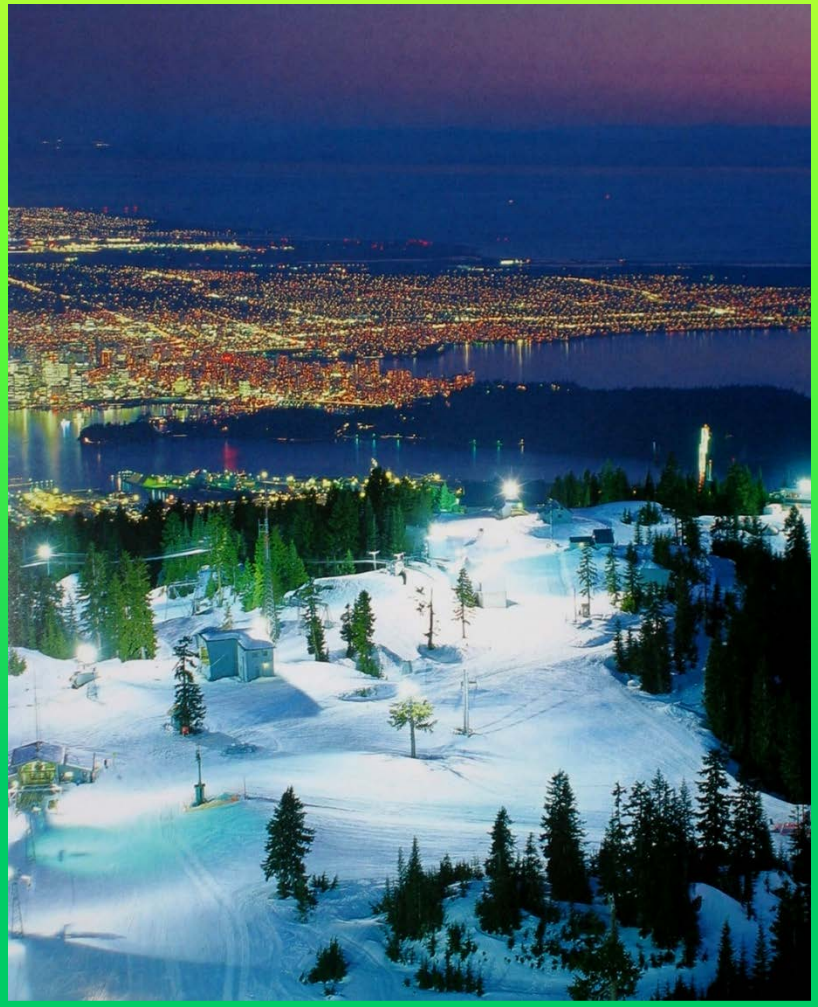
The CWL THEORY of QUANTUM GRAVITY

P.C.E. STAMP

Sakharov meeting, June 06 2021



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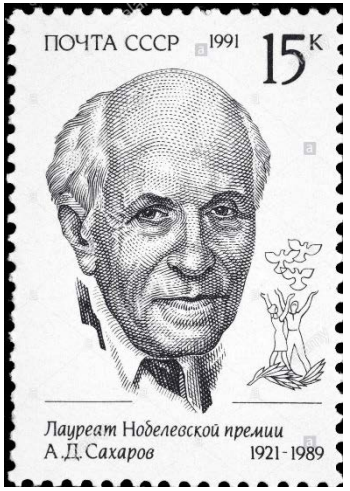

CONFERENCE in honour of A.D.SAKHAROV

Two well known papers in the field of quantum gravity:

1967 Vacuum Quantum Fluctuations in Curved Space and the Theory of Gravitation, Dokl. Akad. Nauk SSSR **177**, No. 1, 70–71 [Sov. Phys. Dokl. **12**, 1040–1041 (1968)

1975 Spectral Density of Eigenvalues of the Wave Equation and Vacuum Polarization, Teor. Mater. Fiz. **23**, No. 2, 178–190 [Theor. Math. Phys. **23**, 435–444 (1976)

The CORRELATED WORLDLINE (CWL) THEORY of QUANTUM GRAVITY

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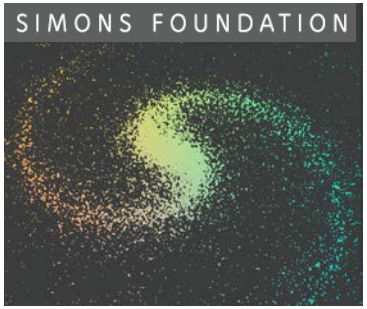
RESEARCH SUPPORT



PCE Stamp, Phil Trans Roy Soc A370, 4429 (2012)
" , New J. Phys. 17, 06517 (2015)
AO Barvinsky, PCE Stamp, Phys Rev D98, 084052 (2018)
D Carney, PCE Stamp, J Taylor, Class Q Grav 36, 034001 (2019)
AO Barvinsky, J Wilson-Gerow, PCE Stamp, Phys Rev D103, 064028 (2021)
J Wilson-Gerow, PCE Stamp, /arXiv: 2011.14242
J Wilson-Gerow, PCE Stamp, to be published
Y Chen, J Wilson-Gerow, PCE Stamp, to be published

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C Delisle, J Wilson-Gerow, PCE Stamp, /arXiv: 1905.05333
C DeLisle, J Wilson-Gerow, PCE Stamp, JHEO 03 (2021), 290
J Wilson-Gerow, PCE Stamp, /arXiv: 2011.05305

CORRELATED WORLDLINE (CWL) THEORY

CWL theory incorporates key ideas from QFT and GR – it is a quantum field theory of gravity in which QM breaks down because of gravity.

KEY IDEAS

* Full non-linearity of General Relativity is incorporated into QFT. Makes quantized theory non-linear → breakdown of superposition principle.
* This done by inter-path correlation via gravity
* Gravity only sees $T_{\mu\nu}(x)$; it cannot distinguish (i) n paths for a set of n particles, from (ii) a set of n paths for the same particle. This, plus the equivalence principle, leads to a unique form for CWL theory

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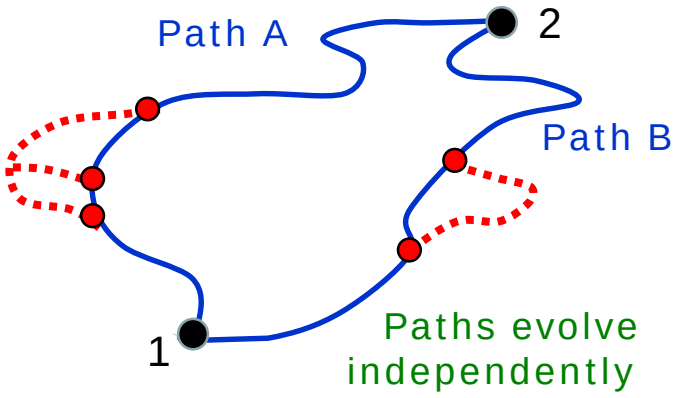
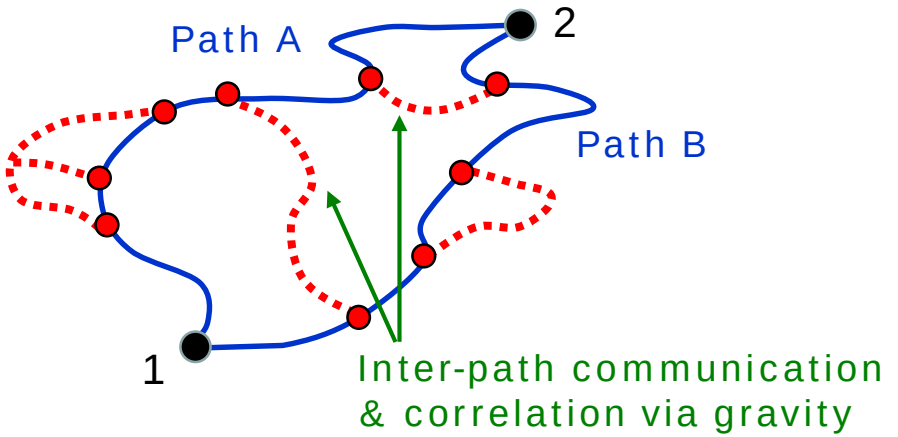
CWL theory is NECESSARILY formulated in terms of paths - these are the primitive objects of the theory. The difference between CWL theory and conventional quantum gravity is intuitively understood in this language:

Conventional QM/QFT



CWL Theory



BACKGROUND HISTORY 1

RP Feynman (Chapel Hill (1957)

I would like to suggest that it is possible that quantum mechanics fails at large distances and for large objects. If this failure of quantum mechanics is connected with gravity, we might speculatively expect this to happen for masses such that $GM^2/\hbar c = 1$, of M near 10^{-5} grams, which corresponds to some 10^{18} particles.

RP Feynman (1920-1987)

TWB Kibble (1978-82)

TWB Kibble, Comm Math Phys 64, 73 (1978); TWB Kibble, ibid 65, 189 (1979)
TWB Kibble S Radjbar-Daemi, J Phys A13, 141 (1980)
TWB Kibble, in "Quantum Gravity 2", ed. CJ Isham et al., (Clarendon, 1981)

We are interested in states like:

$$|\Psi\rangle = a_1(t)|\Phi_1; g^{\mu\nu}_{(1)}(x)\rangle + a_2(t)|\Phi_2; g^{\mu\nu}_{(2)}(x)\rangle \equiv a_1(t)|\psi_1\rangle + a_2(t)|\psi_2\rangle$$

Kibble argued that gravity → a non-linear generalization of QM; but we must drop the Hilbert space + operator + Q measurement framework.

TWB Kibble (1932-2016)

R Penrose (1996 et seq)

R Penrose: Gen Rel Grav 28, 581 (1996); W Marshall et al., PRL 91, 130401 (2003)

"conventional quantum theory provides no clear answer .. to the problem of the stability of a quantum superposition of 2 different gravitating states".

Using a non-relativistic argument, Penrose suggests a dephasing between 2 branches – with dephasing time $\tau_\phi = \hbar/\Delta E$ where:

$$\Delta E = 2E_{1,2} - E_{1,1} - E_{2,2}. \qquad E_{i,j} = -G\int\int d\vec{r}_1 d\vec{r}_2 \frac{\rho_i(\vec{r}_1)\rho_j(\vec{r}_2)}{|\vec{r}_1 - \vec{r}_2|}$$

"...none of the considerations of the present paper give any clear indication of the mathematical nature of the theory that would be required to incorporate a plausible gravitationally induced spontaneous state-vector reduction."

R Penrose (1931 -)

BACKGROUND HISTORY 2

Question: HOW MACROSCOPIC is QUANTUM MECHANICS?

(1) PHASE SUPERPOSITION/ENTANGLEMENT: Consider cases where the 2 are not physically separate, but out of phase. A famous example is the SQUID macroscopic superposition experiment (Leggett). Define the N-particle entanglement:

$$\Delta N_{tot} = \sum_{\mathbf{k},\sigma} \langle \circlearrowleft | \hat{c}^{\dagger}_{\mathbf{k},\sigma} \hat{c}_{\mathbf{k},\sigma} | \circlearrowleft \rangle - \langle \circlearrowright | \hat{c}^{\dagger}_{\mathbf{k},\sigma} \hat{c}_{\mathbf{k},\sigma} | \circlearrowright \rangle$$

Small in expts:

		L	ΔI_p	$\Delta\mu$	ΔN_{tot}
SUNY	Nb	560 μm	2–3 μA	$5.5 - 8.3 \times 10^9 \mu_B$	3800–5750
Delft	Al	20 μm	900 nA	$2.4 \times 10^6 \mu_B$	42
Berkeley	Al	183 μm	292 nA	$4.23 \times 10^7 \mu_B$	124

Korsbakken et al., Phys Rev A75, 042106 (2007)
Korsbakken et al., Europhy Lett 89, 30003 (2010)
Volkoff & Whaley, Phys Rev A89, 012122 (2014)

(2) SPIN SUPERPOSITION EXPTS: Expts show very large number of spins in identical superposed states:

B Julsgaard et al., Nature 413, 400 (2001)
S Takahashi et al., Nature 476, 76 (2011)

However these are not Cat states. The maximum ΔN_{tot} ~ O(10^2 - 10^3) in spin systems.

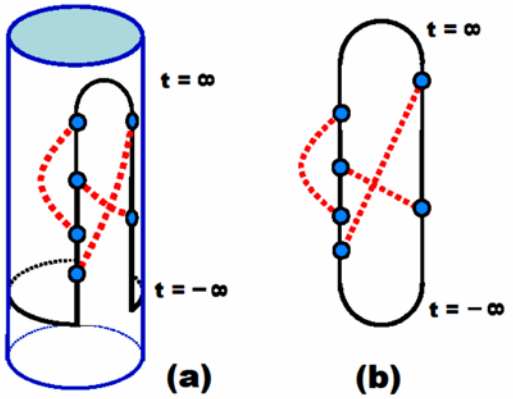
(3) MASS INTERFERENCE EXPERIMENTS: Done using a 2-slit device (Zeilinger, Arndt). The largest masses for which this has so far been done are only m ~ 10^5 AMU (ie., m ~ 10^{-14} M_P , where M_P is the Planck mass).

M Arndt, K Hornberger, Nat Phys 10, 271 (2014)
T Juffmann et al., Rep Prog Phys. 76, 086402 (2013)

SO – QM is very far from being demonstrated at macroscopic scale

FORMAL STRUCTURE of CWL THEORY: GENERATING FUNCTIONAL

A scalar field has generating functional $Z_\phi[g,J] = \oint D\phi\, e^{i(S_\phi[g,\phi] + \int J\phi)}$



Conventional Quantum Gravity:

This has generating functional:

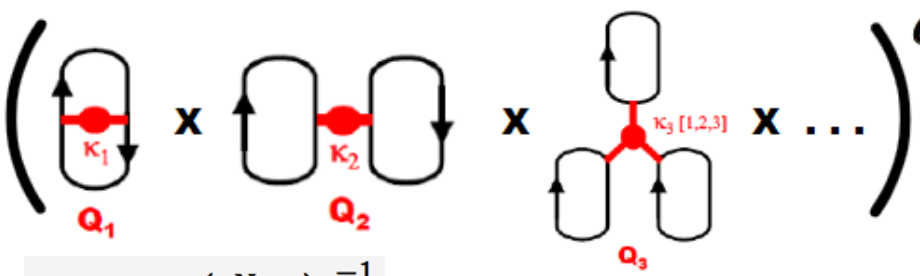
$$\mathcal{Z}[J] = \oint Dg\, e^{i(S_G[g] + \frac{1}{2}\chi^\mu c_{\mu\nu}\chi^\nu - i\mathrm{Tr}\ln\Xi)}\, Z_\phi[g,J]$$

$$= \oint \mathcal{D}g\, e^{iS_G[g]}\Delta[g]\delta(\chi^\mu(g))\, Z_\phi[g,J]$$

CWL Theory: This has generating functional

$$\tilde{\mathbb{Q}}[J] = \lim_{N\to\infty}\left(\prod_{n=1}^{N}\mathcal{Q}_n[J]\right)^{\alpha_N} = \lim_{N\to\infty}\left[\prod_{n=1}^{N}\int \mathcal{D}g_n\, e^{inS_G[g_n]}\prod_{k=1}^{n}\int \mathcal{D}\phi_k^{(n)}\, e^{iS[g_n,\phi_k^{(n)}]+J\phi_k^{(n)}}\right]^{\alpha_N}$$

$$= \lim_{N\to\infty}\left(\quad \times \quad \times \quad \times \ldots \quad\right)^{\alpha_N}$$

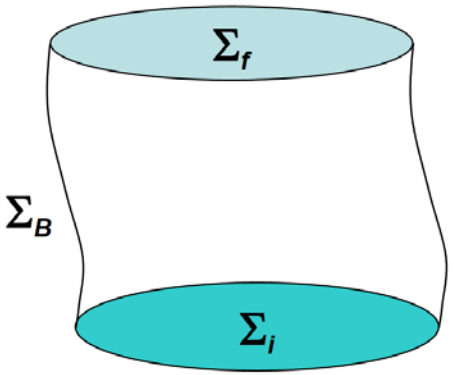


We note that log Q[J] is additive over these "tower" or "path" contributions, and α_N rescales things.

where $\alpha_N = \left(\sum_{n=1}^{N} n\right)^{-1} = \frac{2}{N(N-1)}$

KEY RESULT: Following consistency requirements are obeyed: well-behaved h and ℓ_P^2 expansions, classical limit, Ward identities

FORMAL STRUCTURE of CWL THEORY: PROPAGATORS



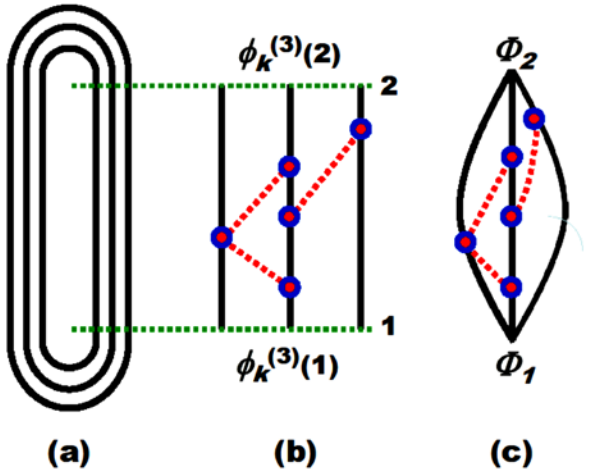
Conventional Quantum Gravity: We write a propagator

$$K(2,1) \equiv K(\Phi_2, \Phi_1; \mathfrak{h}_2^{ab}, \mathfrak{h}_1^{ab})$$
$$= \int_{\mathfrak{h}_1}^{\mathfrak{h}_2} \mathcal{D}g\, e^{\frac{i}{\hbar} S_G[g]} \Delta(g)\, \delta(\chi^\mu) \int_{\Phi_1}^{\Phi_2} \mathcal{D}\phi\, e^{iS_\phi[\phi, g]}$$

with metric & matter fields defined between hypersurfaces as shown.

CWL Theory: The matter propagator takes the form (here we suppress FP factors, etc):

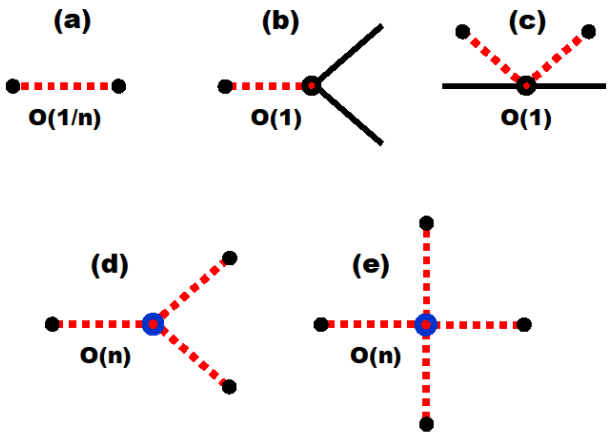
$$\mathcal{K}(2,1) = \lim_{N\to\infty} \left(\prod_{n=1}^{N} \mathcal{K}_n(2,1) \right)^{\alpha_N}$$
$$= \lim_{N\to\infty} \left[\prod_{n=1}^{N} \mathcal{N}_n^{-1} \int \mathcal{D}g_n\, e^{inS_G[g_n]} \prod_{k=1}^{n} \int_{\Phi_1}^{\Phi_2} \mathcal{D}\phi_k^{(n)}\, e^{iS[\phi_k^{(n)}, g_n]} \right]^{\alpha_N}$$



A perturbation expansion in powers of ℓ_P^2 produces diagrams like those shown – these are generated by cutting diagrams for the generating functional Q (the diagram depicts a contribution from Q_3), ie., from the 3rd level, involving 3 different paths or "histories" for the field).

We cut the lines on the 2 hypersurfaces, & then "tether" them to the initial and final states.

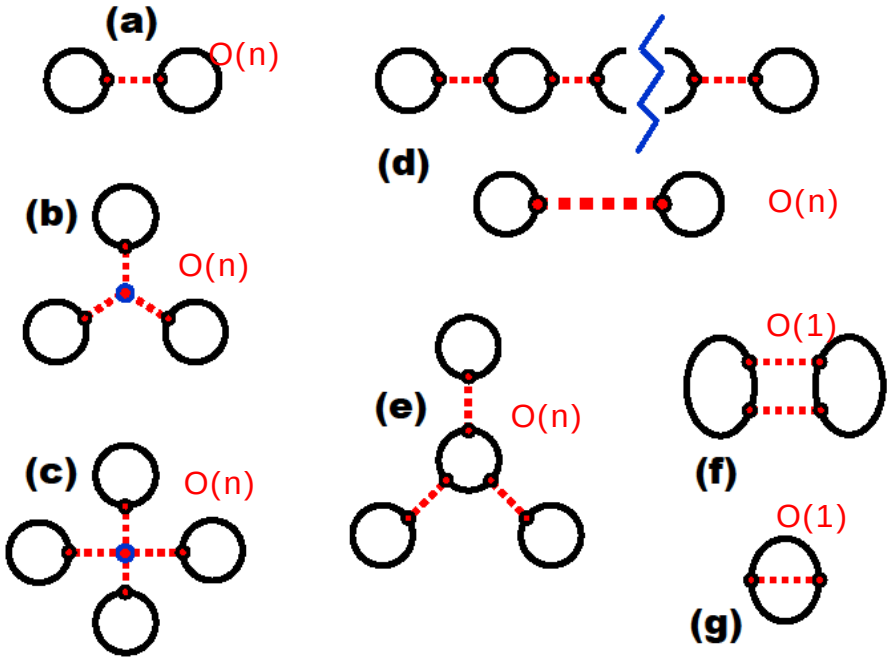
NON-PERTURBATIVE RESULTS I: GENERATING FUNCTIONAL



Some Diagram Rules: We see at right how different kinds of vertex are weighted by *n*, for *n* paths.

For large n only some graphs survive – those which are ~ O(n).

Connected Generating Functional: This gives vacuum amplitudes, energies, etc., at *T = 0* (diagrams at left below). Key conclusion – any graphs with loops containing gravitons contribute zero.



Exact Eikonal Result

We can find the generating functional exactly:

$$\mathbb{Q}[J] = e^{i(S_G[\bar{g}_J] + W_0[J|\bar{g}_J])}$$

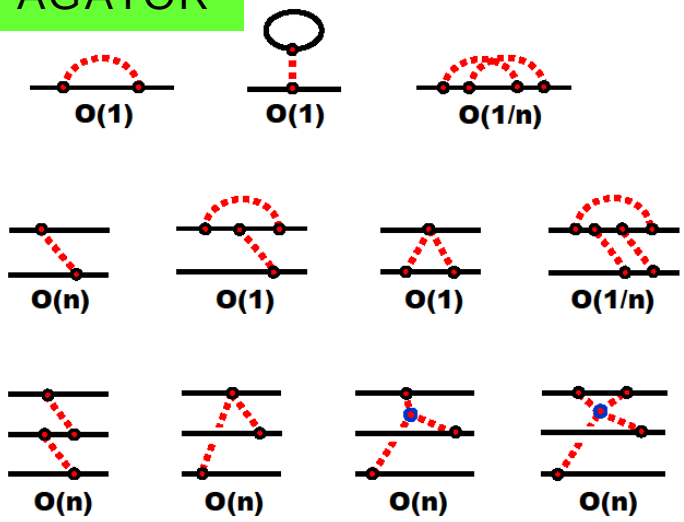
which yields as a solution the semiclassical Einstein eqtn of motion for the metric:

$$G_{\mu\nu}(x|\bar{g}_J) = 8\pi G_N \langle T_{\mu\nu}[x|\bar{g}_J] \rangle_J$$

This is true even in the quantum regime of small masses.

NON-PERTURBATIVE RESULTS II: MATTER PROPAGATOR

Consider the "untethered graphs" for K(2,1) with *n* open matter lines. For large n, again only those ~ O(n) survive, & no loops containing gravitons survive – only "skeleton" tree graphs.



Exact Eikonal Result

We switch off gravitational dynamics, & define the propagator in a background g:

$$K^0_\phi(\Phi_2,\Phi_1|g) \;=\; \int_{\Phi_1}^{\Phi_2} \mathcal{D}\phi\; e^{iS_\phi[\phi,g]} \;=\; e^{i\psi_0(\Phi_2,\Phi_1|g)}$$

Then the full CWL propagator is

$$\mathcal{K}(2,1) = e^{i(S_G(2,1|[\bar{g}])+\psi_0(2,1|\bar{g}))}$$

with $$\frac{\delta}{\delta g}\Big(S_G(2,1|[g]) + \psi_0(2,1|g)\Big)\Big|_{g=\bar{g}} = 0$$

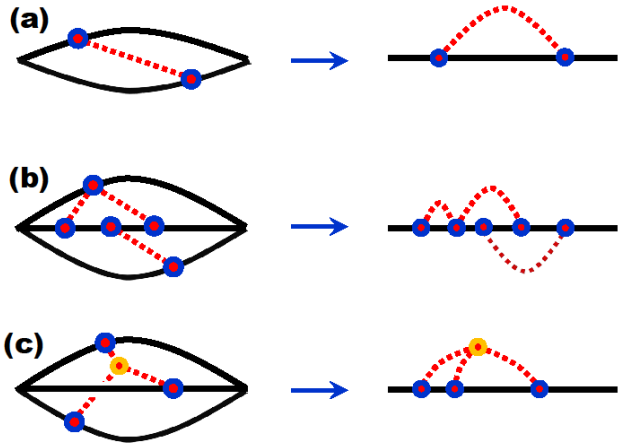
The functional derivative is

$$\frac{\delta}{\delta g^{\mu\nu}}\psi_0(2,1|g) \;=\; -\tfrac{1}{2}\frac{\langle\Phi_2|T_{\mu\nu}|\Phi_1\rangle}{\langle\Phi_2|\Phi_1\rangle}$$

So, the result is that the particle propagates in the Einstein field produced by all paths; but it still shows superposition. For small masses get conventional QM

LARGE MASSES – CLASSICAL LIMIT

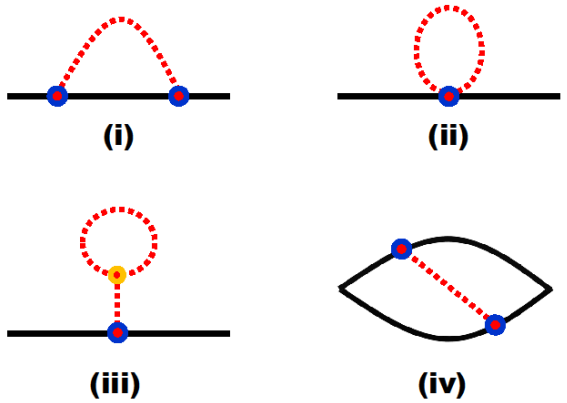
Particle lines collapse onto each other, reproducing classical mass dynamics (including radiation reaction, etc.)



PERTURBATION THEORY for SMALL MASSES

PERTURBATIVE EXPANSION to O(ℓ_P^2)

The 4 lowest order graphs, beyond the simple free field propagator, contributing to K(2,1), are at right.



However only the 4th one contributes – all others are zero (they have loops containing a graviton). We then get:

$$\mathcal{K}(2,1) \sim K_0^{-1}(2,1)\int_{\Phi_1}^{\Phi_2}\mathcal{D}\phi\int_{\Phi_1}^{\Phi_2}\mathcal{D}\phi'\, e^{i(S[\phi]+S[\phi'])}\, e^{iS_{CWL}[\phi,\phi']} + O(\ell_P^4)$$

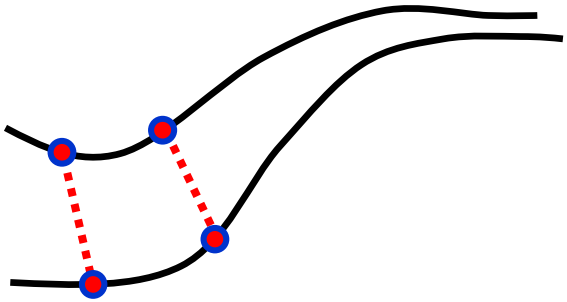
where $$S_{CWL}[\phi,\phi'] = -\frac{\ell_P^2}{8}\int d^4x\int d^4x' D^{\mu\nu\alpha\beta}(x-x')T_{\mu\nu}(\phi(x))T_{\alpha\beta}(\phi'(x'))$$

PATH-BUNCHING: Suppose we are dealing with a particle. Then

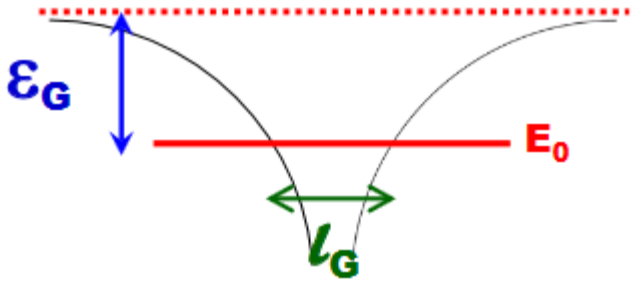
$$S_{CWL}[q,q'] = -\frac{\ell_P^2}{2}\int d^4x\int d^4x'\, D^{\mu\nu\alpha\beta}(x,x')T_{\mu\nu}(q,x)T_{\alpha\beta}(q',x')$$

$$\underset{v\ll c}{\rightarrow\lim} \frac{1}{8}\int_{t_1}^{t_2}dt\frac{Gm^2}{|\mathbf{r}(t)-\mathbf{r}'(t)|}$$

ie., a Newtonian attraction between paths.



SLOW PARTICLE DYNAMICS to O(ℓ_P^2)



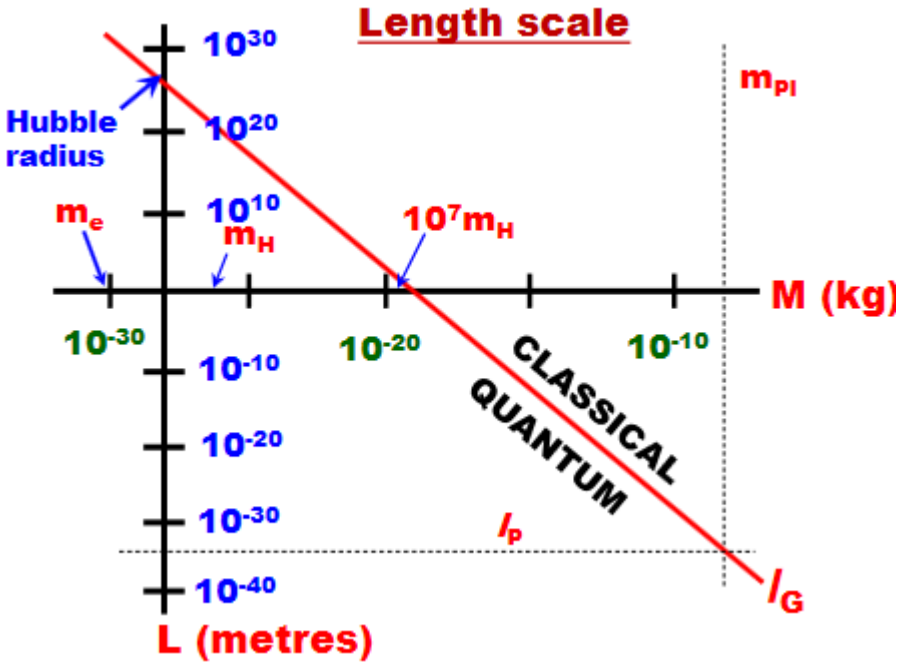
In this perturbative calculation, we see that the paths for a single particle are attracted to each other by a PATH-BUNCHING potential, which tries to bind paths together. The characteristic scales are

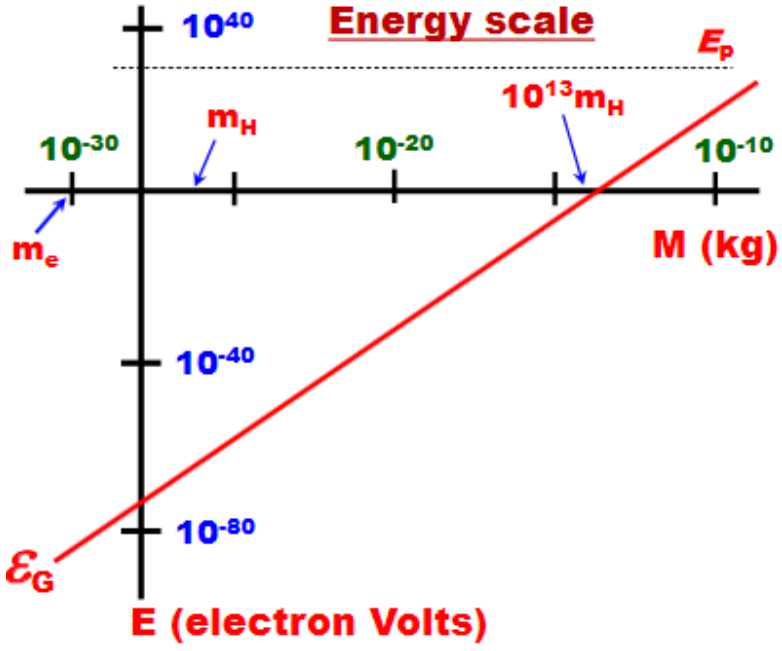
$$l_G(m) = \left(\frac{M_p}{m}\right)^3 L_p$$ **Newton radius (gravitational analogue of the Bohr radius)**

$$\epsilon_G(m) = G^2m^2/l_G(m) \equiv E_p(m/M_p)^5$$ **Mutual binding energy for paths**

} **(QM)**

$$R_s = 2Gm/c^2$$ **Schwarzchild radius for the particle** **(Classical)**





BUT – these results do NOT describe CWL dynamics for an extended body!

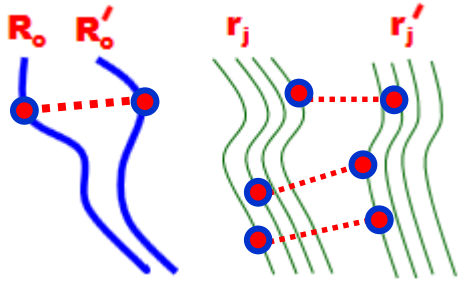
SLOW MOTION of an EXTENDED MASS to ~ O(ℓ_P^2)

A solid extended body has action: $$S_o[\mathbf{R}_o,\{\mathbf{r}_j\}] = \int d\tau \left[\frac{M_o}{2}\dot{\mathbf{R}}_o^2 + \sum_{j=1}^{N}\frac{m_j}{2}\dot{\mathbf{r}}_j^2 - \sum_{i<j}^{N} V(\mathbf{r}_i-\mathbf{r}_j)\right]$$

Centre of mass coordinate: $$\mathbf{R_o}(t) = \frac{1}{N}\sum_{j=1}^{N}\mathbf{q}_j(t)$$

Relative coordinates: $$\mathbf{q}_j = \mathbf{R_o} + \mathbf{r}_j$$

System can be either crystalline or amorphous



The N-ion QM propagator is

$$G_o^{(N)}(2,1) = \int \mathcal{D}\mathbf{R}_o \prod_j \mathcal{D}\mathbf{r}_j\ \delta(\sum_j \mathbf{r}_j/N)\ \exp\frac{i}{\hbar}S_{2,1}[\mathbf{R}_o,\{\mathbf{r}_j\}]$$

to which we add CWL corrections in IP2 approximation

We assume $$\omega^2_{\mathbf{Q}\mu} = \frac{1}{m}\sum_{i\neq j} V_{ij} e^{i\mathbf{Q}\cdot\mathbf{r}_{ij}^{(o)}}$$ Phonon spectrum

and $$\langle u_i^\alpha(t_1) u_j^\beta(t_1)\rangle = \frac{1}{N}\sum_{\mathbf{Q}\mu}\frac{\hat{e}^\alpha_{\mathbf{Q}\mu}\hat{e}^\beta_{\mathbf{Q}\mu}}{2m\omega_{\mathbf{Q}\mu}}\, e^{i[\mathbf{Q}\cdot\mathbf{r}_{ij}^{(o)} - \omega_{\mathbf{Q}\mu}(t_1-t_2)]}$$ Phonon Correlator

RESULTS: New effective Potential has smooth and "spike" components

(i) Smooth potential term:

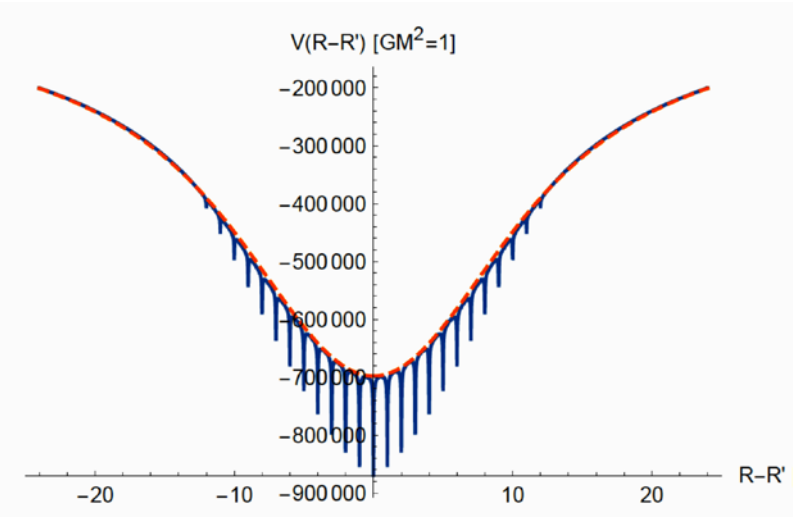
$$\omega_{eff} = \left(\frac{\pi}{6}\gamma^3 G\rho_{avg}\right)^{1/2}$$ Eg., 6.7 x 10^{-5} s^{-1} (Au)

(1 week timescale)

(ii) Toothcomb term:

$$\omega_{eff} = \left(\sqrt{\frac{2}{\pi}}\frac{Gm}{3\sigma^3}\right)^{\frac{1}{2}}$$ Eg., 0.38 s^{-1} (SiO_2)

(16 sec timescale)



Interaction potential for cube, with relative path displacement along cubic axis

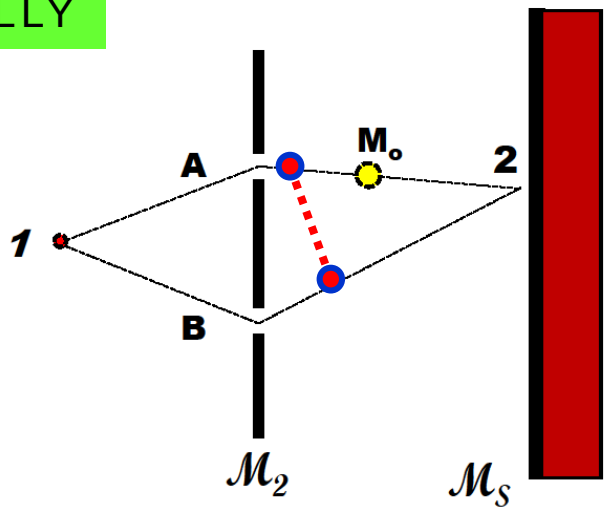
WHAT THIS MEANS EXPERIMENTALLY

We have the usual 2-path set-up; to be definite, model this as a 2-slit system.

We can assume $\mathcal{M}_s$ to be infinite; the recoil of $\mathcal{M}_2$ is essential to the analysis.

The functional derivative of the matter phase is

$$\frac{\delta\psi_0(x_2,x_1|g)}{\delta g^{\mu\nu}(x)} = -\tfrac{1}{2}\sum_{\alpha}^{A,B} T_{\mu\nu}(x;[q^{(\alpha)}|g])$$



where on the α-th path, we assume a simple particle propagator, so that

$$T^{(\alpha)}_{\mu\nu}(x|q) = m\int ds\, u^{(\alpha)}_{\mu}(s)u^{(\alpha)}_{\nu}(s)\,\delta^{(4)}(x-q^{(\alpha)}(s))$$

Then the metric field satisfies

$$G_{\mu\nu}(x;2,1|\bar{g}) = 8\pi G\sum_{\alpha}^{A,B} T_{\mu\nu}(x;[q^{(\alpha)}|\bar{g}])$$

and the particle 2-path propagator is

$$\mathcal{K}(2,1) = e^{iS_G(2,1;[\langle\bar{g}\rangle_{AB}])}\sum_{\alpha}^{A,B} e^{iS_M[q^{(\alpha)}|\langle\bar{g}\rangle_{AB}]}$$

SMALL MASS: The mass propagates in field of both paths: each path acts on the other via gravity (similar to Penrose picture). For masses < 10^{-14} kg (10^{13} amu, or 10^{-6} M_P), the gravity is negligible, and QM is obeyed.

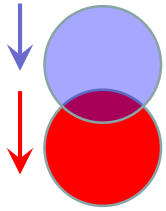
LARGE MASS: Now path bunching occurs. However - path bunching dynamics is controlled by dissipative coupling to the environment.

In interference experiments with mirrors the Q-factor may be very large - the path-bunching time will then be $\tau_{PB} \sim Q/\omega_{eff}$ which will then be very long.

It then follows that the presence or otherwise of path-bunching will depend on how the system state is initially prepared.

SOME PROPOSED EXPERIMENTS

(1) One can look at interference between 2 separate states of a moving object – the 2 paths here, corresponding to the 2 different positions of the mass, will interact gravitationally in the CWL theory according to what we have seen. One can imagine lots of different ways to do this – eg., with either a freely falling mass, or a levitated mass.



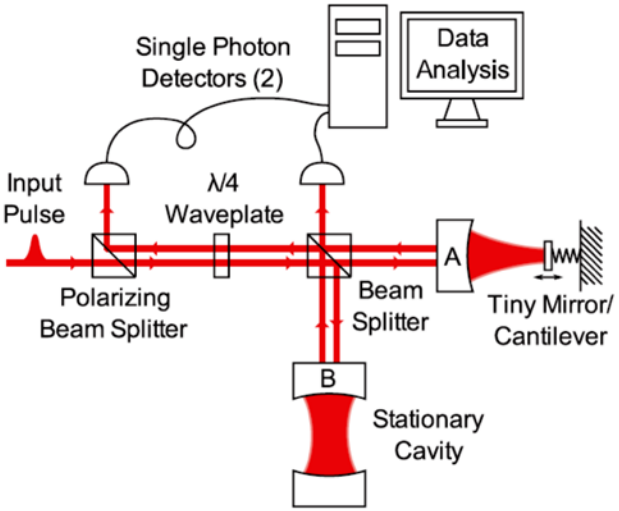
U Delic et al., Science 367, 892 (2020)

(2) One can look at interference between the 2 paths of an oscillating heavy mass. One way to do this is to entangle a photon with a heavy mirror, and then look for gravitational effects. Starting from a state

$$|\psi(0)\rangle = (1/\sqrt{2})(|0\rangle_A|1\rangle_B + |1\rangle_A|0\rangle_B)|0\rangle_m$$

we get

$$|\psi(t)\rangle = \frac{1}{\sqrt{2}} e^{-i\omega_c t}[|0\rangle_A|1\rangle_B|0\rangle + e^{i\kappa^2(\omega_m t - \sin\omega_m t)}|1\rangle_A|0\rangle_B \; |\kappa(1 - e^{-i\omega_m t})\rangle_m],$$



and one looks at interference between the 2 branches. Another alternative is to look at interference between a 0-phonon and a 1-phonon state

D Kleckner et al., N J Phys 10, 095020 (2008)

I Pikowski et al., Nat Phys 8, 393 (2012)

(3) The difficulty here is to reduce environmental decoherence effects – coming from the interaction with photons, or between, eg., charged defects in the system (or spin defects/nuclear spins) and EM fields.

A KEY RESULT: Gravitational effects depend in a completely different way on system parameters than do decoherence effects.

SUMMARY & CONCLUSIONS

1. One can find a consistent CWL theory – in which inter-path correlations by a quantized gravitational field cause the breakdown of the superposition principle for large masses. The CWL theory is a low-energy theory ($E << M_P$)

2. There are no adjustable parameters in this theory. For small masses it reduces to standard QM or QFT. For large masses it reduces to classical GR. The crossover between the two limits can be estimated in perturbation theory to be for masses ~ 10^{-13} kg ~ 10^{-5} M_P

3. The gravitational interaction between matter paths causes path bunching for massive systems, on a timescale ~ 10Q secs, where Q^{-1} parametrizes the dissipation.

4. Experimental tests will be hard, but the technology is not too far beyond current limits.

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