Title: Time, cosmology and quantum foundations

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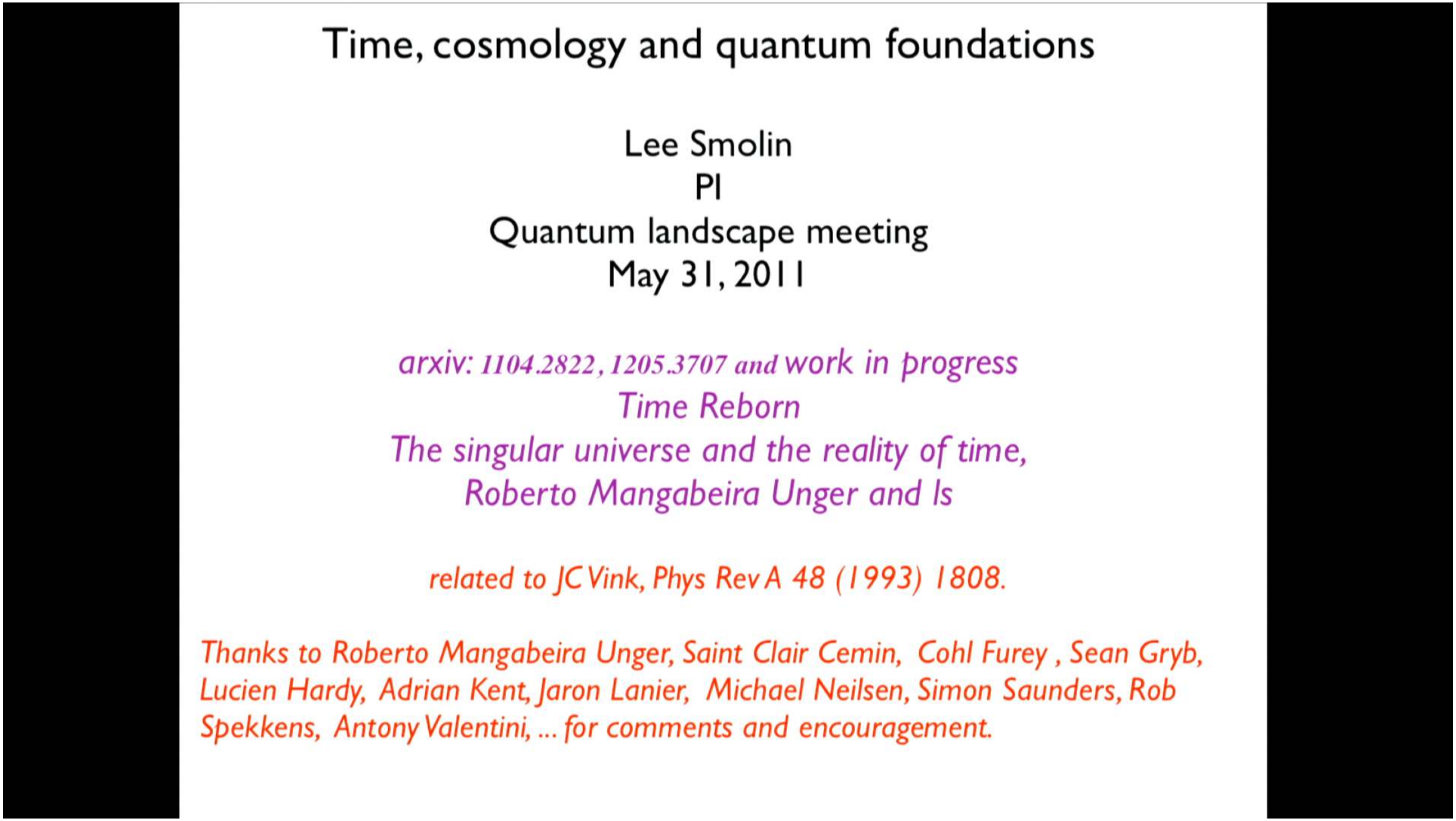
Abstract: I argue that quantum mechanics cannot usefully be extended to a theory of the whole universe, so the task of quantum foundations is to discover that cosmological theory which reduces to quantum mechanics when restricted to small subsystems of the universe. I argue that that cosmological theory will be based on a global notion of physical time which implies the distinction between past, present and future is real and objective. These motivate two examples of novel formulations of quantum theory: the real ensemble formulation and the principle of precedence. Each may imply departures from the expected quantum evolution for sufficiently large and complex quantum systems.



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Quantum landscape meeting
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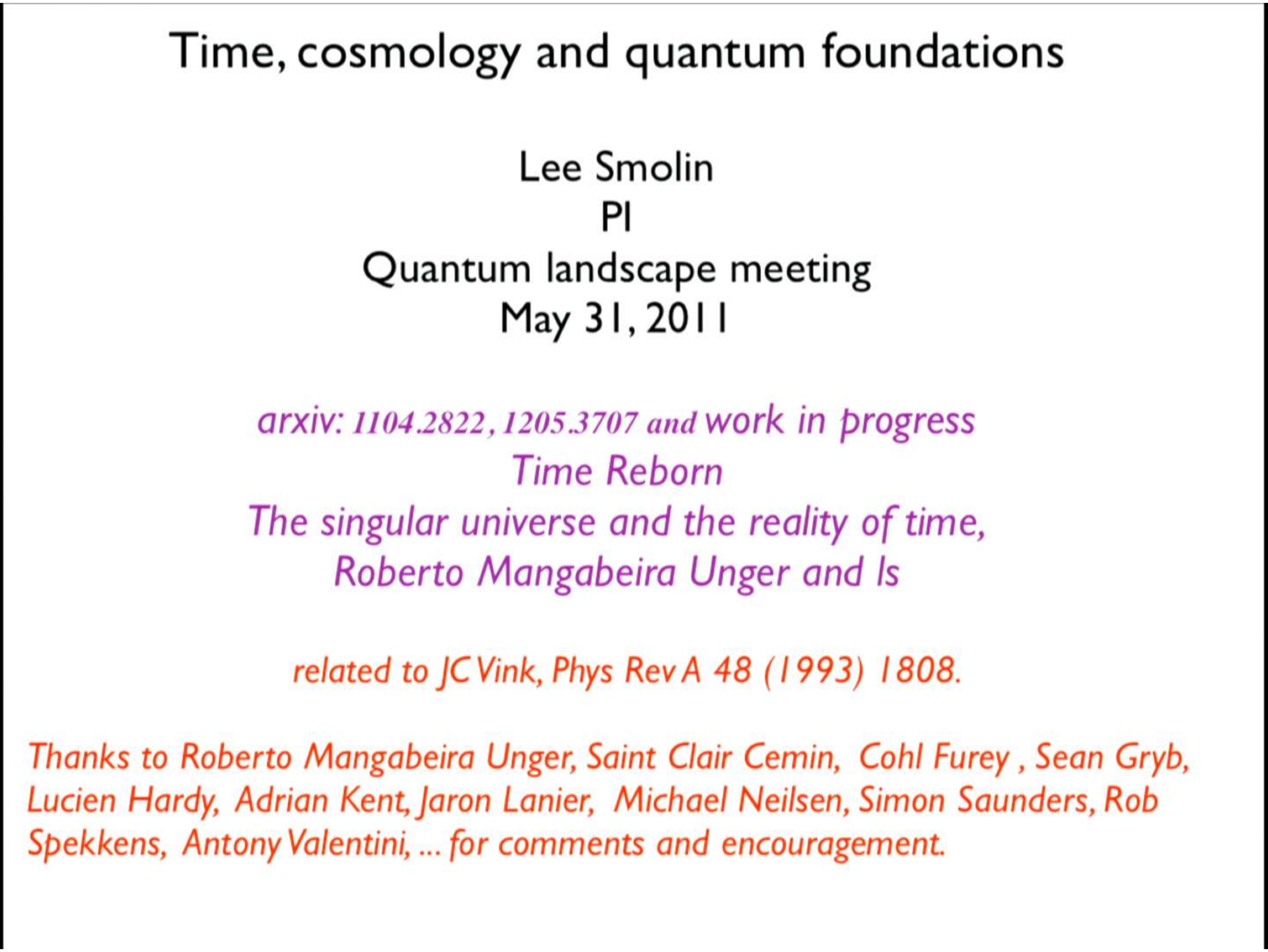

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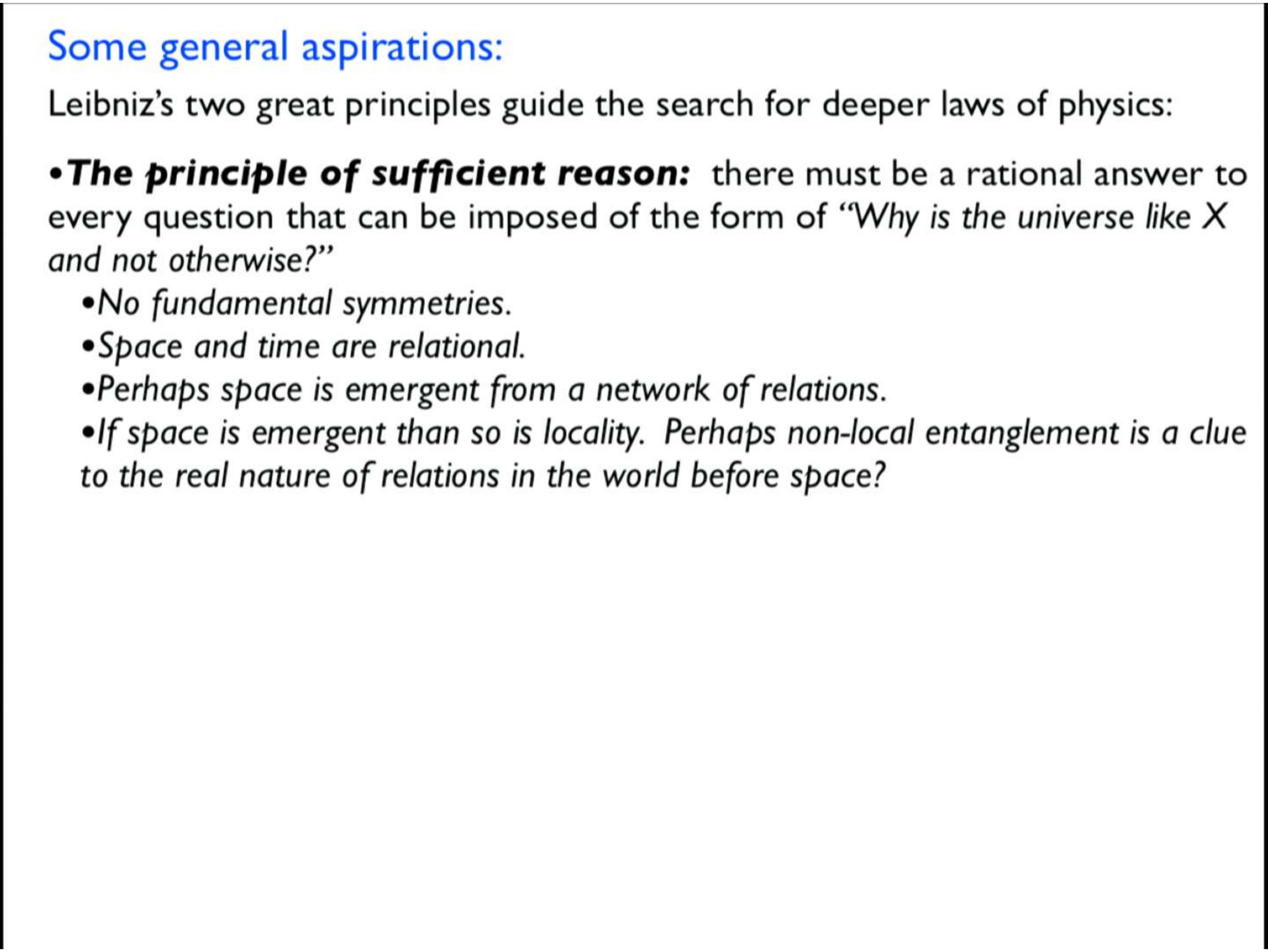

Some general aspirations:

Leibniz's two great principles guide the search for deeper laws of physics:

•***The principle of sufficient reason:*** there must be a rational answer to every question that can be imposed of the form of "*Why is the universe like X and not otherwise?*"

- *No fundamental symmetries.*
- *Space and time are relational.*
- *Perhaps space is emergent from a network of relations.*
- *If space is emergent than so is locality. Perhaps non-local entanglement is a clue to the real nature of relations in the world before space?*

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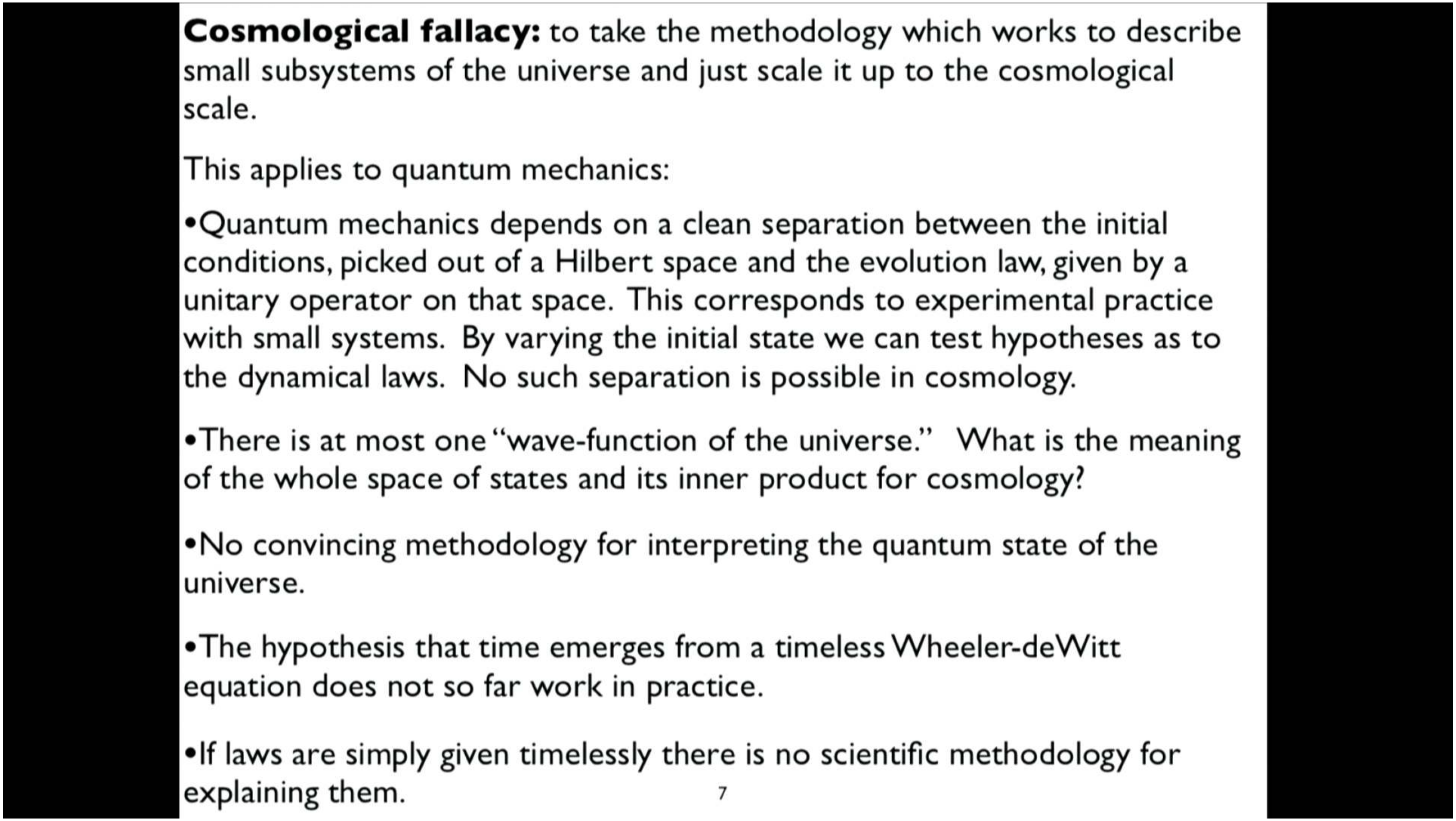
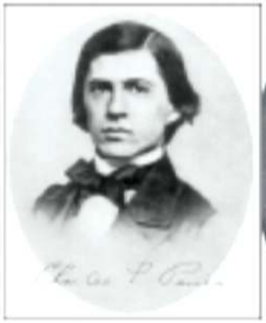


Cosmological fallacy: to take the methodology which works to describe small subsystems of the universe and just scale it up to the cosmological scale.

This applies to quantum mechanics:

- Quantum mechanics depends on a clean separation between the initial conditions, picked out of a Hilbert space and the evolution law, given by a unitary operator on that space. This corresponds to experimental practice with small systems. By varying the initial state we can test hypotheses as to the dynamical laws. No such separation is possible in cosmology.
- There is at most one "wave-function of the universe." What is the meaning of the whole space of states and its inner product for cosmology?
- No convincing methodology for interpreting the quantum state of the universe.
- The hypothesis that time emerges from a timeless Wheeler-deWitt equation does not so far work in practice.
- If laws are simply given timelessly there is no scientific methodology for explaining them.

Why these laws?



"To suppose universal laws of nature capable of being apprehended by the mind and yet having no reason for their special forms, but standing inexplicable and irrational, is hardly a justifiable position. Uniformities are precisely the sort of facts that need to be accounted for. Law is par excellence the thing that wants a reason. ***Now the only possible way of accounting for the laws of nature, and for uniformity in general, is to suppose them results of evolution.****"*

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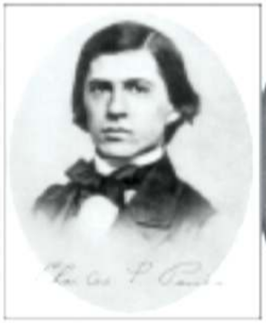

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Main claim: the unknown cosmological theory that quantum physics approximates when truncated to small subsystems requires a real time, with an objective distinction between a completed past and an, at least partly, open future.

- Allows laws to evolve in ways that imply testable predictions.

- Resolves the problem of time in quantum gravity and cosmology: no need to make sense of constrained evolution on an Hilbert space.

- Allows space to emerge given a real time (see CDT, quantum graphity...)

- Allows a realist completion of quantum physics, ie hidden variables and collapse models require a preferred simultaneity.

What about the experimental evidence for the relativity of simultaneity?

This is resolved by SHAPE DYNAMICS (SD) which is a reformulation of general relativity with preferred spatial slices (constant mean curvature) which trades the relativity of time for a relativity of scale. More technically, the many fingered time gauge invariance of GR is traded for a gauge invariance under volume preserving local conformal transformations.

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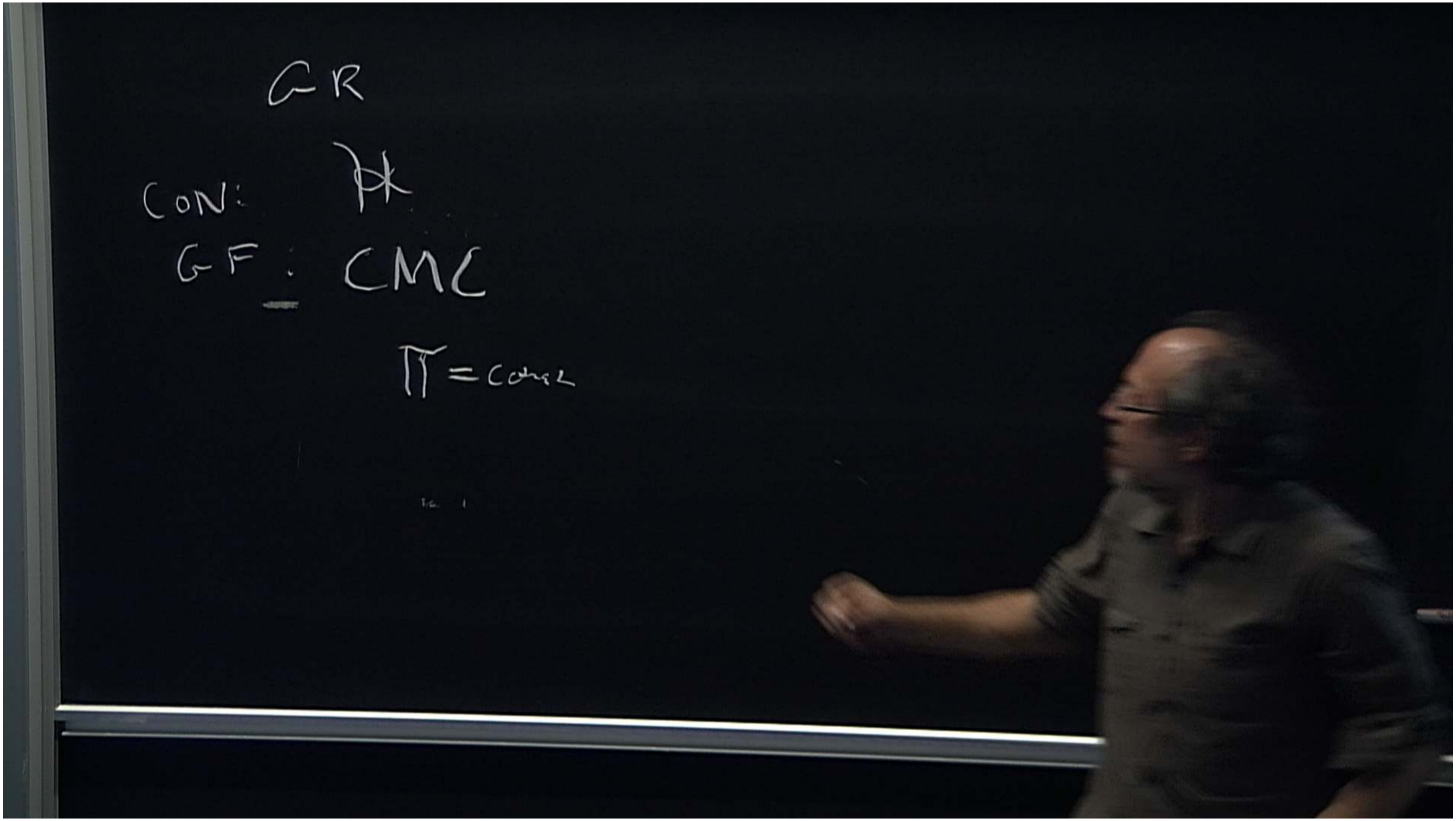
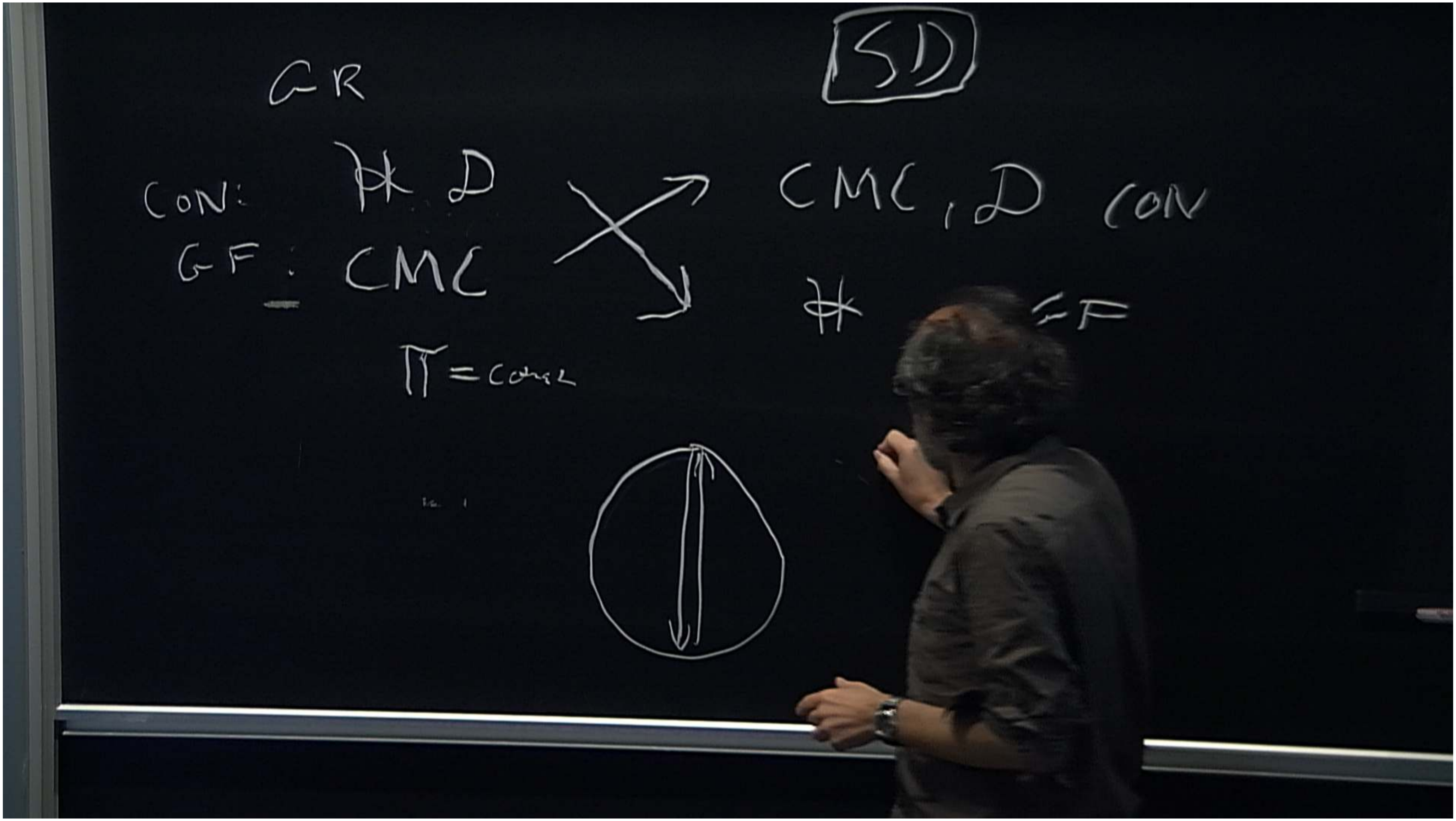


GR

CON: $\mathcal{H}$

GF: CMC

$\Pi = \text{const}$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CMC, D CON
H
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GR

$\boxed{SD}$

$$\begin{tikzcd} \text{CON: } \mathcal{H}, \mathcal{D} \arrow[dr] & \text{CMC}, \mathcal{D} \quad \text{CON} \\ \text{GF: CMC} \arrow[ur] & \mathcal{H} \quad \text{GF} \end{tikzcd}$$

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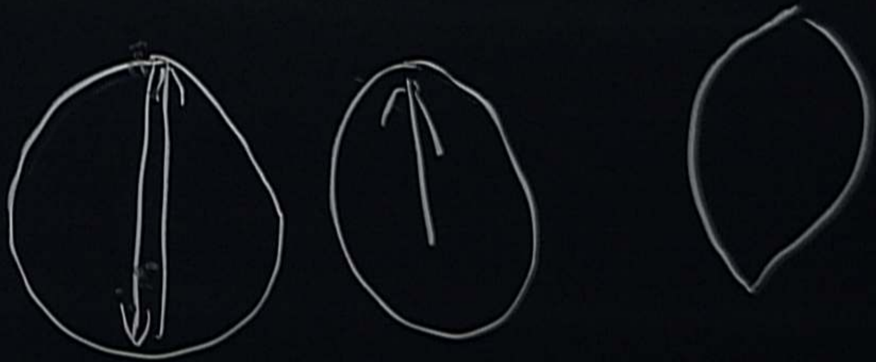

The principle of explanatory closure: *Everything that causally influences the behavior of a physical system within the universe must be another physical system within the universe.*

Hence:

- *No influence of "potentialities" on "actualities":*
- *No influence of epistemic ensembles which represent what might be true on the dynamics of a real particle.*

If an ensemble influences an individual system, then every single member of that ensemble must be a real system somewhere in the universe.

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Two possible places to look for that real ensemble:

- *In the present*
- *In the past.*

The Principle of Precedence:

There is a less radical assumption: What was just stated is the only law of nature needed.

If we prepare and measure a quantum system we have studied many times in the past, the response will be ~~as if the outcome were~~ randomly chosen from the ensemble of past instances of that preparation and measurement.

Eliminate double ontology

In dBB every individual system has a wavefunction:

$$\Psi(x,t) = \sqrt{\rho(x,t)}e^{\imath S(x,t)/\hbar}$$

$x(t)$ is a beable

$\rho(x)$ certainly looks like a property of an ensemble

$S(x,t)/h = \varphi(t)$ could be a property of the individual system. ie the system at x at time t carries a phase $e^{i\,\delta(t)}$.

The whole ensemble is needed to carry the information about the function $S(x,t)$.

Hypotheses: *The beables of an individual particle are the position $x(t)$ and phase $e^{i\,\varphi(t)}$. The Schrodinger equation reflects the interplay between the dynamics of an individual and an ensemble.*

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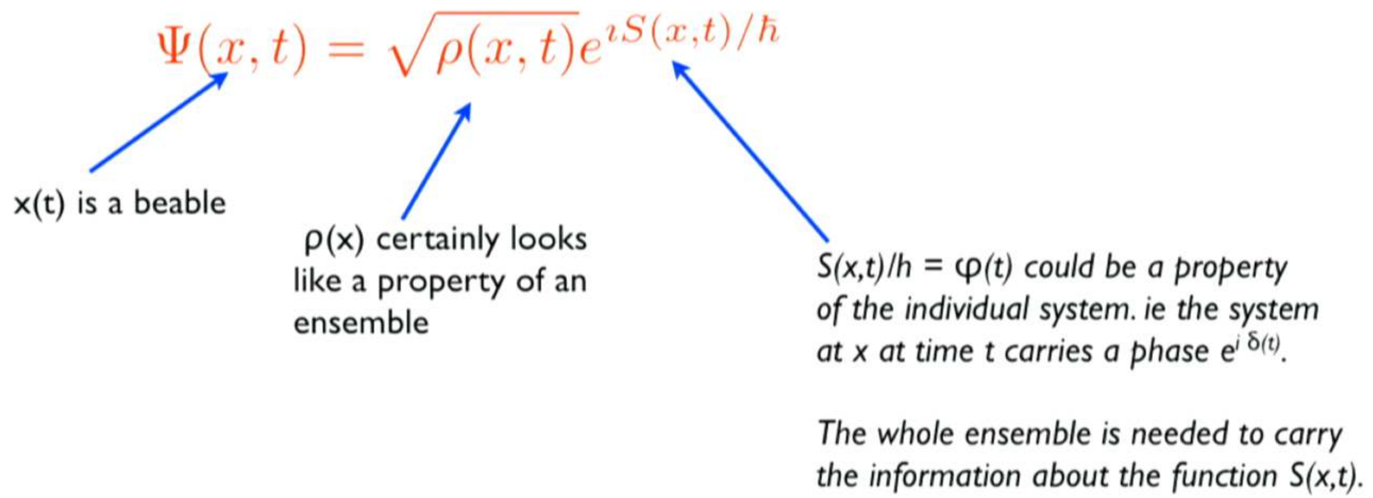

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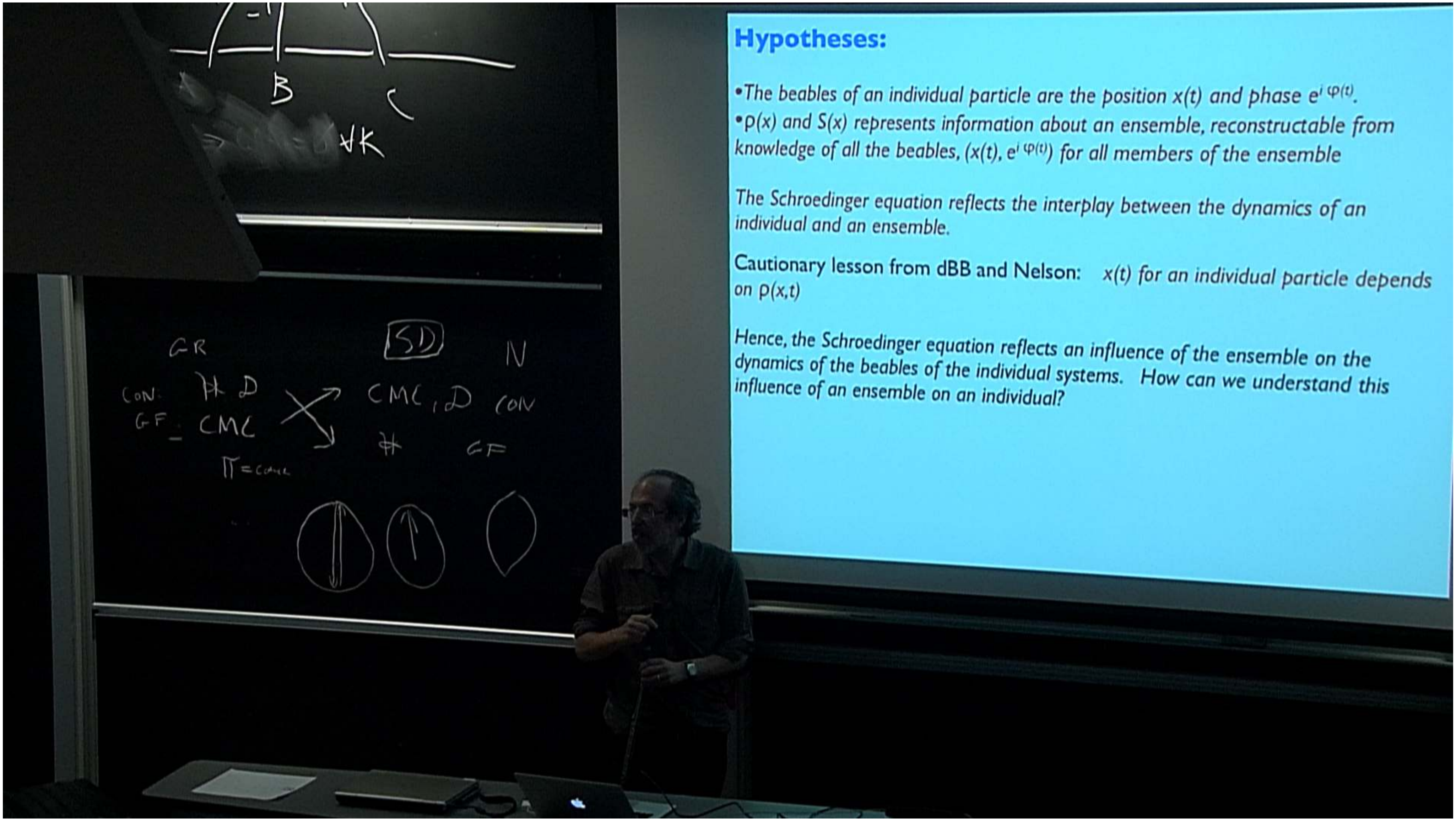

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- $\rho(x)$ and $S(x)$ represents information about an ensemble, reconstructable from knowledge of all the beables, $(x(t), e^{i\varphi(t)})$ for all members of the ensemble

The Schroedinger equation reflects the interplay between the dynamics of an individual and an ensemble.

Cautionary lesson from dBB and Nelson: *$x(t)$ for an individual particle depends on $\rho(x,t)$*

Hence, the Schroedinger equation reflects an influence of the ensemble on the dynamics of the beables of the individual systems. How can we understand this influence of an ensemble on an individual?

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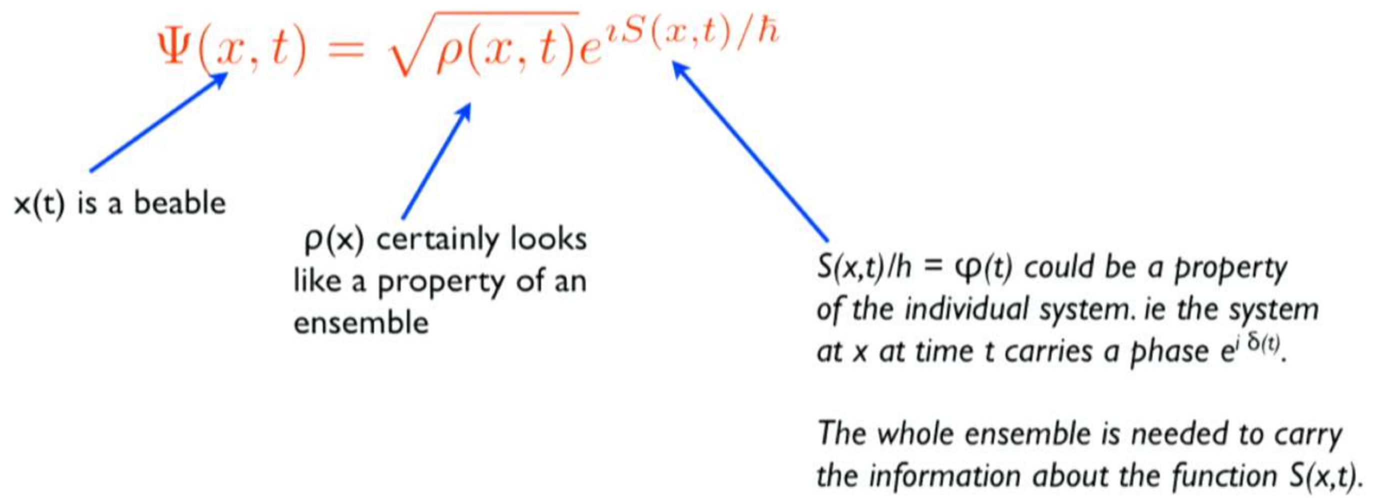

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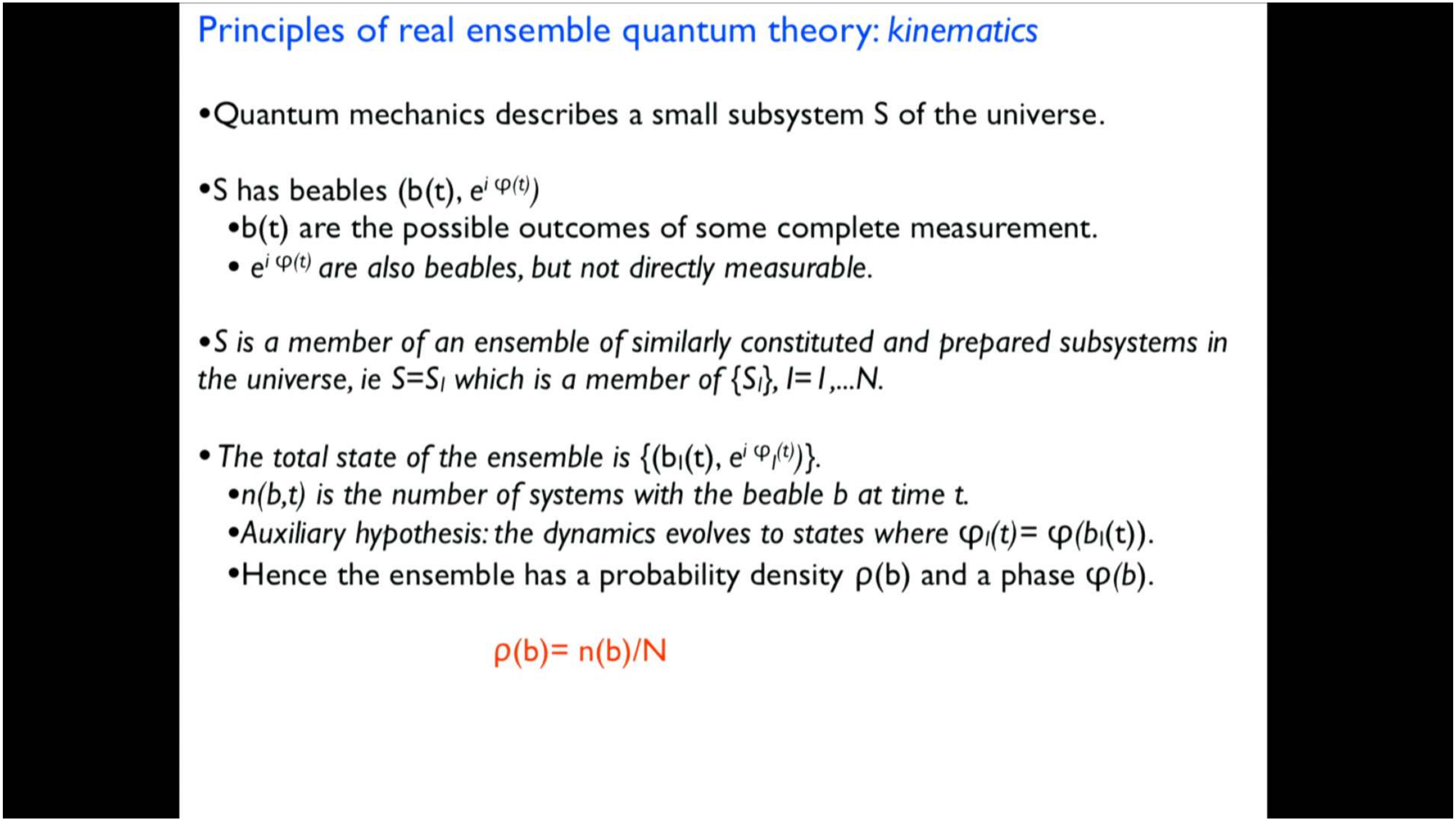
Where in the universe are the members of the ensemble described by the wavefunction of a hydrogen atom in its ground state?

Could that ensemble be nothing but the collection of all the hydrogen atoms in their ground state in the universe? Might they somehow interact by virtue of their sharing the same state, leading to the influence of the ensemble on the individual?

Can we take the identity of the indescernible so seriously that atoms in indistinguishable states (apart from the values of their beables) can be confused for each other even if they are far seperated in space?



Principles of real ensemble quantum theory: *kinematics*

- Quantum mechanics describes a small subsystem S of the universe.

- S has beables $(b(t), e^{i\,\varphi(t)})$
  - $b(t)$ are the possible outcomes of some complete measurement.
  - $e^{i\,\varphi(t)}$ *are also beables, but not directly measurable.*

- *S is a member of an ensemble of similarly constituted and prepared subsystems in the universe, ie* $S=S_I$ *which is a member of* $\{S_I\}$, $I=1,\ldots N$.

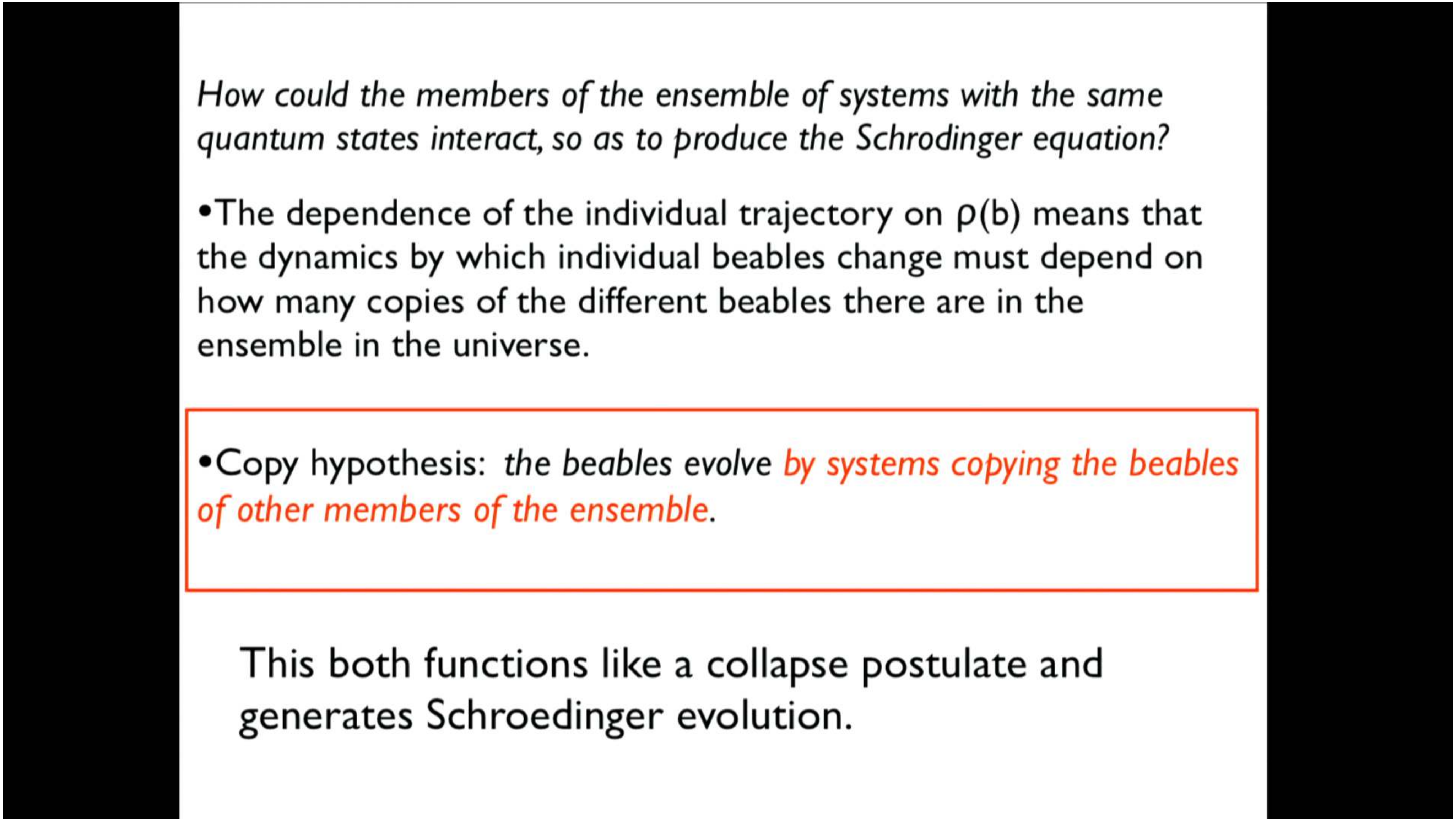
- *The total state of the ensemble is* $\{(b_I(t), e^{i\,\varphi_I(t)})\}$.
  - $n(b,t)$ *is the number of systems with the beable b at time t.*
  - *Auxiliary hypothesis: the dynamics evolves to states where* $\varphi_I(t)= \varphi(b_I(t))$.
  - Hence the ensemble has a probability density $\rho(b)$ and a phase $\varphi(b)$.

$$\rho(b)= n(b)/N$$

How could the members of the ensemble of systems with the same quantum states interact, so as to produce the Schrodinger equation?

- The dependence of the individual trajectory on $\rho(b)$ means that the dynamics by which individual beables change must depend on how many copies of the different beables there are in the ensemble in the universe.

- Copy hypothesis: *the beables evolve by systems copying the beables of other members of the ensemble*.



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This both functions like a collapse postulate and generates Schroedinger evolution.

How do the phases $\varphi_I(t)$ evolve?

- There is a continuous and deterministic evolution rule for the $\varphi_I(t)$

$$\boxed{\dot{\phi}^I = \sum_J G(n_I, \phi_I, n_J, \phi_J, b_I, b_J)}$$

Summary of *dynamics*

- Copy hypothesis: *the beables evolve by systems copying the beables of other members of the ensemble. This is given by a stochastic rule:*
- *The rate P(I copy J) that system I copies the beables of system J:*

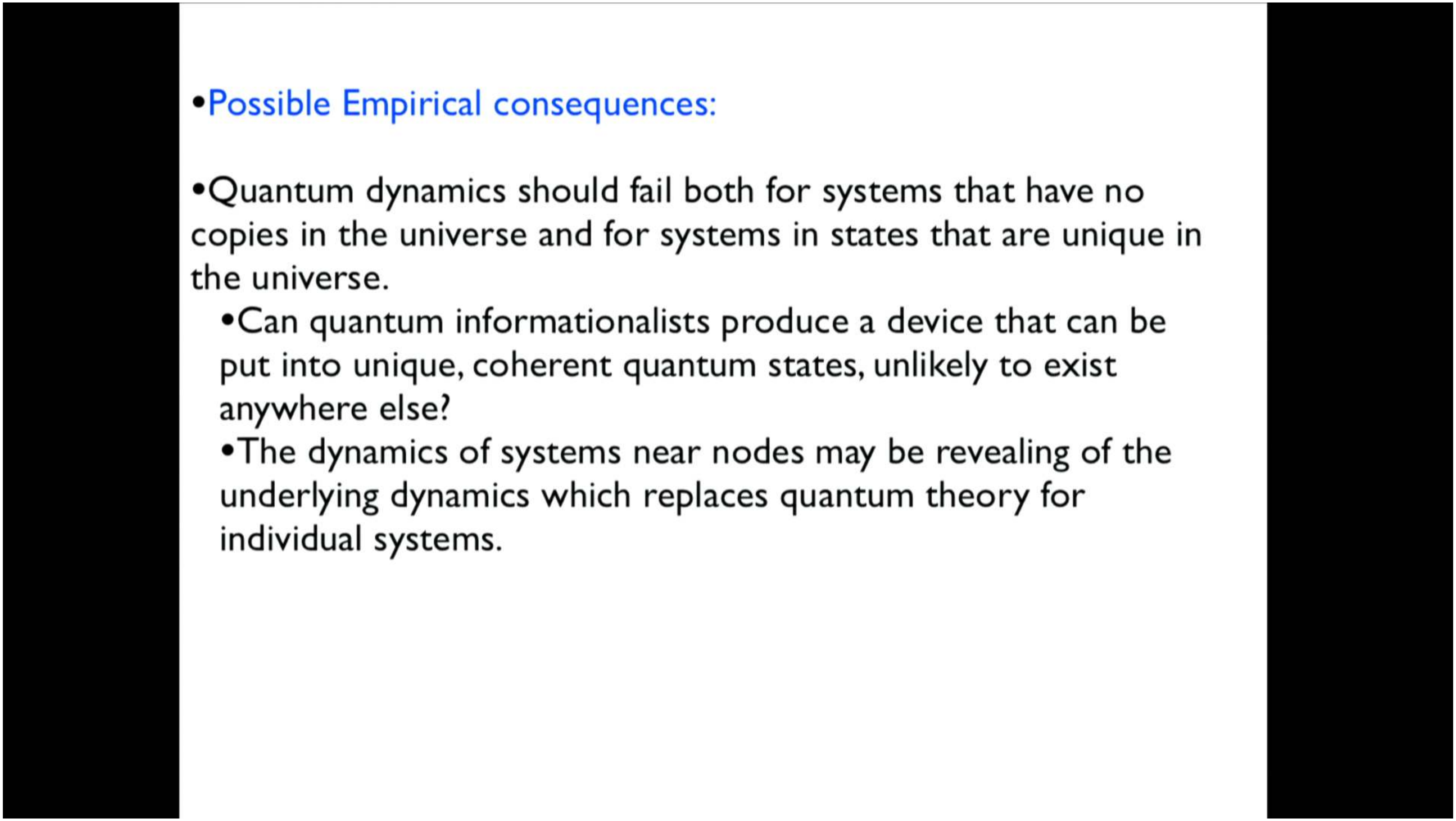
$$P(I\mathrm{copy}J) = F(n_I, \phi_I, n_J, \phi_J, b_I, b_J)$$

When this happens

$$b_I \rightarrow b_J, \qquad \phi_I \rightarrow \phi_J$$

- *There is otherwise a continuous and deterministic evolution rule for the* $\varphi_I(t)$

$$\dot{\phi}^I = \sum_J G(n_I, \phi_I, n_J, \phi_J, b_I, b_J)$$



- Possible Empirical consequences:

- Quantum dynamics should fail both for systems that have no copies in the universe and for systems in states that are unique in the universe.
  - Can quantum informationalists produce a device that can be put into unique, coherent quantum states, unlikely to exist anywhere else?
  - The dynamics of systems near nodes may be revealing of the underlying dynamics which replaces quantum theory for individual systems.

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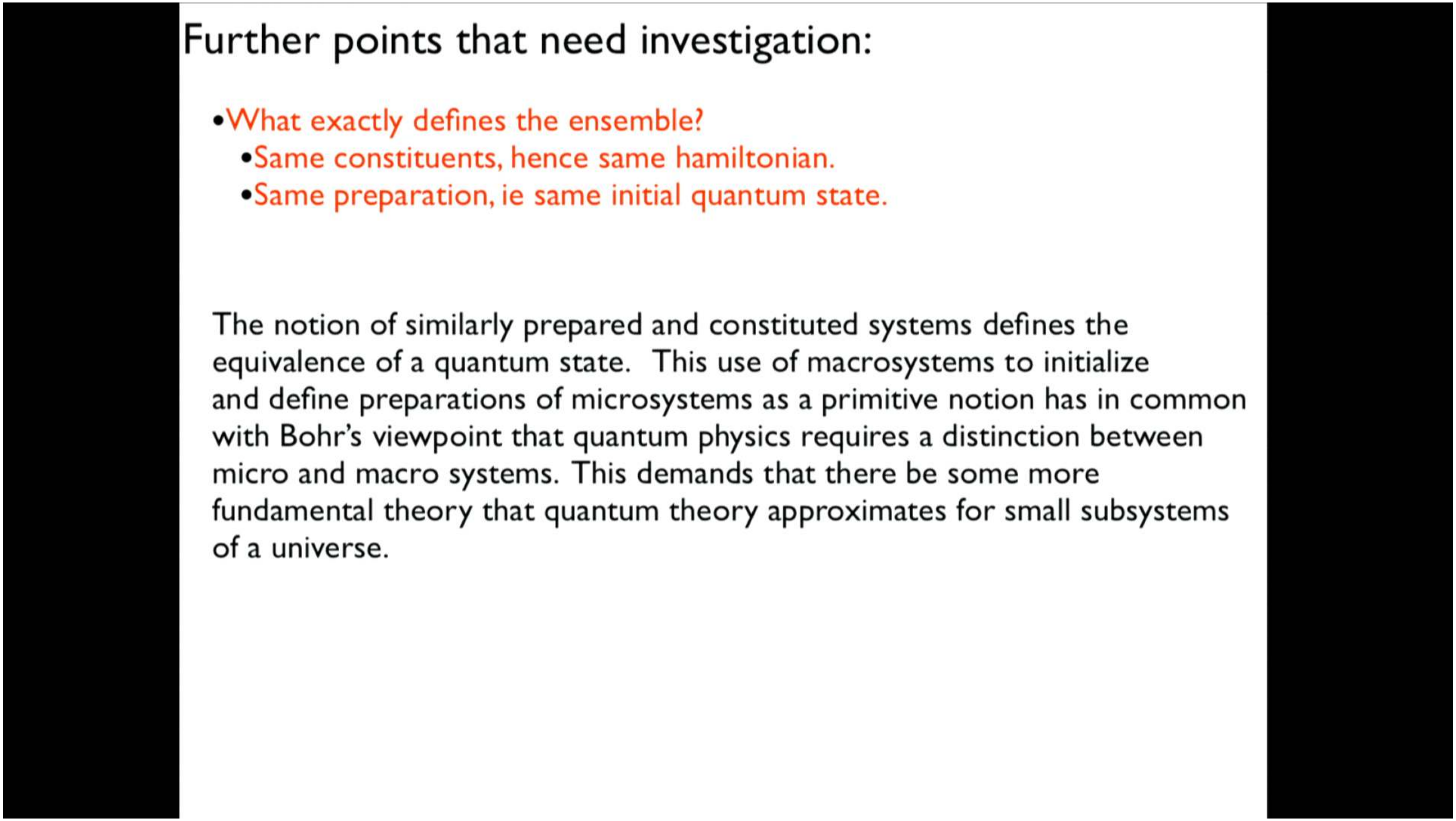


Further points that need investigation:

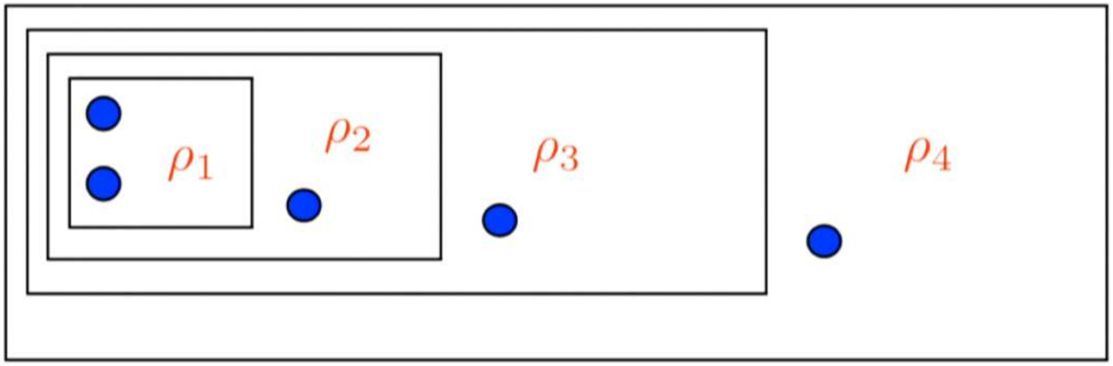
- What exactly defines the ensemble?
  - Same constituents, hence same hamiltonian.
  - Same preparation, ie same initial quantum state.

The notion of similarly prepared and constituted systems defines the equivalence of a quantum state. This use of macrosystems to initialize and define preparations of microsystems as a primitive notion has in common with Bohr's viewpoint that quantum physics requires a distinction between micro and macro systems. This demands that there be some more fundamental theory that quantum theory approximates for small subsystems of a universe.

The subsystem problem

Consider a quark. It is a subsystem of a proton, which is a subsystem of a nucleus, which is a subsystem of an atom, a molecule, etc. What determines which ensemble is relevant for purposes of the copy dynamics?

At each level the subsystem is described by a density matrix. $\rho_I = Tr \rho_{I+1}$



There is only one level, I such that ρ_I is pure and not a product state. That is the pure state the ensemble refers to.