Classical Spacetimes of Bouncing Universes and Evaporating Black Holes

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Classical Behavior of Quantum Systems

- A quantum system behaves classically when the probability is high for histories that exhibit correlations in time governed by classical deterministic laws.

- Probabilities for histories arise from the system’s theory of dynamics and its quantum state $\Psi$.

- This applies to the flight of a tennis ball, the orbit of the moon around the Earth, and the classical spacetime of our quantum universe.
Bouncing Universes
Bouncing Universes of the No-Boundary Quantum State

A state of the universe $\Psi$ lives on a configuration space of three-geometries and matter field configurations

$$V(\phi) = \frac{1}{2}m\phi^2 + \Lambda$$

Minisuperspace of homo-iso geometries and fields.

$$ds^2 = b^2 d\Omega_3^2 \quad \phi \equiv \chi$$

$$\Psi = \Psi(b, \chi)$$

$H\Psi = 0$ is the Wheeler-DeWitt eqn which evolves $\Psi$ in superspace.
Histories

Histories are curves in config.
space. A classical history is a
curve satisfying the Einstein eq.

The NBWF is a model
quantum state which
semiclassically has the form

\[ \Psi(b, \chi) \propto \exp[-I(b, \chi)/\hbar] \]

\( I(b, \chi) \) is the action of a
complex saddle point regular
on a 4-disk with one boundary
matching \( (b, \chi) \)
Ensemble of Classical Spacetimes

\[ \Psi(b, \chi) \propto \exp\left\{ \frac{[I_R(b, \chi) + iS(b, \chi)]}{\hbar} \right\} \]

WKB: When \( S \) varies rapidly compared to \( I_R \), we predict an ensemble of possible classical spacetimes that are the integral curves of \( S \), \( \pi = \nabla S \)

This defines a one parameter family of classical histories labeled by \( \varphi_0 \).
Classical Extrapolation

• The WKB approximation breaks down for small b because $\nabla S \gg \nabla I_R$ doesn’t hold.

• Extrapolating with classical equations anyway gives universes that **bounce at a radius much larger than the Planck scale** --- no breakdown in the eqns or solutions.

• But the results are inconsistent with the time-reversal invariance of the NBWF.
Quantum Extrapolation

• There is a quantum amplitude to go through the bounce from one classical history to any other that can be calculated from WdW.

• These are consistent with time reversal invariance of NBWF.

A WdW `S-matrix'
Lessons of Bouncing U’s

• There may be no global spacetime. Classicality may only hold in patches of configuration space.

• In each patch there is generally not one, but an ensemble of possible classical spacetimes.

• Quantum transitions between classical patches can be calculated by WdW evolution.

• Classical spacetime can break down at energy densities well below the Planck scale.
Evaporating Black Holes
WdW for Evaporating Black Holes

\[ \Psi = \Psi[h_{ij}(x), \chi(x), t] \]

- WdW evolution is not field theory in curved spacetime. There is generally no fixed background spacetime.
- WdW evolution is formally unitary.
- The WdW equation is neither local or non-local, neither causal or a-causal.
Classical Patches

- We expect classical spacetimes only in asymptotic patches. (Certainly not near the classical singularity.)
- Many final asymptotic class. spacetimes for each initial one.
- WdW supplies an `S-matrix’ between these.
- The quantum state remains pure.
There is no horizon defined as the boundary of the past of $I^+$, because there is no global classical spacetime to define it.

There will be apparent horizons that are defined locally in a patch.
Its often asked: Why and where does classical spacetime break down?

In quantum mechanics the question is: Why and where do we have classical spacetime at all?
A Prior for Planck

$\Psi_{HH} \propto e^{-I_E}$

Landscape

Hertog
Classical spacetime exists only where quantum mechanics permits it to.