The equivalence principle and inertial-gravitational decoherence

G.Torrieri

Synopsis

The original question (Bronstein) and what it means

The necessity of detector-system interaction and its formalism

A possible Quantum gravity Experiment and what Bronstein says about it (Recoil and gravitation!)

A formalism Density matrices and partition functions and incorporating detectors

From partition functions to interferometres

Tentative results and developments

One of the greatest "unknown" physicists

Matvei Bronstein

1906−1938

Recommend bio by Gennady Gorelik

First serious paper about quantum gravity

Phys.Zeit. Sowjetunion, 9 20133, (1936).

A simple PhD project: quantize gravity, analogously to Heisenberg-Pauli QED. Landau: Quantum fields? nonsense! local fields can't fluctuate! . Fraenkel: Gravity "macroscopic", it's energy-momentum are pseudotensors!

Bronstein, 1934: Fields and quantum mechanics

Quantum field theory "problematic" since field needs to be localized at every point, but detector implies fluctuations. Bohr-Rosenfeld "compensator charges" (qualitative renormalization), but the problem is detector-system backreaction

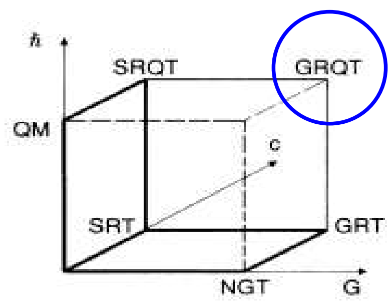
EM: $\Delta\vec{E}$ from backreaction charge density ρ,mass density μ,size Δx

$$\Delta\vec{E} \sim \underbrace{\frac{ch}{\rho\Delta x^5}}_{\Delta E \sim \frac{\Delta p}{Q\Delta t} \quad momentum} + \underbrace{\frac{\rho h}{\mu c\Delta x^3}}_{backreaction, \sim \frac{Q\Delta p}{M}} \neq \sqrt{\left\langle \left[\hat{A},\hat{B}\right]\right\rangle^2}$$

Canonical uncertainity relations recovered if $\rho,\mu,\mu/\rho \to \infty$, i.e. "large" $\Delta x \gg h/k$ infinitely massive infinitely charged detector with Charge $\times$ field $\ll$ Mass . And you see the problem!

Gravity: Charge/Mass always=1, so canonical $\Delta h_{\mu\nu}$ impossible, due to EP
NB: Further than Bohr-Rosenfeld compensator charges (a.k.a. renormalizeability) ,bakcreaction (detector dephased)

Bronstein's conclusion 1934
To remove these logical contradictions we should radically reconstruct the theory; in particular, we should renounce Riemannian geometry that is operating here with the quantities that could not be observed in principle; it seems that we should probably reject the common ideas about space and time in favor of some much deeper and less visual concepts. Wer's nicht glaubt. bezahlt einen Taler.



$E^2 X\ Gch \sim 1$

Fig. 3. The "space" of the physical theories in the $cG\hbar$ system of coordinates.

NGT – Newton's gravitation theory
SRT – Special relativity theory
QM – Quantum mechanics
GRT – General relativity theory
SRQT – Special relativity quantum field theory
GRQT – General relativity quantum theory

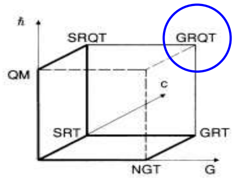


Fig. 3. The "space" of the physical theories in the cGħ system of coordinates.

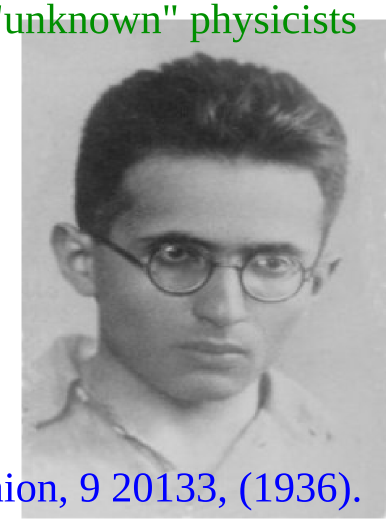
E^2 X Gch~1

NGT – Newton's gravitation theory
SRT – Special relativity theory
QM – Quantum mechanics
GRT – General relativity theory
SRQT – Special relativity quantum field theory
GRQT – General relativity quantum theory

One of the greatest "unknown" physicists

Matvei Bronstein
1906−1938

Recommend bio by Gennady Gorelik



First serious paper about quantum gravity
Phys.Zeit. Sowjetunion, 9 20133, (1936).

That paper is remarkable in how little solid and conceptually substantial development has been done since it!

The questions he asked have been answered with increasingly speculative proposals LQG,Strings,Non-commutative spacetime,entropic gravity,breakdown of QM,... But perhaps we do not need to go that far! his calculation says something different From his conclusion! It is actually a statement about "minimal detector-system entanglement".

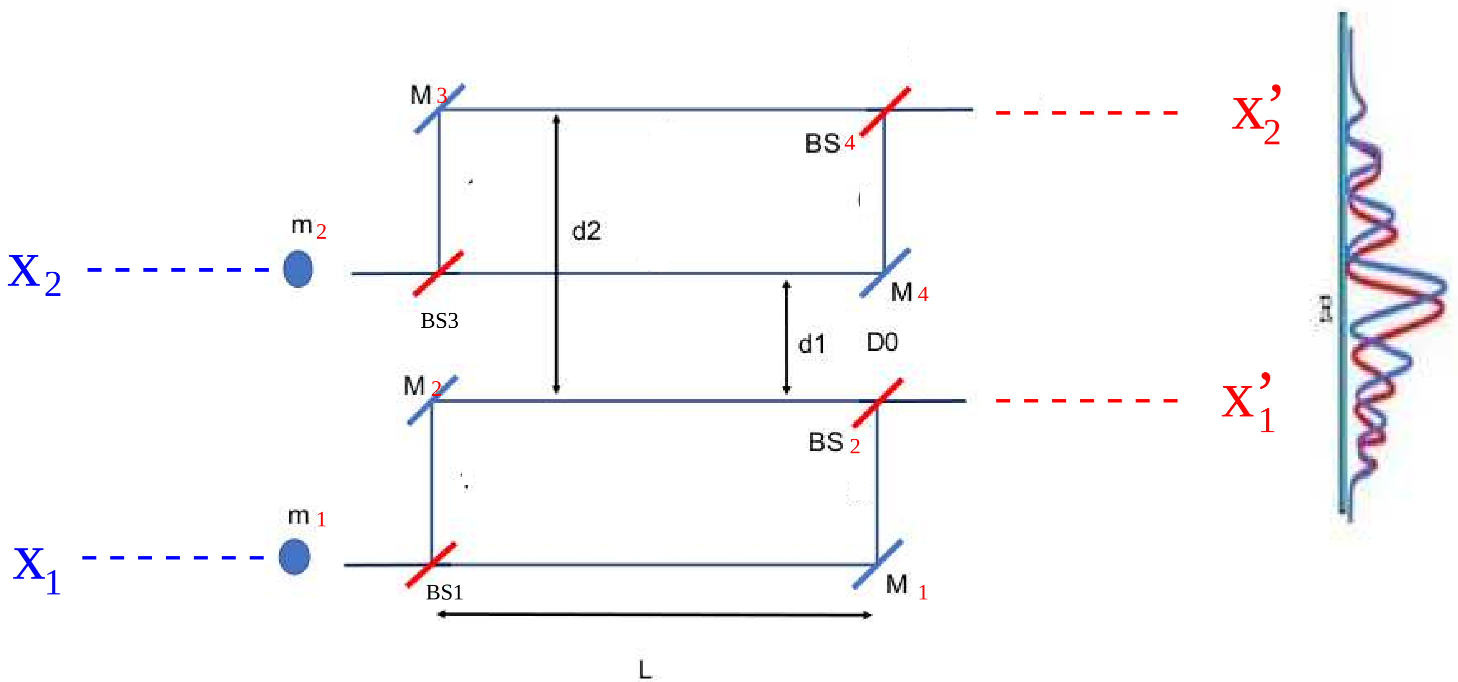
The usual formalism with collapse of eigenvectors at observation, commutation relations etc. applies for "classical" detectors that

- Only couple to a system via the quantity observed
- Are "heavy enough" so as not to backreact
- Are "large/long enough" to maintain state purity

this is impossible with gravity! Backreaction should be included!
Another way of seeing it: Wigner–Araki–Yanase theorem and absence of global symmetries in gravity

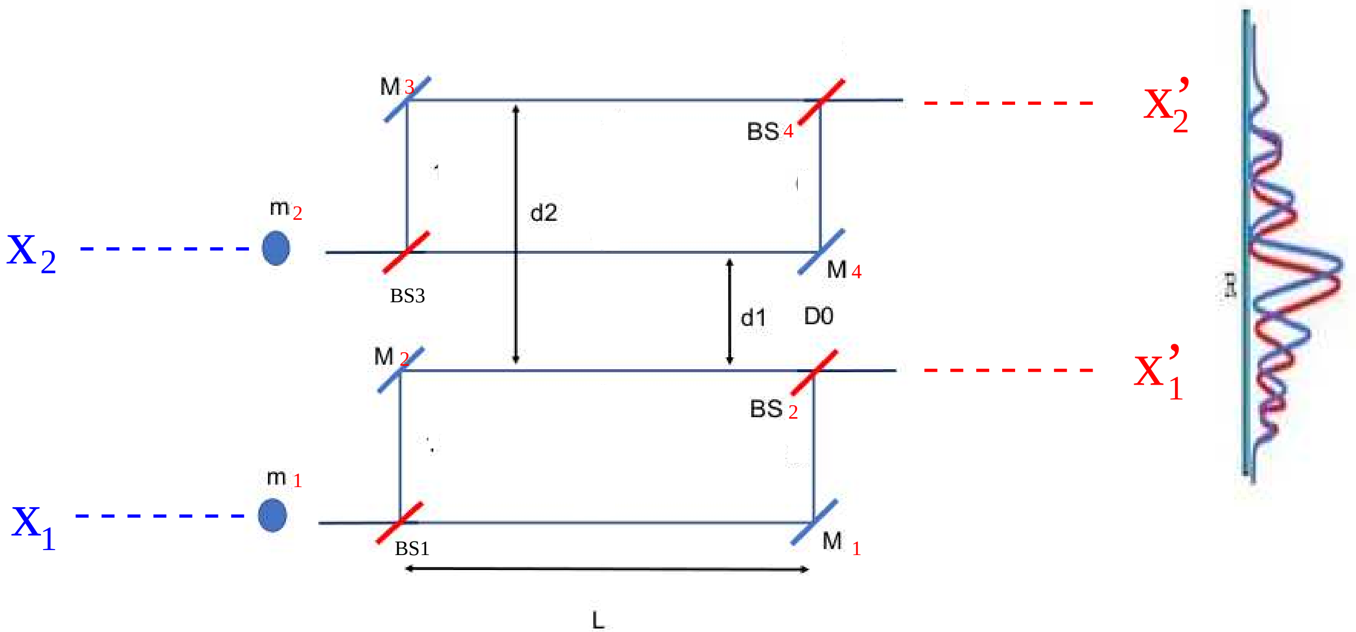
Since Bronstein our understanding of QM has progressed to the point we can address this issue directly

Experimental quantum gravity from nanoparticle interferometry?



Two PRLS: S.Bose et. al., 1707.06050 (spin measurement), C. Marletto,V.Vedral 1707.06036 (direct interferometry)

My best guess of a first experimental probe into quantum gravity!



Basic idea: Gravitational mutual attraction of nanoparticles going through interferometer $\Delta\phi \sim T\Delta E$, $\Delta E \sim \frac{Gm_1m_2}{\Delta r}$. Dehasing of the 2 positions $\equiv$ gravity canonically quantized! Soon we will be sensitive to this!

There are objections but IMHO it is a good test of the canonical quantization of gravity

The phase difference requires, basically, at least a "virtual spin zero graviton" (field commutation relations in configuration space)

QFT Unitarity requires a real graviton follows from the existence of a virtual one automatically (Also experimentally seen by gravitational waves)

Relativistic causality and the equivalence principle (independently well-tested) require the graviton to be spin 2, of which spin 0 is the non-relativistic h_{00}

Quantum gravity... or test of Bronstein's ideas?

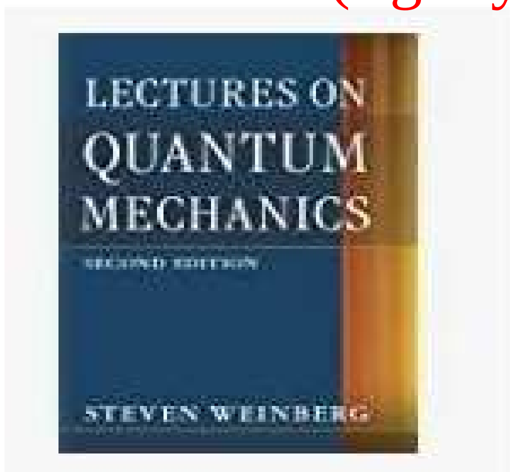
If detector, beam splitter, magnet heavy it gravitationally interacts with the nanoparticles
"Higher order" emission of gravitational waves simple, but "Zeroth order" is a classical-quantum backreaction

If detector, beam splitter, magnet light it recoils
Classical-quantum backreaction

Both introduce decoherence which can be quantitatively examined. Difficoulty: cannot use "qubits", $|left>$ vs $|right>$ etc. Recoil messy (continuum in momentum).

Interferometry easy with functional methods, but how to translate source, $\hat{\rho}_{system,detector,rest}$ to this set-up? took years of thinking for me!

A (rightly!) renowned physicist



1933−2021

The purpose of quantum theories is not generally to calculate "states" and "wavefunctions", but rather Observables and correlations between them

Therefore the "fundamental" object of QM is not the "state" or the "wavefunction", but the density matrix, of which the wavefunction is a basis in certain limits

There might be no "Quantum gravity state" but a QG density matrix!

The reason: It is as appropriate for pure, impure, open systems with any kind of detector coupling

$$\hat{\rho} = \mathrm{Tr}_{rest}\left[\hat{\rho}_{sys} \times \hat{\rho}_{rest}\right]$$

"Rest" could mean detector, or enviroenment. Non-trivial relations between them incorporated in Hamiltonian or Lagrangian. No systematic non-ad hoc way to understand ρ_{rest}

Backreacting detectors can be accomodated by a judicious choice of $\hat{O}$, entangling system and detector

$$\langle O \rangle = \mathrm{Tr}\left[\hat{O}\hat{\rho}_{sys} \times \hat{\rho}_{detector}\right]$$

And this is what Bronstein places a limit on! Operators become messy (quantitatively, unitarity and completeness generally violated for ρ_{sys} .), but we can use functional integrals

For functional integrals (T.Nishioka, 1801.10352),

$$\langle x_i | \hat{\rho} | x_i' \rangle = \frac{\delta^2}{\delta J_+(x_i) \delta J_-(x_i')} \ln \mathcal{Z}(J_+(y(0^+)) + J_-(y'(0^-)))$$

With $J_\pm$ generating a basis

$$\mathcal{Z}[J(y)] = \int \mathcal{D}\phi \mathcal{D}x_i \mathcal{D}x_j \exp\left[i \int d^4x \mathcal{L}\left(\phi, x_i, x_j, \phi\right) + J(x,\phi)\left\{x,\phi\right\}\right]$$

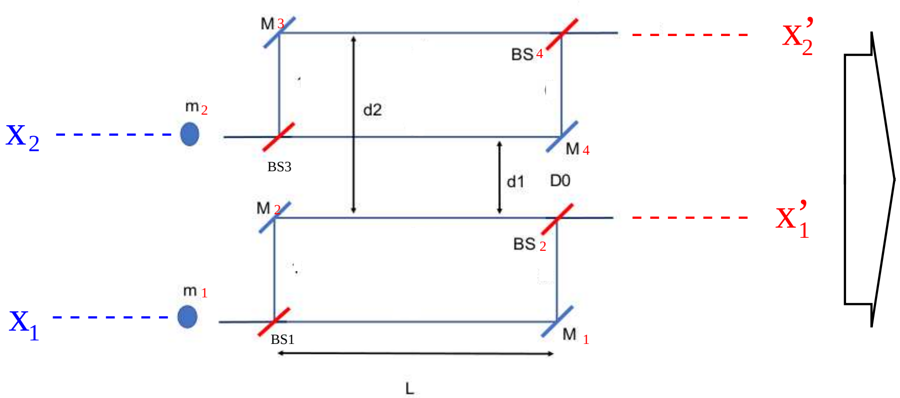
The "classical detector and quantum system" limit is ($\mathcal{L} \sim \ln \mathcal{Z}$)

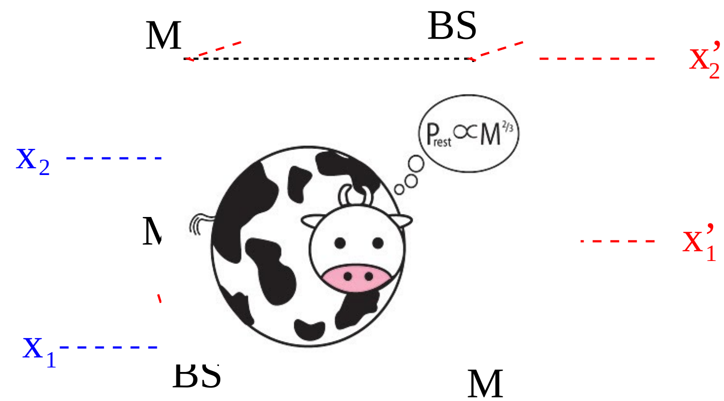
$$\mathcal{L}_{int} \simeq J_i(\tau) x_i \quad , \quad \mathcal{L}_J \gg \mathcal{L}_{int}, \mathcal{L}_\phi$$

$$\ln \mathcal{Z} \sim \ln \mathcal{Z}|_J + \ln \mathcal{Z}|_{rest} \quad , \quad \ln \mathcal{Z}|_{rest} \ll \ln \mathcal{Z}|_J \simeq \ln \mathcal{Z}|_J^{WKB} \sim \mathcal{L}_{int}$$

From partition functions to interferometers

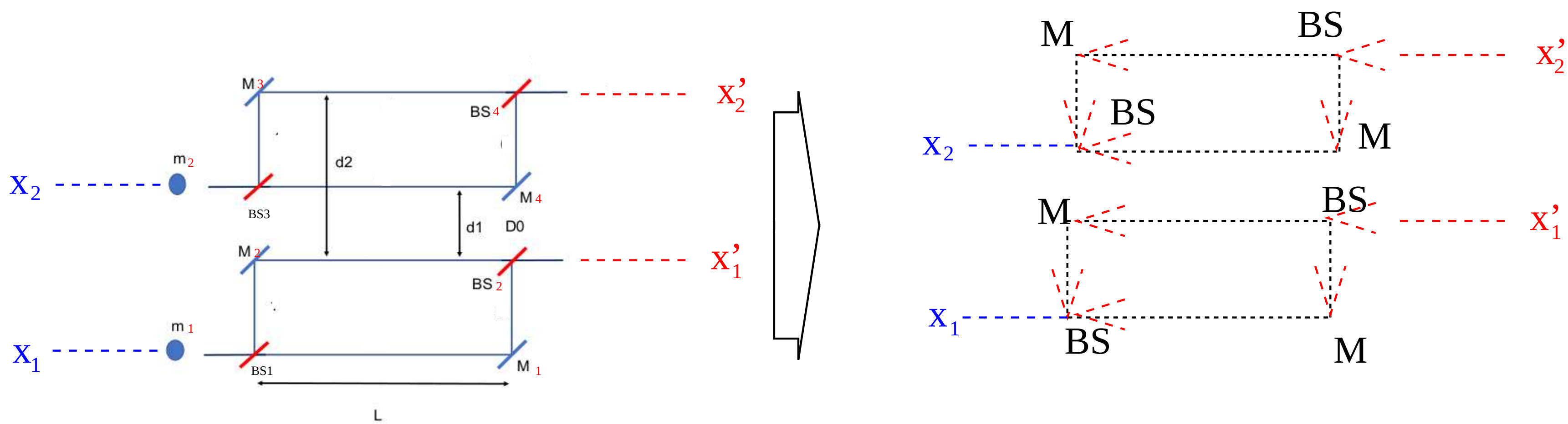
How does one go from functional integrals to walls, beam splitters (BS) and mirrors (M)? This is not scattering!





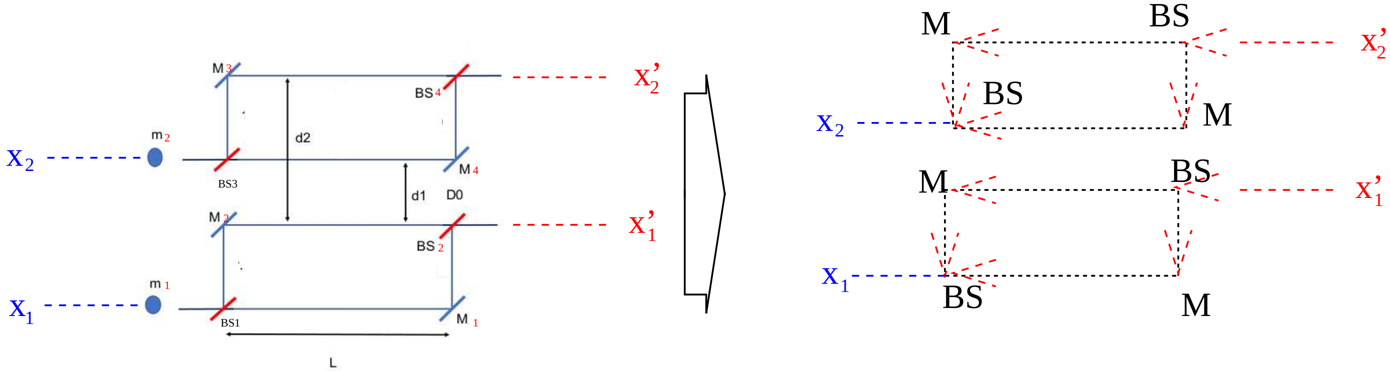
Backreaction requires continuus momentum Eigenstates, <u>not</u> discrete $|left \quad arm>, |right \quad arm>$

From partition functions to interferometers



Eliminate all walls, simply only count, via correlators, certain trajectories. (particles scatter in all directions but we count only those events that follow arm trajectories) At this point can use $\delta(x)$ potentials! All interactions with mirrors M and Beam splitters BS implemented this way!

Quantum gravity interferometry with recoil and decoherence

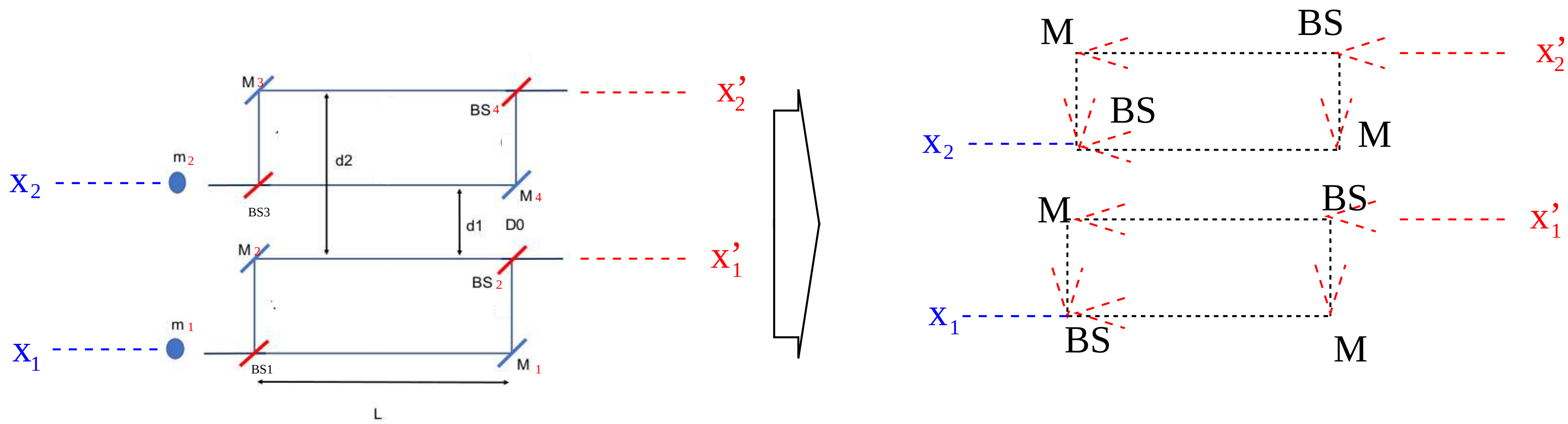


$$\mathcal{Z}[J(y)] = \int \mathcal{D}\phi \mathcal{D}x_i \mathcal{D}x_j \exp\left[iS\left(J(y), x_i, x_j, \phi\right)\right]$$

$$S\left(J(y), x_i, x_j, \phi\right) = \int d\tau \left[\mathcal{L}_J(x_i(\tau), x_j(\tau)) + \right.$$

$$\left. + \int d^3x \left(\mathcal{L}_\phi(\phi(x)) + \mathcal{L}_{int}(\phi(x), x_i(\tau), x_j(\tau))\right)\right]$$

The gravity Lagrangian, $\mathcal{L}_\phi$ The gravitational field lagrangian

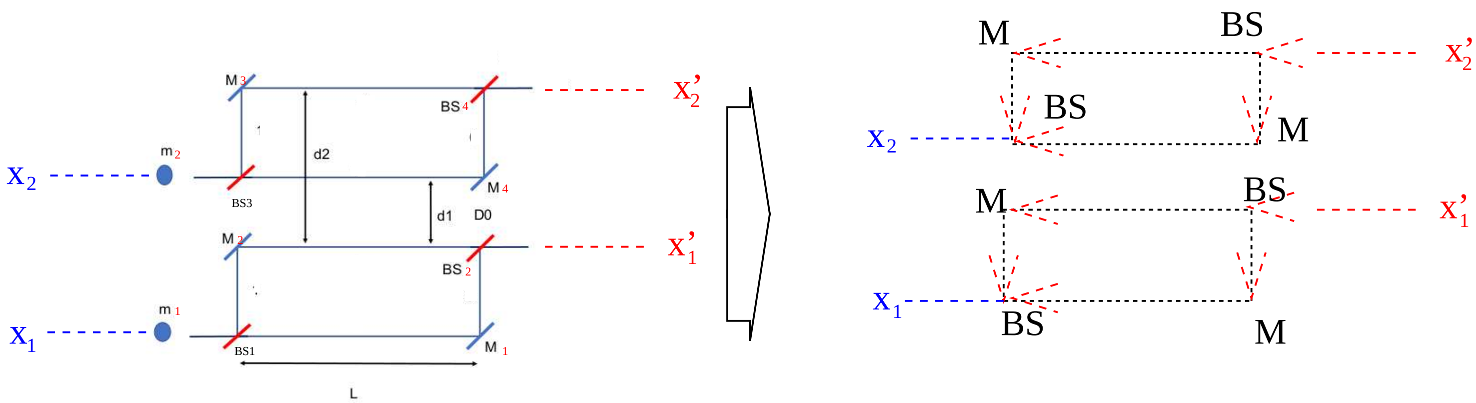


Newtonian non-relativistic limit, so

$$h_{\mu\nu} \rightarrow h_{00} \equiv \phi \quad , \quad \mathcal{L}_\phi = (\nabla\phi)^2 + \mathcal{L}_{int}$$

(The original idea can be thought of as "entanglement harvesting" of ϕ)

Field interaction with nanoparticle and detector

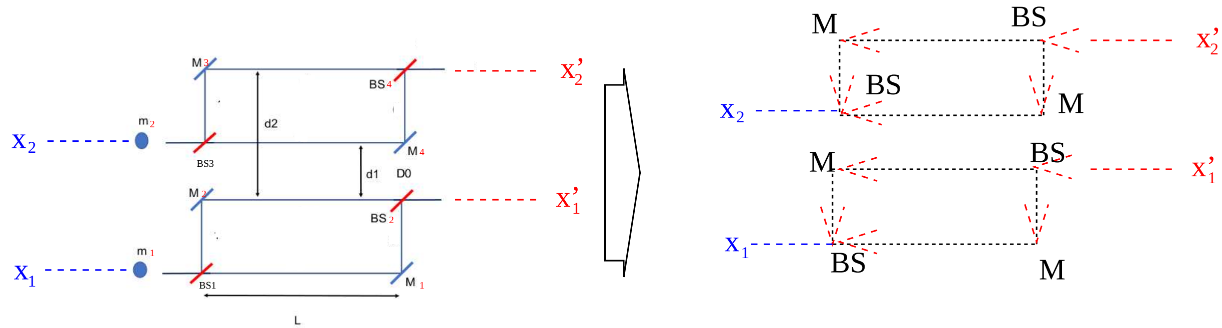


Assume nanoparticles (denoted by i ,mass m) and detector components (denoted by j , mass M) all pointlike

$$\mathcal{L}_{int} = -G\rho(x,t)\phi$$

$$\rho(x,t) = M \sum_{j=M_n,BS_n} \delta\left(x - x_j(t)\right) + m \sum_{i=1,2} \delta\left(x - x_i(t)\right)$$

Nanoparticles (mass m),detector (Mirror M,Beam splitter BS, mass M)



Both are non-relativistic conserved particles, interacting with $\delta-$ potentials

$$\mathcal{L}_J = \underbrace{\sum_{i=1,2} \vec{J}_i(\tau)\cdot\vec{x}_i + \sum_{j=M,BS} \vec{J}_j(\tau)\cdot\vec{x}_j}_{detection} + \underbrace{\frac{1}{2m}\sum_{i=1,2} \dot{\vec{x}}_i^{\,2}}_{nano-particles} +$$

$$+\underbrace{\frac{1}{2M}\sum_{j=M,BS} \dot{\vec{x}}_j^{\,2} - \alpha_{ij}\sum_{i=1,2}\sum_{j=M,BS}\delta\left(|\vec{x}_i-\vec{x}_j|\right)}_{detector\quad backreaction}$$

Summarizing

$$\ln \mathcal{Z}[J_i, J_j] = \int \mathcal{D}\phi \mathcal{D}x_{i,j}(t) \exp\left[i\mathcal{L} dt_{i,j} d^4 x_\phi\right]$$

$$\mathcal{L} = (\nabla\phi)^2 + \sum_{i=1,2} \vec{J}_i(\tau) \cdot \vec{x}_i + \sum_{j=M,BS} \vec{J}_j(\tau) \cdot \vec{x}_j + \frac{1}{2m} \sum_{i=1,2} \dot{\vec{x}}_i^{\,2} +$$

$$+ \frac{1}{2M} \sum_{j=M,BS} \dot{\vec{x}}_j^{\,2} - \alpha_{ij} \sum_{i=1,2} \sum_{j=M,BS} \delta\left(|\vec{x}_i - \vec{x}_j|\right)$$

$$G\phi \left(M \sum_{j=M_n,BS_n} \delta\left(x - x_j(t)\right) + m \sum_{i=1,2} \delta\left(x - x_i(t)\right) \right)$$

Note recoils of detectors taking care of by treating them as “quantum” objects interacting with system

Believe it or not, this is soluble analytically!

and we note that the exact Green's function of a δ-function potential $G(x-y)$ in terms a "bare Green's function $G_0(x-y)$

$$G(x-y) = \mathcal{F}(G_0, \lambda) = G_0(x,y) + \frac{G_0(x,0)G_0(0,y)}{\lambda^{-1} - G_0(0,0)}$$

in our case the free particle propagator for nanoparticles/detectors is

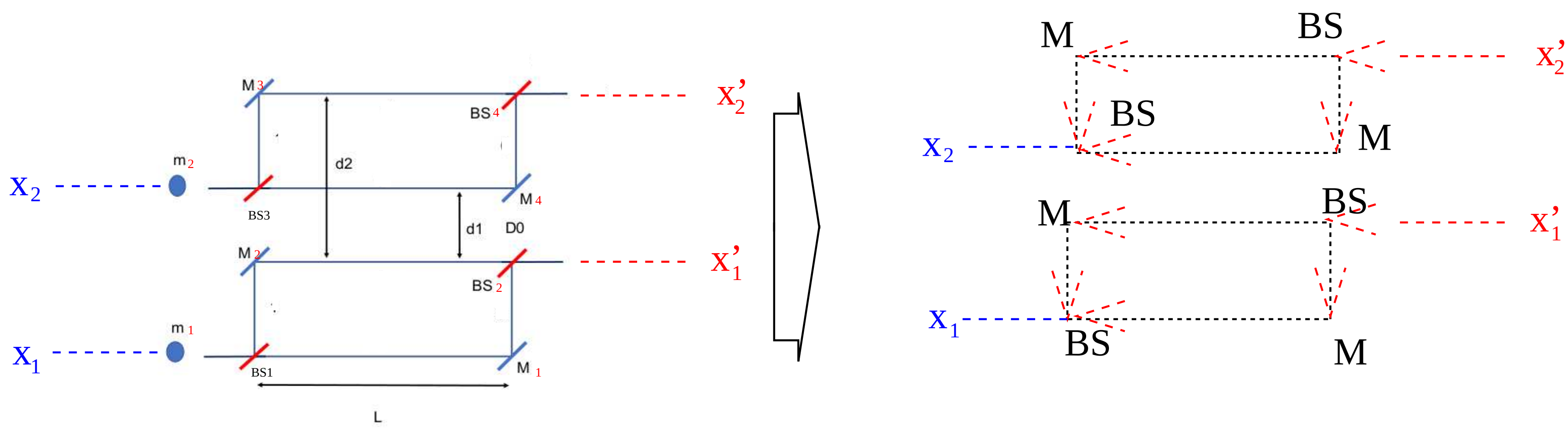
$$G_{ij0}(x,y) = \int d^3k dw \frac{e^{i[iwt - k.(x-y)]}}{\frac{k^2}{2\mu_{ij}} - w} \quad , \quad \mu_{ij} = \left(\frac{1}{m_i} + \frac{1}{m_j}\right)^{-1}$$

$$G_\phi(x,y) = \int d^3k dw \frac{e^{i[iwt - k.(x-y)]}}{k^2 - w^2}, G_{int}(x,x_0) = G_\phi(x,x_0) + \frac{G_\phi(x,0)G_\phi(0,x_0)}{-\frac{2}{GM} - G_\phi(0,0)}$$

And of course

$$Z \sim \exp\left[J(x)G(x-y)J(y)\right]$$

From the partition function to observables

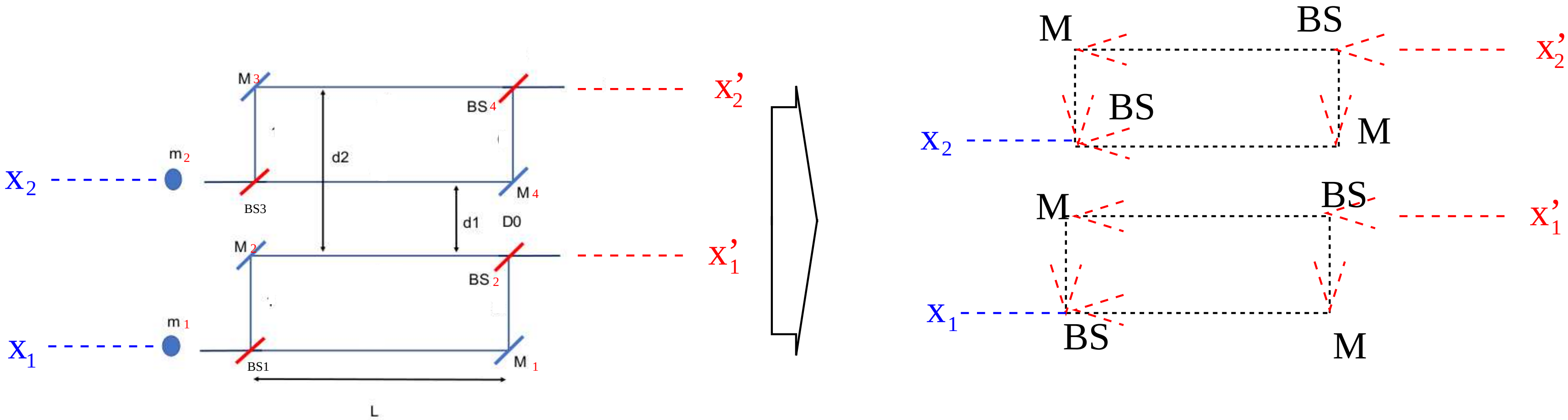


$$\langle x_1 x_2 | \, \rho \, | x_1' x_2' \rangle |_{reduced} = \mathrm{Tr}_{\Phi, J, K}$$

$$\langle x_1 x_2 | \, \rho \, | \Phi_{BS1} \Phi_{BS3} \rangle \langle \Phi_{BS1} \Phi_{BS3} | \, \rho \, | \Psi_J \Psi_K \rangle$$

$$\langle \Psi_J \Psi_K | \, \rho \, | \Phi_{BS2} \Phi_{BS4} \rangle \langle \Phi_{BS2} \Phi_{BS4} | \, \rho \, | x_1' x_2' \rangle$$

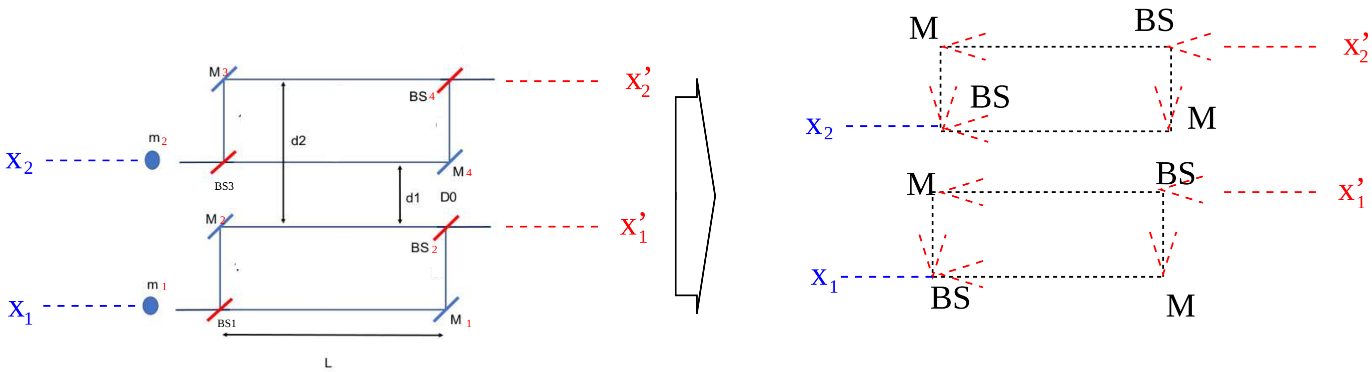
Or in integral function form



$$\int \mathcal{D}\Psi_J \mathcal{D}\Psi_K \prod_{i=1}^{4} \mathcal{D}\Phi_{BSi} \frac{\delta^4}{\delta J_{1+}\delta J_{2+}\delta J_{BS1}\delta J_{BS3}} \ln \mathcal{Z} \frac{\delta^4}{\delta J_{BS1}\delta J_{BS3}\delta J_{\Psi_J}\delta J_{\Psi_K}} \ln \mathcal{Z}$$

$$\times \frac{\delta^4}{\delta J_{\Psi_J}\delta J_{\Psi_K}\delta J_{BS2}\delta J_{BS4}} \ln \mathcal{Z} \frac{\delta^4}{\delta J_{BS2}\delta J_{BS4}\delta J_{1-}\delta J_{2-}} \ln \mathcal{Z}$$

The source functions are superpositions of wavepackets



$$\Psi_J = \frac{1}{\sqrt{2}}(\Phi_{M1} + \Phi_{M2}) \quad , \quad \Psi_K = \frac{1}{\sqrt{2}}(\Phi_{M3} + \Phi_{M4})$$

Nanoparticles are put into position Eigenstates in beginning and end, and into Gaussian wavepackets $\mathcal{G}$ at mirrors M and beamsplitters BS

$$J_i \equiv J_x(\tau) \sim \hat{e}\delta(\vec{y}(\tau) - \vec{x}) \quad , \quad J_j \sim \hat{e} \int d^2 p e^{i(\vec{y}(\tau) - \vec{y_J}) \cdot \vec{p}} \mathcal{G}\left(\phi_p(p) - \phi_J, \sigma_\phi\right)$$

This is the story so far I am convinced this is an exactly soluble system which includes both recoil and gravitational decoherence, but there is reams of long calculations. “This isn’t what they pay us for” so progress slow

But!!! qualitatively its clear semiclassical state is not recovered $\forall m, M$

$$\mathcal{L}_J \sim \mathcal{O}\left(\frac{1}{2m}+\frac{1}{2M}\right) \quad , \quad \mathcal{L}_{int} \sim \mathcal{O}\left(M+m\right)$$

Remember that the “pure classical+pure quantum” limit is

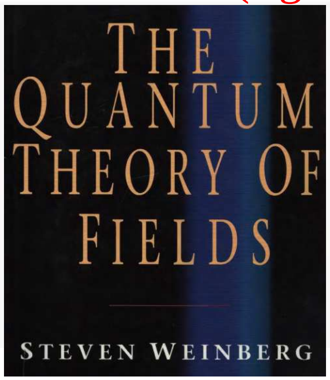
$$\mathcal{L}_{int} \simeq J_i(\tau)x_i \quad , \quad \mathcal{L}_J \gg \mathcal{L}_{int}, \mathcal{L}_\phi$$

$$\ln \mathcal{Z} \sim \ln \mathcal{Z}|_J + \ln \mathcal{Z}|_{rest} \quad , \quad \ln \mathcal{Z}|_{rest} \ll \ln \mathcal{Z}|_J \simeq \underbrace{\ln \mathcal{Z}|_J^{WKB}}_{\sim \mathcal{L}_{int}}$$

This cannot happen for any M,m . Bronstein demonstrated!

Speculations: Away from $c \to \infty$ Horizons alongside recoil!

A (rightly!) renowned physicist



1933–2021

Combining Lorentz symmetry with quantum mechanics was really problematic, because of the different role of space,time in Quantum Mechanics (X unitary,T anti-unitary).
Only way to restore unitarity (up to renormalization),causality,locality and full Lorentz invariance was QFT.

Both space,time are labels . Observables,operators are fields

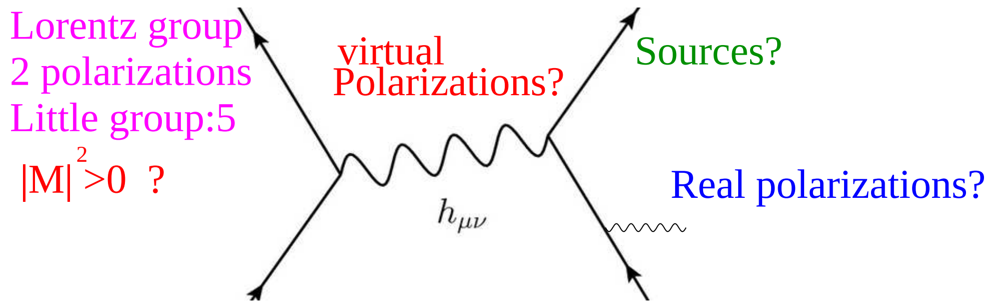
The "price" of QM $\rightarrow$ QFT

neither space nor time are observables. Fields and their correlators are.

"States" are irrelevant ("ill defined", need to be renormalized), but correlators transform according to symmetries

Physics scale-dependent but renormalizeability,EFT provides natural way to organize these effects. inter-scale communication weak!

THis was real progress. It is amusing that most approaches in quantizing gravity are based on "going back" (quantizing spacetime and metrics), rather than building on this progress (general covariance of field correlators)



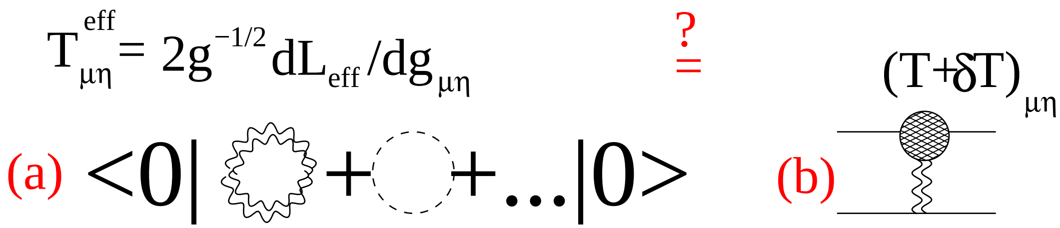
The equivalence principle actually required in tree-level gravity,in the same way as Gauge invariance required in Gauge theory! Graviton state not-really Lorentz invariant because 5 polarizations, only two physical!

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \quad , \quad h_{\mu\nu} = \int \tilde{h}_{\mu\nu} e^{ikx}$$

No anomalies requires general covariance (Feynman,Weinberg) as

$$\tilde{h}_{\mu\nu} \to \tilde{h}_{\mu\nu} + \epsilon_\mu(x) k_\nu + \epsilon_\nu(x) k_\mu \quad , \quad \mathcal{L} \sim \underbrace{T_{\mu\nu}}_{\partial_\mu T^{\mu\nu}=0(\nu?)} h^{\mu\nu}$$

The problem comes from loops!



unlike for gauge theory General loop corrections break the relationship above! Eg. Donoghue et al 1410.7590 . Spin dependent effects.

Open system correction helps enforcing $\partial_\mu T^{\mu\nu} = 0$ (graviton exchange means no unitarity) but not enough! Perhaps EP is "only tree level" approximation? Most of the field seems to think so!

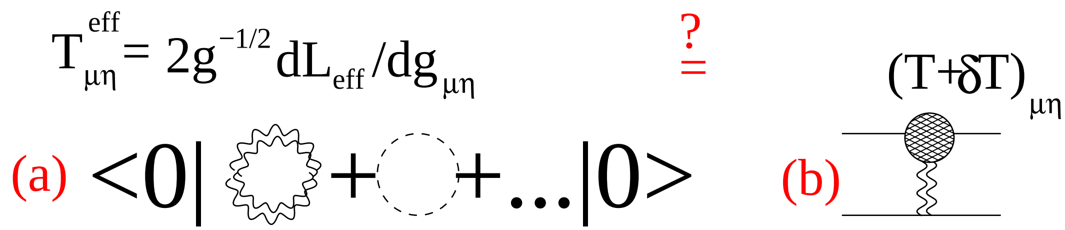
A generally covariant quantum field theory?

Let's remember that GR is easy once you understand general covariance! No wonder quantizing gravity is a problem, how do you quantize general covariance?

$$\Pi = \frac{dL}{d\dot{\phi}} \quad , \qquad \{\phi(x_\mu)\Pi(x'_\nu)\} = g_{\mu\nu}\delta(x-x') \Rightarrow \left[\hat{\phi}(x_\mu), \hat{\Pi}(x_\nu)\right] = i g_{\mu\nu}\delta(x-x')$$

Observables $\langle[\phi^n(x_\mu), \phi^m(x'_\nu)\rangle]$ NOT covariant (even with spin-2 field!), but can "something like quantization" be made with observables generally covariant? Perhaps with the relativistic version of a partition function we examined earlier (with horizons!)

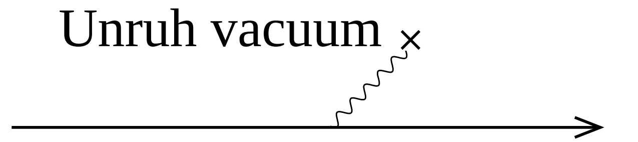
Gravity, general covariance and quantum mechanics



Usual statement of the problem: non-renormalizeability . But what this means is that quantum fluctuations generally break fundamental local symmetries. Easy to see why: As unitarity/causality determined by $g_{\mu\nu}, \tau$

$$\Psi = \frac{1}{\sqrt{2}} \int d\tau e^{H\tau} \left(|\Psi, g_{\mu\nu} >_1 + |\Psi, g_{\mu\nu} >_2 \right) \underbrace{\rightarrow}_{measurement} |\Psi, g_{\mu\nu} >_{1,2}$$

generally ambiguus w.r.t. it! Detector backreaction progress but need something else for causality, horizons and dissipation!



Crispino,Higuchi,Matsas
0710.5373 (Phys.Repts.)

NB: concept of accelleration is "classical" (dp/dt classical!), so Unruh effect might be the leading term of an eft with loss of unitarity due to horizons!

$$EFT \quad , \quad 1/\tau \ll a \ll M \quad \Leftrightarrow \quad \nabla \ll T_{unruh} \ll M$$

key idea: Even if the lagrangian is generally covariant, horizons mean $\int \mathcal{D}\phi$ is NOT generally covariant. Can be fixed with bulk and dynamical boundary term, which acts as a heat bath in Rindler limit. non-unitary!
Scale separation: Non-unitrary "horizon" term ultra-soft ,"fluctuation" ultra-hard (detector mass),canonical QM in-between

Why is gravity geometric?

The (strong) equivalence principle: <u>all</u> laws of nature in a freely falling frame locally identical to inertial frame. ("no local experiment" can tell you if your elevator is falling or floating in space).

$$Mathematically \qquad \partial_\mu \to \partial_\mu + \Gamma$$

Implies gravity "force" indistinguishable from accelleration, gravity "field" implies curved space, where <u>no</u> truly inertial frames exist!

non-inertial transformations are for all effective purposes non-unitary

Von Neumann's theorem: Unitary transformations preserve entropy. For QFT "Haag's theorem" (more general): An infinitesimal deformation of the a QFT not protected by a symmetry usually produces orthogonal Eigenstates

Rindler horizons topologically distinct from Minkowski space. Bianchi,Satz infinitesimally perturbing Rindler/Unruh horizon requires gravity, "rocket dropping bucket"

A quantum theory symmetric w.r.t. non-unitary transformations cannot exist. Yet the equivalence principle requires it. Most "quantum gravity theories" not really clear on this

String theory defined on S-matrix on semi-classical background. Equivalence principle not expected to work beyond semi-classical gravity and tree level, and even there if moduli stabilized

Loop Quantum Gravity "wavefunction of the universe" quantized canonically in a generally covariant way. but not clear role of detector. What "detector" measures "wavefunction of the universe", geometric variables. Such a detector is generally impossible (not causal)! And what is a quantum theory with no detectors?

Alternative I

I like the equivalence principle for purely aesthetic reasons. A generic spin 2 theory respects it for tree level but not for loop corrections (see Feynman lectures on gravitation).

perhaps its just not valid exactly! Most experimental tests of GR (bending of light, gravity waves etc) really test spin 2 theories and/or are not sensitive to loop effects.

So far only explored signature of the strong equivalence principle is the Nordveldt effect

Alternative II: Building EFT around equivalence principle in continuum limit

Take "classical" gravity ($Gp^2 \ll 1$ Further? Not sure, but ask me about Gribov-Zwanziger!)
A curved space implies the presence of causally connected horizons (distinct from Null surfaces). If the strong equivalence principle holds, these horizons are really inaccessible. This means degrees of freedom living beyond them must be traced over.

but this is not a unitary operation, and the size of the horizon (and hence the number of DoFs traced over) depends on frame!
Not tracing DoFs $\rightarrow$ probing trans-horizon DoFs possible $\rightarrow$ not true horizon

NB: DoFs "beyond the horizon" means their worldines are never connected to observer. Light-cone null surface. dS,AdS,etc. horizons

This cannot be background independent

$$S_{bulk} = \int \sqrt{g^{1/2}} d^n x L(\phi) + J(x^\mu(\tau))\phi \quad , \quad Z = \int \mathcal{D}\phi \exp[iS]$$

Because measure $\mathcal{D}\phi$ depends on background

This may be if $S_{bulk}, S_{horizon}$ chosen carefully (holography?) and backreaction included)

$$Z = \int_{\Omega[J]} \mathcal{D}\phi \exp[iS_{bulk}] \int_{\partial\Omega[J]} \mathcal{D}\phi \exp[iS_{horizon-boundary}]$$

where

$$S_{horizonboundary} = \int \mathcal{D}\phi_{\partial\phi} (g_\sigma)^{1/2} d^{n-1} x_\partial x_\Sigma$$

Σ killing horizon of the metric ($S_{horizonboundary}$ could be complex)

QFT with functional integral only within horizon

$$Z = \int_{\Omega[J]} \mathcal{D}\phi \exp[iS_{bulk}] \int_{\partial\Omega[J]} \mathcal{D}\phi \exp[iS_{horizon-boundary}]$$

$$S = \int \sqrt{g^{1/2}} d^n x L(\phi) + J(x^\mu(\tau))\phi$$

- $\mathcal{O}\left(Gp^2\right)$, exact in $J-\phi$ interaction Metric via detector worldline J
- Essentially Gibbons-Hawking term, but with "detector" represented by J , with backreaction on detector $\sim \frac{\delta^n \ln Z}{\delta \phi^n}$. Z quantum but detector response stochastic (decoherence).
- Contour chosen via local proper time, dissipation via Schwinger-Keldysh

QFT with functional integral only within horizon

$$Z = \int_{\Omega[J]} \mathcal{D}\phi \exp[iS_{bulk}] \int_{\partial\Omega[J]} \mathcal{D}\phi \exp[iS_{horizon-boundary}]$$

$$S = \int \sqrt{g^{1/2}} d^n x L(\phi) + J(x^\mu(\tau))\phi$$

- Effective lagrangian $\ln Z$ generally complex Parikh-Wilczek at leading order . Indicates dissipative evolution.

- For spacetimes which are static and have timelike Killing vectors (AdS) equilibrium reached. But generally time-dependent.

- At $c \to \infty$ horizons go away but backreaction should remain!

Getting effective Lagrangian unsurprisingly not easy, Connected to backreaction problem.

Parikh-Wilczek approach "tunneling" advantage gives semiclassical limit including quantum and horizon fluctuations on same footing

- Write down maximal coordinate system (not causal)
- Semiclassical field theory $\rightarrow \int_{\forall x_{1,2}} \int_{x_1}^{x_2} L \left(g_{\mu\nu} dx^{\mu} dx^{\nu} \right)^{1/2}$

Applications: The FRW solution (work with Juliano Choi) Imposing homogeneity and isotropy "by hand" changes functional integrals into ordinary ones. de-Sitter universe with backreaction decay of QFT cosmological constant from inflation to dark energy? Similar approach to Tommi Markkanen,Emil Mottola but not with this approach!

Fluctuation-dissipation instead of unitarity?

$$Z = \int_{\Omega[J]} \mathcal{D}\phi \exp[iS_{bulk}] \int_{\partial\Omega[J]} \mathcal{D}\phi \exp[iS_{horizon-boundary}]$$

$$S = \int \sqrt{g^{1/2}} d^n x L(\phi) + J(x^\mu(\tau))\phi$$

- First order in G , all orders in $J-\phi$ interaction Metric and horizon set by detector worldline J
- Essentially Gibbons-Hawking term, but with "detector" via J , with backreaction from $\frac{\delta^n \ln Z}{\delta\phi^n}$. Z quantum but detector response stochastic

Physically: Unitarity replaced by fluctuation-dissipation

No generalized symmetries and always observe a subsystem so "states", operator algebra etc. irrelevant, observe correlators. But need something to replace unitarity/commutations

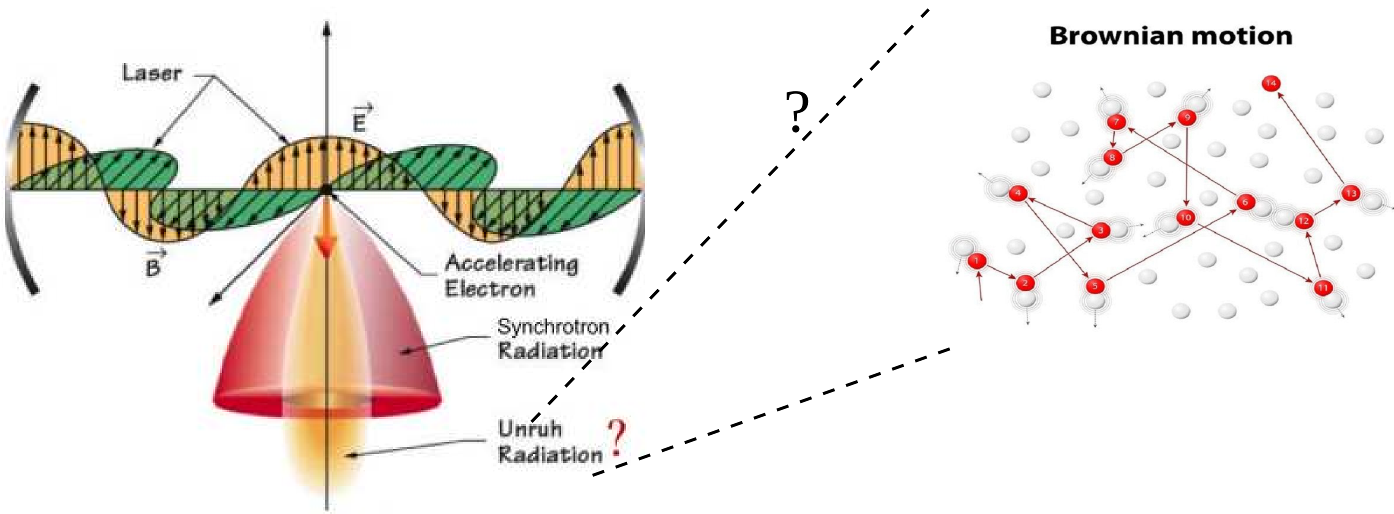
Correlators generally covariant causality structure metric dependent, so requires fluctuation ("one initial condition→ many outcomes) and dissipation ("Many initial conditions → one outcome") terms. Dissipation comes from tracing over boundary , fluctuation from backreaction on J . Constraint on $\frac{\delta^2 \ln Z}{\delta J_1 \delta J_2}$

Can't work in Minkowski (no causal horizon), but we live in FRW universe! UV bulk perturbation ↔ "wobble" of horizon

(After general covariance understood GR is "easier"?)

Some possible consequences

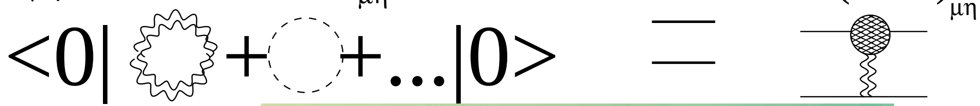
Brownian motion in strong EM fields L.Labun,Ou Z.Labun,H.Truran, 2201.10457 (PRD)

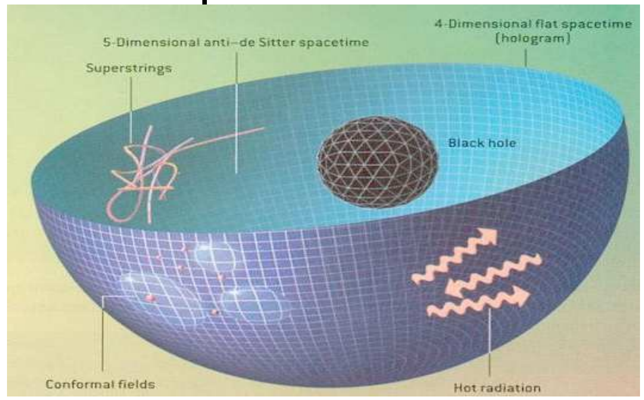


Thermal EFT can be tested with strong lasers, electron and photon propagator in strong field measured directly. Fluctuation-dissipation?

Relationship with holography 1501.00435 (Int.J.Geom.Meth.Mod.Phys.)

$$T^{eff}_{\mu\eta} = 2g^{-1/2} dL_{eff}/dg_{\mu\eta}$$

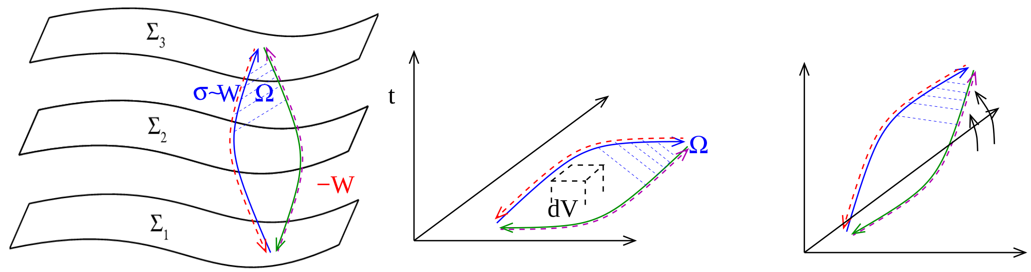




Usually holography is taken to mean bulk dynamics encoded in a surface , but perhaps an interpretation due to general covariance is possible! One needs $S_{bulk}, S_{boundary}$ and constraint . If boundary time-independent (AdS!) "usual" QFT on boundary dual to bulk automatic!

Note that flat space holography impossible , no causal horizon!

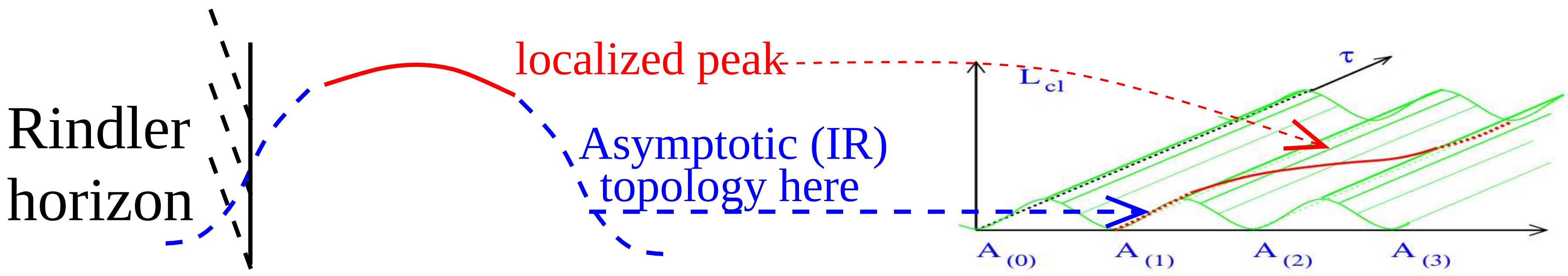
Entropic gravity and fluctuating hydrodynamics via Crooks theorem
2007.09224 (JHEP),2109.06389 (Ann.of Physics)
Hydrodynamics: EP with local SO(3) . Quantum EP $\leftrightarrow$ fluctuating hydro!



Crooks fluctuation theorem: $P(W)/P(-W) = \exp\left[\Delta S\right], W \sim T_{\mu\nu} d\Sigma^{\nu} \beta^{\mu}$

together with Jacobson's entropic GR equation (gr-qc/9504004) , provides a background-independent dynamics for fluctuation-dissipation. Fluctuation-dissipation "gauge symmetry" ensures general covariance! A candidate for the theory of everything: "The universe is governed by Crooks!"

Strong CP problem? 2007.13183 (CQG) (With H.Truran)

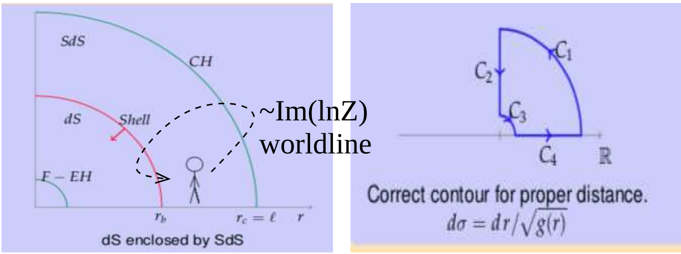


In case of non-zero $|0>=\sum_n |n> \exp[in\theta]$
Vasuum coherent sum of winding numbers. But coherence frame dependent because winding hidden under Rindler horizon, so

$$|a>=\sum_n |n> \alpha(T) \exp[in\theta(T)] \neq \sum_n |n> \exp[in\theta(T)]$$

this might explain $\theta = 0$ and predict no axions!

Cosmology and the cosmological constant via Parikh-Wilczek WKB calculation J.Choi Rodriguez
http://www.repositorio.unicamp.br/handle/REPOSIP/325424

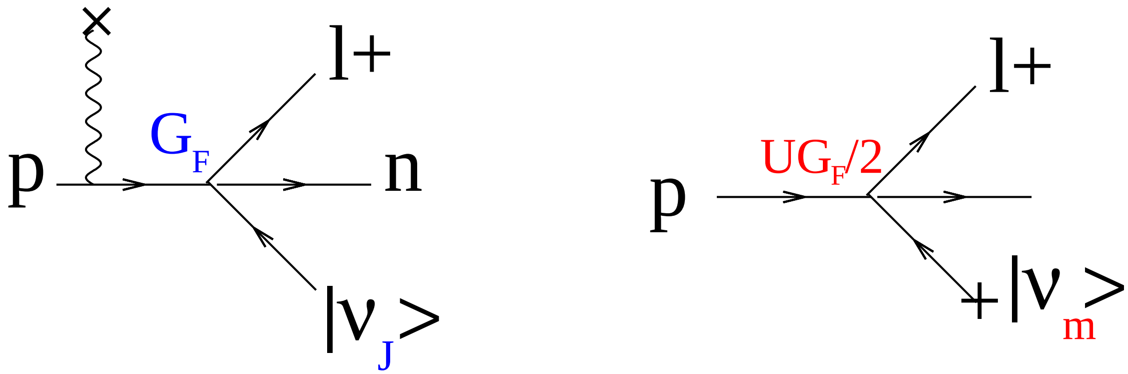


Once you choose a contour that respects local Lorentz invariance, dS space becomes unstable (A. Polyakov, 0709.2899 In contrast to Bunch-Davis , where contours set by global coordinates).

$$\Lambda_{eff} \propto \frac{\delta \ln \mathcal{Z}}{\delta g_{\mu\nu}} \quad , \quad \mathrm{Im} \ln \mathcal{Z} \sim f(\rho, A_{ds})$$

Dynamical cosmological constant, backreaction to FRW equations?

Neutrino oscillations 1508.03091 (EPJA) (L.Labun,D.Ahluwalia)



Problem at root Graviton couples to <u>conserved</u> quantity!

Non-thermal? Loce local Lorentz invariance

Condensate? finite temperature calculation

A generally covariant QFT? "hidden" charge?

Conclusions

- Anything mixing quantum and gravity, inherently speculative. Experimentalists are doing heroic work to change this and any fresh thinking on phenomenology is to be applauded

- My money is on interferometric direct tests on quantization of gravity. KEEP AN EYE ON IT! IT COULD PRODUCE SURPRISES! (Also, ultra-strong EM fields with large accellerations)

- Conceptually we did not go far beyond Bronstein... but progress in QM might be used to proceed without much theory-building

- A generally covariant background independent non-unitary QM/QFT?