Title: Vacuogenesis (Vision Talk)

Speakers: Ted Jacobson

Collection/Series: QIQG 2025

Subject: Quantum Gravity, Quantum Information

Date: June 24, 2025 - 10:00 AM

URL: https://pirsa.org/25060008

Abstract:

I will offer perspectives on the creation of degrees of freedom, relational observables, probability, observable algebras, and gravity.

Vacuogenesis

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QIQG 2025, Perimeter Institute
24 June, 2025

Vision

Mike Lazaridis

Howard Burton

Rob Myers and Lee Smolin

Perimeter staff

- creation of degrees of freedom?
- QM without probability?
- gravitational algebras
- entanglement equilibrium
- non-perturbative vacum entropy?

creation of degrees of freedom?

If there is a short distance cutoff, d.o.f. creation is apparently needed for

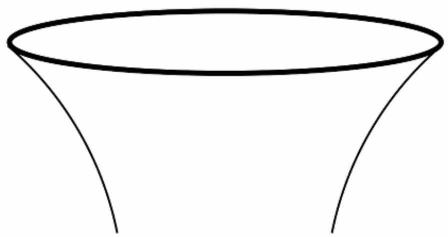
- expanding universe
- outgoing black hole modes

The latter is presumably explained holographically. But how?

Expanding universe seems to require true creation. How could this work?

creation of degrees of freedom?

Consider an expanding universe with a proper UV cutoff.



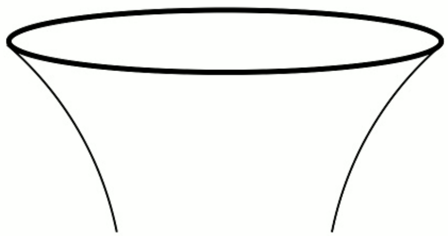
✦ <u>Challenges</u>:

- ✳ The (interacting) "adiabatic vacuum" should be preserved, so new d.o.f. must be born with the appropriate entanglement with the rest.
- ✳ Local Lorentz and diffeomorphism symmetry should be preserved.
- ✳ Unitarity should be preserved, or suitably modified.

How could this happen?

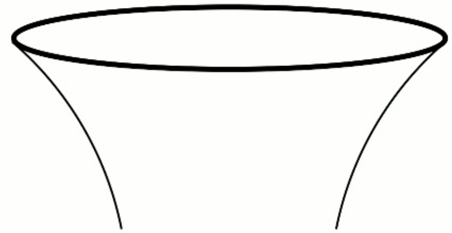
creation of degrees of freedom?

✦ Proposal: Consider a universe wave function $\Psi[h_{ij}, \phi]$, defined by some path integral, that would satisfy the Wheeler-DeWitt equation, but include a diff invariant, "low pass filter" on the boundary data, so that a larger space admits more modes.



E.g, in EFT impose an upper bound on sectional curvatures of h_{ij} and on the eigenvalues of the Laplacians for matter fields ϕ; or, discretize everything.

creation of degrees of freedom?



- This should produce something close an evolving adiabatic vacuum with a UV cutoff. (Halliwell & Hawking)
- It would satisfy "approximately" the Wheeler-DeWitt equation.
- It would reproduce semiclassical gravity at the EFT level. (Lapchinsky & Rubakov, Banks)
- It would not implement exact unitarity, but that's anyway only approximate and emergent in quantum gravity in a closed universe.

quantum mechanics without probability?

- ✦ Emergent probability: Probabilities are unsuitable for a fundamental theory.
  QM probabilities are emergent, in a way that depends on the universe being a big place with lots of entangled stuff. The idea was explored formally by Gell-Mann and Hartle via the decoherence functional, and was recently sharpened by Harlow, Usatyuk and Zhao using quantum information theory methods.

- ✦ Probability enters quantum physics via subjective "decision theory" (Deutsch '99)
  Alternatives related by a symmetry are assigned equal probability $\Longrightarrow$ Born rule.
  Since such symmetries are only emergent and approximate, the same holds for probabilities.

- ✦ So what is QM fundamentally about?: The algebra of observables predicts their spectra, i.e., the possible alternatives and their values, and their casual relations.

gravitational algebras

✦ Impressive recent progress finding the algebra of relational, diff-invariant observables, for weak gravity perturbations around symmetric backgrounds. (CPW, CLPW + numerous others).

✦ For perturbations of dS static patch containing an "observer",
a perturbatively diff-invariant observable algebra is obtained that is of type II_1,
unlike the type III QFT algebra,
which implies that it admits a maximum entropy state,
which coincides with the dS vacuum.

Invariant states and quantized gravitational perturbations

Vincent Moncrief

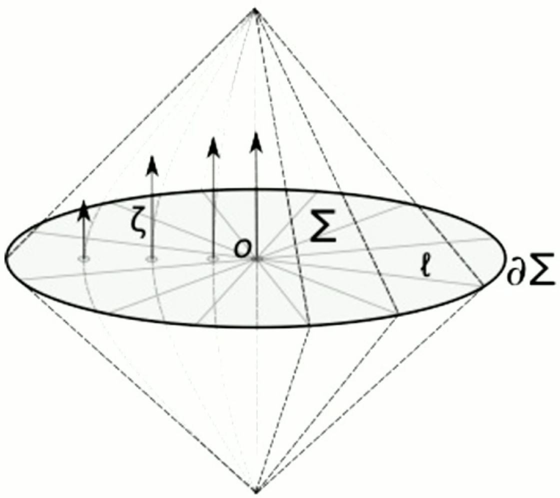
Department of Physics, Yale University, New Haven, Connecticut 06520

(Received 3 April 1978)

We study the problem of quantizing the gravitational fluctuations about a symmetric vacuum background spacetime with compact Cauchy surfaces. In the context of lowest-order perturbation theory we show that the allowed physical states must all be invariant under the symmetry transformations of the background spacetime. This constraint does not unduly restrict the range of allowed states and is consistent with temporal evolution (in the presence of a timelike symmetry) or spacial localization (for a spacelike symmetry) provided the evolution or localization is interpreted intrinsically rather than with reference to the background spacetime.

gravitational algebras

✦ Can the dS algebraic construction be applied to a round causal diamond in Minkowski?



Doesn't admit a Killing vector or infinitely long-lived observer.
BUT: admits a <u>conformal</u> Killing vector ζ that

1. is Killing on Σ
2. has constant $\nabla \cdot \zeta$ on Σ
3. has infinite conformal Killing time range
4. admits a first law: $\delta H_\zeta^{\rm matter} = -\dfrac{\kappa}{8\pi G}(\delta A - k\delta V)$

Manus Visser & TJ, 2019

✦ It seems there should be a link between the existence of a maximal entropy state in dS and the "maximal vacuum entanglement hypothesis", i.e., "entanglement equilibrium". TJ, 2016

entanglement equilibrium

common
numerical
factor!

$\Longrightarrow G = 1/4\eta\hbar \Longrightarrow \eta = 1/4G\hbar$

$$\delta S_{\text{gen}}|_V = \eta\delta A|_V + \frac{2\pi}{\hbar}\delta\langle K\rangle = \frac{\Omega_{d-2}R^d}{d^2-1}\left[-\eta G_{00} + \frac{2\pi}{\hbar}(\delta\langle T_{00}\rangle + \delta X)\right].$$

universal
area density
of entropy

matter
entanglement
entropy

scalar offset for
non-conformal matter

- Remarkable that it's consistent with Bekenstein-Hawking $1/4G\hbar$
- Why fixed volume?
- Is the non-conformal matter kludge valid? Does the Carroll-Remmen ('16) improvement work?
- How to (i) define and (ii) check whether S_{gen} is at least perturbatively <u>maximal</u> in the vacuum?

  Dressed algebra method shows that it is for dS static patch.

gravitational algebras

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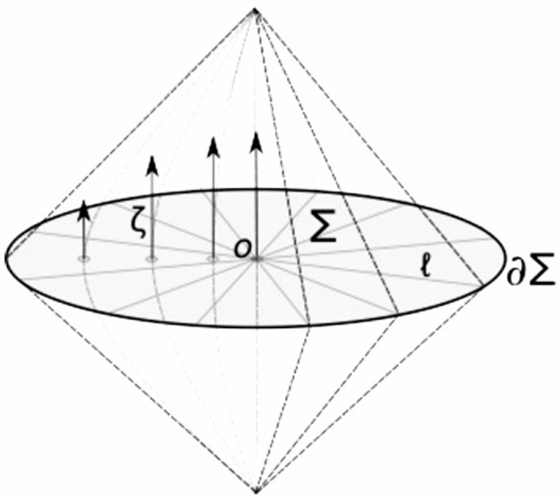

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Non-perturbative meaning of vacuum entropy?

Sphere partition function formally counts $Z = \mathrm{Tr}\ I_{\mathscr{H}}$.

This can be interpreted as the dimension of space of states of a topological ball.

With positive cosmological constant, Euclidean saddle is a 4-sphere (in 4D) whose action yields $A/4G\hbar$, the dS entropy. (Gibbons & Hawking, 1978)

Non-perturbative meaning of vacuum entropy?

Is the correct integral truly approximated by the sphere saddle?
What about the imaginary one-loop phase factor?
What is the correct integral to begin with?

(Batoul Banihashemi & TJ, '22, '24)

Start with a reduced phase space path integral, $Z = \mathrm{Tr}\, I_{\mathscr{H}} = \int \mathscr{D}p_i \mathscr{D}q^i \exp\left(i \oint dt\, p_i \dot{q}^i \right)$
We have failed, so far, to recover $A/4G$ from this viewpoint. (Horizon boundary term?)

But one may integrate out the momenta to obtain a covariant integral.
The "lapse" contour must be displaced, $N \to N - i\epsilon$ to allow interchange of integration order.
(The argument uses gauge-fixed K, since $K^2 \sim \pi^2$ appears with the "wrong sign" in the action.)

The result is neither Euclidean nor Lorentzian. (Can it help with the unwanted phase factor?)
The complex action has branch cuts, but the lapse contour avoids these, and in a toy model can indeed be deformed to pass through the Euclidean saddle. (Bianca Dittrich, José Padua-Argüelles & TJ, 24)

Where are we?

close to the time for a big leap?

Like abandoning attempts to prove in the wrong theory that the ether is unobservable, and instead (Einstein) simply assuming it.

Like abandoning attempts to account for atomic structure and spectra in the wrong theory, and instead (Heisenberg) simply assuming that transition amplitudes satisfy equations of motion, or (Schrödinger) simply assuming that a particle can be described by a wave equation.

Those leaps were motivated by compelling evidence, but landed in unknown territory of a new theory whose meaning had to be discovered.

Where are we?

Is there a leap we should take?

Assume the algebra is really Type I?

Assume the metric is really defined by entanglement, or by the algebra?

Let's be bold!