A healthier stochastic semiclassical gravity: world without Schrödinger cats

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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.

Tool of 'healing' the meanfield coupling

Q-monitoring (time-continuous measurement, filtering)
$\hat{q}$=monitored observable; q^{signal}=outcome; γ=strength of monitoring; w=stndrd white-noise

Stochastic formalism

$$q^{signal} = \langle\hat{q}\rangle + \delta q^{noise}, \qquad \delta q^{noise} = w/\sqrt{\gamma}$$

$$\dot{\Psi} = \left(-\frac{i}{\hbar}\hat{H} - \tfrac{1}{8}\gamma(\hat{q} - \langle\hat{q}\rangle)^2 + \tfrac{1}{2}\gamma\delta q^{noise}(\hat{q} - \langle\hat{q}\rangle)\right)\Psi$$

$$\dot{\hat{\rho}} = -\frac{i}{\hbar}[\hat{H},\hat{\rho}] - \tfrac{1}{8}\gamma[\hat{q},[\hat{q},\hat{\rho}]] + \gamma\delta q^{noise}\mathrm{Herm}(\hat{q} - \langle\hat{q}\rangle)\hat{\rho}$$

Hybrid formalism

$$q^{signal} = \dot{Q}$$

$$\dot{\hat{\rho}}(Q) = -\frac{i}{\hbar}[\hat{H},\hat{\rho}(Q)] - \mathrm{Herm}\,\hat{q}\partial_Q\hat{\rho}(Q) - $$

$$-\tfrac{1}{8}\gamma[\hat{q},[\hat{q},\hat{\rho}(Q)]] + \tfrac{1}{2}D\partial_Q^2\hat{\rho}(Q), \qquad (D = 1/\gamma)$$

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):

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

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

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

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

$T_{ab}^{signal} = \hat{T}_{ab}$'s spontaneously monitored value

Includes fluctuations of $\hat{T}_{ab}$, restores linearity of QM.

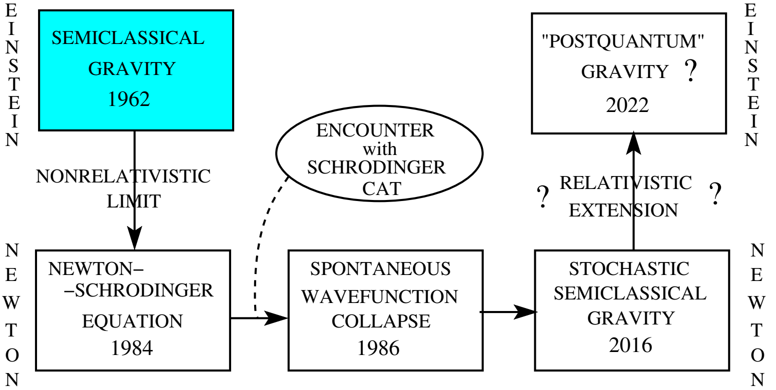
Structure/precision of spontaneous monitoring is defined by

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

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

Tour: GenRel SCG→NonRel SCG→'Healtier' NonRel SCG→'Healthier' GenRel SCG

From standard SCG we 'descend' to its non-relativistic Newtonian limit. There, it's easy to identify the fundamental quantum anomalies of the meanfield coupling and to construct the 'healthy' stochastic SCG based on spontaneous quantum monitoring and feedback. Then we 'ascend' to the relativistic realization to find the old obstacles.



Standard SCG (Moller,Rosenfeld)

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

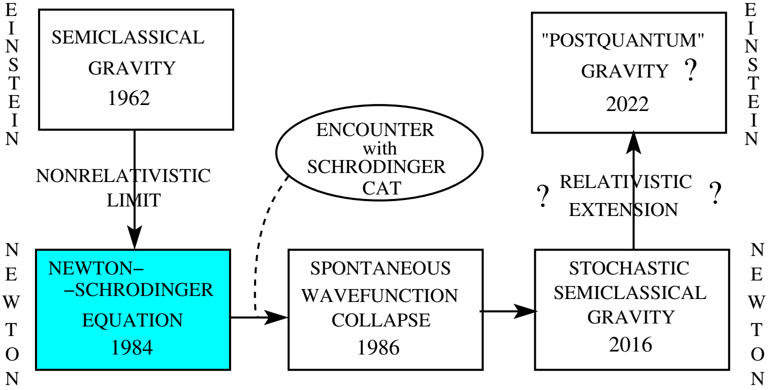
$$
\begin{aligned}
\frac{d|\Psi\rangle}{dt} &= -\frac{i}{\hbar}\hat{H}[\mathrm{g}]|\Psi\rangle \qquad \textit{action } C \to Q \ (\textit{nonlinear}) \\
\mathrm{G}_{ab} &= \frac{8\pi G}{c^4}\langle\Psi|\hat{\mathrm{T}}_{ab}|\Psi\rangle \quad \textit{backaction } Q \to C \ (\textit{meanfield})
\end{aligned}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

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.

Tour: GenRel SCG→NonRel SCG→'Healtier' NonRel SCG→'Healthier' GenRel SCG

We are down in the Newtonian limit of SCG
The Newton-Schrödinger Equation.



Nonrelativistic SCG (Schrödinger-Newton Eq.

(D.,Penrose)

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

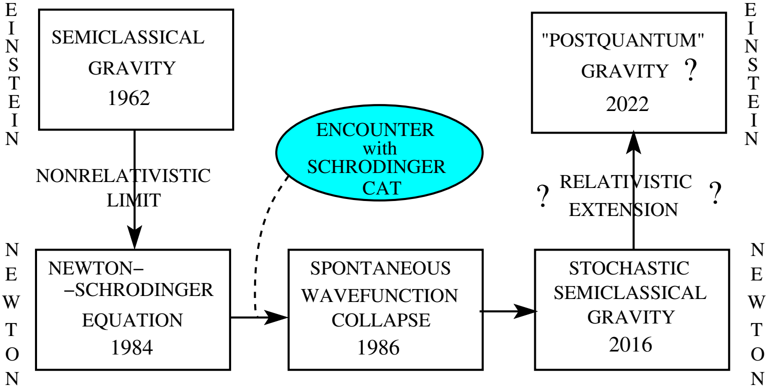
$$\begin{aligned} \frac{d|\Psi\rangle}{dt} &= -\frac{i}{\hbar}\left(\hat{H}_0 + \int \hat{\mu}\Phi dV\right)|\Psi\rangle && \textit{action (nonlinear)} \\ \Phi &= 4\pi G \nabla^{-2}\langle\Psi|\hat{\mu}|\Psi\rangle && \textit{backaction (meanfield)} \end{aligned}$$

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 nonrelativisti- cally for large masses, already for nanogram's.
Doors open: 'Newtonian Qauntumgravity' for theorists,
'Quantumgravity in the Lab' for experimentalists.

Tour: GenRel SCG→NonRel SCG→'Healtier' NonRel SCG→'Healthier' GenRel SCG

We are down in the Newtonian limit.
The DP cpontaneous collapse.



Spontaneous collapse of Schrödinger Cats (D.,Penrose)

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

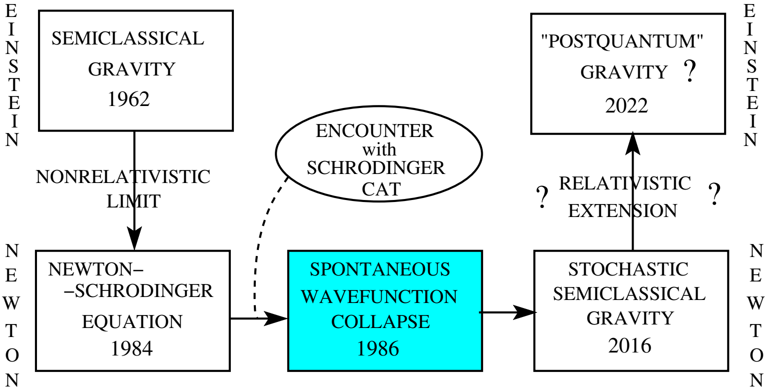
SPONTANEOUS COLLAPSE RATE:

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

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 $\tau_{1mg} \sim \mu s$.

Tour: GenRel SCG→NonRel SCG→'Healtier' NonRel SCG→'Healthier' GenRel SCG

We are down in the Newtonian limit.
The D(P) dynamics of spontaneous collapse



DP Gravity-Related Spontaneous Collapse (D.)

Generalizaing spontaneous collapse of Schrödinger Cats
Time-continuous spontaneous collapse of massive macrosopic superpositions
Concept: spontaneous monitoring of $\hat{\mu} = \hat{T}_{00}/c^2$

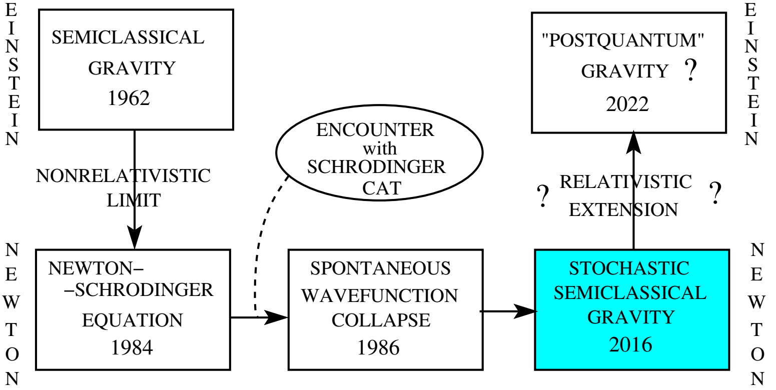
$$\begin{aligned} \frac{d|\Psi\rangle}{dt} &= -\frac{i}{\hbar}\hat{H}_0|\Psi\rangle + \textit{stochastic terms of monitoring } \hat{\mu} \\ \mu^{signal} &= \langle\Psi|\hat{\mu}|\Psi\rangle + \delta\mu^{noise} \end{aligned}$$

$$\mathrm{E}\left[\delta\mu(^{noise}(\mathbf{r},t)\delta\mu^{noise}(\mathbf{s},\tau)\right] = -\frac{\hbar}{8\pi G}\nabla^2\delta(\mathbf{r}-\mathbf{s})\delta(t-\tau)$$

Yields the DP collapse rate $1/\tau = (V_G^i - V_G^f)/\hbar$.
EXPLAINS HOW QM GOES CLASSICAL IN THE MACRO-WORLD “WITHOUT SCH CATS”

Tour: GenRel SCG→NonRel SCG→'Healtier' NonRel SCG→'Healthier' GenRel SCG

We are down in the Newtonian limit.
The healthier Newton-Schrödinger SCG



Healthier SCG - Newtonian limit (Tilloy&D.)

Causality and Born statistical interpretation restored

Concept: spontaneous monitoring $\hat{\mu}$ (as before)

$+$ feedback of $\Phi = 4\pi G \nabla^{-2} \mu^{signal}$

$$\frac{d|\Psi\rangle}{dt} = -\frac{i}{\hbar}\left(\hat{H}_0 + \int \hat{\mu}\Phi dV\right)|\Psi\rangle + stoch.\ terms\ of\ monitoring\ \hat{\mu}$$

$$\Phi = 4\pi G \nabla^{-2}\left(\langle\Psi|\hat{\mu}|\Psi\rangle + \delta\mu^{noise}\right)$$

Feedback of classical Φ generates the Newton pair-potential:

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

$$+\ stoch.\ terms\ of\ monitoring\ \hat{\mu}\ \&\ of\ feedback\ \Phi$$

Prices to pay:

tiny nonunitarity because $|\Psi\rangle$ collapses

tiny stochasticity of gravity because of $\delta\mu^{noise}$

Healthier SCG - Newtonian limit (Tilloy&D.)

Stochastic formalism

$$\Phi = \frac{4\pi G}{\nabla^2}\langle\hat{\mu}\rangle + \delta\Phi, \quad \mathrm{E}\left[\delta\Phi(\mathbf{r},t)\delta\Phi(\mathbf{s},\tau)\right] = \frac{\hbar G/2}{|\mathbf{r}-\mathbf{s}|}\delta(t-\tau)$$

$$\dot{\hat{\rho}} = -\frac{i}{\hbar}[\hat{H}_0 + \hat{V}_G, \hat{\rho}] - \frac{G}{2\hbar}\int [\hat{\mu}(\mathbf{r}), [\hat{\mu}(\mathbf{s}), \hat{\rho}]]\frac{d\mathbf{r}d\mathbf{s}}{|\mathbf{r}-\mathbf{s}|} - $$
$$-\frac{1+i}{\hbar}\int (\hat{\mu} - \langle\hat{\mu}\rangle)\delta\Phi dV - H.C.$$

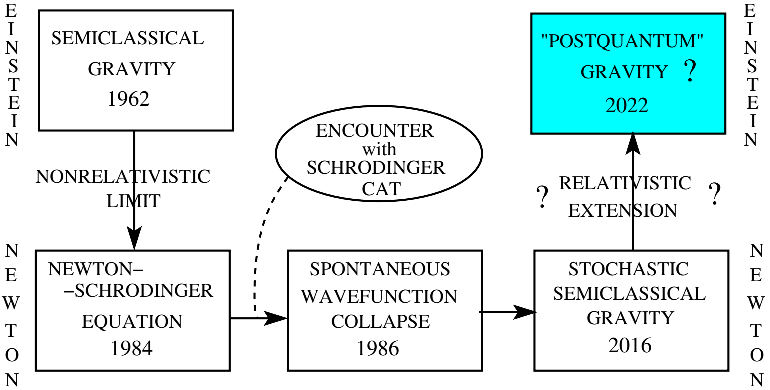
Hybrid formalism

$$\Phi = \dot{\Xi}$$

$$\dot{\hat{\rho}}[\Xi] = -i\left[\hat{H}_0 + \hat{V}_G\ ,\ \hat{\rho}[\Xi]\right] - 4\pi G\int (\nabla^{-2}\hat{\mu})\frac{\delta}{\delta\Xi}dV\hat{\rho}[\Xi] -$$
$$-\frac{G}{2\hbar}\int \left[\hat{\mu}(\mathbf{r}), \left[\hat{\mu}(\mathbf{s}), \hat{\rho}[\Xi]\right]\right]\frac{d\mathbf{r}d\mathbf{s}}{|\mathbf{r}-\mathbf{s}|} + \frac{\hbar}{16\pi G}\int\left(\nabla\frac{\delta}{\delta\Xi}\right)^2 dV\hat{\rho}[\Xi]$$

Tour: GenRel SCG→NonRel SCG→'Healtier' NonRel SCG→'Healthier' GenRel SCG

We climb up to General Relativity.
Toward a healthier SCG (aka Postquantum Gravity)?



Healthier SCG - Relativistic?

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

Concept: spontaneous monitoring $\hat{\mathrm{T}}_{ab}$ + feedback of T_{ab}^{signal}

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

Metric g_{ab} is diffusive because T_{ab}^{signal} is diffusive.

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

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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