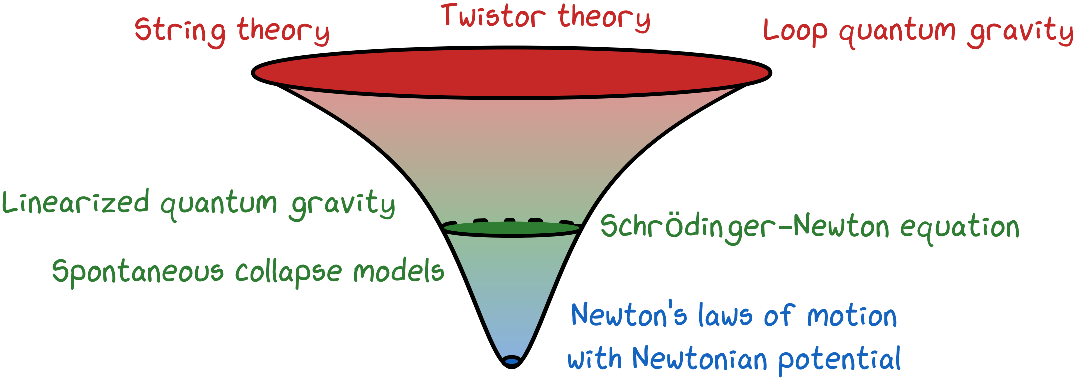
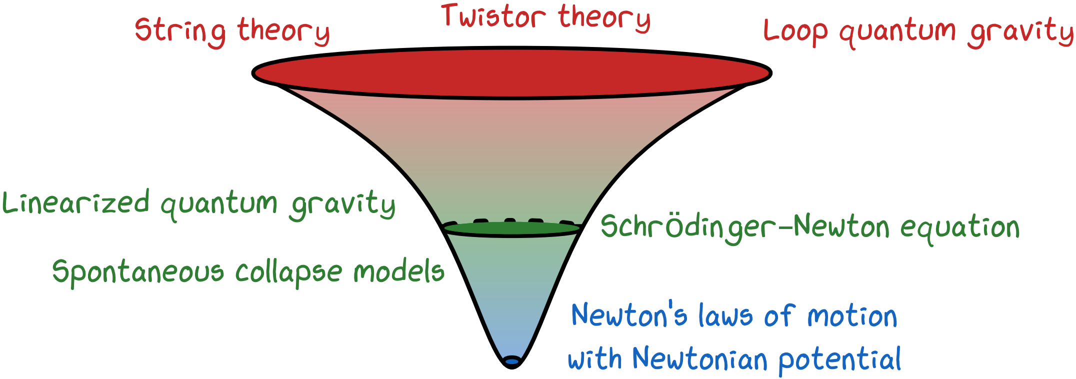
How to do physics without physics and why it helps experimentally verify the quantum nature of gravity

Martin Plávala
Leibniz University Hannover

Landscape of quantum gravity



Landscape of quantum gravity



Important question: Is gravity even quantum?

YES argument: every other fundamental theory we know is quantum.

NO argument: quantization of gravity does not seem to work.

So what can gravity be?

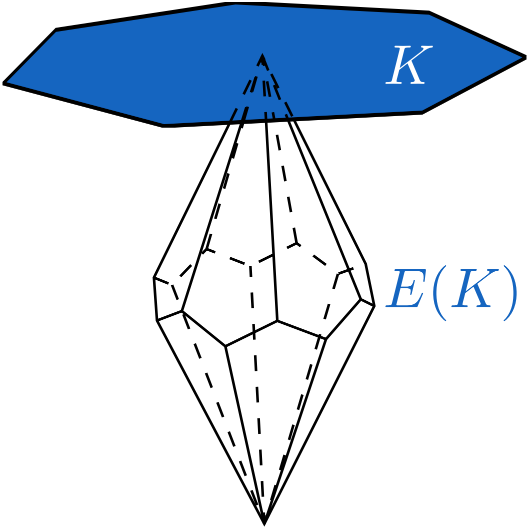
How can we explore physics without commiting to a specific model?

Very short introduction to General Probabilistic Theories (GPTs)

Main idea: GPTs are an exhaustive class of theories including classical theory, quantum theory, and many other exotic possibilities.[1]
Every experiment consists of

- preparation of initial state,
- transformation / interaction,
- measurement.

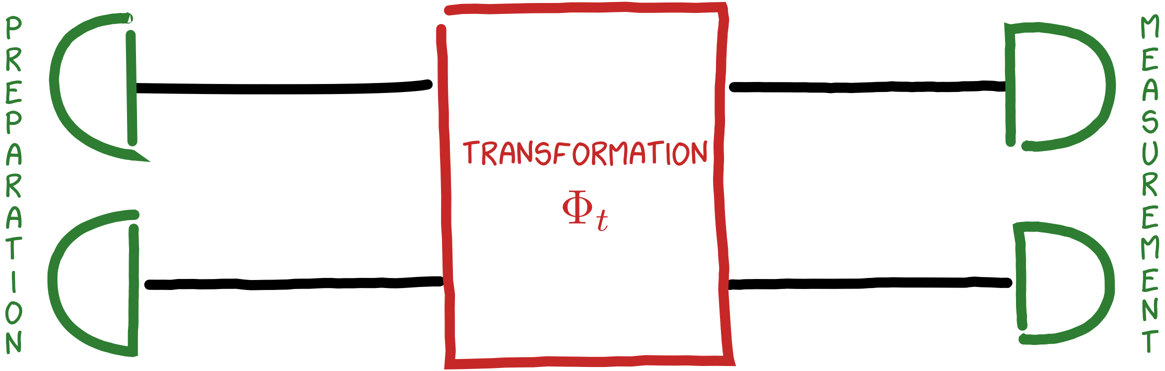
We can randomize between various options.



Single building block:
K - set of states (compact convex set)
Derived concepts:
$E(K)$ - measurement outcomes (effect algebra)
transformations are affine maps $K_A \to K_B$

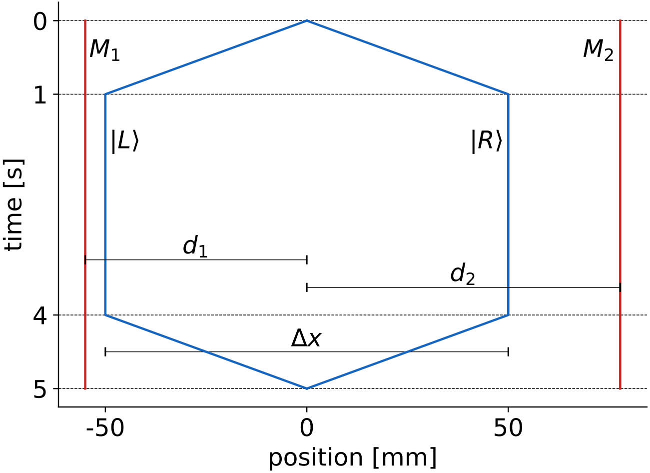
[1] M. Plávala: Phys. Rep. 1033, 1-64 (2023)

GPT perspective on experiments



We can use **quantum information techniques**
to measure the unknown transformation exactly.

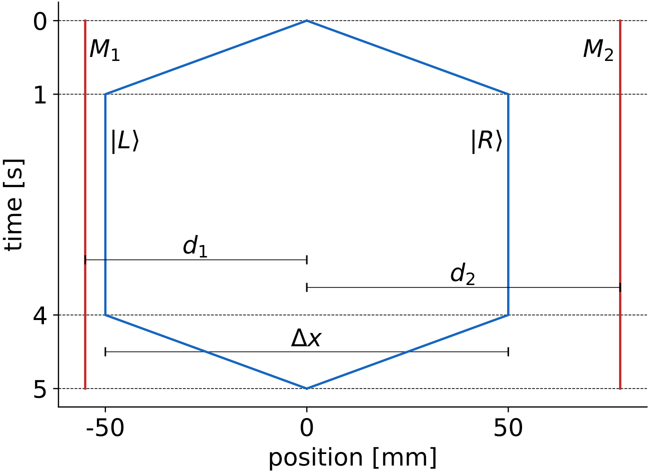
How to measure the time-evolution



- Already demonstrated with atoms $m \approx 10^{-25}\,\mathrm{kg}$ and heavier molecules.
- Just a **qubit** described by $\mathcal{H} = \mathrm{span}(|L\rangle, |R\rangle)$.

[2] M. Plávala, S. Nimmrichter, M. Kleinmann: Class. Quantum Grav. 42, 225023 (2025)

How to measure the time-evolution



- Already demonstrated with atoms $m \approx 10^{-25}\,\mathrm{kg}$ and heavier molecules.
- Just a **qubit** described by $\mathcal{H} = \mathrm{span}(|L\rangle, |R\rangle)$.
- Can test Schrödinger equation **beyond the classical limit.**[2]

[2] M. Plávala, S. Nimmrichter, M. Kleinmann: Class. Quantum Grav. 42, 225023 (2025)

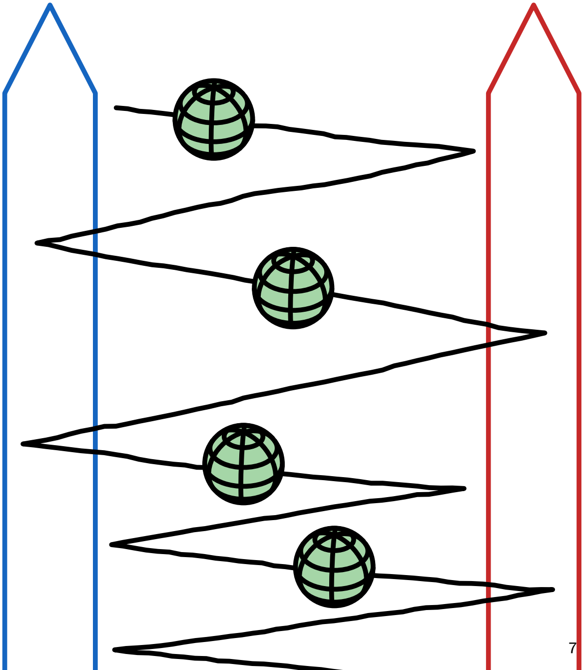
The proposal everyone is talking about:

gravity-mediated entanglement

Gravity-mediated entanglement

Setup

- Two massive particles in superposition in which-path basis.
- Only gravitational interaction.



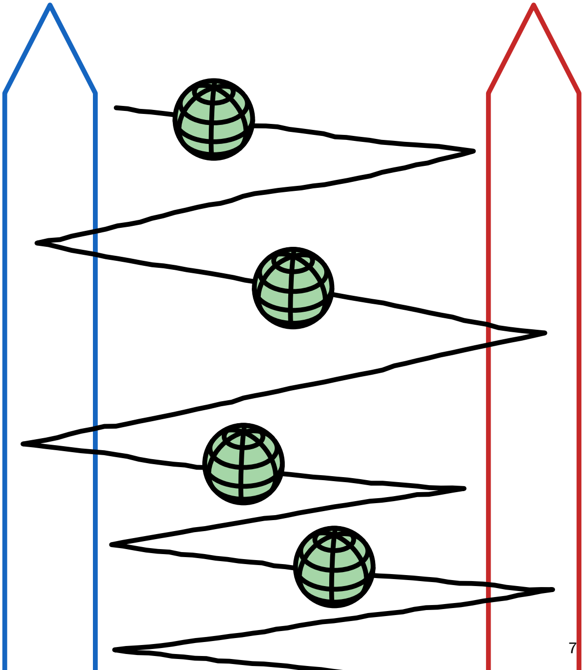
Gravity-mediated entanglement

Setup

- Two massive particles in superposition in which-path basis.
- Only gravitational interaction.

Naive idea

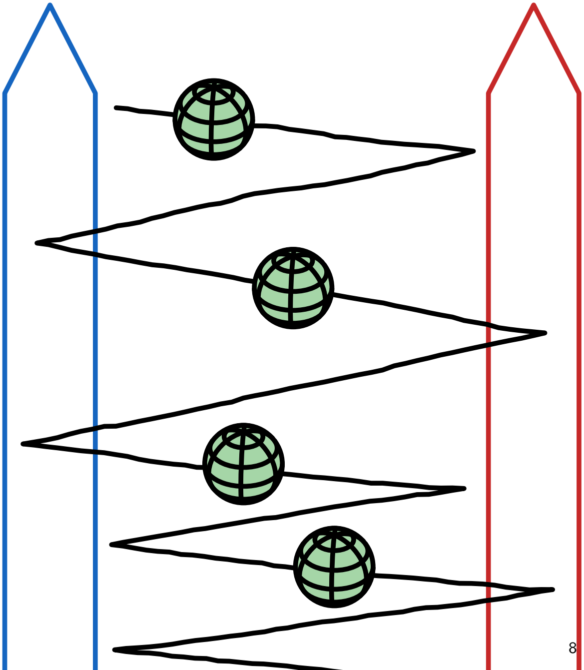
- Gravitational interaction is due to gravitons interacting with both systems separately.
- Classical systems (LOCC) cannot mediate entanglement between remote quantum systems.
- If gravitons mediate entanglement, then they cannot be classical, and **hence gravitational field is quantized.**



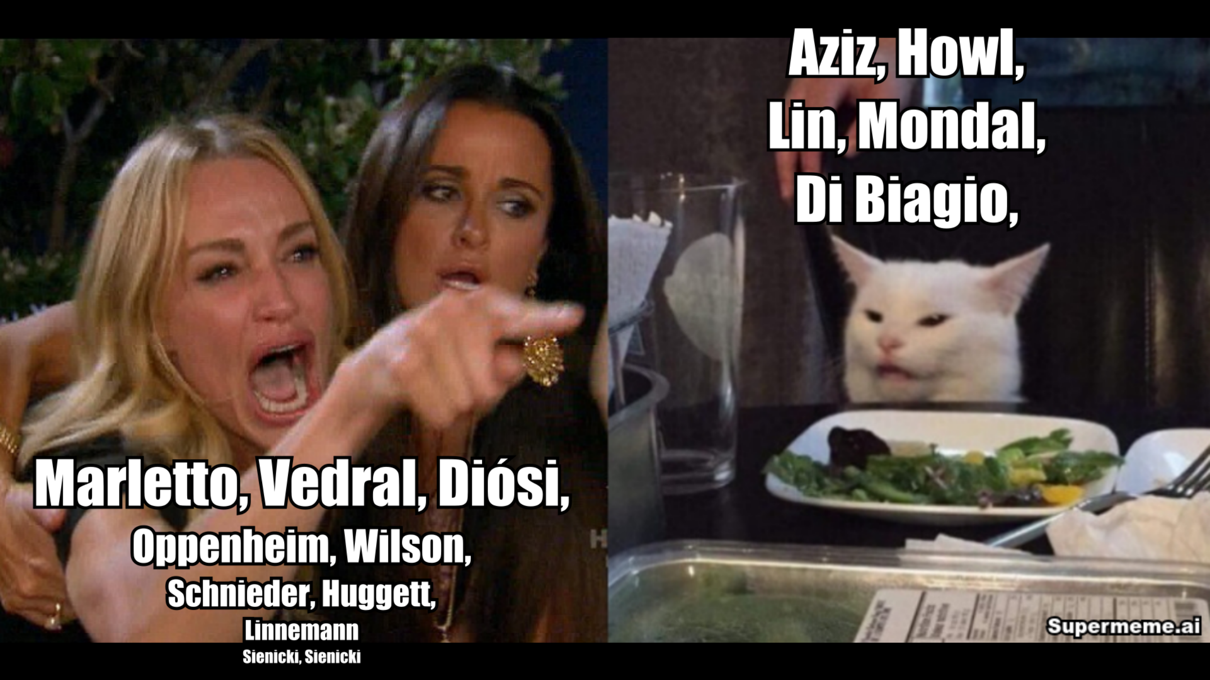
Gravity-mediated entanglement

Problems

- Relativistic locality (QFT) is strictly different from subsystem locality (QI).
- LOCC does not apply to off-shell particles.
- Classical limit of dynamics is already sufficient to get entanglement.[3]
- Exact implication of this experiment is a subject of a hot debate.



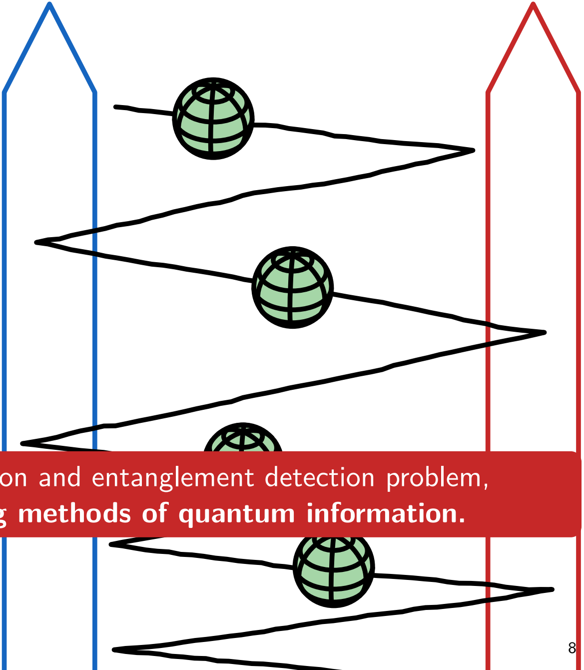
[3]M. Marchese, M. Plávala, M. Kleinmann, S. Nimmrichter: Phys. Rev. A 111, 042202 (2025)


Aziz, Howl,
Lin, Mondal,
Di Biagio,
Marletto, Vedral, Diósi,
Oppenheim, Wilson,
Schnieder, Huggett,
Linnemann
Sienicki, Sienicki
Supermeme.ai

Gravity-mediated entanglement

Problems

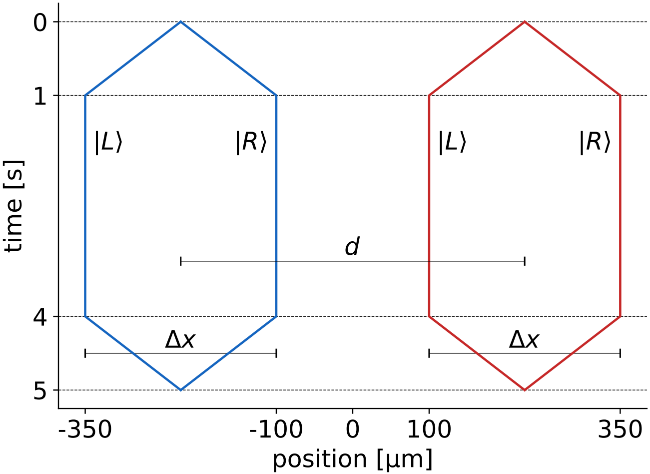
- Relativistic locality (QFT) is strictly different from subsystem locality (QI).
- LOCC does not apply to off-shell particles.
- Classical limit of dynamics is already sufficient to get entanglement.[3]
- Exact implication of this experiment is a subject of a hot debate.



This is nothing but entanglement generation and entanglement detection problem, which is just **naturally addressed using methods of quantum information.**

[3] M. Marchese, M. Plávala, M. Kleinmann, S. Nimmrichter: Phys. Rev. A 111, 042202 (2025)

Interacting interferometers



The only unknown term is the time-evolution $\Phi_t : \mathcal{D}(\mathcal{H} \otimes \mathcal{H}) \to \mathcal{D}(\mathcal{H} \otimes \mathcal{H})$

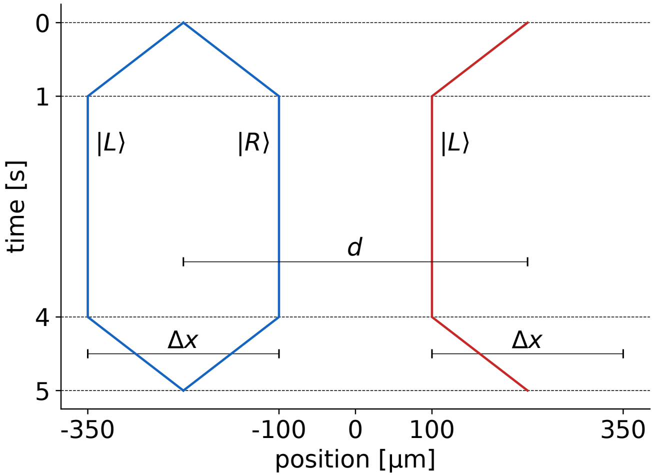
Requirements

- Φ_t is a linear map.
- Φ_t does not produce negative probabilities:
  - Φ_t is completely positive, or
  - Φ_t is positive.

So far **experimentally not demonstrated** in the requested mass regime of $m \approx 10^{-14}\,\mathrm{kg}$.

From 2 to 1 interferometer

From 2 to 1 interferometer



The only unknown term is the time-evolution $\Phi_t : \mathcal{D}(\mathcal{H} \otimes \mathcal{H}) \to \mathcal{D}(\mathcal{H} \otimes \mathcal{H})$

Strategy

- Measure partial data about Φ_t:

$$\Phi_t(|\psi\rangle\langle\psi| \otimes |L\rangle\langle L|)$$

- Bound the rest using semidefinite programming (SDP).

From mesoscopic to microscopic masses

From mesoscopic to microscopic masses

The problem

We have atom interferometers with mass $m \approx 10^{-25}\,\mathrm{kg}$.
We want matter-wave interferometers with mass $m \approx 10^{-14}\,\mathrm{kg}$.

From mesoscopic to microscopic masses

The problem

We have atom interferometers with mass $m \approx 10^{-25}\,\mathrm{kg}$.
We want matter-wave interferometers with mass $m \approx 10^{-14}\,\mathrm{kg}$.

Assumption

Φ_t depends only on the product of the masses $m_1 \cdot m_2$ (and not on m_1 and m_2 separately).

From mesoscopic to microscopic masses

The problem

We have atom interferometers with mass $m \approx 10^{-25}\,\mathrm{kg}$.
We want matter-wave interferometers with mass $m \approx 10^{-14}\,\mathrm{kg}$.

Assumption

Φ_t depends only on the product of the masses $m_1 \cdot m_2$ (and not on m_1 and m_2 separately).

What this gives us:

$$10^{-25} \cdot 10^{1} = 10^{-12} \cdot 10^{-12}$$

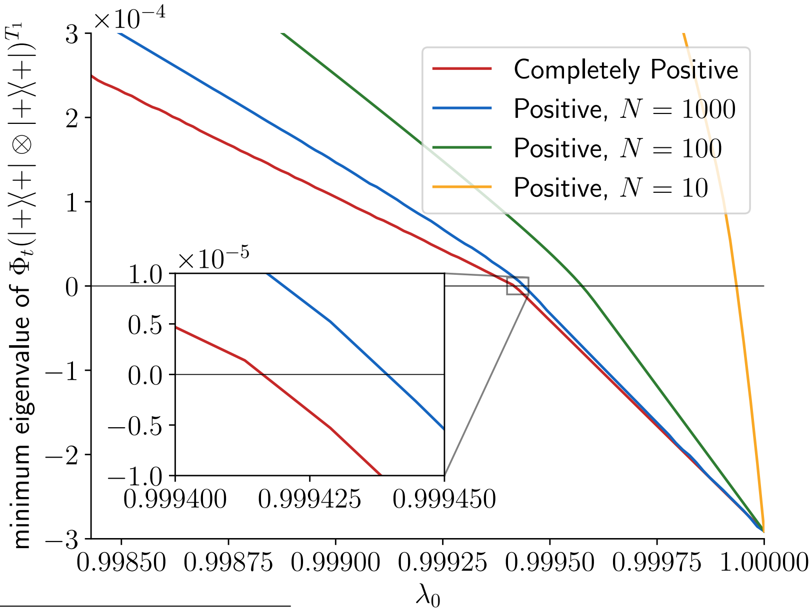
The result

The result

- Single interferometer experiment tests Schrödinger equation for delocalized microscopic system m in gravitational field of nearby mass M.
- **Observed data:** Upper bound on decoherence λ_0 such that

$$\Phi_t(|L\rangle\langle R| \otimes |x\rangle\langle x|) = \lambda_t \, \mathrm{e}^{-\frac{it\hat{H}}{\hbar}} \, |L\rangle\langle R| \otimes |x\rangle\langle x| \, \mathrm{e}^{\frac{it\hat{H}}{\hbar}}$$

  and $\lambda_t \geq \lambda_0$.
- We can now **numerically check whether for given λ_0 there is some Φ_t that does not generate gravity mediated entanglement.**



[4] M. Plávala: Phys. Rev. D 113, 085004 (2026)

Conclusions

- **Indirect experimental proof of gravity-mediated entanglement is on the horizon.**
- Soon, theory will be the bottleneck, not the experiment.

Future steps

- More physical constraints on Φ_t to reduce the necessary visibility λ_0.
- Adapt for realistic experimental proposals and do noise analysis.

Thank you for your attention!