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RESEARCH

A healthier stochastic semiclassical gravity: world without Schrödinger cats

Lajos Diósi[1,2]

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Abstract

Semiclassical gravity couples classical gravity to the quantized matter in meanfield approximation. The meanfield coupling is problematic for two reasons. First, it ignores the quantum fluctuation of matter distribution. Second, it violates the linearity of the quantum dynamics. The first problem can be be mitigated by allowing stochastic fluctuations of the geometry but the second problem lies deep in quantum foundations. Restoration of quantum linearity requires a conceptual approach to hybrid classical-quantum coupling. Studies of the measurement problem and the quantum-classical transition point the way to a solution. It is based on a postulated mechanism of spontaneous quantum monitoring plus feedback. This approach eliminates Schrödinger cat states, takes quantum fluctuations into the account, and restores the linearity of quantum dynamics. Such conceptionally 'healthier' semiclassical theory is captivating, exists in the Newtonian limit, but its relativistic covariance hits a wall. Here we will briefly recapitulate the concept and its realization in the nonrelativistic limit. We emphasize that the long-known obstacles to the relativistic extension lie in quantum foundations.

Keywords Semiclassical gravity · Back-reaction · Quantum monitoring and feedback · Quantum foundations

Contents

✉ Lajos Diósi
diosi.lajos@wigner.hu

1 Wigner Research Center for Physics, 29-33 Konkoly-Thege M. Str., Budapest 1121, Hungary

2 Eötvös Loránd University, Pázmány Péter stby. 1/A, Budapest 1117, Hungary

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1 Introduction

Quantum theory was invented for the microscopic world, and proved accurate there. Is it valid in the macroscopic world as well? Is quantum theory universal from particle physics to cosmology? We might like to think so. Except that the experimental evidences are lacking, the relevant quantum gravity theories limp along, and there are crippling conceptual problems. Maybe we cannot quantize gravity because it does not need to be quantized: space-time is classical. Then Einstein classical metrics would interact with the quantized fields of matter. This raises the problem of hybrid classical-quantum coupling. The prototype of such hybrid dynamics is the standard semiclassical gravity [1, 2], based on the semiclassical Einstein equation:

$$G_{ab}(x) = 8\pi G\langle\Psi|\hat{T}_{ab}(x)|\Psi\rangle. \tag{1}$$

The curvature of the space-time is sourced by the quantum expectation value—the meanfield—of the energy-momentum operator of the matter. The fluctuations of $\hat{T}_{ab}$ are ignored, do not back-react on the space-time geometry but the mean values do. Standard semiclassical gravity is plagued by fundamental anomalies because the meanfield coupling violates the obligate linearity of quantum dynamics (see in Sect. 2).

The stochastic semiclassical gravity [3, 4] takes lowest order quantum fluctuations into the account. It mimics them by the zero-mean stochastic field δT_{ab}, defined by the following quantum correlator

$$\mathsf{E}\delta T_{ab}(x)\delta T_{cd}(y) = \mathrm{Herm}\langle\Psi|\hat{T}_{ab}(x)\hat{T}_{cd}(y)|\Psi\rangle - \langle\Psi|\hat{T}_{ab}(x)|\Psi\rangle\langle\Psi|\hat{T}_{cd}(y)|\Psi\rangle. \tag{2}$$

Then the modified semiclassical equation

$$G_{ab} = 8\pi G\left(\langle\Psi|\hat{T}_{ab}|\Psi\rangle + \delta T_{ab}\right) \tag{3}$$

implies stochastic fluctuations δg_{ab} of the metrics as well. Unfortunately, this stochastic semiclassical gravity does not mitigate the fundamental anomalies of the semiclassical Einstein equation.

Reviving the concept of spontaneous quantum monitoring plus feedback [5], we proposed the 'conceptionally healthier semiclassical' gravity [6, 7] which is free of the said anomalies. It ensures the obligate linearity of quantum dynamics since it is based on standard measurement-plus-feedback mechanisms. Accordingly, one assumes that the energy-momentum operator $\hat{T}_{ab}$ is universally monitored, i.e.: measured everywhere and every time. The monitored (measured) value is a classical random tensor field:

$$T_{ab} = \langle\Psi|\hat{T}_{ab}|\Psi\rangle + \delta T_{ab} \tag{4}$$

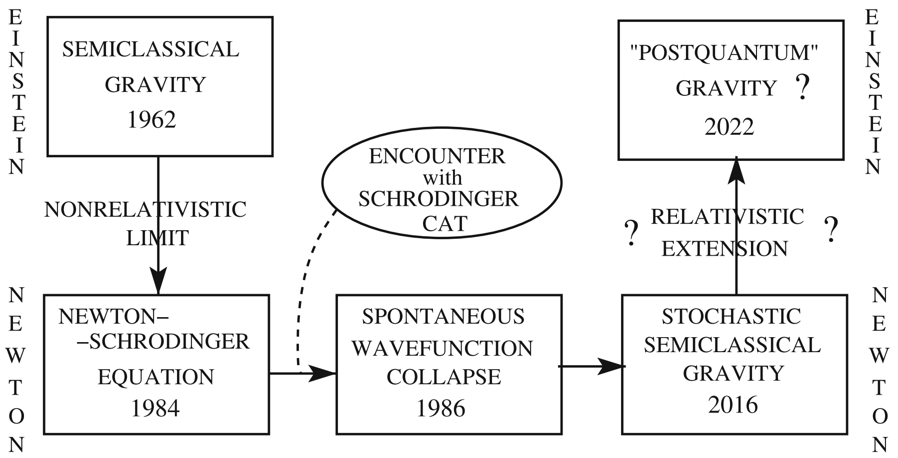
with stochastic fluctuation δT_{ab} around the meanfield. This monitored value is then used for feedback on the r.h.s. of the classical Einstein equation. This T_{ab} coincides formally with the expression in the phenomenological equation (3) of stochastic semiclassical gravity but the difference is crucial. The stochastic term is defined differently.

It is just the measurement noise and its correlation is determined by the chosen precision and correlations of the local measurements constituting the monitoring setup:

$$\mathsf{E}\delta T_{ab}(x)\delta T_{cd}(y) = D_{ab|cd}(x, y). \tag{5}$$

The r.h.s. must be a covariant translation invariant non-negative kernel. Our proposal differs from the phenomenological stochastic theory [3, 4] in a second way, too. The dynamics of the state Ψ must contain the non-Hamiltonian influence of the monitoring. However promising this project was, refs. [5–7] could have only realized the Newtonian non-relativistic limit,. with the clear identification of the obstacle to the relativistic version. Interestingly, the formalism of the 'healthier' semiclassical dynamics was recently applied relativistically, see [8, 9] and refs. therein. The so-called postquantum gravity [8] would be a 'healed' semiclassical gravity, consistent with quantum theory.

This work proposes a tour. We start from the standard semiclassical gravity and then we 'descend' to its non-relativistic Newtonian limit. This is the best way to identify the fundamental quantum anomalies of the meanfield coupling and their resolution by the 'healthy' stochastic modification postulating the mechanism of spontaneous quantum monitoring and feedback. Then we try to 'ascend' to the relativistic realization but we will find the old obstacle that we had known before.



2 Semiclassical gravity

Consider a given foliation of the space-time in spacelike hypersurfaces Σ and the Schrödinger state vector $|\Psi_\Sigma\rangle$ on it. The classical metric g_{ab} which will be the solution of the semiclassical Einstein equation (6). The state vector of the quantized matter evolves with the Tomonaga–Schwinger equation (7) where the Hamiltonian density $\hat{\mathcal{H}}$ depends on the solution g_{ab} which is the Ψ-dependent solution of Eq. (6) causing the non-linearity of Eq. (7):

$$G_{ab}(x) = 8\pi G \langle \Psi_\Sigma | \hat{T}_{ab}(x) | \Psi_\Sigma \rangle, \qquad (x \in \Sigma), \tag{6}$$

$$\frac{\delta |\Psi_\Sigma\rangle}{\delta \Sigma(x)} = -i\hat{\mathcal{H}}(x) |\Psi_\Sigma\rangle. \tag{7}$$

The semiclassical gravity [1, 2] is a powerful hybrid dynamics of classical gravity and quantized matter. In the Newtonian limit the semiclassical eqs. (6,7) become much simpler:

$$\Phi(r,t) = \Phi_{\mathrm{mf}}(r,t) = -G \int \langle \Psi_t | \hat{\mu}(r') | \Psi_t \rangle \frac{d^3 r'}{|r - r'|}, \tag{8}$$

$$\begin{aligned} \frac{d|\Psi_t\rangle}{dt} &= -i\left(\hat{H} + \int \hat{\mu}(r)\Phi_{\mathrm{mf}}(r,t) d^3 r\right) |\Psi_t\rangle \\ &= -i\left(\hat{H} - G \int\int \hat{\mu}(r) \langle \Psi_t | \hat{\mu}(r') | \Psi_t \rangle \frac{d^3 r d^3 r'}{|r - r'|}\right) |\Psi_t\rangle \end{aligned} \tag{9}$$

where Φ_{mf} is the mean-field Newton potential, μ is the distribution of non-relativistic mass density and $\hat{H}$ is the self-Hamiltonian. Observe that the semiclassical equation (9) of non-relativistic quantized matter, called the Schrödinger–Newton equation, does not contain the trivial Newton pair-potential

$$\hat{V}_G = -G \int\int \hat{\mu}(r)\hat{\mu}(r') \frac{d^3 r d^3 r'}{|r - r'|}. \tag{10}$$

Instead, it contains a non-linear meanfield term $\hat{V}_G^{\mathrm{mf}}$ to represent gravity's back-reaction:

$$\hat{V}_G^{\mathrm{mf}} = -G \int\int \hat{\mu}(r) \langle \hat{\mu}(r') \rangle \frac{d^3 r d^3 r'}{|r - r'|}. \tag{11}$$

Note incidentally, that the Eq. (9) had already been used for quantized stellar masses [10]. For long time, impressed by relativistic field theories, its relevance at low energies has remained overlooked. It was revealed finally [11, 12] that both gravity and quantumness might become relevant together non-relativistically for massive degrees of freedoms, e.g., in center-of-mass motion of of objects with masses of the order of nanograms.

The Newtonian limit (8,9) not only perpetuates the fundamental anomalies of semiclassical gravity (6,7) but also understands the causes [13]. Core problems are fake-action-at-a-distance (aka causality violation relativistically) and the breakdown of Born's statistical interpretation of the wavefunction Ψ. They are caused by the Ψ-dependent meanfield potential Φ_{mf} in the Schrödinger–Newton equation (9). The meanfield coupling $\langle \Psi | \hat{\mu} | \Psi \rangle$ should be blamed.

What else should we use? It is necessary that we consider the possible hybrid classical-quantum (CQ) couplings in the light of quantum foundations. Action of C on Q is parametric and makes no problem. Back-reaction of Q on C is the major issue. Still, the answer is there in the fundaments of quantum theory. About an *individual* quantum system, quantum measurement is the only way to consistently define classical variables. Classical numbers like $\langle \Psi | \hat{\mu} | \Psi \rangle$ are not classical variables, their coupling to classical systems is illegitimate. Only the random measurement outcomes are legitimate classical variables suitable to couple to other classical variables. A lesson is important here. Reversibility of hybrid systems is lost for two reasons. First, measurement imposes decoherence on Q. Second, coupling to the random measurement outcome imposes stochasticity of C.

So, back-reaction of quantized matter on classical gravity is only possible via the random measurement outcomes μ of $\hat{\mu}$-monitoring, instead of the meanfield $\langle\Psi|\hat{\mu}|\Psi\rangle$. The measured outcomes $\mu(r,t)$ contain the mean values plus the measurement noise:

$$\mu(r,t) = \langle\Psi_t|\hat{\mu}(r)|\Psi_t\rangle + \delta\mu(r,t), \tag{12}$$

where $\delta\mu$ is a white noise with possible spatial correlations. Accordingly, the calculated Newton potential, too, contains an additional white noise:

$$\delta\Phi(r,t) = -G\int \delta\mu(r',t)\frac{d^3r'}{|r-r'|}. \tag{13}$$

In the Schrödinger–Newton Eq. (9), we shall replace the meanfield Φ_{mf} by $\Phi_{\text{mf}} + \delta\Phi$ for reconciliation of the stochastically modified Schrödinger–Newton semiclassical equation with standard quantum theory. But first we need to answer two questions. Who is measuring (monitoring) the mass density $\hat{\mu}$? That's the truly sensitive question. The other one is more technical: how to parametrize the $\hat{\mu}$-monitoring, i.e., how to choose the spatial correlations of $\delta\mu$. Towards answering both questions, Sect. 3 recalls the postulate of single spontaneous collapse and its gravity-related parametrization. This single spontaneous collapse is then upgraded into the postulate of spontaneous monitoring of the mass density μ. Monitoring means time-continuous measurement. Spontaneity means that no instruments (no observers) are present while the dynamics is undergoing the same standard stochastic modifications as if they were there.

3 Spontaneous collapse of Schrödinger cats

If we extend the validity of quantum theory for large masses, and this is what we do if we believe in quantum cosmology, then we are faced with some counterintuitive situations. The paradigmatic one is the Schrödinger cat state. Consider the quantized center-of-mass motion of a macroscopic mass M prepared in a balanced superposition on the 'left' and 'rigth' respectively, with macroscopic distance from each other. The existence of such a state is trivial in the nontrivial manyworld interpretation of the quantum theory, at least paradoxical in conservative quantum theory, and viewed nonsense by some. Without taking side, one can speculate about a quantum theory that is free of such massive macroscopic superpositions. We postulate the collapse of the macroscopic superposition as if it would happen under a measurement, to happen spontaneously this time:

$$
|CAT\rangle = \frac{|\mathrm{LEFT}\rangle + |\mathrm{RIGHT}\rangle}{\sqrt{2}} \rightarrow \begin{cases} |\mathrm{LEFT}\rangle \\ \quad \mathrm{or} \\ |\mathrm{RIGHT}\rangle \end{cases} . \tag{14}
$$

We should propose a collapse time. Let us follow the proposal of Penrose and the present author. At this point gravitation and Schrödinger cats encounter. Quantized massive objects in spacetime lead to controversies with sharply defined Newtonian potential non-relativistically [14] and with sharply defined time-flow relativistically [12]. Therefore we allow a certain unsharpness $\delta\Phi$ of the Newton potential (of the time-flow, relativistically). If this unsharpness is represented stochastically by a white noise then, despite their different explanations, the proposals in refs. [14] and [12], resp., correspond to the same measure of unsharpness:

$$
\mathsf{E}\delta\Phi(r,t)\delta\Phi(r',t') = \frac{\hbar G/2}{|r-r'|}\delta(t-t'), \tag{15}
$$

Both authors derive that this unsharpness leads to the following characteristic rate of the collapse:

$$
\frac{1}{\tau} = \frac{V_G^i - V_G^f}{\hbar}, \tag{16}
$$

where V_G^i and V_G^f are formally identified as the classical Newtonian pair-potential between two copies of the mass M in the separate and the coincident positions, respectively. Now we see that the postulated spontaneous collapse is ignorable in the microscopic degrees of freedom but it becomes dominant gradually for large masses. The collapse rate, still negligible ($\sim 10^{-6}/s$) for a femtogram, is overwhelming fast ($\sim 10^6/s$) for a milligram mass already.

The non-relativistic theory [14, 15] and [12], based on the above postulate of gravity-related spontaneous collapse rates, is a possible explanation of the classical-quantum transition, a world without Schrödinger cats and a theory without the measurement problem. The next section upgrades it into the consistent non-relativistic hybrid dynamics of quantized matter and classical gravity.

4 On the healthier semiclassical gravity

As Sect. 2 anticipated, the meanfield Newton potential (8) is completed by a noise term:

$$
\begin{aligned}
\Phi(r,t) &= -G\int \left(\langle\Psi_t|\hat{\mu}(r')|\Psi_t\rangle + \delta\mu(r',t)\right)\frac{d^3r'}{|r-r'|} \\
&= \Phi_{\mathrm{mf}}(r,t) + \delta\Phi(r,t).
\end{aligned} \tag{17}
$$

This corresponds to the Newton field sourced by the spontaneously monitored value $\langle\Psi_t|\hat{\mu}(r)|\Psi_t\rangle + \delta\mu(r,t)$ of the mass density. Sec. 3 proposed the expression (15) for the statistics of the noise and we repeat it here for completness:

$$\mathsf{E}\delta\Phi(r,t)\delta\Phi(r',t') = \frac{\hbar G/2}{|r-r'|}\delta(t-t'). \tag{18}$$

If in the Schrödinger–Newton Eq. (9) we replace the meanfield $\Phi_{\rm mf}$ by the expression (17) then we obtain the following:

$$\begin{aligned}\frac{d|\Psi_t\rangle}{dt} &= -\frac{i}{\hbar}\left(\hat{H}_0 + \hat{V}_G^{\rm mf} + \int \hat{\mu}(r)\delta\Phi(r,t))d^3r\right)|\Psi_t\rangle \\ &\quad -\frac{G}{2\hbar}\int\int \frac{\left(\hat{\mu}(r) - \langle\hat{\mu}(r)\rangle_t\right)\left(\hat{\mu}(r') - \langle\hat{\mu}(r')\rangle_t\right)}{|r-r'|}d^3rd^3r'|\Psi\rangle \\ &\quad +\frac{1}{\hbar}\int \left(\hat{\mu}(r) - \langle\hat{\mu}(r)\rangle_t\right)\delta\Phi(r,t)d^3r|\Psi_t\rangle. \end{aligned} \tag{19}$$

The Schrödinger–Newton equation (9) has become modified in three ways. The first line results from the back-reaction engineered by $\Phi_{\rm mf} + \delta\Phi$. The second line contains the decoherence term because the $\hat{\mu}$-monitoring causes dynamic suppression of $\hat{\mu}$'s quantum fluctuations. The third line contains a further term with $\delta\Phi$ and represents the random effect of monitoring. We emphasize that whence the correlation (18) is fixed, the postulated spontaneous monitoring leads uniquely to this result (19) via the standard calculus of quantum monitoring and feedback [6, 7].

Although the 'healthier' semiclassical equations (17–19) are consistent by construction with quantum theory, there is an equivalent formalism where the linearity is restored explicitly. If by the relatioship $\Phi(r,t) = d\chi_t(r)/dt$ we introduce the field χ, we can see that χ_t and Ψ_t undergo correlated diffusions respectively in the functional and Hilbert space. Namely, $d\chi/dt$ is driven by the white noise $\delta\Phi$ according to Eq. (17), meaning its diffusion in the functional space, and $d|\Psi_t\rangle/dt$ is also driven by $\delta\Phi$ according to Eq. (19), meaning its diffusion in the Hilbert space. Therefore the couple (χ, Ψ) can be described by the hybrid of the Fokker–Planck and Lindblad equations. Using the hybrid $\hat{\rho}[\chi]$ of the probability density $\rho[\chi] = \mathrm{tr}\hat{\rho}[\chi]$ and of the density operator $\hat{\rho} = \int \hat{\rho}[\chi]d[\chi]$, ref. [16] derives the following hybrid master equation from the stochastic equations (17–19):

$$\begin{aligned}\frac{d\hat{\rho}[\chi]}{dt} &= -\frac{i}{\hbar}[\hat{H}_0 + \hat{V}_G, \hat{\rho}[\chi]] \\ &\quad +G\iint\left(-\frac{1}{2\hbar}[\hat{\mu}(r),[\hat{\mu}(s),\hat{\rho}[\chi]]] + \mathrm{Herm}(1+i)\hat{\mu}(r)\frac{\delta\hat{\rho}[\chi]}{\delta\chi(s)} + \frac{\hbar}{4}\frac{\delta^2\hat{\rho}[\chi]}{\delta\chi(r)\delta\chi(s)}\right) \\ &\quad \frac{d^3rd^3s}{|r-s|}. \end{aligned} \tag{20}$$

The non-unitary mechanisms are represented by the second line. The first term corresponds to the suppression of $\hat{\mu}$'s 'macroscopic' quantum fluctuations, the middle term is responsible for the back-reaction of $\hat{\mu}$ on the classical Newton potential, and the third term stands for the diffusion of the classical Newton potential. The most important new feature of the above hybrid master equation is the appearance of the Newton pair-potential (10) in place of the non-linear meanfield term $\hat{V}_G^{\rm mf}$ (11) in the Schrödinger–Newton Eq. (9).

The formal relativistic counterpart of either the stochastic eqs. (17–19) or the equivalent master equation (20) can obviously be constructed. The stochastic ones would look like this:

$$G_{ab}(x) = 8\pi G\left(\langle\Psi_\Sigma|\hat{T}_{ab}(x)|\Psi_\Sigma\rangle + \delta T_{ab}(x)\right), \qquad (x\in\Sigma), \tag{21}$$

$$\mathsf{E}\delta\hat{T}_{ab}(x)\hat{T}_{cd}(y) = D_{ab|cd}\delta(x-y), \tag{22}$$

$$\frac{\delta|\Psi_\Sigma\rangle}{\delta\Sigma(x)} = -i\hat{\mathcal{H}}(x)|\Psi_\Sigma\rangle + \left\{\begin{array}{c}\text{nonlinear}\\ \text{stochastic}\end{array}\right\}\text{terms of monitoring.} \tag{23}$$

Such might be the structure of full relativistic equations of the 'healed' stochastic semiclassical gravity, The equivalent hybrid master equation of classical metrics and the quantized relativistic matter would contain the three terms: decoherence term to suppress $\hat{T}_{ab}$'s large quantum fluctuations, back-reaction of $\hat{T}_{ab}$ on the metrics g_{ab}, and the term for the diffusion of g_{ab}. The formal construction of the related 'postquantum' gravity faces multiple issues (e.g.: ensuring diffeomorfism invariance, renormalizability of divergences) recognized immediately [8, 9]. As we mentioned, the theory follows uniquely if the correlation (22) has been chosen. The issues culminate right here. The covariant correlation must contain the four-dimensional $\delta(x-y)$ and it leads to divergences. No covariant regularization and renormalization methods are available.

The obstacles are not simply technical ones, they are multiply rooted in foundations. Wavefuntion collapse depends on the reference frame hence the covariant formalism of selective quantum measurements and quantum monitoring is problematic. On the classical end, diffusion cannot be made relativistic, nor even special relativistic [16].

5 Closing remarks

Unified theory of space-time with quantized matter and the physics of quantum measurement were considered unrelated for long time, studied by two separate research communities. Quantum cosmologists used heavy artillery of mathematics. Quantum measurement problem 'solvers'-, with the present author among them, used light weapons and sometimes whimsical identification of their problems, e.g. in terms of the Schrödinger cat paradox. The bottle-neck of quantum gravity may be this paradox, not the math difficulties to find a good framework of quantization. An improved but still semiclassical theory might be based on the non-relativistic theory of spontaneous quantum monitoring and feedback, eliminating Schrödinger cat states. Such healthier theory exists non-relativistically but its relativistic - even Lorentzian - extension remains a problem.

It seems that the consistent hybrid theory of quantized matter and classical gravity based on relativistic calculus of monitoring plus feedback was first discussed longtime ago [5], with the warning that the relativistic calculus may pose serious problems. Much later, the authors of refs. [6, 7] have repeatedly argued that the 'healthier' relativistic semiclassical gravity is blocked by the continued lack of a relativistic model for quantum monitoring. The recent proposal of 'postquantum' gravity ([8, 9] and refs. therein) is optimistic about the future resolution of its difficulties but it is not conscious of where the difficulties stem from. Refs. [16, 17] point out in strict accordance with the previous warnings [5–7] that the ultimate difficulties of the 'healthier' relativistic hybrid dynamics are difficulties of relativistic quantum monitoring. It seems that as long as this latter is missing, the 'postquantum' gravity cannot be complete. Until we discover the theory of relativistic quantum monitoring, if it exists, the foundational application of the 'healthier' semiclassical dynamics in its present form remains an unfulfilled promise though by no means finally discarded.

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