What can gravity mediated entanglement tell us about quantum gravity?

arXiv:2208.09489

Work in Collaboration with T. Rick Perche

International Loop Quantum Gravity Seminar

Quantum information in gravity

barrio-RQI.org

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Disagreement
Welcome!

Gravity induced entanglement (GIE)

Questions to discuss on this talk:

Can the gravitational interaction entangle two masses?

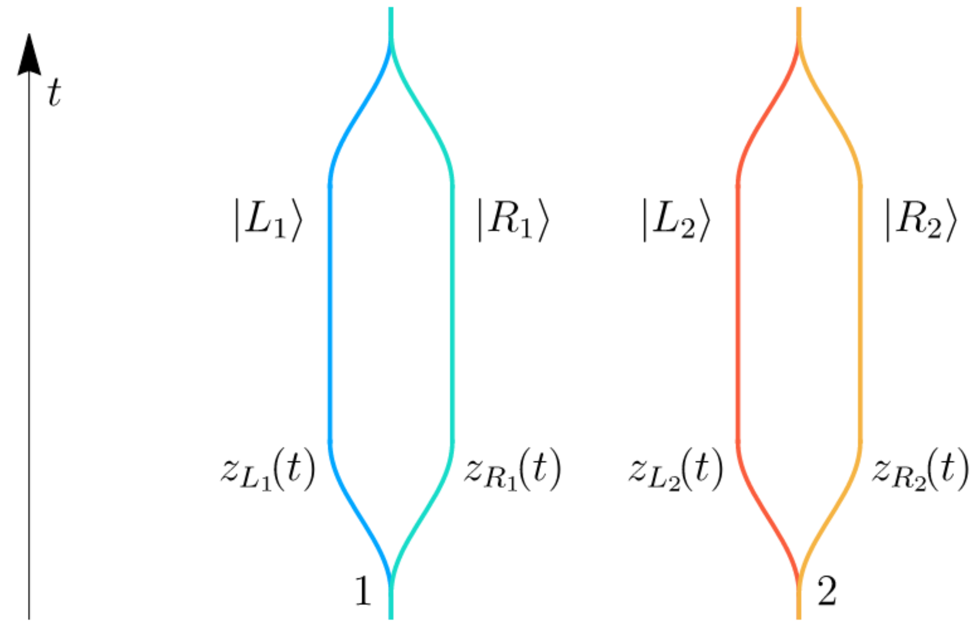
Does that mean anything about the quantum nature of gravity?

If so, what?

The BMV experiment

A Spin Entanglement Witness for Quantum Gravity

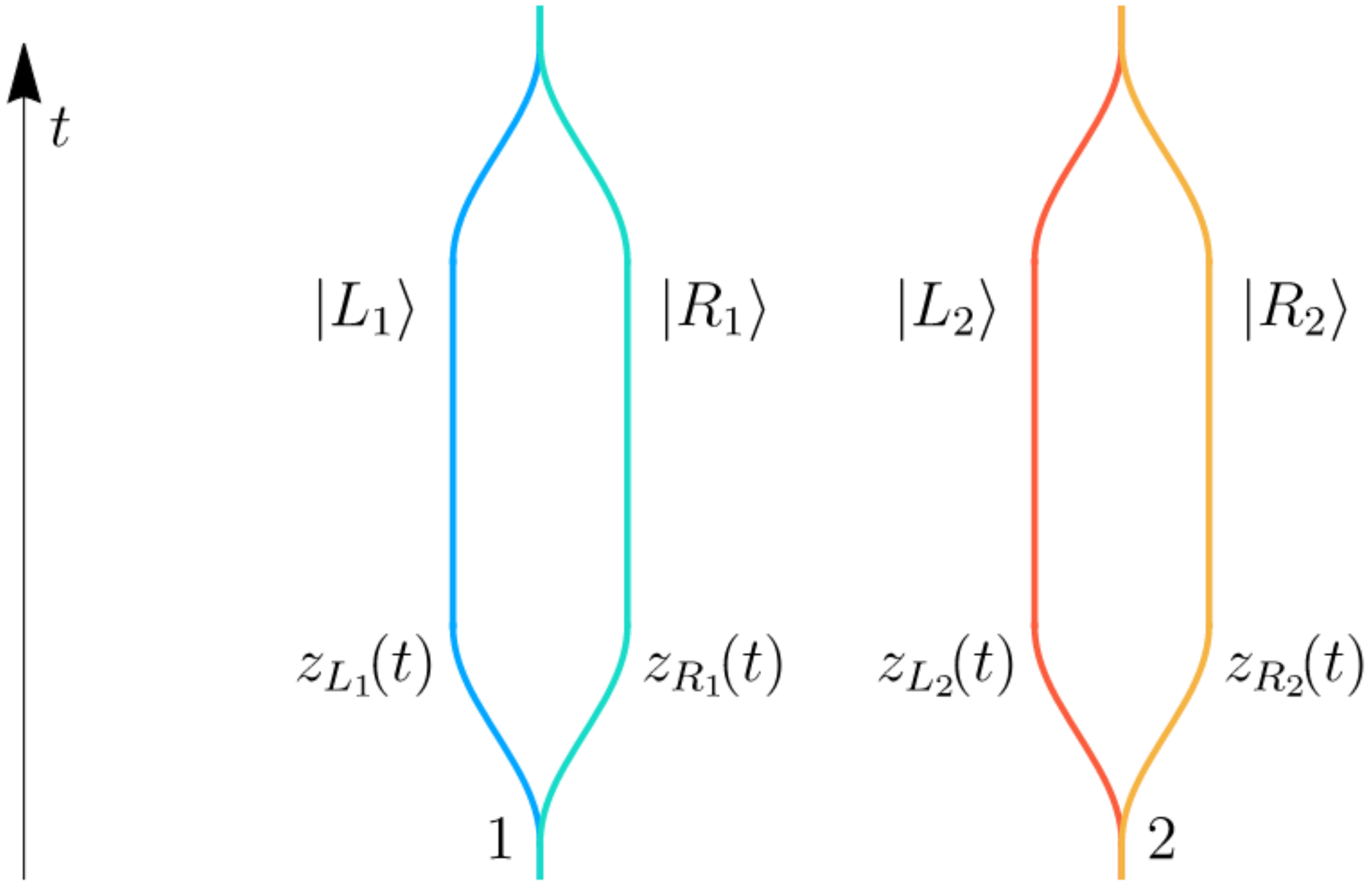
Sougato Bose,[1] Anupam Mazumdar,[2] Gavin W. Morley,[3] Hendrik Ulbricht,[4] Marko Toroš,[4] Mauro Paternostro,[5] Andrew Geraci,[6] Peter Barker,[1] M. S. Kim,[7] and Gerard Milburn[7,8]



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

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

The BMV experiment



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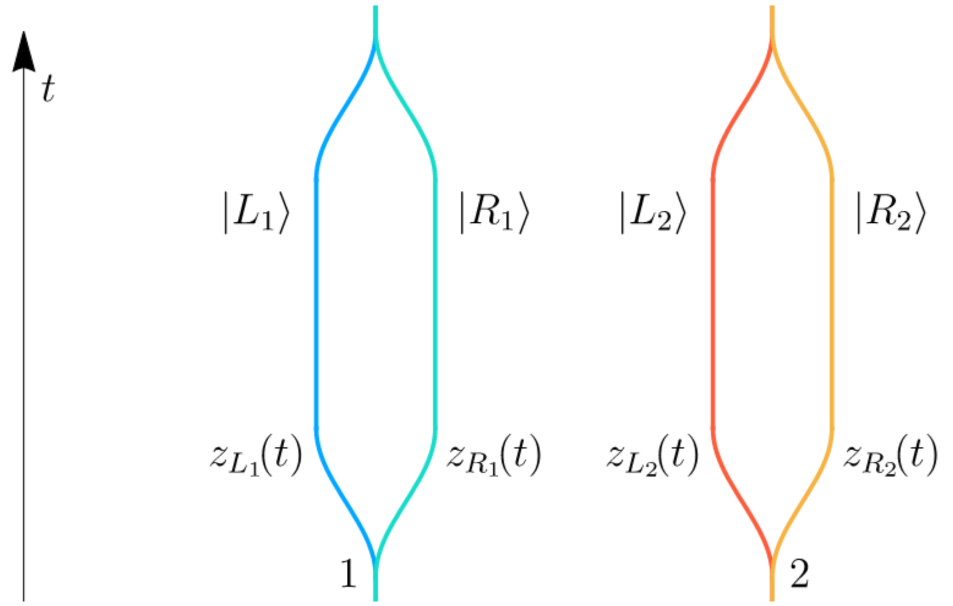
1/r Potential can entangle



$$\hat{\phi} = \frac{G m_1 m_2}{\hat{r}}$$

Bose et al. PRL 119, 240401 (2017)

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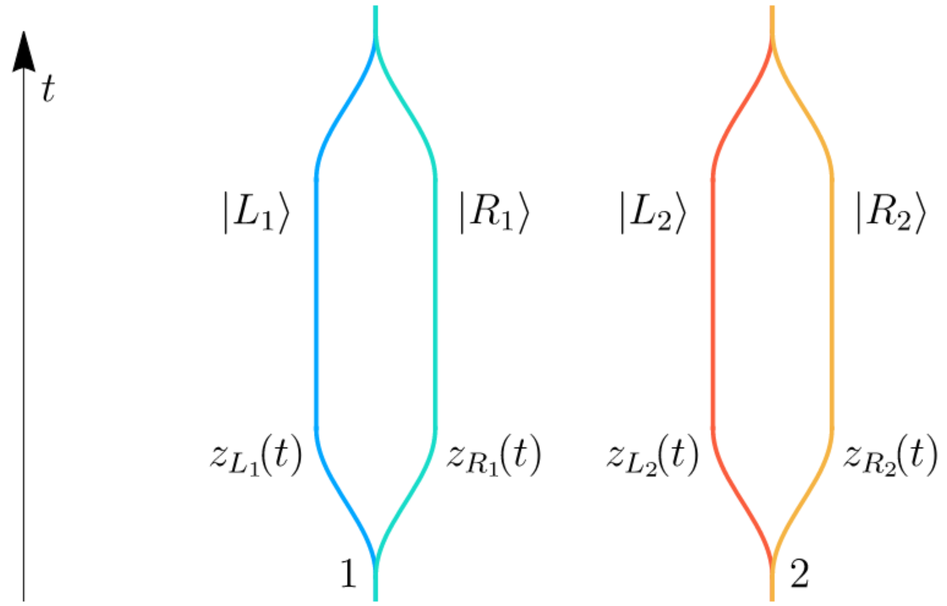

$$\hat{\phi} = \frac{Gm_1m_2}{\hat{r}}$$

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

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

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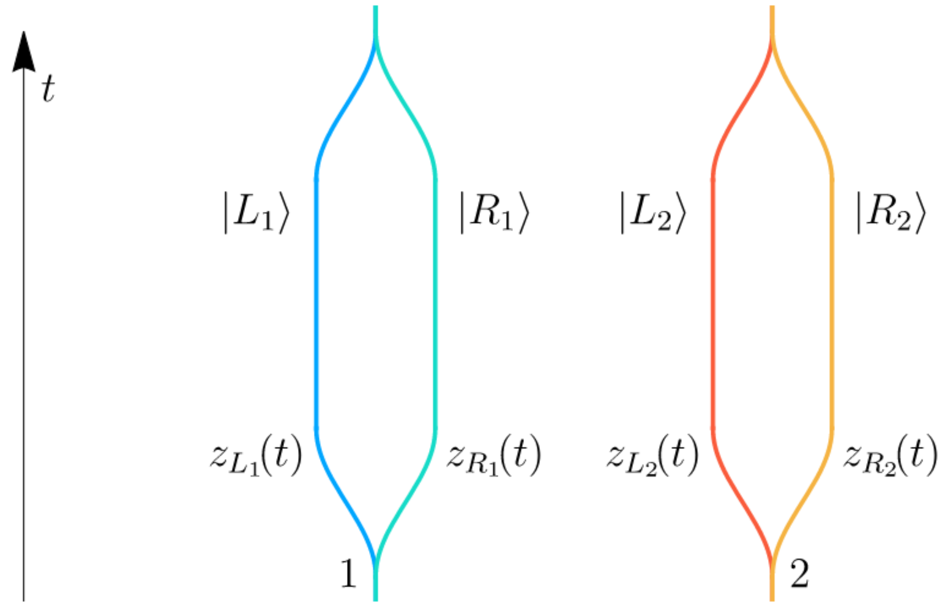

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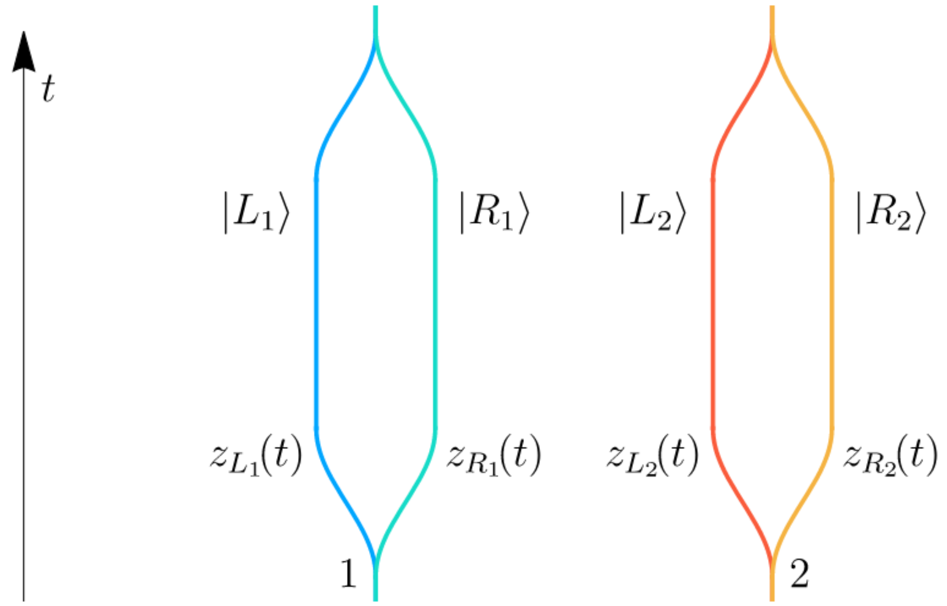

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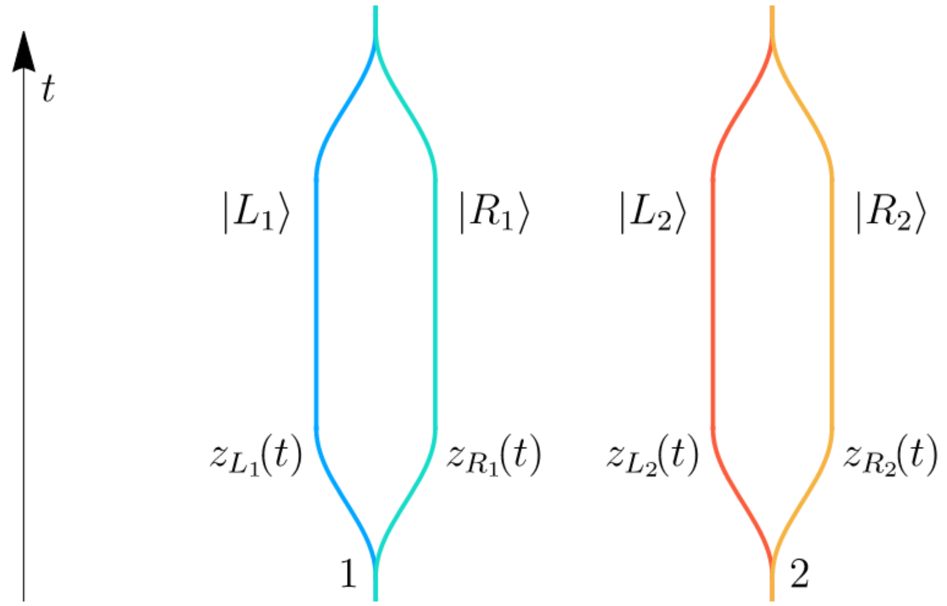

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If a third system locally mediates interaction between systems 1 and 2 and 1 and 2 can get entangled, the intermediary system has to be quantum.

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

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

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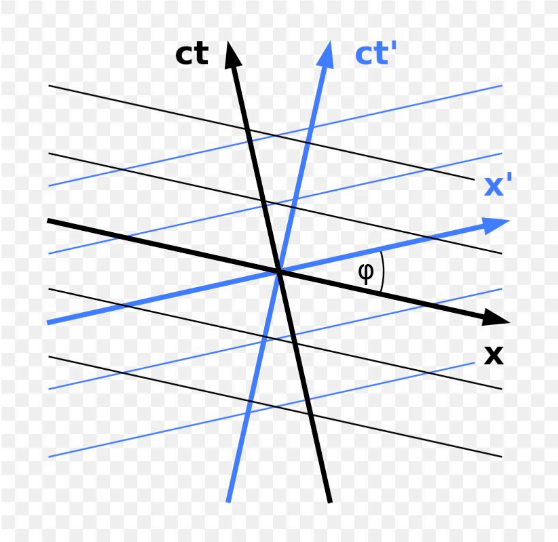
Right?!

Two notions of locality

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



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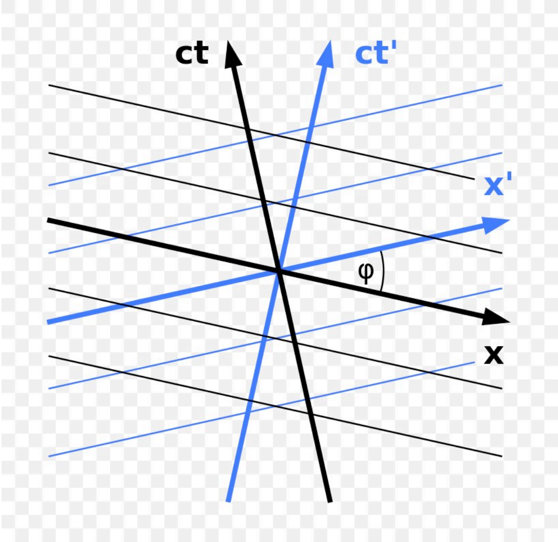

System locality: (Specific to QM) Operations that independently affect two quantum systems must be separable

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

Two notions of locality

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

Fundamental notion.

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

Operational notion.

An event local interaction that is not system local

Consider first weak gravity:

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

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

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Couple a small mass to it:

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

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

An event local interaction that is not system local

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

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

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

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

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

It recovers the Newtonian interaction in the non-relativistic limit $\hat{\phi} = \frac{G m_1 m_2}{\hat{r}}$

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

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

An event local interaction that is not system local

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

However the field has no quantum degrees of freedom!

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

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No action at a distance. It is fully relativistic

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But the interaction is event local:
No action at a distance. It is fully relativistic

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

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.

Comparison with quantum gravity

Consider now the quantization of the gravitational perturbation

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

$$\hat{H}_I(t) = \int \mathrm{d}^3\boldsymbol{x} \, \hat{\mathcal{H}}_I(\mathsf{x}) =$$

$$-\sqrt{4\pi G} \sum_{\substack{p_1 \in \{L_1, R_1\} \\ p_2 \in \{L_2, R_2\}}} |p_i\rangle\langle p_i| \, m_i \frac{u^\mu_{p_i}(t) u^\nu_{p_i}(t)}{u^0_{p_i}(t)} \hat{h}_{\mu\nu}(\mathsf{z}_{p_i}(t))$$

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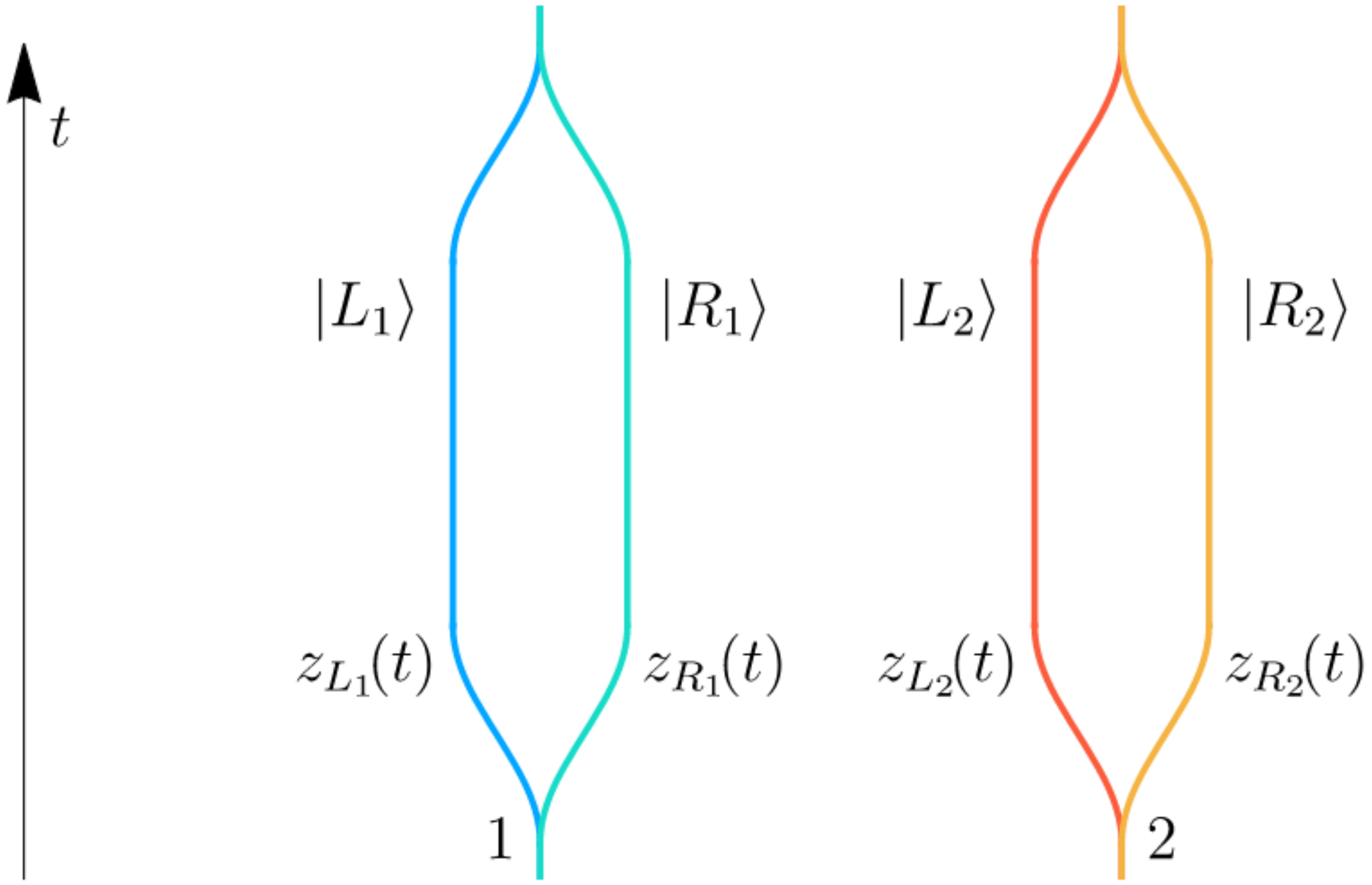

$$|\psi_0\rangle = \frac{1}{\sqrt{2}}\left(|L_1\rangle + |R_1\rangle\right) \otimes \frac{1}{\sqrt{2}}\left(|L_2\rangle + |R_2\rangle\right)$$

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

Comparison with quantum gravity

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$$\mathcal{N}_{\mathrm{G}} = \pi G \left(\left| G_{L_1 L_2} + G_{R_1 R_2} - G_{L_1 R_2} - G_{R_1 L_2} \right| - \mathcal{L} \right) + \mathcal{O}(G^2)$$

The two Masses get entangled

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

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

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

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

The field also gets entangled with the masses

Comparison with quantum gravity

With local quantum degrees of freedom

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Big difference: Entanglement when spacelike separated

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From the gravitational field

If you want to identify local quantum degrees of freedom,
observing entanglement while the masses are space like
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When space like separation we have entanglement harvesting
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If you want to identify local quantum degrees of freedom, observing entanglement while the masses are space like separated is a smoking gun

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

What the current proposals for GIE can tell and cannot tell

Somebody does the experiment and finds entanglement. You are in the Nobel Prize Committee.
You need to analyze what has been proved.

What the current proposals for GIE can tell and cannot tell

The experiment does:

-Prove that semiclassical gravity fails to describe the experiment

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

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(no Hilbert space for the field)

Summary

The detection of entanglement in the BMV experiment is agnostic to the existence of quantum degrees of freedom in gravity

Unless one assumes a connection between event locality and system locality (but that is assuming a framework like QFT from the start)

A smoking gun for the existence of quantum gravity would be the detection of space like gravitational entanglement

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Thank you!