymbol{q}_{in} \\ \boldsymbol{p}_{in} \end{pmatrix}$$

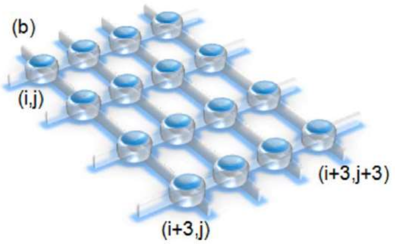
$$\boldsymbol{S} = R_1^T \Delta R_2$$

squeezing

basis change

***Bloch-Messiah reduction***

# Cluster states



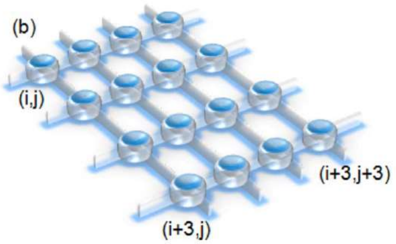

$$|\psi_V\rangle = \hat{C}_Z[V]|0\rangle_p^{\otimes N} = \prod_{j,k}^{N} e^{\frac{i}{2}V_{jk}\hat{q}_j\hat{q}_k}|0\rangle_p^{\otimes N} = e^{\frac{i}{2}\hat{q}^T V \hat{q}}|0\rangle_p^{\otimes N}$$

Collection of N infinitely p-squeezed states (modes)

Nullifiers $\hat{p}_i - \sum_k V_{i,k}\hat{q}_k$

$$\Delta^2\left(\hat{p}_i - \sum_k V_{i,k}\hat{q}_k\right) = \langle\psi_V|\left(\hat{p}_i - \sum_k V_{i,k}\hat{q}_k\right)^2|\psi_V\rangle \longrightarrow 0$$

# Cluster states



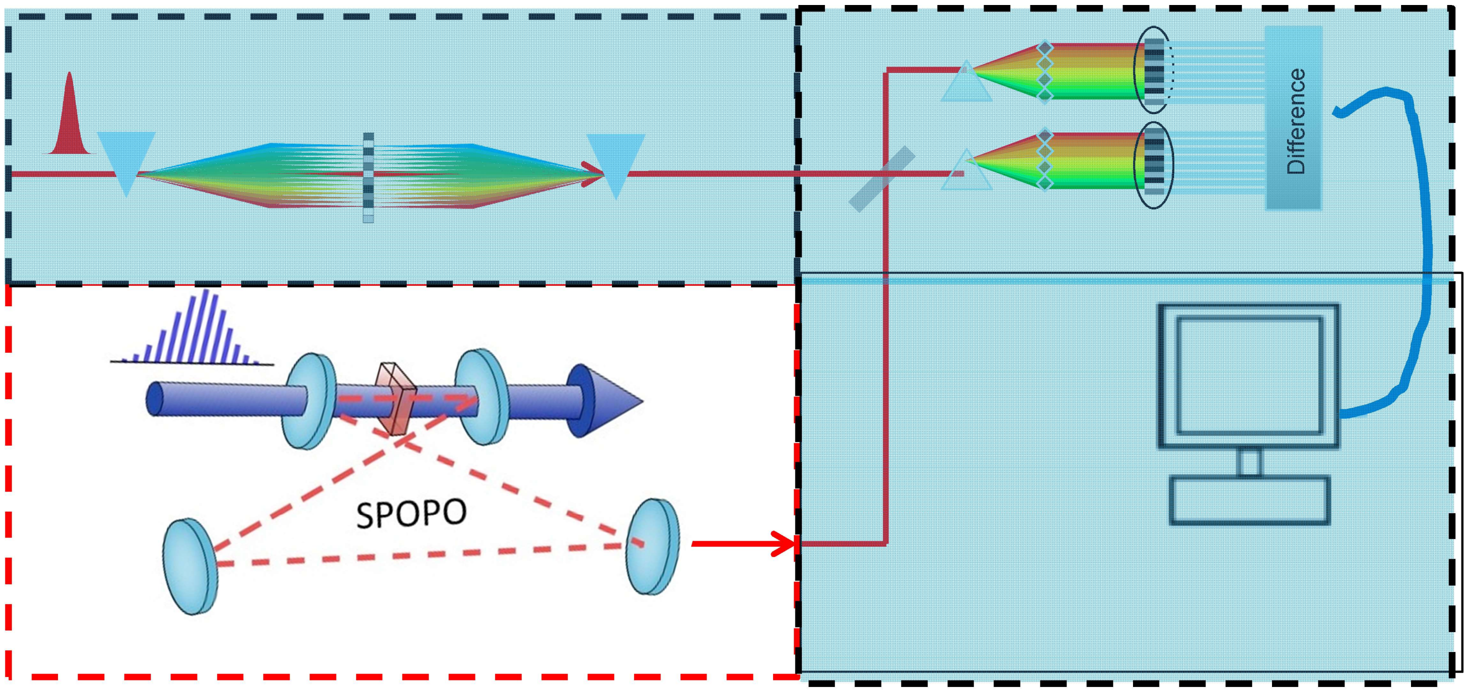

$$|\psi_V\rangle = \hat{C}_Z[V]|0\rangle_p^{\otimes N} = \prod_{j,k}^{N} e^{\frac{i}{2}V_{jk}\hat{q}_j\hat{q}_k}|0\rangle_p^{\otimes N} = e^{\frac{i}{2}\hat{q}^T V \hat{q}}|0\rangle_p^{\otimes N}$$

Collection of N ~~infinitely~~ p-squeezed states (modes)

multimode Gaussian state

## Controlling B-M

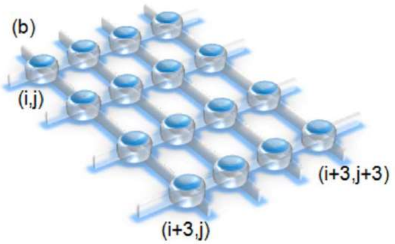
$$\begin{pmatrix} \boldsymbol{q}_{cluster} \\ \boldsymbol{p}_{cluster} \end{pmatrix} = R_1^T \Delta \begin{pmatrix} \boldsymbol{q}_{in} \\ \boldsymbol{p}_{in} \end{pmatrix}$$




Control on $R_1^T$ (basis change) via mode-selective homodyne

G. Ferrini *et al*, New J Phys 15, 093015 (2013)
G. Ferrini *et al.*, PRA **94**, 062332 (2016)

# Cluster states




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

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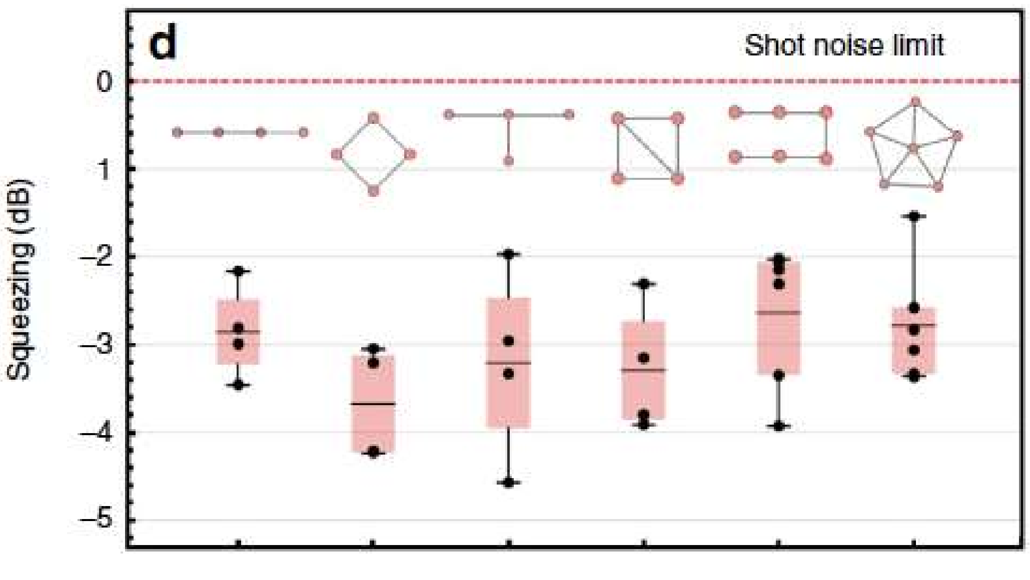
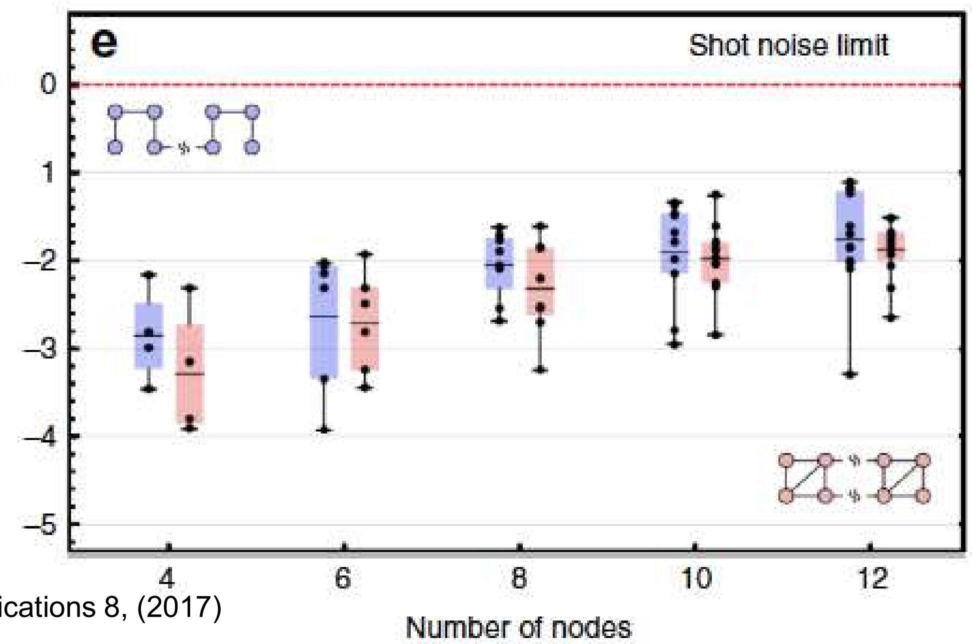
## Cluster states simulation in the current setup

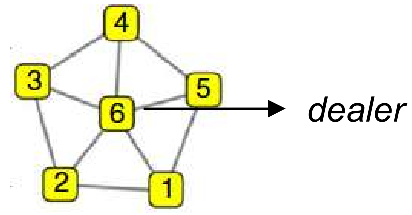



Y Cai, J Roslund, G Ferrini, F Arzani, X Xu, C Fabre, N Treps Nature Communications 8, (2017)

# A cluster for secret sharing

five-partite secret sharing protocol with six mode all-optical quantum graph




- Secret can only be retrieved through a collaboration of subsets of the 3 players

- quantum correlations increase both the protocol **security** as well as its retrieval **fidelity** compared to classical resources

Y. Cai, J. Roslund, G. Ferrini, F. Arzani, X. Xu, C. Fabre & N. Treps, Nature Communications 8,15645 (2017)

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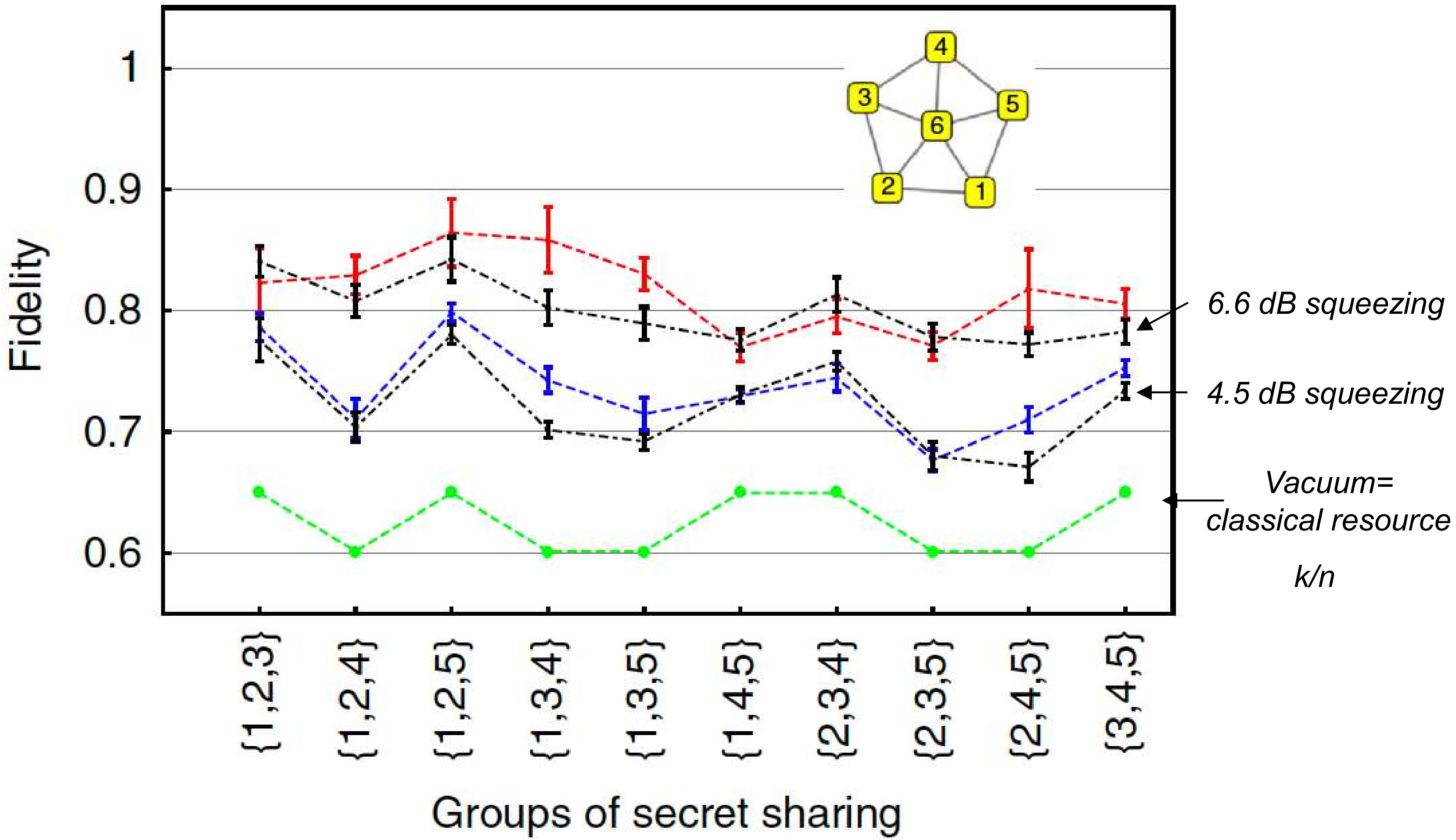


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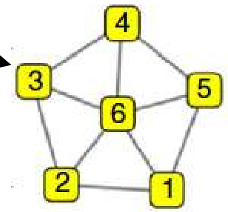
*nodes=*
*frequency modes*
*with complex shape*




*mode sorting for distributing the nodes between parties in different locations is not trivial*

Y. Cai, J. Roslund, G. Ferrini, F. Arzani, X. Xu, C. Fabre & N. Treps, Nature Communications 8,15645 (2017)

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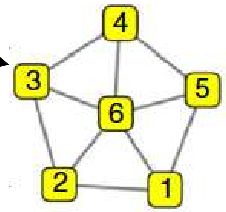
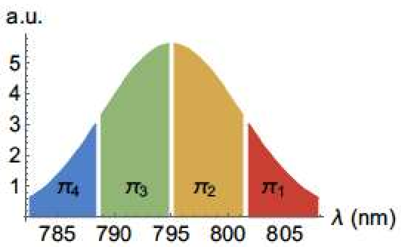
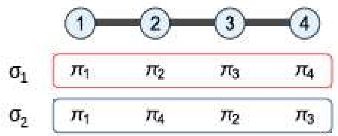



*mode sorting for distributing the nodes between parties in different locations is not trivial*

*can we have nodes= frequency bands?*



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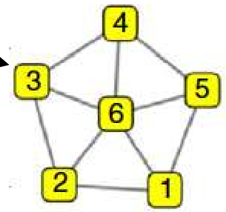


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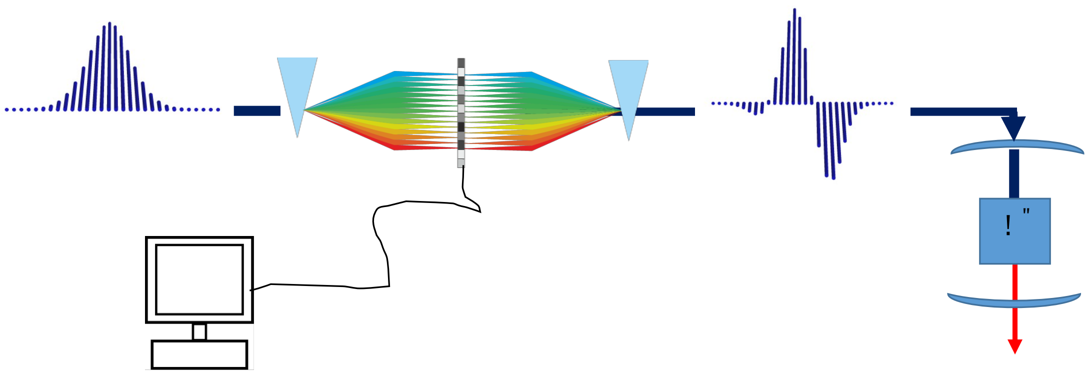

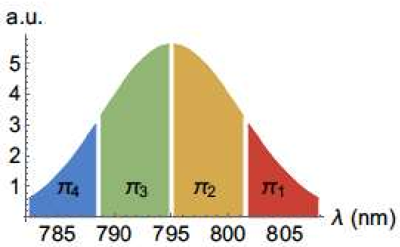


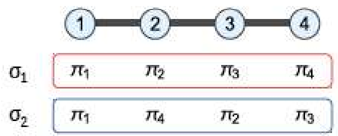


***pump shaping***

*optimization procedure based on an evolutionary algorithm*

*F. Arzani et al, arXiv:1709.10055*

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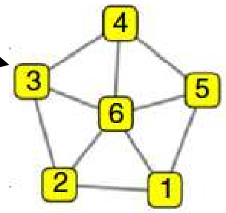
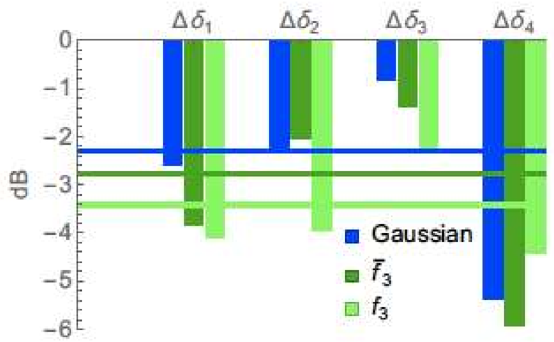
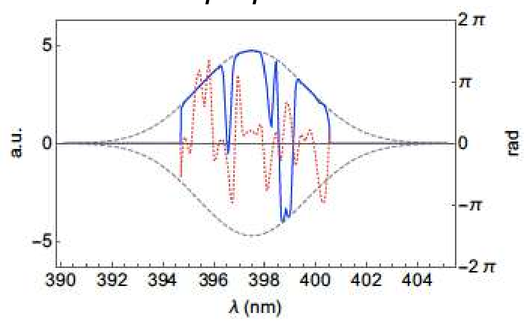


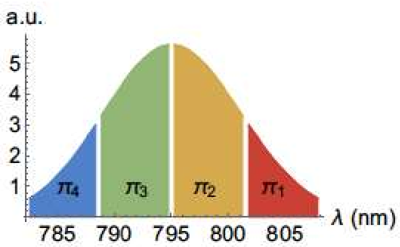

*can we have nodes= frequency bands?*

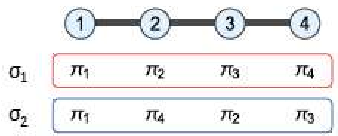
*Nullifiers*




*Pump spectrum*

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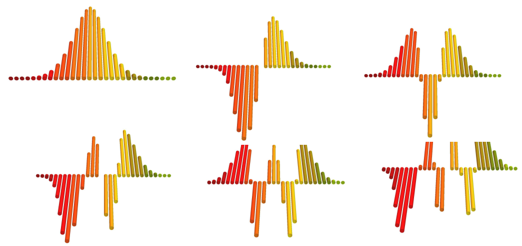
# Outline

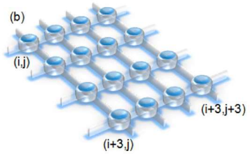
**Multimode quantum optics**

**mutipartite entanglement**

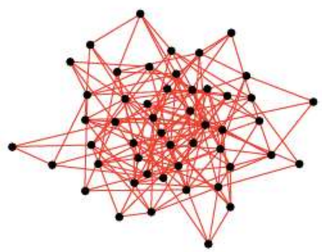


**Study of quantum network**

**cluster  states**

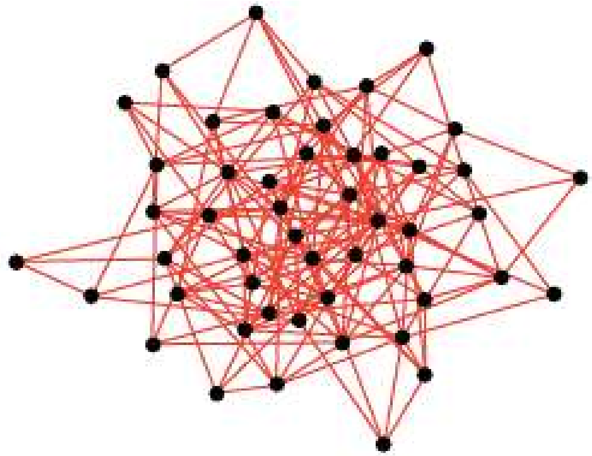



**quantum complex networks**



# Quantum complex networks

Collections of quantum systems arranged in a non-regular topology



*Ex: random-network*

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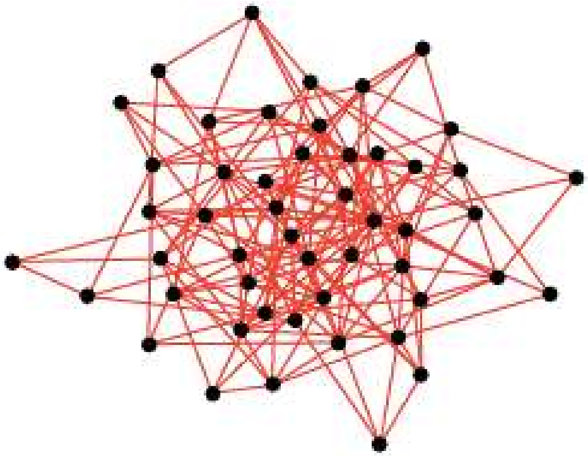

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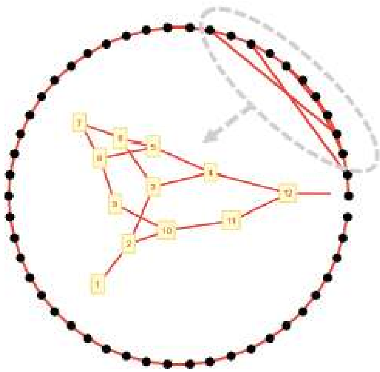
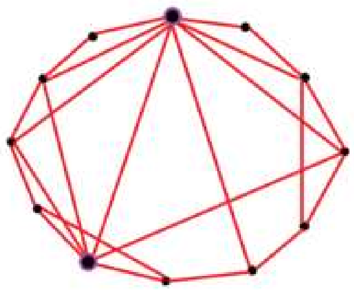
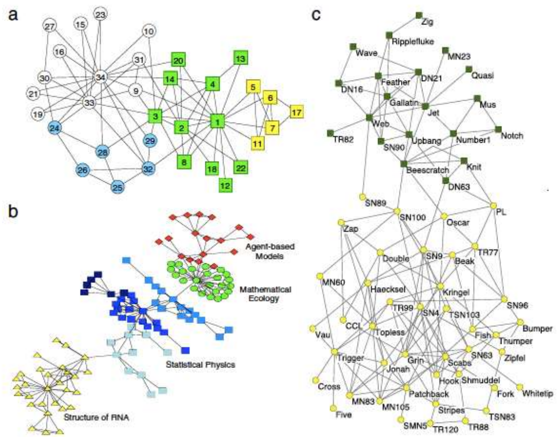


*linear chain with shortcuts*



*small-world network*

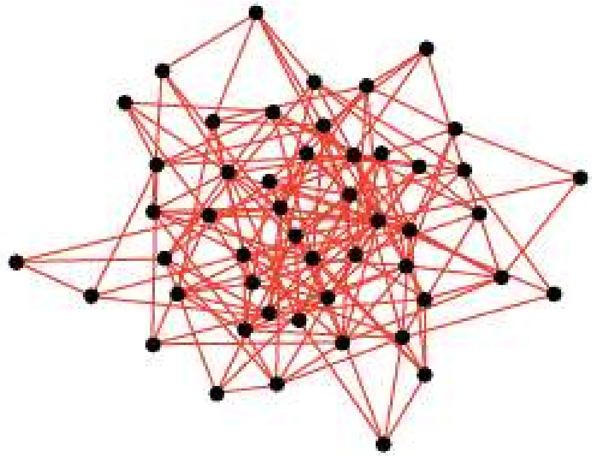



*community structures*

# Quantum complex networks

Collections of quantum systems arranged in a non-regular topology

Why interesting ?



**1) quantum description of complex network = ** different from classical case
localization, quantum walk, phase transition, quantum transport, synchronization, etc

**2) quantum networks with no classical equivalent ( ex. entanglement connections)**
**=** Future quantum communication and information technologies -> ( computational complexity, but also complex topology)

**3) quantum complex networks useful in several contexts,**
**e.g.** open system dynamics, quantum gravity

G. Bianconi, EPL (Europhysics Letters) 111, 56001 (2015). J. Biamonte, M. Faccin, and M. De Domenico, arXiv:1702.08459.

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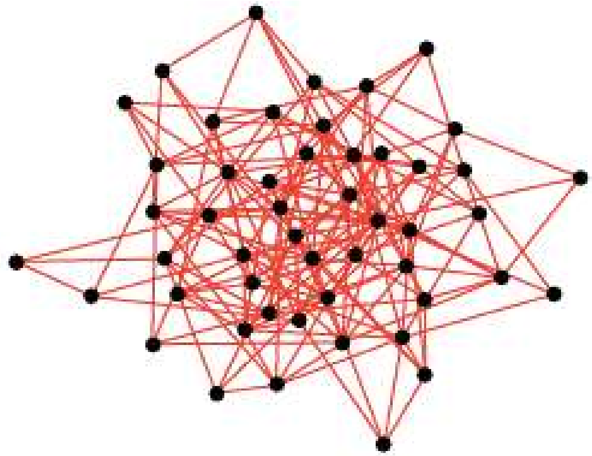

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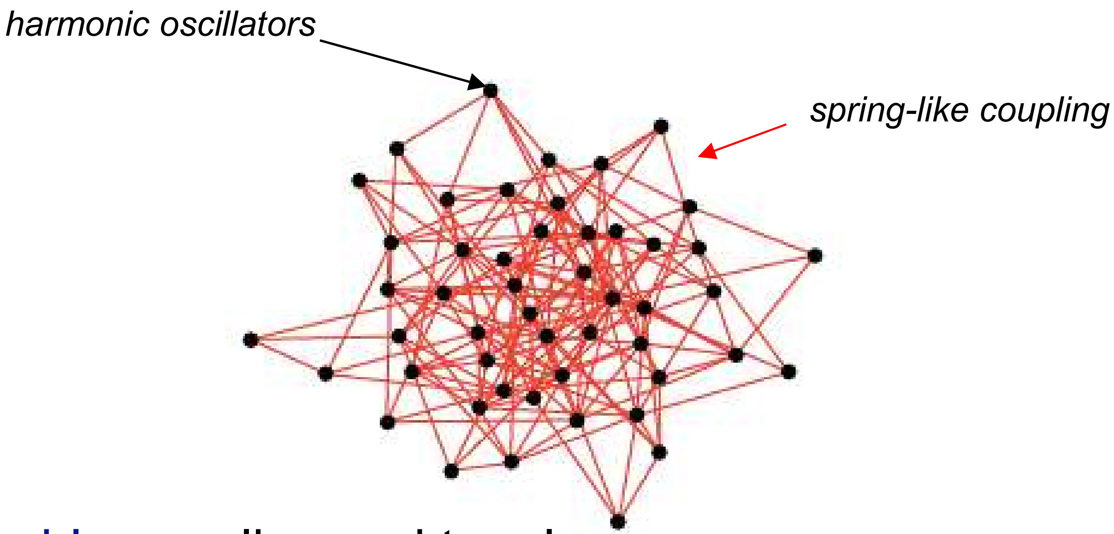
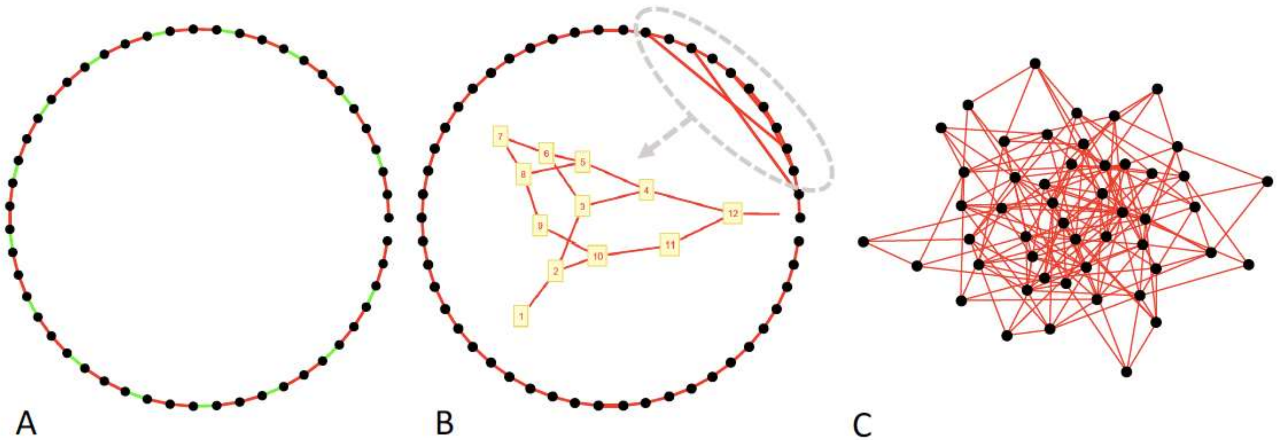
# Quantum complex networks

## Our proposal: reconfigurable optical implementation

Collections of quantum systems arranged in a non-regular topology




reconfigurable coupling and topology,
relevant size (here 50 nodes)




J. Nokkala, F. Arzani, F. Galve, R. Zambrini, S. Maniscalco, J. Piilo, N. Treps, and V. Parigi arXiv:1708.08726

# Quantum complex networks

## Network dynamics

$$H_E = \frac{\mathbf{p}^T \mathbf{\Delta}_\omega \mathbf{p}}{2} + \mathbf{q}^T \sqrt{\mathbf{\Delta}_\omega^{-1}} \mathbf{A} \sqrt{\mathbf{\Delta}_\omega^{-1}} \mathbf{q}$$

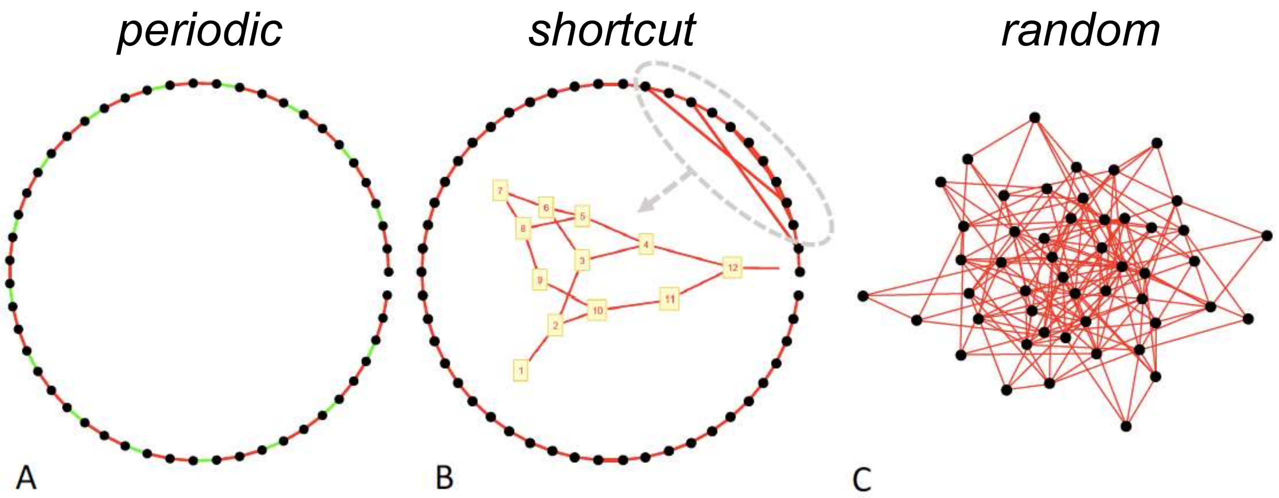
$$\mathbf{A}_{ii} = \omega_i^2/2 + \sum_j g_{ij}/2$$

$$\mathbf{A}_{i \neq j} = g_{ij}/2$$

$$\mathbf{\Delta}_\omega = \mathrm{diag}\{\omega_1, ..., \omega_N\}$$

$$\mathbf{q}^T = (q_1, q_2, \ldots, q_N).$$

$$\mathbf{p}^T = (p_1, p_2, \ldots p_N)$$

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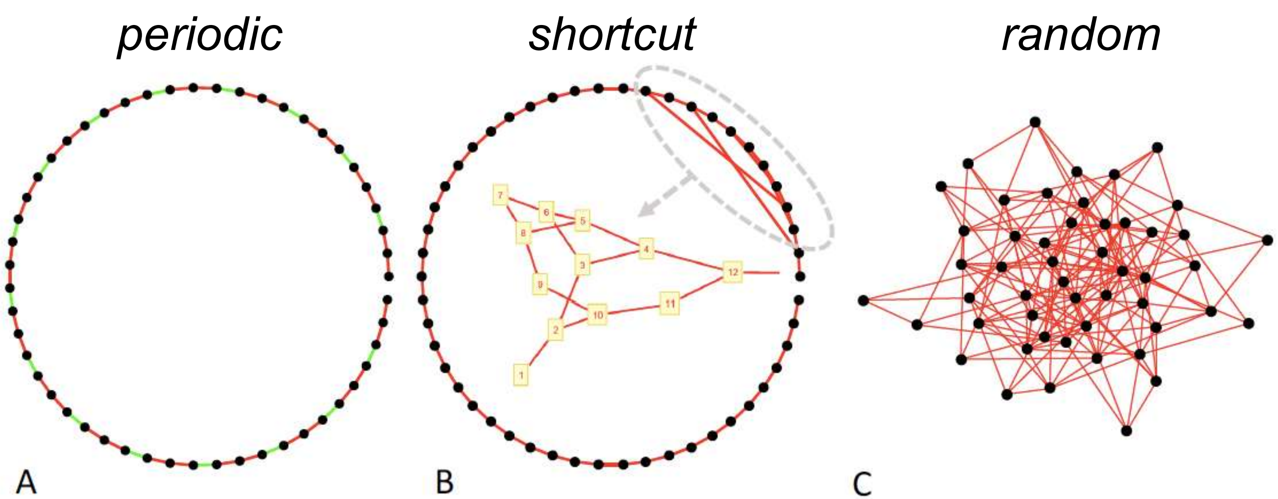


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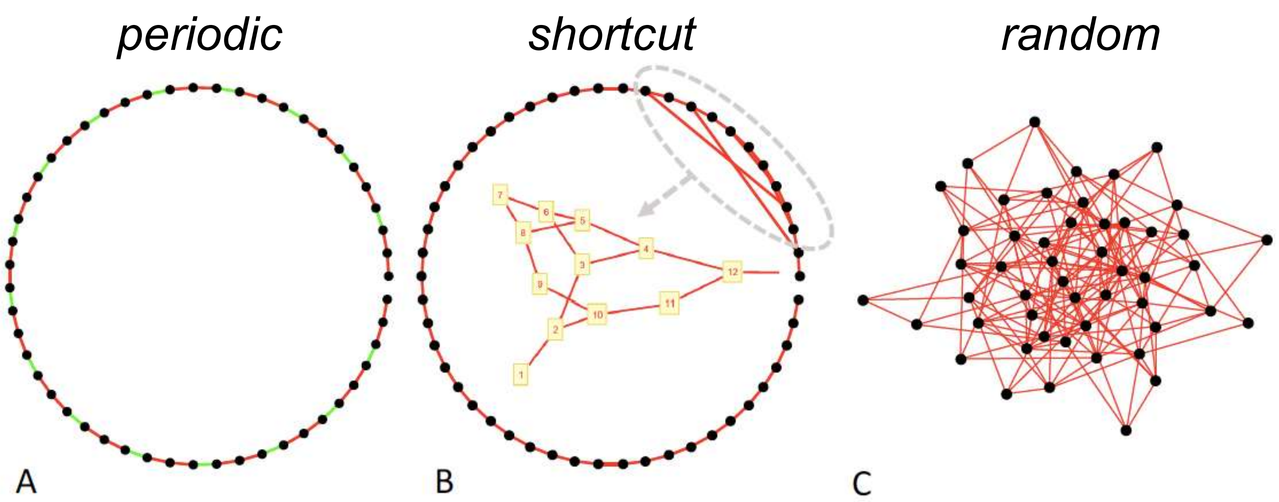
$S_{\mathbf{V}}$

symplectic transformations

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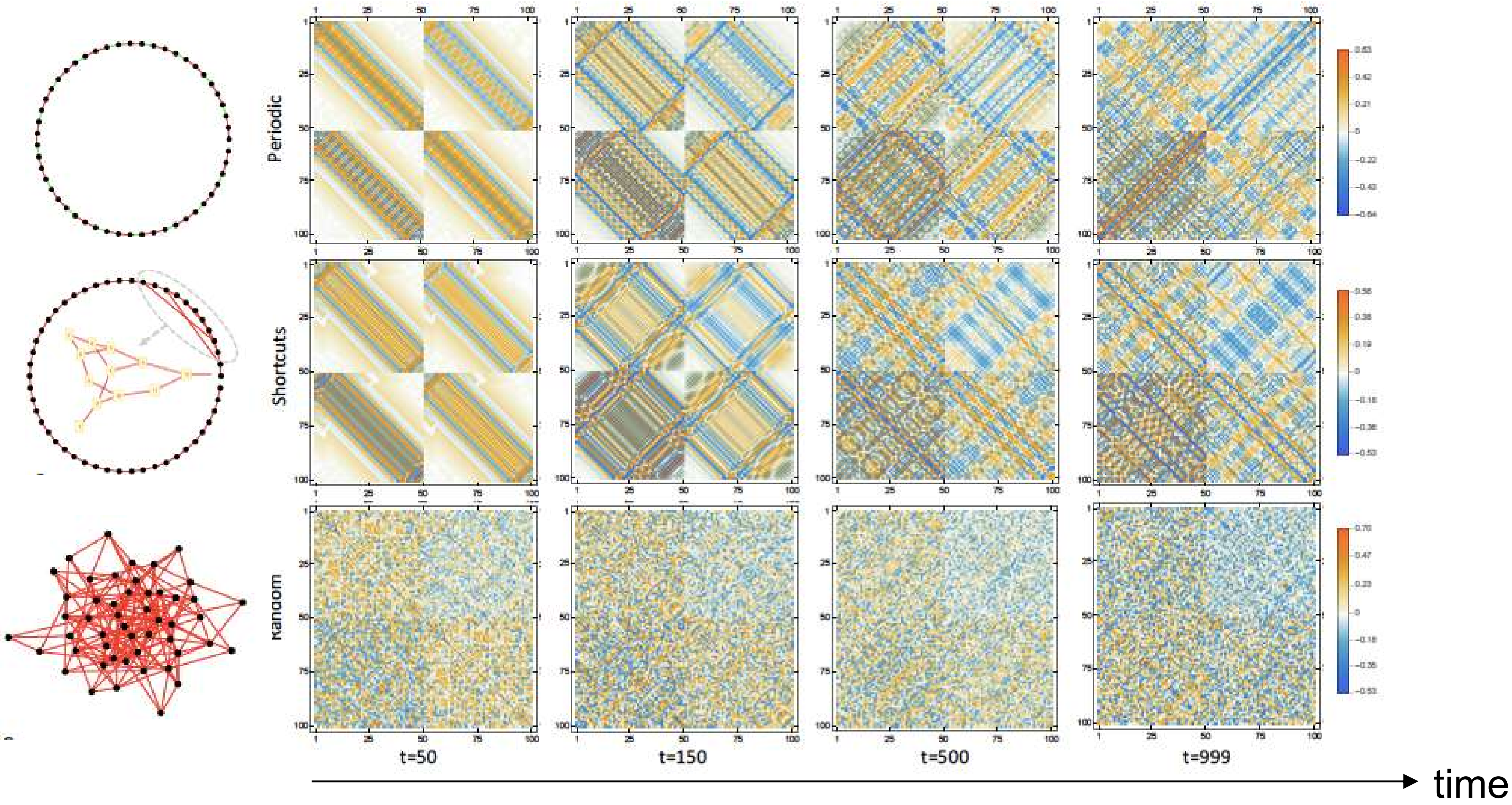
## Network dynamics

$$\begin{pmatrix}\mathbf{q}(t)\\ \mathbf{p}(t)\end{pmatrix} = S_{\mathbf{V}} \begin{pmatrix}\mathbf{q}(0)\\ \mathbf{p}(0)\end{pmatrix}$$

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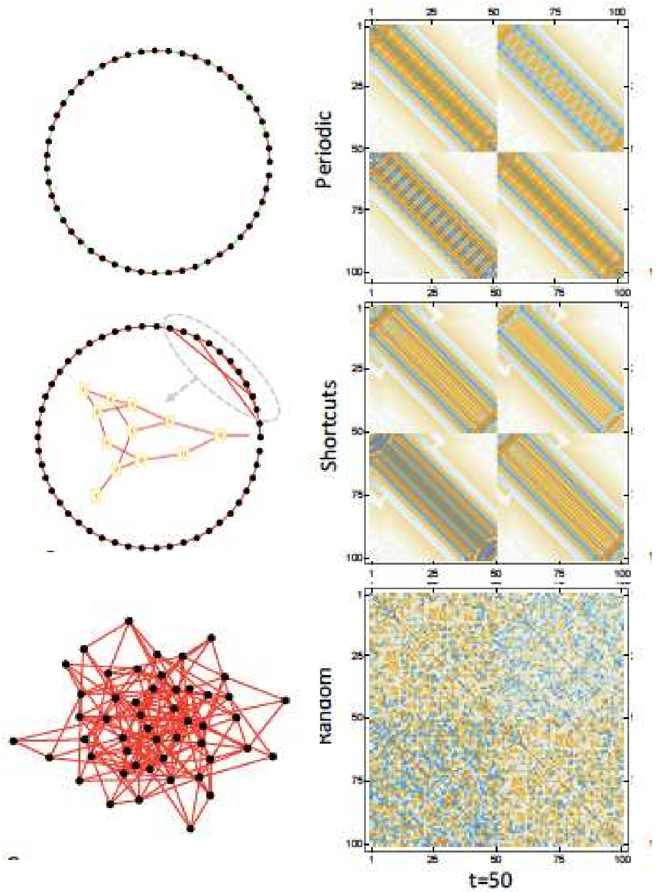
$$S_{\mathbf{V}}$$



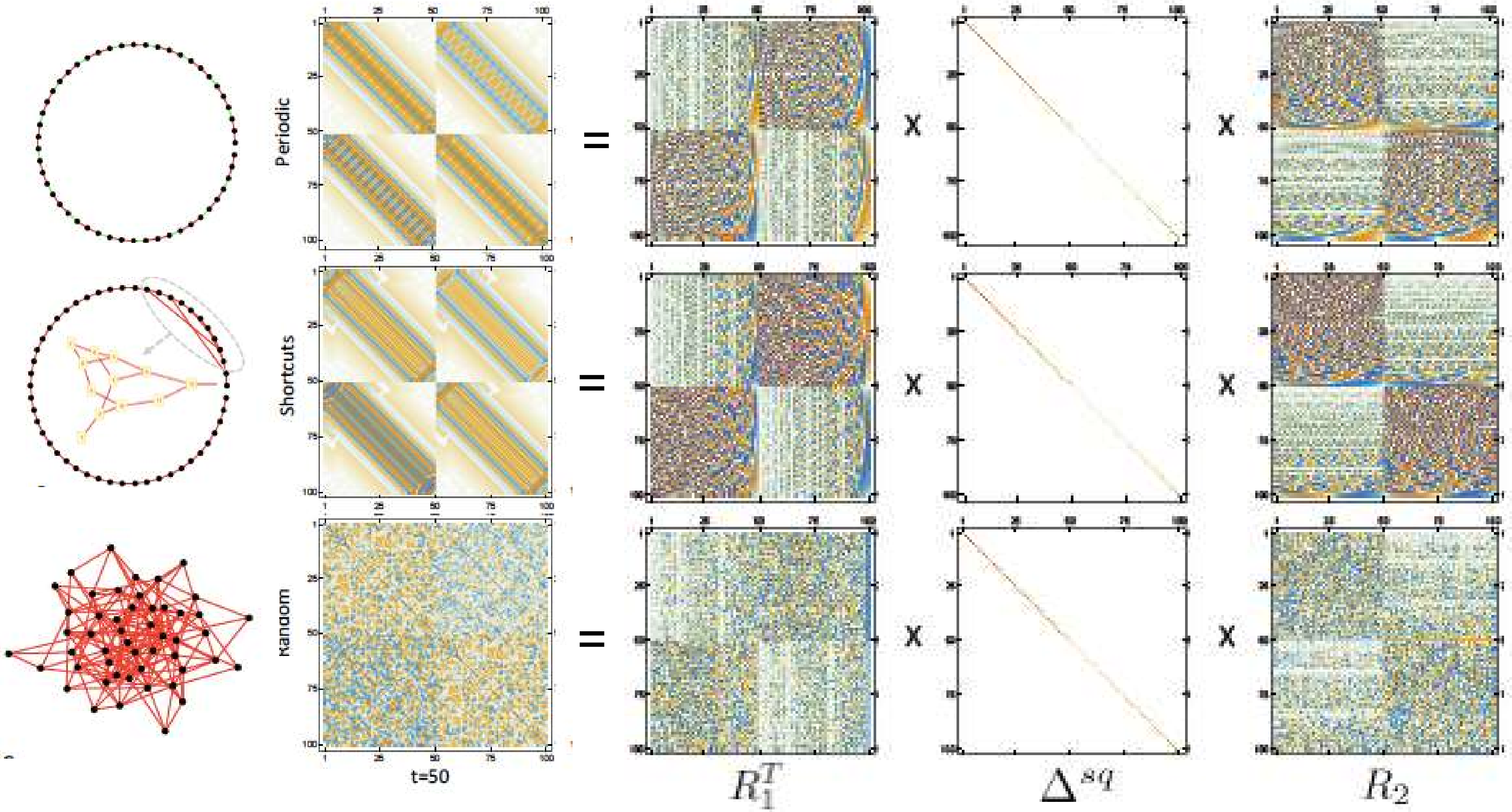

**given time**

J. Nokkala, F. Arzani, F. Galve, R. Zambrini, S. Maniscalco, J. Piilo, N. Treps, and V. Parigi arXiv:1708.08726

# Quantum complex networks

## Network dynamics -> Bloch-Messiah reduction

$$\begin{pmatrix}\mathbf{q}(t)\\ \mathbf{p}(t)\end{pmatrix} = S_{\mathbf{V}} \begin{pmatrix}\mathbf{q}(0)\\ \mathbf{p}(0)\end{pmatrix} = R_1^T \Delta^{sq} R_2 \begin{pmatrix}\mathbf{q}(0)\\ \mathbf{p}(0)\end{pmatrix}$$

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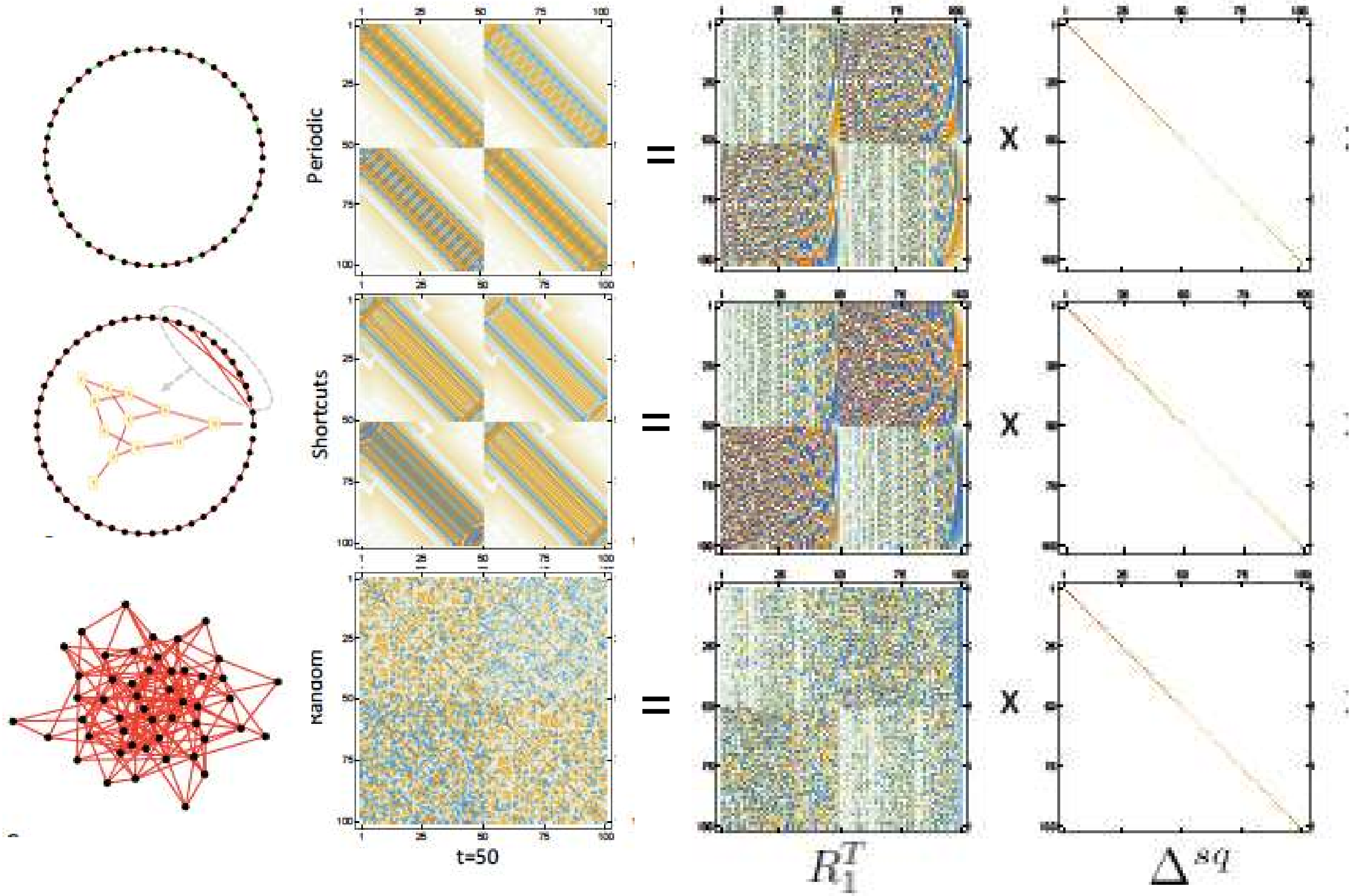
# Quantum complex networks

## Network dynamics -> Bloch-Messiah reduction

if vacuum

$$\begin{pmatrix}\mathbf{q}(t)\\ \mathbf{p}(t)\end{pmatrix} = \underbrace{\begin{pmatrix} T_1 D^{\Omega}_{\cos} T_1^{-1} & T_1 D^{\Omega}_{\sin} T_2^{-1} \\ -T_2 D^{\Omega}_{\sin} T_1^{-1} & T_2 D^{\Omega}_{\cos} T_2^{-1} \end{pmatrix}}_{S_{\mathbf{V}}} \begin{pmatrix}\mathbf{q}(0)\\ \mathbf{p}(0)\end{pmatrix} = R_1^T \Delta^{sq} \not{R_2} \begin{pmatrix}\mathbf{q}(0)\\ \mathbf{p}(0)\end{pmatrix}$$




**given time**

J. Nokkala, F. Arzani, F. Galve, R. Zambrini, S. Maniscalco, J. Piilo, N. Treps, and V. Parigi arXiv:1708.08726

# Quantum complex networks

## *Optical implementation->* Bloch-Messiah reduction

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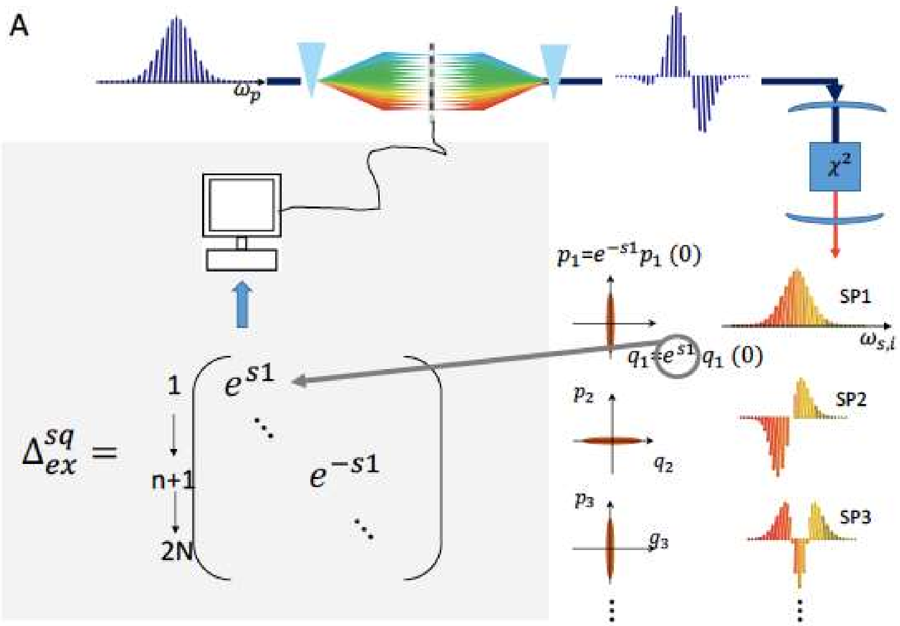
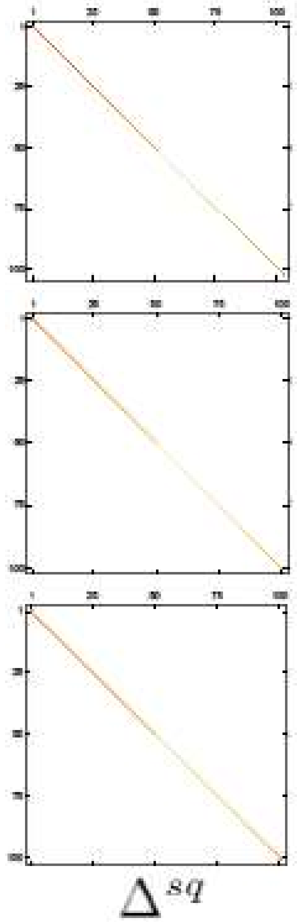
**if vacuum**




**experimental control**

$$\Delta^{sq}_{ex}$$

***pump shaping***

*optimization procedure based on an evolutionary algorithm*

*F. Arzani et al, arXiv:1709.10055*

**given time**

J. Nokkala, F. Arzani, F. Galve, R. Zambrini, S. Maniscalco, J. Piilo, N. Treps, and V. Parigi arXiv:1708.08726

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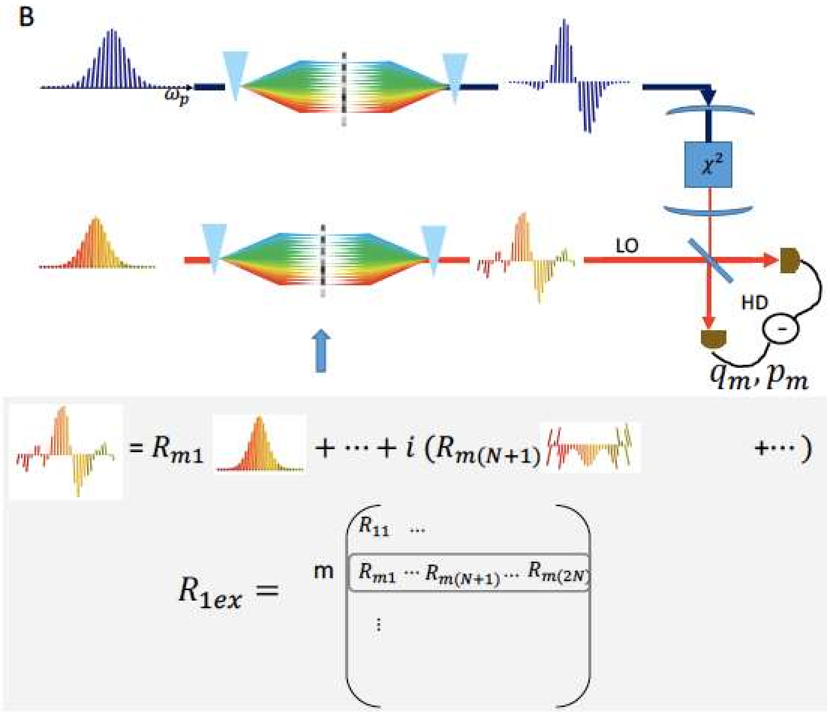
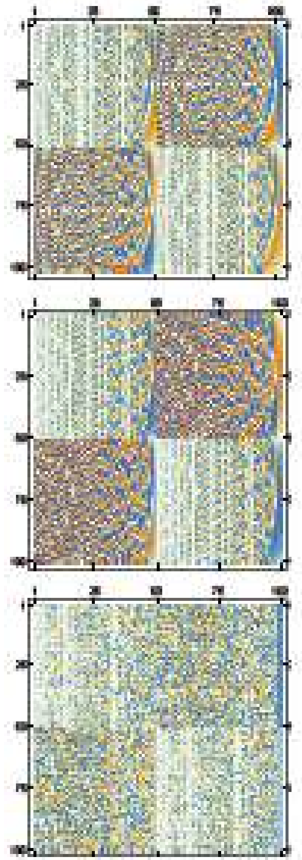
$S_{\mathbf{V}}$

**if vacuum**



$R_1^T$

**given time**

**experimental control**

$R_{1ex}$

***choosing the measurement basis***

*m-th nodes encoded in the mode defined by the m-th row of R1*

J. Nokkala, F. Arzani, F. Galve, R. Zambrini, S. Maniscalco, J. Piilo, N. Treps, and V. Parigi arXiv:1708.08726

# Quantum complex networks

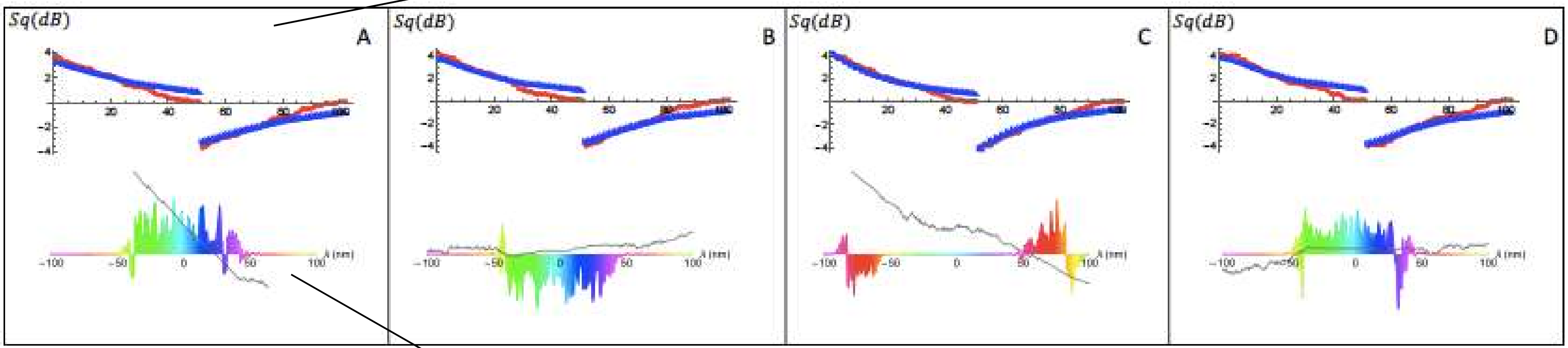
## Network dynamics -> Bloch-Messiah reduction

if vacuum

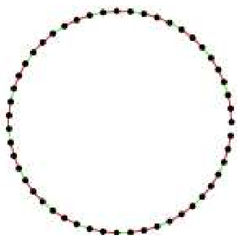
$$\begin{pmatrix} \mathbf{q}(t) \\ \mathbf{p}(t) \end{pmatrix} = \underbrace{\begin{pmatrix} T_1 D^{\Omega}_{\cos} T_1^{-1} & T_1 D^{\Omega}_{\sin} T_2^{-1} \\ -T_2 D^{\Omega}_{\sin} T_1^{-1} & T_2 D^{\Omega}_{\cos} T_2^{-1} \end{pmatrix}}_{S_{\mathbf{V}}} \begin{pmatrix} \mathbf{q}(0) \\ \mathbf{p}(0) \end{pmatrix} = R_1^T \Delta^{sq} R_2 \begin{pmatrix} \mathbf{q}(0) \\ \mathbf{p}(0) \end{pmatrix}$$

**experimental control**

experimentally implementable squeezing (blue) and theoretical values (red)




time



shape of the mode encoding the 26-th oscillators

*BiBO 2.5 mm*

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$S_{\mathbf{V}}$

if vacuum

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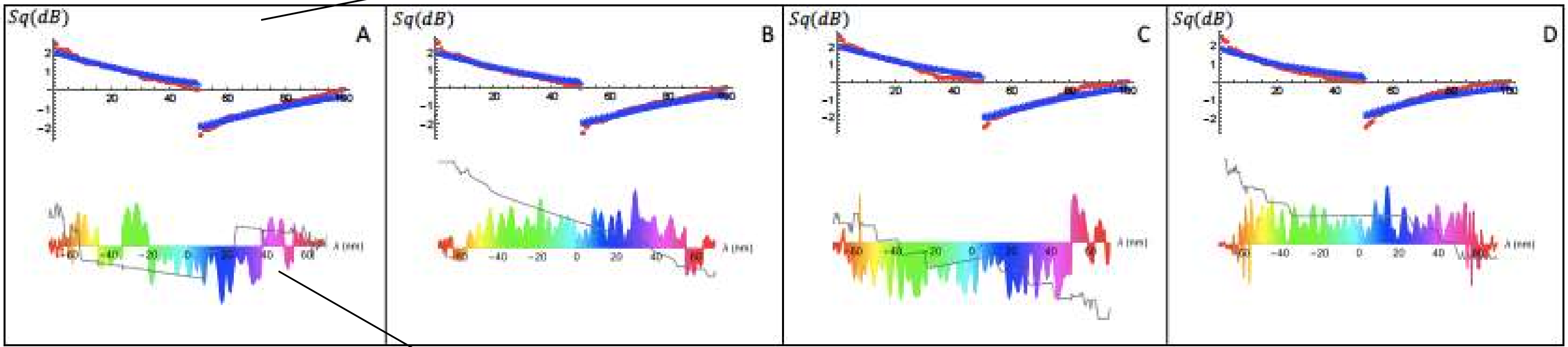


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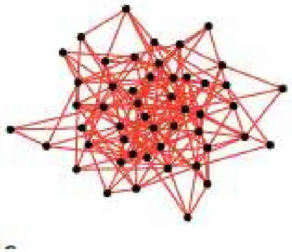

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$S_{\mathbf{V}}$

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experimentally implementable squeezing (blue) and theoretical values (red)

**if not vacuum**

Initialization from vacuum can be included in the dynamics if state is pure and Gaussian

or

initial larger (2N) multimode entangled state -> tracing over half mode to obtain a mixed (thermal) state

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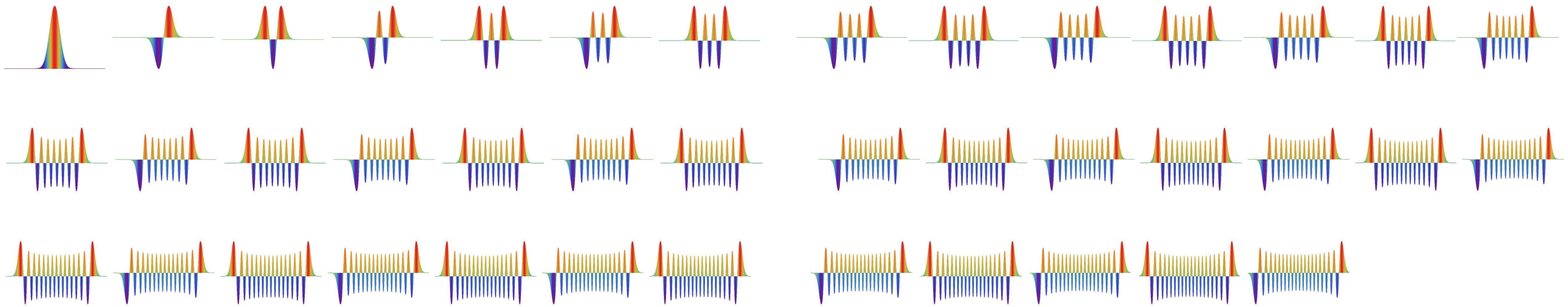
# Quantum complex networks

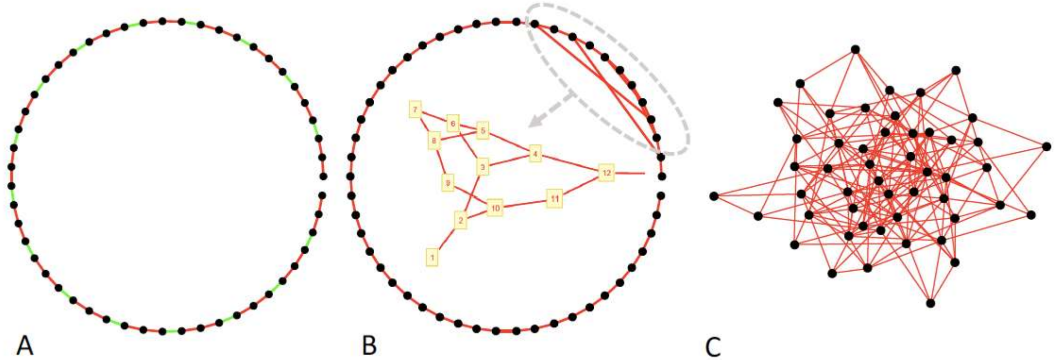
*Experimental feasibility*

*At least 50 nodes needed*

**Current setup**

**50 Hermite-Gauss modes with quantum properties are generated (we can go up to 100)**



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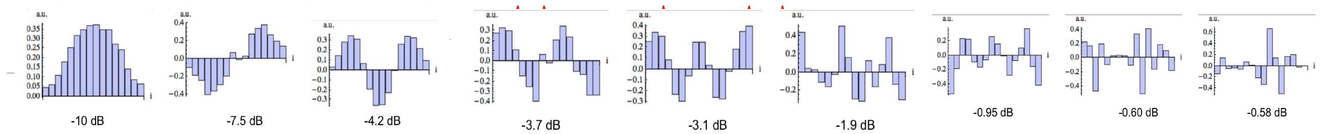
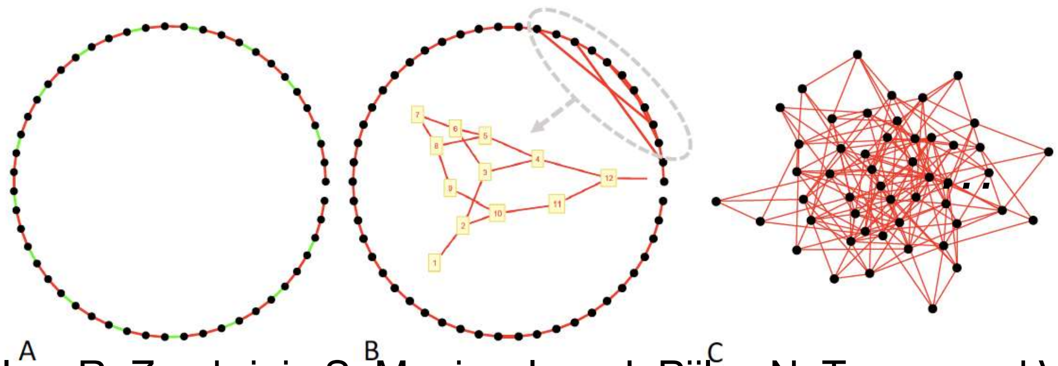



*Detection of the first 16 has been done*

⇩ Work in progress on coherent broadening of the LO spectrum

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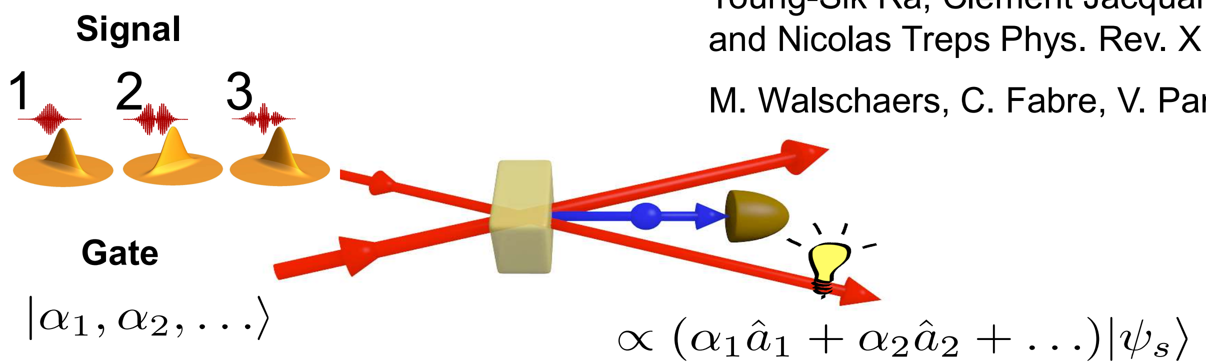
# More and Outlook

***Non-Gaussian operations : coherent mode dependent single-photon subtraction***

Young-Sik Ra, Clément Jacquard, Adrien Dufour, Claude Fabre, and Nicolas Treps Phys. Rev. X **7**, 031012 (2017)

M. Walschaers, C. Fabre, V. Parigi, N. Treps, accepted in Phys. Rev.Lett



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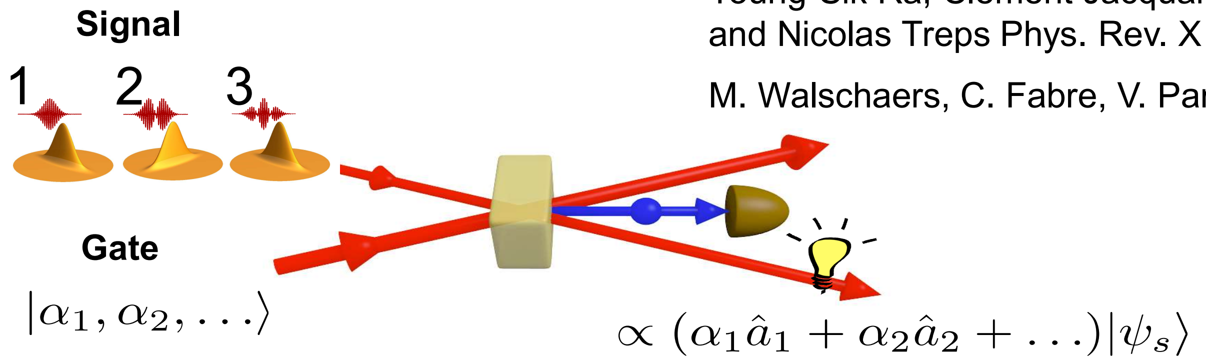
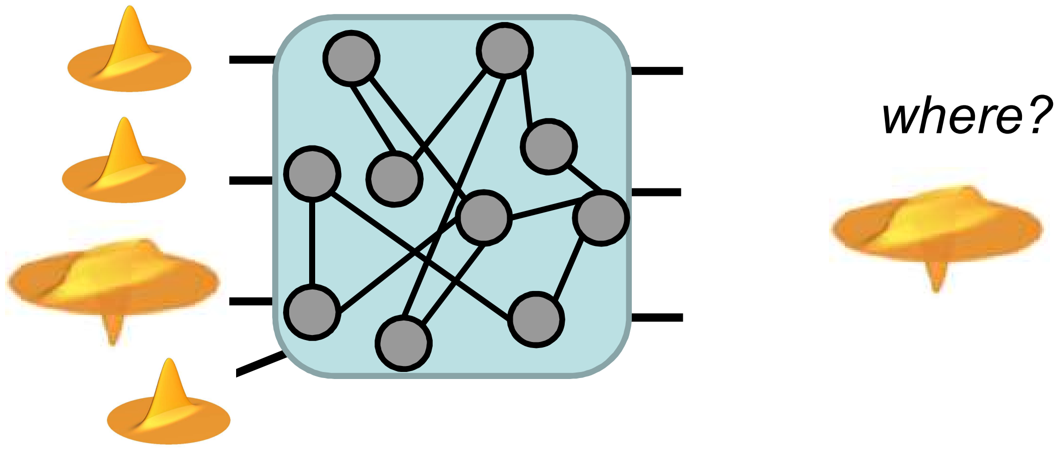



❖**Transport of non-Gaussian information in complex networks**



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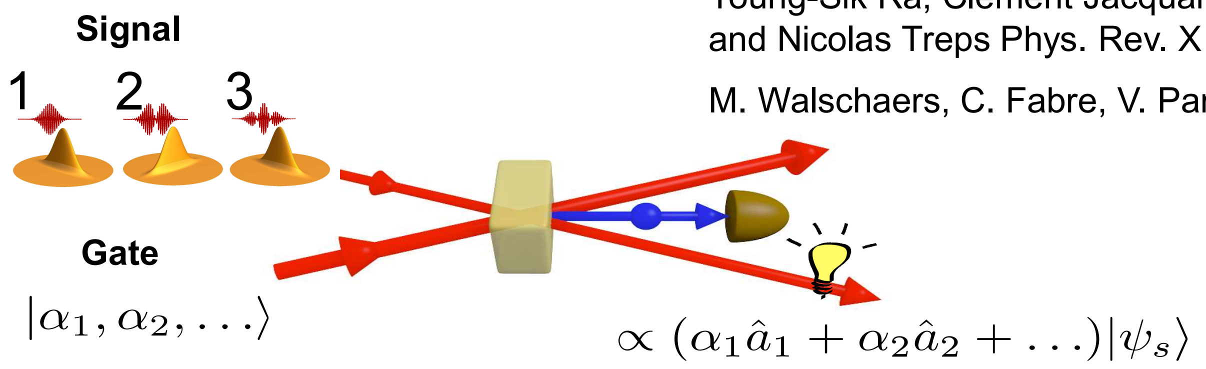
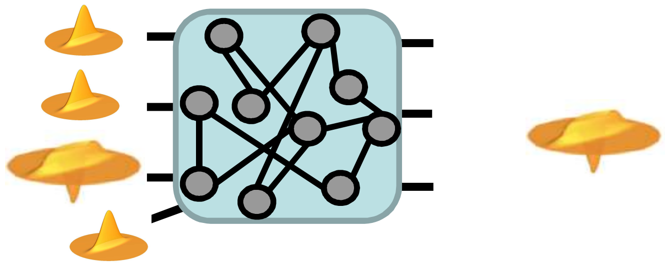
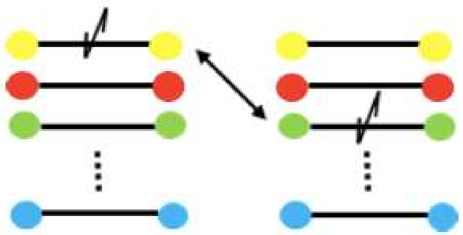



❖Transport of non-Gaussian information in complex networks



❖ All optical quantum repeaters for quantum communication

*collaboration with Peter van Look*



optimal nonlocal preparation of approximate DV Bell states
via photon- subtraction + optimal entanglement swapping
via multiplexing

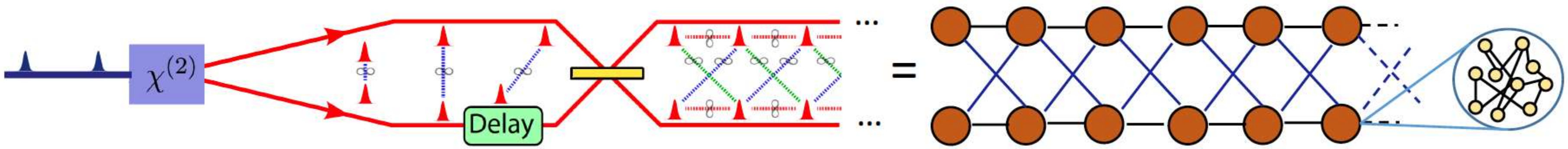
*probability of the process scale as* $(1-P)^N$ *, N = number pf modes*

# *Thank you!*

# Towards larger complex networks ?

- ***Number of modes :16*** *at the moment but they are only limited by the measurement procedure -> they could be around* ***40*** *if we increase the spectral bandwidth of LO*

- *Exploring new experimental setup -> "big-states"* ***10^5*** *modes*




*dual-rail cluster:*
*entanglement structure*
*in the pulses (time) basis*

S.Yokoyama, R. Ukai, S. C. Armstrong, C. Sornphiphatphong, T. Kaji, S. Suzuki, J. Yoshikawa, H. Yonezawa, N. C. Menicucci & A. Furusawa Nature Photonics 7, 982–986 (2013); APL Photonics 1, 060801 (2016)

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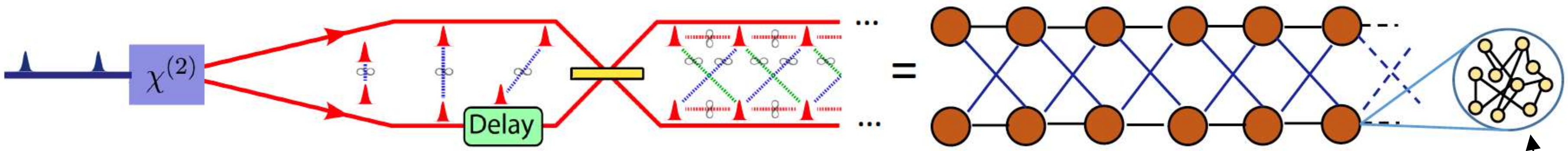


*dual-rail cluster: entanglement structure in the pulses (time) basis*

*the multimode structure in the frequency domain is maintained . Community structures*

S.Yokoyama, R. Ukai, S. C. Armstrong, C. Sornphiphatphong, T. Kaji, S. Suzuki, J. Yoshikawa, H. Yonezawa, N. C. Menicucci & A. Furusawa Nature Photonics 7, 982–986 (2013); APL Photonics 1, 060801 (2016)

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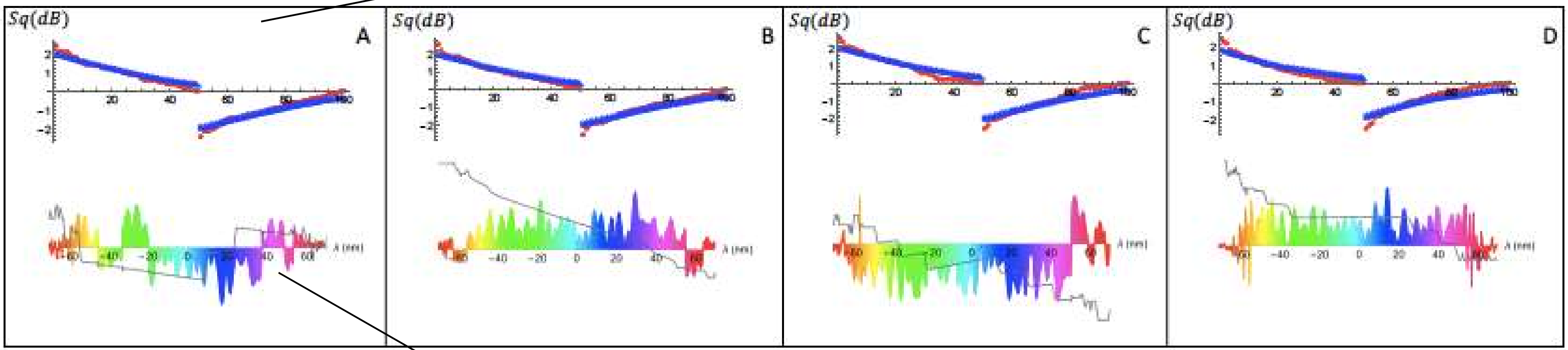


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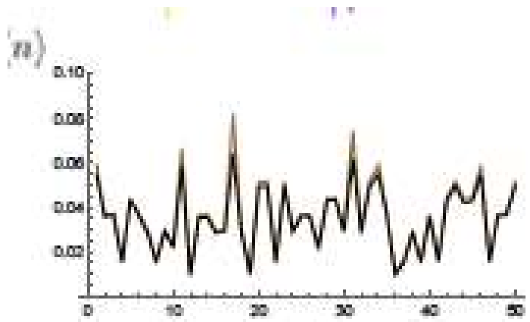

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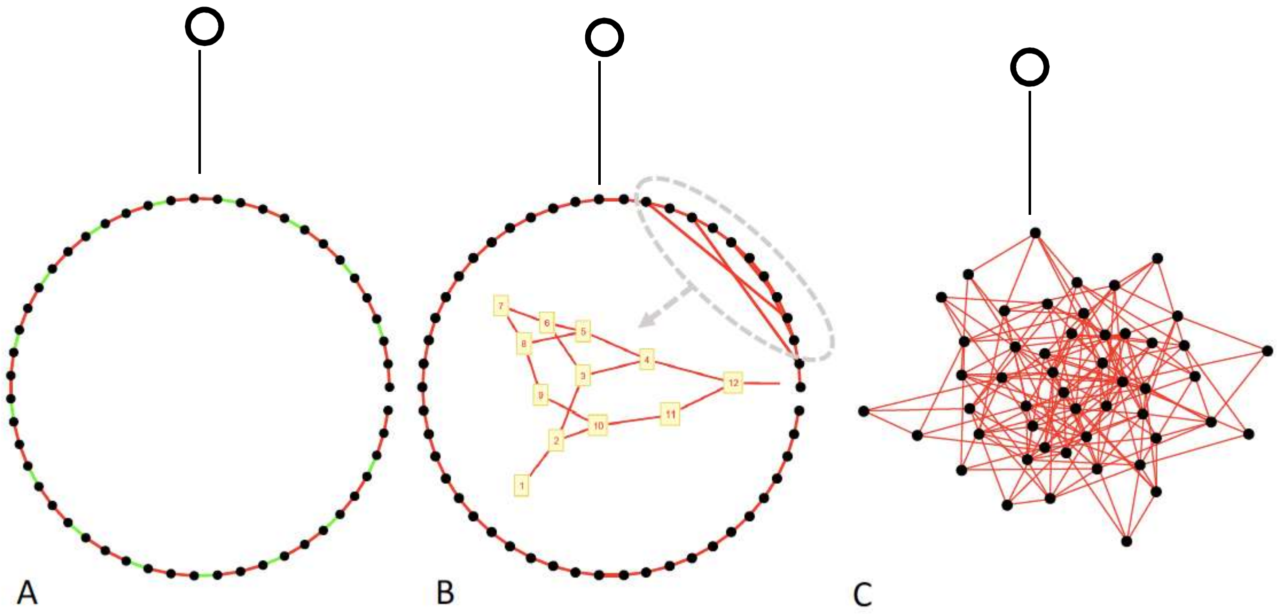
## Ex: complex network = structured environment
## additional oscillator= probe/system

*Additional oscillator*

$$H_S = (p_S^2 + \omega_S^2 q_S^2)/2, \qquad H_E = \frac{\boldsymbol{p}^T \boldsymbol{p}}{2} + \boldsymbol{q}^T \boldsymbol{A} \boldsymbol{q} \qquad H_I = -k q_S q_i$$

*Evolution given by* $H_E + H_S + H_I$ → Measure the state of the probe and recover the structure

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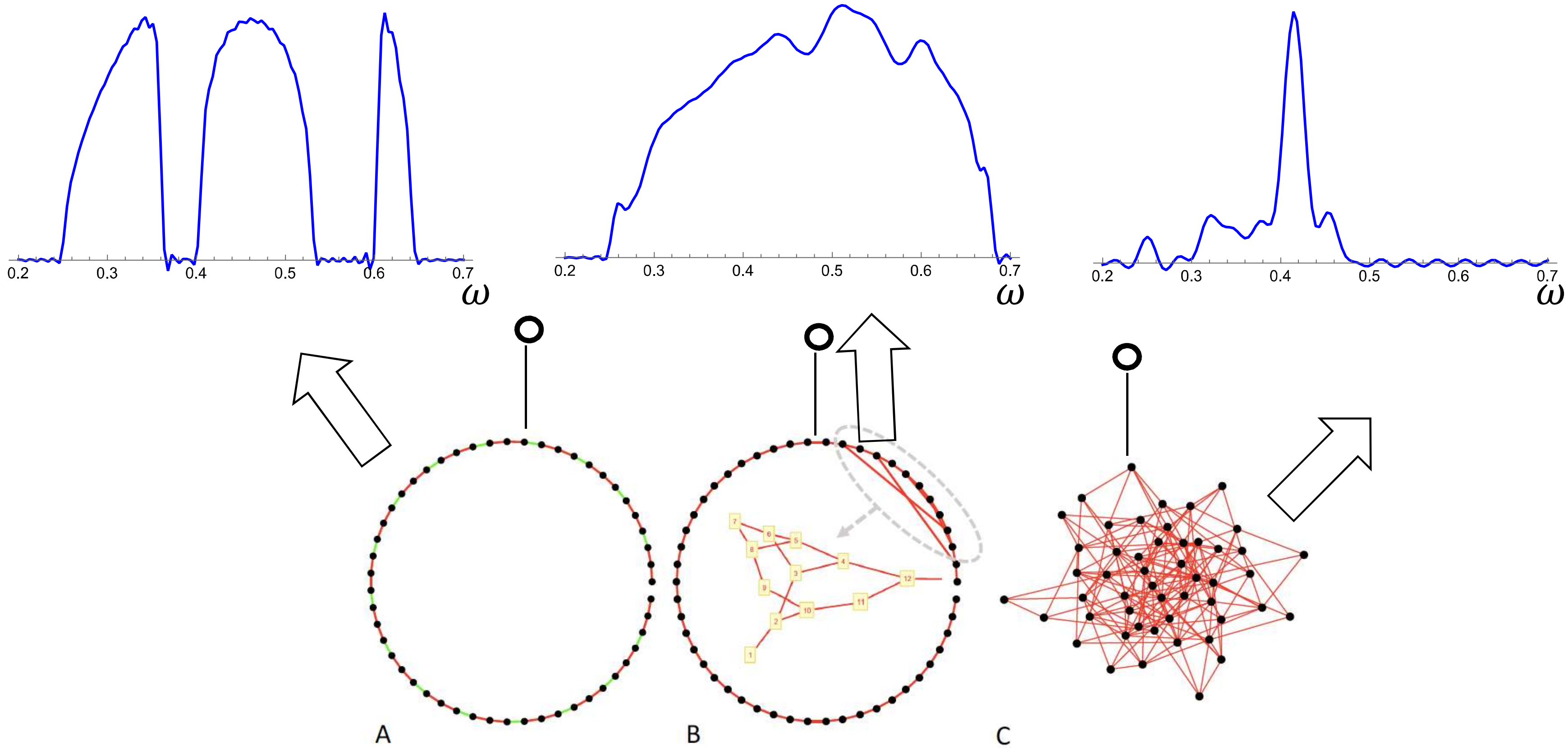
$$J(\omega) = \frac{\pi}{2}\sum_i \frac{k^2 g_i^2}{\Omega_i}\delta(\omega - \Omega_i) \qquad J(\omega) = \omega \int_0^{t_{max}} \gamma(t)\cos(\omega t)\,\mathrm{d}t$$

*spectral density of environmental coupling*

***Analytical***

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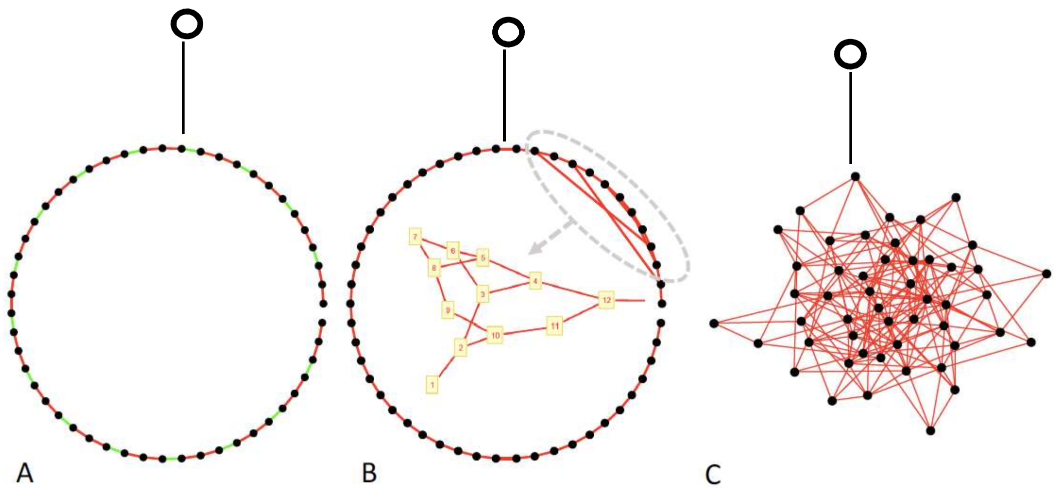


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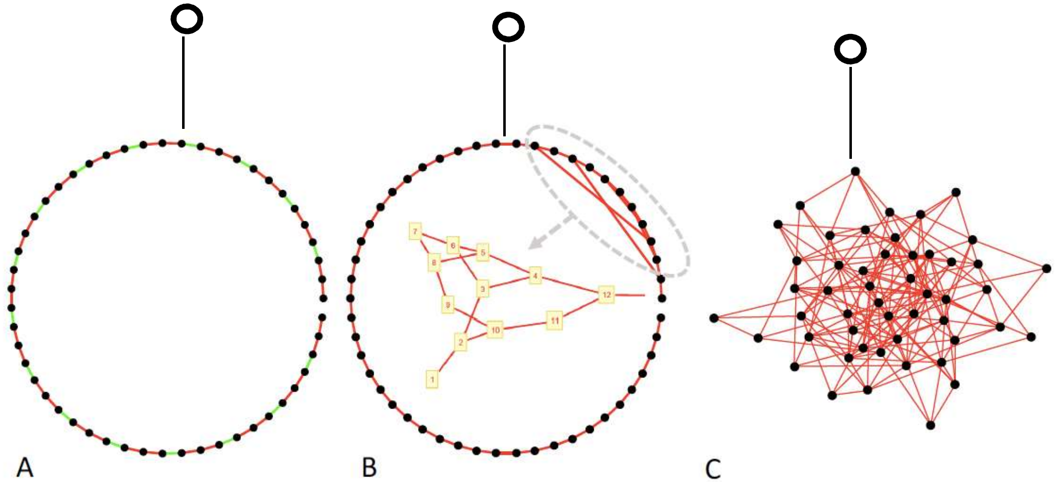


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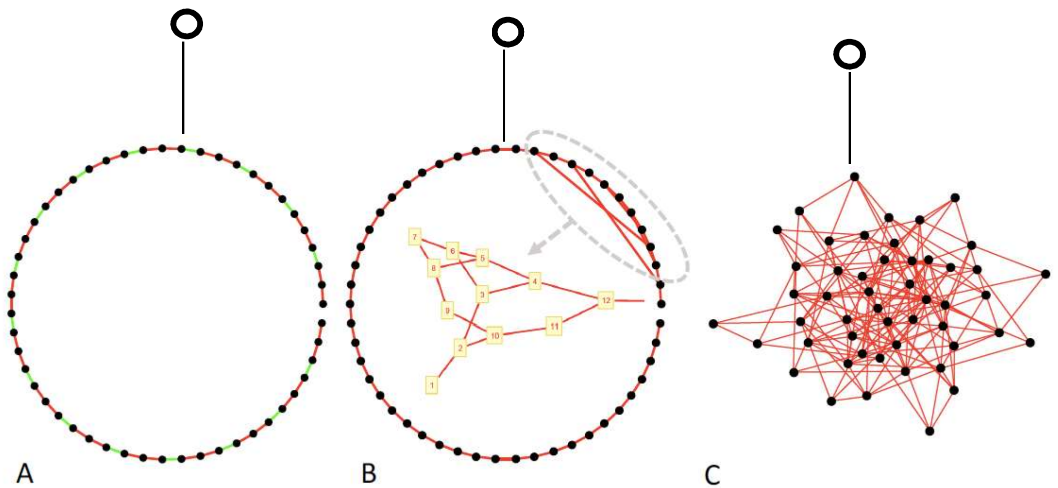
Measure the state of the probe and recover the structure

vacuum?

***doesn't work***

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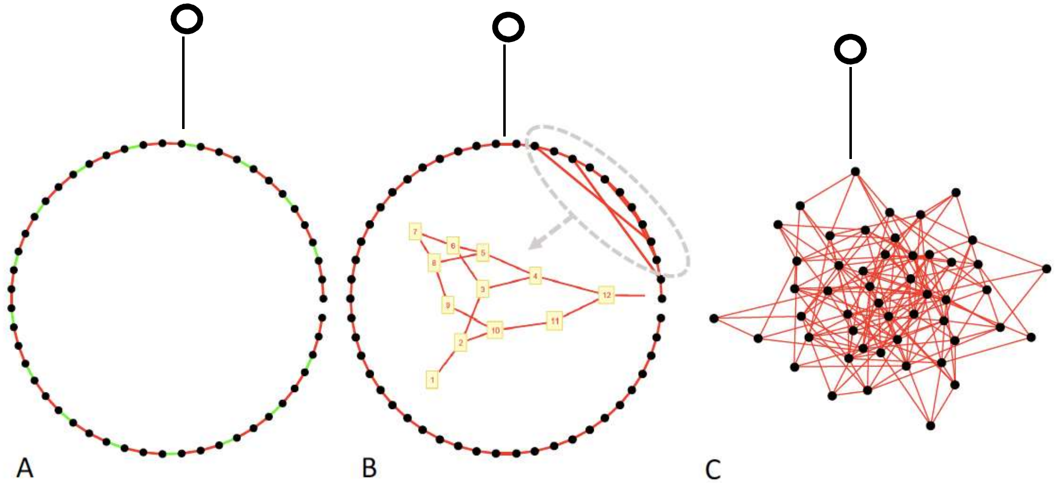
*preparing at least the probe in a non-vacuum state*

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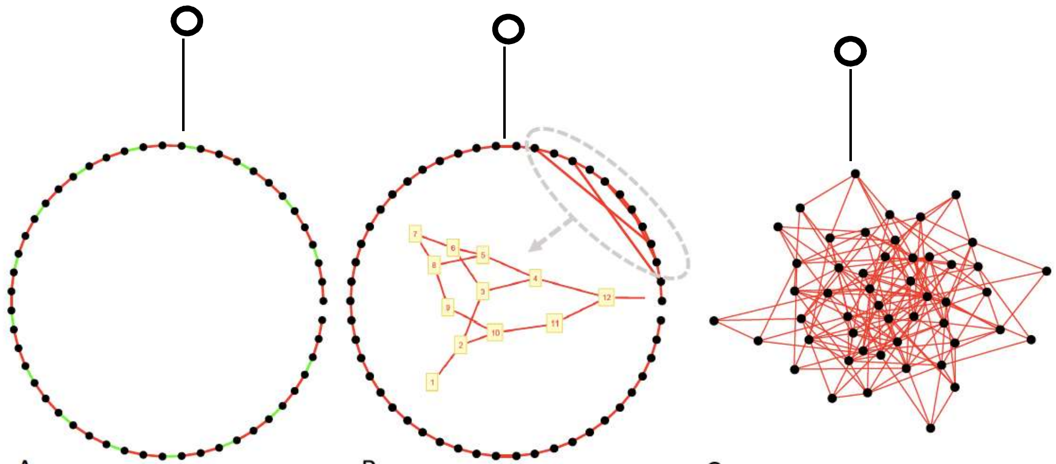
*vacuum*



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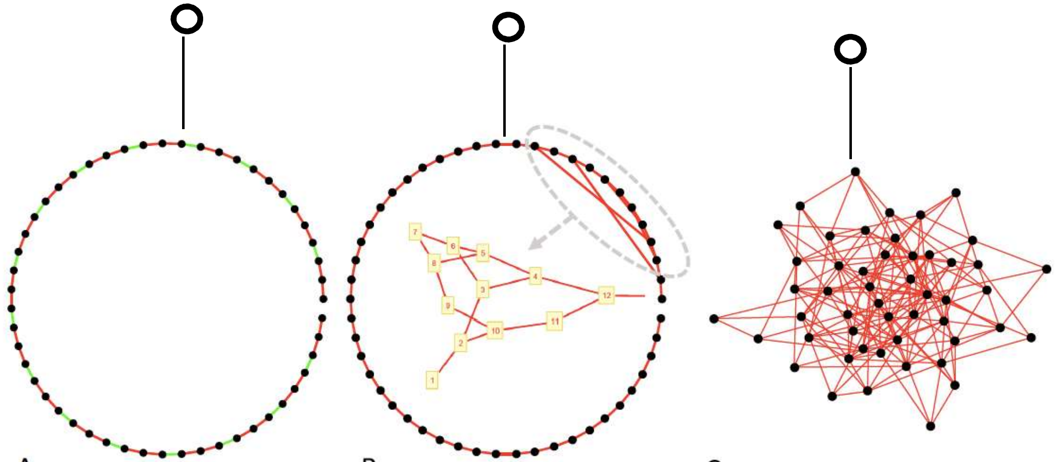
*vacuum*

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*vacuum*

**1) choose a frequency of the probe**

**2) implement experimentally**

J. Nokkala, F. Arzani, F. Galve, R. Zambrini, S. Maniscalco, J. Piilo, N. Treps, and V. Parigi arXiv:1708.08726

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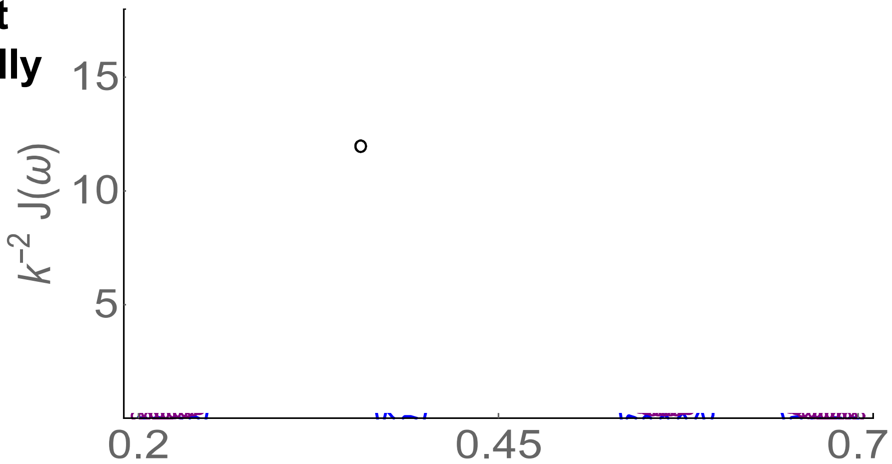
*vacuum*

**1) choose a frequency of the probe**

**2) implement experimentally**

**3) measure the probe get a point**

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$$\begin{pmatrix} \mathbf{Q}(t) \\ \mathbf{q}_S(t) \\ \mathbf{P}(t) \\ \mathbf{p}_S(t) \end{pmatrix} = \begin{pmatrix} O_1 D_{\cos} O_1^{-1} & \\ -O_2 D_{\sin} O_1^{-1} & \end{pmatrix} R_1^T \Delta^{sq} \begin{pmatrix} & \end{pmatrix} \begin{pmatrix} \mathbf{Q}(0) \\ \mathbf{q}_S(0) \\ \mathbf{P}(0) \\ \mathbf{p}_S(0) \end{pmatrix}$$

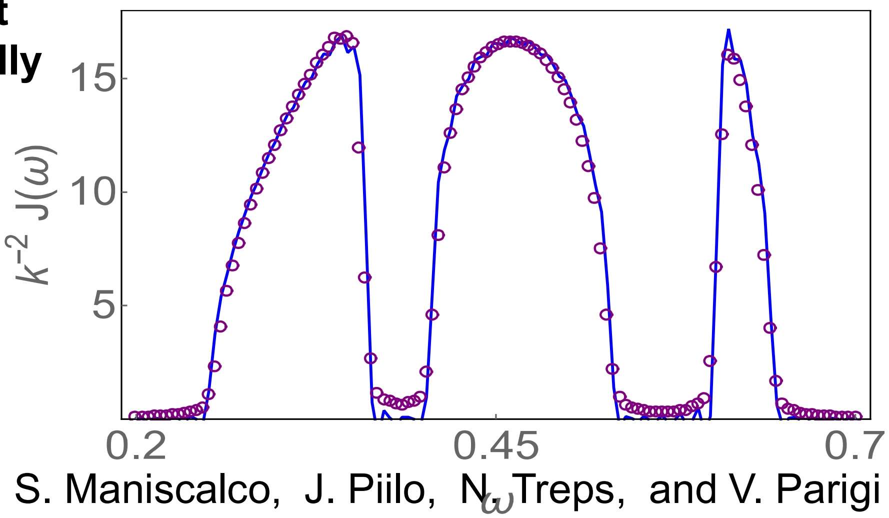
*vacuum*

**1) choose a frequency of the probe**

**2) implement experimentally**

**3) measure the probe get a point**

**repeat**

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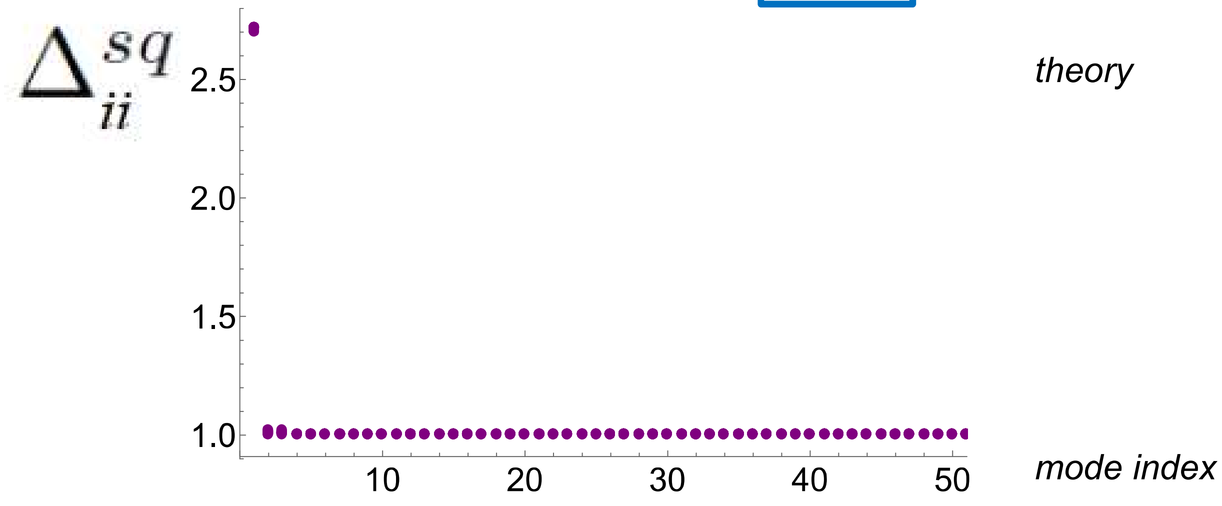
# Quantum complex networks

## Ex: complex network = structured environment
## additional oscillator= probe/system

*Experimental feasibility*

$$\begin{pmatrix} \mathbf{Q}(t)\\ \mathbf{q}_S(t)\\ \mathbf{P}(t)\\ \mathbf{p}_S(t)\end{pmatrix} = \begin{pmatrix} O_1 D_{\cos} O_1^{-1} & \\ -O_2 D_{\sin} O_1^{-1} & \end{pmatrix} R_1^T \Delta^{sq} \begin{pmatrix} & \end{pmatrix} \begin{pmatrix} \mathbf{Q}(0)\\ \mathbf{q}_S(0)\\ \mathbf{P}(0)\\ \mathbf{p}_S(0)\end{pmatrix}$$

vacuum

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# Quantum complex networks

LKB ENS CNRS UPMC

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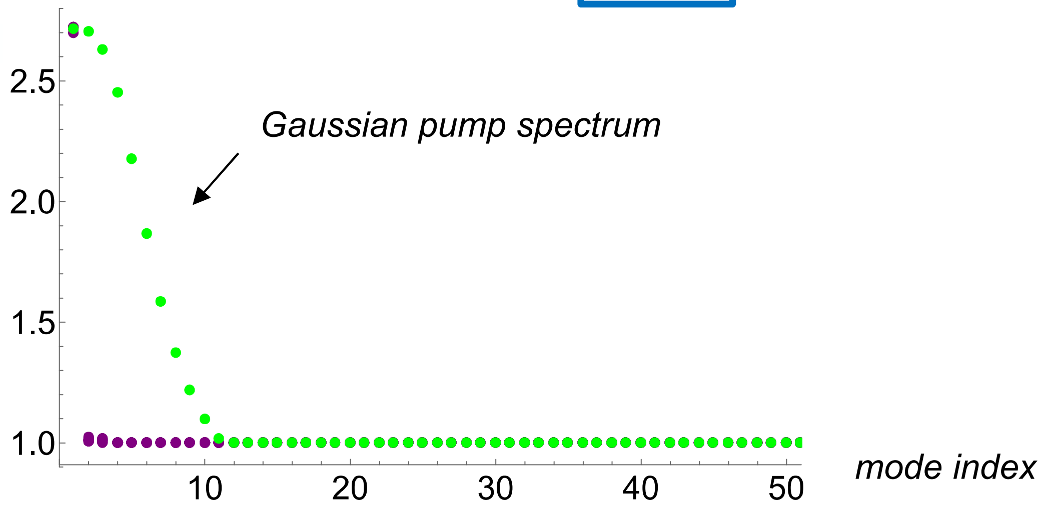
*vacuum*

$\Delta^{sq}_{ii}$

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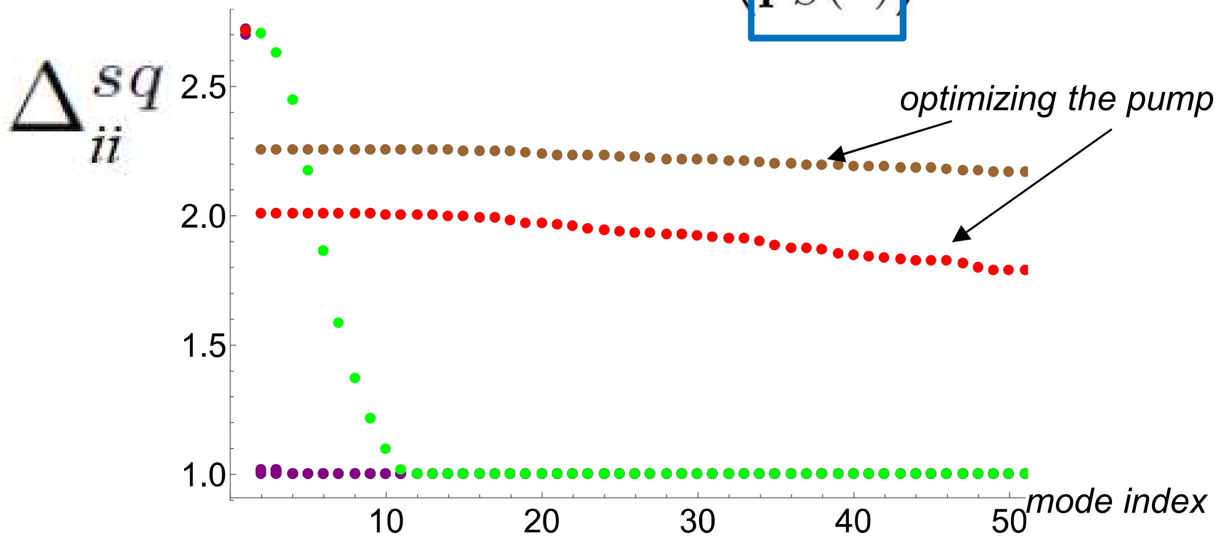
*vacuum*

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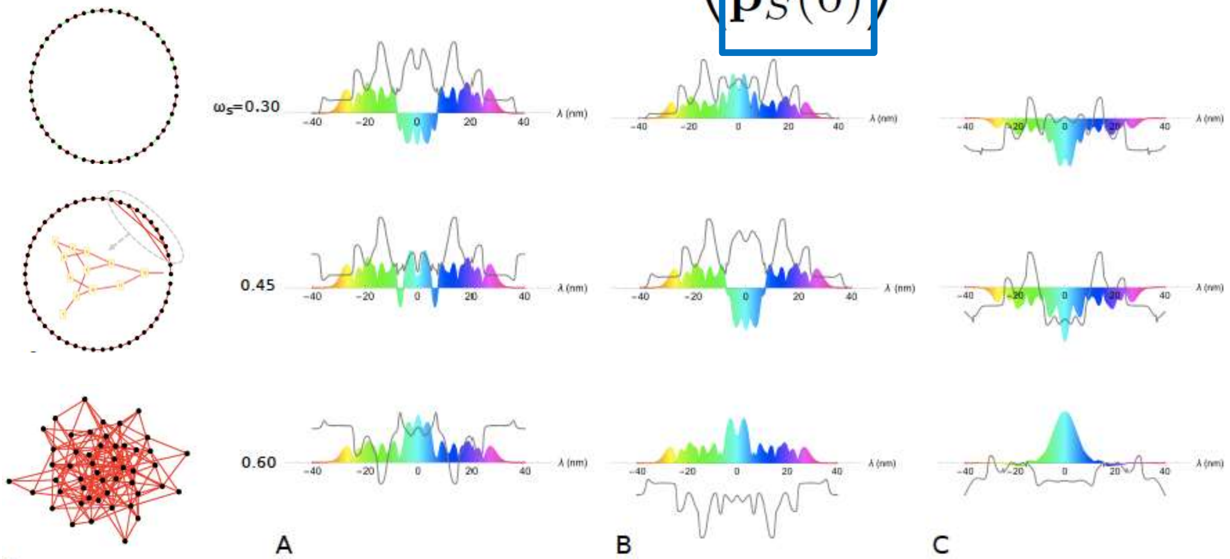
vacuum

***Local oscillator shape***

*(no optimization pump shape)*

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*vacuum*

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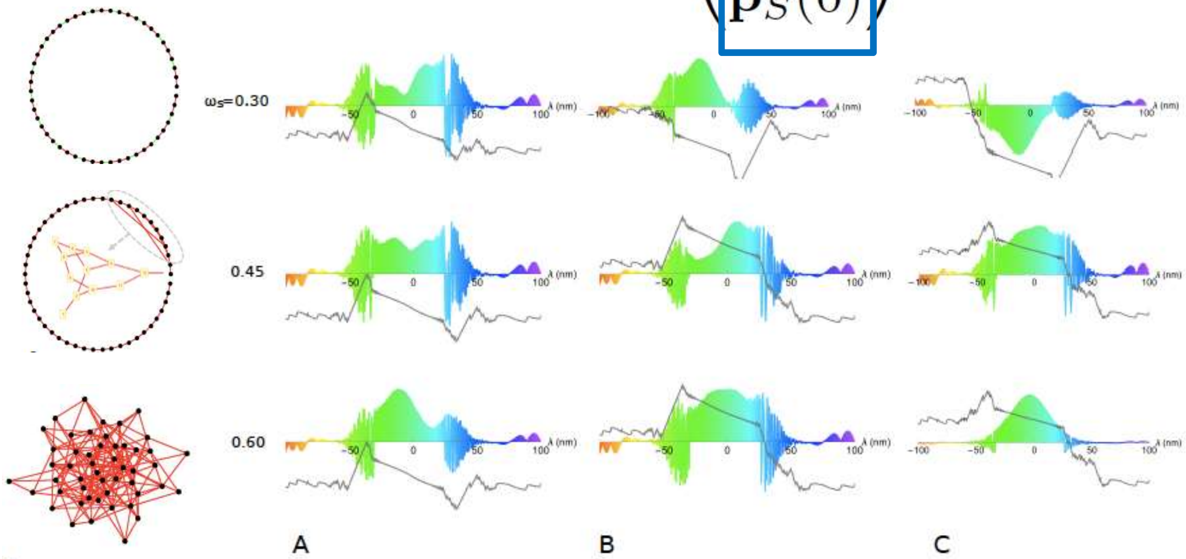
*(optimization pump shape)*

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*vacuum*

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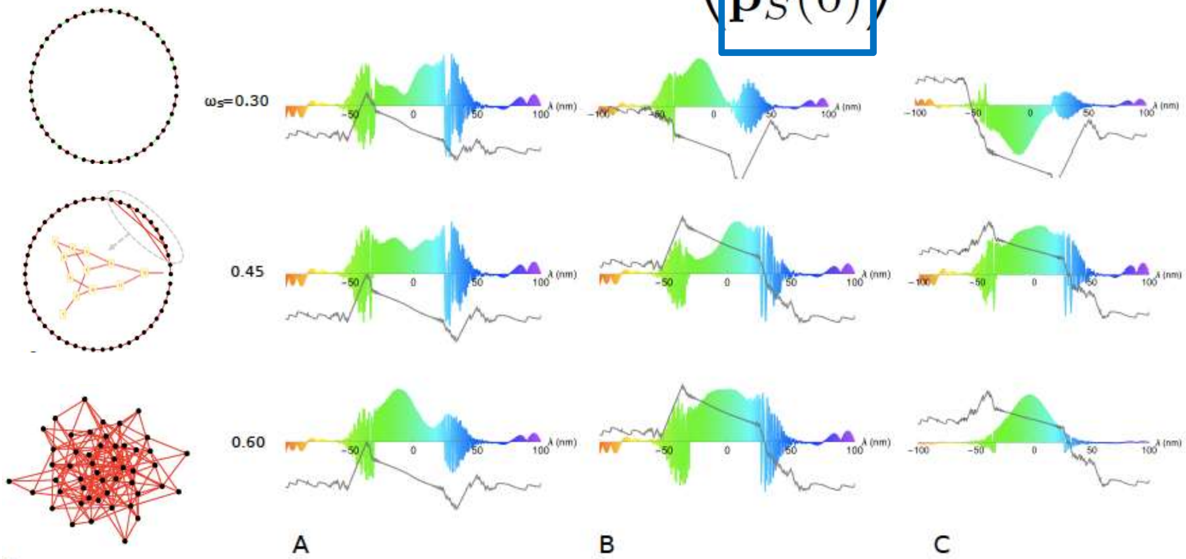


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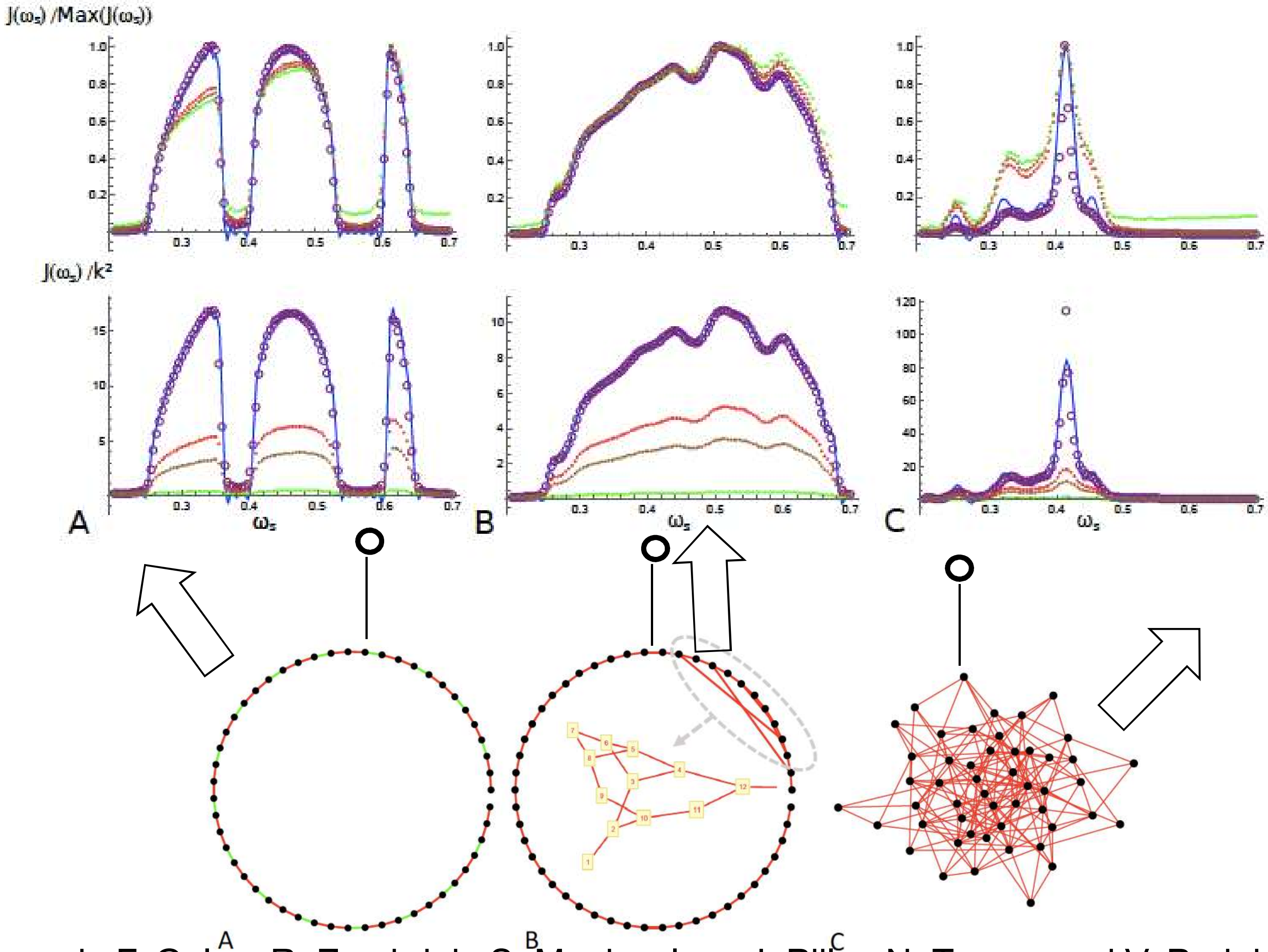
# Quantum complex networks

Ex: complex network = structured environment

additional oscillator= probe/system

*Experimental feasibility*

*Results*

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