The Impact of Cosmology on Quantum Mechanics

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Talk at
Quarks2020

1929-1936
The expansion of the universe.

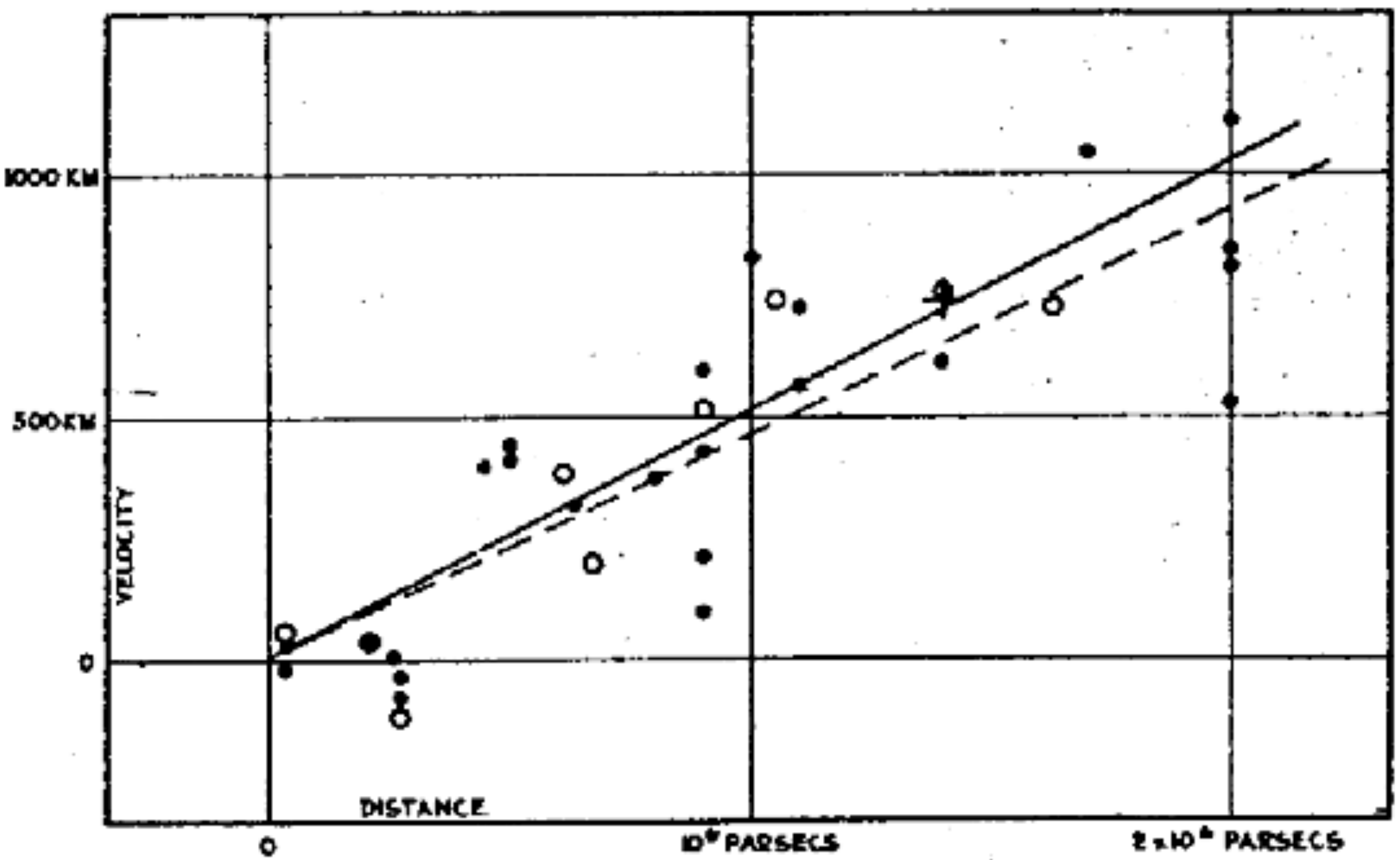


FIGURE 1

The textbook (Copenhagen) quantum mechanics of measurements is the most successful theoretical framework for prediction in the history of physics!

Textbook Quantum Mechanics must be Generalized for Quantum Cosmology

- Assumed a division into ``observer'' and ``observed''.

In a theory of whole thing there can't be any fundamental division into observer and observed.

- Assumed that the outcomes of measurements are the primary focus of science.

Measurements and observers can't be fundamental in a theory of the early universe where neither existed.

- Assumed the classical world as external to the framework of wave function and Schrodinger eqn.

Fundamentally there are no variables that behave classically in all circumstances.

No Retrodiction in Copenhagen QM

Two laws of Evolution:

Unitary evolution by the Schroedinger equation when the system is isolated. Can be time reversed.

$$i\hbar\frac{\partial\psi}{\partial t} = H\psi$$

Projection (or collapse) when the system is measured.
Cannot be time reversed.

$$\psi \rightarrow \frac{P\psi}{||P\psi||}$$

But cosmology is all about the past. We reconstruct the past history of the universe to simplify our predictions of its future.

Not all retrodictions are useful!

Textbook Quantum Mechanics Has to Be Generalized for Cosmology

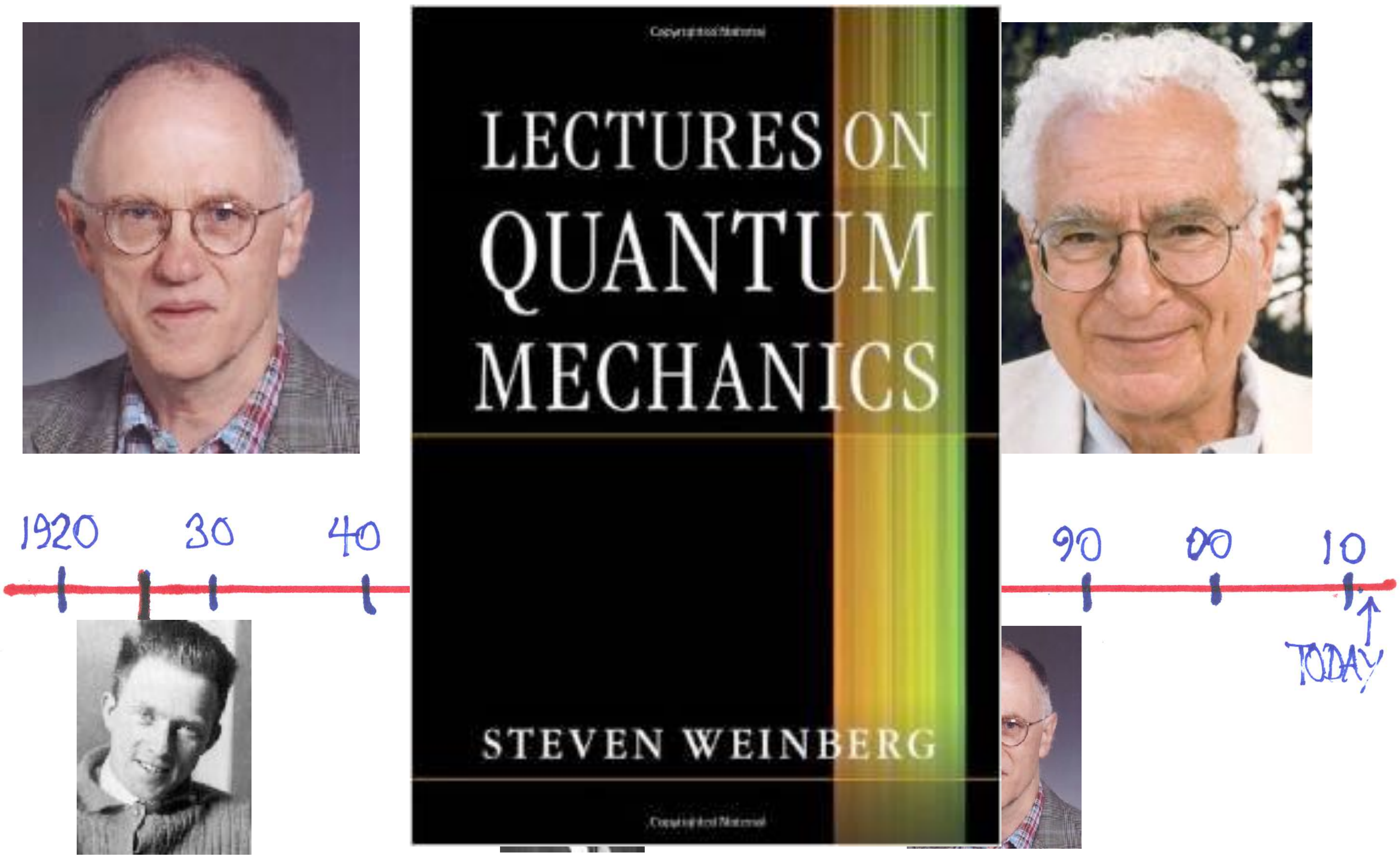
From Copenhagen QM to
Decoherent Histories QM
a Brief History
(endpoints only)

Hugh Everett

Everett's insight was that, as observers, we are physical systems within the universe, not outside it, subject to the laws of quantum mechanics, but playing no special role in its formulation.

Decoherent Histories Quantum Mechanics (DHQM)

Decoherent Histories QM ≈ Consistent Histories QM

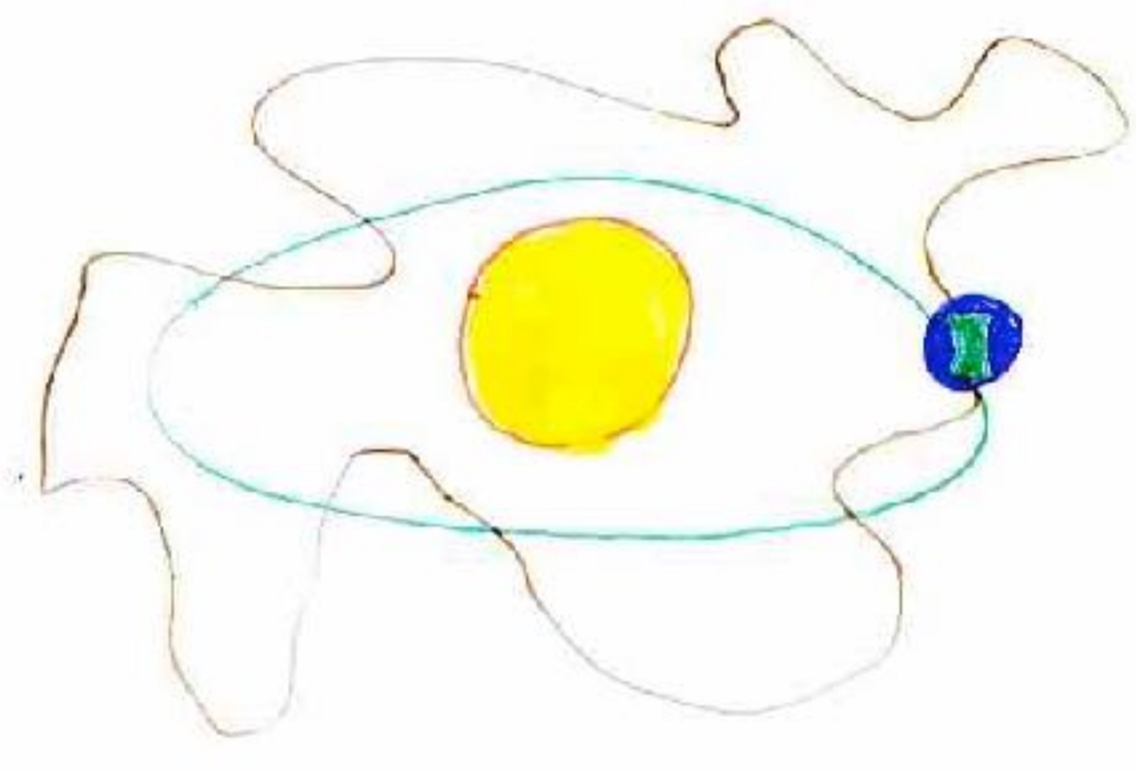


Theoretical Inputs

$$\mathrm{H}$$

$$|\Psi\rangle$$

The most general objective of a quantum theory is the prediction of probabilities for histories.



In cosmology these are the histories of the universe --- cosmological histories of spacetime geometry and fields.

DH Predicts Probabilites for Which of Sets of Alternative Histories Happen.

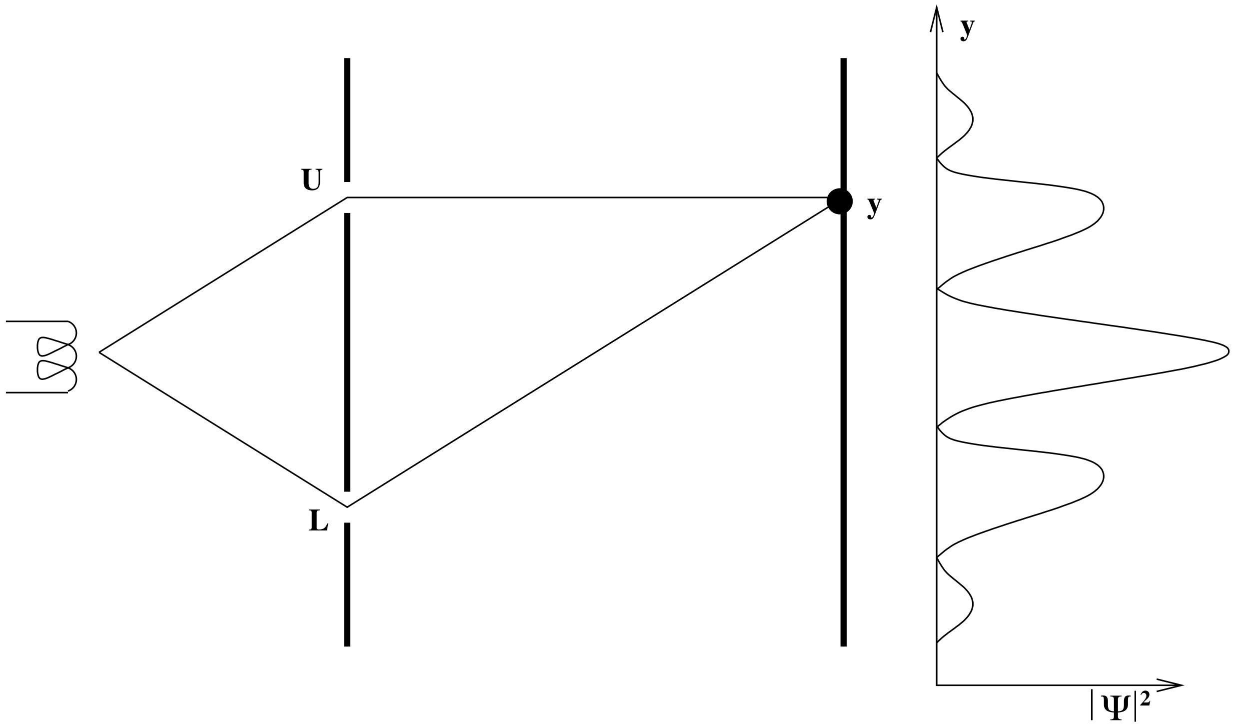
Probabilities for the past given can be calculated using sets of alternative histories extending from the present into the past.

DH Enables Quantum Cosmology

Pasts are Probabilistic

``The principles of quantum mechanics must involve an uncertainty in the description of past events ... analogous to the uncertainty in the prediction of future events.''   Einstein, Tolman, Podolsky 1931

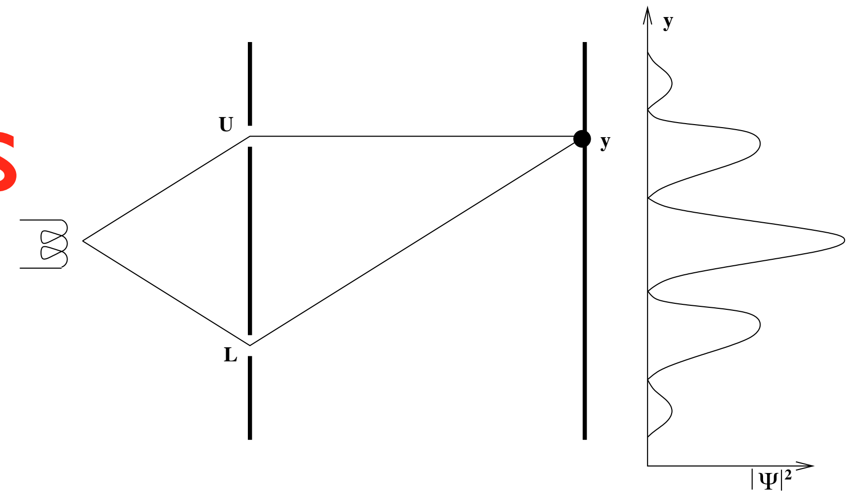
Interference an Obstacle to Assigning Probabilities to Histories



$$|\psi_U(y) + \psi_L(y)|^2 \neq |\psi_U(y)|^2 + |\psi_L(y)|^2$$

It is inconsistent to assign probabilities to this set of histories.

A Rule is Needed to Specify Which Histories Can be Assigned Probabilities



Textbook QM: Assign probabilities only to sets of histories that have been measured.

DH: Assign probabilities to sets of histories that decohere, ie. for which there is negligible interference between members of the set as a consequence of H and Ψ.

Decoherence implies Consistent Probabilities.

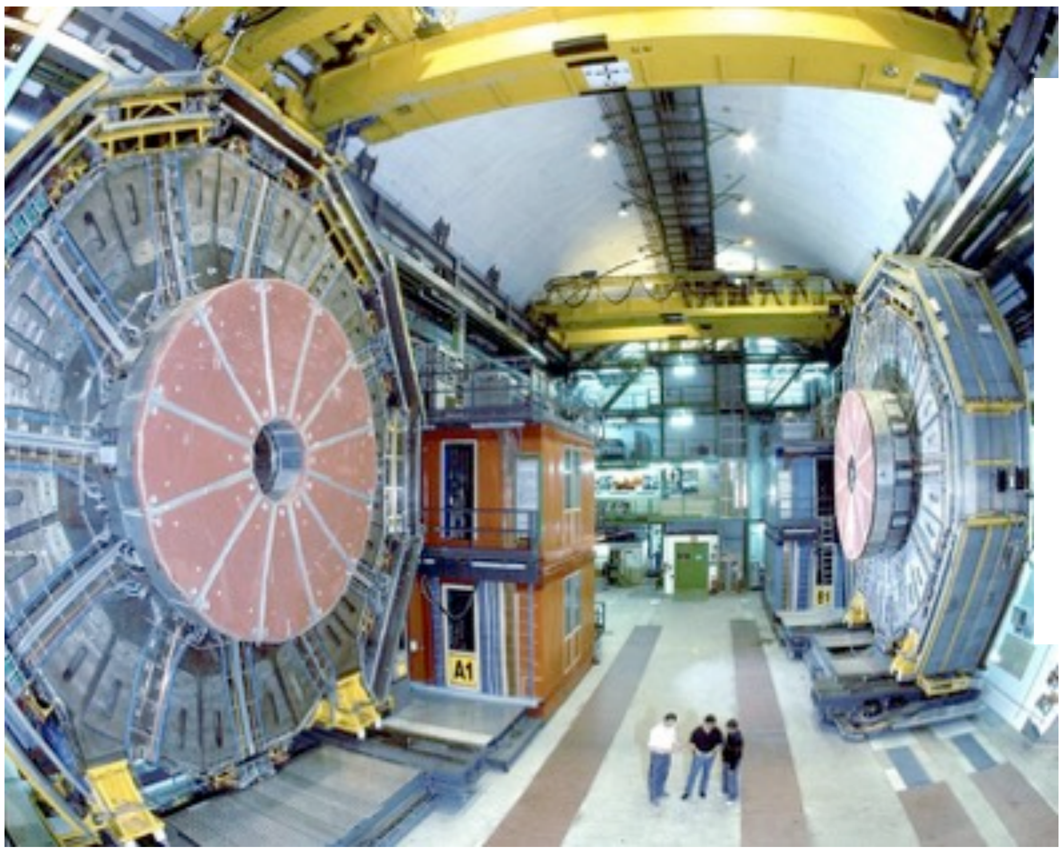
Decoherence is a more general, more observer independent rule for assigning probs. than measurement.

We can assign qm probabilities to:

The position of the moon when no one is looking at it.

Density fluctuations in the early universe when there were no observers around to observe them.

Complex systems like this can be analyzed in DH but play no central role in its formulation.

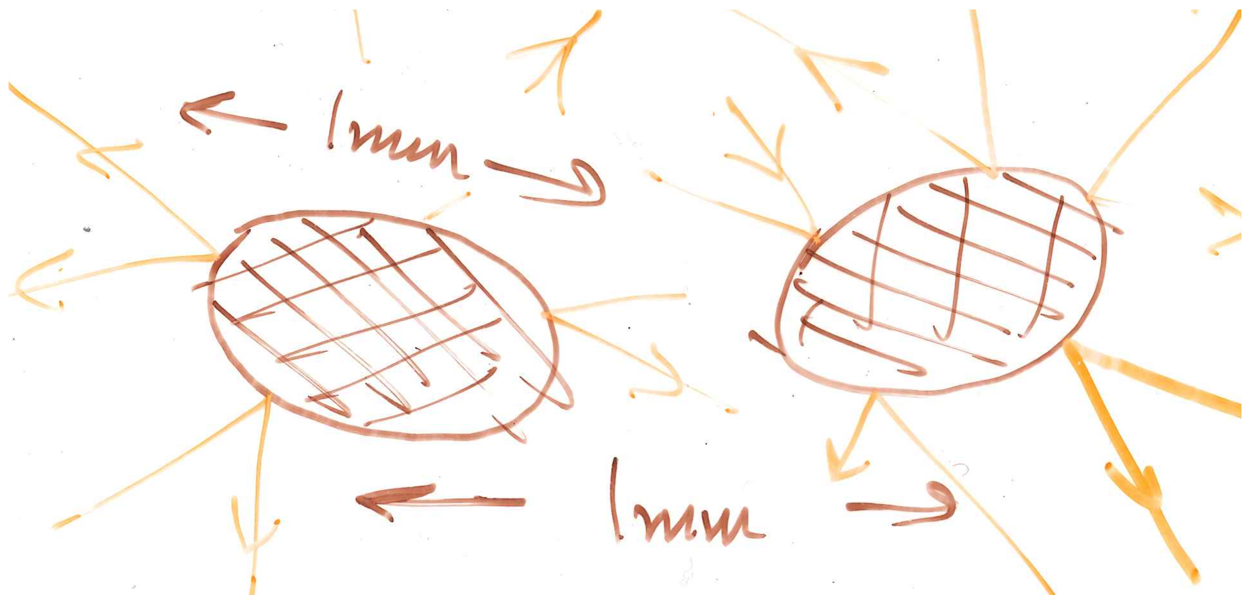


Measurements

consciousness

Decoherence is Widespread in the Universe

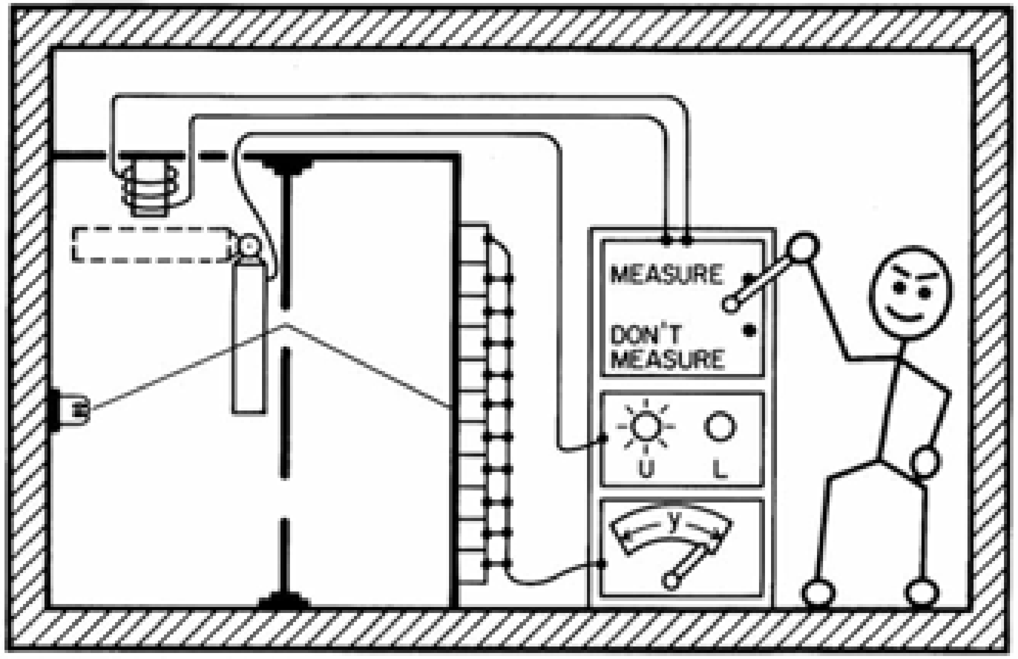
Joos and Zeh '85



- One dust grain in a superposition of two positions, deep in intergalactic space.

- Relative phases dissipate in of order 10^{-9} s from the 10^{11} CMB photons that scatter every second.

Measured Alternatives Decohere



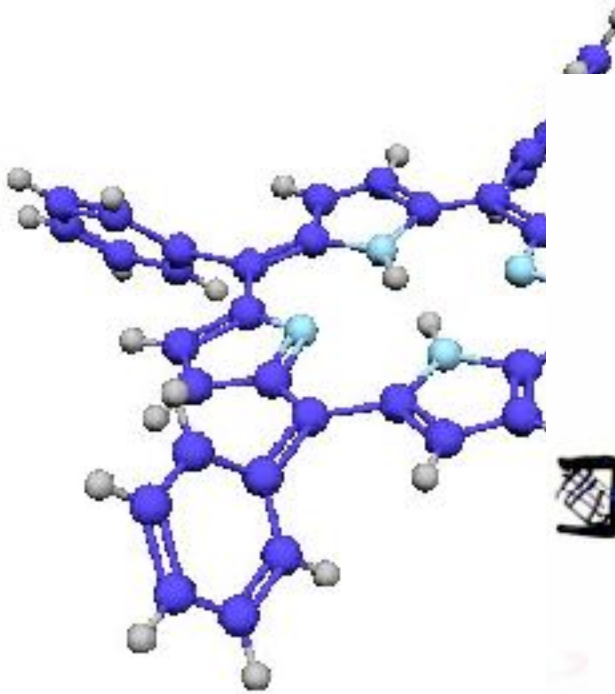
In a measurement situation a variable not normally decohering becomes coupled to a variable of an apparatus that decoheres. The measured variable decoheres and can be assigned probabilities.

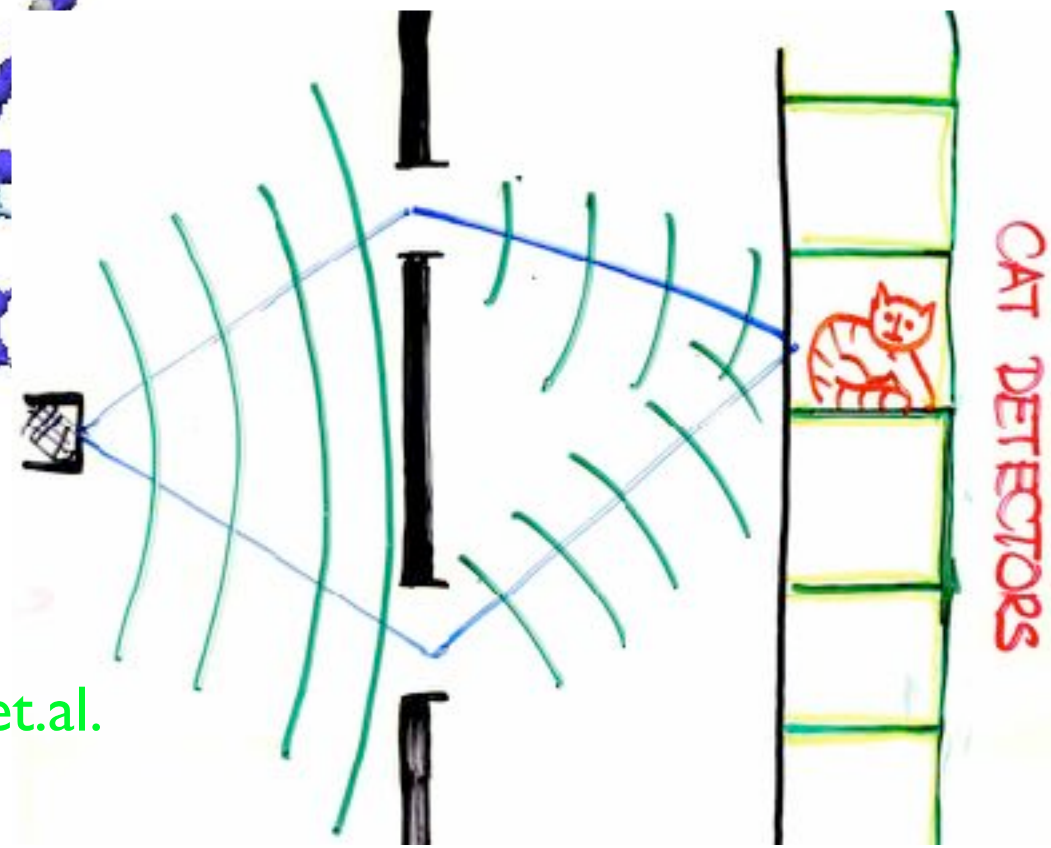
Copenhagen is an approximation to DH
for Measurement Situations

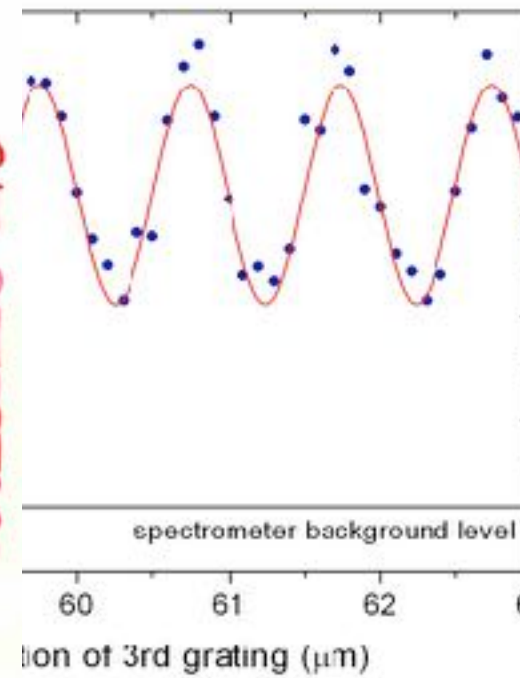
Living in a Superposition

Observers are Part of the System not Outside It.

Experiment has extended the sizes of systems for which the superposition of macroscopically distinct states can be



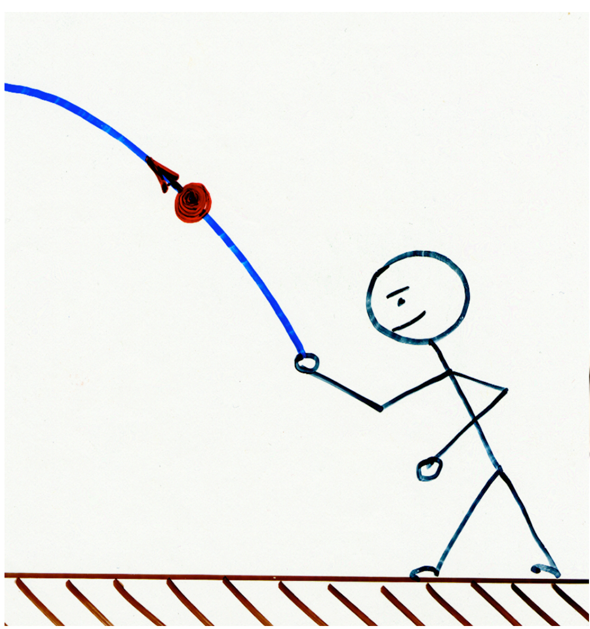
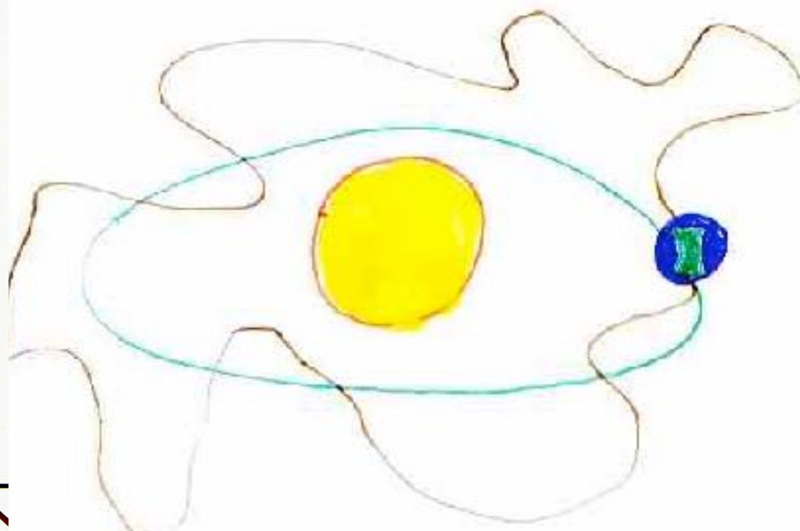
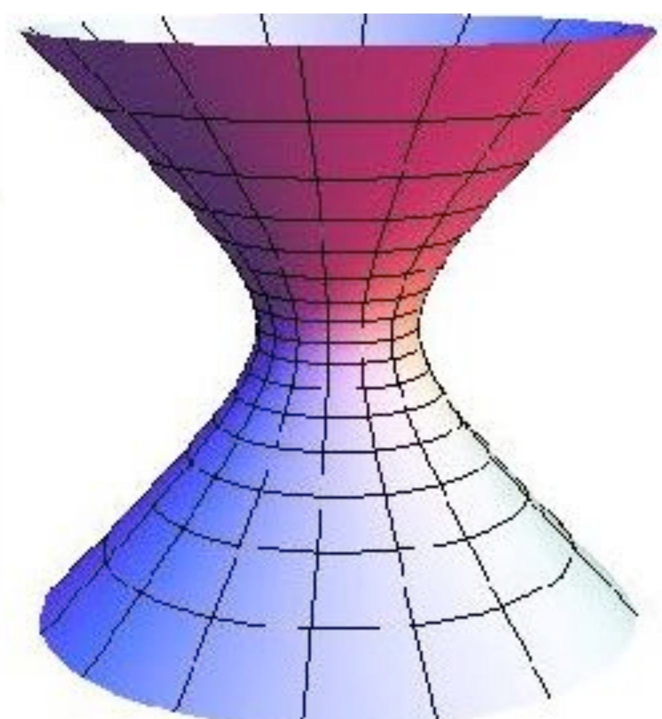




L. Hackenmuller, et.al.

But we won't `see' a superposition that we are a part of.

A quantum system behaves classically when its state and Hamiltonian predict high probabilities for histories with correlations in time governed by deterministic laws.

A formulation of quantum mechanics that does not posit the quasiclassical realm must explain it as a feature of our specific universe, from its particular initial quantum state and dynamics.

Origin of the Quasiclassical Realm

- The state of the universe and quantum gravity imply classical spacetime ie -- histories of geometry correlated by Einstein's eq.
- Local Lorentz symmetries imply conservation laws.
- Sets of histories defined by averages of densities of conserved quantities over suitably small volumes decohere.
- Approximate conservation implies these quasiclassical variables are predictable despite the noise from decoherence.
- Local equilibrium implies closed sets of equations of motion governing classical correlations in time.

A Quantum Universe

If the universe is a quantum mechanical system it has a quantum state.
What is it?

Ψ

A theory of the quantum state is the objective of Quantum Cosmology.

Contemporary Final Theories Have Two Parts

$$H \qquad \Psi$$

Which regularities of the universe come mostly from H and which from ψ ?

An unfinished task of unification?

H

- classical dynamics
- laboratory experiment eg CERN.

Ψ

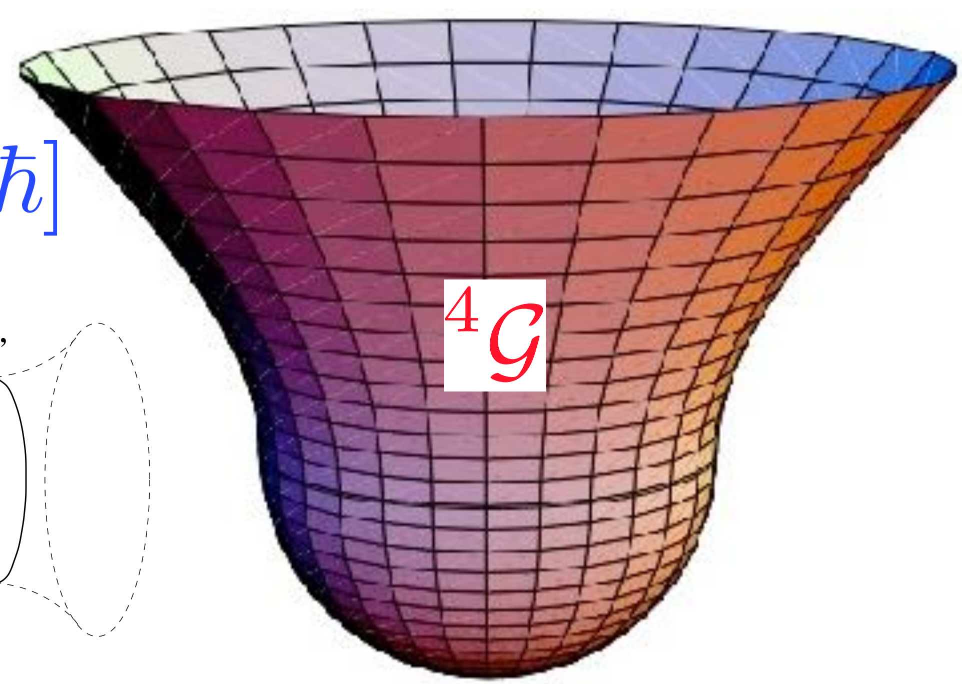
- classical spacetime
- early homo/iso +inflation
- fluctuations in ground state
- arrows of time
- CMB, large scale structure
- isolated systems
- topology of spacetime
- num. of large and small dims.
- num. of time dimensions
- coupling consts. eff. theories

The No-Boundary Quantum State of the Universe

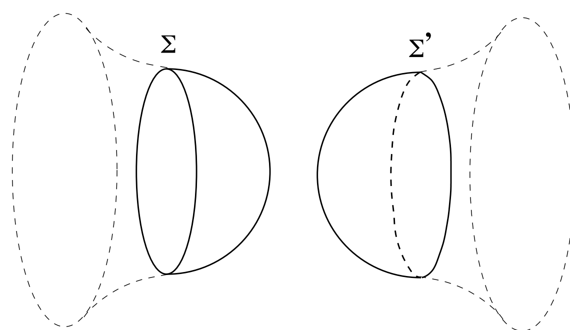
$^3\mathcal{G}$

Hawking and Hartle

$$\Psi(^3\mathcal{G}) = \sum_{^4\mathcal{G}} \exp[-I(^4\mathcal{G})/\hbar]$$



Density Matrix: Barvinsky and Kamenschik



Semiclassical Approx

$$\Psi(^3\mathcal{G}) \approx \exp[-I_{\mathrm{ext}}(^3\mathcal{G})/\hbar]$$

Saddle Point Geometry

Beyond DH

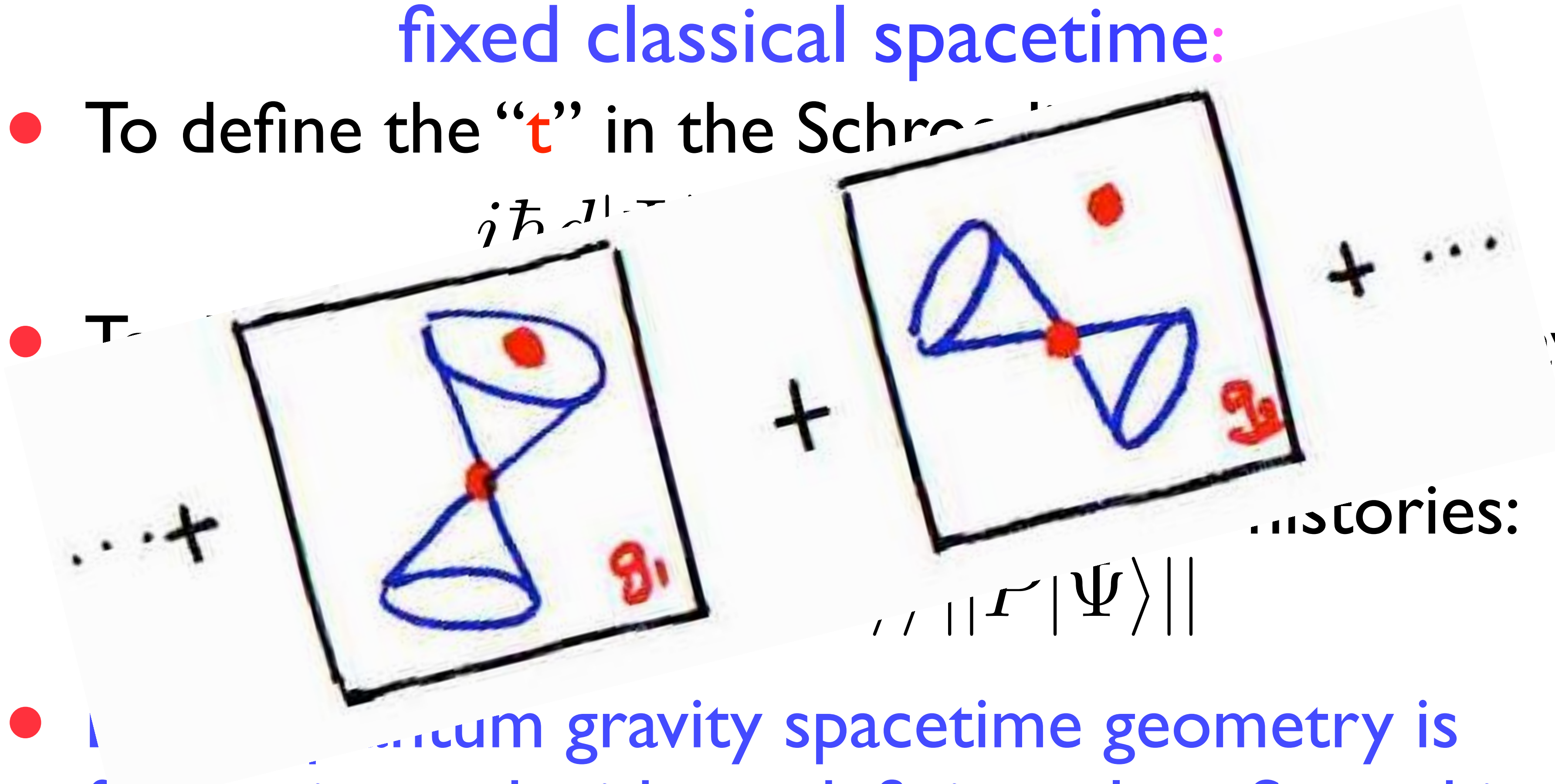
Quantum Spacetime Motivates Going Beyond DH

Familiar quantum theory assumes a fixed classical spacetime:

- To define the "t" in the Schr

- T ... ve ... n ... istories:

- ... ntum gravity spacetime geometry is fluctuating and without definite value. Something beyond DH is needed for quantum gravity.



Key Idea about Histories for Gravity:

Histories need not describe evolution in spacetime but can describe evolution of spacetime.

A Four-Dimensional Generalized QM of Spacetime Geometry

- Fine grained histories: 4d histories of spacetime geometry and matter fields.
- Coarse grainings: partitions of the fine grained histories into 4d diffeomorphism invariant classes.
- Measure of Interference: decoherence functional defined by 4d sums over histories.
- No equivalent 3+1 formulation in terms of states on spacelike surfaces.

Emergent Quantum Mechanics

- The usual quantum mechanics of a Hilbert space of states evolving unitarily through a family of spacelike surfaces requires a classical spacetime to define those surfaces.
- But classical spacetime is not available all over the universe. Not near the big bang (cosmology again) and maybe not in evaporating black holes.
- Rather classical spacetime and usual quantum mechanics emerge together from something deeper.

What is the something deeper ?

Much to Do

In the next 90 years
to work out
the consequences
of cosmology for
quantum mechanics