The Impact of Cosmology on Quantum Mechanics

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Collaborators:
Murray Gell-Mann
Thomas Hertog

1929-1936
The expansion of the universe.

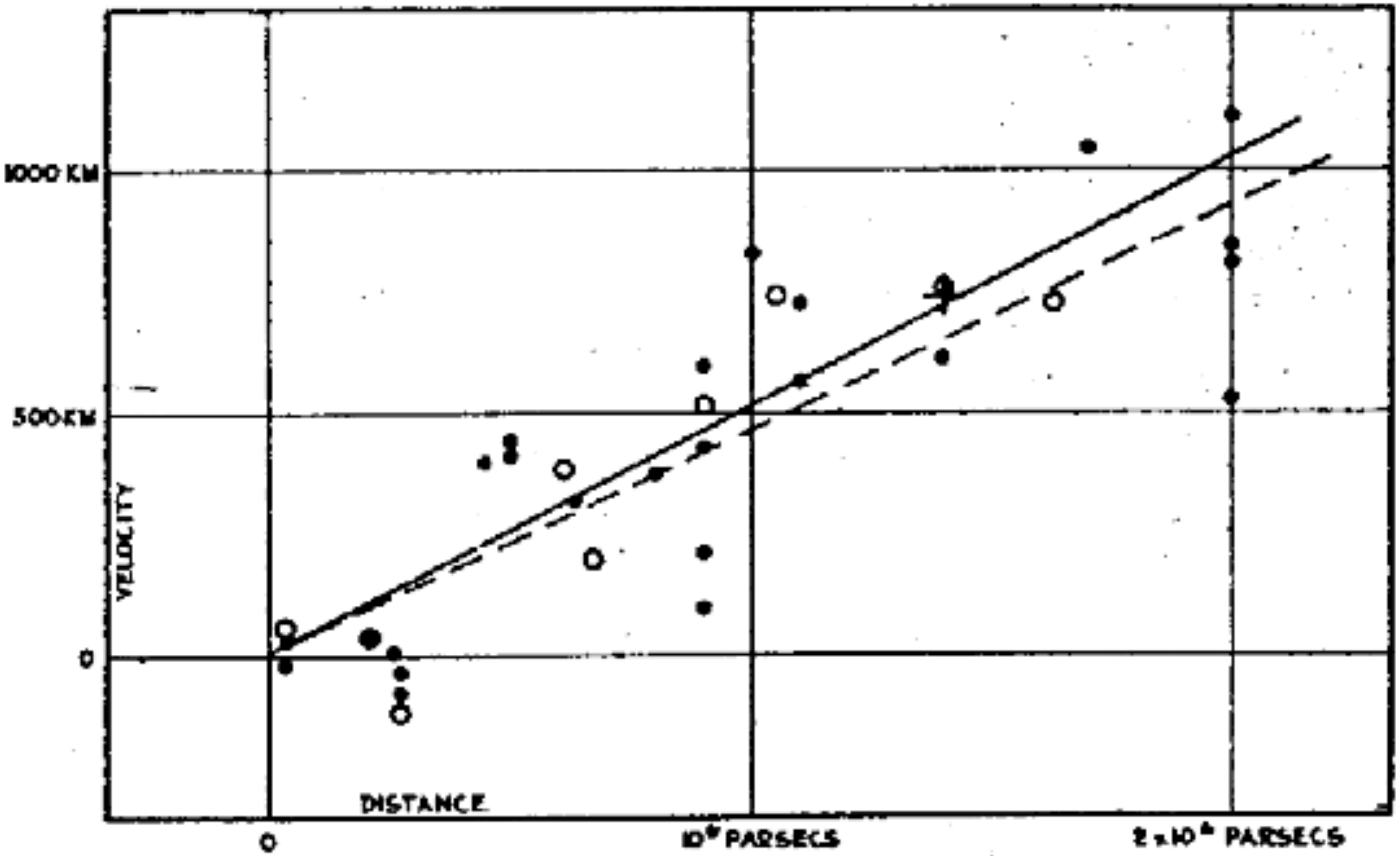


FIGURE 1

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?

Ignorance is not Bliss

Ignorance of the state means: $\rho = I/Tr(I)$

- No evolution $[H, \rho] = 0$
- Infinite temperature equilibrium
- No second law of thermodynamics
- No classical behavior. $< \phi^2(R) >= \infty$

All inconsistent with observation.

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.

H	Ψ
• classical dynamics • laboratory experiment eg CERN.	• 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 Gravity: Back to Basics

It seems unlikely that we will have laboratory experiments that test quantum gravity in the immediate future.

$$E_{\rm pl} \equiv \sqrt{\hbar c^5/G} \sim 10^{19}\text{Gev}$$

But in the beginning and expansion of the universe we have and experiment already done where Planck energies are reached, and there is 14 Gyr of data scattered over 42 Glyr of space.

Quantum Cosmology

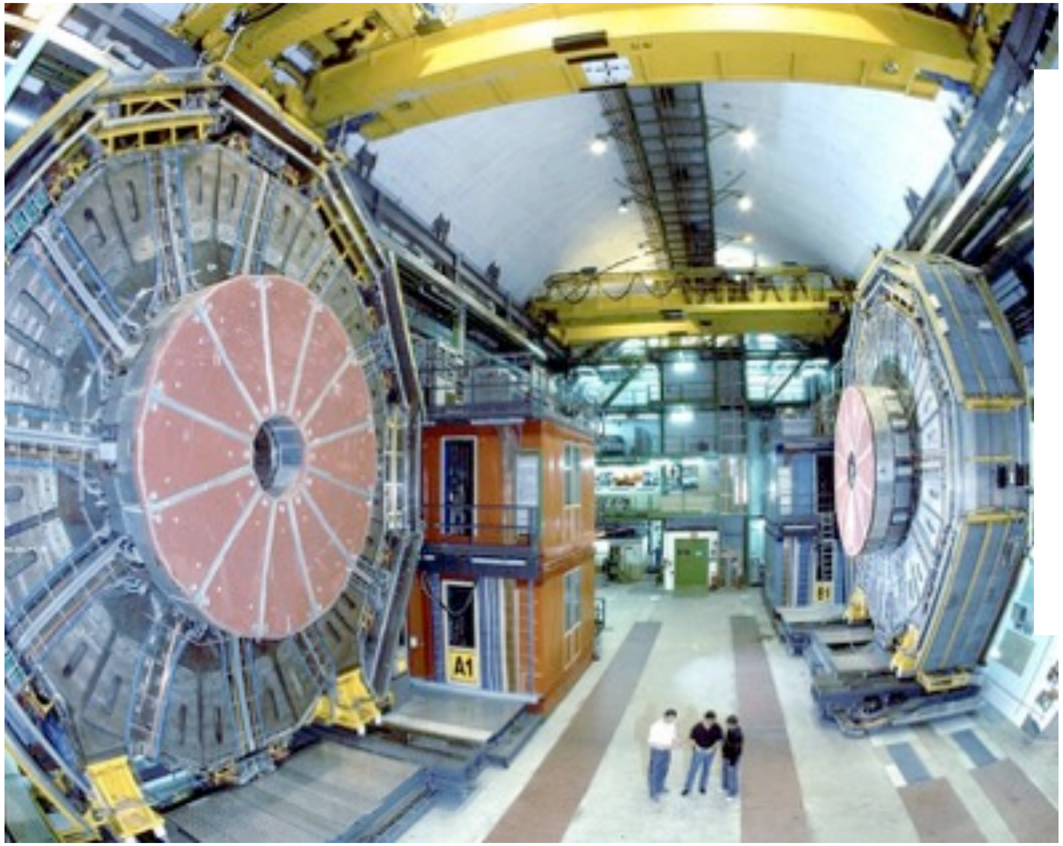
The textbook (Copenhagen) quantum mechanics of measurements is the most successful theoretical framework for prediction in the history of physics!

`Problems', Ambiguities, etc of Copenhagen QM

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

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

The Formulation of Copenhagen QM Involved Complex Systems



Measurements

consciousness

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.

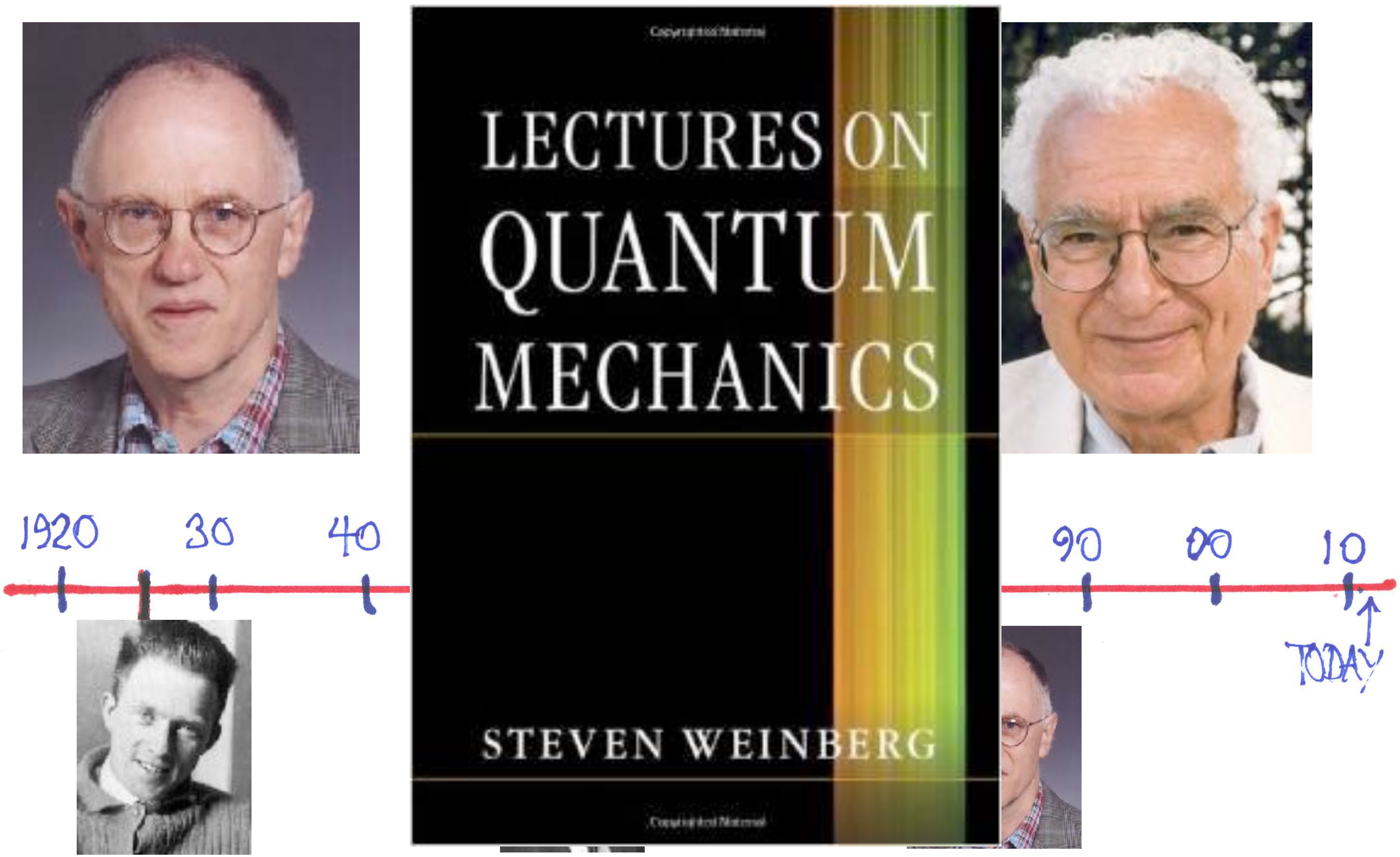
Textbook Quantum Mechanics Has to Be Generalized for Cosmology

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

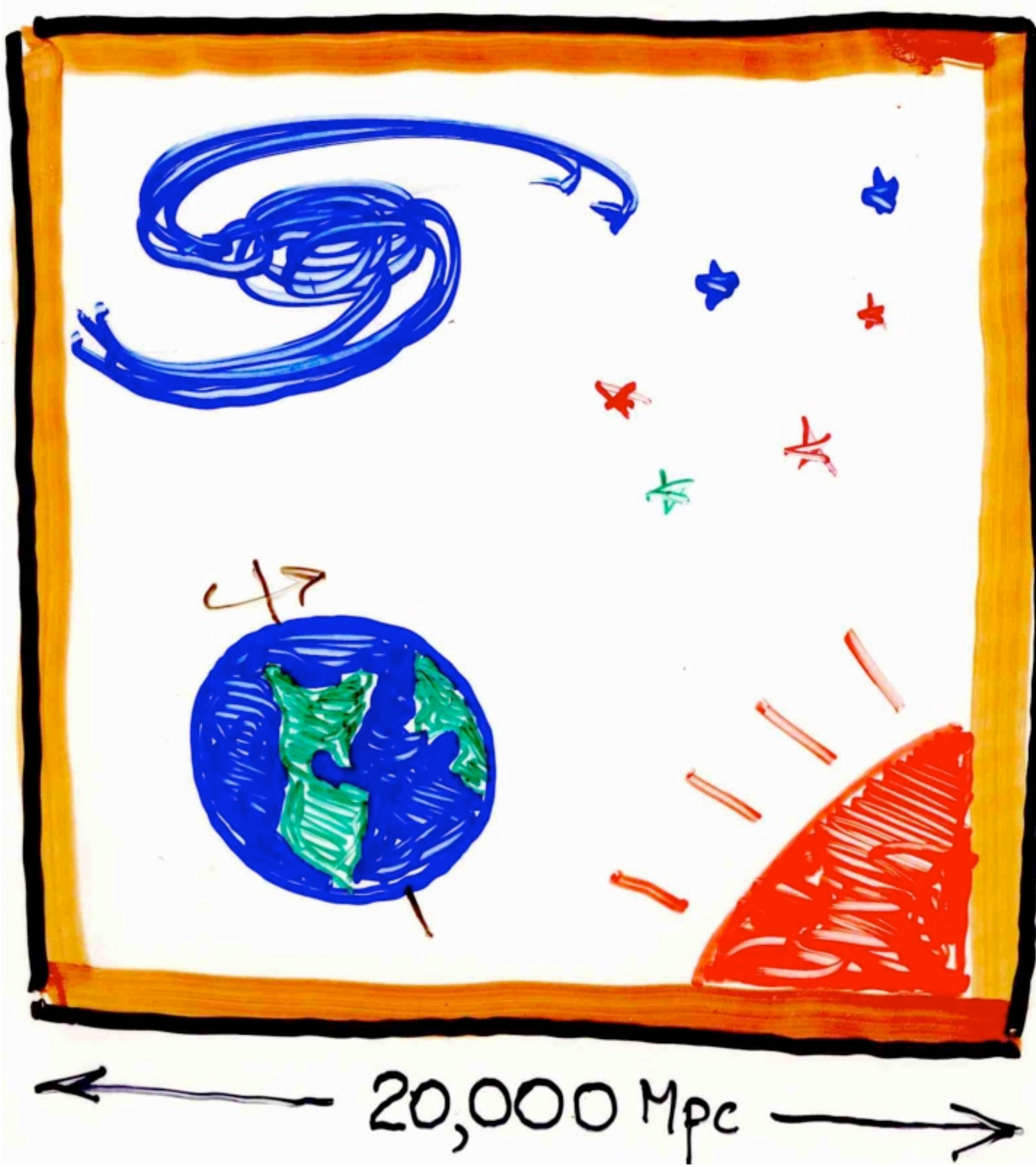


A Model Universe in a Box

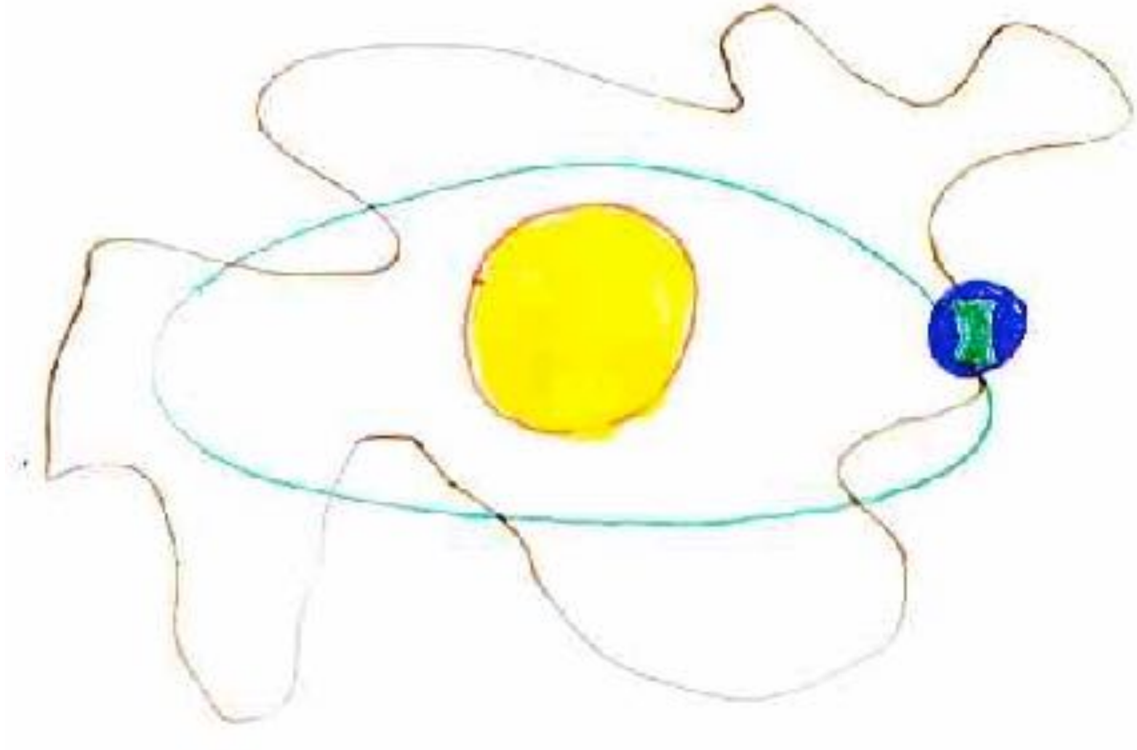
Theoretical Inputs

$$H$$

$$|\Psi\rangle$$



Output of the theory (H, ψ): Probabilities for Coarse-Grained Alternative Histories of the Universe



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

Classical Histories

Classical behavior is not a given in quantum mechanics. It is a matter of quantum probabilities.

A history behaves classically
when in a suitably coarse grained set of histories
the probability is high for that history to have
correlations in time
summarized by deterministic (classical) laws.

DH Predicts Probabilites for Which of a Set of Alternative Histories Happens.

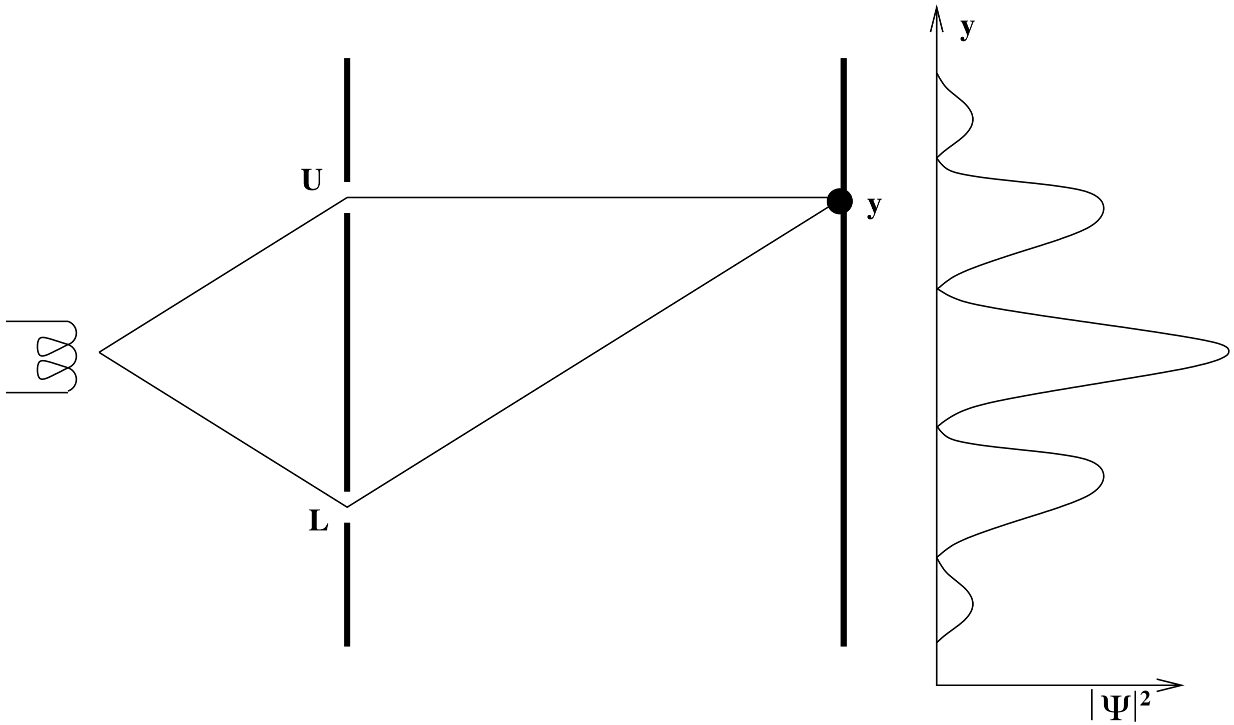
Probabilities for the past given can be calculated using sets of alternative histories extending from the present into the past.

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

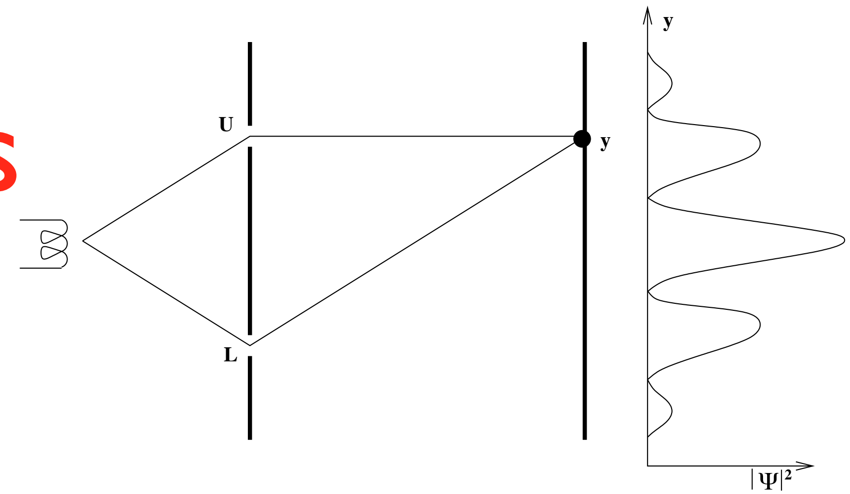
Interference an Obstacle to Assigning Probabilities to Histories



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

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.

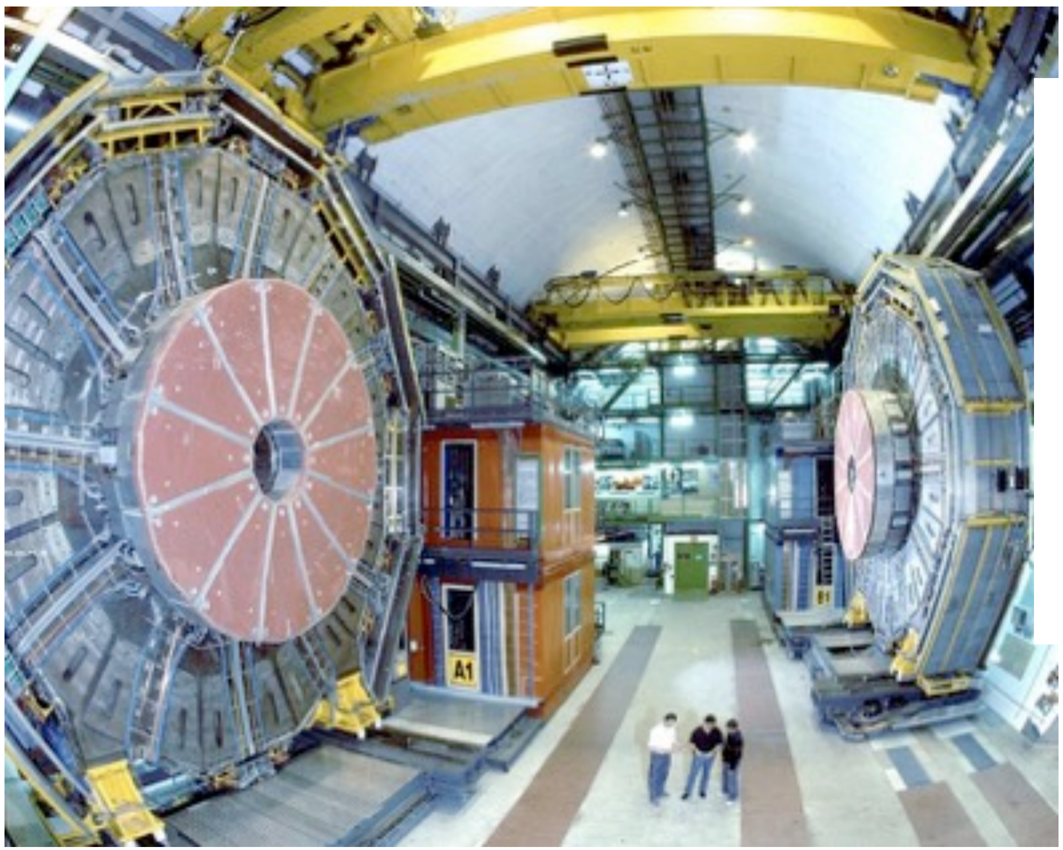
Decoherence is a more general, more observer independent rule for assigning probs. than measurement.

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.

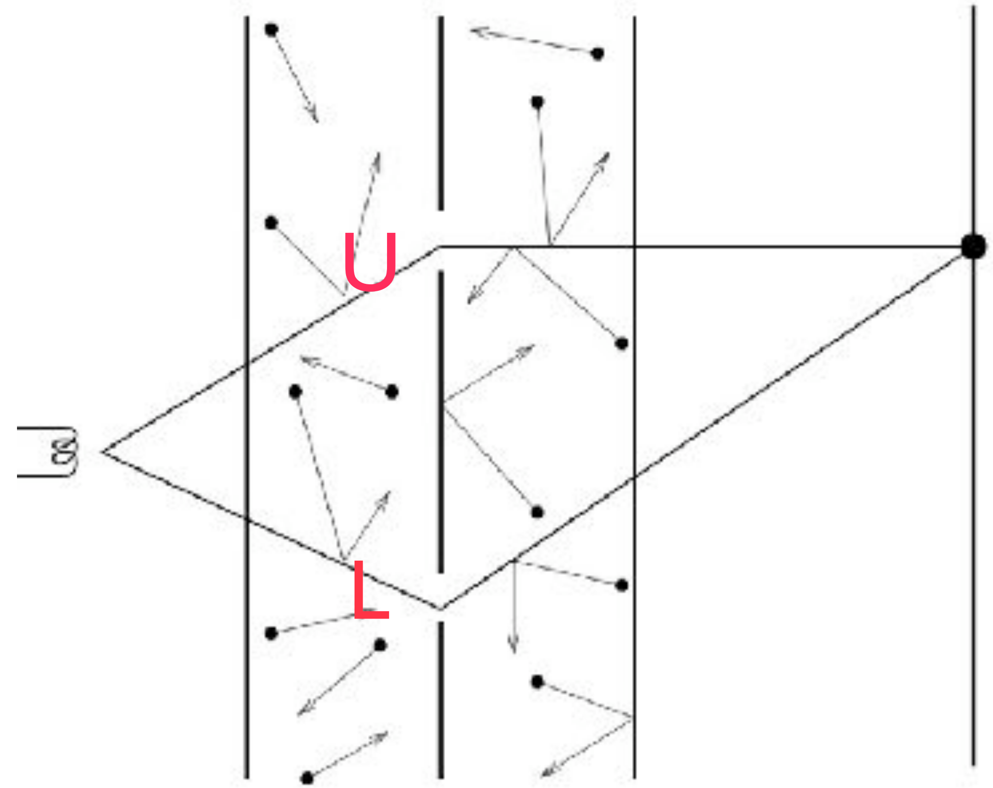
Complex systems like this can be analyzed in DH but play no central role in its formulation.



Measurements

consciousness

Toy Model of Decoherence



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

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

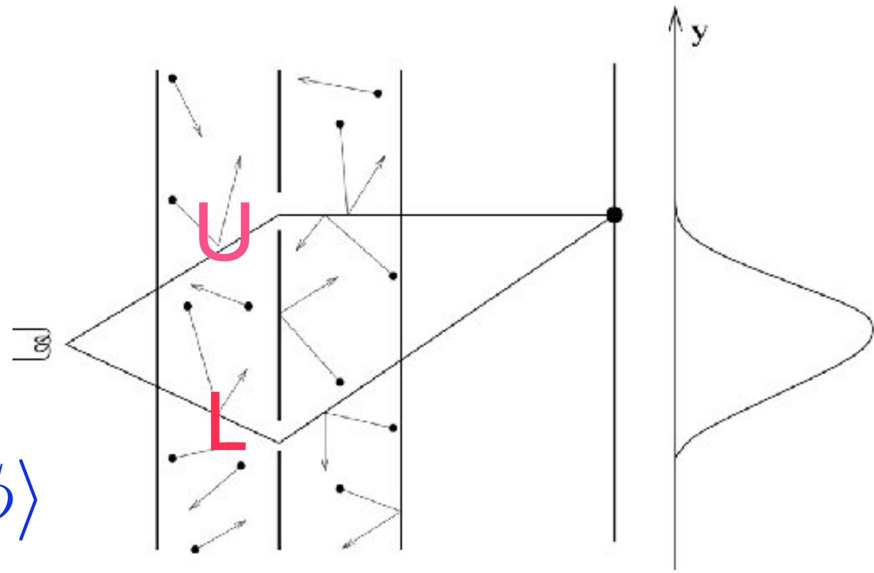
Measure of interference between histories:

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

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:

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

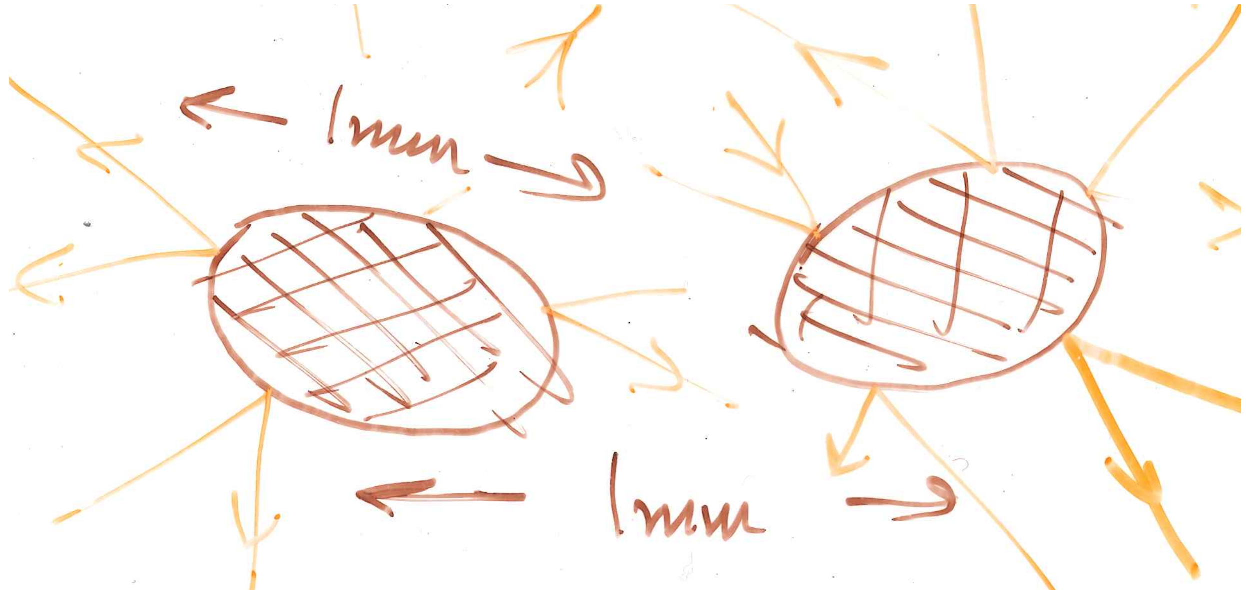
$$|\Psi(y,L)\rangle = \frac{1}{\sqrt{2}}|L\rangle\ S_L|\phi\rangle \cdots S_L|\phi\rangle$$

Interference vanishes with a large enough N:

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

Decoherence is Widespread in the Universe

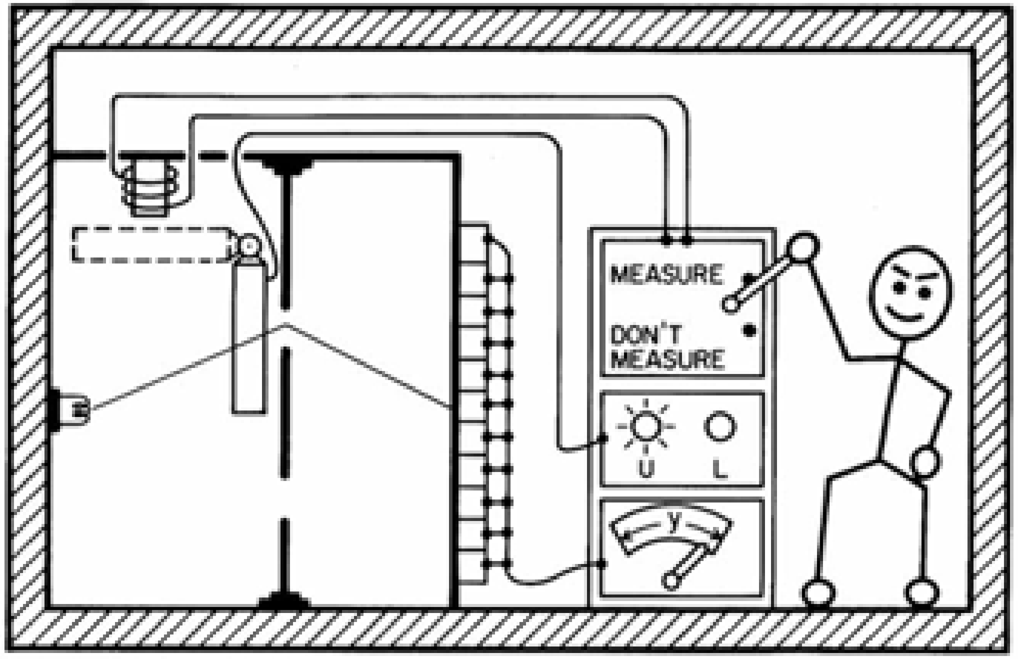
Joos and Zeh '85



- 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



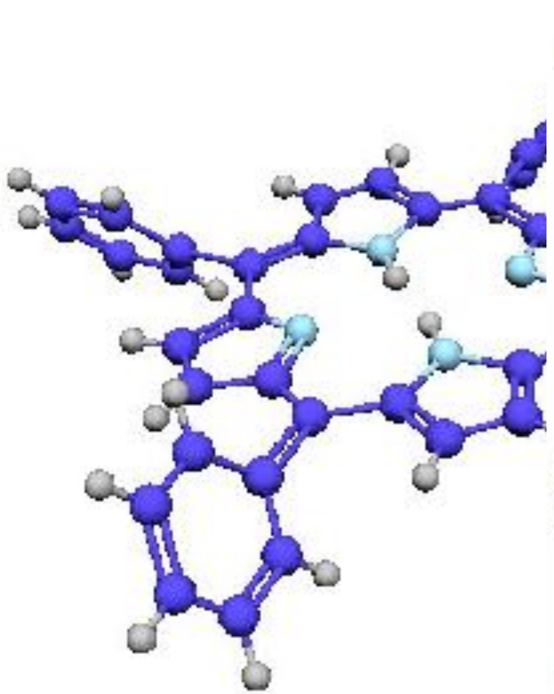
In a measurement situation a variable not normally decohering becomes coupled to a variable of an apparatus that decoheres. The measured variable decoheres and can be assigned probabilities.

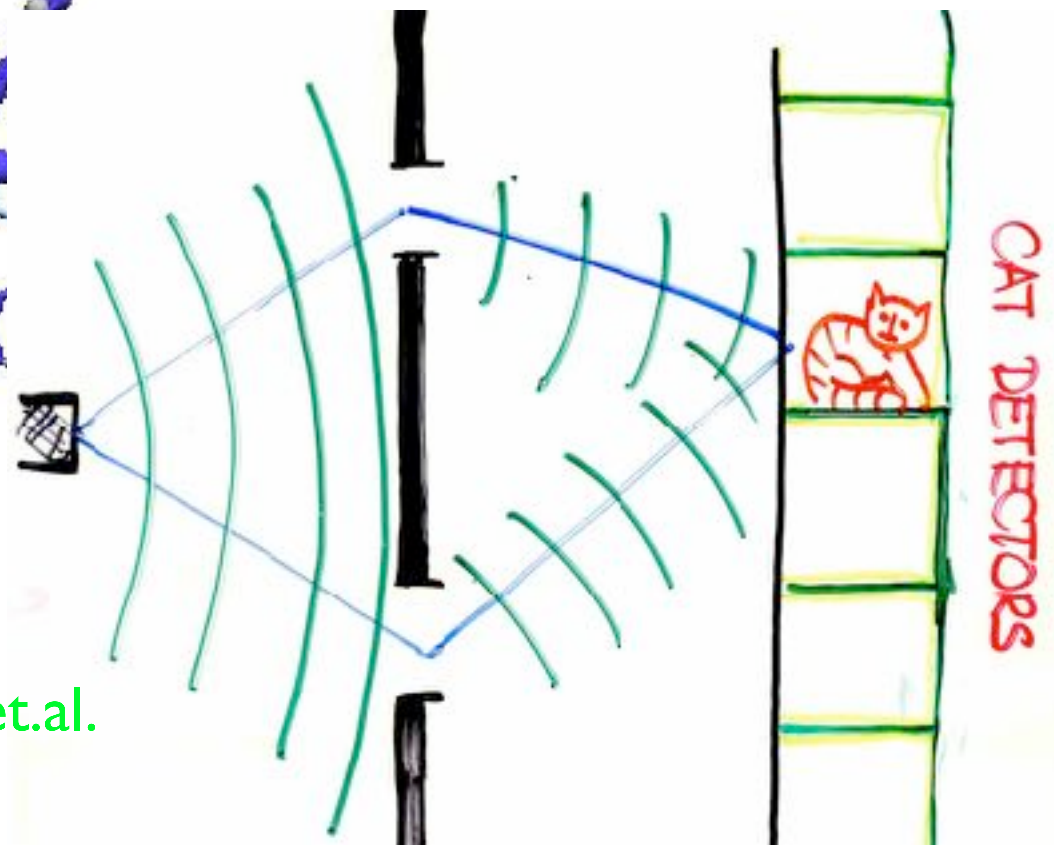
Copenhagen is an approximation to DH
for Measurement Situations

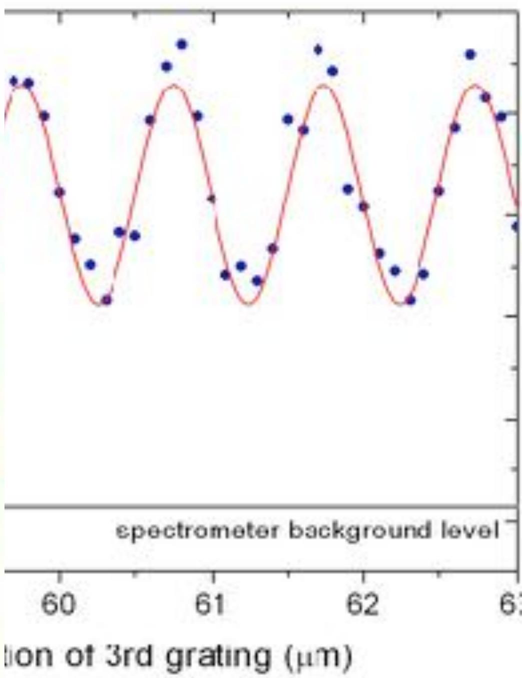
Living in a Superposition

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





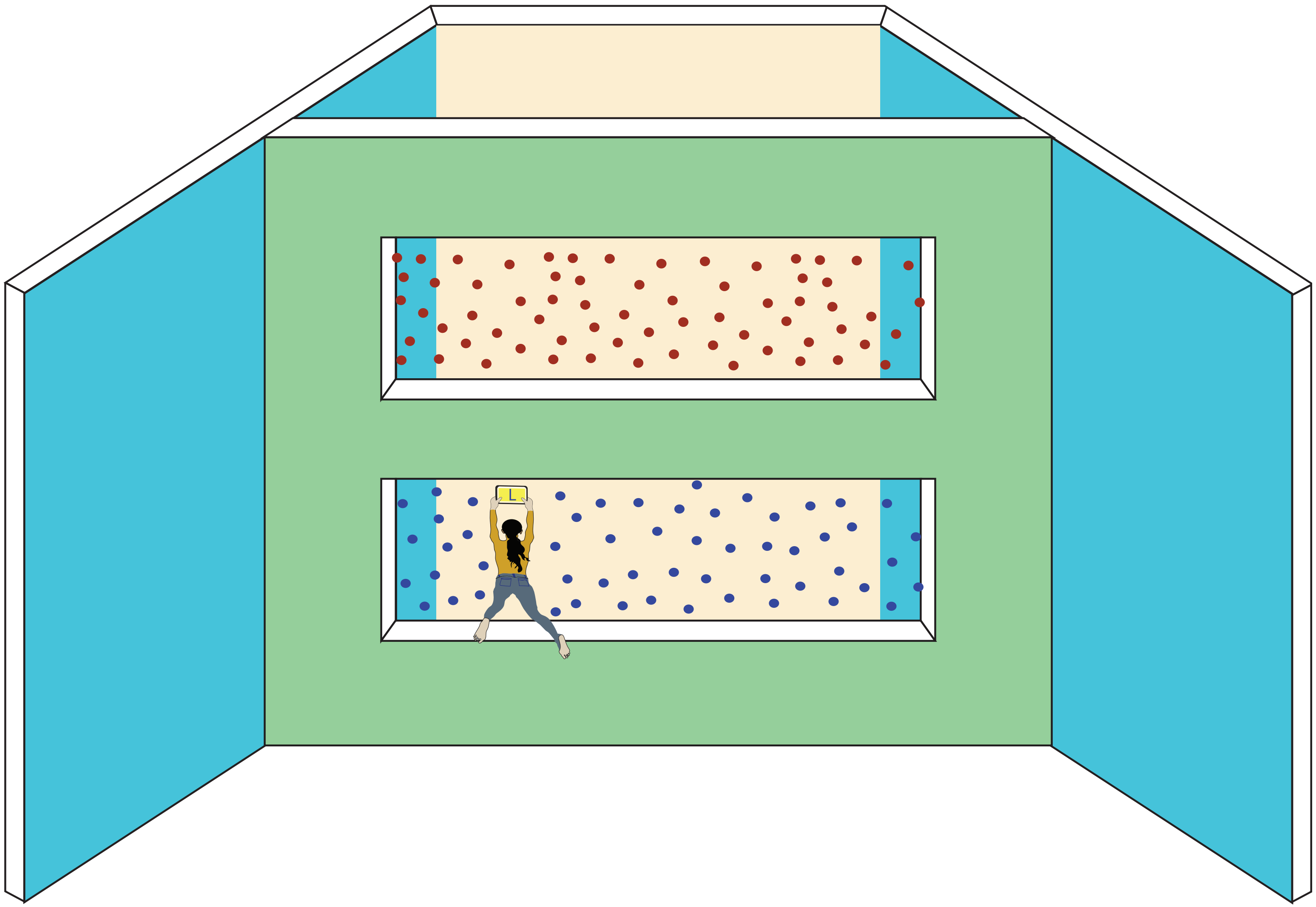


L. Hackenmuller, et.al.

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

Observers are Part of the System not Outside It.

Not Yet But Not Impossible



`Problems', Ambiguities, etc of Copenhagen QM>

Non-contextuality
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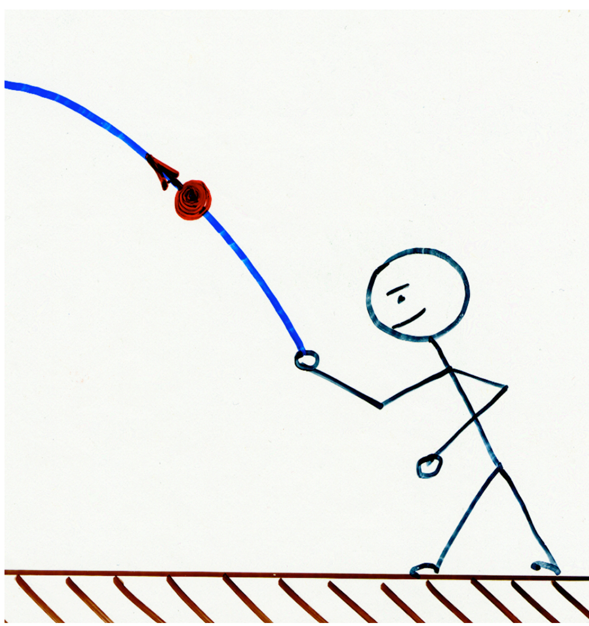
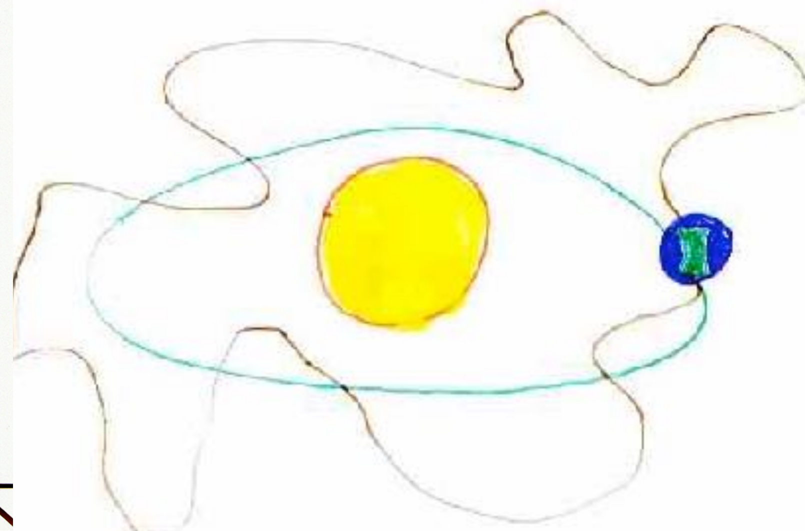
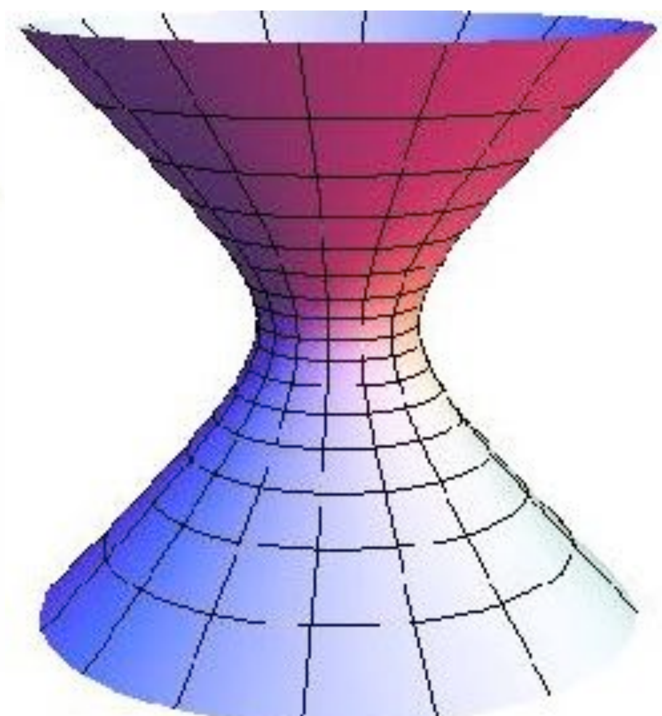
Born's rule
Macroscopic
Non-locality
Contextuality
Measurement problem
What's a measurement
Bayesian probabilities

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

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.

Quantum Multiverses

- A simple, manageable, discoverable quantum state of the universe will not predict our unique classical history with all of its complexity.
- Rather it will predict ensembles of possible classical histories with probabilities.
- The ensemble is a multiverse of classical histories. Only one is experienced and observed.
- If the constants of effective theories vary from history to history, QM predicts probabilities for the constants from the quantum state.

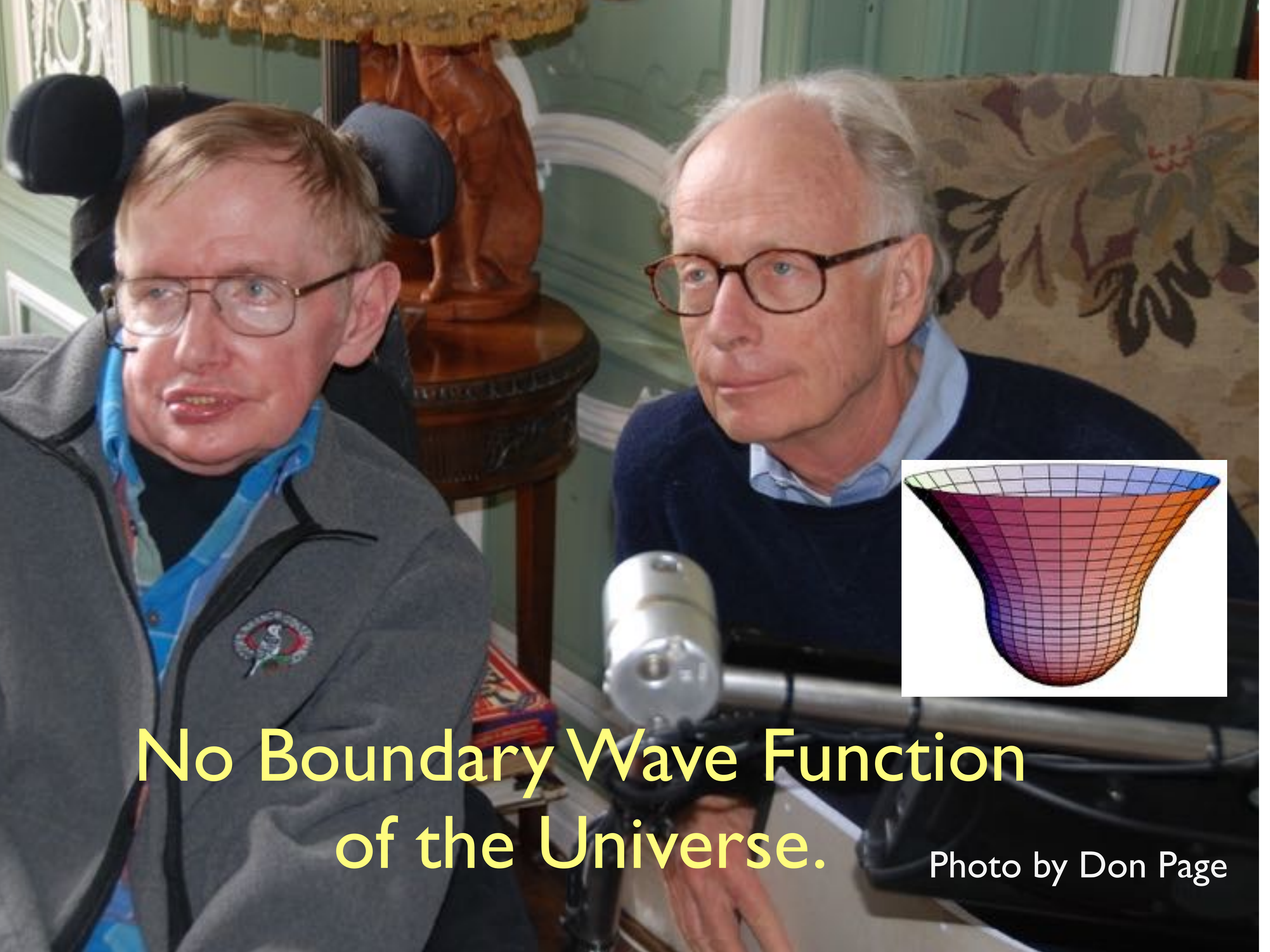
Anthropic Reasoning is Automatic in Quantum Cosmology

We won't observe what is where D cannot exist

$$p(\mathcal{O}|D)) \propto p(D|\mathcal{O})$$

Anthropic reasoning follows from treating observers as physical systems within the universe.

- Does not require a principle.
- Is not an option.
- Is not subjective choice.


No Boundary Wave Function
of the Universe.
Photo by Don Page

Scorecard for the No-Boundary Wave Function

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	
number of time dimensions	hints
coupling consts. of effect. theories	some
complexity from simplicity	
connected to fundamental theory	recent progress

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:

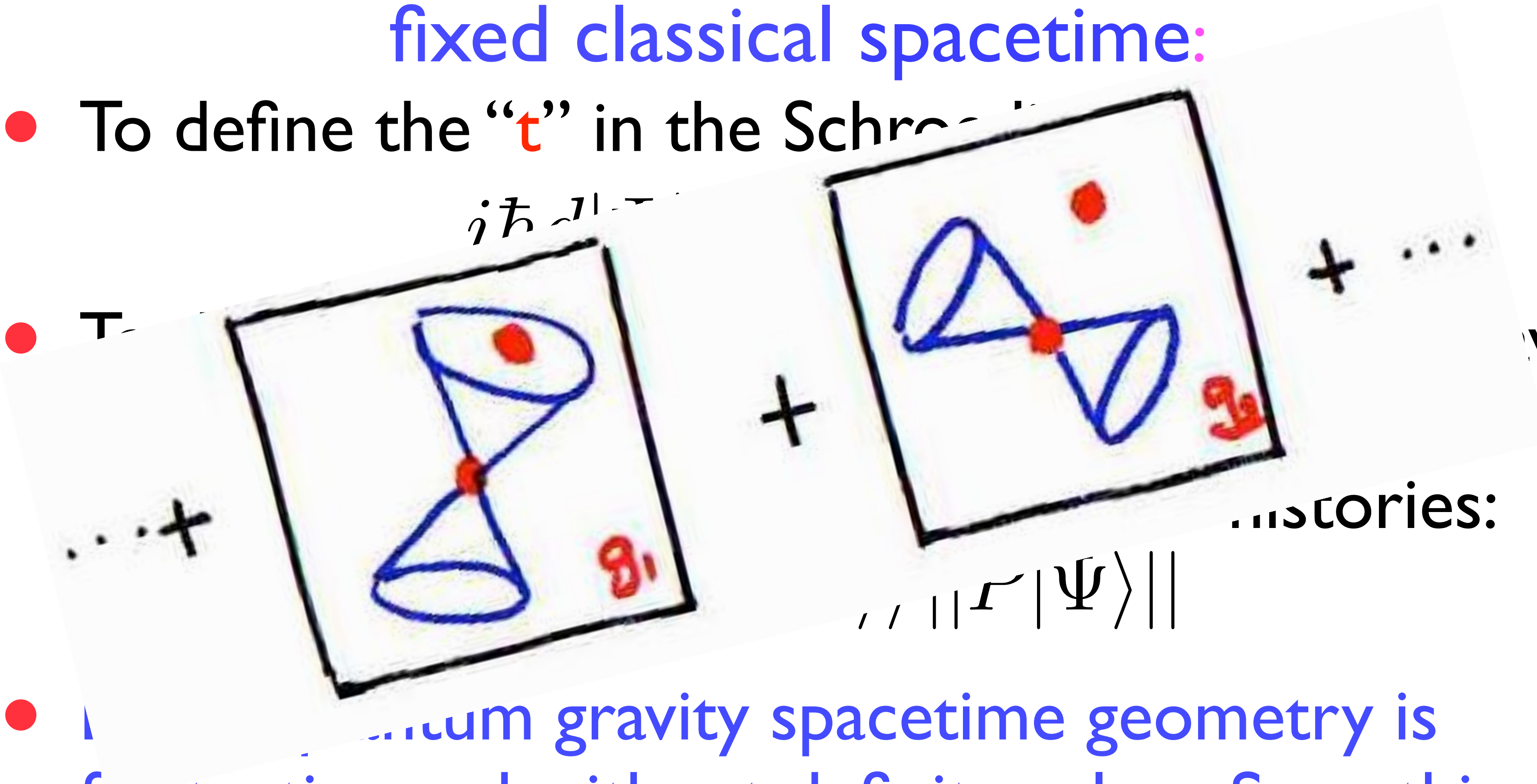
Schroedinger
Einstein
Penrose
Leggett
't Hooft
Weinberg

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...



- T... ...ve ...n ...istories: $\ldots ||P|\Psi\rangle||$
- ...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 ?

OPEN QUESTIONS

DIFFEO INVARIANT COARSE GRAINING

- Quantum mechanics assigns probabilities to the individual members in decoherent sets of alternative coarse-grained histories.
- In QM some information has to be lost to have any infomation at all.

What is the
distance
Between these two
geometries?

What is the mechanism for decoherence of a set of alternative histories of spacetime geometry?

The Modern Formulation of Quantum Mechanics (DH)

Helps us understand:

- The Copenhagen qm of measurement situations an approximation yet more general quantum theory of the universe.
- Our quantum universe both now, and at the beginning when there were no observers.
- The nature of `final theories'.
- Our place in the universe as observers.
- Quantum mechanics for quantum gravity.

Still much to do to
to work out
the consequences
of cosmology for
quantum mechanics

1901.03933

w. many references

Ψ