Title: Reflections on quantum gravity in 2020

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Reflections on QG (in) 2020
Ted Jacobson, University of Maryland, 17 July 2020
Theodore A. Jacobs...

QG? how did we get here?

QM

19th century hints from structure of matter (especially spectra), thermodynamics of gases. In closing days of 19th century, two key developments:

- Planck's discovery that thermal equilibrium of radiation requires $E = h\nu$
- Zeeman's discovery that atoms contain very light charges, whose orbits can be shifted by an external magnetic field and are somehow quantized

Discoveries happened *then* thanks to developments in *technology*: improved ability to precisely measure *spectra.* 25 more years of technology, experiments, and theory achieved QM — a *very* strange theory that would not have been discovered without observations to lead us by the nose.

GR

A fusion of Newtonian gravity and Maxwellian electrodynamics, deduced by Einstein purely theoretically from these inputs, together with deep intuition about the importance of the equivalence principle and background independence. *No* new technology or experiments played a role.

1900 1925 1950 1975 2000 2020

Planck Zeeman | GR | QM | QFT | QFTCS | AdS/CFT

Why no QG yet?

Actually, we *do* have *perturbative* QG. Just as canonical quantization worked for electromagnetism, it can be applied to GR, and yields an effective theory of "Quantum Gravity in Everyday Life" (C. Burgess, *Living Reviews in Relativity*, 2004)

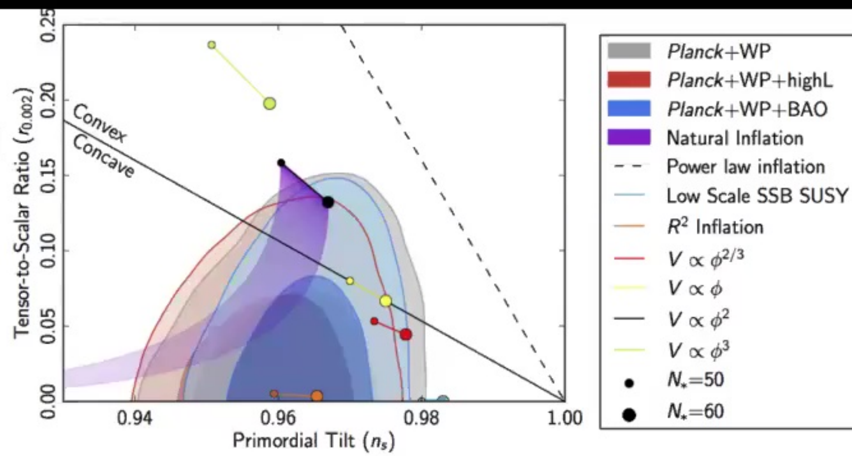
And we even apply it and compare to observation, in the context of *inflationary cosmology,* wherein primordial structure arises from vacuum fluctuations. Again, the ability to measure spectra precisely, in this case, of the CMB, is essential.

The fluctuations involve the *scalar mode of the metric.* Usually this is treated as a ``slave", coupled to a hypothetical scalar *inflaton field.* But it might be just the scalar metric mode itself, activated as a propagating degree of freedom by the R^2 term in the effective action (*Starobinsky inflation*, 1980)

Starobinsky inflation

$R + \alpha R^2$

Contains a slow roll potential, and a universal reheating mechanism, and matches the observed tilt and amplitude of primordial fluctuations with one free parameter: $\alpha \sim 10^{10}\, l_{\mathrm{P}}^2$



the fly in the ointment: unnatural value, and unnatural to restrict to R^2 given this value of α

But there is something special about R^2: it is the *only* higher curvature term that can be added without producing higher time derivative instabilities when taken nonperturbatively. Perhaps that's essential. I cannot believe the success of this model is an accident.

Tensor modes and non-Gaussianity

These are further predictions from the graviton modes and the nonlinearity of quantum GR.

They may or may not lie beyond observational reach.

Technological advances will help.

Desperately seeking other observations

Although not very well motivated, if true might provide observational windows on quantum gravity:

variation of fundamental constants
Lorentz violation
conspicuous extra dimensions
diffusion
black hole firewalls
extra fundamental fields
quantum decoherence
…

Here too, technological developments help. Particularly promising are atomic clocks with 10^{-18} precision, and light and matter interferometers. We can always hope for surprises, and in any case it's good science to place strong constraints on such possibilities.

…but we are more ambitious…

want to understand things we can perhaps never see: black hole singularities, baby universes, the origin of the universe, eternal inflation…

forgive us our sins

QG2020

Paradigms:

Issues

GR all the way

- EFT
- scattering
- asymptotic safety
- CDT
- LQG, spin foams

GR ⊂ "M-theory"

- strings and branes
- AdS/CFT

"from scratch"

- causal sets
- group field theory
- tensor models

UV

- asking for a theory valid at all scales [foolish?]

IR

- observables
- time
- black hole information
- unitarity?
- Hilbert space
- soft modes
- cosmology

AdS/CFT
gravity without gravity

Emerged from string theory, but is "standalone" — could perhaps have emerged from straight QGR, and can make contact with other approaches.

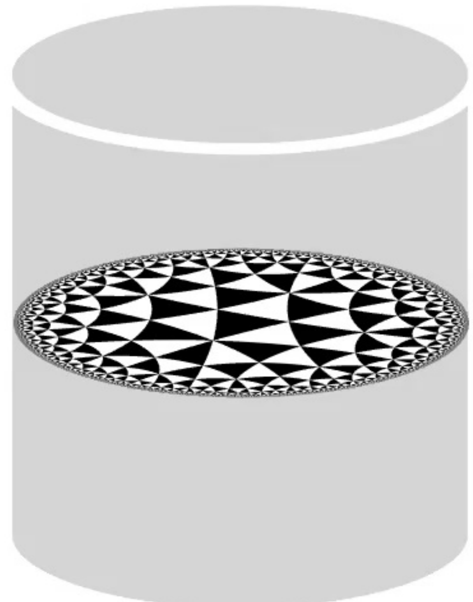
Has certain enormous advantages both for the UV and the IR issues.

CFT has no scale, valid into the arbitrary UV.

Asymptotically AdS boundary condition introduces a *timelike boundary,* where we can use ordinary concepts of QM, time, observables, unitarity, and yet apparently also describe quantum gravity.

Although not "realistic," to fully understand this should put us well on our way to more realistic settings for QG.

Brings into play quantum information theory, central role of entanglement in building emergent spacetime.



metric (and space) from entanglement

who rules the vacuum?

Unruh (1976) found that the vacuum fluctuations of quantum fields determine in the inertial structure of spacetime, i.e. the metric.

Conversely, the metric governs the vacuum fluctuations.

This always seemed uneconomical — a *redundancy* of structure. The vacuum of quantum fields and the metric should be unified.

AdS/CFT goes some way toward realizing this…albeit via entanglement of *boundary* vacuum fluctuations determining *bulk* metric. The (H)RT formula relates the area of bulk extremal surfaces—and thus the metric— to entanglement entropy in boundary subregions. Moreover, this correspondence implies that the metric satisfies the Einstein equation. And the entanglement even seems to account for the topological connectedness of space.

QG & unitarity ?

I don't think unitarity per se can make sense in quantum cosmology.

Inner product and probability are perhaps "emergent".

Without probability, what is left in quantum mechanics?

1. Spectra of operators ?
2. Entanglement

Where does probability come from in QM?

REVIEWS OF MODERN PHYSICS VOLUME 29, NUMBER 3 JULY, 1957

"Relative State" Formulation of Quantum Mechanics*

Hugh Everett, III†
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey

Shows the the Born rule is the unique assignment of probability that distributes over superpositions of *orthogonal* states.
(but it assumes Hilbert space inner product)

I see this as a Bayesian argument: if someone hands an alien QM without telling them the Born rule, and offers them the opportunity to make bets, the smart alien will quickly deduce that the Born rule is the only sensible way to choose their bets, given what they know already about the theory.

See Lubkin, for an operational version of this argument, based on entanglement structure of states:

An Application of Ideal Experiments to Quantum Mechanical Measurement Theory

Elihu Lubkin
Department of Physics, University of Wisconsin–Milwaukee, Milwaukee, Wisconsin 53201

Received January, 1969; revised January, 1979

In the discussion Everett writes:

The "relative state" formulation will apply to all forms of quantum mechanics which maintain the superposition principle. It may therefore prove a fruitful framework for the quantization of general relativity. The formalism invites one to construct the formal theory first, and to supply the statistical interpretation later.

But it uses more than superposition: What to do if we don't have the inner product? *Could probability be extracted from properties of entanglement alone, without appeal to an inner product? It seems not.*

Gell-Mann & Hartle suggest "Generalized QM," to base the theory on a *decoherence functional* associated with a path integral. There the criterion of decoherence is presumably never met exactly, and this bothers me.
If probability is only approximately meaningful, what is the theory *about*?

Thanks!

to

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the speakers
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