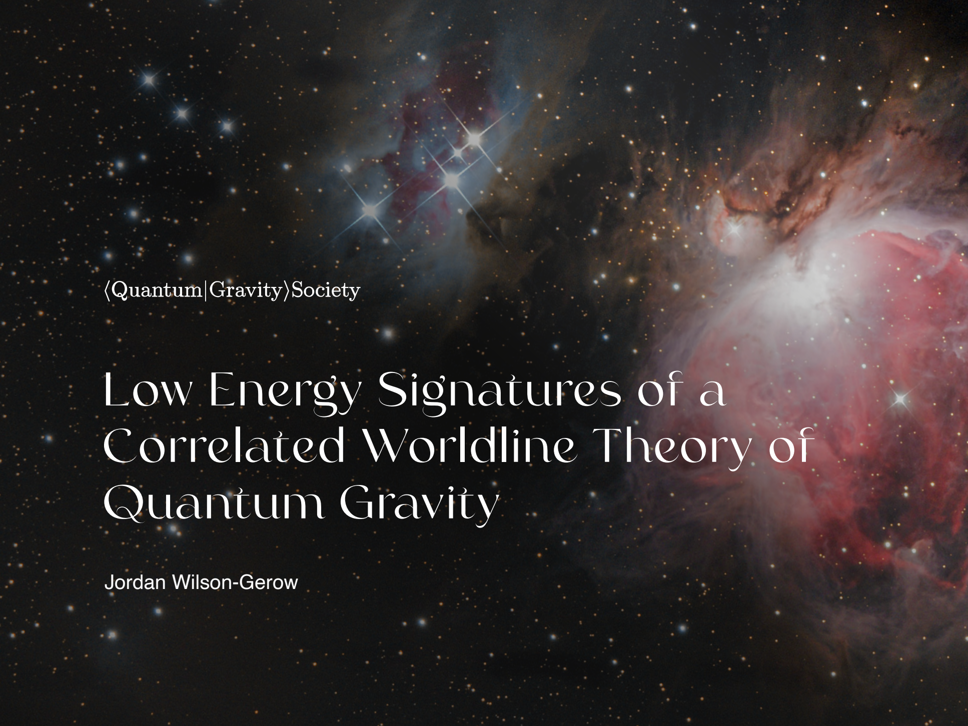

⟨Quantum|Gravity⟩Society

Low Energy Signatures of a Correlated Worldline Theory of Quantum Gravity

Jordan Wilson-Gerow

Low energy signatures of a Correlated Worldline theory of quantum gravity

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Quantum Mechanics & Gravity

⟨Quantum|Gravity⟩society, Vancouver

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Outline

Correlated WorldLine (CWL) Quantum+Gravity theory

Goals:

- Maintain general covariance
- No "external noise"
- Ultimately, abandon projection postulate for measurements (describe dynamically)

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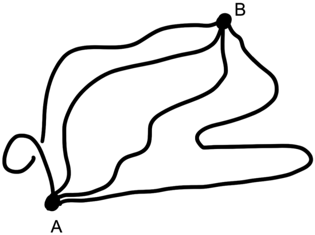
In conventional QM, every path is independent, $K(B, A) = \sum_{\text{paths}} e^{iS[q]}$

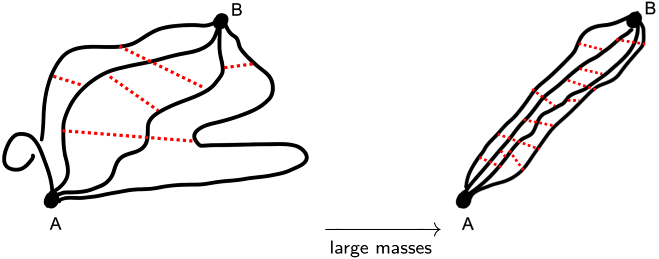


Correlated WorldLine (CWL) Quantum+Gravity theory

Goals:

- Maintain general covariance
- No "external noise"
- Ultimately, abandon projection postulate for measurements (describe dynamically)

Central postulate: Quantum paths **of a single system** have mutual gravitational interactions (correlations).



Outline

CWL Theory Construction

Path-integral evolution in CWL theory:

$$K = \lim_{N\to\infty} \left[\int \mathcal{D}g \, e^{NiS_G[g]} \prod_{j=1}^{N} \int \mathcal{D}\phi_j e^{iS[\phi_j, g]} \right]^{1/N}$$

Infinite number of paths in conventional path-integral
$\Longrightarrow$ CWL is intrinsically a "large N" theory

Effectively a theory with N fields and $N \to \infty$ with GN held constant $= G_{Newton}$

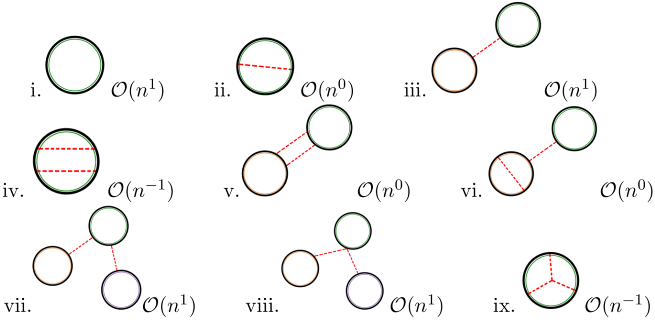
- Tomboulis '77,'80, Hartle-Horowitz '81, Kay '81, Smolin '81

Aside: Field theory - Generating Functional

CWL as a prescription for computing correlation functions:

$$\mathcal{Z}[J] = \lim_{N\to\infty} \left[\int \mathcal{D}g \, e^{NiS_G[g]} \prod_{j=1}^{N} \int \mathcal{D}\phi_j e^{iS[\phi_j,g]+i\int J\phi_j} \right]^{1/N}$$

*Only keep diagrams whose connected parts scale as N^1. **No graviton loops!**

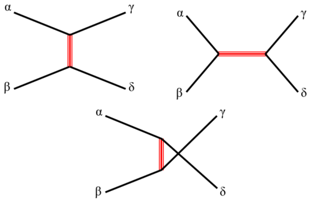


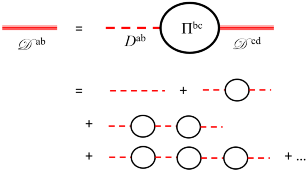
Aside: Field theory - Correlation Functions

Using intrinsic large-N limit one can prove no graviton loops to all orders in G. [Tomboulis, Smolin]

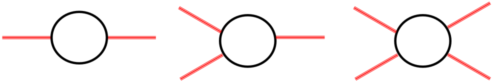
eg. exact scalar 4-pt function: Renormalizable if we add $\Delta\mathcal{L} = \alpha^{-1}(C_{\mu\nu\alpha\beta})^2$

*Asymptotically free, $\alpha \to 0$ at high-energies





*Higher n-point functions are also modified only by these scalar loops



$\sim \frac{q^4(q^2)^2}{(q^2)^2}$ $\sim \frac{q^4(q^2)^3}{(q^2)^3}$ $\sim \frac{q^4(q^2)^4}{(q^2)^4}$

Exact expression for CWL propagator

Large N allows us to formally evaluate gravitational integral:

$$K = e^{iS_G[\bar{g}]} \int_{\Phi_1}^{\Phi_2} \mathcal{D}\phi \, e^{iS[\phi,\bar{g}]}$$

- Metric $\bar{g}$ self-consistently satisfies an **<u>in-out</u>** semi-classical Einstein equation

$$G_{\mu\nu}(\bar{g}) = 8\pi G \frac{\langle \Phi_2 | \hat{T}_{\mu\nu}[\bar{g}] | \Phi_1 \rangle}{\langle \Phi_2 | \Phi_1 \rangle}$$

- This is **not** typical semi-classical gravity $G_{\mu\nu} = 8\pi G \langle \hat{T}_{\mu\nu} \rangle$.

In-Out vs. In-In Semiclassical equation

Standard Semiclassical (In-In):

- Matter state $|\Psi\rangle$ sources gravity via $G_{\mu\nu} = \langle\Psi|\hat{T}_{\mu\nu}|\Psi\rangle$
- Measure λ, the state *jumps* $|\Psi\rangle \to |\lambda\rangle$
- Discontinuous, non-local change in $G_{\mu\nu}$

In-Out Semiclassical:

- Measurement of λ at time t instead gives

$$G_{\mu\nu}(\bar{g}(x)) = 8\pi G \frac{\langle\Phi_2|\mathcal{T}\left\{|\lambda(t)\rangle\langle\lambda(t)|\,\hat{T}_{\mu\nu}(x)\right\}|\Phi_1\rangle}{\langle\Phi_2|\lambda(t)\rangle\langle\lambda(t)|\Phi_1\rangle}$$

- Stress tensor is not discontinuous (in simple example)

Outline

Observable Consequences: Estimate of Scale

Two paths for a non-relativistic **point-like** particle of mass M_0,

Gravitational Bohr radius and Gravitational Rydberg energy:

$$a_G(M_0) = \left(\frac{m_P}{M_0}\right)^3 \ell_P, \qquad \mathcal{E}_G(M_0) = \left(\frac{M_0}{m_P}\right)^5 E_P$$

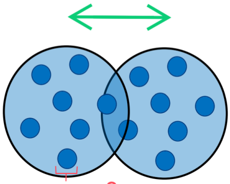
Examples:

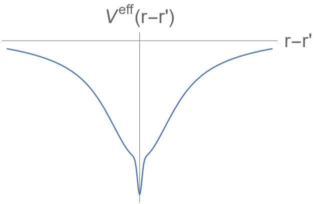
- Virus: $M_0 \sim 10^{-17}\,\mathrm{kg} \sim 10^9\,\mathrm{AMU}$, $\mathcal{E}_G \sim 10^{-19}\,\mathrm{eV}$
- Bacterium: $M_0 \sim 10^{-14}\,\mathrm{kg} \sim 10^{13}\,\mathrm{AMU}$, $\mathcal{E}_G \sim 1\,\mathrm{eV}$
- Planck scale: $M_0 \sim 10^{-8}\,\mathrm{kg} \sim 10^{19}\,\mathrm{AMU}$, $\mathcal{E}_G \sim 10^{28}\,\mathrm{eV}$

To reach energies $\mathcal{E}_G \sim (0.1\,\mathrm{nK})k_B$, need $M_0 \sim 10^{11}\,\mathrm{AMU}$
 * but $a_G(M_0 \sim 10^{11}\,\mathrm{AMU}) \sim 10^{-11}\,\mathrm{m}$

Extended body - Effective CWL interaction

Average over internal atomic motion → effective C.o.M potential





Characteristic frequencies:

$$f^{\mathrm{SiO_2}}_{wide} \propto \sqrt{G\rho_{avg}}, \qquad f^{\mathrm{SiO_2}}_{spike} \propto \sqrt{\frac{Gm}{\sigma^3}} \approx 25\,\mathrm{mHz}$$

cf:

- optically trapped nanoparticles - $(80-300)\,\mathrm{kHz}$
- LIGO - $(10^1 - 10^4)\,\mathrm{Hz}$
- **Torsion pendulum** - $\sim 1\,\mathrm{mHz}$

Refined mass scale estimate

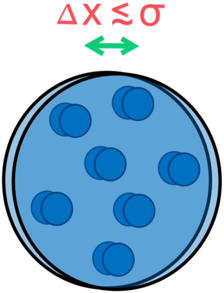
Position uncertainty

$$(\Delta x)^2 = \frac{\hbar}{2M\omega}$$

CWL coupling constant

$$\epsilon^2 = \frac{\Omega^2_{spike}}{2\omega^2}$$

Strongest effect inside the spike: $\Delta x \sim 10^{-12}\,\mathrm{m}$.



$$M \geq \epsilon \times (5 \times 10^{-11}\,\mathrm{kg}) = \epsilon \times (3 \times 10^{16}\,\mathrm{AMU})$$

- At least micron scale quantum objects

Phenomenology: No easy signatures

Linear measurements on gaussian states show no signature.

A wavefunction

$$\psi_{\tilde{x},\tilde{p}}(x) = \exp\left(-\tfrac{1}{4}(x-\tilde{x})^2 - i\tilde{p}x\right)$$

maps to multi-"particle" wavefunction

$$\Psi_f(\{x_j\}) = \prod_{j=1}^{N} \psi_{\tilde{x},\tilde{p}}(x_j) = \exp\left(-\tfrac{N}{4}(Q-\tilde{x})^2 - iN\tilde{p}Q\right) \exp\left(-\tfrac{1}{4}\sum_{j=1}^{N}\delta_j^2\right)$$

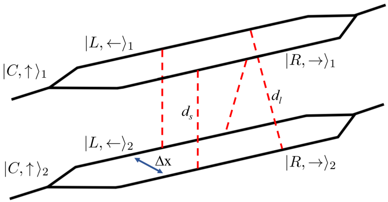
with $\delta_j \equiv Q - x_j$.

- Non-relativistic CWL interaction is the mutual Newton potential (depends only on the δ_j)
- S_0 quadratic $\implies$ Q and δ_j decouple
- In the final amplitude, $\tilde{x}, \tilde{p}$ dependence factors from CWL contributions

Observable Consequences: Gravity Mediated Entanglement

Bose et al., Marletto & Vedral, Carney, Müller & Taylor, Wald, Aspelmeyer,...

Idea: If gravity is *quantum* then it can entangle massive objects*



Initial product:

$$|\psi\rangle = \frac{1}{2}(|L\rangle_1+|R\rangle_1)(|L\rangle_2+|R\rangle_2)$$

Evolve $\rightarrow$ entangled:

$$|\psi\rangle = \frac{e^{i\phi_s}}{2}(|L\rangle_1|L\rangle_2 + |R\rangle_1|R\rangle_2) + \frac{e^{i\phi_l}}{2}(|R\rangle_1|L\rangle_2 + |L\rangle_1|R\rangle_2)$$

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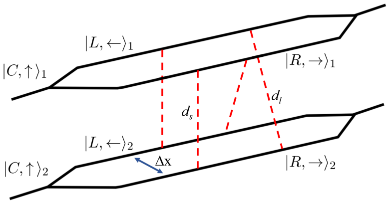

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CWL predicts zero entanglement between particles

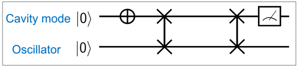
Pulsed cavity quantum optomechanics

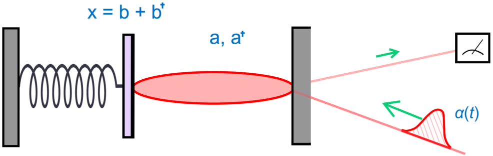
Radiation pressure: $\omega_{cav}(x) \approx \omega_{cav} - g_0(b + b^\dagger)$

Strong laser pulse: $\hat{a} \to \alpha(t) + \hat{a}$

Tunable interaction: $H_{int}^{lin} = -g_0(a + a^\dagger)\alpha(t)(b + b^\dagger)$

- Blue detuning: $\omega_{pump} = \omega_m + \omega_{cav}$ couples $a^\dagger b^\dagger + h.c.$
- Red detuning: $\omega_{pump} + \omega_m = \omega_{cav}$ couples $a^\dagger b + h.c.$





$$p_\gamma(1) = 1$$
$$p_\gamma(0) = 0$$

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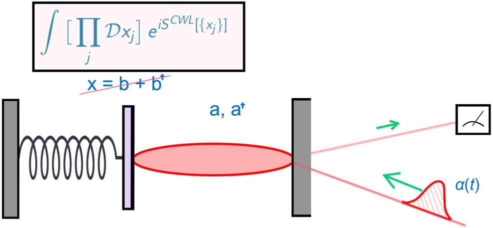

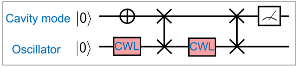

$$p_\gamma(1) = 1 - p_\gamma(0)$$

$$p_\gamma(0) = \frac{\epsilon^4}{(4e)^2}\left(g_0 \int dt\, \alpha(t)\right)^2$$

Summary

The Correlated Worldline (CWL) quantum+gravity theory is:

- conventional quantum theory when $G \to 0$
- classical GR when $\hbar \to 0$
- a type of in-out semiclassical theory

It features:

- interesting connection with asymptotic safety
- no signatures in $\approx$ "classical" quantum states

Proposed tests:

- Low frequency "Macroscopic" quantum optomechanical expts.
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