Quantum and Gravity Together: Cosmic, and Nano?

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Outline

Warning

In Quantum theory: "classical" means non-quantized.
In Gravity theory: "classical" means non-relativistic.

Where do Quantum and Gravity meet?

- Quantum theory = Schrödinger eq. for Ψ:

$$\frac{d\Psi(q,t)}{dt} = -\frac{i}{\hbar} H\left(q, -\mathrm{i}\hbar\partial/\partial q\right)\Psi(q,t)$$

plus von Neumann measurement theory.

- Gravity theory = Einstein eq. for g_{ab} $(a, b = 0, 1, 2, 3)$:

$$R_{ab} - \frac{1}{2} g_{ab} R = \frac{8\pi G}{c^4} T_{ab}$$

g_{ab}: space-time metric, R_{ab}, R: Ricci curvatures, T_{ab}: energy-mom.

Quantum and Gravity meet at Planck scale:

$$\ell_P = \sqrt{\hbar G/c^3} \sim 10^{-33} cm, \quad t_P = \sqrt{\hbar G/c^5} \sim 10^{-43} s, \quad m_P = \sqrt{\hbar c/G} \sim 10^{-5} g$$

WHERE Q AND G MEET: COSMIC BIG BANG.

Theories concerning QG?

No experimental evidence at all! You are free to speculate!
Main stream: Apply Q to G!

- Canonical quantization of Einstein eq.
- Quantum-field theory for Einstein eq.
- String theory approach (I won't adress it.)

Side stream: Revise Q first!

- Hybrid dynamics: Q plus classical d.o.f.
- Decoherent Histories
- Add (tiny) decoherence to Q theory

BE MAIN STREAM CONSERVATIVE, SEE CANONICAL QUANTIZATION FIRST!

Quantum Geometrodynamics

Canonical quantization of (pure) Einstein eq. $R_{ab}-\frac{1}{2}g_{ab}R=0$.
Canonical structure is well hidden, but it exists!
Due to gauge invariance: canonical coordinates are fewer than g_{ab}, they are the spatial 3x3 metric $\tilde{g}_{ij}; i,j=1,2,3$. Hamilton density:

$$H(\tilde{g},\tilde{\pi})=\tilde{G}_{ijkl}\tilde{\pi}^{ij}\tilde{\pi}^{kl}-(\det\tilde{g})^{1/2}\tilde{R}$$

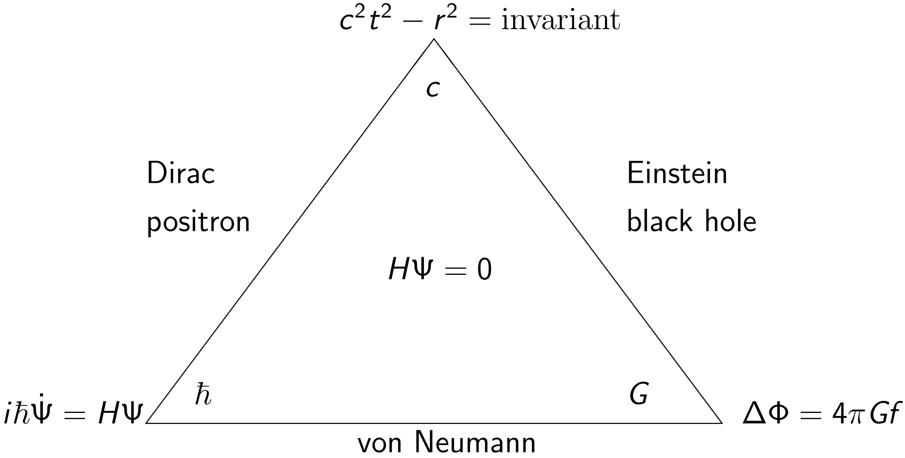
$\tilde{\pi}^{ij}$: conjugate momenta, $\tilde{G}_{ijkl}=\frac{1}{2}(\det\tilde{g})^{-1/2}(\tilde{g}_{ik}\tilde{g}_{jl}+\tilde{g}_{il}\tilde{g}_{jk}-\tilde{g}_{ij}\tilde{g}_{kl})$.
Quantization via Schrödinger eq. for wave functional $\Psi[\tilde{g}]$:

$$H(\tilde{g},-\mathrm{i}\hbar\delta/\delta\tilde{g})\Psi[\tilde{g}]=0.$$

That's the Wheeler-DeWitt eq. of Quantum Geometrodynamics.
GENERIC SOLUTIONS: NO TIME, NO SPACE-TIME!

Bottle-neck of Quantum Gravity: Q OR G?

Mainstream blames G, sidestream blames Q.



WHAT'S WRONG WITH WHEELER-DEWITT QG?

What's wrong with Wheeler-DeWitt QG?

$$H\,(\tilde{g}, -\mathrm{i}\hbar\delta/\delta\tilde{g})\,\Psi[\tilde{g}] \;=\; 0$$

$\tilde{g} =$ 3x3 metric tensor field of spatial geometry
Problem: generic solution $\Psi[\tilde{g}]$ implies no time, no space-time
Why? Because of "Schrödinger Cat" states:

$$\Psi[\tilde{g}] = \Psi_1[\tilde{g}] + \Psi_2[\tilde{g}]; \quad \Psi_1, \Psi_2 \text{ are peaked at } \tilde{g}_1, \tilde{g}_2$$

A remedy: decoherence might kill "Schrödinger Cat".

- Introduce a smart measure of "catness" of $\Psi = \Psi_1 + \Psi_2$.
- Modify Q theory to decohere $\Psi = \Psi_1 + \Psi_2$ if "catness" is big.

Relativistic case is largely unexplored.
Go Newtonian! Surprize: Q and G meet at nanoscales.

Newtonian G-related decoherence (hypothesis)

$$R_{ab} - \frac{1}{2} g_{ab} R = \frac{8\pi G}{c^4} T_{ab} \quad \Rightarrow \quad \Delta\Phi = -4\pi G f$$

Φ: Newton potential, f: mass distribution
Schrödinger Cat: superposition of "very" different f_1 and f_2.
Our choice of "catness" (D., Penrose):

$$\Delta E_G = 2U(f_1, f_2) - U(f_1, f_1) - U(f_2, f_2) \geq 0$$

$U(f_1, f_2)$: Newton interaction potential between f_1, f_2.
Add universal decoherence to QM! Postulate decay time of catness:

$$\tau_d = \hbar / \Delta E_G$$

No effect for atomic systems but for massive ones ($\geq 10^{-15}$g).
Q and G meet already at "nano" scales.

Proposed experimental tests

Detecting Newton-G-related loss of coherence in:

- nucleon decay (Pearle & Squires)
- flavor oscillations of neutrinos from distant cosmic sources (Christian)
- light propagation from distant stars (Christiansen & Ng & vanDam)
- gravity wave interferometer LIGO/VIRGO (Amelino-Camelia)
- seeds of cosmic structure (Sudarsky)
- nano-mechanical oscillator (Marshall & Simon & Penrose & Bouwmeester)
- optically levitated dielectric nano-sphere (Romero-Isart)
- ...

Y 2000-...: LABORATORY RACE FOR A NANOMECHANICAL SCHRÖDINGER CAT.

Nanomechanical Schrödinger Cat

Nanommech. resonator (1mg,10kHz) cooled to ground state (μK)

- Confirm Q theory for massive d.o.f.
- Confirm if "Schrödinger Cats" exist at all.
- Confirm G-related (or other) models of their decay

Experiments: nano-mirror coupled to single photon, nano-resonator coupled to single-electron-transistor, or to single-electron-spin, to Cooper-pair-box

Possible relevance:

- Extension of Q superposition
- Extension of Q-coherent control
- Extension of Q-information technology
- New physics: discovery of Newtonian (non-Cosmic) QG.