The Impact of Cosmology on Quantum Mechanics

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Gravity: Past, Present, Future
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The textbook (Copenhagen) quantum mechanics of measurements is the most successful theoretical framework for prediction in the history of physics.

`Problems', Ambiguities, etc of Copenhagen QM

Non-contextuality
Collapse
Two laws of evolution
Consciousness
What's an observer
Records
State vector reduction
Heisenberg cut
Irreducible amplification
Bell's Theorem
Kochen-Sprecher
Born's rule
Macroscopic
Wigner's friend
EPR
Non-locality
Contextuality
Measurement problem
What's a measurement
Bayesian probabilities

Despite these no mistakes seem to have been made over the 90 year history.

1929-1936
The expansion of the universe.

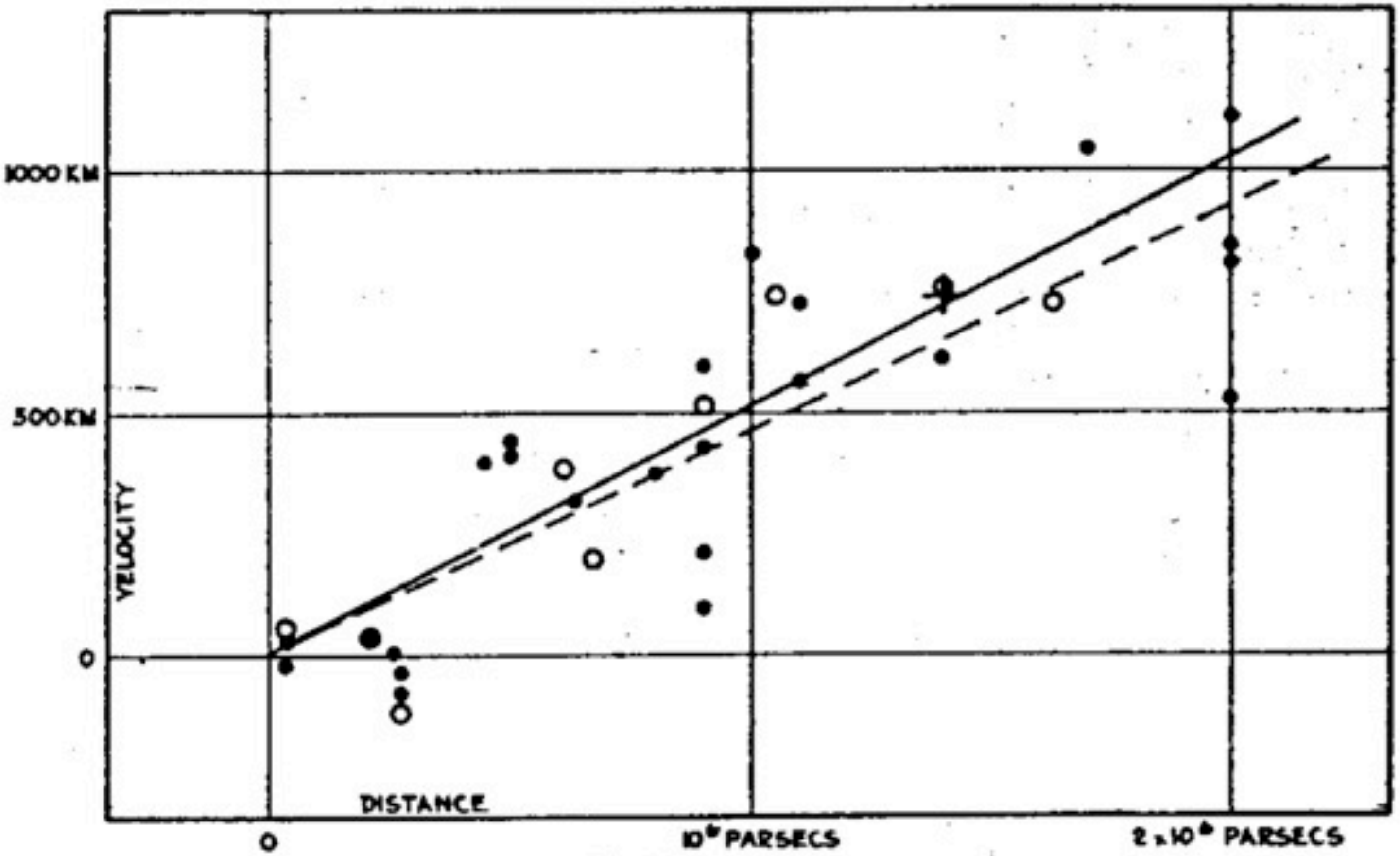


FIGURE 1

Copenhagen QM 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 reduction) when the system is measured. Cannot be time reversed.

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

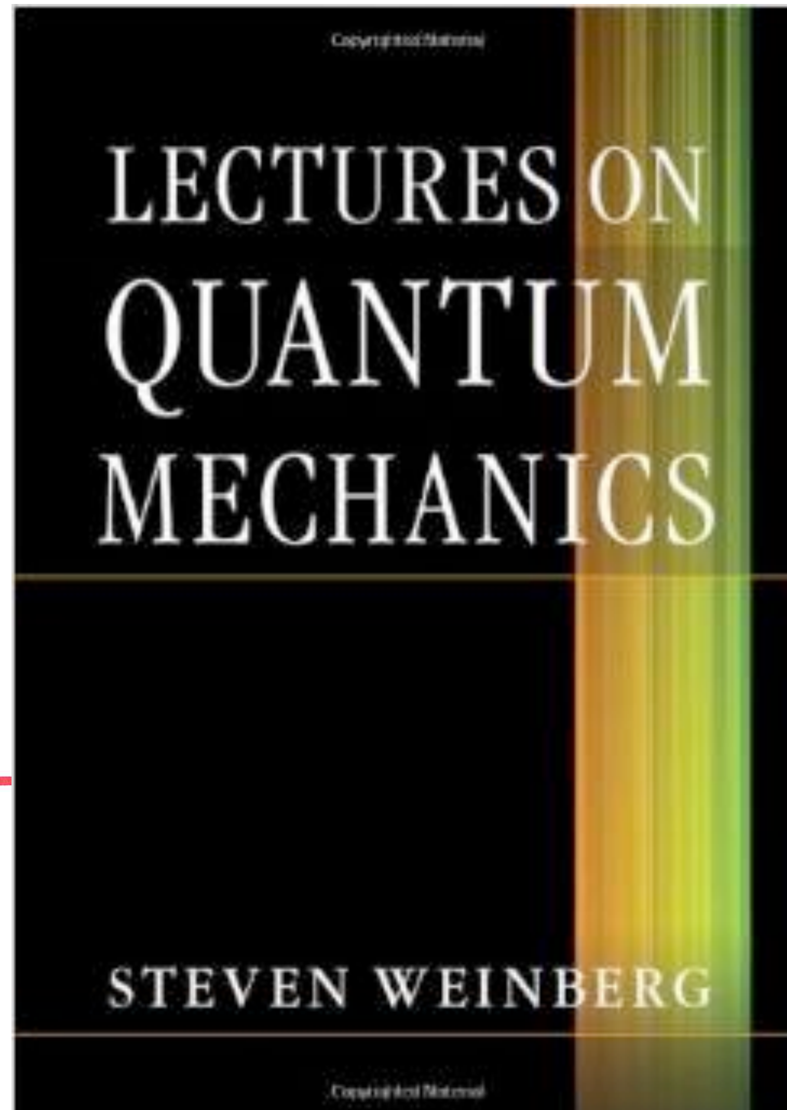
But cosmology is all about the past. We reconstruct the past history of the universe to simplify our predictions of its future.

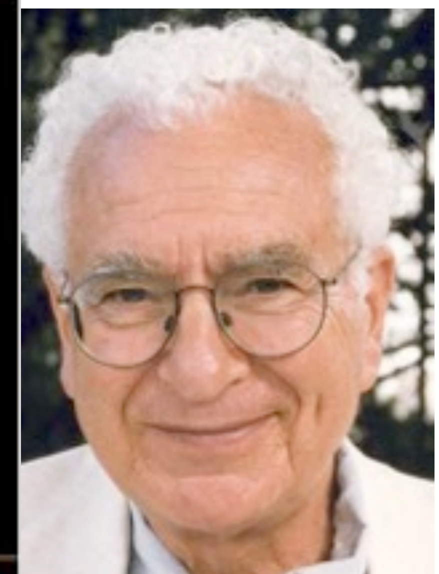
From Copenhagen QM to Decoherent Histories QM a Brief History (endpoints only)

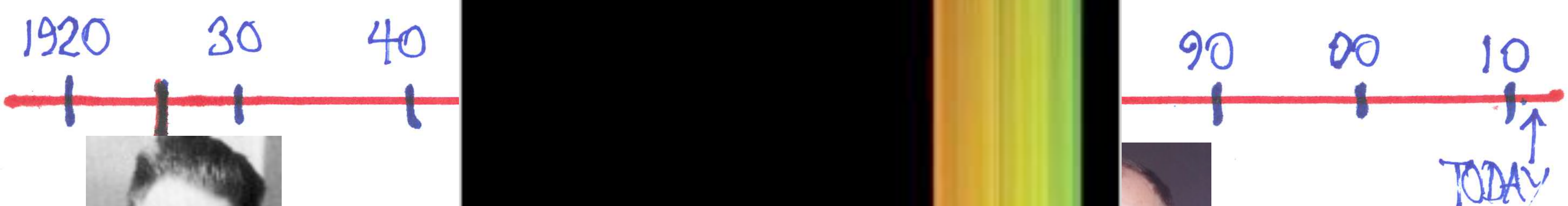
Everett's insight was that, as observers, we are physical systems within the universe, not outside it, subject to the laws of quantum mechanics, but playing no special role in its formulation.

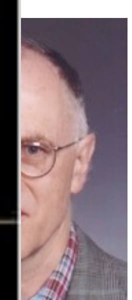
Decoherent Histories Quantum Mechanics (DHQM)

Decoherent Histories QM ≈ Consistent Histories QM

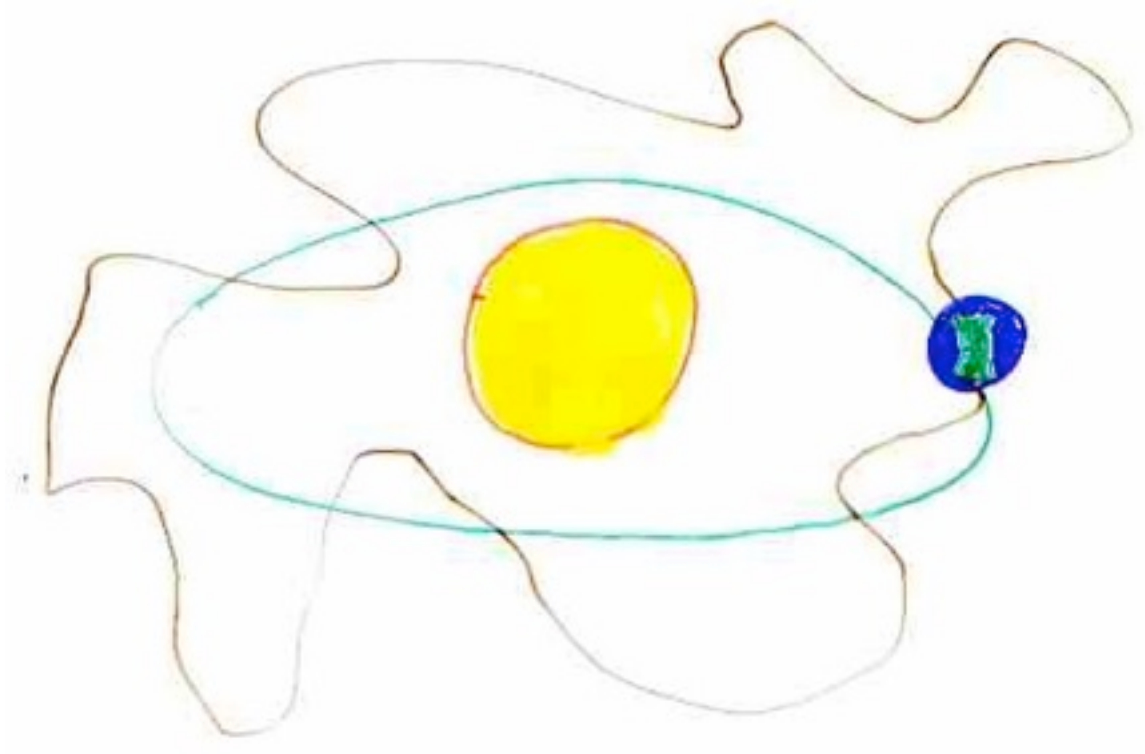






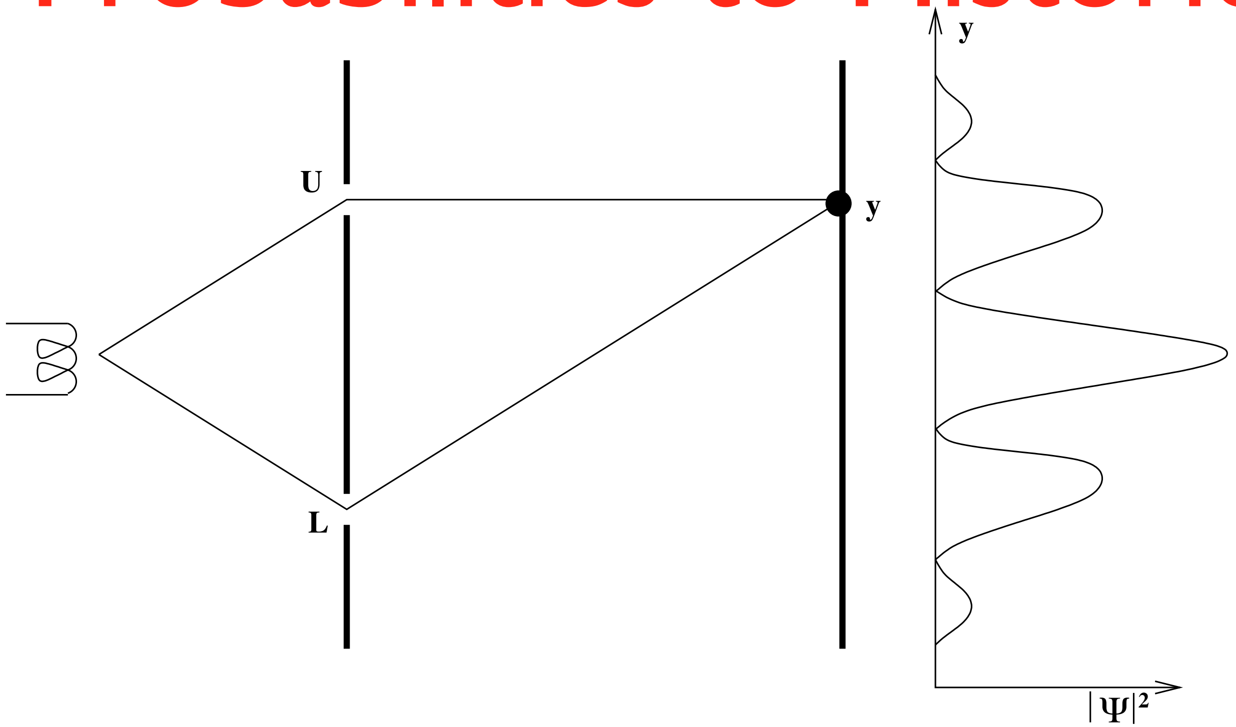


The most general objective of a quantum theory is the prediction of probabilities for histories.



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

Interference an Obstacle to Assigning Probabilities to Histories

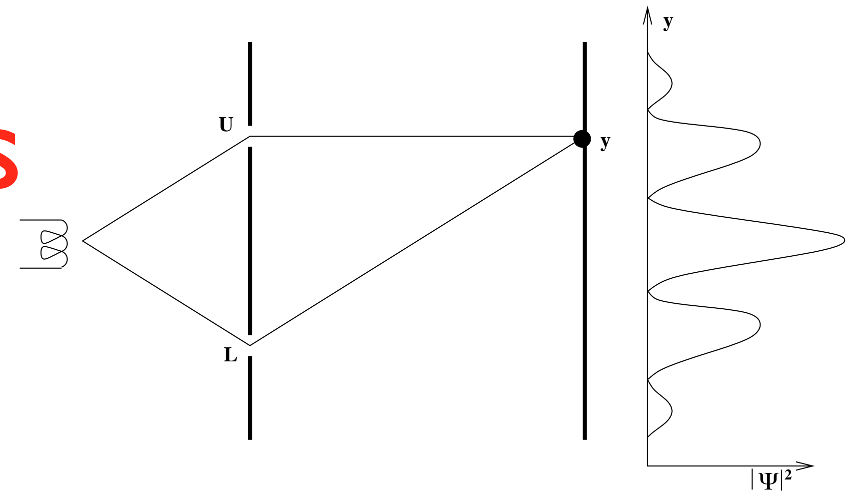


$$p(y) = p(y,U) + p(y,L)$$

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

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

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



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

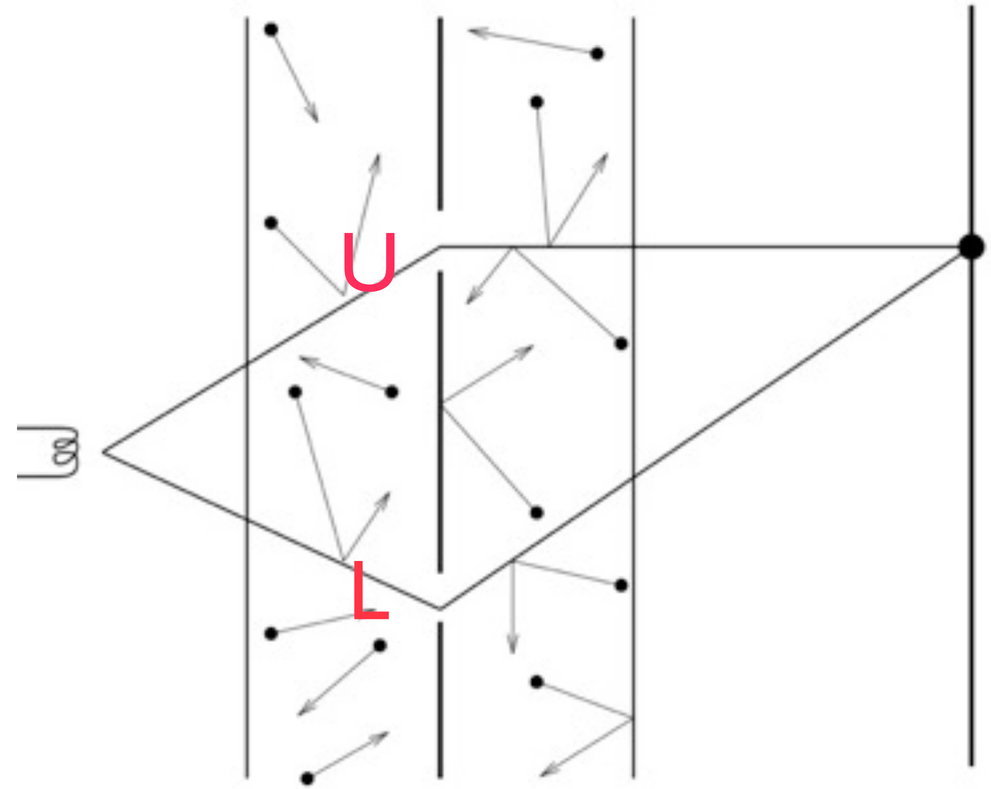
DH: Assign probabilities to sets of histories that decohere, ie. for which there is negligible interference between members of the set as a consequence of H and Ψ.

Decoherence implies Consistent Probabilities.

Toy Model of Decoherence

For given y, two histories with corresponding branch state vectors:

$$\psi(y, U) \qquad \psi(y, L)$$



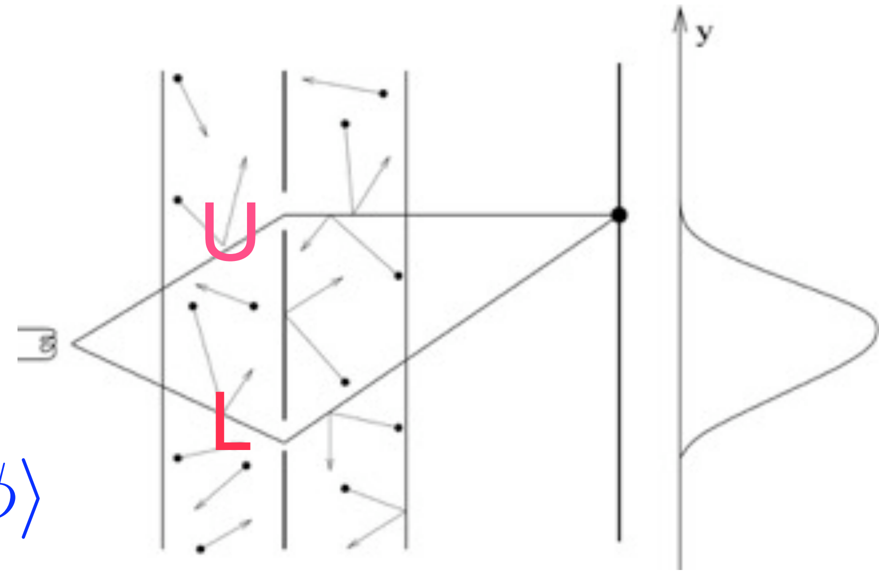
Measure of interference between histories:

$$D(y, S|y', S') \equiv \langle y, S|y', S'\rangle \qquad S = L \text{ or } U$$

Condition for decoherence and probabilities:

$$D(y, S|y', S') \approx \delta_{y,y'}\delta_{S,S'}p(y, S)$$

Toy Model of Decoherence



Initial State:

$$|\Psi(y)\rangle = \frac{1}{\sqrt{2}}(|U\rangle + |L\rangle)\,|\phi\rangle \cdots |\phi\rangle$$

Evolves into a sum of two branch state vectors corresponding to going through U or L:

$$|\Psi(y,U)\rangle = \frac{1}{\sqrt{2}}|U\rangle\; S_U|\phi\rangle \cdots S_U|\phi\rangle$$

$$|\Psi(y,L)\rangle = \frac{1}{\sqrt{2}}|L\rangle\; S_L|\phi\rangle \cdots S_L|\phi\rangle$$

Interference vanishes with a large enough N:

$$D(U,L) \equiv \langle \Psi_U | \Psi_L \rangle \propto [\langle \phi | S_U^\dagger S_L | \phi \rangle]^N = (< 1)^N \to 0$$

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.

DH Predicts Probabilities for Histories that Extend to the past as well as the future.

DH Enables Quantum Cosmology

Pasts are Probabilistic

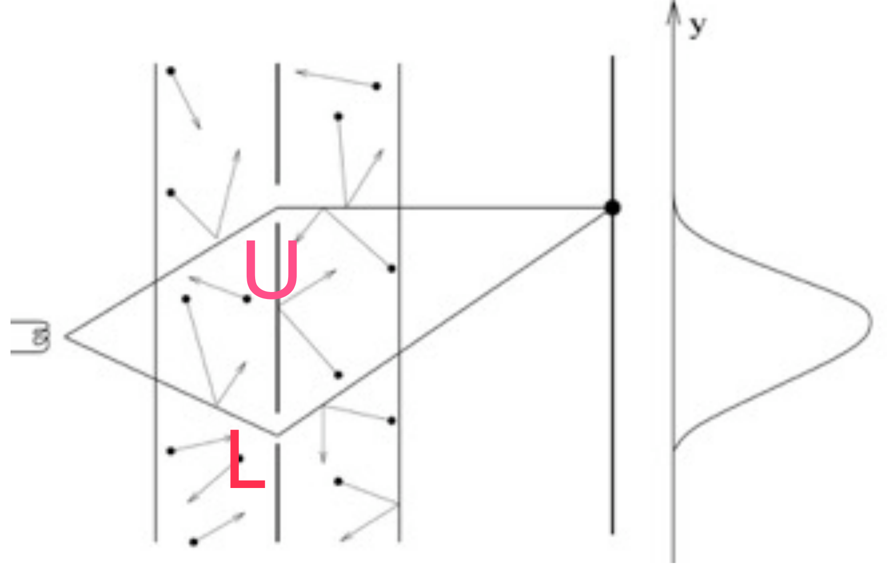
``The principles of quantum mechanics must involve an uncertainty in the description of past events ... analogous to the uncertainty in the prediction of future events.'' Einstein, Tolman, Podolsky 1931

Quantum Pasts

- We reconstruct past history from present records to simplify the prediction of the future (especially in cosmology).
- A quantum past is a set of alternative past histories consistent with present records with probabilities for whether they occurred.
- There is generally more than one set of past histories consistent with present records. The past is not unique.

The past is neither unique,
nor certain,
nor permanent.

Decoherence Enables Retrodicting the Past



State is a sum of two branch state vectors corresponding to histories arriving at Y of going through U or L.

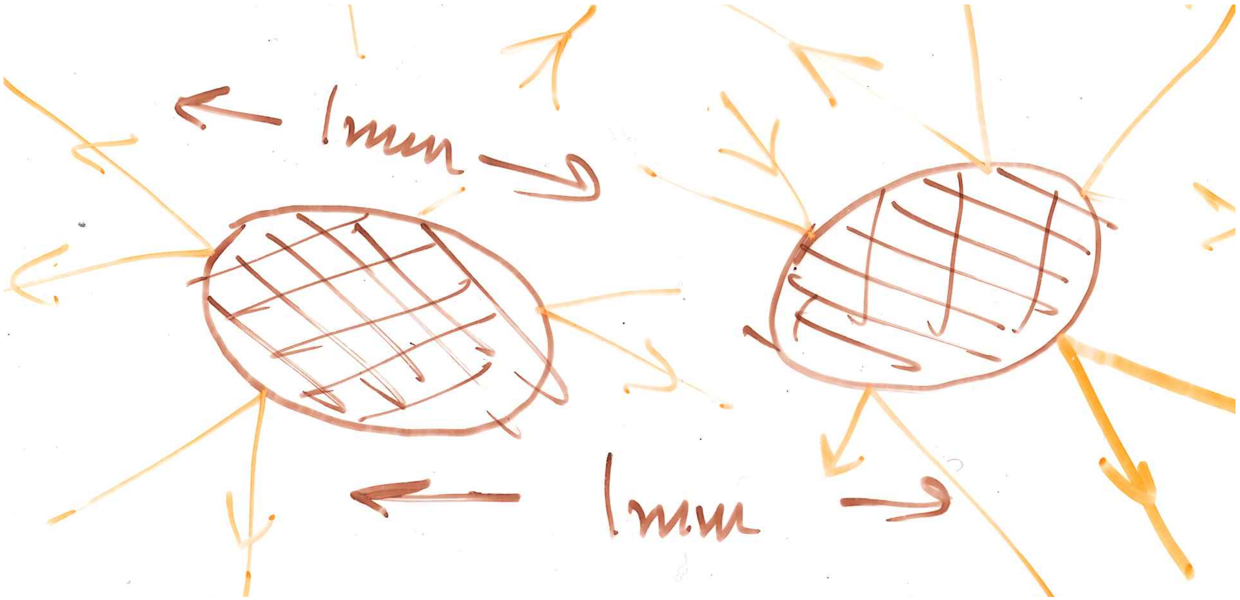
$$p(Y,U) = |\Psi(Y,U)\rangle|^2 \qquad p(Y,L) = |\Psi(Y,L)\rangle|^2$$

Given that the particle has arrived at Y now, we can calculate the probability that it went through U in the past.

$$p(U|Y) = \frac{p(Y,U)}{p(Y,U) + p(Y,L)}$$

Decoherence is Widespread in the Universe

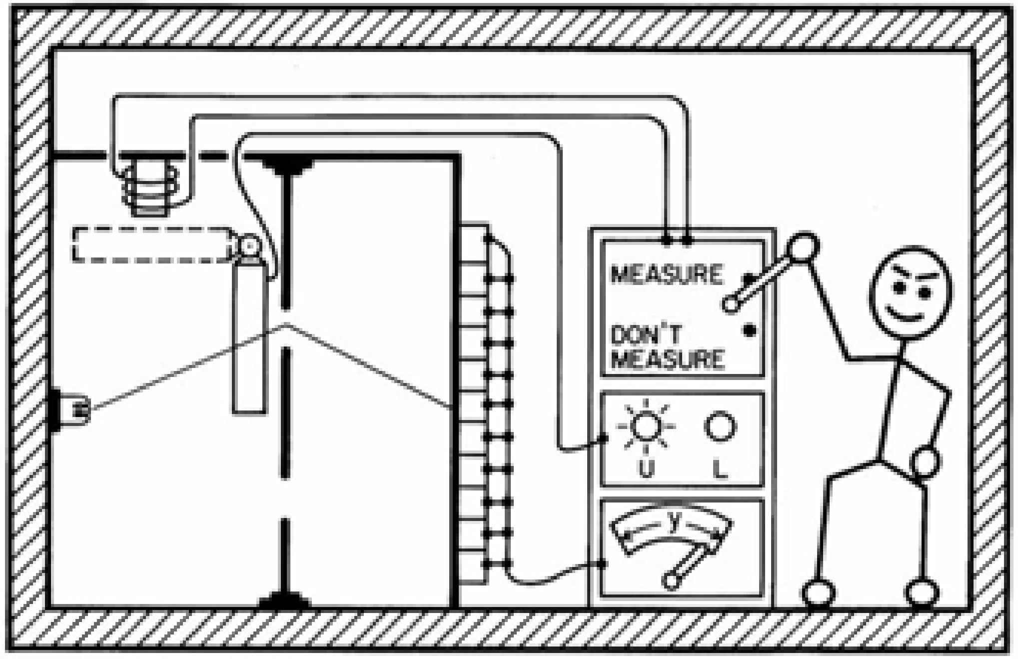
Joos and Zeh '85



- 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

`Problems', Ambiguities, etc of Copenhagen QM>

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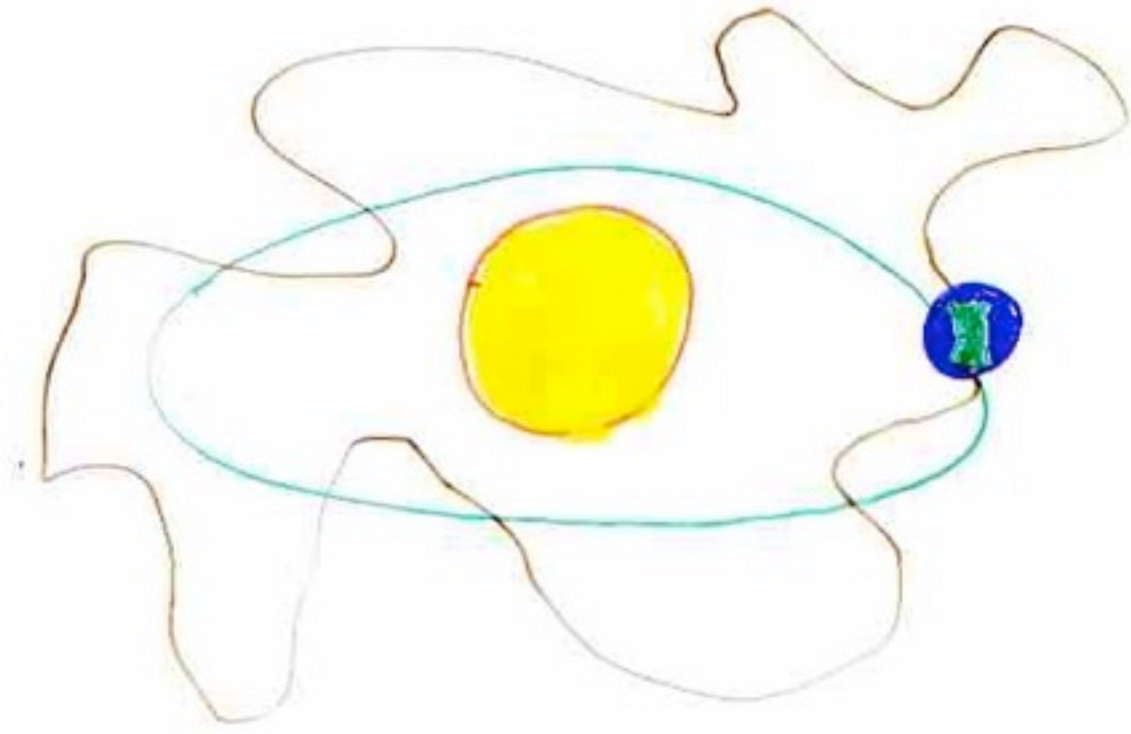
The problems and ambiguities of Copenhagen Quantum theory seem much less serious when it is viewed as an approximation to DH.

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.

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



A subsystem behaves classically when the probability is high for histories exhibiting correlations in time governed by deteministic laws.

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.

No State --- No Predictions

- The probability p at time t of an alternative represented by a projection P(t) (e.g a range of position) on a state $|\Psi\rangle$ is:

$$p = ||P(t)|\Psi\rangle||^2$$

$$P(t) = e^{iHt/\hbar}P(0)e^{-iHt/\hbar}$$

- If we don't have the operator P and H and the state $|\Psi\rangle$ there are no probabilities and no predictions.

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

Quantum Retrodictions from the NBWF

classical lorentzian spacetime	yes
early homo/iso + inflation	yes
fluctuations start in ground state	yes
arrows of time	yes
CMB, large scale structure	yes
isolated systems	yes
topology of spacetime	hints
num. of large & small dimensions	hints
number of time dimensions	hints
cosmological constant	bounds
complexity from simplicity	yes

Decoherent histories quantum mechanics is logically, consistent, consistent with experiment as far as is known, applicable to cosmology, and allows quantum retrodition. It is consistent with the rest of modern physics including special relativity and quantum field theory, and generalizable to include quantum gravity. It may not be the only formulation of quantum mechanics with these properties but its the only one we have at present.

Beyond DH

Why Beyond DH?

- One experiment we can never do is to superpose the state of the universe with some other state.
- If there is only one state why do we need the linear principle of superposition?

Deep Thinkers:

Schroedinger
Einstein
Penrose
Leggett
't Hooft
Weinberg

Is there something deeper than quantum mechanics for the universe as a whole?

Quantum Spacetime Motivates Going Beyond DH

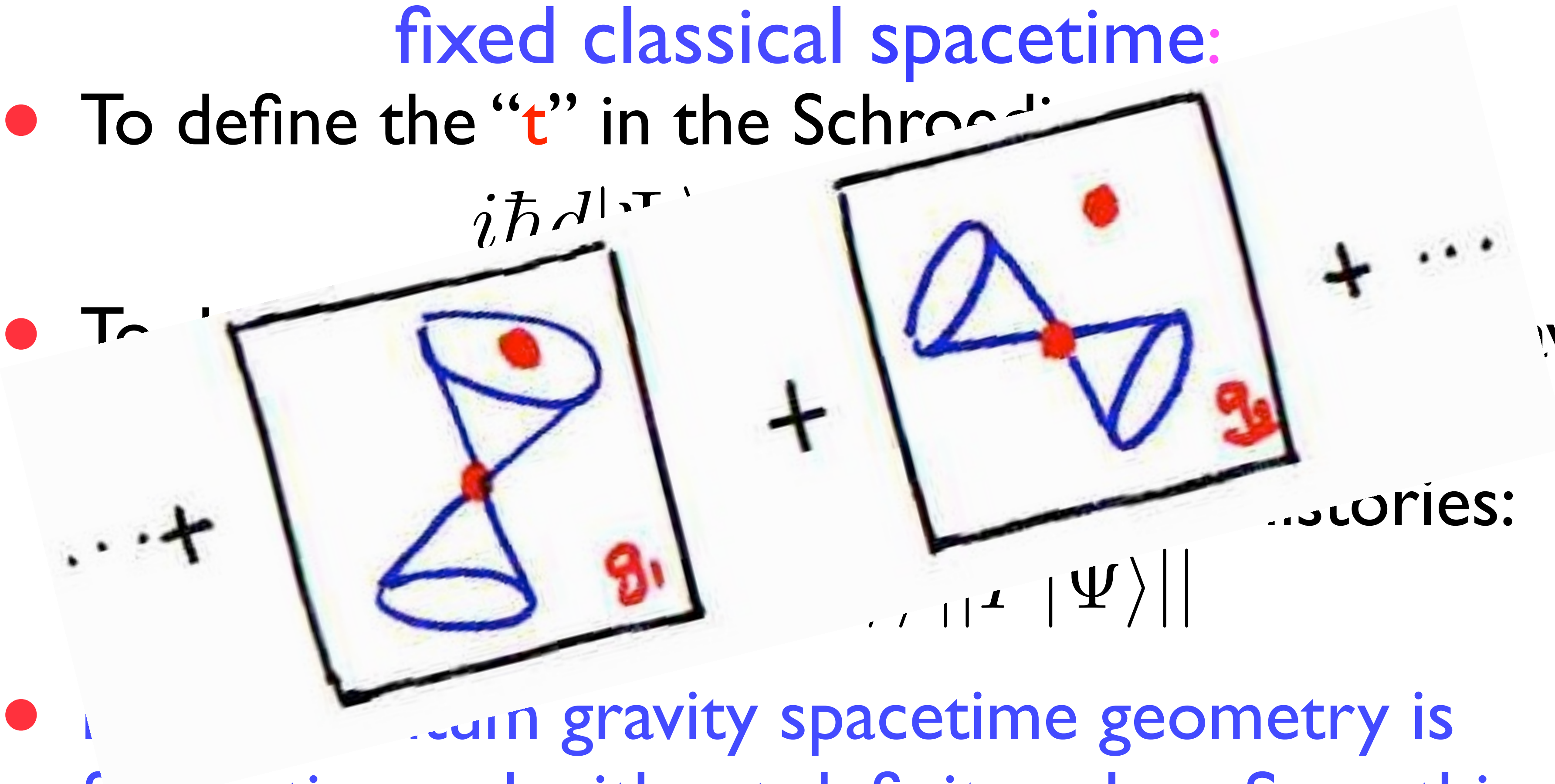
Familiar quantum theory assumes a fixed classical spacetime:

- To define the "t" in the Schro...

  $i\hbar \, d|\Psi\rangle$ ...

- To ... ...ve ... ...istories:

  ... $|\Psi\rangle||$



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

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 ?

The Modern Formulation of Quantum Mechanics (DH)

Helps us understand:

- The Copenhagen quantum mechanics of measurement situations.
- Our universe both now, and at the beginning when there were no observers.
- The nature of `final theories'.
- Our place in the universe as observers.
- Multiverses and anthropic selection.
- Alternatives to modern quantum mechanics.

Ψ

web.physics.ucsb.edu/~quniverse

(under construction)