ICFO Institut de Ciències Fotòniques

COMPAS Meeting

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December, 2009

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Outline

- Multimode non-locality using homodyne measurements

- CV for many body systems

  Dependence of Entanglement with the connectivity of the system

  Presence of bound entanglement in natural systems

  Limits of applicability of standard thermodynamics

- Quantum Networks with CV systems

  CV graph states and measurement Based QC

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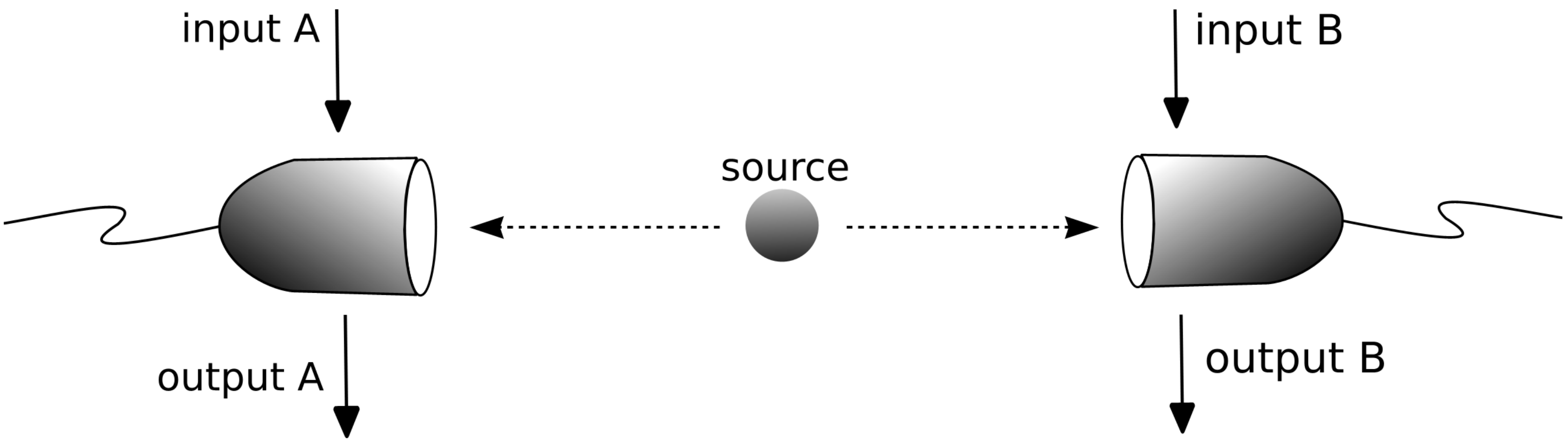
Non-locality Test

"The quantum-mechanical description of physical reality given by wave functions is not complete" (EPR '35)

Typical scenario of a non-locality test:



The statistics in A and B may falsify local realism (lhv): a Bell inequality is violated.

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Present experimental tests suffer from loopholes

Up to now, non-locality experimental tests are not fully conclusive.

Detection-efficiency loophole

Detected events are not fully representative of the whole ensemble

E.g.: photon polarization experiments

Locality loophole

The measured correlations are not collected in space-like separated locations

E.g.: ions experiments

Is it “only” a fundamental issue?

No! Applications: quantum cryptography (device independent)

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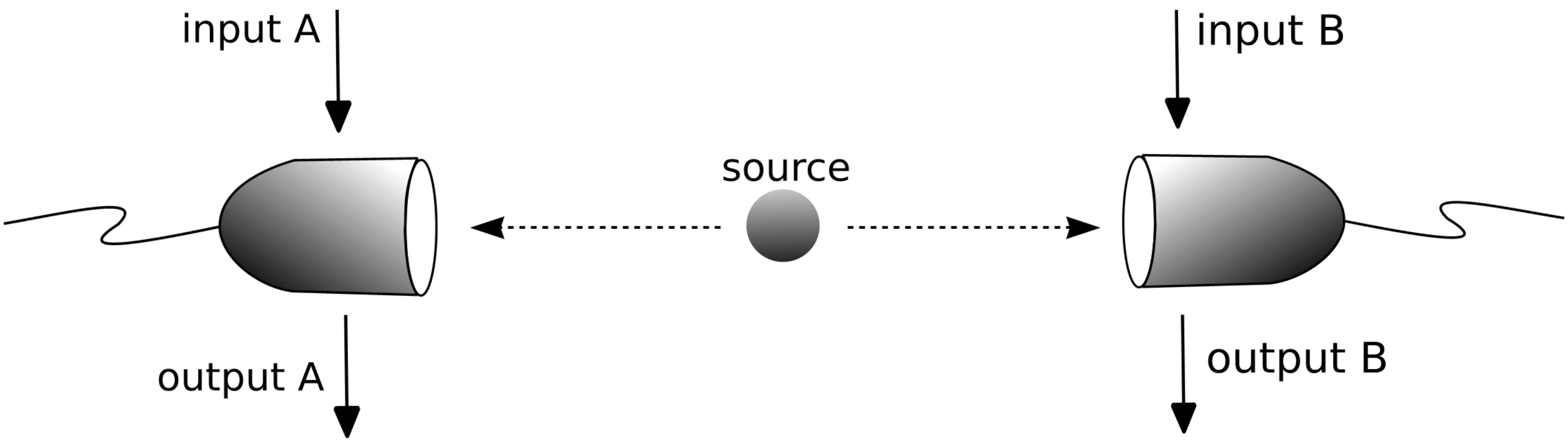
Light modes + homodyne detection may fix the loopholes [Garcia-Patron et al. PRL 04, Nha et al. PRL 04]



homodyne → close detection loophole

light modes → close locality loophole

homodyne → close detection loophole

Present proposals are still too demanding: the violation is too small

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Multimode non-locality using homodyne measurements

Main question:

Is it possible to enhance the violation?
(ideally maintaining the feasibility)

Idea:

Consider more than two parties and homodyne detection
(exponential enhancement expected... but is it actually there?)

A. Acín, N. J. Cerf, A. Ferraro, and N. Niset, Phys. Rev. A 79, 012112 (2009)

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Mermin-Klyshko (MK) Inequalities

- Mermin-Klyshko inequality for m parties $\mathcal{B}_m \equiv |\langle B_m \rangle| \leq 2$
- Which uses two dichotomic observables

The outcomes $x(\theta)$ have to be dichotomized:

Binning: if $x(\theta) \in D^+_{x(\theta)} \longrightarrow +1$

if $x(\theta) \in D^-_{x(\theta)} \longrightarrow -1$

$D^+_{x(\theta)}$ and $D^-_{x(\theta)}$ are *arbitrary* domains

Does this loss of information preclude an exponential (maximal) violation?

Homodyne Bell test with more than two parties:

- An exponentially increasing violation is obtained for GHZ-like states

$$|\mathrm{GHZ}_m\rangle = \frac{1}{\sqrt{2}}(|0...0\rangle + |1...1\rangle)$$

Bell factor: $\mathcal{B}_m = \sqrt{2}\left(\frac{4}{\pi}\right)^{m/2}$ → Exponential violation!

- It is also possible to get the *maximum violation* for all *m*, for a suitable binning strategy*:* $\mathcal{B}_m = 2^{(m+1)/2}$

- It is robust to noise (with probability p the information of the mode is erased). The allowed noise increases with *m.*

- For three parties this state:

$$|\Psi_3'\rangle \propto (|\alpha,\alpha,\alpha\rangle + |\alpha,-\alpha,-\alpha\rangle + |-\alpha,\alpha,-\alpha\rangle + |-\alpha,-\alpha,\alpha\rangle)$$

Gives a Bell factor of: $\mathcal{B}_3 \simeq 2.23$ and can be generated from 4 Schroedinger cat states

Help in devising a loophole free experiment

CV for quantum many body systems

- Dependence of Entanglement with the conectivity of the system

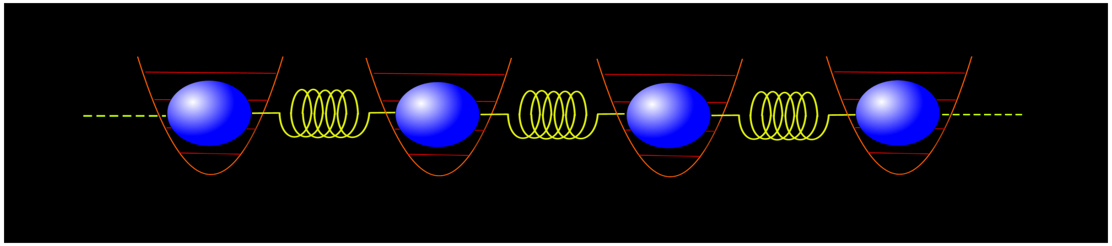
  A. Ferraro, A. García-Saez and A. Acín, PRA (2007).

- Presence of bound entanglement in natural systems

  A. Ferraro, D. Cavalcanti, A. García-Saez and A. Acín, PRL (2008).
  A. Ferraro, D. Cavalcanti, A. García-Saez and A. Acín, PRA (2008).
  A. Ferraro, D. Cavalcanti, A. García-Saez and A. Acín, NJP (2009).

- Limits of applicability of standard thermodynamics

  A. García-Saez, A. Ferraro and A. Acín, PRA (2009).
  A. Ferraro, A. García-Saez and A. Acín, To be Submitted (2009).



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Is bound entanglement a common phenomenon in Nature?

Definition (n parties): an entangled state is *bound entangled* whenever the n parties cannot distill pure-state entanglement out of it by LOCC. Negativity of partial transposition (NPT) is necessary for distillability.

Known examples of bound entanglement are:

- driven by mathematical intuition
- referred to microscopic Hamiltonian systems

What about natural systems?

By natural systems we mean:

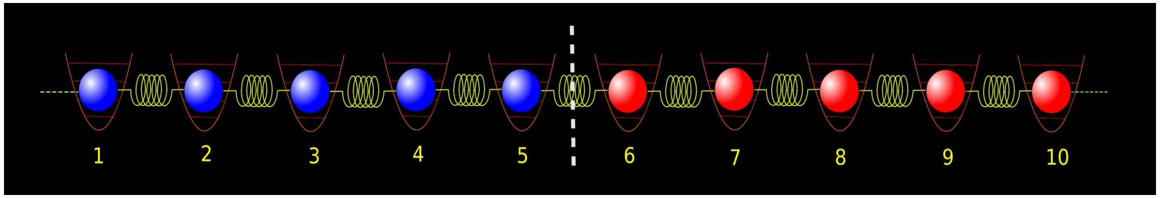
- macroscopic
- at thermal equilibrium
- with local interactions
- characterized by a few coupling parameters

Area laws and bound entanglement are strictly linked

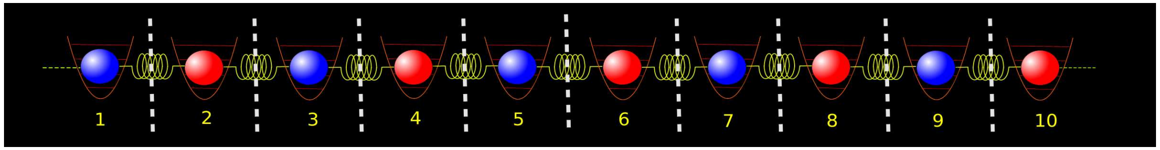
Entanglement-area laws ⟷ bound entanglement
Natural systems usually exhibit entanglement-area laws

Consider the ground state of an n-particle chain (pbc):

half/half (h/h)



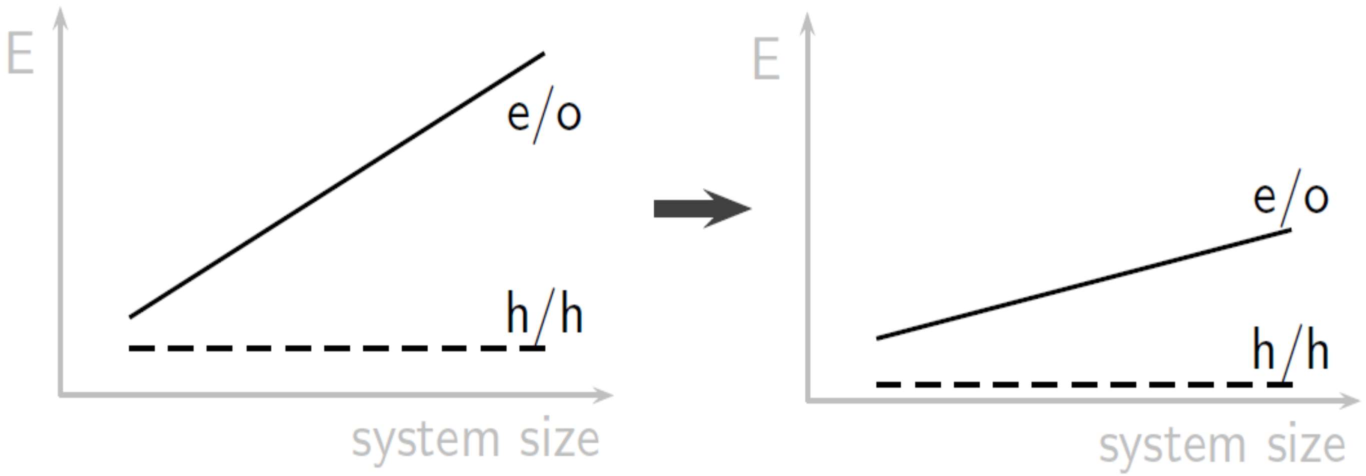
even/odd (e/o)



h/h: area stays constant with n
e/o: area increases with n

Area laws and bound entanglement are strictly linked

When the temperature T increases



Notation: $T^{h:h}$ – threshold temperature for h/h

$T^{e:o}$ – threshold temperature for e/o

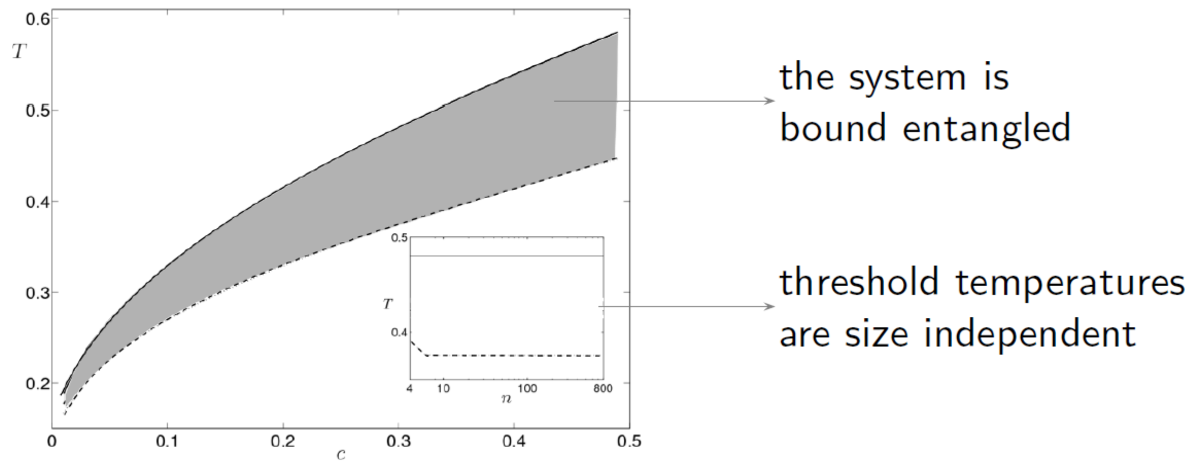
Due to area law, we expect: $T^{e:o} > T^{h:h}$

(and this should be valid even for $n \to \infty$!).

This imply the presence of Bound Entanglement

Main results:

- Numerics confirm bound entanglement appears in finite-size systems (considering up to 800 oscillators)



- Analytical results: bound entanglement is preserved in the *macroscopic* limit
  Via some matrix algebra calculations we obtained for n → ∞:

- For any coupling there is a range of temperatures where bound entanglement exists. The temperature, a single macroscopic measurable quantity, determines the distillability properties of the system

A. Ferraro, D. Cavalcanti, A. García-Saez and A. Acín, PRL (2008).
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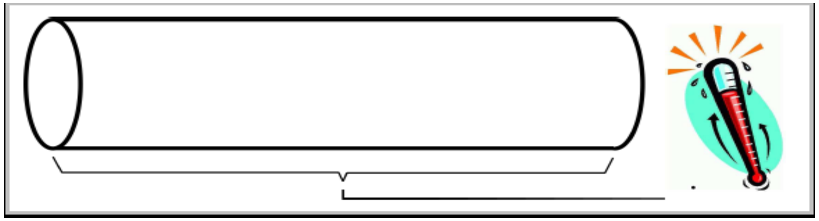
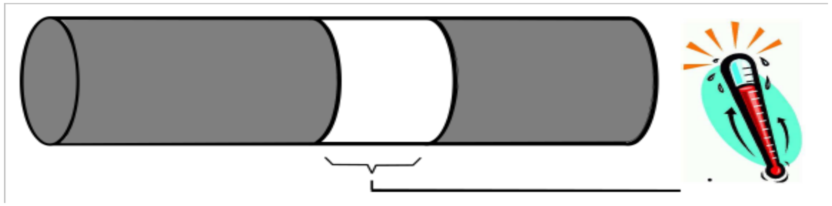
Local temperature in quantum thermal states

In standard thermodynamics a local temperature exists and is intensive
Standard Thermodynamical system
(macroscopic, open, weak interactions...)

System



Sub-blocks



Blocks are thermal (local T exists)
Temperature is an intensive magnitude

What about quantum microscopic blocks?

- When is the temperature intensive?
- When does a local temperature exist?
- Which correlations play a role?

Harmonic chains (CV):

Fidelity: $F(\sigma_1, \sigma_2) = \mathrm{Tr}\left[\sqrt{\sqrt{\sigma_1}\sigma_2\sqrt{\sigma_1}}\right]$

- The temperature is intensive when

$$F_I = F\left[\rho_m(\beta), \Omega'_m(\beta)\right] \approx 1$$

Intensive Fidelity

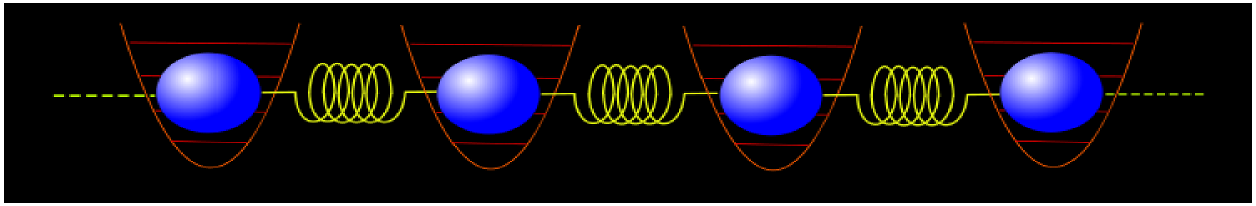
  - $\Omega'_m(\beta_L) = e^{-\beta_L H'}/Z'$
  - H': proper local H (physically motivated and β independent)

- A local temperature exists when there exist β_L s. t.:

$$F_T = F\left[\rho_m(\beta), \Omega'_m(\beta_L)\right] \approx 1$$

Temperature Fidelity

  - β_L is the local temperature (optimized)

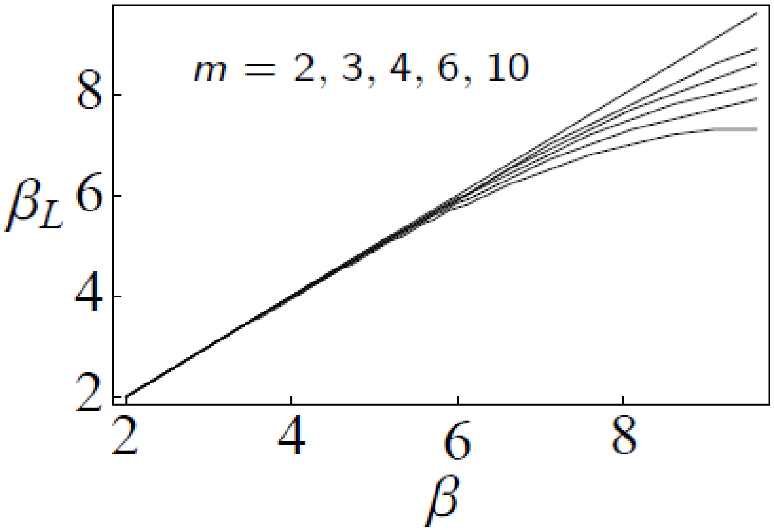


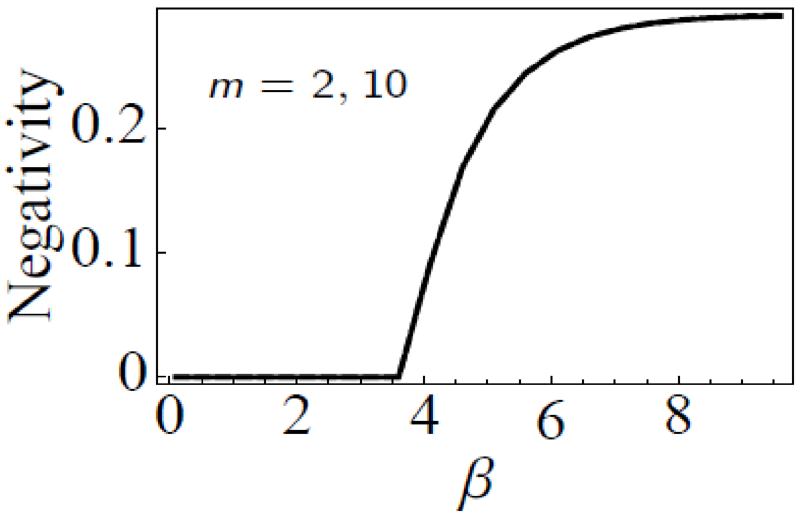
Main Results:

- Temperature is not intensive in microscopic quantum systems even when classically it is strictly intensive at any scale

- A local thermal description is nevertheless valid in the major part of the parameter space. I.e., a local temperature can be defined despite not being intensive

- An approximate link between entanglement and the breakdown of intensiveness and can be seen





A. García-Saez, A. Ferraro and A. Acín, PRA (2009).
A. Ferraro, A. García-Saez and A. Acín, To be Submitted (2009).

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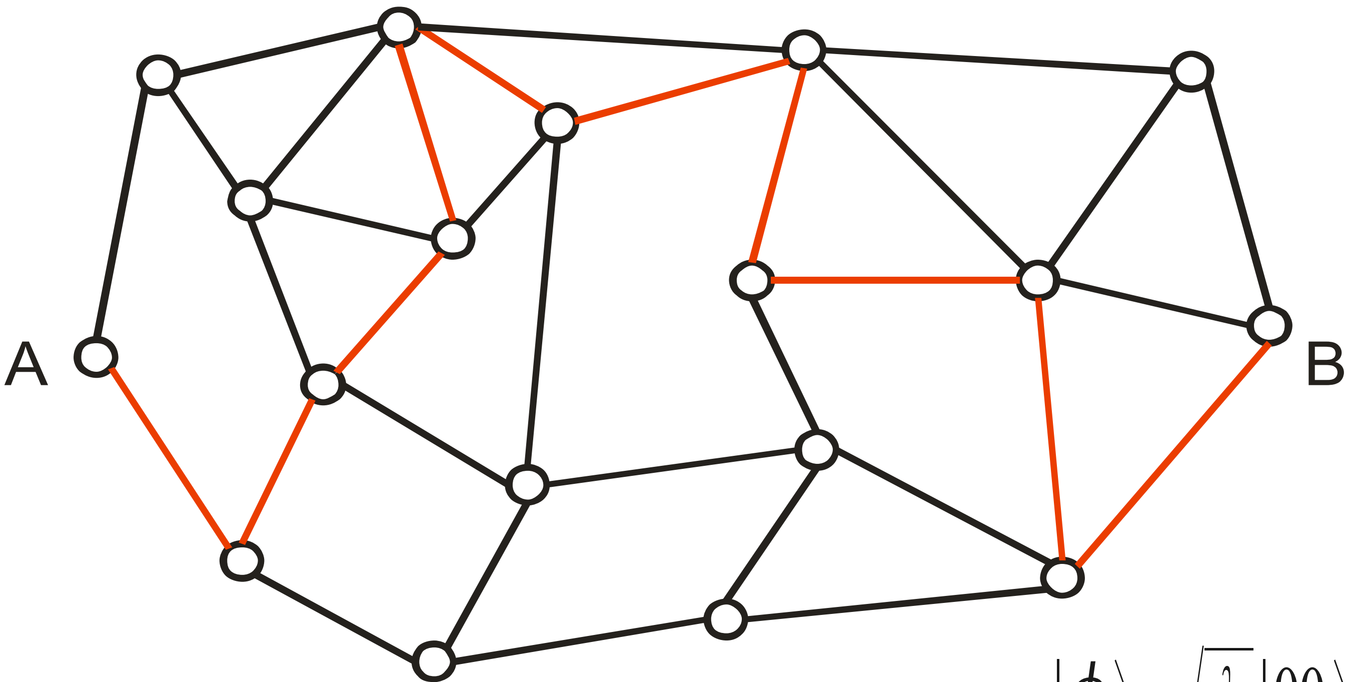
Quantum Networks

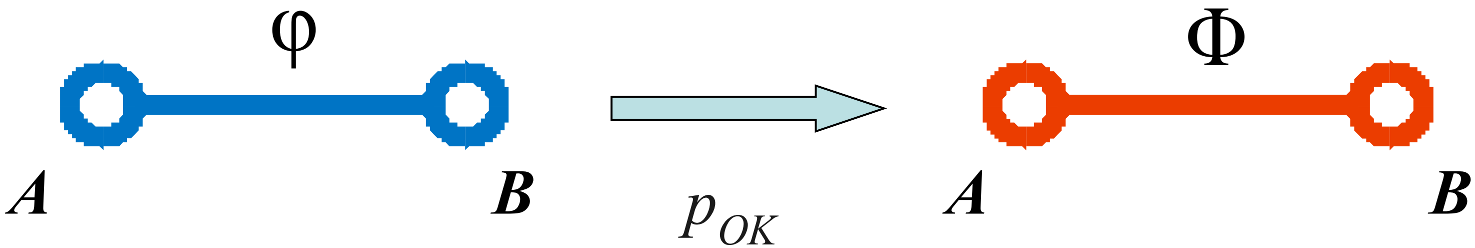
Quantum Network: N distant nodes share a quantum state ρ.



$$|\phi\rangle = \sqrt{\lambda_1}|00\rangle + \sqrt{\lambda_2}|11\rangle$$

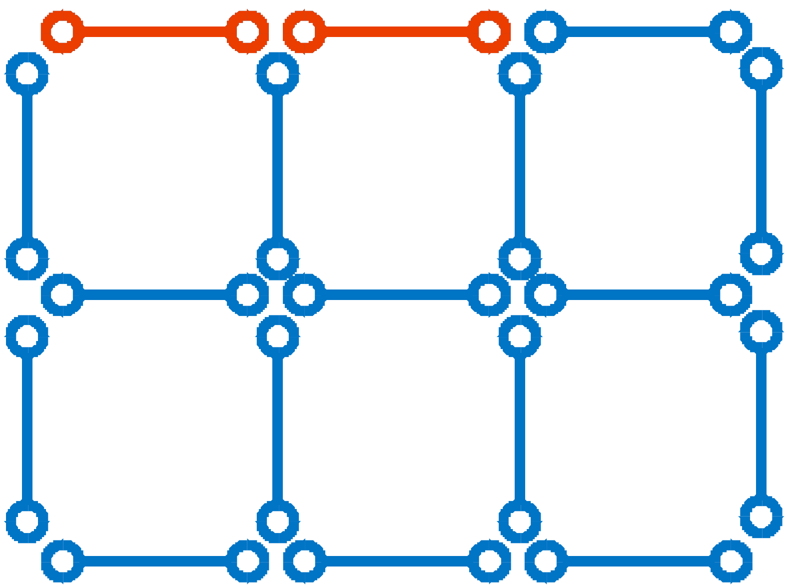
The goal is to establish an entangled state between two distant nodes, *A* and *B*, by local operations and classical communication (LOCC).

Classical Entanglement Percolation



Singlet convertion probability (SCP)

$$p_{OK} = \min\left(1, 2\left(1-\lambda_1\right)\right)$$ Nielsen & Vidal



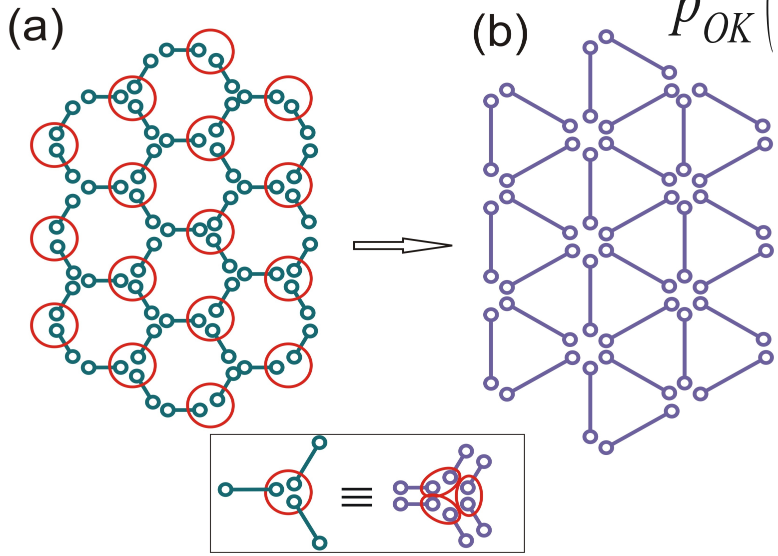
The classical entanglement percolation strategy (CEP) defines bounds for the minimal amount of entanglement for non-exponential decay of entanglement with the network size.

Bond Percolation

Lattice	Percolation Threshold
Square	1/2
Triangular	$2\sin(\pi/18) \approx 0.3473$
Honeycomb	$1-2\sin(\pi/18) \approx 0.6527$

Entanglement percolation: 2D Geometries

$$|\phi\rangle = |\phi_2\rangle^{\otimes 2}$$



$$p_{OK}(\phi_2)$$

$$p_{OK}^{(a)} = 2\left(1-\lambda_1^2\right) < p_h^{th}$$

$$p_{OK}^{(b)} = 2\left(1-\lambda_1\right) > p_t^{th}$$

CEP

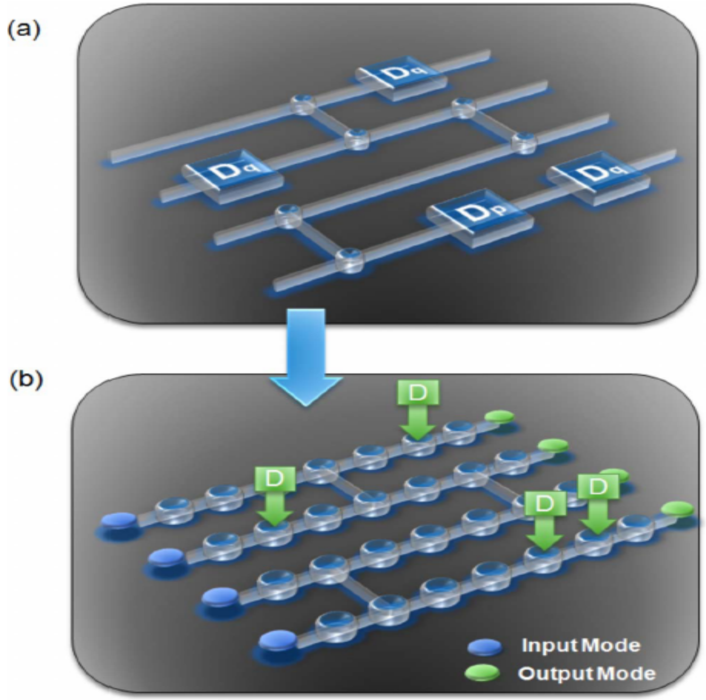
Combining entanglement swapping and CEP, long-distance entanglement can be established in a network where CEP fails.

Acín, Cirac & Lewenstein, Nat. Phys.'07

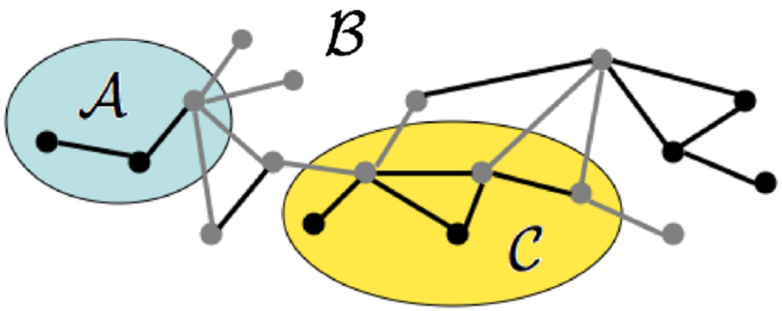
- Can we distribute entanglement considering only local Gaussian operations and classical communication?

- Which are the limitations, and the resources that we need?

CV graph states and one way QC



M. Gu, C. Weedbrook, N. C. Menicucci, T. C. Ralph and P. van Loock, PRA (2009)



D. Cavalcanti, R. Chaves, L. Aolita, L. Davidovich and A. Acín et al. PRL (2009)

- Can we consider new resources?
- Entanglement properties under noise?