Title: On the quantum mechanics of entropic forces

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Collection/Series: Quantum Gravity

Subject: Quantum Gravity

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Abstract:

It has been conjectured that the gravitational interaction may arise as an entropic force rather than as a result of virtual quanta exchange of a fundamental field. In this talk I will present a set of microscopic quantum models which realize this idea in detail. I will describe a simple mechanism by which Newton's law of gravity arises from the extremization of the free energy of a collection of qubits. I will show both a local and non-local model version of the construction and discuss how to distinguish these entropic models from ordinary perturbative quantum gravity using existing observations and near term experiments. Based on 2502.17575 with Daniel Carney, Thilo Scharnhorst, Roshni Singh and Jacob M. Taylor.

Motivation

- *Jacobson (1995)* derived Einstein's equation $G_{ab} = 8\pi G_N T_{ab}$ from the "first law" of Rindler horizons $dQ = TdS$.

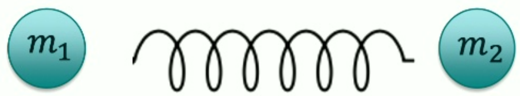
- *Verlinde (2011)* derived Newton's law of gravitation as an "entropic force" using holographic arguments.

Our motivation is:

- Find a phenomenological model of **entropic gravity** that we can **test** in **tabletop quantum gravity** experiments.
  - **Newtonian gravity** is "sufficient" in this context.

Basic idea

Perturbative Quantum Gravity



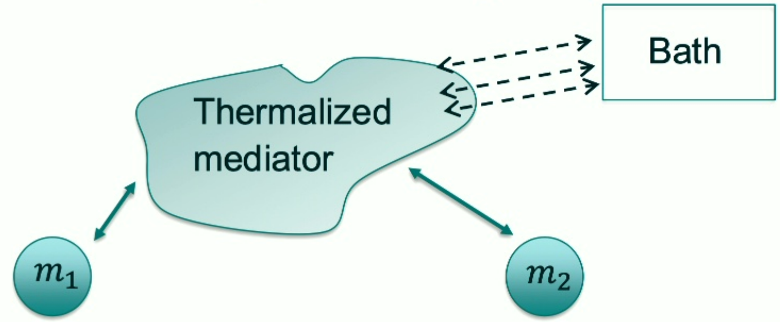
virtual graviton exchange

Von-Neumann equation
$$\dot{\rho}_S = -\frac{i}{\hbar}[H_N, \rho_S]$$

The Hamiltonian is:
$$H = \frac{\mathbf{p}_1^2}{2m_1} + \frac{\mathbf{p}_2^2}{2m_2} + V_{N,\mathrm{ent}}$$

The Newtonian gravitational interaction V_N **entangles** the masses.
$$V_N = -\frac{G_N m_1 m_2}{|\mathbf{x}_1 - \mathbf{x}_2|}$$

Entropic Gravity

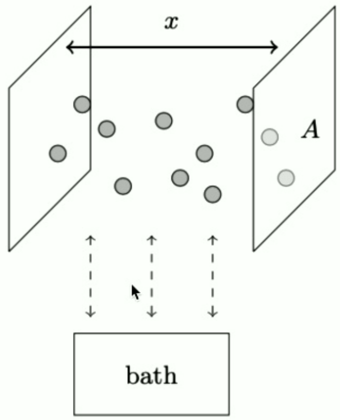


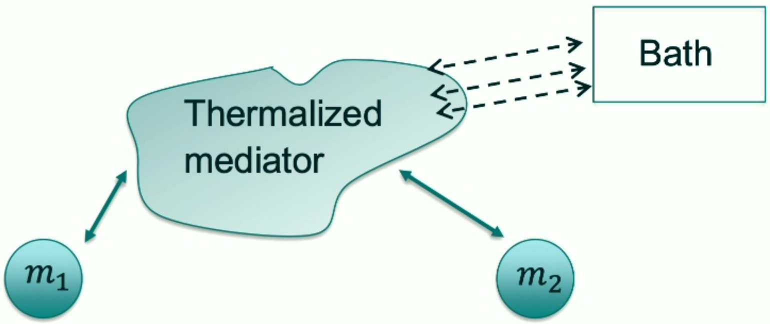
Lindblad equation:
$$\dot{\rho}_S = -\frac{i}{\hbar}[H_{\mathrm{eff}}, \rho_S] + \mathcal{L}(\rho_S)$$

We still recover the entangling Newtonian interaction $H_{eff} = H$. *(surprise No.1)*

The Lindbladian part $\mathcal{L}(\rho)$ is responsible for **decoherence** of spatial superpositions and **noise** in the gravitational force.

Analogy with the ideal gas





Pair of pistons	⟷	Pair of massive bodies (S)
Ideal gas	⟷	Many body mediator (M)
Bath at temperature T	⟷	Bath at T (B)
Force on the pistons.	⟷	Newtonian force

Note the microscopic dynamics of S+M+B are **unitary** $H = H_S + H_M + V_{SM} + H_B + V_{MB}$

Main message

- **Proof of concept:** We have constructed a set of quantum mechanical models where *Newtonian gravity* arises as an *entropic force*.
- Both models predict **new effects** compared to standard perturbative quantum gravity. These effects include:
  - Gravitational noise
  - Decoherence of spatial superpositions
  - Friction

- Past/future experiments can **constrain,** or even **rule out,** these models.

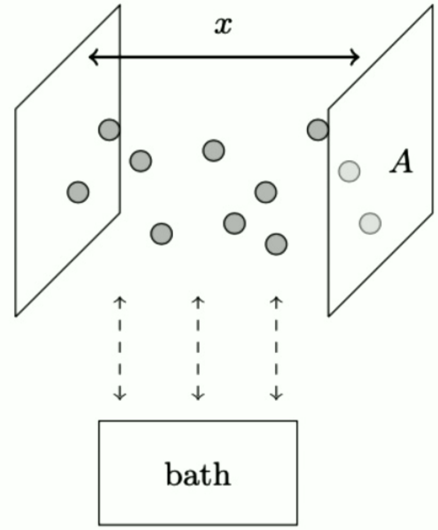
Outline

- Ideal gas law as an entropic force
- Present non-local/local models and derive the Newtonian force.
- Explain the detailed quantum dynamics
- Experiments: predictions/constraints
- Comments/future directions.

Toy model: Ideal gas law as an entropic force

The free energy of the gas is : $\mathcal{A}_{\rm gas}(x) = U_{\rm gas}(x) - TS_{\rm gas}(x)$
The free energy is a function of the piston's distance. How to find it?

- The thermal energy Energy $U_{\rm gas}(x) = Nk_BT$ is position **independent** . (N = number of atoms)
- For the entropy we have the Sackur-Tetrode (ST) formula: $\dfrac{\partial S_{\rm gas}(x)}{\partial x} = \dfrac{k_B N}{x}$



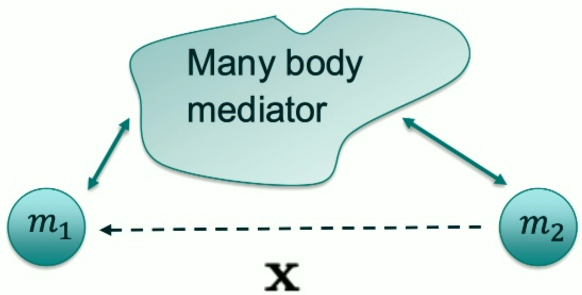
The system is entropically driven toward the minimum free energy by the *entropic force*:

$$\begin{aligned} F_{\rm therm} :&= -\frac{\partial}{\partial x}\mathcal{A}_{\rm gas}(x) \\ &= -\cancelto{0}{\frac{\partial U_{\rm gas}}{\partial x}} + T\frac{\partial S_{\rm gas}}{\partial x} \\ &= \frac{k_B N}{x} \end{aligned}$$

The pistons feel an effective repulsive force $\sim \frac{1}{x}$.

Q: Can we do something analogous and recover Newton's $\sim \dfrac{G_N m_1 m_2}{|\mathbf{x}|^2}$ gravitational force law?

A: Yes. I will describe this next.



Non-local model

In the *non-local model* the mediator consists of a collection of qubits labeled by $\alpha = 1, 2, 3, \ldots$.

- The Hamiltonian of each qubit depends the relative position of the masses $\mathbf{x} = \mathbf{x}_1 - \mathbf{x}_2$. (hence the name non-local)

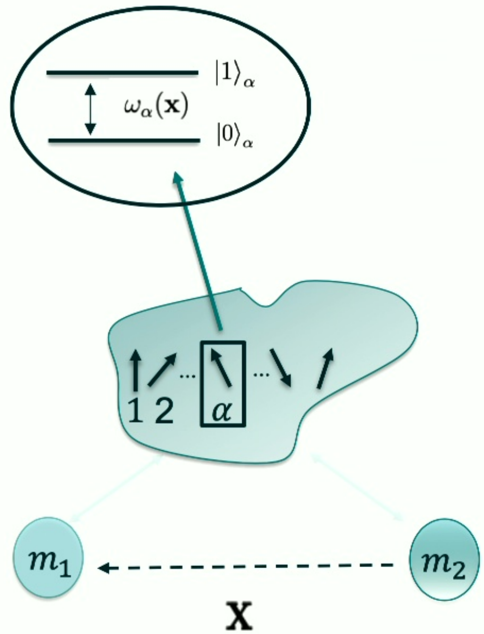
$$V_{SM} = \sum_{\alpha} \omega_\alpha(\mathbf{x}) N_\alpha, \quad N_\alpha = |1\rangle_\alpha \langle 1|_\alpha$$

- The frequencies are taken to have linear spectrum:

$$\omega_\alpha(\mathbf{x}) = f(\mathbf{x})\alpha \ ,$$

where $f(\mathbf{x})$ is unspecified for now.

- We treat as an external *c-number* for now. We will promote it to a **quantum dof** later.
- We will compute the free energy of the qubit-mediators assuming they are **thermalized** at temperature T.



Non-local model

The free energy $\mathcal{A}$ of the mediator qubits at temperature T is:

$$\mathcal{A} = -T \ln Z, \quad Z = \prod_{\alpha} \left[1 + e^{-\omega_\alpha(\mathbf{x})/T}\right], \omega_\alpha(\mathbf{x}) = f(\mathbf{x})\alpha$$

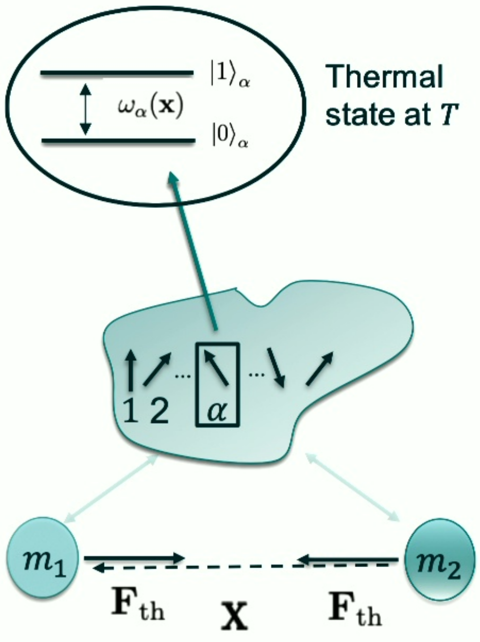
To compute convert the sum to an integral $\sum_\alpha \to \int d\alpha = \int d\omega / f(\mathbf{x})$

We find:

$$\mathcal{A} = -T \int_0^\infty \frac{d\omega}{f(\mathbf{x})} \ln(1 + e^{-\omega/T}) = -\frac{\pi^2}{12} \frac{T^2}{f(\mathbf{x})}$$

Thus, the two masses feel an *effective* force:

$$\mathbf{F}_{\text{th}} = -\nabla \mathcal{A} = \frac{\pi^2}{12} T^2 \nabla \left(\frac{1}{f(\mathbf{x})} \right)$$



Non-local model

$$\mathbf{F}_{\rm th} = -\nabla \mathcal{A} = \frac{\pi^2}{12} T^2 \nabla \left(\frac{1}{f(\mathbf{x})} \right) \quad , \quad \mathcal{A} = -\frac{\pi^2}{12} \frac{T^2}{f(\mathbf{x})}$$

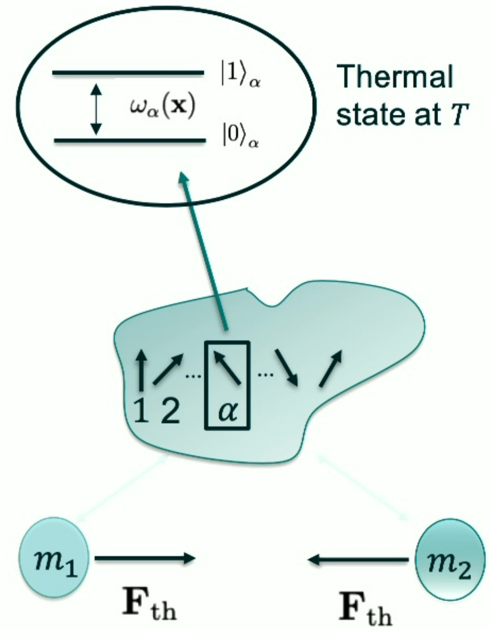
Let us **choose** $\frac{1}{f(\mathbf{x})} = \lambda + \frac{\ell^2}{|\mathbf{x}|}$, with λ, ℓ some microscopic parameters of the model.

We find the two masses feel an *effective* Newtonian force:

$$\mathbf{F}_{\rm th} = -\frac{\pi^2}{12} T^2 \ell^2 \frac{\hat{\mathbf{x}}}{|\mathbf{x}|^2} = -G_N m_1 m_2 \frac{\hat{\mathbf{x}}}{|\mathbf{x}|^2}$$

where we identified $$\boxed{\frac{\pi^2}{12} T^2 \ell^2 \equiv G_N m_1 m_2} \quad (1)$$

- We say that G_N "emerges" from the microscopic parameters T, ℓ.
- Eq. (1) fixes two free parameters in our model in terms of G_N and the two masses m_1, m_2 .



Local model

It is natural to ask: Is there a *local version* of the model?

Einstein gravity is local. Might be helpful step towards deriving GR this way.

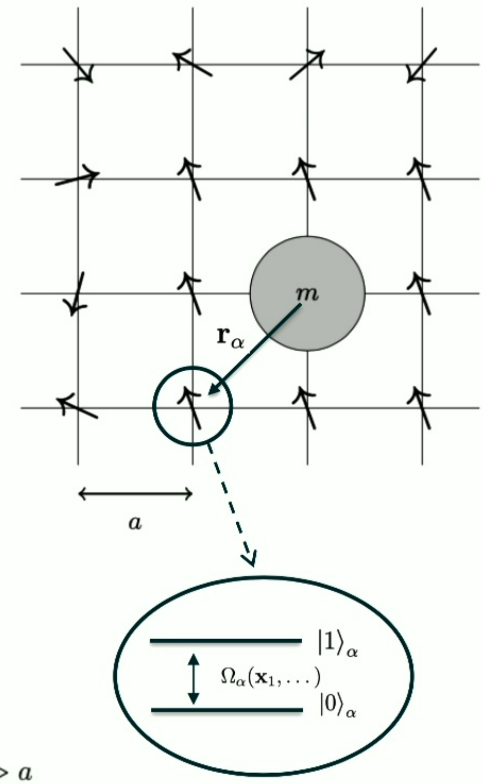
Yes there is.

The many-body mediator is still a collection of qubits.

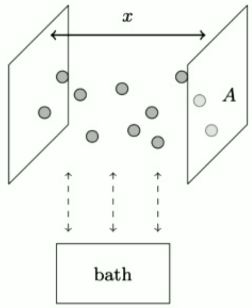
The qubits are now placed on a $\mathbf{3D}$ **lattice** of spacing a .

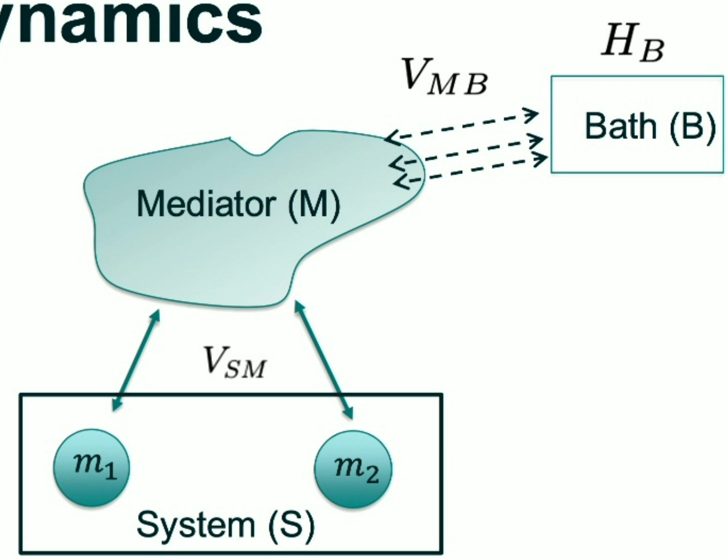
The frequency of each qubit decreases the further away it is located from the massive body.

We again find the free energy for two masses is $\mathcal{A} \approx \text{const.} - \frac{G_N m_1 m_2}{|\mathbf{x}|}, \quad |\mathbf{x}| \gg a$



Effective system dynamics





We want to find effective dynamics of the masses (S).

We can do this assuming the masses are **"slowly moving".**

In the piston-gas system imagine the pistons move slowly such the gas self thermalizes to the instantaneous position of the pistons.

In this *adiabatic* regime we can trace out both **the bath and mediator** [1].

[1] Wang-Taylor (2016)

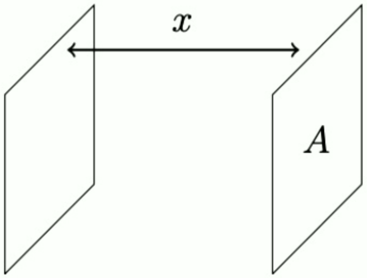
Lindblad for the masses

$$\dot{\rho}_S = -\frac{i}{\hbar}\left[H_{\text{eff}}, \rho_S\right] + \mathcal{L}(\rho_S)$$

System (S)

$$H_{\text{eff}} = \frac{\mathbf{p}_1^2}{2m_1} + \frac{\mathbf{p}_2^2}{2m_2} - \frac{G_N m_1 m_2}{|\mathbf{x}_1 - \mathbf{x}_2|}$$

$$\mathcal{L}(\rho_S) = \sum_{\alpha,\pm} K_{\alpha,\pm}\rho_S K^\dagger_{\alpha,\pm} - \frac{1}{2}\sum_{\alpha,\pm}\left\{K^\dagger_{\alpha,\pm}K_{\alpha,\pm}, \rho_S\right\}$$



$$K_{\alpha,+} = \zeta f_+(\omega_\alpha(\mathbf{x})) \quad , \quad K_{\alpha,-} = \frac{1}{\zeta} f_-(\omega_\alpha(\mathbf{x}))$$

, where ζ is dimensionless microscopic parameter ~ mediator thermalization rate/T.

The ζ and $\frac{1}{\zeta}$ structure implies minimal decoherence rate/noise for some ζ_*.

Experimental predictions/constraints

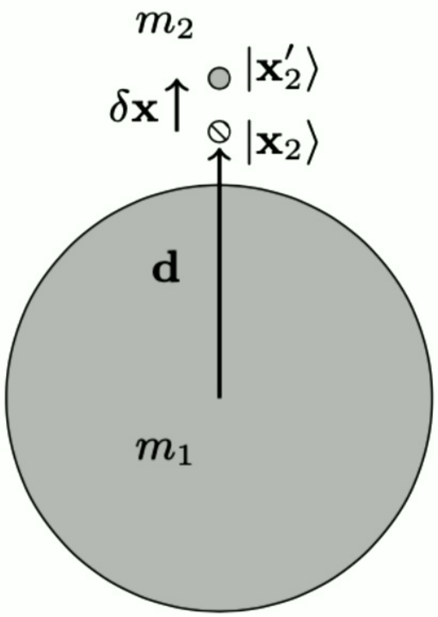
$$\dot{\rho}_S = -\frac{i}{\hbar}\left[H_{\text{eff}}, \rho\right] + \mathcal{L}(\rho_S)$$

Decoherence of spatial superpositions

$$|\psi\rangle = \frac{1}{\sqrt{2}} |\mathbf{x}_1\rangle \otimes (|\mathbf{x}_2\rangle + |\mathbf{x}_2'\rangle)$$

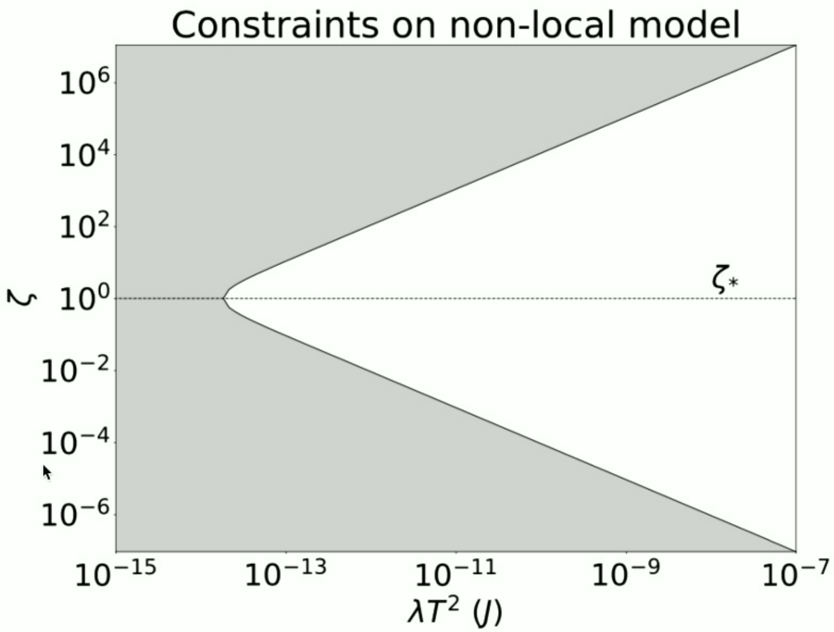
$$\rho(\mathbf{x}, \mathbf{x}', t) = e^{-\Gamma(\mathbf{x}, \mathbf{x}')t} \rho(\mathbf{x}, \mathbf{x}', 0)$$

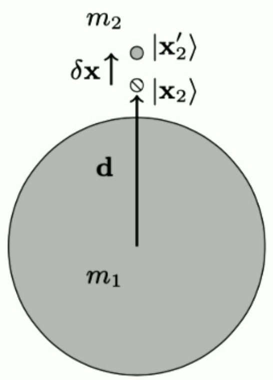
$$\Gamma \approx (\zeta + 1/\zeta) \frac{U_{\text{grav}}}{(1 + (\lambda T^2)/U_{\text{grav}})} \frac{\delta x^2}{d^2} \quad , \quad U_{\text{grav}} = \frac{G_N m_1 m_2}{d}$$



For example atom interferometers at Berkeley, Stanford, Fermilab, Europe, China

Decoherence of spatial superpositions





$$\Gamma \approx (\zeta + 1/\zeta)\frac{U_{\rm grav}}{(1+(\lambda T^2)/U_{\rm grav})}\frac{\delta x^2}{d^2} \quad , \quad U_{\rm grav} = \frac{G_N m_1 m_2}{d}$$

Parameter space excluded by experiments[(1)] using **cesium atoms $m_{Cs} = 133$ GeV** held in spatial superposition at a **scale $\delta x = 0.5\ m$** above the earth, with **coherence time ~seconds**. Shaded region corresponds to $\Gamma > 1$ Hz.

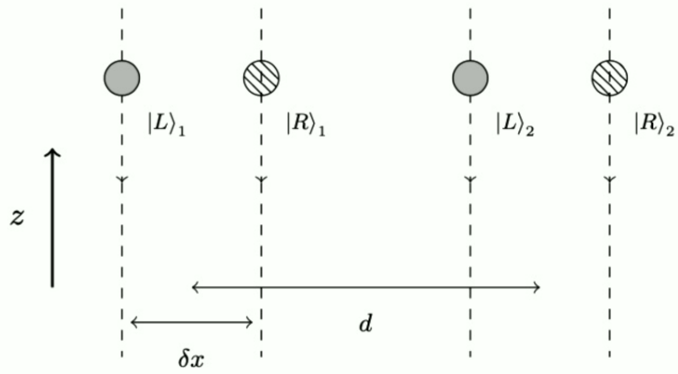
[(1)]Hogan et al (2015)

Entanglement generation between masses

Proposed by *Bose et al (2017)* such experiments aim to test whether gravitational interaction can entangle two massive bodies.

We prepare two masses in an initial product state:

$$|\psi(0)\rangle = \frac{1}{2}\left(|L\rangle + |R\rangle\right) \otimes \left(|L\rangle + |R\rangle\right)$$



We let the two masses fall for Δt . In ordinary perturbative quantum gravity the state evolves into an entangled state:

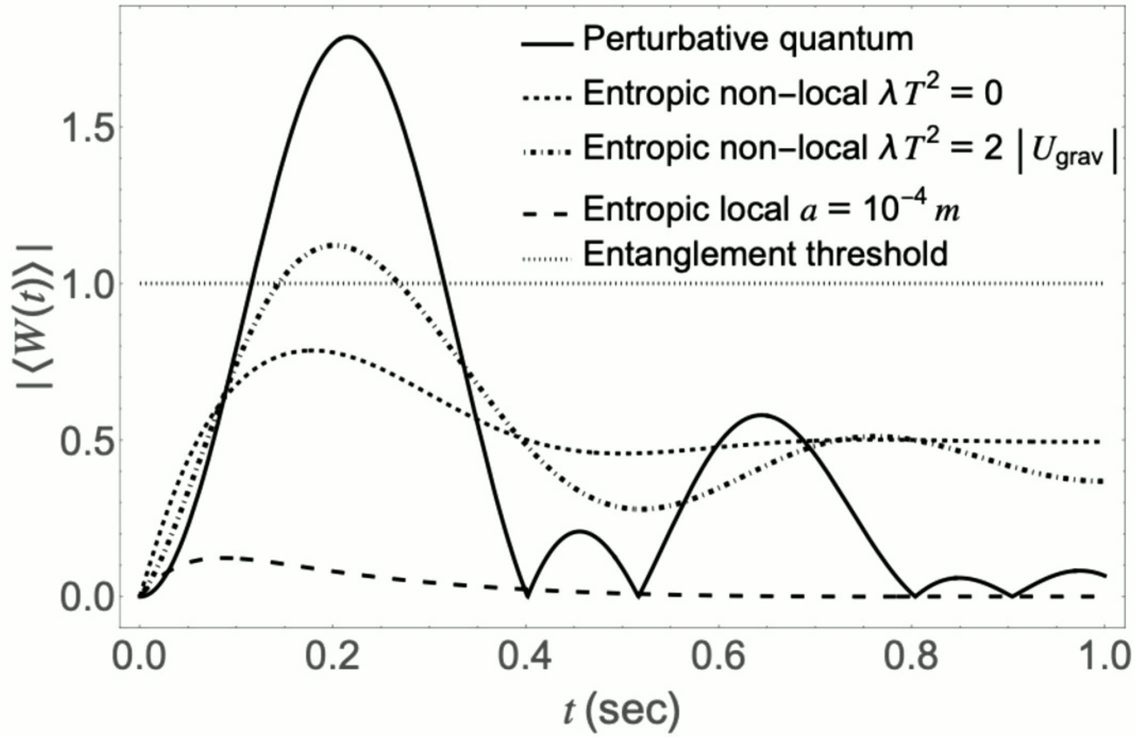
$$|\psi(\Delta t)\rangle = \frac{1}{2}\left(|LL\rangle + e^{i\phi_{LR}}\,|LR\rangle + e^{i\phi_{RL}}\,|RL\rangle + |RR\rangle\right)$$

To quantify this we can use the **entanglement witness** operator $W = X_1 \otimes Z_2 + Y_1 \otimes Y_2$

in the basis $|0\rangle := |L\rangle$, $|1\rangle := |R\rangle$

If you measure $|\langle W\rangle| > 1$ then the state is **definitely entangled** *(Terhal 20').*

Entanglement generation between masses



(surprise No.2)

Plot[1] for $m_1 = m_2 = 10^{-14}$ Kg, $\delta x = 250\,\mu$m , $d = 450\,\mu$m.

[1]Bose et al (2017)

Comments

Could this **actually** work?

A **relativistic version** of such construction (recover GR) is crucial.

Our point of view:

Entropic gravity is phenomenologically relevant for tabletop gravity experiments.

Future directions

- Non-local model: $\lambda \to \infty$ limit?
- Self-thermalizing qubits?
- Interaction between qubits. Can we get waves?
- Is there some generic classification of such entropic models?
- Beyond gravity : Could we see the effective "piston dynamics" in the lab?

Thank you!