A healthier stochastic semiclassical gravity: world without Schrödinger cats

Lajos Diósi

Wigner Research Center for Physics

Eötvös Loránd University

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Abstract

Semiclassical gravity couples classical gravity to the mean field of quantized matter, ignores quantum fluctuation of matter distribution, violates linearity of quantum dynamics. The first problem can 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: a postulated mechanism of spontaneous quantum monitoring plus feedback. This approach eliminates Schrödinger cat states, takes quantum fluctuations into account, and restores the linearity of quantum dynamics. Such conceptually 'healthier' semi-classical theory exists in the Newtonian limit, but relativistic covariance hits a wall.

Healthier semiclassical gravity: what would it be?

- Semiclassical Gravity (SCG) (Moller,Rosenfeld):

$$G_{ab} = 8\pi G c^{-4} \langle\Psi|\hat{T}_{ab}|\Psi\rangle$$

ignores quantum fluctuations of $\hat{T}_{ab}$, violates linearity of QM.

- Stochastic SCG (Martin&Verdaguer,Hu&Verdaguer)

$$G_{ab} = 8\pi G c^{-4} \left(\langle\Psi|\hat{T}_{ab}|\Psi\rangle + \delta T_{ab}\right)$$

mimics quantum fluctuations of $\hat{T}_{ab}$ by stochastic field δT_{ab}.

- 'Healthier' Stochastic SCG (Tilloy&D,Oppenheim&al.)

$$G_{ab} = 8\pi G c^{-4} T_{ab}^{signal}$$

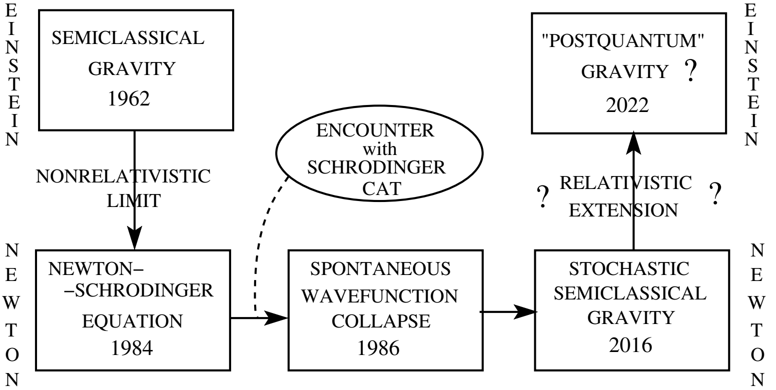
includes fluctuations of $\hat{T}_{ab}$, restores linearity of QM.
$T_{ab}^{signal} = \hat{T}_{ab}$'s spontaneously monitored value $= \langle\Psi|\hat{T}_{ab}|\Psi\rangle + \delta T_{ab}^{noise}$
Structure/precision of spontaneous monitoring is defined by

$$\mathrm{E}\left[\delta T_{ab}^{noise}(x)\delta T_{cd}^{noise}(y)\right] = D_{ab|cd}(x,y).$$

Obstacle: no sensible covariant choice for $D_{ab|cd}(x,y)$.

Encounter of gravity with Schrödinger Cats

Start a tour. From standard SCG we 'descend' to its non-relativistic Newtonian limit. Construct the 'healthy' stochastic SCG based on spontaneous quantum monitoring and feedback. Then 'ascend' to the relativistic realization and find the old obstacles.



Standard SCG (Moller,Rosenfeld)

Powerful effective hybrid dynamics for $(\mathrm{g}_{ab}, |\Psi\rangle)$:

$$\begin{aligned} \frac{d|\Psi\rangle}{dt} &= -\frac{i}{\hbar}\hat{H}[\mathrm{g}]|\Psi\rangle \qquad \textit{action (nonlinear)} \\ \mathrm{G}_{ab} &= \frac{8\pi G}{c^4}\langle\Psi|\hat{\mathrm{T}}_{ab}|\Psi\rangle \quad \textit{backaction} \end{aligned}$$

Breakdown of causality and Born statistical interpretation!
unrelated to relativity (and gravitation, btw)
but to fundamentals of quantum mechanics

Hence we discuss the nonrelativistic limit first.
And we (try to) go back to general relativity after it.

Nonrelativistic SCG (Schrödinger-Newton Eq.

(D.,Penrose)

$\hat{\mu} = \hat{\mathrm{T}}_{00}/c^2 =$ quantized field of nonrelativistic mass density

$$\begin{aligned} \frac{d|\Psi\rangle}{dt} &= -\frac{i}{\hbar}\left(\hat{H}_0 + \int \hat{\mu}\Phi dV\right)|\Psi\rangle \quad & \textit{action (nonlinear)} \\ \nabla^2\Phi &= 4\pi G\langle\Psi|\hat{\mu}|\Psi\rangle & \textit{backaction} \end{aligned}$$

Breakdown of causality and Born statistical interpretation is caused by the nonlinear term in the Schrödinger equation, semiclassicality of coupling $\langle\Psi|\hat{\mu}|\Psi\rangle$ should be blamed.

Surprize: Quantumgravity is thought to be relevant at extreme large energies or curvatures. But SNE shows that both gravity and quantumness can become relevant together nonrelativistically for large masses, already for nanogram's.
Doors open: 'Newtonian Qauntumgravity' for theorists,
'Quantumgravity in the Lab' for experimentalists.

Hybrid Classical-Quantum Coupling — Foundations

Action of C on Q can be trivial (parametric)
Backaction of Q on C is a major issue.

About a quantum system, quantum measurement is the only mean to consistently define classical variables.

About an individual quantum system:
classical numbers like $\langle\Psi|\hat{\mu}|\Psi\rangle$ are not classical variables but the random measurement outcomes are.

Action of quantized matter on classical gravity is only possible via the random outcomes of quantum measurement on $\hat{\mu}$ (instead of $\langle\Psi|\hat{\mu}|\Psi\rangle$) which contains a stochastic term:

$$\mu^{signal} = \langle\Psi|\hat{\mu}|\Psi\rangle + \delta\mu^{noise}$$

Consistent hybrid classical-quantum coupling is irreversible.
Now, who is measuring $\hat{\mu}$?

Spontaneous collapse of Schrödinger Cats (D.,Penrose)

$$|CAT\rangle = \frac{|\text{LEFT}\rangle + |\text{RIGHT}\rangle}{\sqrt{2}} \rightarrow \begin{cases} |\text{LEFT}\rangle \\ \text{or} \\ |\text{RIGHT}\rangle \end{cases}$$

SPONTANEOUS COLLAPSE RATE:

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

V_G^i, V_G^f: gravitational self-energy before/after collapse

Negligible effect for small, dominant for large masses:

$\tau_{1fg} \sim 10^6 s$ but $\tau_{1mg} \sim \mu s$.

DP Gravity-Related Spontaneous Collapse (D.)

Generalizaing spontaneous collapse of Schrödinger Cats

Time-continuous spontaneous collapse of massive macrosopic superpositions

Concept: spontaneous monitoring of $\hat{\mu}$

$$\begin{aligned} \frac{d|\Psi\rangle}{dt} &= -\frac{i}{\hbar}\hat{H}_0|\Psi\rangle \\ &\quad + \mathit{stochastic\ terms\ of\ monitoring}\ \hat{\mu} \\ \mu^{signal} &= \langle\Psi|\hat{\mu}|\Psi\rangle + \delta\mu^{noise} \end{aligned}$$

$\mu^{signal}(\mathbf{r}, t)$ is diffusing around $\langle\Psi(t)|\hat{\mu}(\mathbf{r})|\Psi(t)\rangle$.

$$\mathit{Diffusion\ matrix}: D_\mu(\mathbf{r},\mathbf{s}) = -4\pi\frac{\hbar}{G}\nabla^2\delta(\mathbf{r}-\mathbf{s})$$

EXPLAINS HOW QM GOES CLASSICAL IN THE MACRO-WORLD “WITHOUT SCH CATS”

On spontaneous measurement

Spontaneous/objective measurement/collapse/reduction
acts on $|\Psi\rangle$ and yields measurement outcome
just like standard quantum measurement does
but without assuming the presence of measurement device.
Like standard measurements,
it is stochastic, irreversible, violates conservation rules,
non-relativistic, resists to relativistic extension
Spontaneous monitoring (time-continuous generalization)
acts on $|\Psi\rangle$ and yields measurement outcome (signal),
just like standard quantum monitoring does
but without assuming the presence of lab devices.

Healthier SCG - Newtonian limit (Tilloy&D.)

Causality and Born statistical interpretation restored
Reversibility lost

$$\frac{d|\Psi\rangle}{dt} = -\frac{i}{\hbar}\left(\hat{H}_0 + \int \hat{\mu}\Phi dV\right)|\Psi\rangle$$
$$+stochastic\ terms\ of\ monitoring\ \hat{\mu}$$
$$\nabla^2\Phi = 4\pi G\left(\langle\Psi|\hat{\mu}|\Psi\rangle + \delta\mu^{noise}\right)$$

Feedback of solution Φ in the Hamiltonian yields

$$\frac{d|\Psi\rangle}{dt} = -\frac{i}{\hbar}\left(\hat{H}_0 - G\int\int\frac{\hat{\mu}(\mathbf{r})\hat{\mu}(\mathbf{s})}{|\mathbf{r}-\mathbf{s}|}d\mathbf{r}d\mathbf{s}\right)|\Psi\rangle$$
$$+stochastic\ terms\ of\ monitoring\ \hat{\mu}$$
$$+stochastic\ terms\ of\ feedback\ of\ \Phi$$

Prices to pay:
tiny nonunitarity because $|\Psi\rangle$ collapses
tiny stochasticity of gravity because of $\delta\mu^{noise}$

Healthier SCG - Relativistic?

Concept and obstacles (Tilloy-D.), incomplete 'Postquantum' Gravity (Oppenheim et al.)

Concept: spontaneous monitoring $\hat{\mathrm{T}}_{ab}$

$$\begin{aligned}\frac{d|\Psi\rangle}{dt} &= -\frac{i}{\hbar}\hat{H}[\mathrm{g}]|\Psi\rangle + \\ &\quad + \textit{stochastic contribution of monitoring} \\ \mathrm{G}_{ab} &= \frac{8\pi G}{c^4}\left(\langle\Psi|\hat{\mathrm{T}}_{ab}|\Psi\rangle + \delta\mathrm{T}^{noise}_{ab}\right)\end{aligned}$$

Metric g_{ab} is diffusive because T^{signal}_{ab} is diffusive.
Diffusion matrix (kernel) of T^{signal}_{ab}:

$$\mathsf{E}\left[\delta\mathrm{T}^{noise}_{ab}(x)\delta\mathrm{T}^{noise}_{cd}(y)\right] = D_{ab|cd}(x)\delta(x,y)$$

NO COVARIANT CHOICE of $D_{ab|cd}$.

Obstacle lies in foundations:

Markovian quantum monitoring may not be relativistic.
Non-Markovian quantum monitoring is not yet fully understood.

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 speaker 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. A 'healthier' semiclassical theory -postulates spontaneous wavefunction monitoring and eliminates Schrödinger cat states. Such 'healthier' theory exists nonrelativistically but its relativistic - even Lorentzian - extension remains a problem.

The ultimate difficulties are difficulties of relativistic quantum monitoring. Until we understand it, if it exists at all, the 'healthier' relativistic SCG remains an unfulfilled promise though by no means finally discarded.

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