GRAVITY AND SPONTANEOUS LOCALIZATION MODELS

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ABOUT

Thank **Detlef** who invited me to **Erice** and who involuntarily made this work possible.

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! Lajos may not share all the opinions I will present !

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Objective of the talk

Show that collapse models allow the consistent coupling of quantum matter with a classical space-time making **fundamental** semi-classical gravity possible, at least in principle.

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Semi-classical gravity

Collapse models

Marrying the two

SEMI-CLASSICAL GRAVITY

Why fundamental semi-classical gravity?

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1. Quantum gravity is a mess (time problem, even worse interpretation problems than standard QM)
2. Gravity looks different from the other forces (not just a spin 2 gauge interaction)
3. Intelligent people already do Quantum Gravity.

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Two standard objections to semi-classical gravity

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1. Philosophical: Quantum theory is a meta-theory (a bit like logic or probability theory), a mandatory tool to build physical theories. Every single degree of freedom should be “quantized”.
2. Straw-man fallacy: The standard approach to semi-classical gravity, due to Møller and Rosenfeld, is plagued with problems.

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The first one is well understood and well tested (QM in an external potential at the non-relativistic level or QFT in curved space-time in the general case). The foundational problem lies in the second one.

How matter curves space-time

Einstein equation:

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Use a quantum "average":

$$G_{\mu\nu} = 8\pi G \langle\Psi| \hat{T}_{\mu\nu} |\Psi\rangle$$

This poses many mathematical problems (renormalisation, ambiguities, etc.). A huge body of literature claims they can be solved. We will accept this and focus on simpler issues.

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Physical problems at the non-relativistic limit

1. N-R limit is Schrödinger-Newton equation:

$$i\hbar\,\partial_t\,|\psi\rangle = H(|\psi\rangle)\,|\psi\rangle$$

i.e. **non-linear** deterministic $\underset{\text{Gisin}}{\longrightarrow}$ FTL signaling

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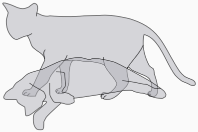
2. Self-interaction —even between incoherent superpositions—: Dead and alive cat do attract each-other



Disproved (if it were even needed) by the infamous Page & Geiker experiment.

Local conclusion

Doing a quantum-classical coupling with a quantum average is a bad idea. In orthodox quantum mechanics, it is hard to think about anything else.

“Either gravitation is non-classical or quantum mechanics is non orthodox” Mielnik (1974) cited by Kibble & Randjar-Daemi

How else? Is there a Bohmian way? (not naively) Is there a collapse way? (it seems so)

COLLAPSE MODELS

A few precautions

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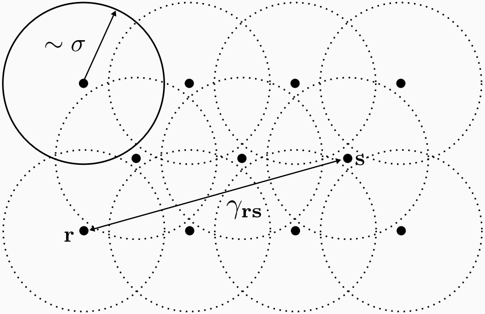
- You do not need to believe in them to find some interest in the following construction
- Slightly different presentation of collapse models based on the formal analogy with continuous measurement theory. Not meant to solve foundational problems

Collapse models = mass density measurement models

Everything happens as if space-time were filled with unsharp entangled mass density detectors



σ codes for the detector resolution

$\gamma_{r,s}$ for the correlation of the unpredictable part of the measurement results at r and s

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More precisely

A smeared version of the mass density operator is measured continuously and weakly in every point of space. e.g. for a single particle of mass m_1:

$$\hat{M}_\sigma(x) = m_1 \int d^3y \, g_\sigma(x - y) \, |y\rangle \langle y|$$

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The system state ρ_t at time t is then a function of the previous (random) measurement results $s_\tau(x), \tau < t$. Intuitively, it verifies a quantum filtering SDE of the form:

$$d\hat{\rho}_t = \#_1 dt + \int d^3x \, \#_2 ds_t(x)$$

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Mathematical ingredients

1. An equation for the measurement results ("the signal"), Doob decomposition in predictable drift + pure noise

$$ds_t(x) = \mathrm{tr}\left[\hat{M}_\sigma(x)\hat{\rho}_t\right] dt \quad + \quad \frac{1}{2\sqrt{\gamma}} \underbrace{dW_t^{(x)}}_{\text{Wiener process}}$$

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2. An equation for the system density matrix

$$\mathrm{d}\hat{\rho} \quad = \quad -i[\hat{H},\hat{\rho}]\mathrm{d}t - \underbrace{\frac{\gamma}{2}\int \mathrm{d}x\,[\hat{M}_\sigma(x),[\hat{M}_\sigma(x),\hat{\rho}]]\,\mathrm{d}t}_{\text{decoherence in position}}$$

$$+\underbrace{\sqrt{\gamma}\int \mathrm{d}x\,\left(\hat{M}_\sigma(x)\hat{\rho}_t + \hat{\rho}_t\hat{M}_\sigma(x) - 2\mathrm{tr}[\hat{M}_\sigma(x)\hat{\rho}_t]\rho_t\right)\,\mathrm{d}W_t^{(x)}}_{\text{localization in position}}.$$

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Two points of view on the signal $m_t(r)$

We define the "mass density" classical stochastic field

$$m_t(x) = \frac{ds_t(x)}{dt} = \langle \hat{M}_\sigma(x) \rangle_t + \text{noise}$$

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1. A field of weak measurement results
2. A continuous analog of the GRW flashes, which can be taken as the primitive ontology of the theory, a "reality" field.

The first point will help insure the mathematical consistency of the theory, the second will make it philosophically appealing.

Aparté on $m_t(r)$

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2. Formally, the "signal" is the "primitive" quantity, the "average" comes from a subsequent Doob decomposition.
3. One can assume that it is known locally without providing an opportunity for FTL signaling
4. Interestingly, it gives meaning to the statement "everything is information" (what is real is what people would call information in orthodox quantum mechanics)

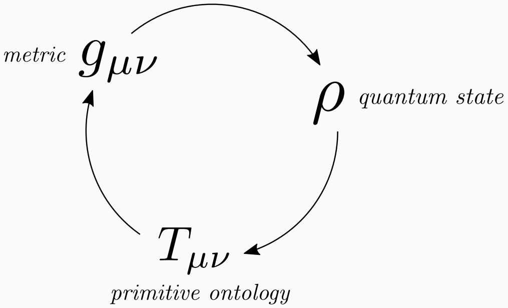
Measuring $\hat{T}_{\mu\nu}$

Suppose we had a relativistic collapse model corresponding to the continuous measurement of $\hat{T}_{\mu\nu}$. We could simply plug the “signal” as a source for Einstein equation.

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Formally, this would equivalent to a local measurement based feedback in ordinary QFT $\to$ Born rule preserved, no FTL signalling, no funny business.

Schematically



The primitive ontology curves space-time which in turn determines the dynamics of the quantum state which fixes the statistics of the stochastic field constituting the primitive ontology.

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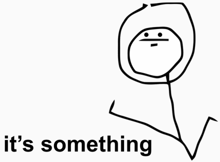
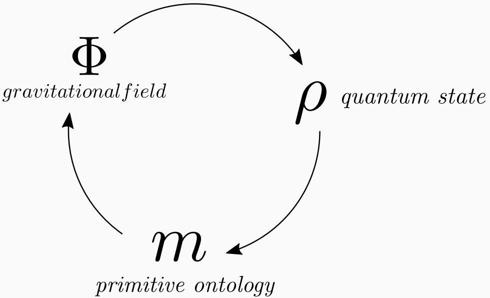
MARRYING THE TWO

Newtonian limit

Actually, building consistent relativistic collapse models is hard. But the problems of semi-classical gravity appear in the non-relativistic limit! Solving problems in the Newtonian limit would already be something...



New schematics in the Newtonian limit



The primitive ontology (now a regularized mass density) creates the gravitational field which in turn determines the dynamics of the quantum state which fixes the statistics of the stochastic field constituting the primitive ontology.

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Equations

Poisson equation to get the gravitational field from the mass "signal":

$$\nabla^2 \Phi = 4\pi G \underbrace{m}_{\text{P.O.}}$$

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Define the gravitational potential from the gravitational field:

$$\hat{V} = \int d^3x \, \Phi(x) \, \hat{M}_{(\sigma)}(x)$$

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Add the potential to the evolution of the quantum state $H \to H + \hat{V}$:

$$\hat{\rho} + d\hat{\rho} = e^{-i\hat{V}dt}(\hat{\rho} + d\hat{\rho}^{\text{free}})e^{i\hat{V}dt}.$$

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RESULT

$$\begin{aligned} d\hat{\rho}_t = \text{what we had before} - i\left[\hat{V}_{new}, \hat{\rho}\right] dt \\ - \frac{1}{2\gamma}\int dx\, [\hat{\Phi}_{(\sigma)}(x), [\hat{\Phi}_{(\sigma)}(x), \hat{\rho}_t]]\, dt \\ + \frac{i}{\sqrt{\gamma}}\int dx\left(\hat{\Phi}_{(\sigma)}(x)\hat{\rho}_t - \hat{\rho}_t\hat{\Phi}_{(\sigma)}(x)\right) dW_t^{(x)} \end{aligned} \quad (1)$$

with a new pair potential $\hat{V}_{new}$:

$$\hat{V}_{new} = -\frac{G}{2}\int dx \frac{\hat{M}_{\sigma}(x)\,\hat{M}_{(\sigma)}(x)}{|x-y|}$$

and $\hat{\Phi}_{(\sigma)}$ is the operator:

$$\hat{\Phi}_{(\sigma)}(x) = -G\int dy \frac{\hat{M}_{(\sigma)}(y)}{|x-y|}$$

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Summary in words

1. In the end, we get a simple direct pair-potential, **without self-interaction** [only constant self-energy].

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2. Additional decoherence term **inversely proportional** to the original one. Gives experimental constraints on the **lower bound** of the collapse rate.

A few words on Diósi-Penrose

We have done computations for any generic continuous localization models. In D.-P. there are a few differences from CSL:

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1. The $\sigma-$smearing is not optional in the "feedback" part
2. The additional decoherence takes the same form as the original decoherence (but for a different prefactor)
3. Requiring that the total decoherence be minimal fixes the collapse rate to the gravitational constant G and gives relatively compact equations in the end.

Difficulties

- "Relativization" is not a trivial hurdle to overcome
- Still additional constants of nature

CONCLUSION

Difficulties

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- Still additional constants of nature

To do

See what the theory would say in specific situations to tackle what people consider to be “hard problems”

- Inflationary cosmology
- Black-hole horizons and information paradoxes

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A few lessons

- Self-interaction is **not** a necessary feature of fundamental semi-classical gravity.
- "Signal" ontology is a nice P.O. because it allows for quantum-classical coupling.
- Collapse models seem to be the only way to do this hybrid coupling while preserving the statistical properties of the quantum state (makes them slightly less ad-hoc).

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