

# The equivalence principle and inertial-gravitational decoherence



Talk in a personal capacity, some results in collaboration with Giulio Gasbarri, Marko Toros (ICTP), Tales Perche (Perimeter) [Still in slow progress](#), as a "side-project" for all of us

## 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! fields defined locally can't fluctuate! . Fraenkel: Gravity "macroscopic",  $p$  is a pseudotensor!

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  $\rho$ , mass density  $\mu$ , size  $\Delta x$

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

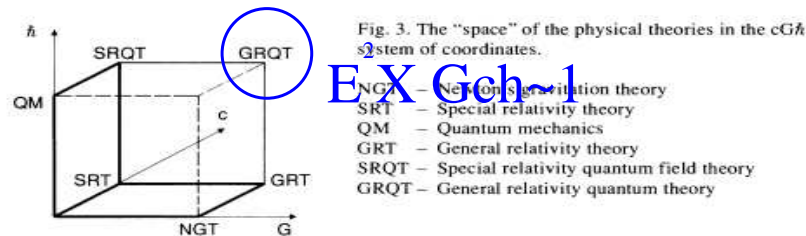
Canonical uncertainty relations recovered if  $\rho, \mu, \mu/\rho \rightarrow \infty$ , i.e. "large"  $\Delta x \gg h/k$  infinitely massive infinitely charged detector with Charge  $\times$  field  $\ll$  Mass. And you see the problem!

Gravity: Charge/Mass always=1, so canonical  $\Delta h_{\mu\nu}$  impossible, due to EP

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.

But Frenkel wrong, as Bronstein showed (discovering the Planck scale)!



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

Due to the difficulty of building a experimentally accessible phenomenology and the speculative theory...

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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

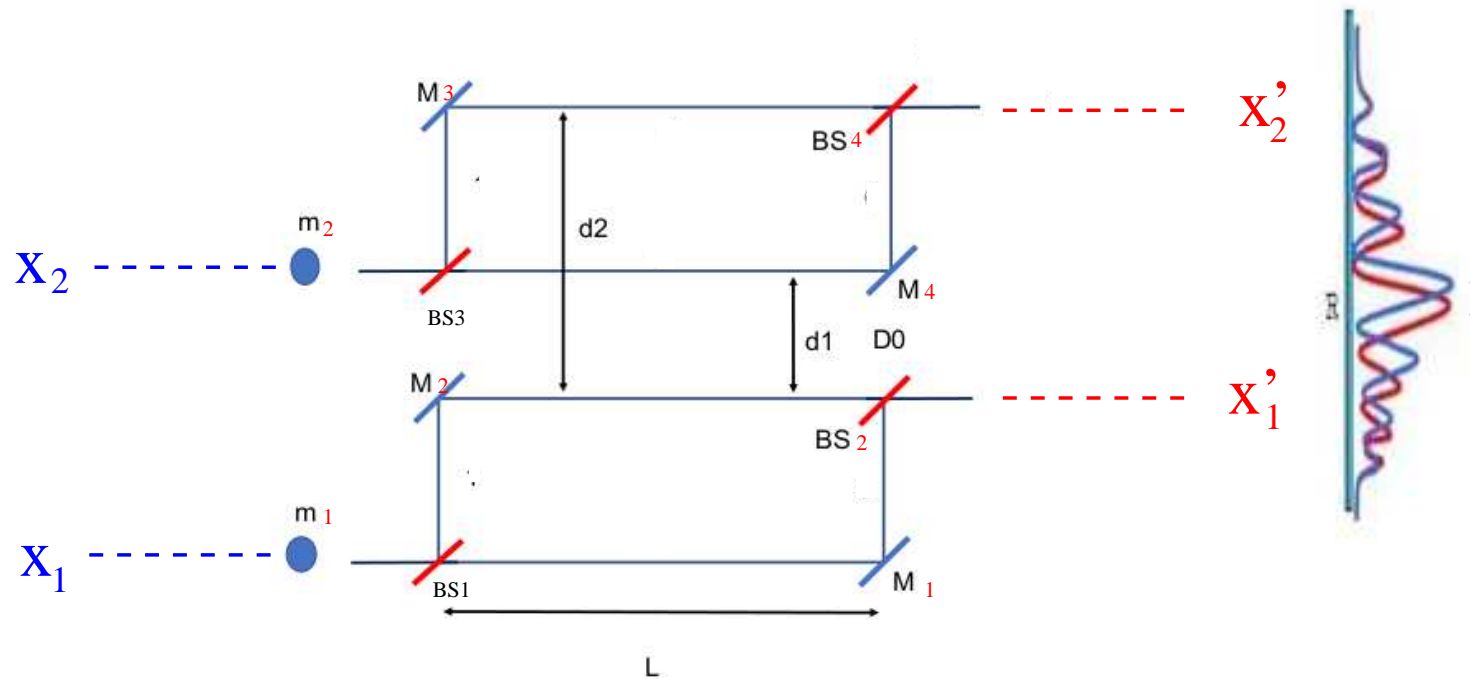
this is impossible with gravity! Backreaction should be included!

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

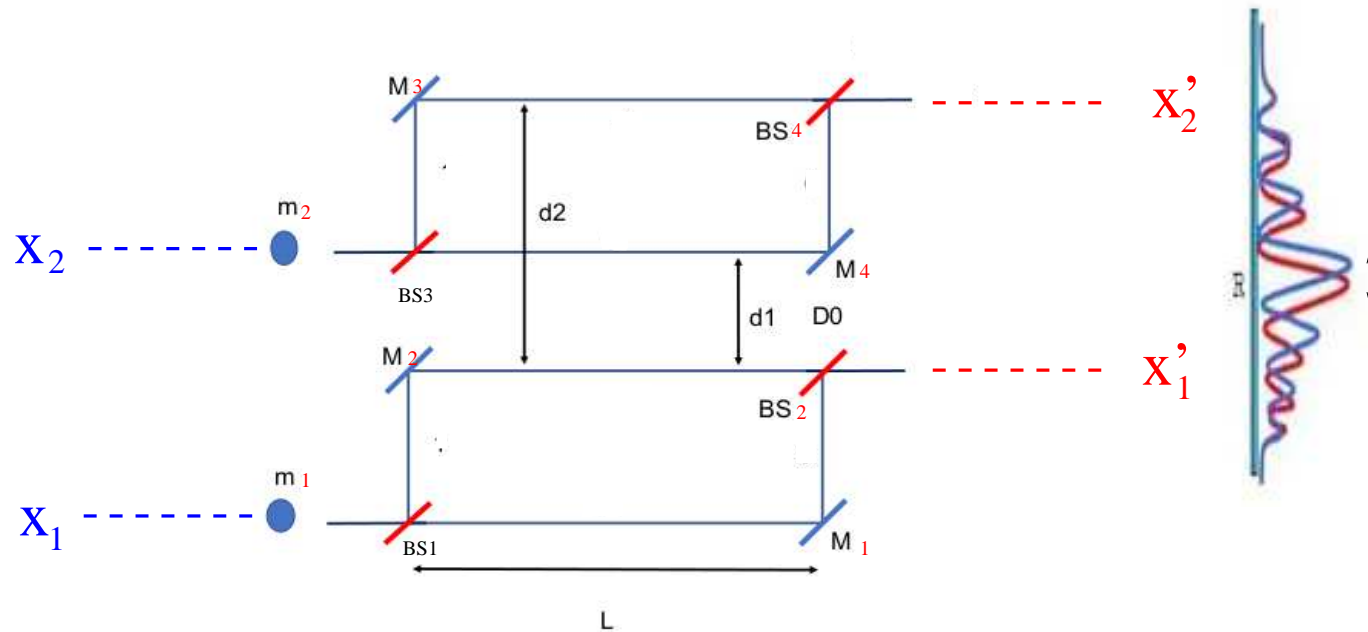


## Experimental quantum gravity from nanoparticle interferometry?



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!

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

If **detector, beam splitter, magnet heavy** it gravitationally interacts  
with the nanoparticles

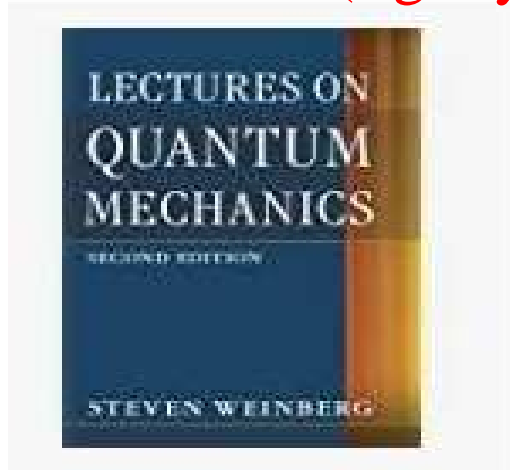
"Higher order" emission of gravitational waves simple, but "Zeroth order"  
is a classical-quantum backreaction

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

Both introduce decoherence which can be quantitatively examined.  
**Difficulty:** cannot use "qubits",  $|left\rangle$  vs  $|right\rangle$  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

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

$$\hat{\rho} = \text{Tr}_{rest} [\hat{\rho}_{sys} \times \hat{\rho}_{rest}]$$

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

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

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

And this is what Bronstein places a limit on! Operators become messy (quantitatively, unitarity and completeness generally violated for  $\rho_{sys}$  . ), 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

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

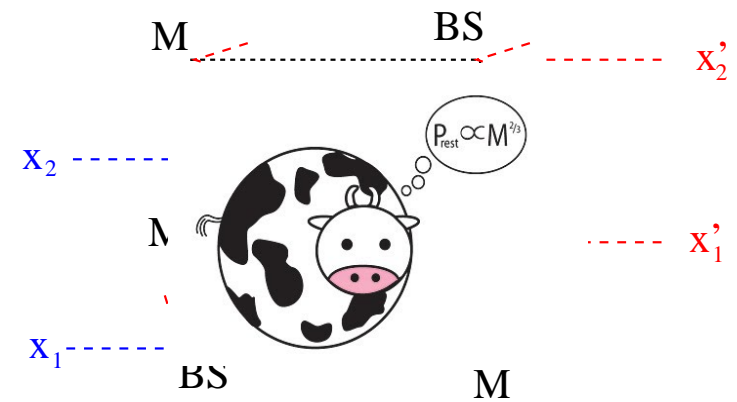
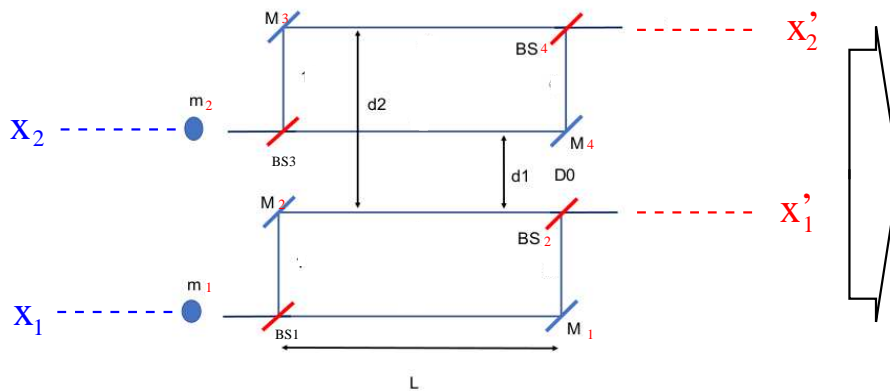
The "classical detector and quantum system" limit is (  $\mathcal{L} \sim \ln \mathcal{Z}$  )

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

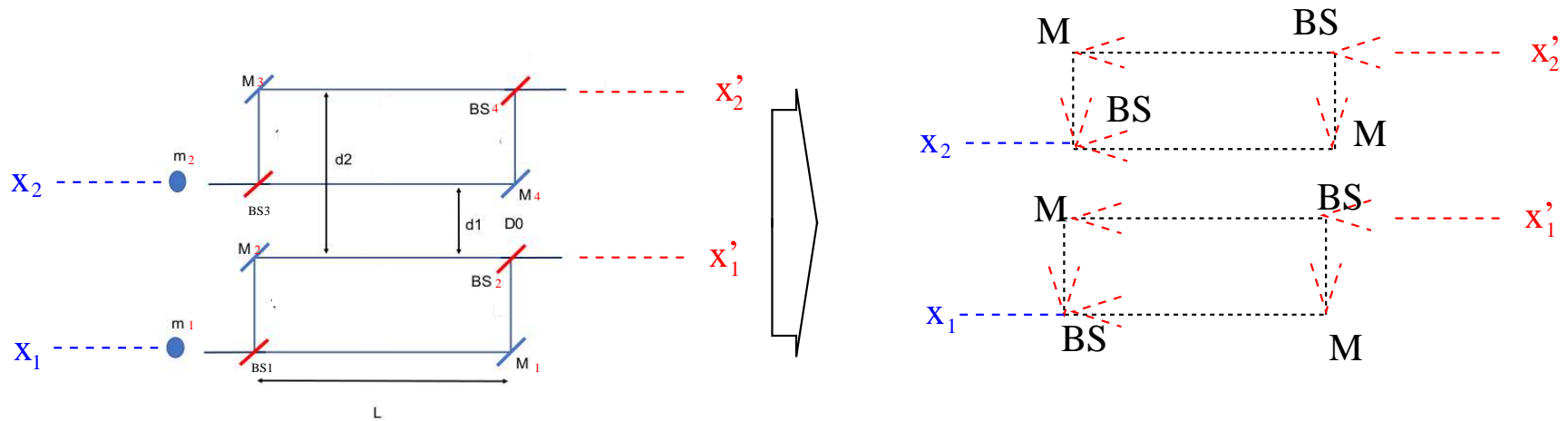
$$\ln \mathcal{Z} \sim \ln \mathcal{Z}|_J + \ln \mathcal{Z}|_{rest} \quad , \quad \ln \mathcal{Z}|_{rest} \ll \ln \mathcal{Z}|_J \simeq \ln \mathcal{Z}|_J^{WKB} \sim \mathcal{L}_{int}$$

## From partition functions to interferometers

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



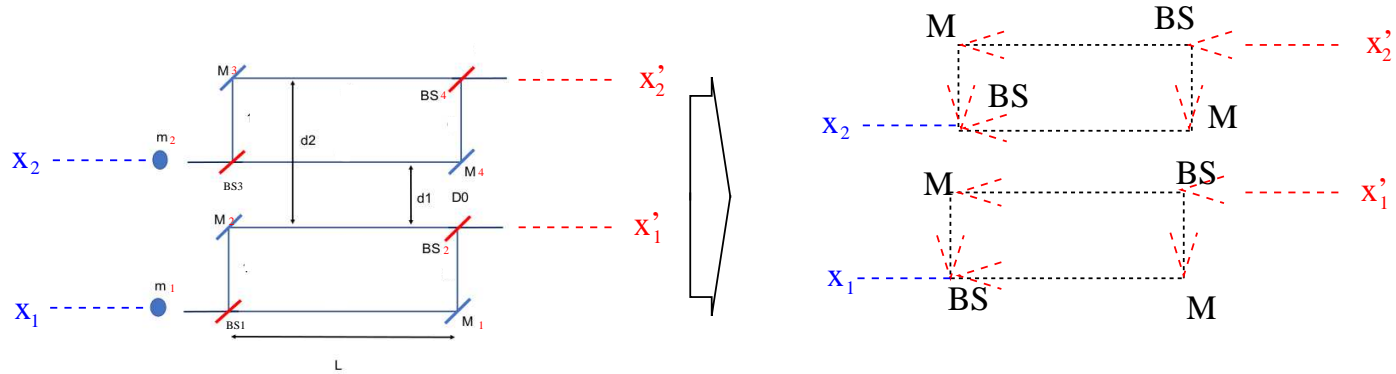
## From partition functions to interferometers



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!



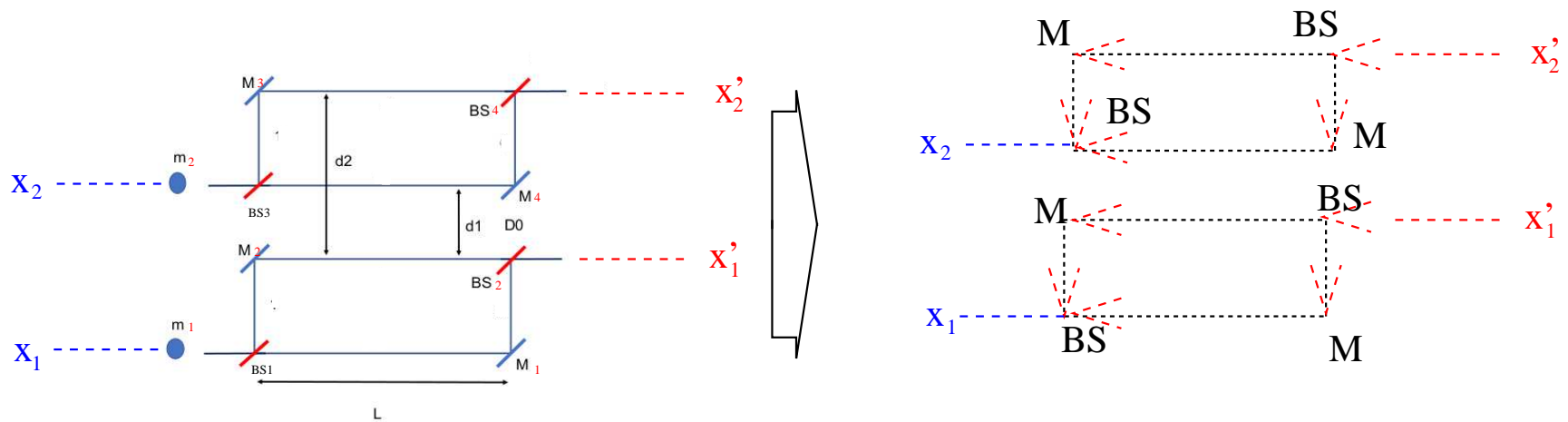
## Quantum gravity interferometry with recoil and decoherence



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

$$S (J(y), x_i, x_j, \phi) = \int d\tau [\mathcal{L}_J(x_i(\tau), x_j(\tau)) + \\ + \int d^3x (\mathcal{L}_\phi(\phi(x)) + \mathcal{L}_{int}(\phi(x), x_i(\tau), x_j(\tau)))]$$

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

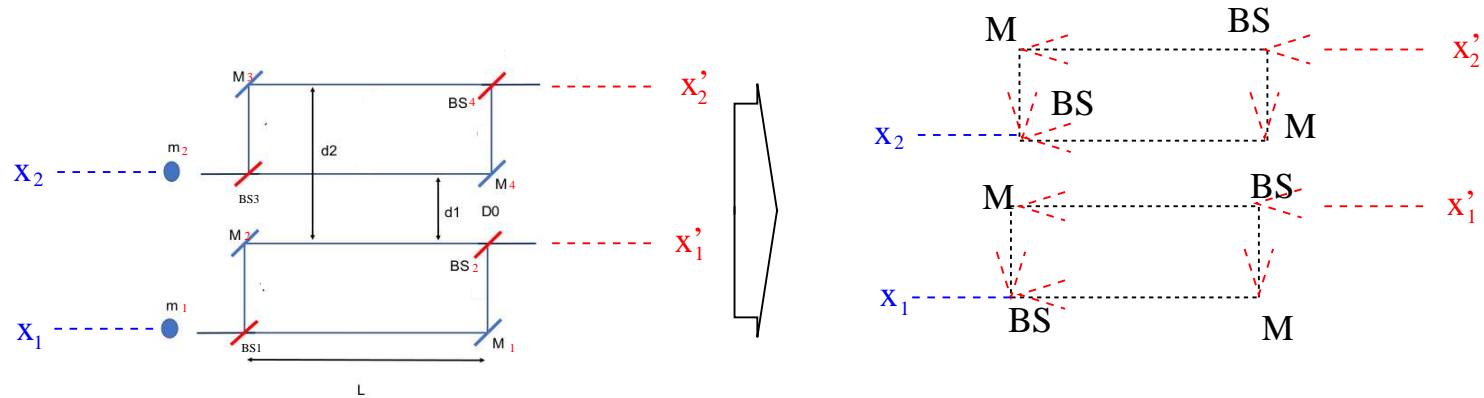


Newtonian non-relativistic limit, so

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

(The original idea can be thought of as "entanglement harvesting" of  $\phi$  )

## Field interaction with nanoparticle and detector

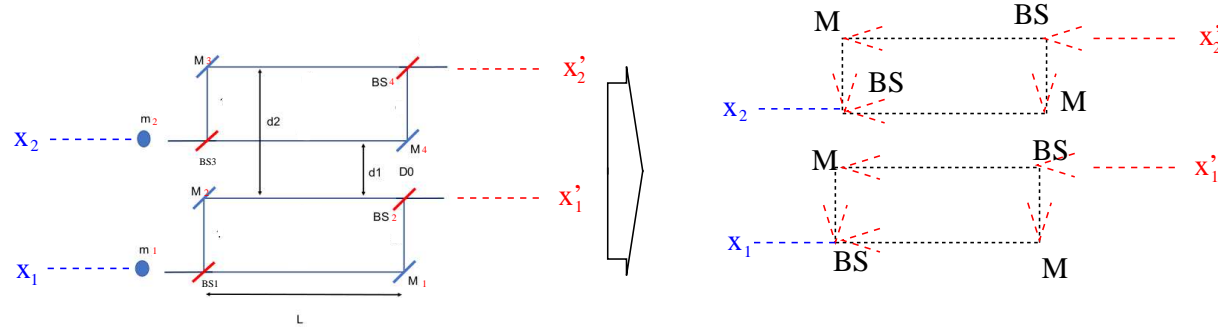


Assume nanoparticles (denoted by  $i$ , mass  $m$ ) and detector components (denoted by  $j$ , mass  $M$ ) all pointlike

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

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

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



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

$$\begin{aligned}
 \mathcal{L}_J = & \underbrace{\sum_{i=1,2} \vec{J}_i(\tau) \cdot \vec{x}_i + \sum_{j=M,BS} \vec{J}_j(\tau) \cdot \vec{x}_j}_{\text{detection}} + \underbrace{\frac{1}{2m} \sum_{i=1,2} \dot{\vec{x}}_i^2}_{\text{nano-particles}} + \\
 & \underbrace{\frac{1}{2M} \sum_{j=M,BS} \dot{\vec{x}}_j^2 - \alpha_{ij} \sum_{i=1,2} \sum_{j=M,BS} \delta(|\vec{x}_i - \vec{x}_j|)}_{\text{detector backreaction}}
 \end{aligned}$$

## Summarizing

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

$$\begin{aligned} \mathcal{L} = & (\nabla\phi)^2 + \sum_{i=1,2} \vec{J}_i(\tau) \cdot \vec{x}_i + \sum_{j=M,BS} \vec{J}_j(\tau) \cdot \vec{x}_j + \frac{1}{2m} \sum_{i=1,2} \dot{\vec{x}}_i^2 + \\ & + \frac{1}{2M} \sum_{j=M,BS} \dot{\vec{x}}_j^2 - \alpha_{ij} \sum_{i=1,2} \sum_{j=M,BS} \delta(|\vec{x}_i - \vec{x}_j|) \\ & G\phi \left( M \sum_{j=M_n,BS_n} \delta(x - x_j(t)) + m \sum_{i=1,2} \delta(x - x_i(t)) \right) \end{aligned}$$

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  $\delta$ -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

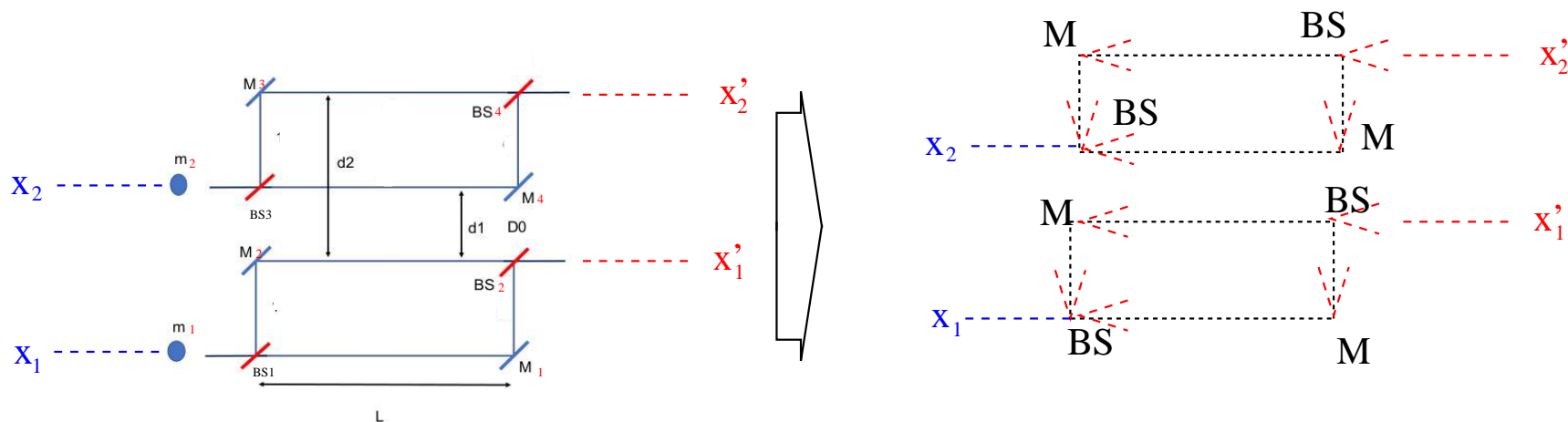
$$G_{ij0}(x, y) = \int d^3k dw \frac{e^{i[i\omega t - k \cdot (x - y)]}}{\frac{k^2}{2\mu_{ij}} - \omega} \quad , \quad \mu_{ij} = \left( \frac{1}{m_i} + \frac{1}{m_j} \right)^{-1}$$

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

And of course

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

## From the partition function to observables

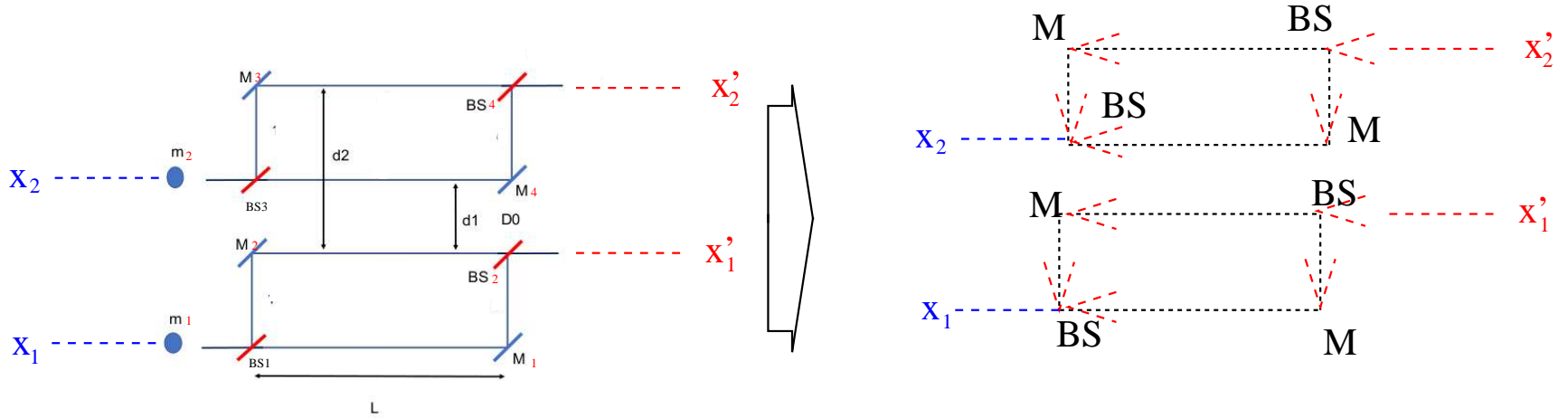


$$\langle x_1 x_2 | \rho | x'_1 x'_2 \rangle_{reduced} = \text{Tr}_{\Phi, J, K}$$

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

$$\langle \Psi_J \Psi_K | \rho | \Phi_{BS2} \Phi_{BS4} \rangle \langle \Phi_{BS2} \Phi_{BS4} | \rho | x'_1 x'_2 \rangle$$

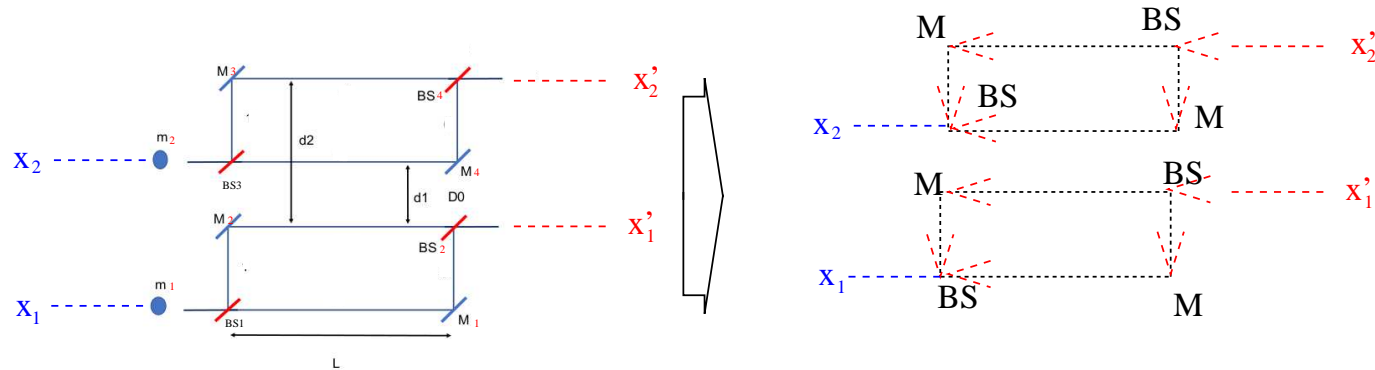
Or in integral function form



$$\begin{aligned}
 & \int \mathcal{D}\Psi_J \mathcal{D}\Psi_K \prod_{i=1}^4 \mathcal{D}\Phi_{BSi} \frac{\delta^4}{\delta J_{1+} \delta J_{2+} \delta J_{BS1} \delta J_{BS3}} \ln \mathcal{Z} \frac{\delta^4}{\delta J_{BS1} \delta J_{BS3} \delta J_{\Psi_J} \delta J_{\Psi_K}} \ln \mathcal{Z} \\
 & \times \frac{\delta^4}{\delta J_{\Psi_J} \delta J_{\Psi_K} \delta J_{BS2} \delta J_{BS4}} \ln \mathcal{Z} \frac{\delta^4}{\delta J_{BS2} \delta J_{BS4} \delta J_{1-} \delta J_{2-}} \ln \mathcal{Z}
 \end{aligned}$$



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  $BS$

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

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  $\forall m, M$

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

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

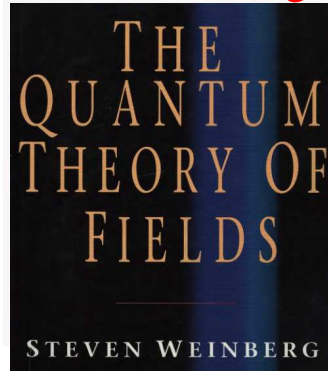
$$\mathcal{L}_{int} \simeq J_i(\tau)x_i \quad , \quad \mathcal{L}_J \gg \mathcal{L}_{int}, \mathcal{L}_\phi$$

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

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

Speculations: Away from  $c \rightarrow \infty$  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.

Only way to restore unitarity (up to renormalization),causality,locality and full Lorentz invariance was QFT.

The "price" of QM  $\rightarrow$  QFT

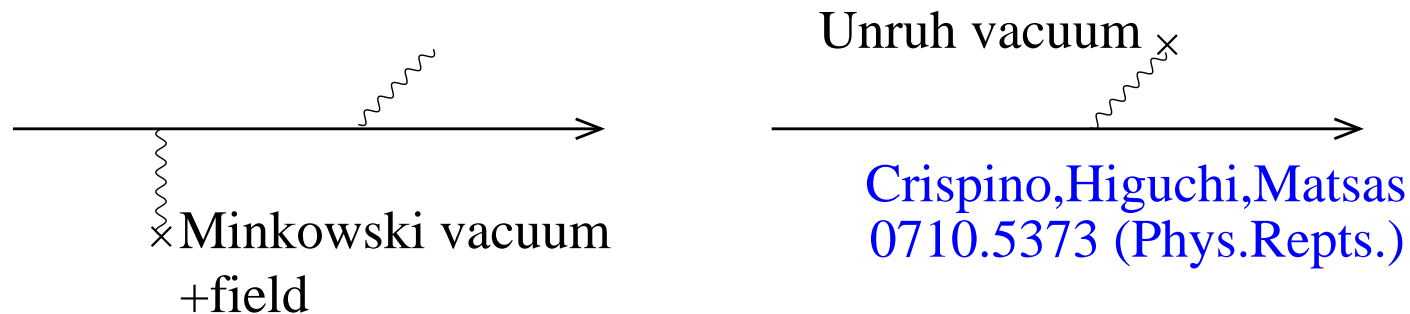
**neither** space nor time are observables. Fields and their correlators are.

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

This was real progress. It is amusing to me 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)

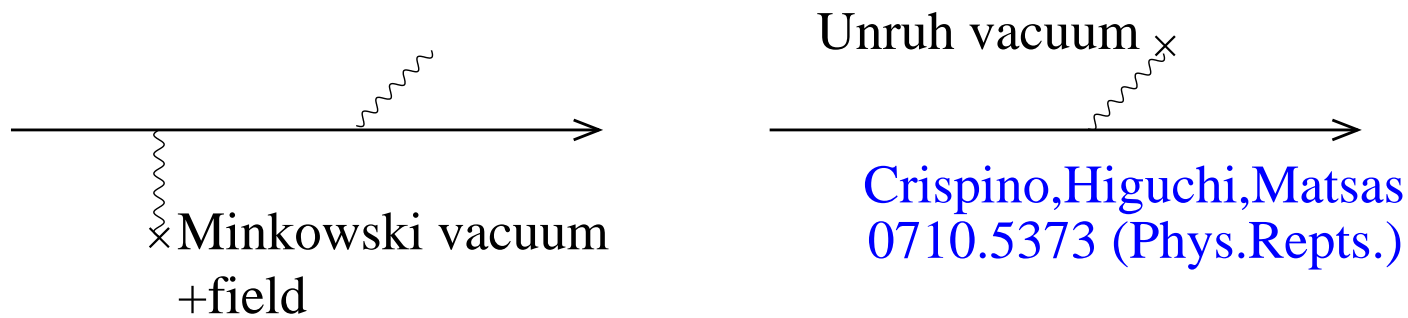
Can the relativistic version of a partition function we examined earlier (with horizons!) be generally covariant?

Which is funny because there is some literature about the extent that quantum mechanics is generally covariant



**NB:** concept of acceleration 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!

Unitarity necessarily broken if boundary not spacelike (no clear commutation, unitary equivalence, completeness,...) .

Fluctuation-dissipation instead of unitarity?

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

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

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

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

QFT with functional integral only within horizon

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

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

- 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  $\frac{\delta^2 \ln Z}{\delta J_1 \delta J_2}$

Not QG, but if we understand this QG might become easy  
(After general covariance understood GR is “trivial” !)

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

**Entropic gravity and fluctuating hydrodynamics** via Crooks theorem

<https://arxiv.org/abs/2007.09224> (JHEP) and colloquium

<https://www.youtube.com/watch?v=oLYouz0YMHM>

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

**Cosmology and the cosmological constant** via Parikh-Wilczek WKB calculation J.Choi Rodriguez,

<http://www.repositorio.unicamp.br/handle/REPOSIP/325424>

**Brownian motion in strong EM fields** Upcoming with L.Labun,Ou Z.Labun,H.Truran

**Soft theorem deformation?** Ongoing work (Igor Mol,L.Pipolo,J.Pitelli)

## 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 accelerations)
- 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?



SPARE SLIDES

## WHy is gravity incompatible with quantum mechanics?

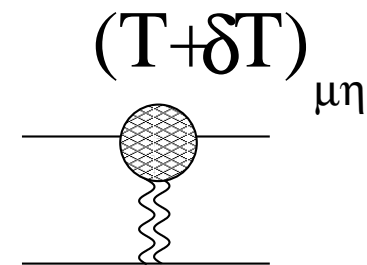
A usually given reason: theory perturbatively non-renormalizable

A technical reason suggesting technical fixes. **Is there anything conceptually deeper?**

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

$$\langle 0 | \text{[diagram: wavy circle]} + \text{[diagram: dashed circle]} + \dots | 0 \rangle$$

(a)



(b)

Lack of normalization really due to anomalies breaking Unitarity  
Robinson+Wilczek, Hawking radiation as an anomaly

## Why is gravity geometric?

The (strong) equivalence principle: all 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).

$$\textit{Mathematically} \quad \partial_\mu \rightarrow \partial_\mu + \Gamma$$

Implies gravity "force" indistinguishable from acceleration, gravity "field" implies curved space, where no 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 worldlines 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

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

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

QFT with functional integral only within horizon

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

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

- First order in  $Gp^2$  , all orders in  $J - \phi$  interaction Metric and horizon set by detector worldline  $J$
- Essentially Gibbons-Hawking term, but with “detector” represented by  $J$  , with backreaction on detector given by  $\frac{\delta^n \ln Z}{\delta \phi^n}$  .  $Z$  quantum but detector response stochastic (decoherence). “Solves” backreaction problem posed earlier

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  $c \rightarrow \infty$  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  $\rightarrow \int_{\forall x_{1,2}} \int_{x_1}^{x_2} L (g_{\mu\nu} dx^\mu dx^\nu)^{1/2}$

**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!