⟨Quantum|Gravity⟩Society

A CWL Primer

Phillip Stamp

A CWL PRIMER

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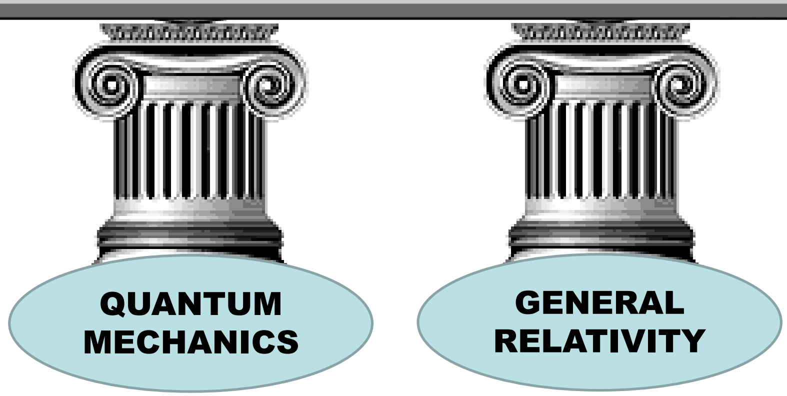
Q Grav meeting, Aug 15, 2022

⟨Quantum|Gravity⟩ Society

SETTING the SCENE – the GREAT CONUNDRUM

ALL of
Physics, Chemistry, Biology, etc…

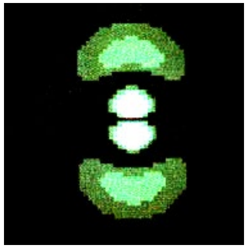


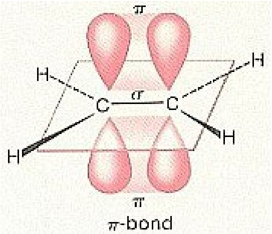
The twin pillars of modern science are Quantum Mechanics & General Relativity

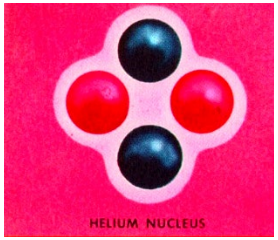
No limits have been found to these theories, between 10^{-19} m and 14 billion light years (a range of 10^{42})

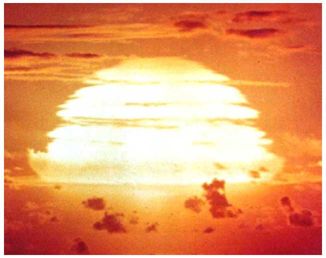
Both theories have had a success unprecedented in human history. However, the 2 theories seem to be incompatible. Finding a theory that encompasses them is the biggest & deepest problem in physics

QUANTUM MECHANICS

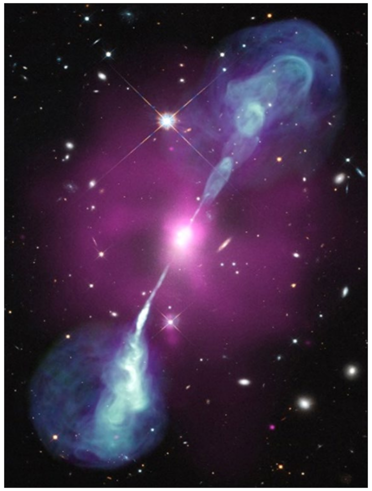


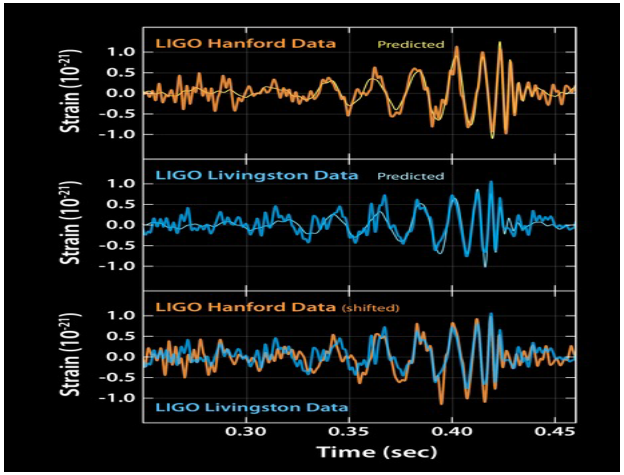






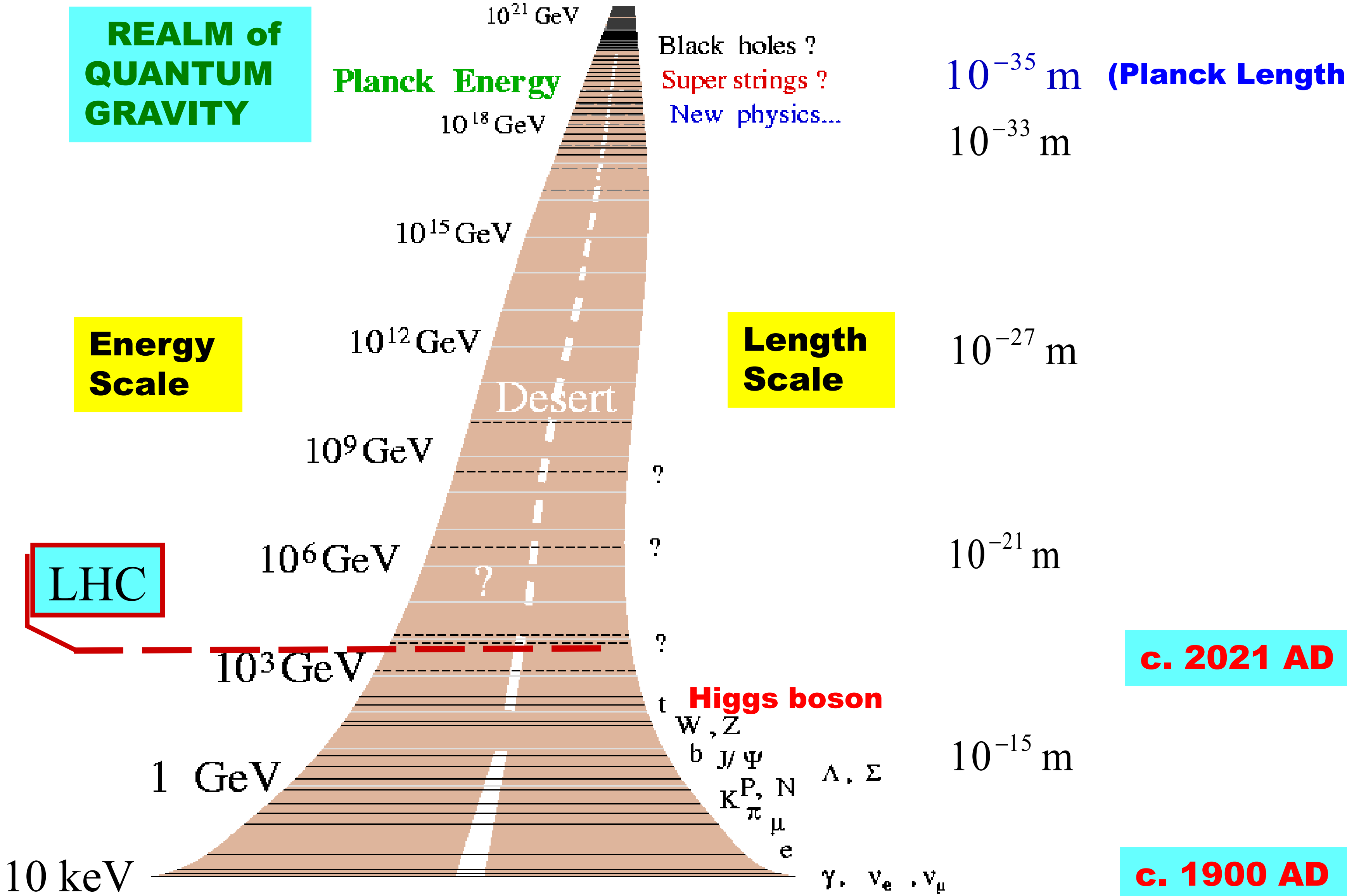
GENERAL RELATIVITY





The CONVENTIONAL "Quantum Field" VIEW

Reality is quantum-mechanical. We need to quantize gravity at Planck scale to get the right theory.
Current efforts: String theory; also loop gravity, etc..



HIGH_ENERGY VIEW: PROBLEM #1

SOME NUMBERS

$$h/2\pi = \hbar = 1.0546 \times 10^{-34}\ \text{kg m}^2\ \text{sec}^{-1}$$
$$G_N = 6.672 \times 10^{-11}\text{m}^3\ \text{kg}^{-1}\ \text{sec}^{-2}$$
$$c = 2.99792458 \times 10^8\ \text{m/sec}$$

Planck Length: $L_P = (hG/2\pi c^3)^{1/2} = 1.616 \times 10^{-35}$ m

Planck Mass: $M_P = (hc/2\pi G)^{1/2} = 2.18 \times 10^{-8}$ kg

Planck Energy: $E_P = (hc^5/2\pi G)^{1/2} = 1.96 \times 10^9$ J $= 1.22 \times 10^{19}$ GeV $= 1.42 \times 10^{32}$ K

A v small grain of sand (0.4 mm diameter) has mass M_P

A Planck energy would raise 5 tons of water from 0°C to 100°C

EXPERIMENTS: at Planck scales, one needs a Planck energy $E_P = M_P c^2$ to be deposited in a volume $V_P = L_P^3$, ie., for a "Planck energy density" $\rho_P = E_P/L_P^3$

Planck Energy Density: $\rho_P = 2\pi c^7/hG^2 = 4.68 \times 10^{113}$ J/m^3 $= 2.61 \times 10^{123}$ GeV/m^3

This energy density is 10^{45} higher than current LHC !!

So – PROBLEM #1 is that a high-energy theory is utterly beyond the reach of any conceivable earth-based experiment.

Only viable testing ground is close to ~ t_P ~ 5.39×10^{-44} s of Big Bang

HIGH-ENERGY VIEW: PROBLEM #2

Field	Force F	Quanta
Maxwell (EM)	$F_{12} = k \frac{Q_1 Q_2}{R^2}$	photons
Weak	$F_{12} = g \frac{T_{12}}{R^2} e^{-M_W R}$	W bosons
Strong	$F_{12} \rightarrow$ Const (for $R \rightarrow \infty$)	gluons
Gravitational	$F_{12} = G \frac{M_1 M_2}{R^2}$	gravitons

The 1st three forces can be treated by conventional quantum field theory. They are "renormalizable", and the short-distance behaviour is OK.

But at short distances & high energies, Gravity blows up, because

$E = Mc^2$ so $M = E/c^2 = h/c\lambda$

$\sim h/cR$ & force becomes $F_{12} \rightarrow G \frac{h^2}{c^2} \frac{1}{R^4} = \frac{8\pi}{\kappa} \frac{L_P^4}{R^4}$

So - PROBLEM #2: Gravity is "perturbatively non-renormalizable".

Thus some new high-energy framework is required. This is hard

> It is not well-appreciated how hard it is to build a consistent theoretical framework to unify general relativity and quantum mechanics. Currently, superstring theory is the only credible theory to have achieved the unification. **H. Ooguri (2021)**

PROBLEM #3: Low-E INCOMPATIBILITY of QM & GR

Consider a 2-slit experiment. Ignoring gravity we write

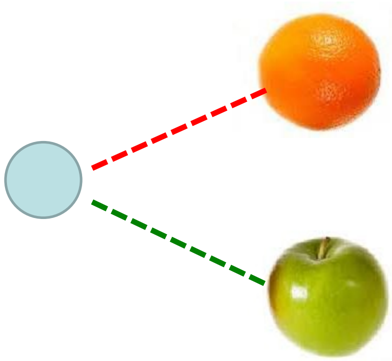
$$\Phi(\mathbf{r},t) \equiv \langle \mathbf{r}|\Phi(t)\rangle \;=\; a_1\Phi_1(\mathbf{r},t) + a_2\Phi(\mathbf{r},t)$$

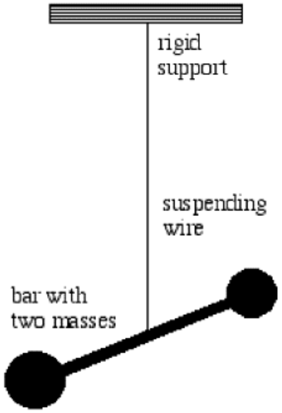
with interference term

$$\langle \Phi_1(t)|\Phi_2(t)\rangle \;=\; \int d^3r\; \langle \Phi_1^*(\mathbf{r},t)|\Phi_2(\mathbf{r},t)\rangle$$

However, with gravity included we must have

$$|\Psi\rangle \;=\; a_1|\Phi_1; \tilde{g}^{\mu\nu}_{(1)}(x)\rangle + a_1|\Phi_2; \tilde{g}^{\mu\nu}_{(2)}(x)\rangle$$





Several problems with this…

(i) There are 2 different coordinate systems, $(\mathbf{r}_j, t_j)$, defined by the 2 different metrics $\tilde{g}^{\mu\nu}_{(j)}(x)$ & in general we cannot relate these. The 2 metrics have different vacua.

(ii) All matter fields in QFT need the background spacetime to define causal relationships. Thus, eg., for a fermionic field we have

$$[\hat{\psi}(x),\, \hat{\psi}(x')] \equiv \hat{\psi}(x)\hat{\psi}(x') - \hat{\psi}(x')\hat{\psi}(x) = 0$$ (spacelike separated – no causal relation)

but non-zero for time-like separated intervals. If the metric field is quantized we then require $[\hat{g}_{ab}(x),\, \hat{g}_{cd}(x')] = 0$ (for x-x' spacelike separated)

But this eqtn. is meaningless: $s^2 = (x-x')^2$ is defined by $g_{\mu\nu}(x)$!! Then a quantum fluctuation in the metric can change matter field causal relations.

(iii) A "wave-function collapse" causes non-local changes; because the matter couples to the metric, this causes drastic unphysical changes in the metric.

So, PROBLEM #3: trying to superpose different spacetimes leads to apparently meaningless results. Causal relations in standard QFT require a specific background spacetime. This problem has noting to do with high energies – it happens instead when we have "mass superpositions"

THE LOW-ENERGY ROAD

or

LOOKING for a FAILURE of QUANTUM MECHANICS

In this view, the key questions have nothing to do with the PLANCK SCALE.

WE'VE BEEN LOOKING IN THE WRONG PLACE…!!

WHY SO MANY PEOPLE HAVE PROBLEMS with QUANTUM MECHANICS

(i) The state of a quantum system is represented by a state vector $|\psi>$

But $|\psi>$ can't represent a real physical object - changes in $|\psi>$ happen non-locally (cf EPR paradox). But if $|\psi>$ only represents 'information', different observers can assign different $|\psi>$. We then lose all reference to the physical world.

(ii) In QM, $|\psi>$ "collapses" when a "measurement" is made.

We write $\langle M_j \rangle = Tr\{\hat{M}_j \hat{\rho}\}$ for a mmt. M_j; the projection operator is an EXTRANEOUS NON-QUANTUM AGENT. But measurements are physical operations, & are part of the world! This is a contradiction.

Either the whole world is quantum mechanical – in which case the foundations of QM are self-contradictory – or the "classical world" of measurements is different, and apparently revolves around external "classical" set-ups, whose defining properties are very ambiguous and seem to devolve on experimenters.

In the latter case QM is formulated completely <u>anthropocentrically</u> – this is a throwback to mediaeval times, & is scientifically implausible

(iii) If QM is generally true, we get "macroscopic superpositions of states".

If QM is generally true then clearly we can have macroscopic quantum states. Even measuring systems can then be in "Schrodinger's Cat" superpositions. But what does it mean for a macroscopic system to be in a superposition of states?

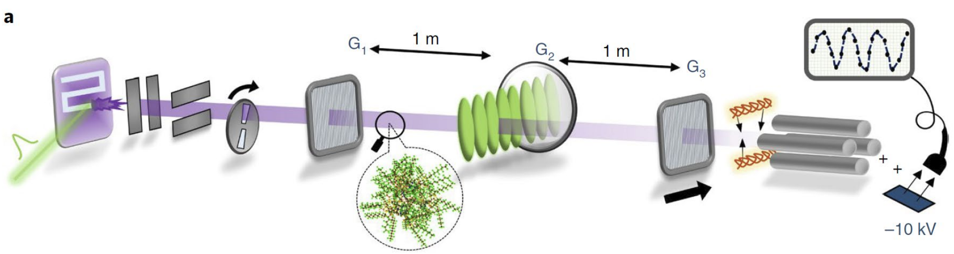
"....I think I can safely say that nobody understand Quantum Mechanics" (R.P. Feynman, 1965)

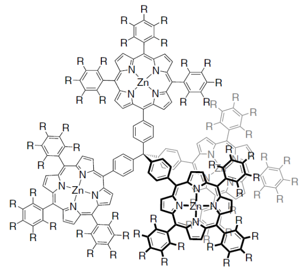
Question: HOW MACROSCOPIC is QUANTUM MECHANICS?

(1) SPIN & MASS SUPERPOSITION EXPTS: Expts show very large number of spins in identical superposed states (likewise for BEC). But these are not "Cat states", and do not involve macroscopic superpositions. One can also try to superpose a massive body in 2 different states. In reality one finds a maximum "degree of macroscopicity" of $\Delta N_{tot} \sim O(10^2 - 10^3)$ for spin systems, and mass superpositions $m \sim 10^5$ AMU $\sim 10^{-14} M_P$

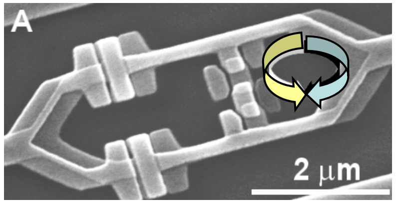
B Julsgaard et al., Nature 413, 400 (2001)
S Takahashi et al., Nature 476, 76 (2011)

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





(2) PHASE SUPERPOSITION/ENTANGLEMENT: A famous example - SQUID macroscopic superposition experiment (Leggett). One finds the N-particle entanglement in expts:



Circulating current in Delft SQUID

		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)

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

SOME HISTORY

ADVICE from 1957

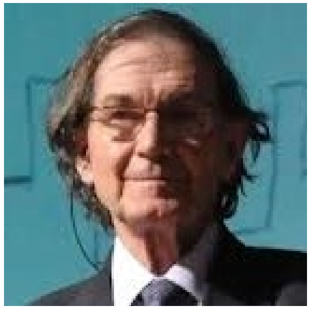
Feynman I would like to suggest that it is possible that quantum mechanics fails at large distances and for large objects. If this failure of quantum mechanics is connected with gravity, we might speculatively expect this to happen for masses such that $GM^2/\hbar c = 1$, of M near 10^{-5} grams, which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

There exists, however, one serious difficulty, and that is the lack of experiments. Furthermore, we are not going to get any experiments, so we have to take a viewpoint of how to deal with problems where no experiments are available. **(Feynman, Chapel Hill, 1957)**

Now, 65 yrs later, this difficulty is near a solution

RP Feynman (1920-1987)

SOME MORE RECENT HISTORY



R Penrose (1931 -)

R. Penrose argued (GRG 28, 581 1996) that the 2 times elapsed in a 2-branch superposition cannot be directly compared; there is a 'time uncertainty', related to an energy uncertainty given in a Newtonian limit by:

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

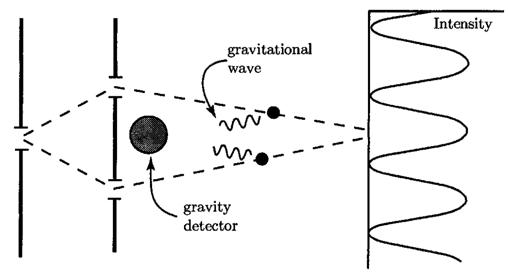
Result: dephasing between the 2 branches – with dephasing time $\tau_\phi = \hbar / \Delta E$ (A sort of 'intrinsic decoherence' time).

PROBLEM: Unable to find a theory

"...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."

TWB Kibble (1932-2016)

TWB Kibble Kibble's very technical attempt to incorporate gravity into QM also involved an analysis of the 2-slit expt using "semiclassical gravity", for which one writes



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

where the quantum stress tensor is replaced by its expectation value.

Kibble concluded there was no such consistent non-linear QFT: that the usual QM structure of operators, mmts, Hilbert space, etc. ruined any such attempt. Similar conclusions were reached by S Weinberg, J Polchinski (1989-91), who also showed that any such modifications led to superluminal propagation.

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)

The CWL THEORY

COLLABORATORS

Andrei Barvinsky	(Lebedev, Moscow)
Dan Carney	(Berkeley)
Yanbei Chen	(Caltech)
Jordan Gerow-Wilson	(UBC)

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, Phys Rev D105, 084015 (2022)
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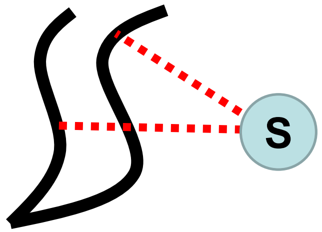
J Wilson-Gerow, C Delisle, PCE Stamp, Class Q Grav 35, 164001 (2018)
C Delisle, J Wilson-Gerow, PCE Stamp, /arXiv: 1905.05333
C DeLisle, J Wilson-Gerow, PCE Stamp, JHEP 03 (2021), 290
J Wilson-Gerow, PCE Stamp, Ann. Phys (NY) 442, 168898 (2022)

ONE KEY IDEA behind CWL THEORY: PATHS ARE FUNDAMENTAL

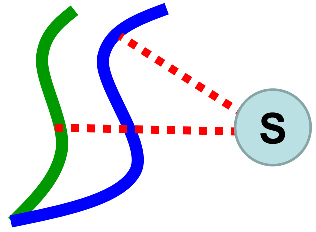
Gravity (the metric field $g^{\mu\nu}$) sees all fields the same – all it sees is the stress-energy tensor $T_{\mu\nu}$

But this means that it can't even distinguish multiple paths for a single particle from multiple paths for multiple particles!



2 paths for SINGLE object

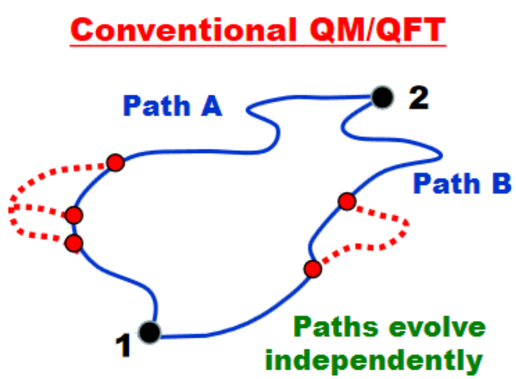
Gravity does not distinguish this from:

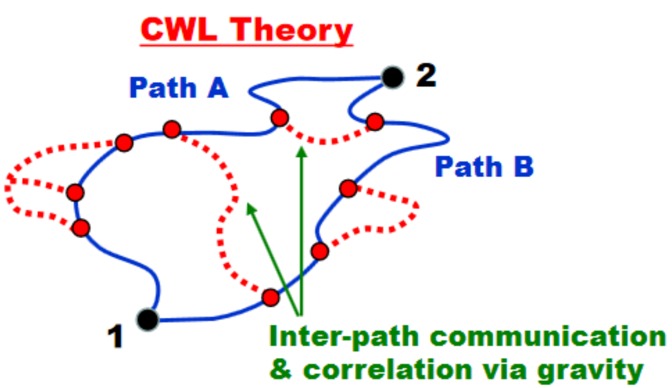


2 paths for TWO DIFFERENT objects

CONCLUSION: paths for a SINGLE OBJECT can interact via gravity

This implies a breakdown of the superposition principle





FORMAL STRUCTURE of CWL THEORY: GENERATING FUNCTIONAL

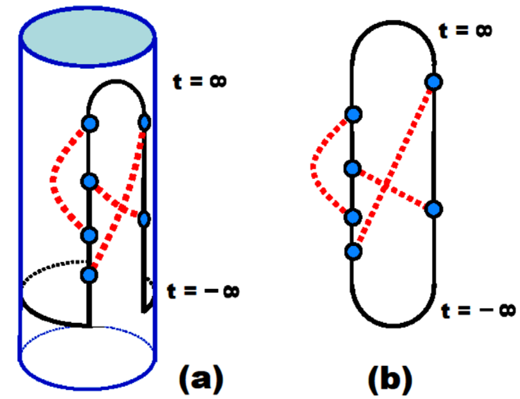
A scalar field has generating functional $Z_\phi[g,J] \;=\; \oint D\phi\, e^{i(S_\phi[g,\phi] \,+\, \int J\phi)}$

Conventional Quantum Gravity:

This has generating functional:

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

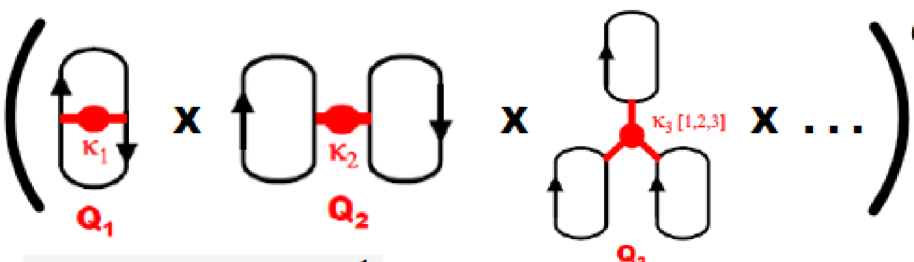
$$= \oint \mathfrak{D}g\, e^{iS_G[g]}\Delta[g]\delta(\chi^\mu(g))\, Z_\phi[g,J]$$



CWL Theory: This has generating functional

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

$$= \lim_{N\to\infty}\Big(\cdots \Big)^{\alpha_N}$$

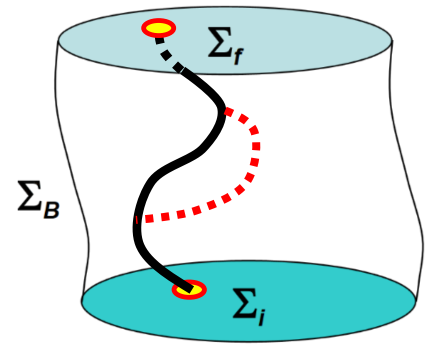


We note that log Q[J] is additive over these "tower" or "path" contributions, and α_N rescales things.

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



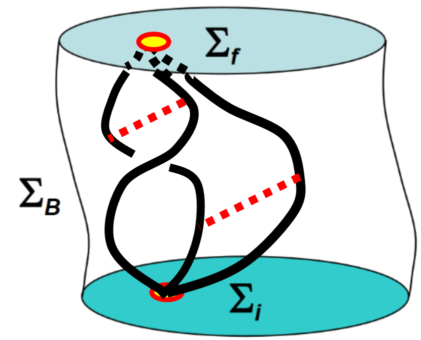
Conventional Quantum Gravity: We write a propagator

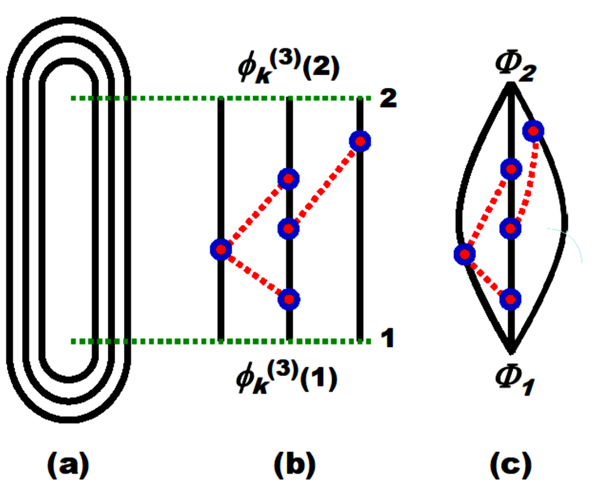
$$K(2,1) \;\equiv\; K(\Phi_2, \Phi_1; \mathfrak{h}_2^{ab}, \mathfrak{h}_1^{ab})$$
$$= \int_{\mathfrak{h}_1}^{\mathfrak{h}_2} \mathcal{D}g \, e^{\frac{i}{\hbar} S_G[g]} \Delta(g)\, \delta(\chi^\mu) \int_{\Phi_1}^{\Phi_2} \mathcal{D}\phi \; e^{i S_\phi[\phi, g]}$$

with metric & matter fields defined between hypersurfaces.

CWL Theory: The matter propagator takes the form (suppressing 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.

SOME
KEY FEATURES
of the
CWL THEORY

"A theory is not a theory until it produces a number"

R.P. Feynman (Lectures on Physics, 1965)

BEYOND PERTURBATION THEORY: EXACT RESULTS

CONSISTENCY

1. Consistent classical limit ☺
2. Well-behaved *h* and l_P^2 expansions ☺
3. All Ward identities obeyed ☺
4. Renormalizable ☺

Thus, string theory is not the only consistent theory of quantum gravity!

MATTER PROPAGATOR

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

The functional derivative is

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

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

GENERATING FUNCTIONAL

We can find the generating functional exactly:

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

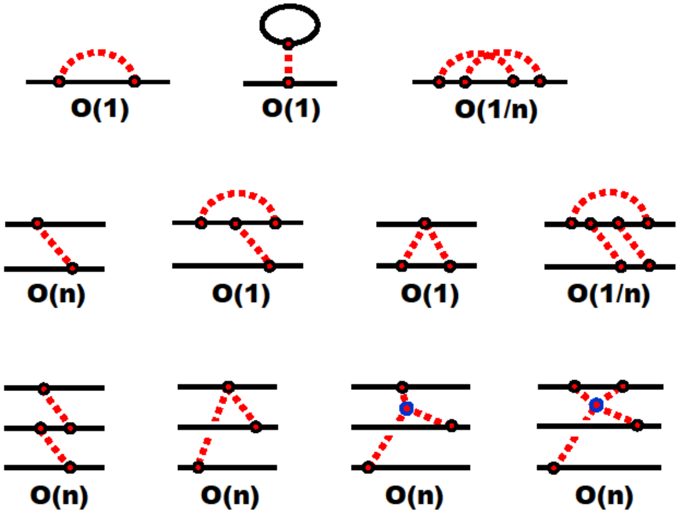
which yields as a solution the semiclassical Einstein eqtn of motion for the metric:

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

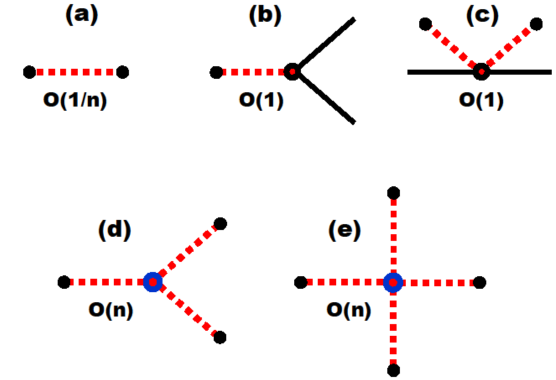
This is true even in the quantum regime of small masses.

So: the sum over the QUANTUM Paths tells the QUANTUM spacetime metric field how to move; & the paths interact with each other via distorted metric field, sourced by quantum paths.

ALL ORDERS in PERTURBATION THEORY



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

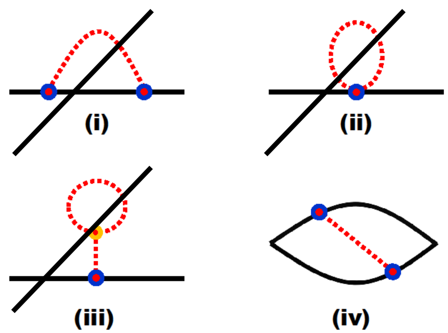


Lowest-order Perturbation theory

The expansion parameter is

$$\ell_P^2 = 8Gh$$

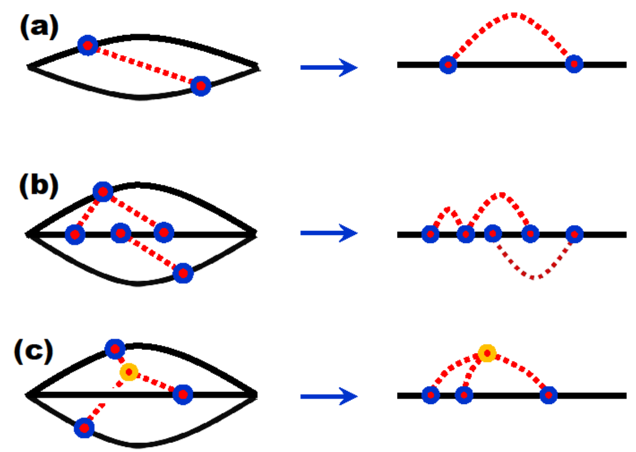
which is NOT Dimensionless (this is related to the non-renormalizability of GR).



Only one graph survives (ie., graph (iv)). It describes the interaction between 2 paths of a single particle – we see the key feature of CWL here, that Q superposition has broken down.

LARGE MASSES

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

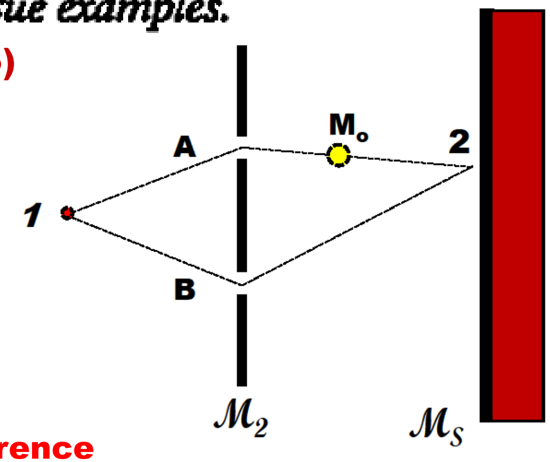


A key physical question we will come to: what is the DYNAMICS of this collapse ?

The 2-PATH EXPERIMENT in QUANTUM GRAVITY

Only wimps specialize in the general case. Real scientists pursue examples.

MV Berry: Ann NY Acad Sci 755, 303 (1995)



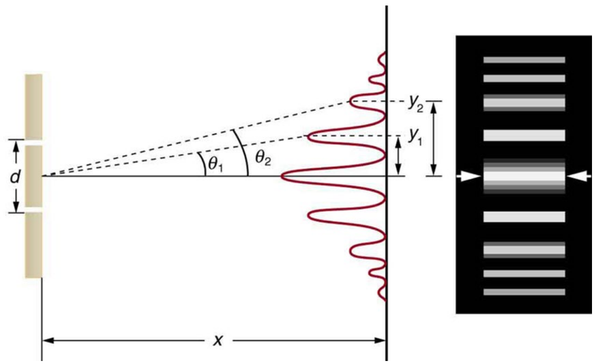
As discussed by, eg., Feynman, the 2-path experiment encapsulates key features of QM. If we ignore gravity, we just have

$$K_0(2,1) \;=\; \sum_{\alpha}^{A,B} \Omega_o^{(\alpha)}\, e^{iS^0_{21}[q^{(\alpha)}|\eta]}$$

Sum amplitudes over 2 paths

This then gives $K_0(2,1) \;=\; 2\,\Omega_o\, e^{i\bar{S}^0_{21}}\, \cos(\Delta S_{21})$

Envelope **interference**



here

$$\bar{S}^0_{21} \;\equiv\; \tfrac{1}{2}\Big(S^0_{21}[q^{(A)}] + S^0_{21}[q^{(B)}]\Big)$$

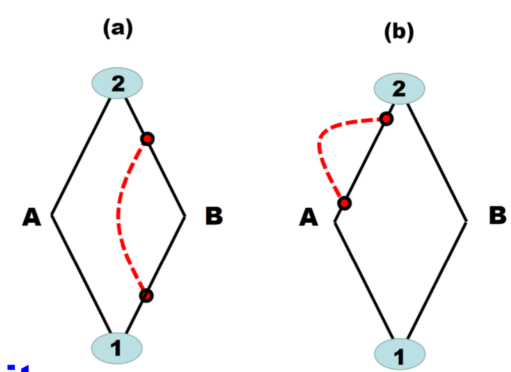
$$\Delta S_{21} \;\equiv\; \tfrac{1}{2}\Big(S^0_{21}[q^{(A)}] - S^0_{21}[q^{(B)}]\Big)$$

& the probability of arriving at point 2 on the screen is then $|K_o(2,1)|^2$

What happens when we add gravity?

1. <u>CONVENTIONAL QUANTUM GRAVITY</u>: Then we just get

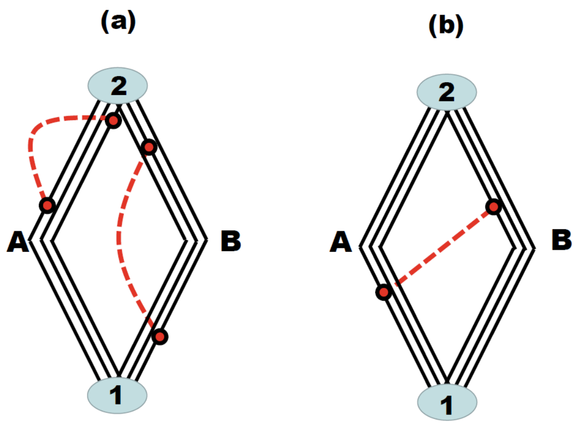
$$K(2,1) \;=\; \sum_{\alpha}^{A,B} K_0^{(\alpha)}(2,1)\; e^{\frac{i}{2}\int d^4x \int d^4x'\, T_{\mu\nu}(x|q^{(\alpha)})\, D^{\mu\nu\lambda\sigma}(x,x')\, T_{\lambda\sigma}(x'|q^{(\alpha)}}$$



Each path is renormalized SEPARATELY by gravitons. We never see these renormalizations, since we can't switch off gravity.

2. CWL THEORY: Then we get $\mathcal{K}(2,1) = K_0(2,1)\, e^{i\Theta_{21}}$ **where $K_o(2,1)$ is the QM result, and the COMPLEX phase is**

$$\Theta_{21} = \frac{G_N}{4}\int_{t_1}^{t_2} dt \int \frac{d^3r d^3r'}{|\mathbf{r}-\mathbf{r}'|}\left\{\left[(T_A T'_A + T_B T'_B)(1-\tan^2(\Delta S_{21})) + 2\frac{T_A T'_B}{\cos^2(\Delta S_{21})}\right] + 2i\,(T_A T'_A - T_B T'_B)\tan(\Delta S_{21})\right\}$$



Analysis of this expression shows that the CWL "inter-path" correlations (shown at left for triple path contributions) strongly affect the regions of destructive interference (the "dark" fringes). The divergence in the phase can be corrected by a non-perturbative analysis.

For masses < 10^{-14} kg (10^{13} amu, or 10^{-6} M_P), the CWL corrections are negligible, and QM is obeyed.

3. SEMICLASSICAL GRAVITY THEORY: Although this theory has been known since Kibble to be internally inconsistent, we can still calculate with it. We get

$K_{sc}(2,1) = A^{(sc)}(2,1)e^{i\Phi_{21}}$ **where** $A^{(sc)}(2,1) = 2\Omega_o\cos(\Delta S_{21})$

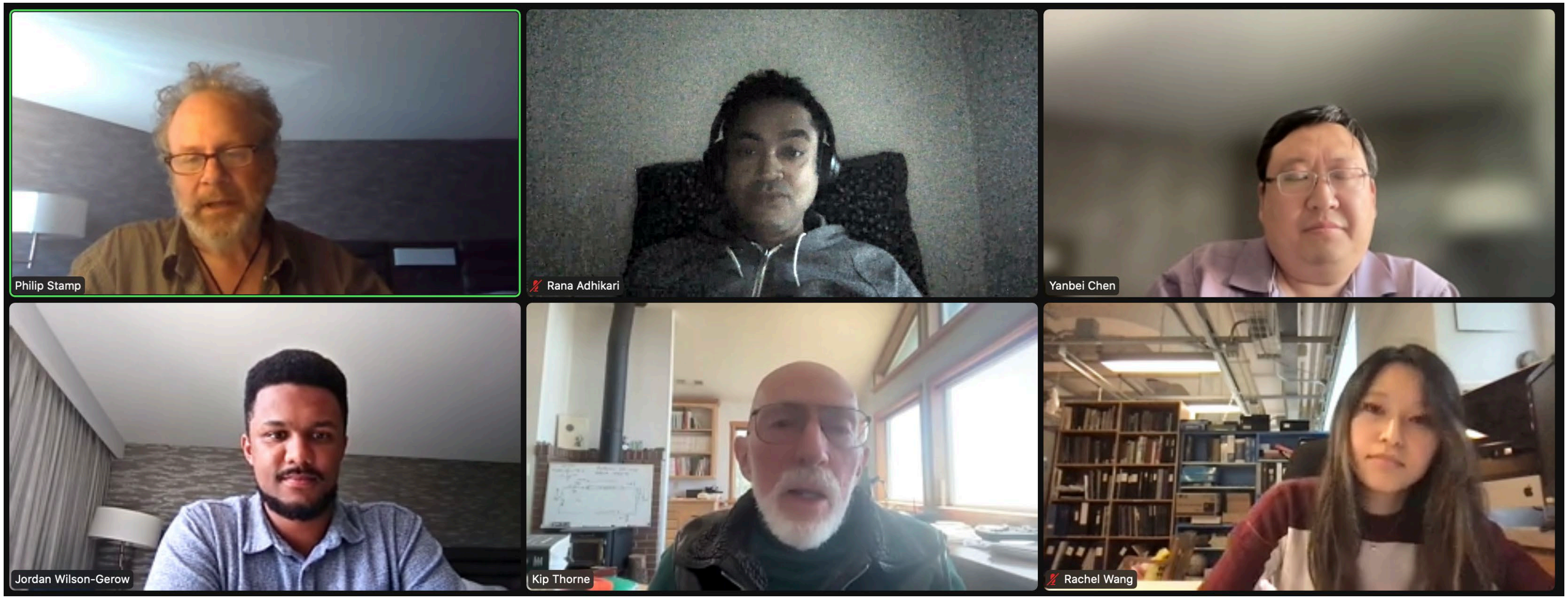
and

$$\Phi_{21}^{(sc)} = \bar{S}^o_{21} + \frac{G_N}{4}\int_{t_1}^{t_2} dt \int \frac{d^3r d^3r'}{|\mathbf{r}-\mathbf{r}'|}\left[(T_A T'_A + T_B T'_B) + (T_A T'_B + T'_A T_B)\right]$$

3 different theories, 3 different predictions.....

The
PATH-BUNCHING
MECHANISM

(or, engaging with experiment)



2nd-ORDER PERTURBATION RESULTS for a SINGLE PARTICLE

Consider dynamics at 2nd-order, for a SINGLE PARTICLE or SINGLE FIELD. The field propagator is

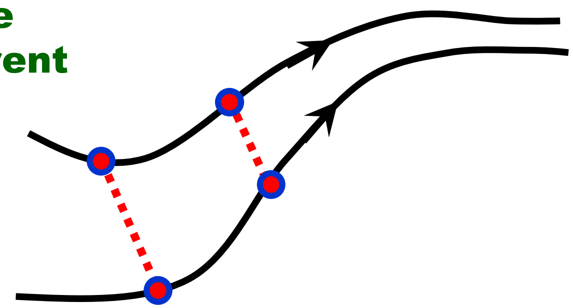
$$\mathcal{K}(2,1) \sim K_0^{-1}(2,1) \int_{\Phi_1}^{\Phi_2} \mathcal{D}\phi \int_{\Phi_1}^{\Phi_2} \mathcal{D}\phi' \, e^{i(S[\phi]+S[\phi'])} \, e^{iS_{CWL}[\phi,\phi']} \; + \; O(\ell_P^4)$$

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

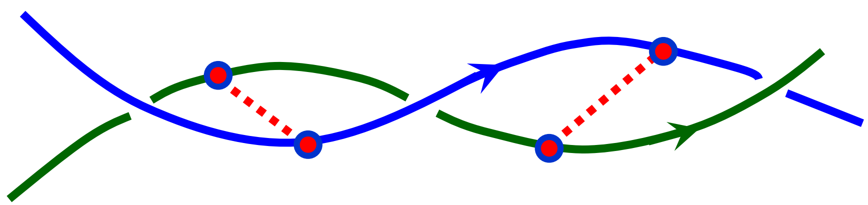
For a single SLOW PARTICLE we get: $$S_{CWL}[q,q'] \rightarrow \lim_{v \ll c} \frac{1}{8} \int_{t_1}^{t_2} dt \frac{Gm^2}{|\mathbf{r}(t) - \mathbf{r}'(t)|}$$

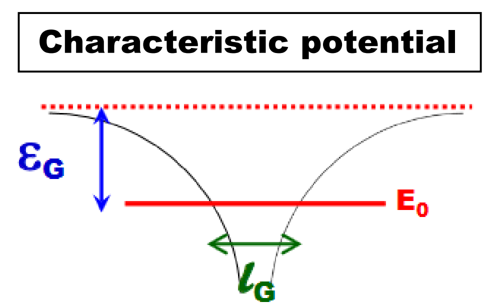
Newton

PATH-BUNCHING: Consider a single particle. Naively the effect of the attractive interaction will be to cause different paths for the same particle to "bunch" together as time increases.



However the actual motion, in the absence of dissipation, is more complex – we get oscillations in the Newtonian potential well between paths.





CHARACTERISTIC SCALES of POTENTIAL

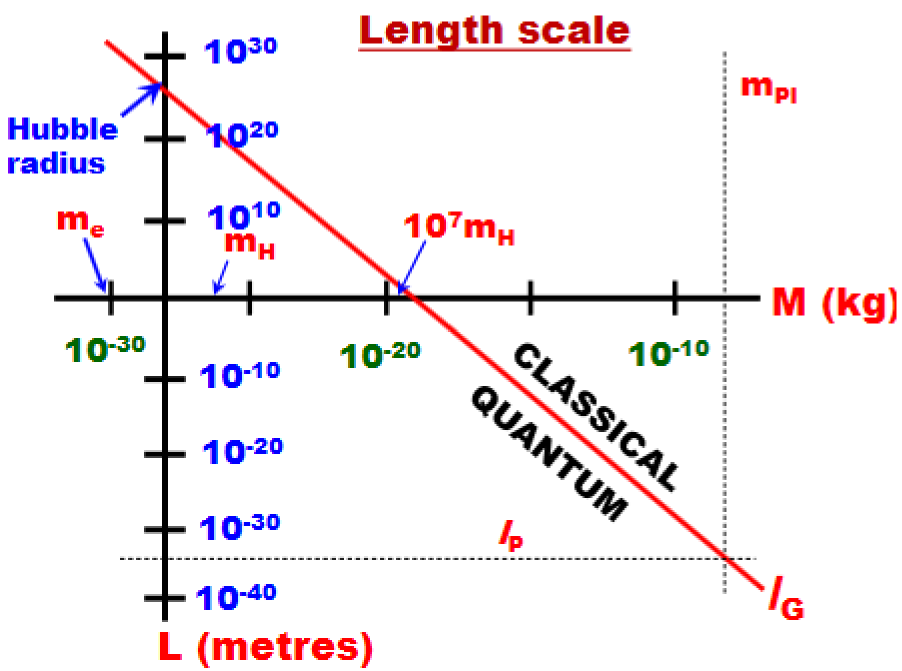
$l_G(m) = \left(\frac{M_p}{m}\right)^3 L_p$ **Newton radius (gravitational analogue of the Bohr radius)**

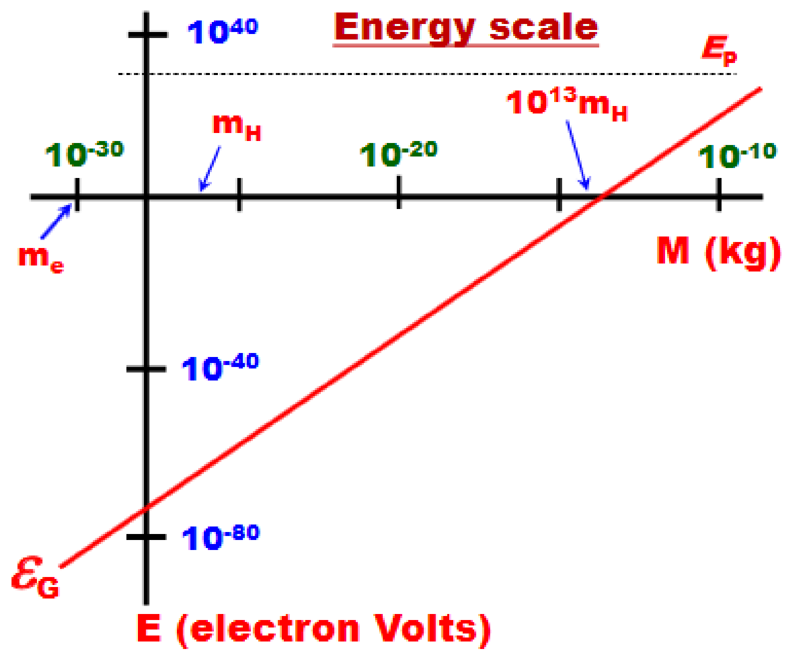
$\epsilon_G(m) = G^2m^2/l_G(m) \equiv E_p(m/M_p)^5$ **Mutual binding energy for paths**

} **(QM)**

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

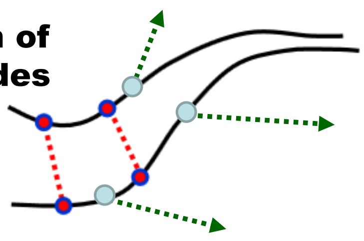
SINGLE PARTICLE "TOY MODEL" : Variation of scales with MASS

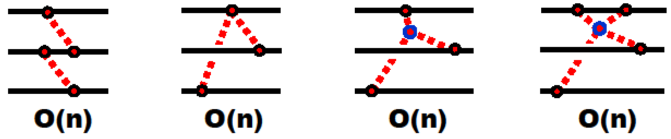




There are 3 things wrong with this toy model

1. It does not describe an extended body
2. the centre of mass will couple to a "bath" of "environmental" degrees of freedom
3. It only describes interactions between pairs of paths





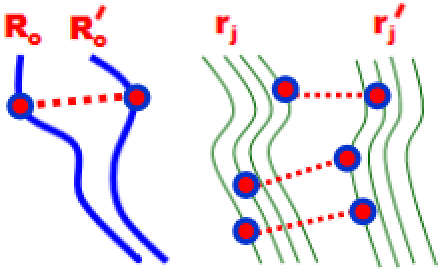
3-path graphs

EXTENDED MASS MOTION

A solid extended body has action:

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

System is crystalline or amorphous



Assume

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

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

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

(i) Smooth potential term:

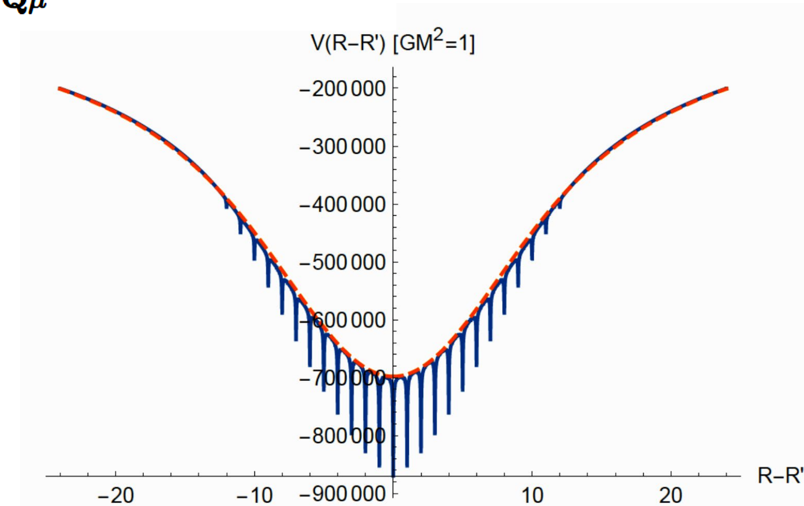
$$\omega_{eff} = \left(\frac{\pi}{6}\gamma^3 G\rho_{avg}\right)^{1/2}$$ **Eg., 6.7 x 10^{-5} s^{-1} (Au)**

(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

DISSIPATION & PATH BUNCHING

Now path bunching dynamics is controlled by dissipative coupling to environment. If dissipation can be parametrized by a Q-factor, the path-bunching time will be

$$\tau_{PB} \sim Q/\omega_{eff}$$

& so depends on system state preparation (NB: for LIGO, can have $Q \sim 10^{10}$)

REAL EXPERIMENTS

I pass with relief from the tossing sea of Cause and Theory to the firm ground of Result and Fact.

W. Churchill: *The Story of the Malakand Field Force: An Episode of Frontier War* (1898)

See other talks at this meeting


THANK YOU TO:
Harvey Brown
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Yanbei Chen
Philip Stamp
Bill Unruh
Birgitta Whaley
Collaborators
Andrei Barvinsky
Dan Carney
Yanbei Chen
Colby Delisle
Jordan Gerow-Wilson

FORMAL ASPECTS of ENVIRONMENTAL DECOHERENCE

density matrix propagator:

$$K(Q_2, Q_2'; Q_1, Q_1'; t, t') = \int_{Q_1}^{Q_2} \mathscr{D}q \int_{Q_1'}^{Q_2'} \mathscr{D}q' e^{-i/\hbar(S_0[q]-S_0[q'])} \mathscr{F}[q, q'],$$

with $\mathcal{F}[Q, Q'] = \prod \langle \hat{U}_k(Q, t) \hat{U}_k^{\dagger}(Q', t) \rangle$

Here the unitary operator $\hat{U}_k(Q, t)$ describes the evolution of the kth environmental mode, given that the central system follows the path $Q(t)$ on its 'outward' voyage, and $Q'(t)$ on its 'return' voyage; and $\mathcal{F}[Q, Q']$ acts as a weighting function, over different possible paths $(Q(t), Q'(t'))$.

Easy for oscillator baths (it is how Feynman set up quantum field theory); we integrate out a set of driven harmonic oscillators, with Lagrangians:

$$L = \frac{M}{2}\dot{x}^2 - \frac{M\omega^2}{2}x^2 - \gamma(t)x$$

Thus:

$$\mathcal{F}[Q,Q'] = \prod_{q}^{N_o} \int \mathcal{D}x_q(\tau) \int \mathcal{D}x_q(\tau') \exp\left[\frac{i}{\hbar}\int d\tau \frac{m_q}{2}[\dot{x}_q^2 - \dot{x}_q'^2 + \omega_q^2(x_q^2 - x_q'^2)] + [F_q(Q)x_q - F_q(Q')x_q']\right]$$

Bilinear coupling →

$$F[q,q'] = \exp\left[-\frac{1}{\hbar}\int_{t_o}^{t} d\tau_1 \int_{t_o}^{\tau_1} d\tau_2 [q(\tau_1) - q'(\tau_2)][\mathcal{D}(\tau_1 - \tau_2)q(\tau_2) - \mathcal{D}^*((\tau_1 - \tau_2)q'(\tau_2)]\right]$$

Bath propagator

For spin baths it is more subtle:

$$\mathcal{F}[Q,Q'] = \prod_{k}^{N_s} \int \mathcal{D}\boldsymbol{\sigma}_k(\tau) \int \mathcal{D}\boldsymbol{\sigma}_k(\tau') \exp\left[\frac{i}{\hbar}(S_{int}[Q,\boldsymbol{\sigma}_k] - S_{int}[Q',\boldsymbol{\sigma}_k'] + S_E[\boldsymbol{\sigma}_k] - S_E[\boldsymbol{\sigma}_k'])\right]$$

$$S_{int}^{sp}(Q,\boldsymbol{\sigma}_k) = -\int d\tau \sum_{k}^{N_s} \boldsymbol{F}_k(P,Q)\cdot\boldsymbol{\sigma}_k$$

$$S_{env}^{sp} = \int d\tau \left[\sum_{k}^{N_s}(\mathcal{A}_k \cdot \frac{d\boldsymbol{\sigma}_k}{dt} - \mathrm{h}_k \cdot \boldsymbol{\sigma}_k) - \sum_{k,k'}^{N_s} V_{kk'}^{\alpha\beta}\sigma_k^{\alpha}\sigma_{k'}^{\beta}\right]$$

Vector coupling

Berry phase coupling

DENSITY MATRIX DYNAMICS for CWL THEORY


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