Title: Quasiclassical Realms and Copenhagen Quantum Theory in a Quantum Universe

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Abstract: One of the most remarkable features of our quantum universe is the wide range of time, place, scale, and epoch on which the deterministic laws of classical physics apply to an excellent approximation. This talk reviews the origin of such a quasiclassical realm in a universe governed fundamentally by quantum mechanical laws characterized by indeterminacy and distributed probabilities. We stress the important roles in this origin played by classical spacetime, coarse-graining in terms of approximately conserved quantities, local equilibrium, and the initial quantum state of the universe. The discussion is carried out first in the decoherent (or consistent) histories formulation of the quantum mechanics of closed systems (most generally the universe) assuming spacetime geometry is fixed. This is an Everettian generalization of the usual Copenhagen text book quantum mechanics of measurement situations that assumes the quasiclassical realm. Conversely we isolate the assumptions and approximations necessary to derive Copenhagen quantum mechanics from the more general quantum mechanics of closed systems. We describe a further generalization of usual quantum theory that is necessary to deal with quantum spacetime and describe under what conditions it predicts our observed coarse-grained classical spacetime that is a prerequisite for a quasiclassical realm.

Quasclassical Realms and Copenhagen Quantum Mechanics in a Quantum Universe

James Hartle, University of California, Santa Barbara

The Quasiclassical Realm - A feature of our Universe

The wide range of time, place and scale on which the laws of classical physics hold to an excellent approximation.

- Time --- from the Planck era forward.
- Place --- everywhere in the visible universe.
- Scale --- macroscopic to cosmological.

What is the origin of this quasiclassical realm in a quantum universe characterized fundamentally by indeterminacy and distibuted probabilities?

Copenhagen QM Assumed a Quasiclassical Realm

There was a separate classical physics and quantum physics with a movable boundary between them.

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- In a theory of the universe there can't be any fundamental division into two kinds of physics.
- Measurements and observers can't be fundamental in a theory that seeks to describe the early universe where neither existed.
- In quantum mechanics there are no variables that behave classically in all circumstances.

Copenhagen quantum theory is not general enough for cosmology.

The Decoherent (consistent) histories quantum theory (DH) of closed systems provides such a generalization.

Probabilities are predicted for the members of any set of alternative histories, classical or not, for whic quantum interference is negligible between member

Griffiths, Omnes, Gell-Mann, Joos, Zeh, Zurek, etc.etc.

Alternatives to DH are of great interest, if only to guide experiment.

Where's the beef?

Why Histories?

A better question would be ``How could we get along without histories?” Every other part of physics below the Planck scale (including QM and GR) has histories.

Histories are needed:

- To reconstruct the past and allow cosmology.
- To define classicality.
- To define records.
- To understand how we work.
- To predict the future.

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A forumulation 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.

Ehrenfest Deriv. of Classical Eqns

A particle of mass m moving in one dimension x.

Ehrenfest's Theorem: $$m\frac{d^2\langle x\rangle}{dt^2} = -\left\langle \frac{dV}{dx} \right\rangle$$

For special states, typically narrow wave packets this becomes an equation of motion for the expected value:

$$m\frac{d^2\langle x\rangle}{dt^2} \approx -\frac{dV(\langle x(t)\rangle)}{dx}$$

If a series of measurements is made with sufficient imprecision not to disturb this approximation the expected value will follow Newton's law.

Deficiencies of Ehrenfest Derivation

- Limited to expected values, but classical behavior is defined by probabilities of histories.
- Deals with `measurements' on isolated subsystems wit a few degrees of freedom that we choose. We are interested in classical behavior over the visible universe
- Relies on a connection between the equations of a fundamental action and the classical equations. The fundamental theory may be very different.
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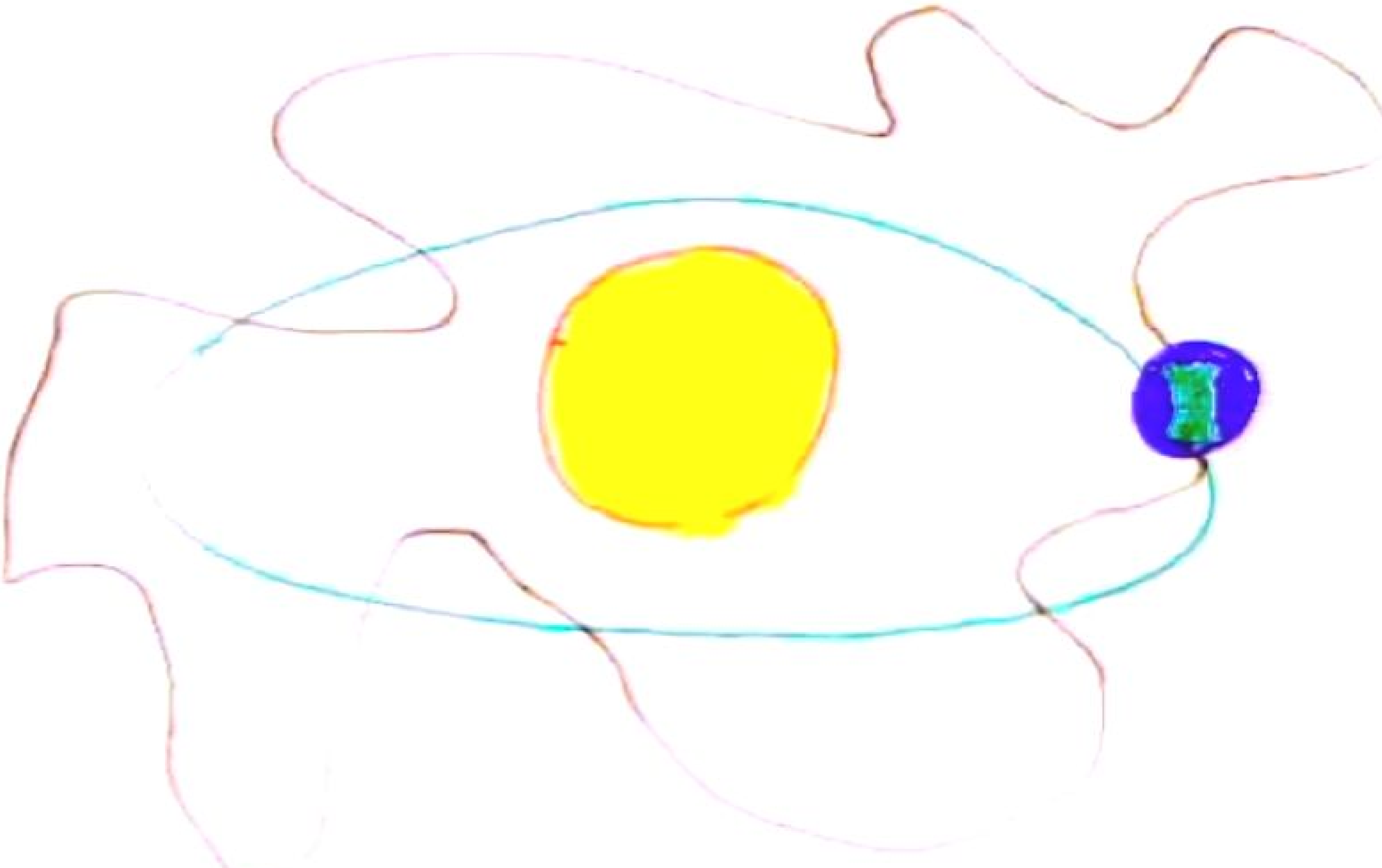

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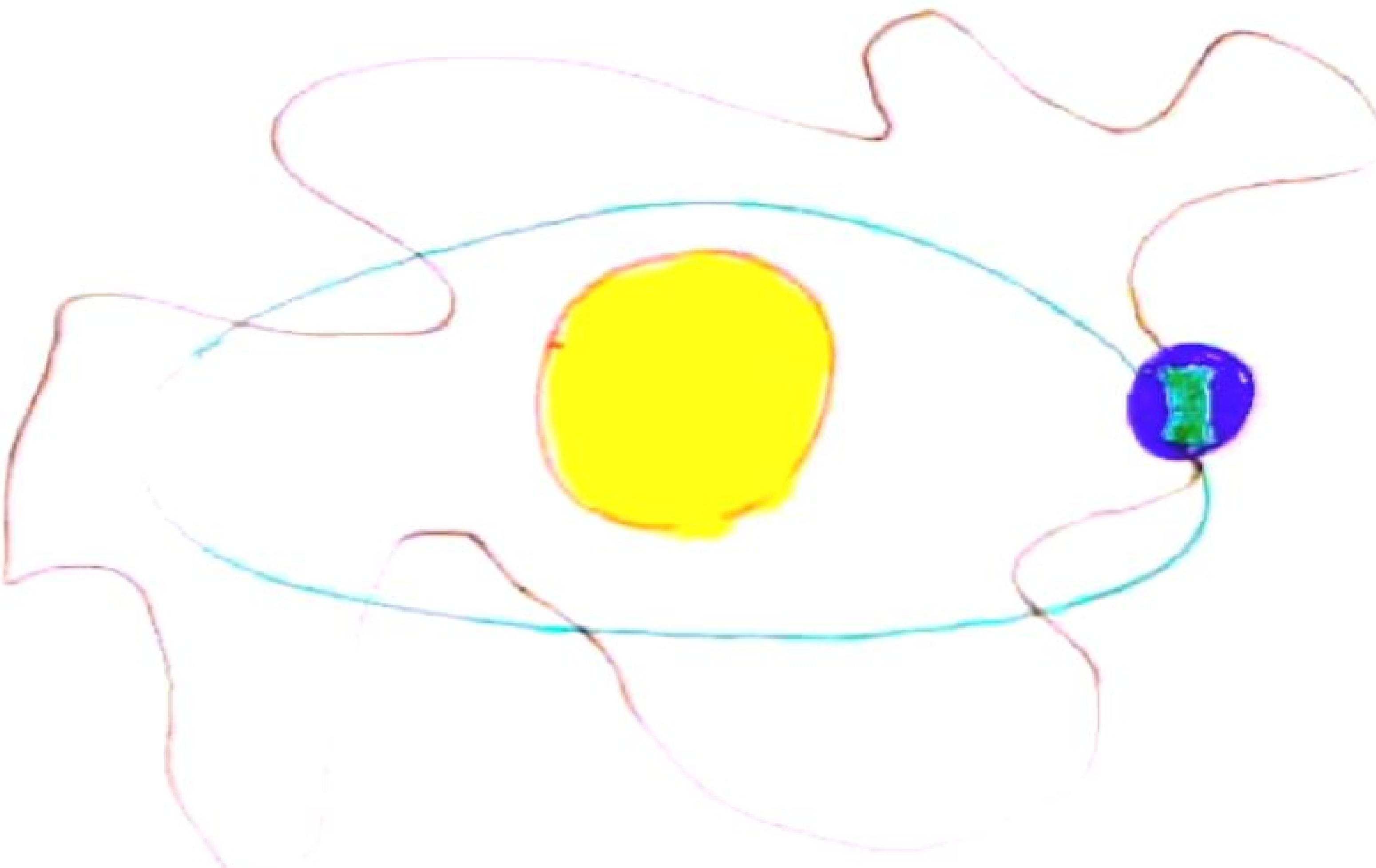

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Necessary Requirements for Classical Behavior

As seen in the Ehrenfest derivation.

Coarse graining of a particular kind.

Some restriction on the state.

Decoherent Histories QM

- Input: Dynamics S, Initial state $|\Psi\rangle$
- Sets of Fine Grained Histories: all Feynman paths for particles, all 4-d field configurations for fields.
- Sets of Coarse Grained Histories: partitions of a fine grained set into classes c_α which are the coarse-grained histories represented by operators:

$$C_\alpha = P^n_{\alpha_n}(t_n)\cdots P^1_{\alpha_1}(t_1) \quad \text{or} \quad C_\alpha \equiv \sum_{hist\in\alpha} \exp(iS[hist])$$

- Decoherence functional measuring interference between coarse-grained histories:

$$D(\alpha',\alpha) \equiv Tr(C^\dagger_{\alpha'}\rho C_\alpha)$$

- Probabilities $p(\alpha)$ are predicted for sets that decohere:

$$D(\alpha',\alpha) \approx \delta_{\alpha'\alpha}p(\alpha)$$

Terminology for this talk

Decoherence means absence of interference between branches (histories) not the diagonalization of a density matrix.

Decoherent = Consistent

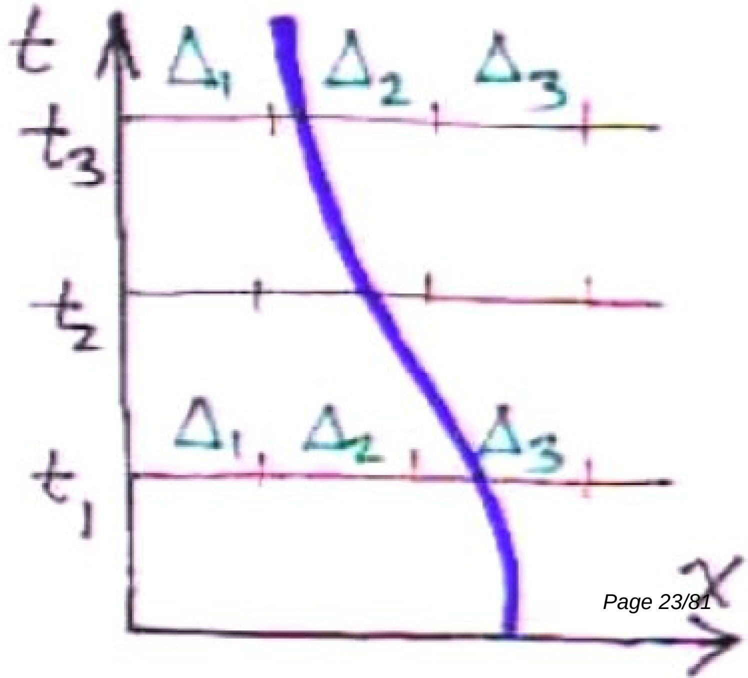
Classicality in Oscillator Models

- System: Non-relativistic particles with q=(x,Q). One distinguished oscillator x with mass M and frequency ω linearly coupled to a bath of other oscillators Q with a coupling γ.
- Dyn: $S[q(\tau)] = S_{free}[x(\tau)] + S_0[Q(\tau)] + S_{int}[x(\tau), Q(\tau)]$
- Initial State: Product with thermal bath at temp. T

$$\rho(q', q) = \bar{\rho}(x', x)\rho_T(Q', Q)$$

- Coarse graining: Follow x through intervals $\{\Delta_\alpha\}$ at a series of times $t_1, \cdots, t_n$ giving a history

$$\alpha \equiv (\alpha_n, \cdots, \alpha_1)$$



Influence Phase

For histories defined by sequences of intervals in q=(x,Q) the decoherence functional $D(\alpha',\alpha) \equiv Tr(C^{\dagger}_{\alpha'}\rho C_{\alpha})$ can be written.

$$D\left(\alpha',\alpha\right) = \int_{\alpha'} \delta q' \int_{\alpha} \delta q \, \delta\left(q'_f - q_f\right) e^{i(S[q'(\tau)] - S[q(\tau)])/\hbar} \rho\left(q'_0, q_0\right)$$

Since only x is restricted and the exponent is quadratic because of linearity of the interaction and the thermal bath, the integral over Q can be done exactly giving:

$$D(\alpha',\alpha) = \int_{\alpha'} \int_{\alpha} \delta x' \delta x \delta(x'_f - x_f) e^{i\{S_{free}[x'] - S_{free}[x] + W[x',x]\}/\hbar} \bar{\rho}(x'_0, x_0$$

The complex functional W is called the influence phase. (Feynman and Vernon, Caldeira and Leggett, etc.)

Decoherence

$$D(\alpha',\alpha) = \int_{\alpha'}\int_{\alpha} \delta x' \delta x \delta(x'_f - x_f) e^{i\{S_{free}[x'] - S_{free}[x] + W[x',x]\}/\hbar} \bar{\rho}(x'_0, x_0$$

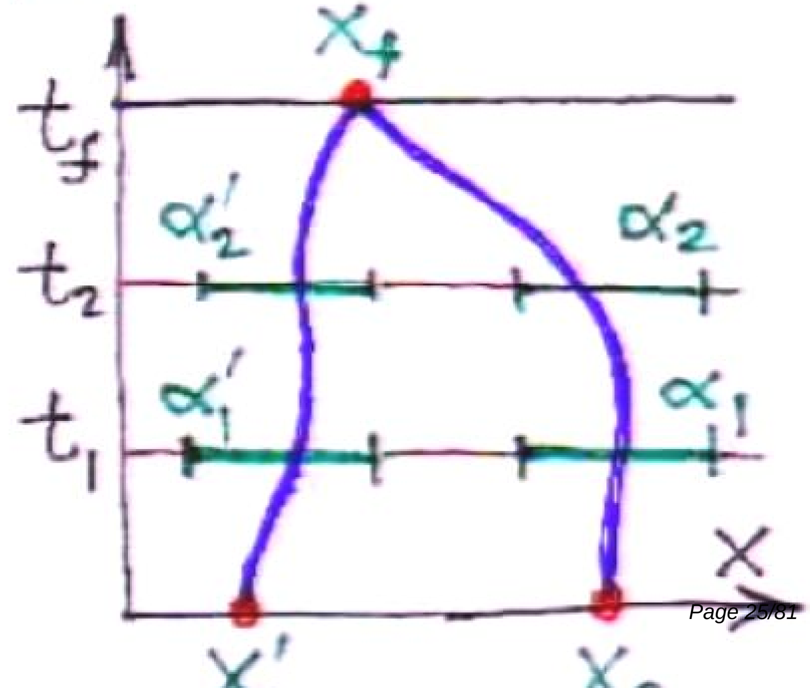
In the high bath temperature limit the functional W has a simple imaginary part, local in time:

$$Im W[x'(\tau), x(\tau)] = \frac{2M\gamma k T_B}{\hbar} \int_0^T dt\, (x'(t) - x(t))^2$$

This squeezes x'(t) and x(t) together and makes $D(\alpha',\alpha)$ negligible except when $\alpha' = \alpha$

That's decoherence!

$$t_{\text{decoh}} \sim \frac{\hbar}{2M\gamma k T_B \Delta^2}$$



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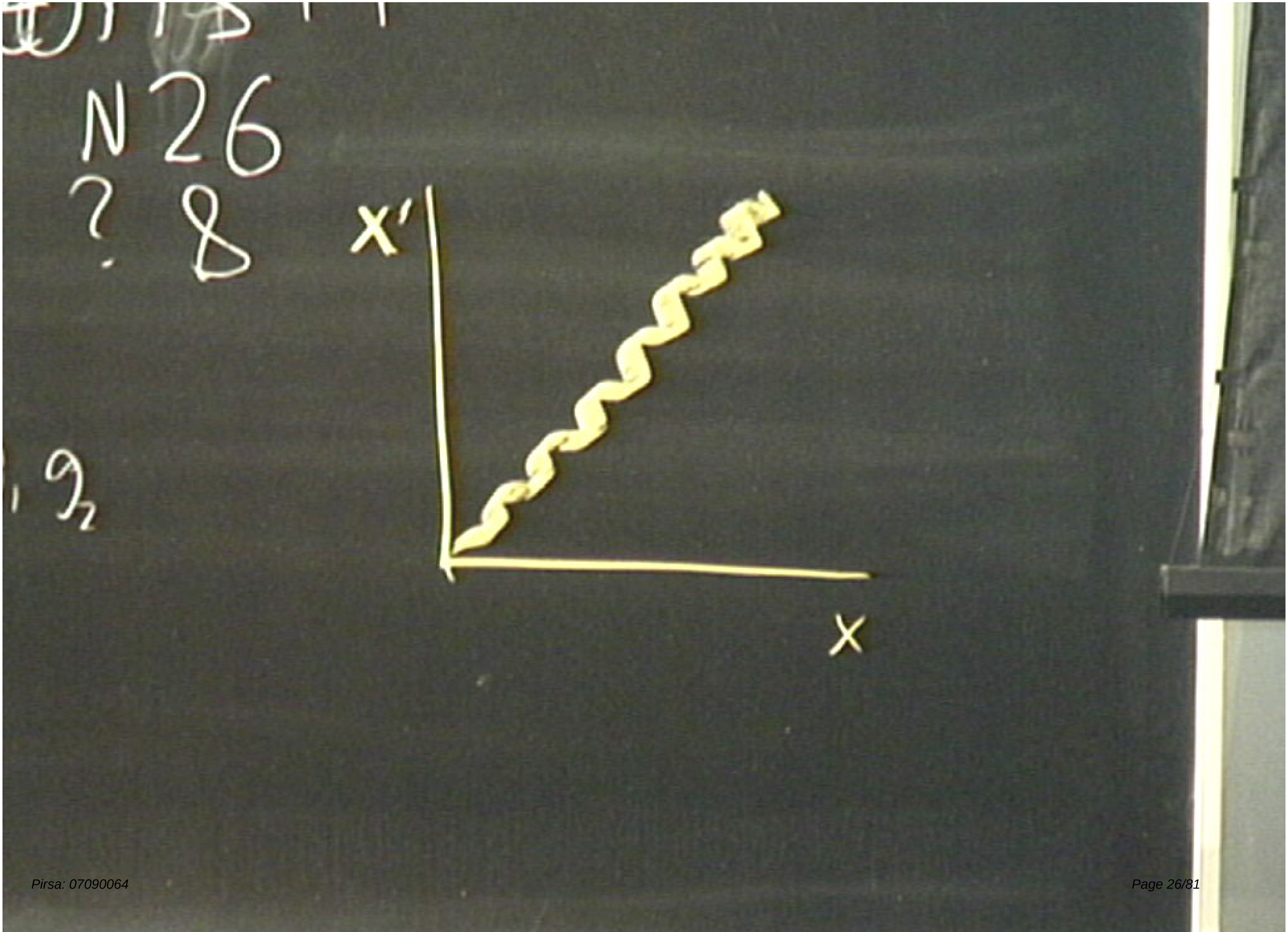
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Probabilities for Classical Eqns

In the approximation that the decoherence functional is diagonal, the probabilities for histories are:

$$p(\alpha) = \int_\alpha \delta x \ (\cdots) \exp\left[- \int dt \left(\frac{M}{2\hbar} \right)^2 \left(\frac{\hbar}{2M\gamma k T_B} \right) E(x(t))^2 \right] w(x_0, p_0)$$

where $w(x_0, p_0)$ is the Wigner distribution of $\bar{\rho}(x_0', x_0)$
$E(x(t)) \equiv \ddot{x} - \omega^2 x + 2\gamma \dot{x}$ is the classical equation of motion. The probabilities are highest when the classical equations of motion E=0 are satisfied.

That is a prediction of classical correlations in time!

The width of the distribution represents thermal and quantum noise causing deviations from classical predictability.

Decoherence, Noise, and Inertia

$$ImW[x'(\tau), x(\tau)] = \frac{2M\gamma kT_B}{\hbar}\int_0^T dt\,(x'(t) - x(t))^2$$

$$p(\alpha) = \int_\alpha \delta x\ (\cdots)\exp\left[-\int dt\left(\frac{M}{2\hbar}\right)^2(\frac{\hbar}{2M\gamma kT_B})E(x(t))^2\right]w(x_0, p_0)$$

Stronger coupling γ and higher temperature T_B mean faster decoherence but also increased noise and less predictability.

Increased inertia M ensures classical predictability.

Classical predictability occurs for variables that have the inertia to persist in the face of the noise that typical mechanisms of decoherence produce.

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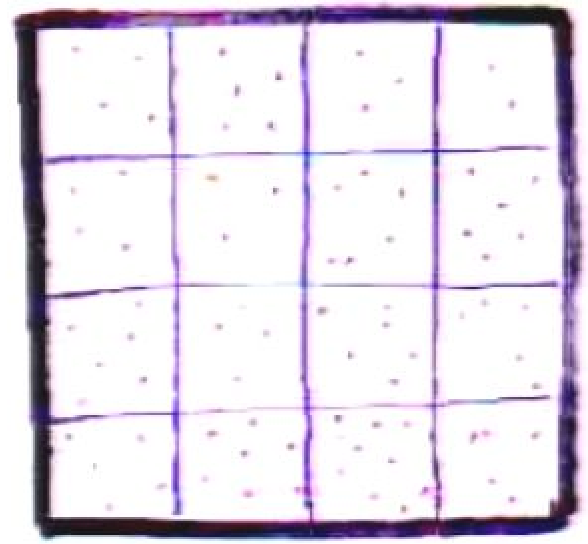
What variables generally define coarse-grained histories that exhibit classical correlations in time governed by closed systems of deterministic equations?

asuming classical spacetime and no long range fields

Equilibrium and Local Equilibrium

standard non-equilibrium statistical mechanics

- A closed system of particles in a non-rotating box.
- After a long time the box will approach equilibrium characterized by the total conserved energy, momentum, and number.



- On a shorter time the box will approach local equilibrium characterized by values of the energy, momentum and number in small volumes.
- The approach to total equilibrium is then described by a closed system of equations for the energy, momentum, and number in each small volume.

Classical Behavior of Expected Values I

•Classical Variables (eg energy/vol.):

$$\epsilon_V(\vec{y},t) \equiv \frac{1}{V}\int_{\vec{y}} d^3x\,\epsilon(\vec{x},t)$$

same for mom. $\vec{\pi}(\vec{y},t)$ and num. $\nu(\vec{y},t)$.

•Equilibrium effective density matrix:

$$\tilde{\rho}_{\rm eq} = Z^{-1}\exp[-\beta(H - \vec{U}\cdot\vec{P} - \mu N)]$$

•Local Equilibrium:

$$\langle\epsilon_V(\vec{y},t)\rangle \equiv Tr(\epsilon_V(\vec{y},t)\rho) = Tr(\epsilon_V(\vec{y},t)\tilde{\rho}_{\rm leq})$$

$$\tilde{\rho}_{\rm leq} = Z^{-1}\exp\left[-\int d^3x\,\beta(\vec{x},t)\Big(\epsilon(\vec{x},t) - \vec{u}(\vec{x},t)\cdot\vec{\pi}(\vec{x},t) - \mu(\vec{x},t)\,\nu(\vec{x},t)\Big)\right]$$

where $\beta, \vec{u}, \mu$ can be expressed in terms of $\langle\epsilon\rangle, \langle\vec{\pi}\rangle, \langle\nu$

Two very different time scales.

Class. Behavior of Expected Values II

- Classical Equations for expected values:

$$\frac{\partial\langle\pi^i\rangle}{\partial t} = -\frac{\partial\langle T^{ij}\rangle}{\partial x^j} \qquad \frac{\partial\langle\epsilon\rangle}{\partial t} = -\vec{\nabla}\cdot\langle\vec{\pi}\rangle \qquad \frac{\partial\langle\nu\rangle}{\partial t} = -\vec{\nabla}\cdot\langle\vec{\jmath}\rangle$$

- Local Equilibrium ensures closure:

$$\langle\epsilon_V(\vec{y},t)\rangle \equiv Tr(\epsilon_V(\vec{y},t)\tilde{\rho}) \approx Tr(\epsilon_V(\vec{y},t)\tilde{\rho}_{\text{eq}})$$

$$\tilde{\rho}_{\text{leq}} = Z^{-1}\exp\left[-\int d^3x\,\beta(\vec{x},t)\Big(\epsilon(\vec{x},t) - \vec{u}(\vec{x},t)\cdot\vec{\pi}(\vec{x},t) - \mu(\vec{x},t)\,\nu(\vec{x},t)\Big)\right]$$

- Further assumptions give familiar equations (e.g. linearity in velocity gradients implies Navier-Stokes.)

$$\tilde{T}^{ij} = p\delta^{ij} + m\nu\,u^iu^j - \eta\left[\frac{\partial u^i}{\partial x^j} + \frac{\partial u^j}{\partial x^i} - \frac{2}{3}\,\delta_{ij}\left(\vec{\nabla}\cdot\vec{u}\right)\right] - \zeta\,\delta_{ij}\left(\vec{\nabla}\cdot\vec{u}\right)$$

pressure, viscosities, etc have their local equilibrium values in terms of $\langle\epsilon\rangle, \langle\vec{\pi}\rangle, \langle\nu\rangle$.

Classical Behavior of Histories of Quasiclassical Variables

Approximate conservation allows decoherence while preserving predictability and closure.

- Volumes V: Large enough to give enough coarse graining to ensure decoherence and beyond that to ensure predictability in the face of the noise typical mechanisms of decoherence produce.
- Volumes V: Small enough to allow local equilibrium and so the the quasiclassical realm is a maximally refined description of the universe and not our choice.

Such histories exhibit patterns of classical correlations in time with high probability (Halliwell, Brun)

Origin of the Quasiclassical Realm

- Classical spacetime emerges from the quantum gravitational fog at the beginning.
- 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.

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Why do we focus on QC Variables?

- An answer to this question requires a description of 'we' as a physical system.
- For most of our history we focussed on qc variables because evolution has equipped us to measure these.
- But with quantum mechanics we have evolved to measure a few non-QC variables.
- Alternative evolutionary outcomes are in principle calculable in quantum cosmology but beyond our reach
- But there is no interpretation of 'we' that does not involve some QC description.

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The Story of Zargon

- The inhabitatants of the planet Zargon have understood DH for 50,000 Earth-yrs.
- They decide to replicate their identities in topological q-bits while simultaneously destroying their old QC selves.
- That way they can resist decoherence and live forever.
- They have evolved to use more non-QC variables than most.

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Unfortunately they forgot......

Copenhagen QM Recovered

- Measurement: An interaction between an otherwise isolated subsystem (the system) and another (the apparatus) resulting in correlation between a system variable and a quasiclassical variable of the apparatus.

- Decoherence: Histories of measured alternatives decohere since they are correlated with decohering quasiclassical histories of the apparatus.

- Measurement Models: In idealized models the probabilities of sequences of measurements can be approximately expressed in terms of histories of the system alone. (Impt practically!)

- AQMMS: Copenhagen QM is an approximation to DH appropriate for measurement situations. It is not separate but rather but contained within DH

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Thermodynamic Features of Our U.

- The tendency of the total entropy to increase.
- The tendency of the entropy of each presently isolated subsystem to increase in the same direction in time.

Together these are the second law of thermodynamics.

These features are connected to the quasiclassical realm and the coarse-graining defining it.

But they require further restrictions on the initial quantum state beyond classical spacetime.

Thermodynamic Entropy

- Information is sacrificed in the coarse-graining necessary for decoherence and for predictability.
- Entropy is a measure of missing information.
- The entropy of the second law is the maximum of $S(\tilde{\rho}) \equiv -Tr(\tilde{\rho}\log\tilde{\rho})$ over $\tilde{\rho}$ which preserve the expected values of the quasiclassical variables, eg.

$$\langle \epsilon_V(\vec{y},t)\rangle \equiv Tr(\epsilon_V(\vec{y},t)\rho) = Tr(\epsilon_V(\vec{y},t)\tilde{\rho})$$

- Usual entropy uses quasiclassical coarse graining.

Conditions for the Second Law

- The initial state is such that the initial entropy is near the minimum it could have for the coarse-graining defining it. It then has nowhere to go but up.
- The relaxation time to equilibrium is long compared to the present age of the universe so that the general tendency to increase will dominate its evolution.

The 'no-boundary' state satisfies the first of these.

Approximate conservation of qc-variables helps with the second because the variables defining the entropy approach equilibrium slowly.

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Classical Spacetime is the Key to the Origin of the Quasiclassical Realm.

The quantum state of the universe is the key to the origin of classical spacetime.

Hawking's no-boundary quantum state does implies classical spacetime.

$$\Psi = \int_C \delta g \delta \phi \exp(-I[g, \phi])$$

Quantum spacetime requires a further generalization of quantum mechanics.

Quantum Mechanics and Spacetime

Familiar quantum theory assumes a fixed spacetime:

- To define the "t" in the Schroedinger equation:

$$i\hbar d|\Psi\rangle/dt = H|\Psi\rangle$$

- To define the spacelike surfaces on which the wave function is reduced on measurement or on which alternatives are defined in decoherent histories:

$$|\Psi\rangle \rightarrow P|\Psi\rangle/||P|\Psi\rangle||$$

$$|\Psi_\alpha\rangle = P^n_{\alpha_n}(t_n)\cdots P^1_{\alpha_1}(t_{\alpha_1})|\Psi\rangle$$

- But in quantum gravity spacetime geometry is fluctuating and without definite value so a generalization of these laws of evolution is needed.

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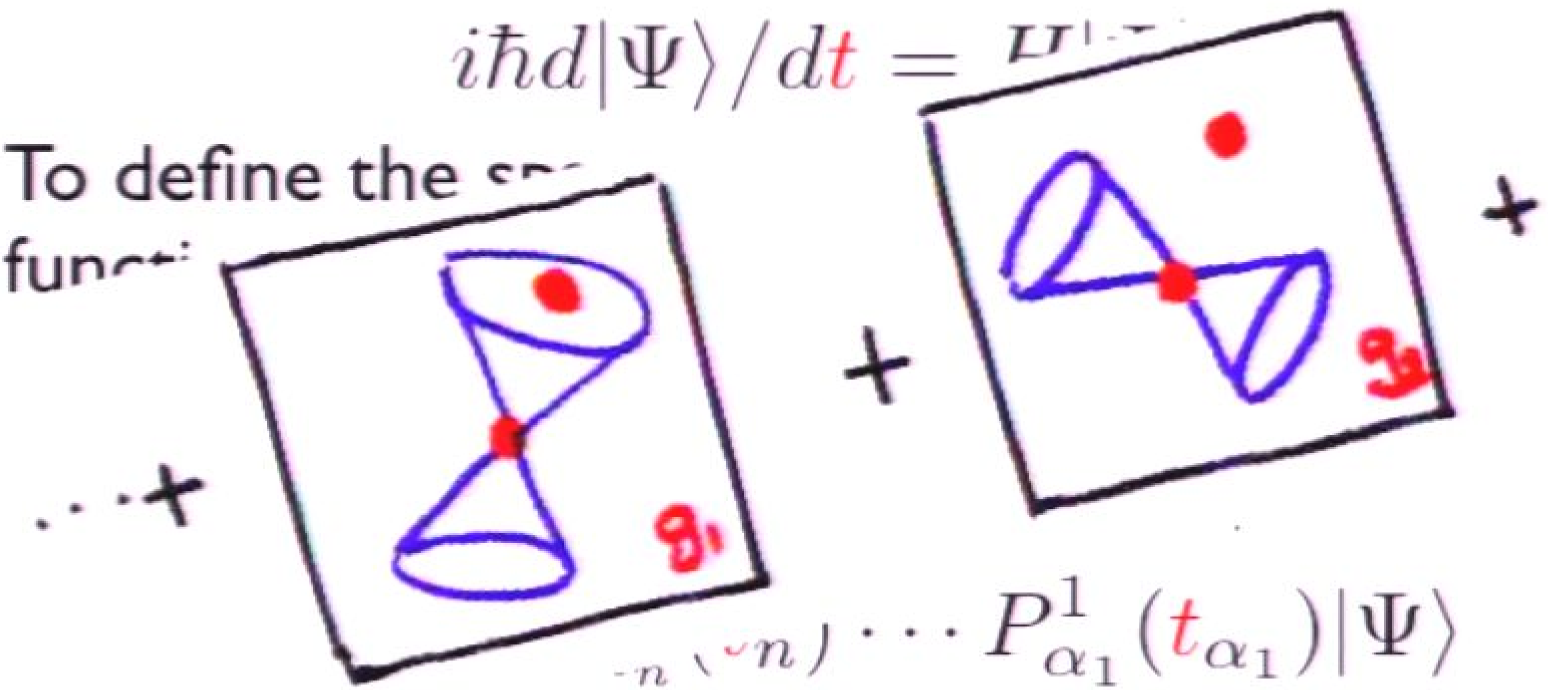

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Key Idea about Histories:

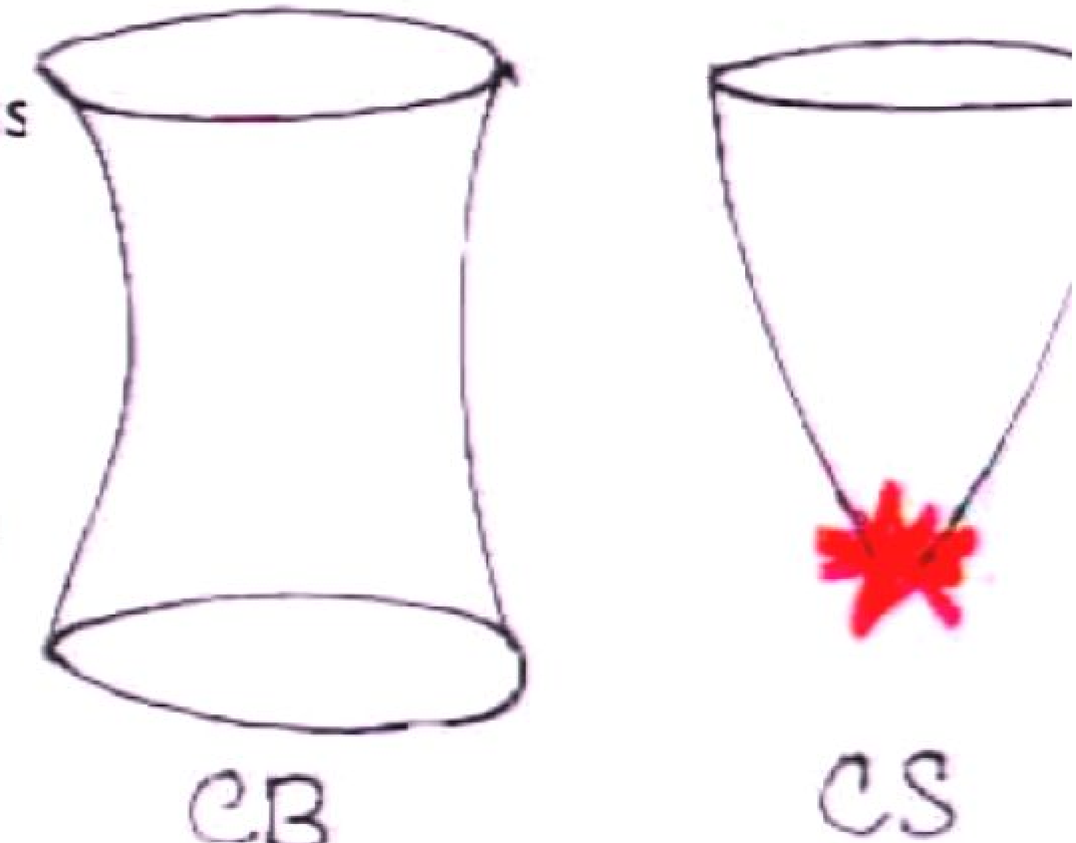
Histories need not describe evolution
in spacetime
but can describe evolution
of spacetime.

Coarse Graining

Every assertion that can be made about the universe corresponds to a partition of the fine-grained histories in the class where it is true and the class where it is false.

Example: Bounce Problem:

- A partition in to the class C that are classical (to some approx.) and the class (NC) that are not.
- A partition of C into the class CB which bounce and the class CS which are singular.



A Four-Dimensional Generalized QM

- 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.

Classical spacetime is predicted in states for which the probability is high for decoherent histories exhibiting patterns of correlation implied of the Einstein equation.

Hawking's no-boundary state is such a quantum state.

$$\Psi = \int_C \delta g \delta \phi \exp(-I[g,\phi])$$

To do

- More detailed, quantitative, and realistic calculations of quasiclassical realms (decoherence, noise, probabilities) in more realistic initial states.
- Better intuition concerning mechanisms of decoherence of QC variables and their time scales.
- Realistic coarse graining: Narratives, branch dependence, forms, maximal refinement.
- Comparison of QC realms with other realms our universe exhibits. (Information theoretic measures.)
- Diffeomorphism invariant coarse grainings of spacetime geometry and mechanisms for their decohrence.

Deficiencies of Ehrenfest Derivation

- Limited to expected values, but classical behavior is defined by probabilities of histories.
- Deals with `measurements' on isolated subsystems with a few degrees of freedom that we choose. We are interested in classical behavior over the visible universe
- Relies on a connection between the equations of a fundamental action and the classical equations. The fundamental theory may be very different.
- Posits a classical variable x , We are interested in deriving the variables of the quasiclassical realm.
- Assumes classical spacetime but we are interested in deriving classical spacetime in quantum gravity.

Everett showed us how the quantum mechanics of the universe could help us understand quantum mechanics in the laboratory.

Freud showed how neglected, seemingly trivial everyday phenomena such as dreams, lapses, etc could shed light on the fundamental in psychology.

Quantum cosmologists should do no less with their trivial everyday phenomena such as classical spacetime, four-dimensions, quasiclassical realm, the laws of thermodynamics, the arrows of time, past-present-future, etc etc.

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Thermodynamic Features of Our U.

- The tendency of the total entropy to increase.
- The tendency of the entropy of each presently isolated subsystem to increase in the same direction in time.

Together these are the second law of thermodynamics.

These features are connected to the quasiclassical realm and the coarse-graining defining it.

But they require further restrictions on the initial quantum state beyond classical spacetime.

Why do we focus on QC Variables?

- An answer to this question requires a description of 'we' as a physical system.
- For most of our history we focussed on qc variables because evolution has equipped us to measure these.
- But with quantum mechanics we have evolved to measure a few non-QC variables.
- Alternative evolutionary outcomes are in principle calculable in quantum cosmology but beyond our reach
- But there is no interpretation of 'we' that does not involve some QC description.

Classical Behavior of Histories of Quasiclassical Variables

Approximate conservation allows decoherence while preserving predictability and closure.

- Volumes V: Large enough to give enough coarse graining to ensure decoherence and beyond that to ensure predictability in the face of the noise typical mechanisms of decoherence produce.

- Volumes V: Small enough to allow local equilibrium and so the the quasiclassical realm is a maximally refined description of the universe and not our choice.

Such histories exhibit patterns of classical correlations in time with high probability (Halliwell, Brun)

Decoherence, Noise, and Inertia

$$ImW[x'(\tau),x(\tau)] = \frac{2M\gamma kT_B}{\hbar}\int_0^T dt\,(x'(t)-x(t))^2$$

$$p(\alpha) = \int_\alpha \delta x\;(\cdots)\exp\left[-\int dt\left(\frac{M}{2\hbar}\right)^2\left(\frac{\hbar}{2M\gamma kT_B}\right)E(x(t))^2\right]w(x_0,p_0)$$

Stronger coupling γ and higher temperature T_B mean faster decoherence but also increased noise and less predictability.

Increased inertia M ensures classical predictability.

Classical predictability occurs for variables that have the inertia to persist in the face of the noise that typical mechanisms of decoherence produce.

Decoherence

$$D(\alpha',\alpha) = \int_{\alpha'}\int_{\alpha} \delta x' \delta x \delta(x'_f - x_f) e^{i\{S_{free}[x'] - S_{free}[x] + W[x',x]\}/\hbar} \bar{\rho}(x'_0, x_0$$

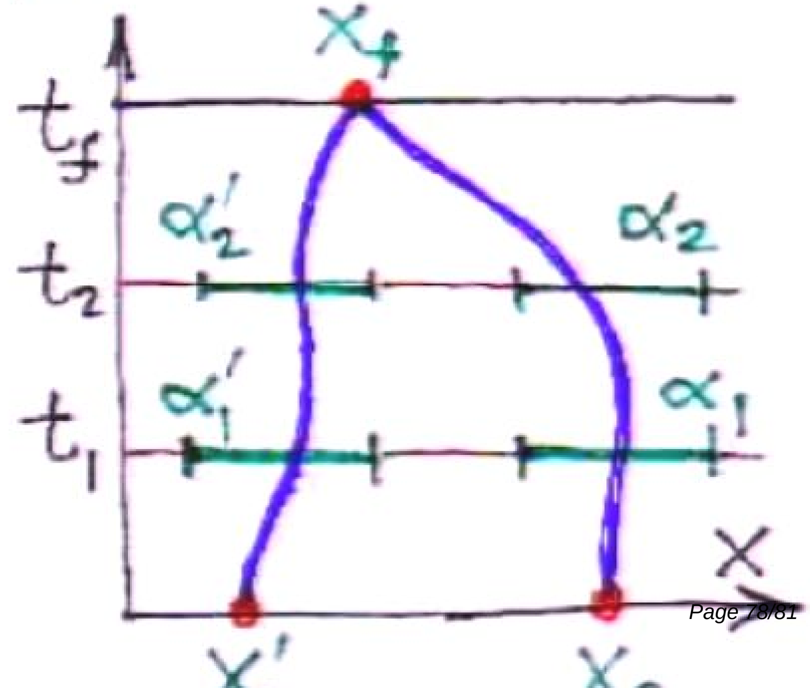
In the high bath temperature limit the functional W has a simple imaginary part, local in time:

$$ImW[x'(\tau), x(\tau)] = \frac{2M\gamma kT_B}{\hbar}\int_0^T dt\,(x'(t) - x(t))^2$$

This squeezes x'(t) and x(t) together and makes $D(\alpha',\alpha)$ negligible except when $\alpha' = \alpha$

That's decoherence!

$$t_{\text{decoh}} \sim \frac{\hbar}{2M\gamma kT_B\Delta^2}$$



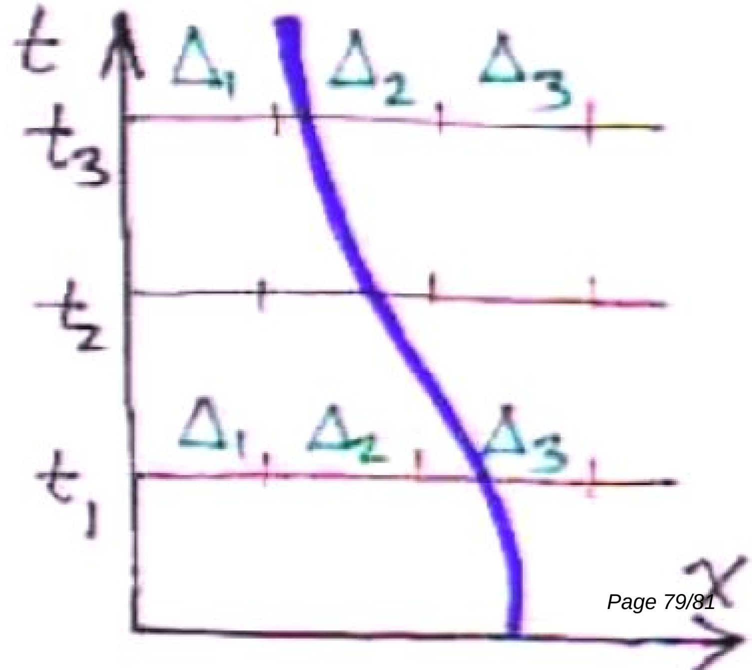
Classicality in Oscillator Models

- **System:** Non-relativistic particles with q=(x,Q). One distinguished oscillator x with mass M and frequency ω linearly coupled to a bath of other oscillators Q with a coupling γ.
- **Dyn:** $S[q(\tau)] = S_{free}[x(\tau)] + S_0[Q(\tau)] + S_{int}[x(\tau), Q(\tau)]$
- **Initial State:** Product with thermal bath at temp. T

$$\rho(q', q) = \bar{\rho}(x', x)\rho_T(Q', Q)$$

- **Coarse graining:** Follow x through intervals $\{\Delta_\alpha\}$ at a series of times $t_1, \cdots, t_n$ giving a history

$$\alpha \equiv (\alpha_n, \cdots, \alpha_1)$$



Terminology for this talk

Decoherence means absence of interference between branches (histories) not the diagonalization of a density matrix.

Decoherent = Consistent

Decoherent Histories QM

- Input: Dynamics S, Initial state $|\Psi\rangle$
- Sets of Fine Grained Histories: all Feynman paths for particles, all 4-d field configurations for fields.
- Sets of Coarse Grained Histories: partitions of a fine grained set into classes c_α which are the coarse-grained histories represented by operators:

$$C_\alpha = P^n_{\alpha_n}(t_n)\cdots P^1_{\alpha_1}(t_1) \quad \text{or} \quad C_\alpha \equiv \sum_{hist\in\alpha} \exp(iS[hist])$$

- Decoherence functional measuring interference between coarse-grained histories:

$$D(\alpha', \alpha) \equiv Tr(C^\dagger_{\alpha'}\rho C_\alpha)$$

- Probabilities $p(\alpha)$ are predicted for sets that decohere:

$$D(\alpha', \alpha) \approx \delta_{\alpha'\alpha}p(\alpha)$$