Title: Talk 81 - Testing the quantumness of gravity without entanglement

Speakers: Ludovico Lami

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Abstract: We propose a conceptually new class of dynamical experiments whose goal is to falsify the hypothesis that an interaction between quantum systems is mediated by a purely local classical field. The systems we study implement a dynamics that cannot be simulated by means of local operations and classical communication (LOCC), even when no entanglement is ever generated at any point in the process. Using tools from quantum information theory, we estimate the maximal fidelity of simulation that a local classical interaction could attain while employing only LOCC. Under our assumptions, if an experiment detects a fidelity larger than that calculated threshold, then a local classical description of the interaction is no longer possible. As a prominent application of this scheme, we study a general system of quantum harmonic oscillators initialised in normally distributed coherent states and interacting via Newtonian gravity, and discuss a possible physical implementation with torsion pendula. One of our main technical contributions is the calculation of the above bound on the maximal LOCC simulation fidelity for this family of systems. As opposed to existing tests based on the detection of gravitationally mediated entanglement, our proposal works with coherent states alone, and thus it does not require the generation of largely delocalised states of motion nor the detection of entanglement.

Testing the quantumness of gravity without entanglement

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arXiv:2302.03075

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Perimeter Institute, 2 August 2023

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Research Center for Quantum Software

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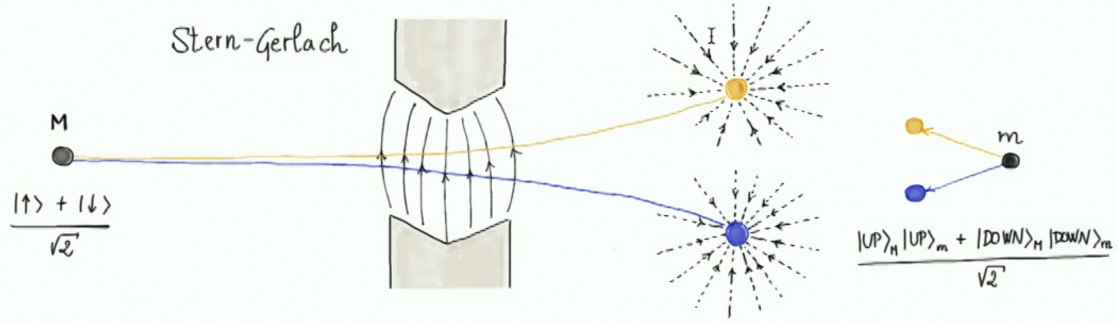
Motivation

What happens to the gravitational field of a delocalised mass?[1]



[1] Feynman, Chapel Hill conference, 1957.

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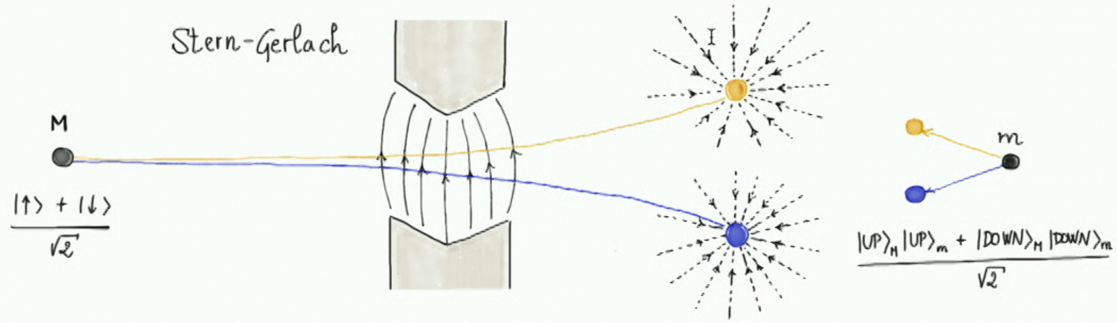

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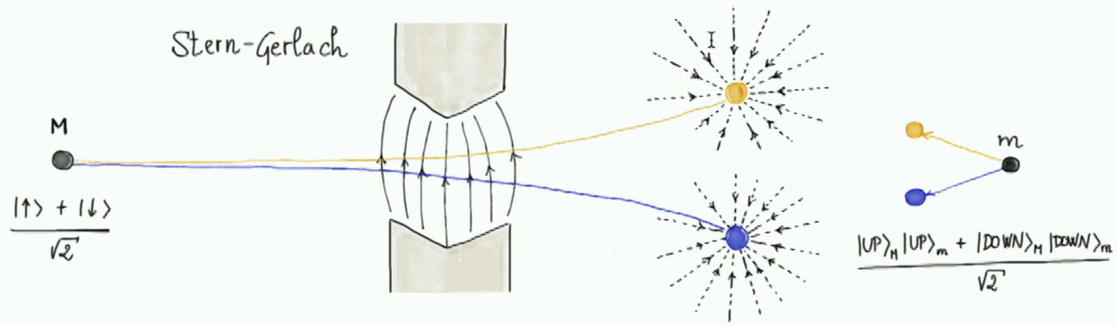

1. The gravitational field follows matter → enters a superposition → creates entanglement with test particle
2. Gravity is classical → no superposition → something else happens (e.g. gravity tries to measure positions, decohering the state)

Can we discriminate between these two options, experimentally?

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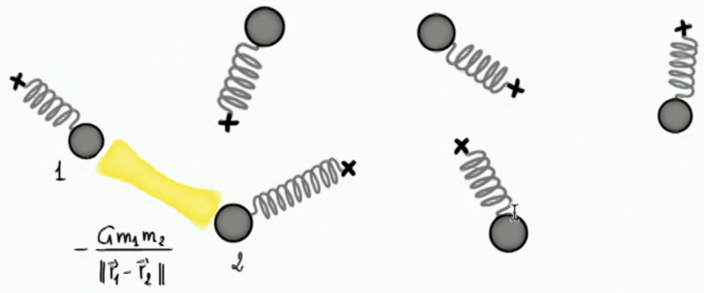
General system of interest:



Two main hypotheses:

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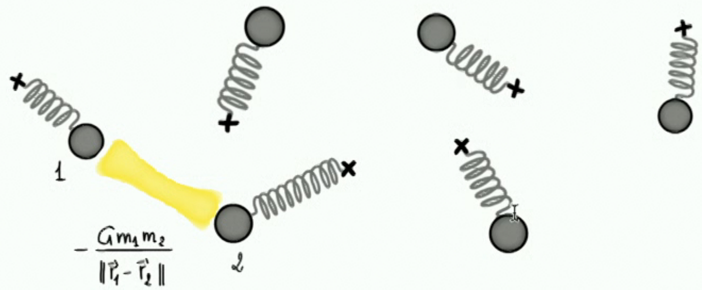

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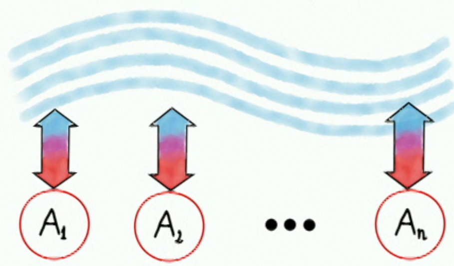
1. Gravity acts as the unitary $U_G = e^{-iH_G t/\hbar}$, where[2]

$$H_G = \text{Newtonian Hamiltonian} = -\sum_{i<j} \frac{Gm_i m_j}{\|\vec{r}_i - \vec{r}_j\|}$$

2. Gravity is an underlying classical field:



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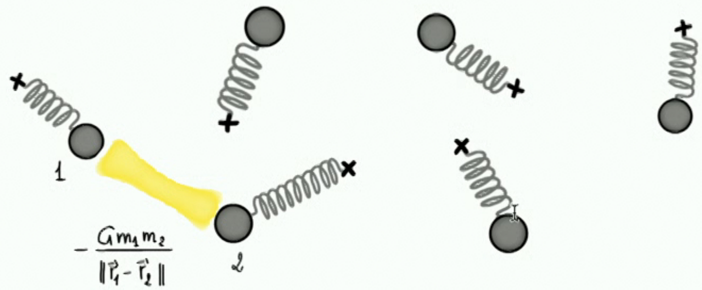

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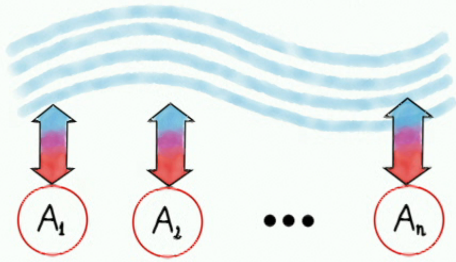

Assuming linearity,
the interaction must be an LOCC!

[2] Carney, Stamp, and Taylor, *Class. Quantum Grav.* **36**, 034001, 2019.

What is an LOCC?

Definition

Any state-to-state transformation that Alice and Bob can implement with many rounds of local quantum operations and classical communication of the measurement outcomes.

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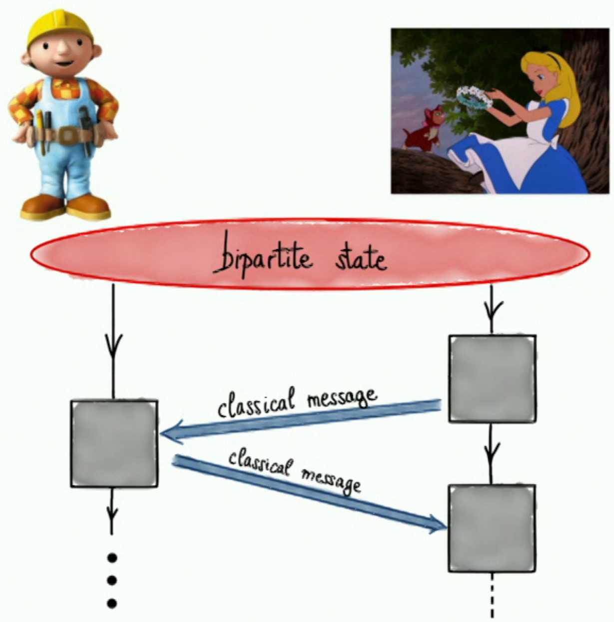

The problem

Main question

Given an isometry $U : A_1 \ldots A_n \to A'_1 \ldots A'_n$ on a multi-partite quantum system $1 : 2 : \ldots : n$, how well can it be simulated by means of LOCC?

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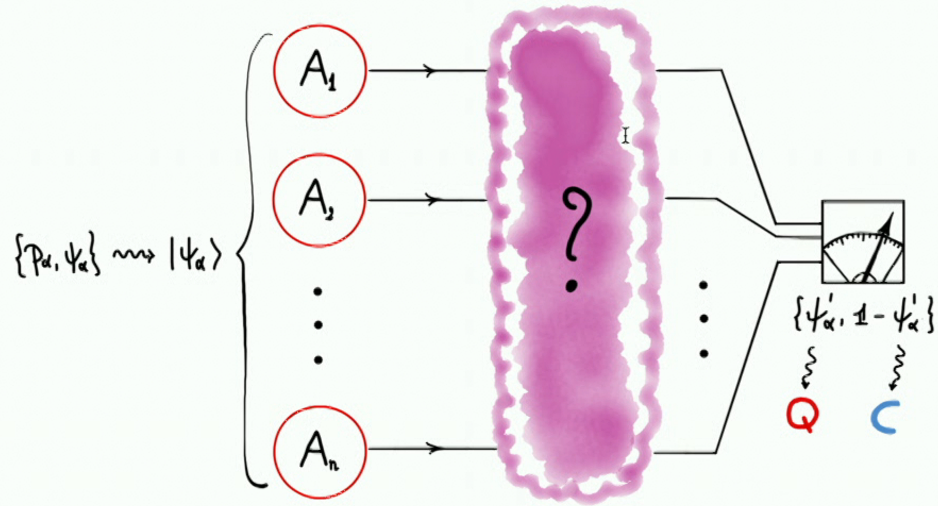
In practice, the initial states of the system are limited by technology.

We can only prepare states from the ensemble $\mathscr{E} = \{p_\alpha, |\psi_\alpha\rangle\}_\alpha$
$\longrightarrow$ a good figure of merit is

$$F_{\mathcal{L}}(\mathscr{E}, U) := \sup_{\Lambda \in \mathrm{LOCC}(A \to A')} \sum_\alpha p_\alpha \operatorname{Tr}\left[\Lambda(\psi_\alpha)\psi'_\alpha\right],$$

$$\psi'_\alpha := U\, |\psi_\alpha\rangle\!\langle\psi_\alpha|\, U^\dagger .$$

Operational interpretation



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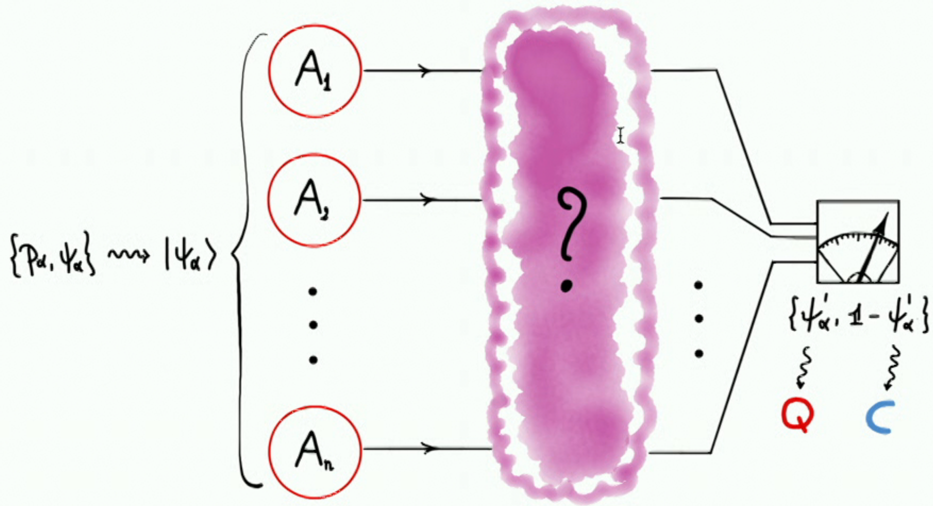

$$P(\boldsymbol{Q}|U) = \sum\nolimits_\alpha p_\alpha \operatorname{Tr} \psi'_\alpha U \psi_\alpha U^\dagger = 1\,,$$

$$P(\boldsymbol{Q}|\mathrm{LOCC}) = \sum\nolimits_\alpha p_\alpha \operatorname{Tr} \psi'_\alpha \Lambda(\psi_\alpha) \leq F_{cl}(\mathscr{E}, U)\,.$$

$\text{Frequency}(\boldsymbol{Q}) > F_{cl}(\mathscr{E}, U) \implies$? $\neq \mathrm{LOCC}$

Example

- Known ensemble of states $\{p_\alpha, |\psi_\alpha\rangle\}_\alpha$.
- Can A and B swap *unknown* states from the ensemble via LOCC?

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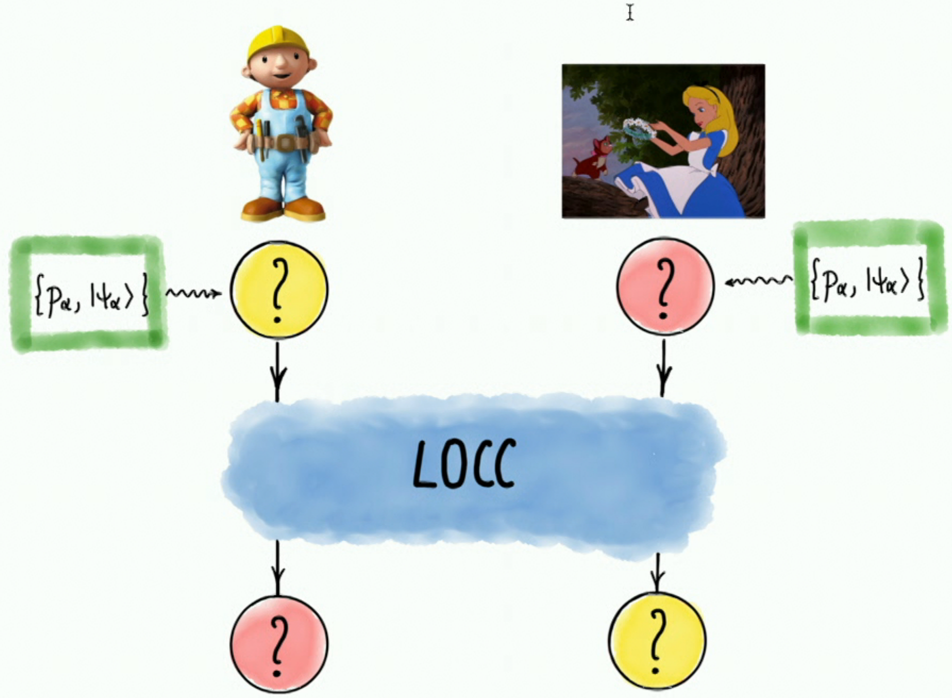

A general 'LOCC inequality'

Theorem 1 (LOCC inequality)

For all ensembles $\mathscr{E} = \{p_\alpha, \psi_\alpha\}_\alpha$ and isometries $U : A \to A'$, it holds that

$$F_{c\ell}(\mathscr{E}, U) \leq \min_{J \subseteq [n]} f_J\left(R_{AA'}\right),$$

$$R_{AA'} := \sum_\alpha p_\alpha \, (\psi_\alpha^*)_A \otimes (\psi'_\alpha)_{A'} \,,$$

$$f_J\left(R_{AA'}\right) := \inf\left\{ \operatorname{Tr}\omega_A : \; R_{AA'}^{\Gamma_J} \leq \omega_A \otimes \mathbb{1}_{A'}, \; \omega_A \geq 0 \right\}.$$

where $\psi'_\alpha = U\psi_\alpha U^\dagger$ and $\Gamma_J =$ partial transpose on A_J and A'_J.

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- Example: $n = 2$, $J = \{2\}$; then

$$\left(X_{A_1} \otimes Y_{A_2} \otimes W_{A'_1} \otimes Z_{A'_2}\right)^{\Gamma_J} = X_{A_1} \otimes Y_{A_2}^\intercal \otimes W_{A'_1} \otimes Z_{A'_2}^\intercal .$$

- Any choice of J gives you a SDP-computable upper bound $f_J(R_{AA'})$.

- This can be thought of as an analogue to Bell inequality but for dynamics:

$$\Lambda \in \mathrm{LOCC} \implies \sum_\alpha p_\alpha \mathrm{Tr}[\Lambda(\psi_\alpha)\psi'_\alpha] \leq F_{cl}(\mathscr{E}, U) \leq \min_{J\subseteq[n]} f_J\left(R_{AA'}\right).$$

In other words:

$$\sum_\alpha p_\alpha \,\mathrm{Tr}\left[\Lambda(\psi_\alpha)\psi'_\alpha\right] > \min_{J\subseteq[n]} f_J\left(R_{AA'}\right) \implies \Lambda \text{ is } \underline{\text{not}} \text{ an LOCC.}$$

- In the setting of Bell inequalities,

$$p(ab|xy) \text{ admits LHV model} \implies \sum_{a,b,x,y} s_{abxy}\, p(ab|xy) \leq S_{\mathrm{cl}},$$

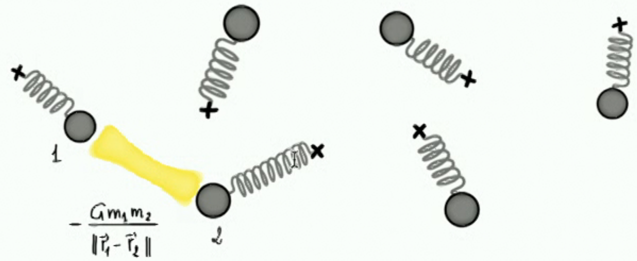
thus

$$\sum_{a,b,x,y} s_{abxy}\, p(ab|xy) > S_{\mathrm{cl}} \implies p(ab|xy) \text{ is } \underline{\text{not}} \text{ LHV.}$$

Application to a specific system

System of interest:
mechanical oscillators.

$$H_G = -\sum_{i<j} \frac{G m_i m_j}{\|\vec{r}_i - \vec{r}_j\|} .$$



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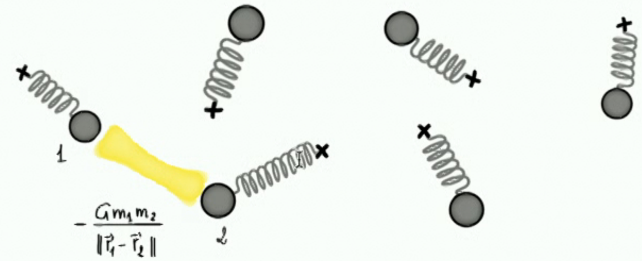

Each oscillator is 1-dim. Hilbert space $L^2(\mathbb{R})^{\otimes n} \simeq L^2(\mathbb{R}^n)$.

- Canonical operators $r := (x_1, p_1, \ldots, x_n, p_n)^\intercal$. Commutation relations

$$[r, r^\intercal] = i\Omega\,, \qquad \Omega := \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}^{\oplus n}.$$

- **Coherent states** are 'easy' to prepare. Single mode:

$$\mathbb{C} \ni \alpha = \alpha_R + i\alpha_I \longrightarrow |\alpha\rangle := \exp\left[i\sqrt{2}\,(\alpha_I x - \alpha_R p)\right] |0\rangle\ .$$

Gaussian coherent state ensemble. $\lambda > 0$, fixed n: i.i.d. ensemble

$$\mathscr{E}_\lambda := \left\{ p_\lambda(\alpha)\, d^2\alpha,\ |\alpha\rangle\!\langle\alpha| \right\}_{\alpha\in\mathbb{C}}^{\otimes n}, \quad p_\lambda(\alpha) := \frac{\lambda}{\pi} e^{-\lambda|\alpha|^2}.$$

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Gaussian unitary U_{G}:

- Definition #1:

$$U_{\mathrm{G}}^\dagger\, r\, U_{\mathrm{G}} = Sr + \delta\,;$$

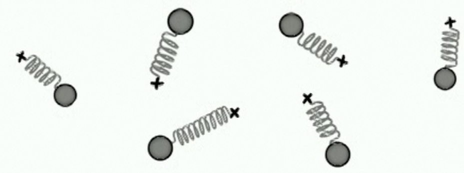
  S: $2n \times 2n$ real 'symplectic' matrix; $\delta \in \mathbb{R}^{2n}$.

- Definition #2: $U_{\mathrm{G}} = \prod_{\ell=1}^N e^{-iH_\ell}$, where H_ℓ is of degree at most 2:

$$H_\ell = \sum_j (a_j x_j + b_j p_k) + \sum_{j,k} \left(A_{jk} x_j x_k + B_{jk} p_j p_k + C_{jk} x_j p_k\right).$$

- Fact: *these two definitions are equivalent.*

Distance between oscillators $\gg$ oscillation amplitude



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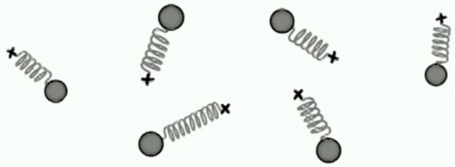

$\Longrightarrow$ Taylor expand $H_G = -\sum_{i<j} \frac{Gm_i m_j}{\|\vec{r}_i - \vec{r}_j\|}$ up to 2^{th} order w.r.t. displacement of masses from equilibrium position.

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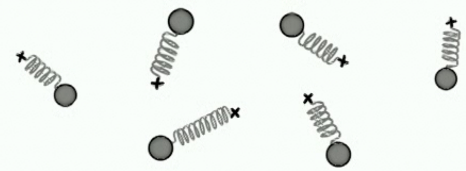

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$\Longrightarrow$ $e^{-iH_G t/\hbar} \approx$ Gaussian unitary U_{G}.

Problem

Estimate the upper bound on $F_{\mathcal{cl}}(\mathscr{E}, U)$ in Theorem 1 for

- $\mathscr{E} = \mathscr{E}_\lambda$ Gaussian coherent state ensemble;
- $U = U_{\mathrm{G}}$ Gaussian unitary.

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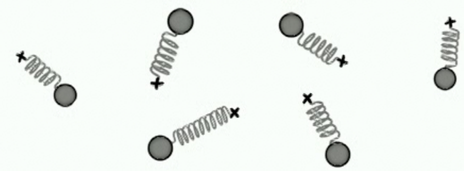

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$\rightarrow$ Experimentally feasible scenario.

Main result

Theorem 2

Gaussian i.i.d. ensemble $\mathscr{E}_\lambda$, $\lambda > 0$. Gaussian unitary U_{G} s.t. $U_{\mathrm{G}}^\dagger\, r\, U_{\mathrm{G}} = Sr + \delta$. Then

$$F_{c\ell}\left(\mathscr{E}_\lambda,\, U_{\mathrm{G}}\right) \leq f(\lambda, S) := \min_{J\subseteq[n]} \frac{2^n(1+\lambda)^n}{\prod_{\ell=1}^{2n} \sqrt{2+\lambda+|z_\ell(\lambda,S,J)|}},$$

where $z_\ell(\lambda, S, J)$ is the ℓ^{th} eigenvalue of the Hermitian matrix

$$(1+\lambda)\, S^\intercal i\Omega_J S - i\Omega_J,$$

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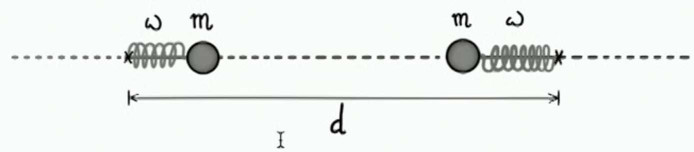
- S orthogonal symplectic $\Rightarrow$ sends coherent states to coherent states $\Rightarrow$ U_{G} never entangles states in $\mathscr{E}_\lambda$.
- Nevertheless, $F_{c\ell}(\mathscr{E}_\lambda, U_{\mathrm{G}}) < 1$! *Processes mapping product states to product states can be very far from LOCC (e.g. swap).*

Recap & example

Simplest example:
two oscillators on a line.



Protocol

1. Initialise oscillators in $|\alpha\rangle \otimes |\beta\rangle$, with $\alpha, \beta \in \mathbb{C}$ drawn i.i.d. from Gaussian ensemble $p_\lambda(\alpha)$.
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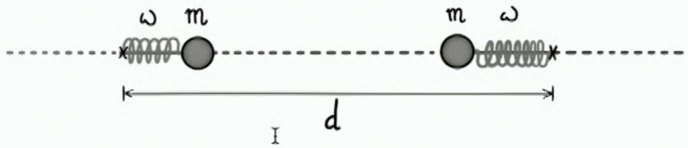

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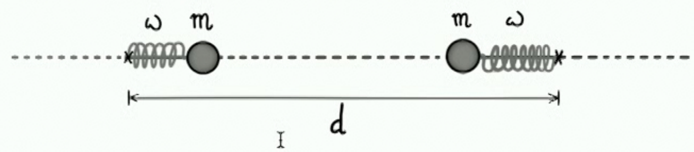

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4. If outcome '$\Psi'_{\alpha,\beta}$' is obtained with frequency $> f(\lambda, S(t))$, then the process was not LOCC.

What have we gained?

What does one need to build an experiment?

Ludovico Lami arXiv:2302.03075 15 / 16

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Our LOCC-inequality proposal: Entanglement-based proposals:

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Our LOCC-inequality proposal:

- Ability to prepare coherent states with great precision

Entanglement-based proposals:

4

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What does one need to build an experiment?

Our LOCC-inequality proposal:

- Ability to prepare coherent states with great precision $\Rightarrow$ **cool down** macroscopic oscillators close to ground state.
- Very precise single-phonon detectors, precise clocks, etc.

Entanglement-based proposals:

- Excellent control over noise — e.g. wind blowing at $\sim 500\,\mathrm{m}$ (!)

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Entanglement-based proposals:

- Ability to prepare large **delocalised states** of macroscopic objects.

- Excellent control over noise — e.g. wind blowing at $\sim 500\,\mathrm{m}$ (!)

4

[3] Fein et al., *Nat. Phys.* **15**:1242, 2019.

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Thank you!