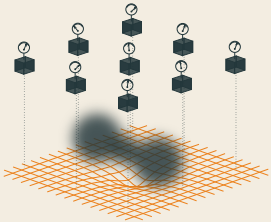
New Directions in the Foundations of Physics · Lake Bohinj, Slovenia · May 28–31, 2026

Hybrid quantum-classical theories of gravity

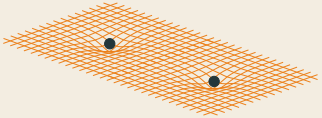


Antoine Tilloy

What we know about gravity

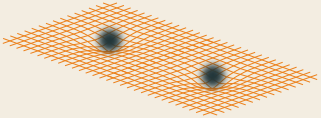
Gravity

Classical gravity



- **Matter** is classical
- Spacetime is classical

Semiclassical gravity



- **Matter** is quantum
- Spacetime is classical

Fully quantum gravity

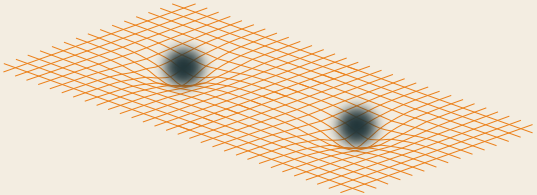


- **Matter** is quantum
- Spacetime is quantum

“Standard” semi-classical gravity

2 parts of the story:

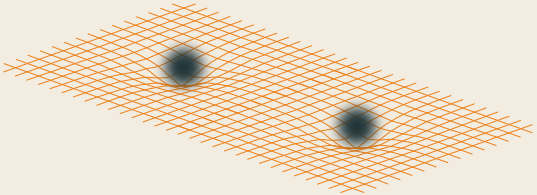
1. Quantum matter moves in a curved classical space-time
2. The classical space time is curved by quantum matter



“Standard” semi-classical gravity

2 parts of the story:

1. Quantum matter moves in a curved classical space-time
2. The classical space time is curved by quantum matter



1 is known (QFTCST), **2** is not

We don’t know how quantum matter sources curvature!

Electrodynamics was a different story

For QED :

- Hydrogen atom $\psi(\mathbf{x}_1)$

$$V(\hat{\mathbf{x}}_1) \propto \frac{1}{|\hat{\mathbf{x}}_1 - \mathbf{y}|} \propto \int_{\mathbb{R}^3} \mathrm{d}^3\mathbf{x}_1 \, \Phi(\mathbf{x}_1) \, |\mathbf{x}_1\rangle\langle\mathbf{x}_1|$$

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- Helium atom $\psi(\mathbf{x}_1, \mathbf{x}_2)$

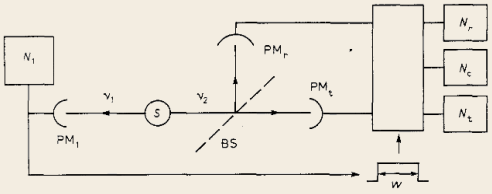
$$V(\hat{\mathbf{x}}_1, \hat{\mathbf{x}}_2) \propto \frac{1}{|\hat{\mathbf{x}}_1 - \hat{\mathbf{x}}_2|} \neq \int_{\mathbb{R}^3} \mathrm{d}^3\mathbf{x} \, \Phi(\mathbf{x}) \, \hat{O}(\mathbf{x})$$

Impossible to find the `He` spectrum without quantum Coulomb.

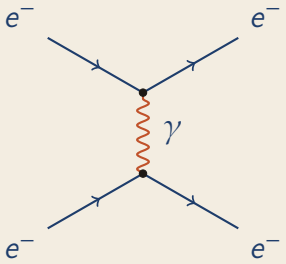
Probing the mediator is more difficult

Falsifying alternatives to QED without photons:

- Einstein's photo-electric argument inconclusive [Lamb & Scully 1960]
- Grangier - Roger - Aspect 1986 measure $g^{(2)} \leq 0.18$



The mediator of quantum gravity?



Sometimes “quantum gravity” = “there is a graviton” with analogies to the history of QED:

- Newtonian potential is a pure constraint
- Need “propagating” degrees of freedom
- We “knew” for QED only after 1986

In defense of “testing” Newtonian gravity

We should start with the easiest thing we don’t know:

$$\hat{V}_{\mathrm{QG}} \propto -\sum_{i \neq j} \frac{1}{|\hat{\mathbf{x}}_i - \hat{\mathbf{x}}_j|}$$

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$$\hat{V}_{\mathrm{QG}} \propto -\sum_{i \neq j} \frac{1}{|\hat{\mathbf{x}}_i - \hat{\mathbf{x}}_j|}$$

Are there reasonable alternatives we can falsify?

Møller-Rosenfeld semi-classical gravity

Møller-Rosenfeld semi-classical gravity

The **CHOICE** of Møller and Rosenfeld it to take:

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} = 8\pi G \langle \hat{T}_{\mu\nu} \rangle$$

$\longrightarrow$ source gravity via expectation values

There are:

- **technical relativistic** difficulties [renormalization of $\langle T_{\mu\nu} \rangle$]
- **conceptual non-relativistic** difficulties [Born rule,$\cdots$].



Christian Møller



Leon Rosenfeld

Schrödinger-Newton

1. Non-relativistic limit of the “sourcing” equation:

$$\nabla^2\Phi(\mathbf{x}, t) = 4\pi G\, m\, |\psi(\mathbf{x})|^2$$

Schrödinger-Newton

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$$\frac{\partial}{\partial t}\psi_t(\mathbf{x}) = -i(H_0\psi_t)(\mathbf{x}) - i\,\Phi(\mathbf{x}, t)\;\psi_t(\mathbf{x})$$

Schrödinger-Newton

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Putting the two together: Schrödinger-Newton equation

$$\frac{\partial}{\partial t}\psi_t(\mathbf{x}) = -i(H_0\psi_t)(\mathbf{x}) + i\,G\int_{\mathbb{R}^3} \mathrm{d}^3\mathbf{y}\,\frac{m^2\,|\psi_t(\mathbf{y})|^2\,\psi_t(\mathbf{x})}{|\mathbf{x}-\mathbf{y}|}.$$

The problems with Schrödinger-Newton



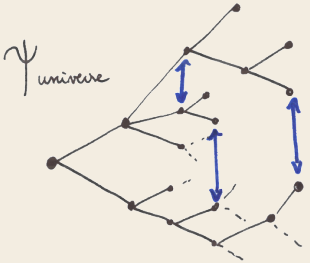
Deterministic non-linearity is not allowed (Gisin, Diósi, Polchinski)

Proof is **interpretation dependent**

- If there is **no fundamental collapse** [Many Worlds, Bohm, $\cdots$]
- If there is **fundamental collapse** [Copenhaguen, Collapse models]

The problems with Schrödinger-Newton

Without collapse upon measurement (Bohm, Many Worlds, $\cdots$)



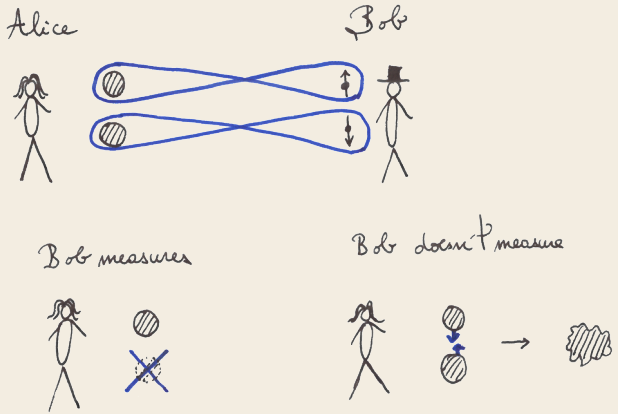
Decohered branches interact with each other $\longrightarrow$ **empirically inadequate**



$\longrightarrow$ even experimentally tested by Page and Geiker '81

The problems with Schrödinger-Newton

With collapse upon measurement (either from pure Copenhaguen or collapse models).



Possible fixes

It's not fully over:

- Schrödinger-Newton + new collapse rules [Adrian Kent]
- Bohmian particles as sources [Ward Struyve]

Lose Born rule in both cases

Discrete hybrid theories

Desiderata for quantum-classical dynamics

Not sacrifice the toolbox of operational quantum mechanics if possible:

- Keep some statistical interpretation of ψ or ρ
- Do not signal faster than light

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- Keep some statistical interpretation of ψ or ρ
- Do not signal faster than light

$\longrightarrow$ start from primitives we know do not bring problems

Hybrid quantum-classical states

A quantum-classical state is a *particular* density matrix on $\mathscr{H}_Q \otimes \mathscr{H}_C$

$$\varrho_{\mathsf{qc}} = \sum_z \rho(z) \otimes |z\rangle\langle z| \tag{1}$$

where $\{|z\rangle\}$ is a fixed basis of states (the possible classical values).

Most general quantum dynamics

Kraus representation theorem

The most general **fully quantum** map is

$$\rho \mapsto \Phi(\rho) = \sum_{\mu} \Lambda_{\mu} \rho \Lambda_{\mu}^{\dagger}$$

where $\mathrm{tr}(\rho) \equiv 1 \implies \sum_{\mu} \Lambda_{\mu}^{\dagger} \Lambda_{\mu} = \mathbb{1}$

Most general quantum-classical dynamics

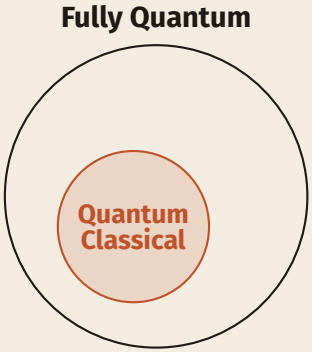
General quantum classical map

The most general map is

$$\rho(z) \mapsto \Phi(\varrho)(z) = \sum_{z'} \sum_{\mu} \Lambda_\mu(z|z')\, \rho(z')\, \Lambda_\mu^\dagger(z|z')$$

where

$\mathrm{tr}(\varrho) \equiv 1 \implies \forall\, z',\ \sum_z \sum_\mu \Lambda_\mu^\dagger(z|z')\Lambda_\mu(z|z') = \mathbb{1}$



Unraveling

Since we stay diagonal in z, we can assume we measure μ and z at every step

$$\{\rho, z\} \longrightarrow \left\{ \frac{\Lambda_\mu(z'|z)\ \rho\ \Lambda_\mu^\dagger(z'|z)}{\mathrm{tr}\left[\Lambda_\mu(z'|z)\,\rho\,\Lambda_\mu^\dagger(z'|z)\right]}, z' \right\}$$

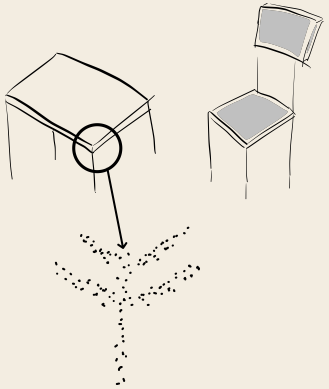
with probability

$$p(z', \mu) := \mathrm{tr}\left[\Lambda_\mu(z'|z)\,\rho(z)\,\Lambda_\mu^\dagger(z'|z)\right]$$

Unraveling is empirically equivalent so we can take it as primitive!

Consequence for foundations

Non-trivial quantum classical theories solve the measurement problem



z is a natural **ontology**

Interpretation as measurement and feedback

$$\{\rho, z\} \longrightarrow \left\{ \frac{\Lambda_\mu(z'|z)\ \rho\ \Lambda_\mu^\dagger(z'|z)}{\mathrm{tr}\left[\Lambda_\mu(z'|z)\,\rho\,\Lambda_\mu^\dagger(z'|z)\right]}, z' \right\}$$

- Generalized measurement yields z', μ
- Quantum state is updated accordingly – `quantum backaction`
- Classical state jumps $z \longrightarrow z'$ based on the result – `"sourcing"`
- The future quantum map depends on z' – `feedback`

Experimentalists have been doing hybrid dynamics all along!

Continuous hybrid theories

Continuum limit

We prefer our laws continuous in space and time.

Two distinct time-continuous limits:

- Jumps in ρ, z aka photo-detection
- Diffusion in ρ, z aka homodyne measurement

General continuous hybrid equation

For $\rho_t(z)$ with z classical variable $\in \mathbb{R}$ [Oppenheim 2018] :

$$\frac{\partial \rho_t(z)}{\partial t} = \underbrace{-i\,[H, \rho_t(z)] + \mathcal{D}[\hat{c}]\,\rho_t(z)}_{\text{Lindblad}}$$

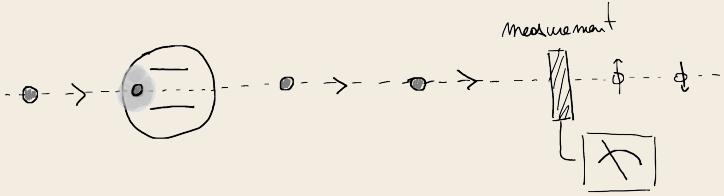
$$- \frac{\partial}{\partial z}\left[F(z)\,\rho_t(z) + \frac{G(z)}{2}\left(\hat{c}\rho_t(z) + \rho_t(z)\hat{c}^\dagger\right)\right]$$

$$+ \frac{1}{2}\frac{\partial^2}{\partial z^2}\left[\frac{G(z)^2}{4}\,\rho_t(z)\right]$$

A second order PDE with subtle constraints ($G, \hat{c}, F$ are arbitrary)

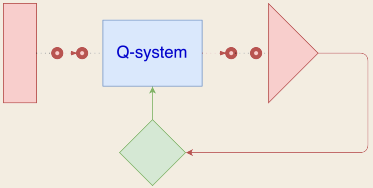
Continuous measurement

Continuous measurement without Zeno effect — from repeated interactions



- Time between ancillas $\Delta t \propto \varepsilon$
- Interaction strength $\omega \propto 1/\sqrt{\varepsilon}$, i.e. $U = e^{-i\sqrt{\varepsilon}H_{\text{int}}}$

Continuous measurement and general feedback



Step 1: Classical z_t depends on the integrated signal r_t

$$\frac{\mathrm{d}z}{\mathrm{d}t} = F(z) + G(z)\frac{\mathrm{d}r}{\mathrm{d}t}$$ ← measurement result

Step 2: Quantum depends on the classical

$$H \longrightarrow H + V(z)$$

$\Longrightarrow$ Equivalent Langevin description of the “Fokker-Planck” PDE above

Link with continuous collapse models

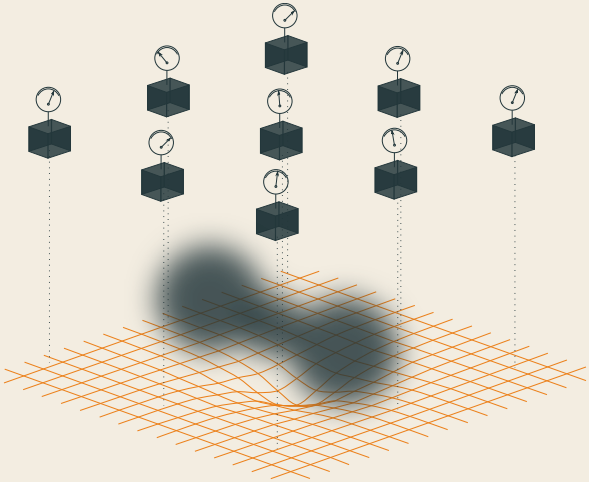
3 constructions give the same mathematical space of theories:

1. General hybrid dynamics for $\rho(z)$ ← Fokker-Planck
2. Continuous measurement and feedback coupling ρ, z ← Langevin
3. Collapse models with a well chosen primitive ontology (flash-like)

$\Longrightarrow$ empirical consequences well understood
$\Longrightarrow$ solution of the measurement problem well discussed

Back to gravity

Intuition



Markovian/Newtonian limit

$$\nabla^2 \Phi(\mathbf{x}) = 4\pi G\, S(\mathbf{x})$$

Technically easier

Newtonian limit = Markovian feedback limit

`classical variable at time` $t \propto$ `measurement signal at time` t

$\Longrightarrow$ technically infinitely easier $\Longrightarrow$ one can say something

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$$\texttt{classical variable at time } t \propto \texttt{measurement signal at time } t$$

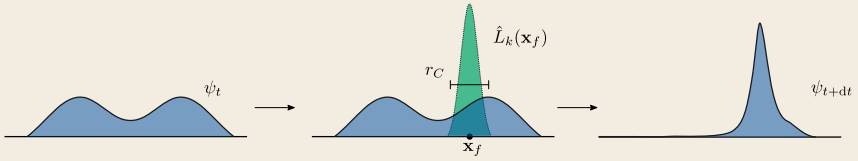
$\Longrightarrow$ technically infinitely easier $\Longrightarrow$ one can say something

Experimentally motivated

Hard to probe anything else in the near future **and unknown!**

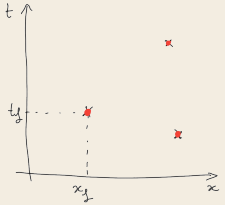
A toy model: GRW with “massive” flashes

The GRW model



Making the flashes source gravity

$$\nabla^2\Phi(\mathbf{x},t) \propto \delta^{(4)}(t-t_f, \mathbf{x}-\mathbf{x}_f)$$



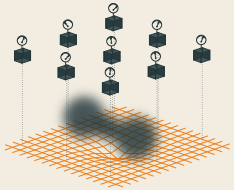
Mass density ontology would not work

General continuous model

1. **Step 1: continuous mass density measurement**
Free functonal parameter

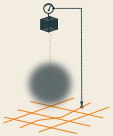
$\gamma(\mathbf{x}, \mathbf{y})$ coding detector strength and correlation

associated “mass density signal” $S(\mathbf{x})$ in every point



2. **Step 2: sourcing** Φ

$$\nabla^2\Phi(\mathbf{x}) = 4\pi G\, S(\mathbf{x})$$



3. **Step 3: feedback**
$\Phi(x)$ is added as external field

Result

Standard quantum feedback computations give for $\rho_t = \mathbb{E}[|\psi_t\rangle\langle\psi_t|]$:

$$\partial_t \rho = -i\left[H_0 + \frac{1}{2}\iint \mathrm{d}\mathbf{x}\,\mathrm{d}\mathbf{y}\; \mathscr{V}(\mathbf{x},\mathbf{y})\,\hat{M}(\mathbf{x})\hat{M}(\mathbf{y}),\ \rho_t\right] - \frac{1}{8}\iint \mathrm{d}\mathbf{x}\,\mathrm{d}\mathbf{y}\; \mathscr{D}(\mathbf{x},\mathbf{y})\Big[\hat{M}(\mathbf{x}),\big[\hat{M}(\mathbf{y}),\rho_t\big]\Big],$$

with the **gravitational pair-potential**

$$\mathscr{V}(\mathbf{x},\mathbf{y}) = \left[\frac{4\pi G}{\nabla^2}\right](\mathbf{x},\mathbf{y}) = -\frac{G}{|\mathbf{x}-\mathbf{y}|} \qquad \leftarrow \text{ like in Quantum Gravity}$$

and **positional decoherence** $\mathscr{D}(\mathbf{x},\mathbf{y}) = \left[\frac{\gamma}{4} + \mathscr{V}\circ\gamma^{-1}\circ\mathscr{V}^{\mathsf{T}}\right](\mathbf{x},\mathbf{y})$.

Principle of least decoherence

Decoherence:

$$\mathscr{D}(\mathbf{x}, \mathbf{y}) = \left[\frac{\gamma}{4} + \mathscr{V} \circ \gamma^{-1} \circ \mathscr{V}^{\top}\right](\mathbf{x}, \mathbf{y})$$

- Large $\|\gamma\| \implies$ strong *measurement*-induced decoherence
- Small $\|\gamma\| \implies$ strong *feedback* decoherence

Principle of least decoherence

Decoherence:

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- Large $\|\gamma\| \implies$ strong *measurement*-induced decoherence
- Small $\|\gamma\| \implies$ strong *feedback* decoherence

There is an optimal (non-local) kernel that minimizes decoherence.

Global minimum for $\gamma = 2\sqrt{\mathscr{V}\circ\mathscr{V}^{\top}} = -2\mathscr{V}$, giving:

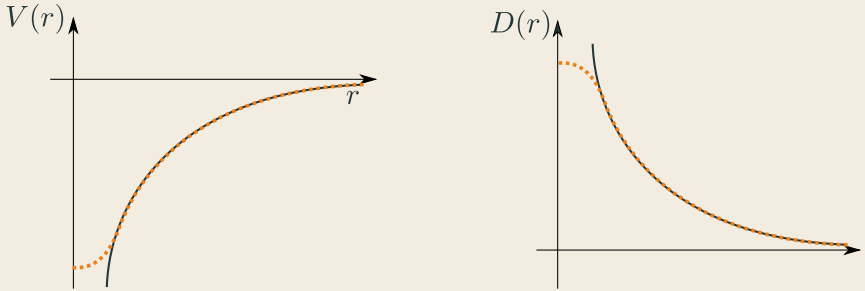
$$\mathscr{D}(\mathbf{x},\mathbf{y}) = -\mathscr{V}(\mathbf{x},\mathbf{y}) = \frac{G}{|\mathbf{x}-\mathbf{y}|}$$

aka the Diósi-Penrose model!

Regularization

For the minimal decoherence prescription, decoherence is **infinite**.

Adding a regulator at length scale σ has two effects:

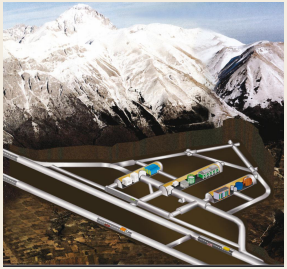


There is a tradeoff.

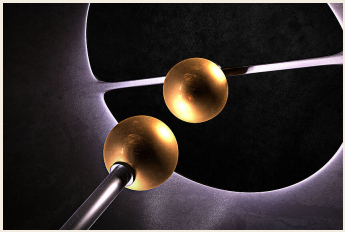
Tests of the cutoff length

$$\underbrace{10^{-15} \longrightarrow 10^{-10}\,\mathrm{m}}_{\text{decoherence constraint}} \ll \sigma \leq \underbrace{10^{-4}\,\mathrm{m}}_{\text{gravitational constraint}}$$

Importantly $\sigma > \ell_{\text{Compton}} \gg \ell_{\text{Planck}}$.



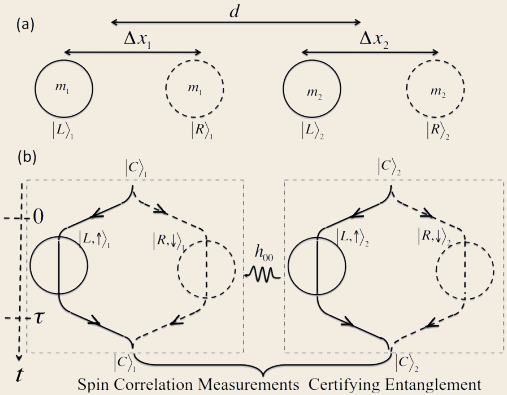
credit VIP collaboration – Catalina Curceanu



copyright Jonas Schmöle – Aspelmeyer group

What about entanglement generation?

Entanglement as a smoking gun for quantumness



Bose et al. 2017

Entanglement and LOCC

Bipartite Hilbert space $\mathscr{H}_A \otimes \mathscr{H}_B$

- Measure with operators acting only on A or B
- Act on A or B depending on the result

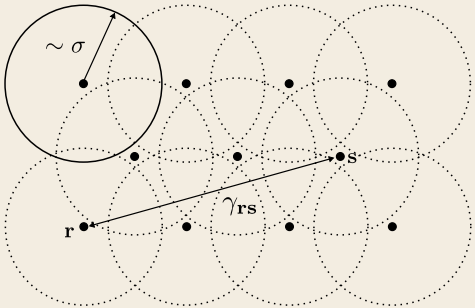
LOCC implies entanglement decreases

Under such operations, all good measures of entanglement between A and B decrease.

Hybrid theories where the measurement part is local are not entangling.

A little bit subtle

Entanglement generated because measurement *not exactly spatially local* (not strict LOCC):



[Trillo & Navascues 2024] [Feng, Marletto, Vedral 2025]

Very different entanglement generation, but not a YES/NO answer!

Summary

- We don't know if gravity is quantum, even at the Newtonian level
- Questions about the mediator (graviton?) are second order
- Standard semiclassical theories of gravity are sick
- There are fairly simple quantum-classical theories that are not sick
- Structurally, they are equivalent to measurement + feedback
- In the context of gravity they include the Diósi-Penrose model as the model least different from quantum gravity
- Big flaws: fairly large new lengthscale σ and difficult to construct relativistic extension
- Probably shouldn't *believe* in it, but the logic remains important