**Title:** What gravity induced entanglement can tell us about gravity

**Speakers:** Eduardo Martin-Martinez

**Collection/Series:** Quantum Gravity

**Subject:** Quantum Gravity

**Date:** February 24, 2025 - 3:00 PM

**URL:** https://pirsa.org/25020029

**Abstract:**

In this talk, we will explore what low-energy experiments on gravitationally mediated entanglement (GME) can reveal about the quantum nature of gravity. We will analyze the key assumptions necessary to interpret GME experiments as evidence for quantum aspects of the gravitational interaction and examine how these assumptions influence our conclusions. Additionally, we will discuss possible modifications to experimental designs aimed at minimizing dependence on assumptions. Then we will discuss what these experiments in different regimes can and cannot probe about gravity's quantum nature.

# What gravity mediated entanglement can tell us about quantum gravity

Phys. Rev. D 108, L101702 (2023)
Phys. Rev. A 107, 042612 (2023)
arXiv:2412.16288

Work in Collaboration with T. Rick Perche, E. Telali

Perimeter QG seminar

barrio-RQI.org

Eduardo Martín-Martínez
Department of Applied Mathematics (University of Waterloo)
Inst. for Quantum Computing
Perimeter Institute for Theoretical Physics

T(ales) Rick Perche

Eirini Telali

## What gravity mediated entanglement can really tell us about quantum gravity

Eduardo Martín-Martínez[1, 2, 3, *] and T. Rick Perche[1, 2, 3, †]

[1] *Department of Applied Mathematics, University of Waterloo, Waterloo, Ontario, N2L 3G1, Canada*
[2] *Perimeter Institute for Theoretical Physics, Waterloo, Ontario, N2L 2Y5, Canada*
[3] *Institute for Quantum Computing, University of Waterloo, Waterloo, Ontario, N2L 3G1, Canada*

## The role of quantum degrees of freedom of relativistic fields in quantum information protocols

T. Rick Perche[1, 2, 3, *] and Eduardo Martín-Martínez[1, 2, 3, †]

[1] *Department of Applied Mathematics, University of Waterloo, Waterloo, Ontario, N2L 3G1, Canada*
[2] *Perimeter Institute for Theoretical Physics, Waterloo, Ontario, N2L 2Y5, Canada*
[3] *Institute for Quantum Computing, University of Waterloo, Waterloo, Ontario, N2L 3G1, Canada*

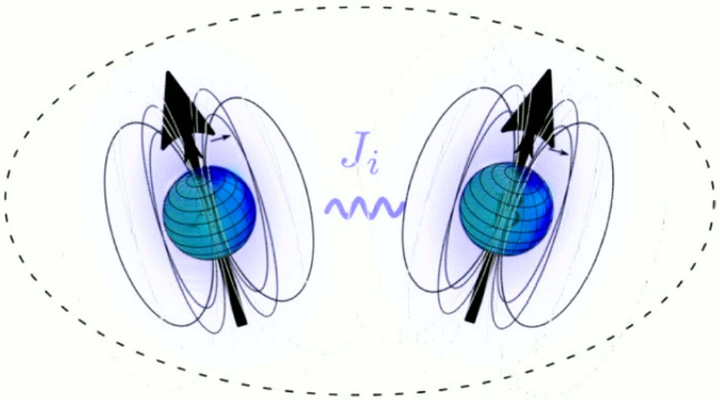
## Causality in relativistic quantum interactions without mediators

Eirini Telali,[1, 2, *] T. Rick Perche,[1, 3, 4, †] and Eduardo Martín-Martínez[1, 3, 4, ‡]

[1] *Perimeter Institute for Theoretical Physics, Waterloo, Ontario, N2L 2Y5, Canada*
[2] *Department of Physics and Astronomy, University of Waterloo, Waterloo, Ontario, N2L 3G1, Canada*
[3] *Department of Applied Mathematics, University of Waterloo, Waterloo, Ontario, N2L 3G1, Canada*
[4] *Institute for Quantum Computing, University of Waterloo, Waterloo, Ontario, N2L 3G1, Canada*

# Two levels of "quantum" fields

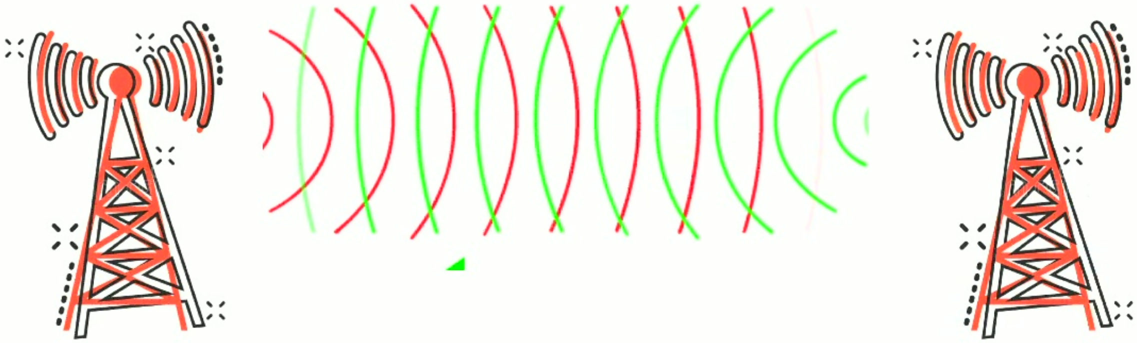
$$\hat{H}_{\text{int}} = J\hat{\boldsymbol{\sigma}}_{\text{A}} \cdot \hat{\boldsymbol{\sigma}}_{\text{B}} = -\frac{1}{2}\left(\hat{\boldsymbol{\mu}}_{\text{A}} \cdot \boldsymbol{B}_{\text{B}}(\hat{\boldsymbol{r}}_{\text{A}}) + \hat{\boldsymbol{\mu}}_{\text{B}} \cdot \boldsymbol{B}_{\text{A}}(\hat{\boldsymbol{r}}_{\text{B}})\right)$$




$$\hat{H}_{\text{int}} = -\frac{1}{2}\Big(\hat{\boldsymbol{\mu}}_{\text{A}} \cdot \hat{\boldsymbol{B}}(t, \boldsymbol{x}) + \hat{\boldsymbol{\mu}}_{\text{B}} \cdot \hat{\boldsymbol{B}}(t, \boldsymbol{x})\Big)$$

IN BOTH CASES WE CAN PUT SOURCES IN SUPERPOSITIONS OF POSITION

# Reviewing Classical Field Theory: Two emitters coupled to a scalar field



# Reviewing Classical Field Theory: Two emitters coupled to a scalar field

$$H(t) = H_{\rm A}(t) + H_{\rm B}(t) + \frac{\lambda}{2}\int \mathrm{d}^3\boldsymbol{x}\left(j^{(\rm A)}(\mathsf{x})\phi_{\rm B}(\mathsf{x}) + j^{(\rm B)}(\mathsf{x})\phi_{\rm A}(\mathsf{x})\right)$$

$$\phi_{\rm I}(\mathsf{x}) = \int \mathrm{d}V' G_R(\mathsf{x},\mathsf{x}') j^{(\rm I)}(\mathsf{x}')$$ Field Sourced by I-th emitter

$$G_R(\mathsf{x},\mathsf{x}') = -\frac{1}{4\pi}\delta\left(-(t-t')^2 + (\boldsymbol{x}-\boldsymbol{x}')^2\right)\theta(t-t'),$$

# Reviewing Classical Field Theory: Two emitters coupled to a scalar field

$$H(t) = H_{\mathrm{A}}(t) + H_{\mathrm{B}}(t) + \frac{\lambda}{2}\int \mathrm{d}^3\boldsymbol{x}\,\Big(j^{(\mathrm{A})}(\mathsf{x})\phi_{\mathrm{B}}(\mathsf{x}) + j^{(\mathrm{B})}(\mathsf{x})\phi_{\mathrm{A}}(\mathsf{x})\Big)$$

$$\phi_{\mathrm{I}}(\mathsf{x}) = \int \mathrm{d}V' G_R(\mathsf{x},\mathsf{x}')j^{(\mathrm{I})}(\mathsf{x}')$$ Field Sourced by I-th emitter

$$G_R(\mathsf{x},\mathsf{x}') = -\frac{1}{4\pi}\delta\left(-(t-t')^2 + (\boldsymbol{x}-\boldsymbol{x}')^2\right)\theta(t-t'),$$

Two pointlike sources on trajectories $\boldsymbol{z}_{\mathrm{I}}(t)$

$$j^{(\mathrm{I})}(\mathsf{x}) = \lambda\mu_{\mathrm{I}}(t)\delta^{(3)}(\boldsymbol{x}-\boldsymbol{z}_{\mathrm{I}}(t))$$

# Reviewing Classical Field Theory: Two emitters coupled to a scalar field

$$H(t) = H_{\rm A}(t) + H_{\rm B}(t) + \frac{\lambda}{2}\int \mathrm{d}^3\boldsymbol{x}\left(j^{(\rm A)}(\mathsf{x})\phi_{\rm B}(\mathsf{x}) + j^{(\rm B)}(\mathsf{x})\phi_{\rm A}(\mathsf{x})\right)$$

$$\phi_{\rm I}(\mathsf{x}) = \int \mathrm{d}V' G_R(\mathsf{x},\mathsf{x}')j^{(\rm I)}(\mathsf{x}')$$ Field Sourced by I-th emitter

$$G_R(\mathsf{x},\mathsf{x}') = -\frac{1}{4\pi}\delta\left(-(t-t')^2 + (\boldsymbol{x}-\boldsymbol{x}')^2\right)\theta(t-t'),$$

Two pointlike sources on trajectories $\boldsymbol{z}_{\rm I}(t)$ $\quad j^{(\rm I)}(\mathsf{x}) = \lambda\mu_{\rm I}(t)\delta^{(3)}(\boldsymbol{x}-\boldsymbol{z}_{\rm I}(t))$

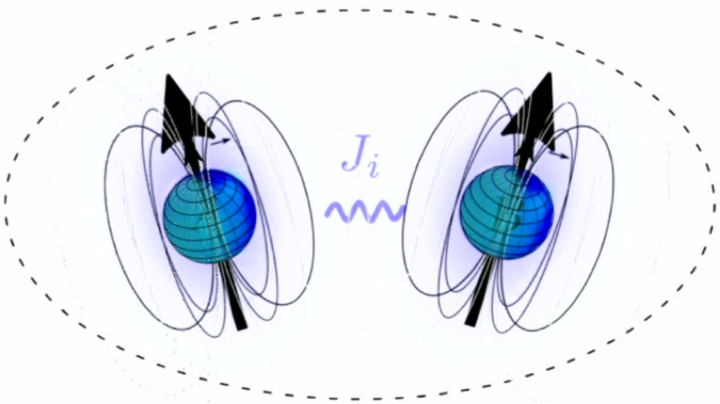
$$H_{\rm int}(t) = \frac{\lambda^2}{2}\int \mathrm{d}t'\big(\mu_{\rm A}(t)\mu_{\rm B}(t')G_R(\mathsf{z}_{\rm A}(t),\mathsf{z}_{\rm B}(t')) + \mu_{\rm B}(t)\mu_{\rm A}(t')G_R(\mathsf{z}_{\rm B}(t),\mathsf{z}_{\rm A}(t'))\big)$$

$$\int \mathrm{d}t\, H_{\rm int}(t) = \frac{\lambda^2}{2}\int \mathrm{d}t\mathrm{d}t'\mu_{\rm A}(t)\mu_{\rm B}(t')\Delta(\mathsf{z}_{\rm A}(t),\mathsf{z}_{\rm B}(t'))$$

# Reviewing Classical Field Theory: Two emitters coupled to a scalar field

$$\int \mathrm{d}t\, H_{\mathrm{int}}(t) = \frac{\lambda^2}{2}\int \mathrm{d}t\mathrm{d}t'\mu_{\mathrm{A}}(t)\mu_{\mathrm{B}}(t')\Delta(\mathsf{z}_{\mathrm{A}}(t),\mathsf{z}_{\mathrm{B}}(t'))$$

$$\Delta(\mathsf{x},\mathsf{x}') = G_R(\mathsf{x},\mathsf{x}') + G_A(\mathsf{x},\mathsf{x}')$$

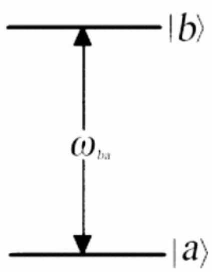


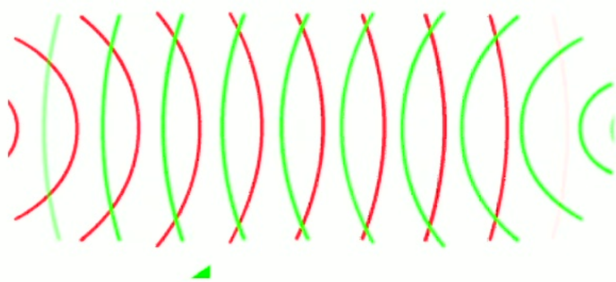
# What if the emitters are quantum?

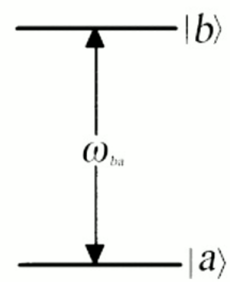
$$\hat{H}(t) = \hat{H}_{\mathrm{A}}(t) + \hat{H}_{\mathrm{B}}(t) + \frac{\lambda}{2}\int \mathrm{d}^3\boldsymbol{x}\,\Big(\hat{j}_{\mathrm{A}}(\mathsf{x})\hat{\phi}^{\mathrm{qc}}_{\mathrm{B}}(\mathsf{x}) + \hat{j}_{\mathrm{B}}(\mathsf{x})\hat{\phi}^{\mathrm{qc}}_{\mathrm{A}}(\mathsf{x})\Big)$$

$$\hat{\phi}^{\mathrm{qc}}_{\mathrm{I}}(\mathsf{x}) = \int \mathrm{d}V' G_R(\mathsf{x},\mathsf{x}')\hat{j}_{\mathrm{I}}(\mathsf{x}') \qquad j^{(\mathrm{I})} \to \hat{j}_{\mathrm{I}}$$

$$\hat{j}_{\mathrm{I}}(\mathsf{x}) = \lambda\hat{\mu}_{\mathrm{I}}(t)\delta^{(3)}(\boldsymbol{x}' - \boldsymbol{z}_{\mathrm{I}}(t))$$





# What if the emitters are quantum?

$$\hat{H}(t) = \hat{H}_{\mathrm{A}}(t) + \hat{H}_{\mathrm{B}}(t) + \frac{\lambda}{2}\int \mathrm{d}^3\boldsymbol{x}\left(\hat{j}_{\mathrm{A}}(\mathsf{x})\hat{\phi}^{\mathrm{qc}}_{\mathrm{B}}(\mathsf{x}) + \hat{j}_{\mathrm{B}}(\mathsf{x})\hat{\phi}^{\mathrm{qc}}_{\mathrm{A}}(\mathsf{x})\right)$$

$$\hat{\phi}^{\mathrm{qc}}_{\mathrm{I}}(\mathsf{x}) = \int \mathrm{d}V' G_R(\mathsf{x},\mathsf{x}')\hat{j}_{\mathrm{I}}(\mathsf{x}') \qquad j^{(\mathrm{I})} \to \hat{j}_{\mathrm{I}}$$

$$\hat{j}_{\mathrm{I}}(\mathsf{x}) = \lambda\hat{\mu}_{\mathrm{I}}(t)\delta^{(3)}(\boldsymbol{x}' - \boldsymbol{z}_{\mathrm{I}}(t))$$

$$\int \mathrm{d}t\,\hat{H}_{\mathrm{int}}(t) = \frac{\lambda^2}{2}\int \mathrm{d}t\mathrm{d}t'\hat{\mu}_{\mathrm{A}}(t)\hat{\mu}_{\mathrm{B}}(t')\Delta(\mathsf{z}_{\mathrm{A}}(t),\mathsf{z}_{\mathrm{B}}(t'))$$

$$\hat{U} = \mathcal{T}\exp\left(-\mathrm{i}\int \mathrm{d}t\hat{H}_{\mathrm{int}}(t)\right) = \mathbb{1} - \mathrm{i}\int \mathrm{d}t\hat{H}_{\mathrm{int}}(t) + \mathcal{O}(\lambda^4).$$

# How does this compare to QFT

$$\hat{H}^{\text{qc}}_{\text{int}}(t) = \frac{\lambda}{2}\int \mathrm{d}^3\boldsymbol{x}\,\Big(\hat{j}_{\mathrm{A}}(\mathsf{x})\hat{\phi}^{\text{qc}}_{\mathrm{B}}(\mathsf{x}) + \hat{j}_{\mathrm{B}}(\mathsf{x})\hat{\phi}^{\text{qc}}_{\mathrm{A}}(\mathsf{x})\Big)$$

$$\hat{\phi}^{\text{qc}}_{\mathrm{I}}(\mathsf{x}) = \int \mathrm{d}V' G_R(\mathsf{x},\mathsf{x}')\hat{j}_{\mathrm{I}}(\mathsf{x}') \quad \hat{j}_{\mathrm{I}}(\mathsf{x}) = \lambda\hat{\mu}_{\mathrm{I}}(t)\delta^{(3)}(\boldsymbol{x}' - \boldsymbol{z}_{\mathrm{I}}(t))$$

VS

$$\hat{H}_{\text{int}}(t) = \lambda\left(\int \mathrm{d}^n\boldsymbol{x}\Lambda_{\mathrm{A}}(\mathsf{x})\hat{\mu}_{\mathrm{A}}(t)\hat{\phi}(\mathsf{x}) + \int \mathrm{d}^n\boldsymbol{x}\Lambda_{\mathrm{B}}(\mathsf{x})\hat{\mu}_{\mathrm{B}}(t)\hat{\phi}(\mathsf{x})\right)$$

$$\left[\hat{\phi}(\mathsf{x}), \hat{\phi}(\mathsf{x}')\right] = \mathrm{i}\, E(\mathsf{x},\mathsf{x}')$$

Implements the dynamics and commutation relations.

# How does this compare to QFT

Consider two Unruh-DeWitt detectors

$$\hat{\mu}_{\rm I}(t) = \chi_{\rm I}(\tau)[e^{{\rm i}\Omega t}\hat{\sigma}_{\rm I}^{+} + e^{-{\rm i}\Omega t}\hat{\sigma}_{\rm I}^{-}]$$

Both initially in their ground states

Time evolution

Quantum Field Theory model (with field in vacuum)
Vs
Quantum Controlled model

# Comparing Quantum Fields and qc-fields

These are the results for the quantum and quantum controlled cases:

***Quantum*** (mixed state)

$$\hat{\rho}_{\mathrm{D}} = \begin{pmatrix} 1-\mathcal{L}_{\mathrm{AA}}-\mathcal{L}_{\mathrm{BB}} & 0 & 0 & \mathcal{M}^* \\ 0 & \mathcal{L}_{\mathrm{AA}} & \mathcal{L}_{\mathrm{AB}} & 0 \\ 0 & \mathcal{L}_{\mathrm{AB}}^* & \mathcal{L}_{\mathrm{BB}} & 0 \\ \mathcal{M} & 0 & 0 & 0 \end{pmatrix}$$

***Quantum-Controlled*** (pure state)

$$\hat{\rho}_{\mathrm{C}} = \begin{pmatrix} 1-|\mathcal{M}_{\mathrm{C}}|^2 & 0 & 0 & \mathcal{M}_{\mathrm{C}}^* \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ \mathcal{M}_{\mathrm{C}} & 0 & 0 & |\mathcal{M}_{\mathrm{C}}|^2 \end{pmatrix}$$

$$\mathcal{L}_{\mathrm{IJ}} = \lambda^2 \int \mathrm{d}t\mathrm{d}t' \chi_{\mathrm{I}}(t)\chi_{\mathrm{J}}(t') e^{-\mathrm{i}\Omega(t-t')} W(\mathsf{z}_{\mathrm{I}}(t), \mathsf{z}_{\mathrm{J}}(t'))$$

$$\mathcal{M} = -\lambda^2 \int \mathrm{d}t\mathrm{d}t' \chi_{\mathrm{A}}(t)\chi_{\mathrm{B}}(t') e^{\mathrm{i}\Omega(t+t')} G_F(\mathsf{z}_{\mathrm{A}}(t), \mathsf{z}_{\mathrm{B}}(t'))$$

$$\mathcal{M}_{\mathrm{C}} = -\lambda^2 \int \mathrm{d}t\mathrm{d}t' \chi_{\mathrm{A}}(t)\chi_{\mathrm{B}}(t') e^{\mathrm{i}\Omega(t+t')} \frac{\mathrm{i}}{2} \Delta(\mathsf{z}_{\mathrm{A}}(t), \mathsf{z}_{\mathrm{B}}(t'))$$

## Quantum Field Theory

Many Predictions of the theory (as we will see) can be written in terms of the **Wightman function** and the **Feynman propagator**:

state independent

$$W(\mathsf{x},\mathsf{x}') = \langle \hat{\phi}(\mathsf{x})\hat{\phi}(\mathsf{x}')\rangle_\omega = \frac{\mathrm{i}}{2}E(\mathsf{x},\mathsf{x}') + \frac{1}{2}H(\mathsf{x},\mathsf{x}')$$

$$G_F(\mathsf{x},\mathsf{x}') = \langle \mathcal{T}\hat{\phi}(\mathsf{x})\hat{\phi}(\mathsf{x}')\rangle_\omega = \frac{\mathrm{i}}{2}\Delta(\mathsf{x},\mathsf{x}') + \frac{1}{2}H(\mathsf{x},\mathsf{x}')$$

state independent

state dependent terms

[1] Advances in Algebraic Quantum Field Theory, edited by R. Brunetti, C. Dappiaggi, K. Fredenhagen, and J. Yngvason (Springer International Publishing, Cham, 2015)

# Not only perturbative

QFT:

$$Z\left[J_{\mathrm{A}}, J_{\mathrm{B}}, J\right] = \int \mathcal{D}\psi_{\mathrm{A}} \mathcal{D}\psi_{\mathrm{B}} \mathcal{D}\phi \, e^{iS_{\psi_{\mathrm{A}}}} e^{iS_{\psi_{\mathrm{B}}}} e^{iS_{\phi}^{(0)}} e^{i\int \mathrm{d}V \, \phi(\mathsf{x})(\psi_{\mathrm{A}}(\mathsf{x})+\psi_{\mathrm{B}}(\mathsf{x})+J(\mathsf{x}))}$$

$$Z\left[J_{\mathrm{A}}, J_{\mathrm{B}}, J\right] = \int \mathcal{D}\psi_{\mathrm{A}} \mathcal{D}\psi_{\mathrm{B}} \, e^{iS_{\psi_{\mathrm{A}}}} e^{iS_{\psi_{\mathrm{B}}}} \exp\left[\frac{\mathrm{i}}{2}\int \mathrm{d}V \mathrm{d}V' J_{\mathrm{tot}}(\mathsf{x}) \Delta_F(\mathsf{x},\mathsf{x}') J_{\mathrm{tot}}(\mathsf{x}')\right].$$

How to obtain the QC model:

$$J(\mathsf{x}) \mapsto 0$$

$$\Delta_F(\mathsf{x},\mathsf{x}') \mapsto -\frac{1}{2}\Delta(\mathsf{x},\mathsf{x}')$$

$$Z_{\mathrm{QC}}\left[J_{\mathrm{A}}, J_{\mathrm{B}}\right] = \int \mathcal{D}\psi_{\mathrm{A}} \mathcal{D}\psi_{\mathrm{B}} \, e^{iS_{\psi_{\mathrm{A}}}} e^{iS_{\psi_{\mathrm{B}}}} \exp\left[-\frac{\mathrm{i}}{2}\int \mathrm{d}V \mathrm{d}V' \psi_{\mathrm{A}}(\mathsf{x}) \Delta(\mathsf{x},\mathsf{x}') \psi_{\mathrm{B}}(\mathsf{x}')\right]$$

# Comparing Quantum Fields and qc-fields

These are the results for the quantum and quantum controlled cases:

**Quantum** (mixed state)

$$\hat\rho_{\rm D} = \begin{pmatrix} 1-\mathcal{L}_{\rm AA}-\mathcal{L}_{\rm BB} & 0 & 0 & \mathcal{M}^* \\ 0 & \mathcal{L}_{\rm AA} & \mathcal{L}_{\rm AB} & 0 \\ 0 & \mathcal{L}_{\rm AB}^* & \mathcal{L}_{\rm BB} & 0 \\ \mathcal{M} & 0 & 0 & 0 \end{pmatrix}$$

**Quantum-Controlled** (pure state)

$$\hat\rho_{\rm C} = \begin{pmatrix} 1-|\mathcal{M}_{\rm C}|^2 & 0 & 0 & \mathcal{M}_{\rm C}^* \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ \mathcal{M}_{\rm C} & 0 & 0 & |\mathcal{M}_{\rm C}|^2 \end{pmatrix}$$

$$\mathcal{L}_{\rm IJ} = \lambda^2 \int {\rm d}t{\rm d}t' \chi_{\rm I}(t)\chi_{\rm J}(t') e^{-{\rm i}\Omega(t-t')} W(\mathsf{z}_{\rm I}(t), \mathsf{z}_{\rm J}(t'))$$

$$W(\mathsf{x},\mathsf{x}') = \frac{\rm i}{2}\cancel{E(\mathsf{x},\mathsf{x}')} + \frac{1}{2}\cancel{H(\mathsf{x},\mathsf{x}')}$$

$$\mathcal{M} = -\lambda^2 \int {\rm d}t{\rm d}t' \chi_{\rm A}(t)\chi_{\rm B}(t') e^{{\rm i}\Omega(t+t')} G_F(\mathsf{z}_{\rm A}(t), \mathsf{z}_{\rm B}(t'))$$

$$G_F(\mathsf{x},\mathsf{x}') = \frac{\rm i}{2}\Delta(\mathsf{x},\mathsf{x}') + \frac{1}{2}\cancel{H(\mathsf{x},\mathsf{x}')}$$

$$\mathcal{M}_{\rm C} = -\lambda^2 \int {\rm d}t{\rm d}t' \chi_{\rm A}(t)\chi_{\rm B}(t') e^{{\rm i}\Omega(t+t')} \frac{\rm i}{2}\Delta(\mathsf{z}_{\rm A}(t), \mathsf{z}_{\rm B}(t'))$$

# Predictions of the two models

Very similar: QC approximates QFT

Except:
- In spacelike separation
- In less-than-twice light crossing time between sources

Notice that both models are relativistic and (spacetime) local!

Very similar: QC approximates QFT

# Predictions of the two models

$$\hat{H}^{\text{qc}}_{\text{int}}(t) = \frac{\lambda}{2}\int \mathrm{d}^3\boldsymbol{x}\left(\hat{j}_{\text{A}}(\mathsf{x})\hat{\phi}^{\text{qc}}_{\text{B}}(\mathsf{x}) + \hat{j}_{\text{B}}(\mathsf{x})\hat{\phi}^{\text{qc}}_{\text{A}}(\mathsf{x})\right)$$

$$\hat{\phi}^{\text{qc}}_{\text{I}}(\mathsf{x}) = \int \mathrm{d}V' G_R(\mathsf{x},\mathsf{x}')\hat{j}_{\text{I}}(\mathsf{x}') \quad \hat{j}_{\text{I}}(\mathsf{x}) = \lambda\hat{\mu}_{\text{I}}(t)\delta^{(3)}(\boldsymbol{x}' - \boldsymbol{z}_{\text{I}}(t))$$

**VS**

$$\hat{H}_{\text{int}}(t) = \lambda\left(\int \mathrm{d}^n\boldsymbol{x}\Lambda_{\text{A}}(\mathsf{x})\hat{\mu}_{\text{A}}(t)\hat{\phi}(\mathsf{x}) + \int \mathrm{d}^n\boldsymbol{x}\Lambda_{\text{B}}(\mathsf{x})\hat{\mu}_{\text{B}}(t)\hat{\phi}(\mathsf{x})\right)$$

Notice that both models are relativistic and (spacetime) local!

# Gravity Mediated Entanglement (GME)

# A table-top experiment for QG?

Observation:

Quantum matter interacts gravitationally!

# A table-top experiment for QG?

We know that hybrid models are inconsistent:

D. R. Terno,
**Inconsistency of quantum—classical dynamics, and what it implies,**
Found. Phys. 36, 102 (2006).

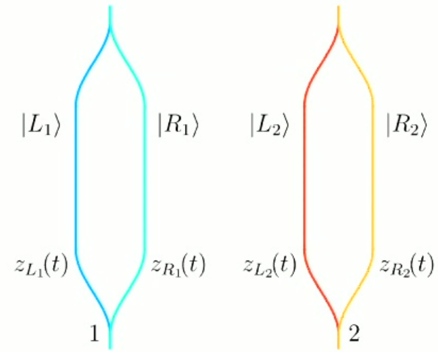
C. Barceló, R. Carballo-Rubio, L. J. Garay, and R. Gómez-Escalante,
**Hybrid classical-quantum formulations ask for hybrid notions.**
Phys. Rev. A 86, 042120 (2012)

What would we learn from a tabletop quantum gravity experiment?

# The BMV experiment

**A Spin Entanglement Witness for Quantum Gravity**

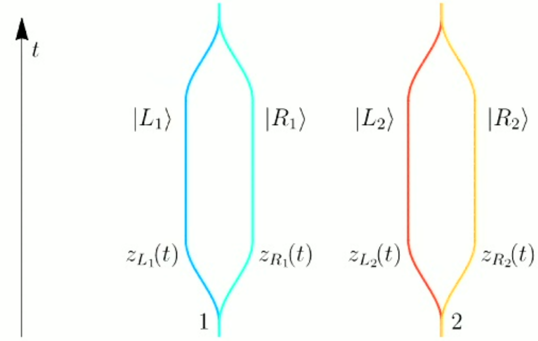
Sougato Bose,[1] Anupam Mazumdar,[2] Gavin W. Morley,[3] Hendrik Ulbricht,[4] Marko Toroš,[4] Mauro Paternostro,[5] Andrew Geraci,[6] Peter Barker,[1] M. S. Kim,[7] and Gerard Milburn[7,8]




**Gravitationally-induced entanglement between two massive particles is sufficient evidence of quantum effects in gravity**

C. Marletto[a] and V. Vedral [a,b]

# 1/r Potential can entangle



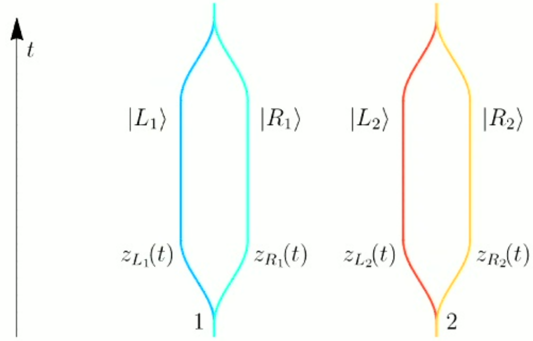

$$\hat{\phi} = \frac{Gm_1m_2}{\hat{r}}$$

$$|\Psi(t=0)\rangle_{12} = \frac{1}{\sqrt{2}}(|L\rangle_1 + |R\rangle_1)\frac{1}{\sqrt{2}}(|L\rangle_2 + |R\rangle_2)$$

$$|\Psi(t=\tau)\rangle_{12} = \frac{e^{i\phi}}{\sqrt{2}}\left\{|L\rangle_1 \frac{1}{\sqrt{2}}(|L\rangle_2 + e^{i\Delta\phi_{LR}}|R\rangle_2) + |R\rangle_1 \frac{1}{\sqrt{2}}(e^{i\Delta\phi_{RL}}|L\rangle_2 + |R\rangle_2)\right\}$$

Bose et al. PRL 119, 240401 (2017)

# 1/r Potential can entangle




$$\hat{\phi} = \frac{Gm_1m_2}{\hat{r}}$$

If the experiment reveals entanglement between the masses:

1-LOCC does not increase the entanglement between quantum systems.

2-Thus, if the masses interact only gravitationally and get entangled, the gravitational field which mediates the interaction is going beyond 'CC'.

Bose et al. PRL 119, 240401 (2017)

# 1/r Potential can entangle

$$\hat{\phi} = \frac{Gm_1 m_2}{\hat{r}}$$

1-LOCC does not increase the entanglement between quantum systems.

2-Thus, if the masses interact only gravitationally and get entangled, the gravitational field which mediates the interaction is going beyond 'CC'.

3-Hence the field cannot be classical since it establishes a quantum channel.

If a third system locally mediates interaction between systems 1 and 2 and 1 and 2 can get entangled, the intermediary system has to be quantum.

Marletto and Vedral, Phys. Rev. D, 102 086012 (2020)

Marletto and Vedral, Phys. Rev. Lett., 119, 240402 (2020)

# 1/r Potential can entangle

$$\hat{\phi} = \frac{Gm_1 m_2}{\hat{r}}$$

1-LOCC does not increase the entanglement between quantum systems.

2-Thus, if the masses interact only gravitationally and get entangled, the gravitational field which mediates the interaction is going beyond 'CC'.

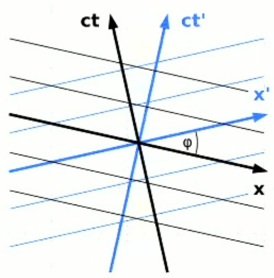
3-Hence the field cannot be classical since it establishes a quantum channel.

If a third system locally mediates interaction between systems 1 and 2 and 1 and 2 can get entangled, the intermediary system has to be quantum.

But is gravity an intermediary system? Am I making a hidden assumption?

# Two notions of locality

**Event Locality**: Operations happen at events in spacetime, and do not affect other events which are causally disconnected from them.



# 1/r Potential can entangle

The interaction can be system non-local and yet relativistically local!!

**Mass 1 couples to the field and then the field carries quantum information to mass 2, or otherwise we would have non locality or action-at-a-distance.**

This statement assumes much more than Lorentz Invariance!!!

It assumes the existence of local degrees of freedom for the field

# An event local interaction that is not system local (QC-field)

Consider first weak gravity:

$$g_{\mu\nu} = \eta_{\mu\nu} + \sqrt{16\pi G}\, h_{\mu\nu}$$

$$h^{\mu\nu}(\mathsf{x}) = \sqrt{4\pi G} \int \mathrm{d}V' G_{R\ \alpha'\beta'}^{\mu\nu}(\mathsf{x},\mathsf{x}') T^{\alpha'\beta'}(\mathsf{x}')$$

Couple a small mass to it:

$$T_{p_i}^{\mu\nu}(\mathsf{x}) = m_i\, u_{p_i}^{\mu}(t) u_{p_i}^{\nu}(t) \frac{\delta^{(3)}(\boldsymbol{x} - \boldsymbol{z}_{p_i}(t))}{u_{p_i}^{0}(t)\sqrt{-g}}$$

What about two masses in some quantum superposition as in BMV?

# An event local interaction that is not system local (QC-field)

Let us prescribe the interaction as associating to each state of the particles the classical field sourced by each particle undergoing each path.

$$\hat{H}_I(t) = \sum_{\substack{p_1\in\{L_1,R_1\}\\ p_2\in\{L_2,R_2\}}} \Phi_{p_1p_2}(t)\,|p_1p_2\rangle\langle p_1p_2|$$

$$\hat{U}_I = \exp\left(-\mathrm{i}\int \mathrm{d}t\,\hat{H}_I(t)\right) = \sum_{\substack{p_1\in\{L_1,R_1\}\\ p_2\in\{L_2,R_2\}}} e^{2\pi\mathrm{i}G\Delta_{p_1p_2}}\,|p_1p_2\rangle\langle p_1p_2|$$

$$\Delta_{p_1p_2} := \int \mathrm{d}V\,\mathrm{d}V' T^{\mu\nu}_{p_1}(\mathsf{x})\Delta_{\mu\nu\alpha'\beta'}(\mathsf{x},\mathsf{x}')T^{\alpha'\beta'}_{p_2}(\mathsf{x}')$$

$$\Delta^{\mu\nu\alpha'\beta'}(\mathsf{x},\mathsf{x}') = \left(G_R^{\mu\nu\alpha'\beta'}(\mathsf{x},\mathsf{x}') + G_A^{\mu\nu\alpha'\beta'}(\mathsf{x},\mathsf{x}')\right)$$

It recovers the Newtonian interaction in the non-relativistic limit $\hat{\phi} = \dfrac{Gm_1m_2}{\hat{r}}$

# An event local interaction that is not system local (QC-field)

Let us prescribe the interaction as associating to each state of the particles the classical field sourced by each particle undergoing each path.

$$\hat{H}_I(t) = \sum_{\substack{p_1 \in \{L_1, R_1\} \\ p_2 \in \{L_2, R_2\}}} \Phi_{p_1 p_2}(t) \, |p_1 p_2\rangle\langle p_1 p_2|$$

Under this evolution the system of two masses evolves to an entangled state

$$\begin{aligned} \mathcal{N}_{\mathrm{C}} &= \frac{1}{2} \sin\Big(\pi G \Big| \Delta_{L_1 L_2} + \Delta_{R_1 R_2} - \Delta_{L_1 R_2} - \Delta_{R_1 L_2} \Big|\Big) \\ &= \frac{\pi G}{2} \Big| \Delta_{L_1 L_2} + \Delta_{R_1 R_2} - \Delta_{L_1 R_2} - \Delta_{R_1 L_2} \Big| + \mathcal{O}(G^2). \end{aligned}$$

# An event local interaction that is not system local (QC-field)

This evolution establishes a quantum channel between the masses:
It gets them entangled.

However the field has no quantum degrees of freedom!

Finding entanglement on the masses through their gravitational interaction
Does not mean gravity has local quantum degrees of freedom

The interaction is not system-local. But the interaction is event local:
No signalling

An interaction establishing a quantum channel does not mean that it is mediated by a quantum system, and **can still be event local**!

# Comparison with quantum gravity

Consider now the quantization of the gravitational perturbation

$$\hat{\mathcal{H}}_I(\mathsf{x}) = -\sqrt{4\pi G} \sum_{p_i \in \{L_i, R_i\}} |p_i\rangle\langle p_i|\, T^{\mu\nu}_{p_i}(\mathsf{x})\hat{h}_{\mu\nu}(\mathsf{x})$$

Put hats on the metric perturbation.

Coupling the stress energy tensor of the particles to the quantum gravitational field

No matter your quantum gravity, one could expect that this would be its weak limit.

Same setup but now gravity is locally quantized and starts in the vacuum in the far past

# Comparison with quantum gravity

$$\hat{\mathcal{H}}_I(\mathsf{x}) = -\sqrt{4\pi G} \sum_{p_i \in \{L_i, R_i\}} |p_i\rangle\langle p_i|\, T^{\mu\nu}_{p_i}(\mathsf{x})\hat{h}_{\mu\nu}(\mathsf{x})$$

$$\mathcal{N}_{\mathrm{G}} = \pi G\left(\left|G_{L_1L_2} + G_{R_1R_2} - G_{L_1R_2} - G_{R_1L_2}\right| - \mathcal{L}\right) + \mathcal{O}(G^2)$$

The two Masses get entangled

$$G_{p_1p_2} = \int \mathrm{d}V\mathrm{d}V' T^{\mu\nu}_{p_1}(\mathsf{x}) G_{\mu\nu\alpha'\beta'}(\mathsf{x},\mathsf{x}') T^{\alpha'\beta'}_{p_2}(\mathsf{x}')$$

$$G_{\mu\nu\alpha'\beta'}(\mathsf{x},\mathsf{x}') = \langle 0|\, \mathcal{T}\left(\hat{h}_{\mu\nu}(\mathsf{x})\hat{h}_{\alpha'\beta'}(\mathsf{x}')\right) |0\rangle$$

$$G_{\mu\nu\alpha'\beta'}(\mathsf{x},\mathsf{x}') = -\frac{\mathrm{i}}{2}\Delta_{\mu\nu\alpha'\beta'}(\mathsf{x},\mathsf{x}') + \frac{1}{2}H_{\mu\nu\alpha'\beta'}(\mathsf{x},\mathsf{x}')$$

$$H_{\mu\nu\alpha'\beta'}(\mathsf{x},\mathsf{x}') = \langle 0|\, \{\hat{h}_{\mu\nu}(\mathsf{x}), \hat{h}_{\alpha'\beta'}(\mathsf{x}')\}\, |0\rangle$$

The field also gets entangled with the masses

# Comparison with quantum gravity

With local quantum degrees of freedom

$$\hat{\mathcal{H}}_I(\mathsf{x}) = -\sqrt{4\pi G} \sum_{p_i \in \{L_i, R_i\}} |p_i\rangle\langle p_i|\, T^{\mu\nu}_{p_i}(\mathsf{x})\hat{h}_{\mu\nu}(\mathsf{x})$$

$$\mathcal{N}_{\mathrm{G}} = \pi G\left(\left|G_{L_1L_2} + G_{R_1R_2} - G_{L_1R_2} - G_{R_1L_2}\right| - \mathcal{L}\right) + \mathcal{O}(G^2)$$

With quantum-controlled classical gravity

$$\hat{H}_I(t) = \sum_{\substack{p_1 \in \{L_1, R_1\} \\ p_2 \in \{L_2, R_2\}}} \Phi_{p_1p_2}(t)\, |p_1p_2\rangle\langle p_1p_2|$$

$$\mathcal{N}_{\mathrm{C}} = \frac{\pi G}{2}\left|\Delta_{L_1L_2} + \Delta_{R_1R_2} - \Delta_{L_1R_2} - \Delta_{R_1L_2}\right| + \mathcal{O}(G^2)$$

# Comparison with quantum gravity

Big difference: Entanglement when spacelike separated

When space like separation we have entanglement harvesting
From the gravitational field[1]

Also differences in short-time dynamics

However the current proposals work with regimes where
the masses are well within causal contact

# What the current proposals for GIE can tell

The experiment does:

-Prove that semiclassical gravity fails to describe the experiment

-Prove that gravity can set up a quantum channel between masses

The experiment does not:

-Prove that Gravity has local quantum degrees of freedom

In absence of further hypotheses

The experiment can be improved to actually test it
without extra assumptions

# Summary

There are regimes of GME experiments that are agnostic about the existence of local degrees of freedom of gravity without further hypotheses.

Most experimental efforts seem to be focused on those regimes.

However there are regimes for which the experiment does not need to rely on that hypothesis.

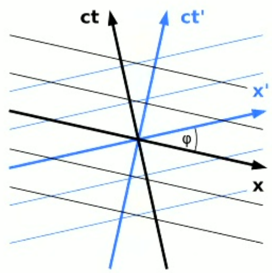
Thank you!

# A thought

The fact that the field does not have sharp values in general, That is “knowledge of the (quantum) state of the world only gives a probabilistic prediction about its value”. Does happen in the QC-model.

# Two notions of locality

**Event Locality**: Operations happen at events in spacetime, and do not affect other events which are causally disconnected from them.




**System locality:** (Specific to QM) Operations that independently affect two quantum systems must be separable

$$\hat{U}_{\mathrm{AB}} = \hat{U}_{\mathrm{A}} \otimes \hat{U}_{\mathrm{B}}$$