Title: Relative states and the environment: Einselection, envariance, quantum Darwinism, and the existential interpretation (Part 2)

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Abstract:

Quantum Foundations

Relative States and the Environment

(Everett '57)

Wojciech Hubert Zurek
Theory Division, Los Alamos

"BEYOND DECOHERENCE"

WHZ, quant-ph arXiv:0707.2832 "**Relative states & the environment**:…"
Phys. Today **44**, 36-44 (1991) (quant-ph/0306072)
Rev. Mod. Phys. **75**, 715 (2003) (quant-ph/0105127)
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Textbook Quantum Theory

0. State of a composite system is a vector in the tensor product of the constituent Hilbert spaces. ("**Complexity**")
1. Quantum states of a system are represented by vectors in its Hilbert space. **("Quantum Superposition Principle"**)
2. Evolutions are unitary (e.g. generated by Schroedinger equation). **("Unitarity")**
3. Immediate repetition of a measurement yields the same outcome. **("Predictability")**
4. Outcomes restricted to orthonormal states $\{|s_k>\}$ (eigenstates of the measured observable). Just one outcome is seen each time. **("Collapse Postulate")**
5. Probability of finding an outcome $|s_k>$ given states $|f>$ is $p_k=|<s_k|f>|^2$. **("Born's Rule")**

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Summary: Observables are Hermitean

Theorem: Outcomes of a measurement that satisfy postulates 1-3 must be orthogonal.

Proof (another version): measurement is an information transfer from a quantumsystem *S* to a **quantum** apparatus *A*. So, for any two possible **repeatable (predictable)** (Axiom 3) outcome states of the same measurement it must be true that:

$$|u\rangle|A_0\rangle \Rightarrow |u\rangle|A_u\rangle$$

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By **unitarity** (Axiom 2) scalar product of the total (*S*+*A*) state before and after must be the same. So:

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But $\langle A_0|A_0\rangle = 1$**. So either** $\langle A_u|A_v\rangle = 1$ **(measurement was not successful) or** $\langle u|v\rangle = 0$ **. QED!!!!!**

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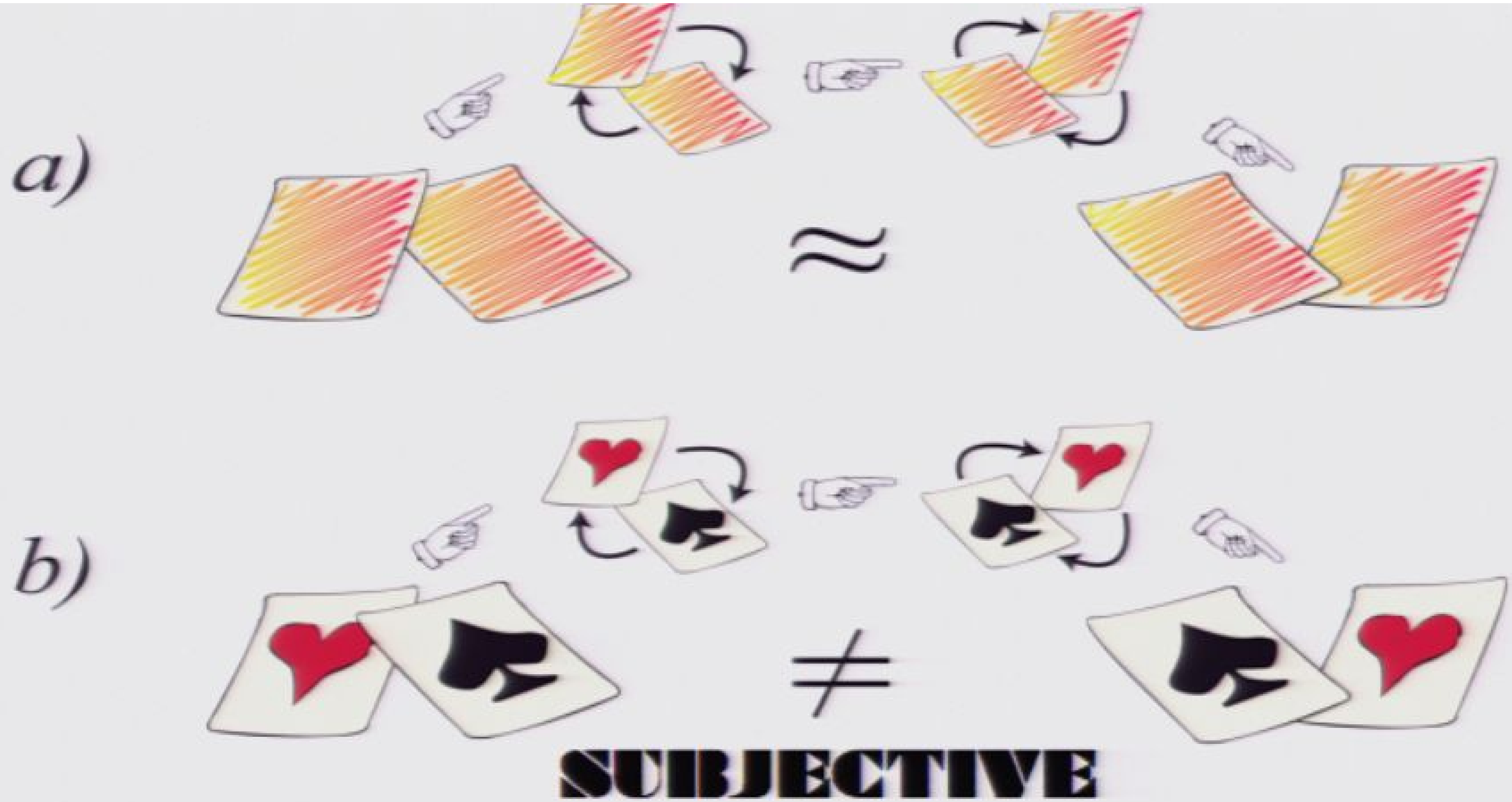
EVENTS!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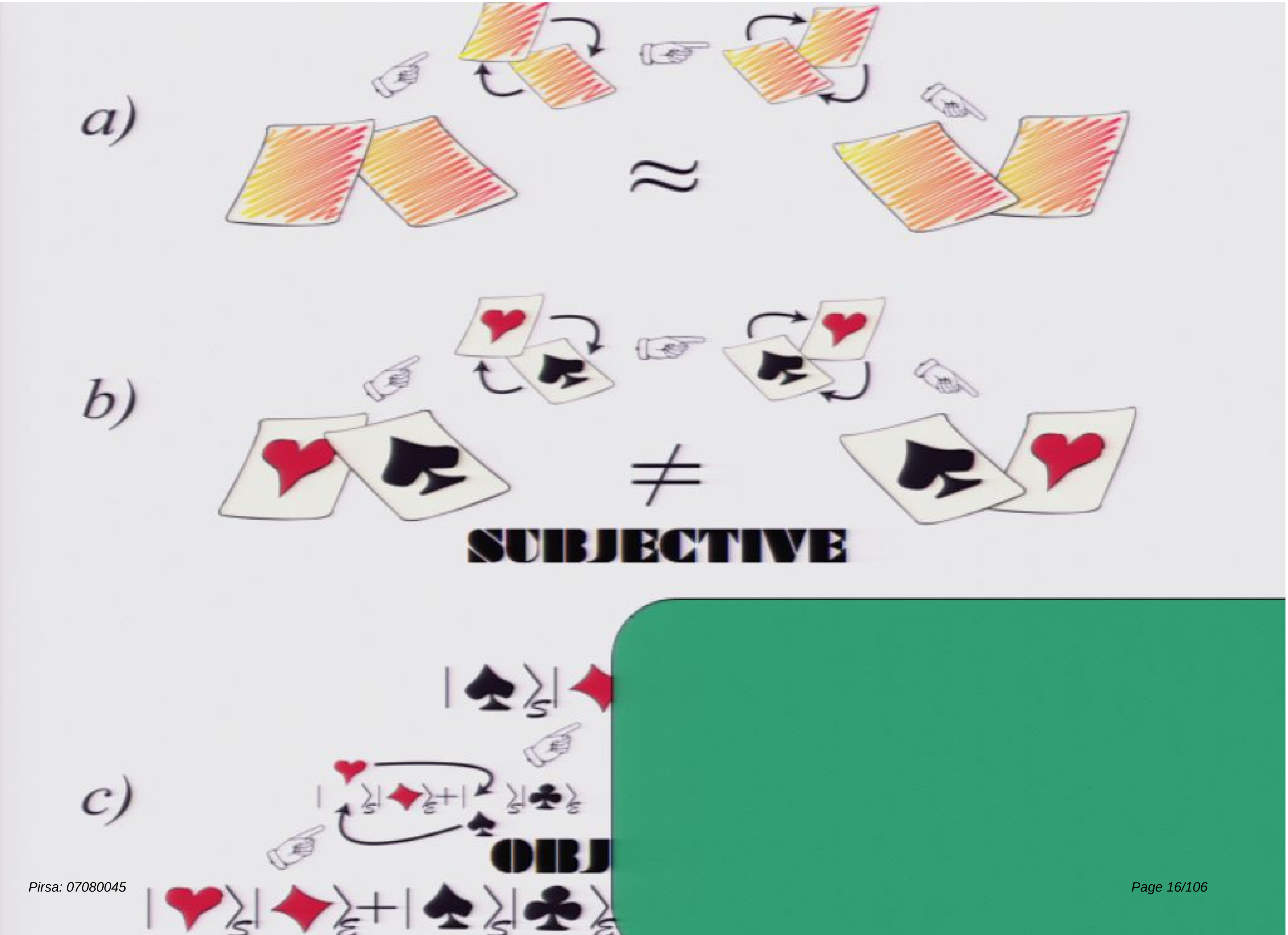
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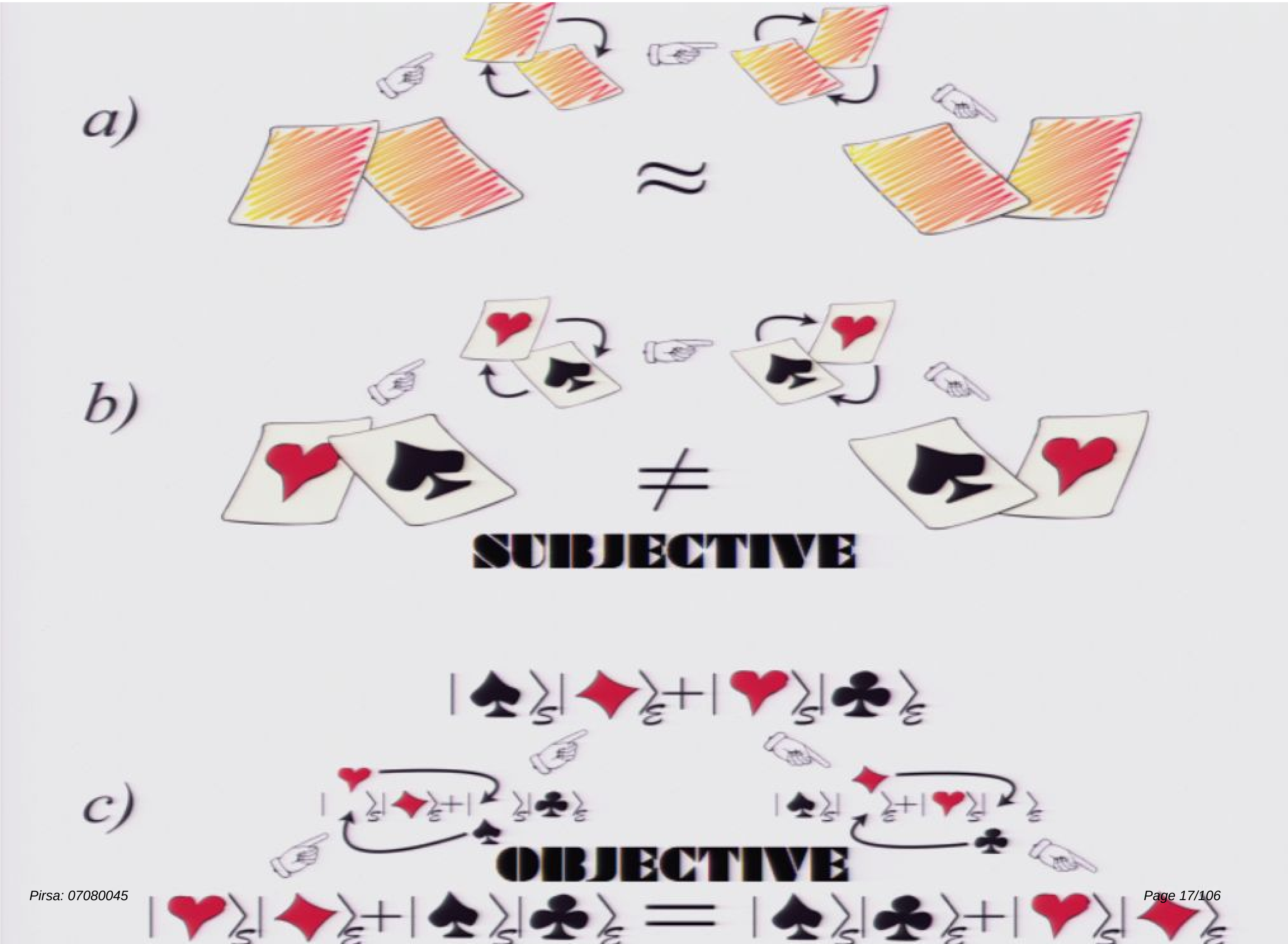
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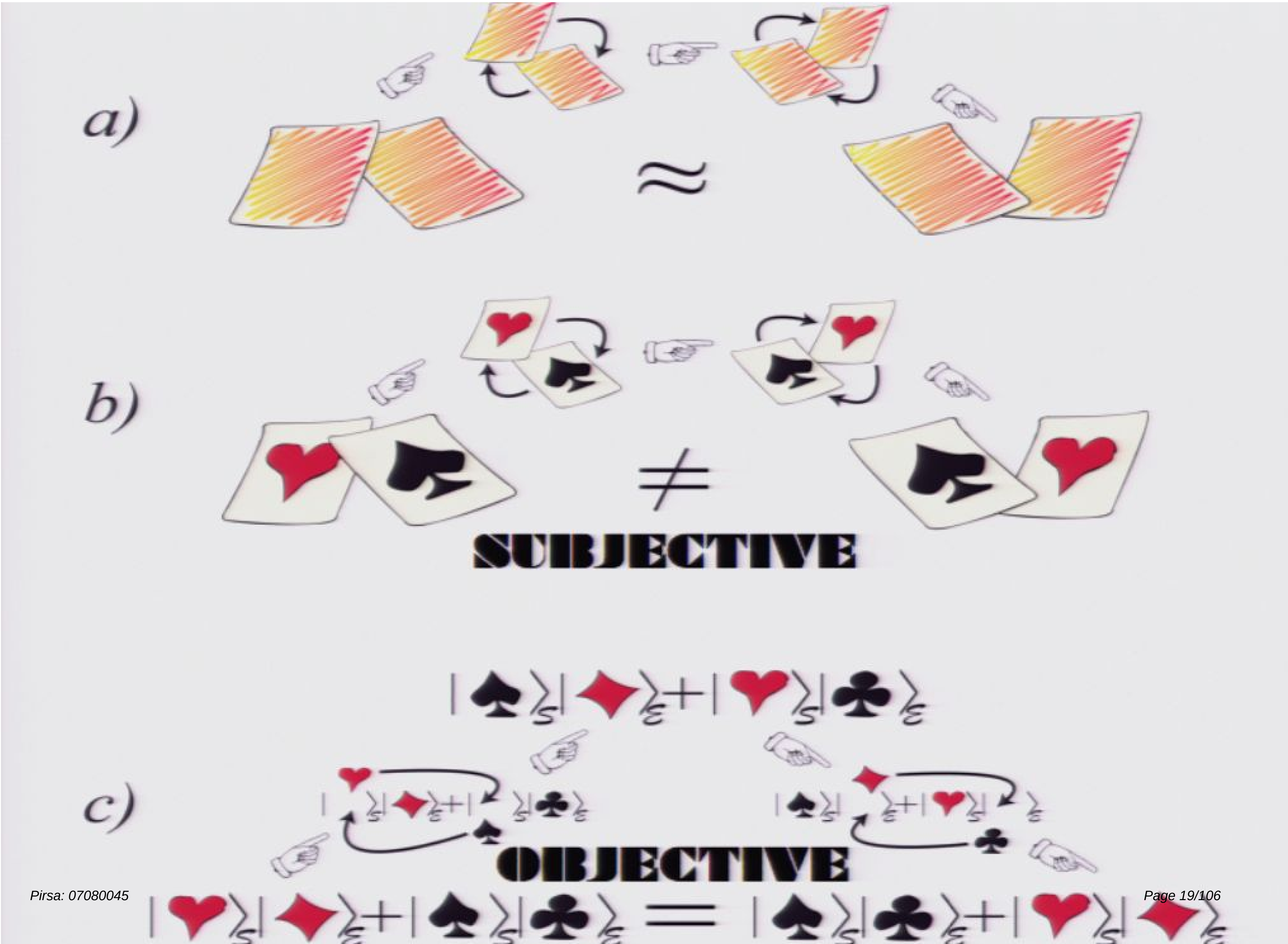
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Plan of the Lectures

LECTURE 1

- Decoherence 101; the basic idea, and why it is not basic enough for "foundations"
- Origin of quantum jumps (orthogonality & collapse)
- Derivation of probability in quantum theory --Born's rule $\left(p_k = |\psi_k|^2\right)$

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(ii) Have a way to assign probability to Schmidt states.

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- Existential interpretation

"...Let ψ_1 and ψ_2 be two solutions of the same Schrödinger equation... When the system is a macrosystem and when ψ_1 and ψ_2 are 'narrow' with respect to position, then in by far the greater number of cases this is no longer true for $\psi_{12} = \psi_1 + \psi_2$. Narrowness with respect to macrocoordinates is not only *independent* of the principles of quantum mechanics, but is, moreover, *incompatible* with them."

Einstein to Born (letter, dated April 1954)

Space is big, really big... you just won't believe how hugely mind-bogglingly big it is...

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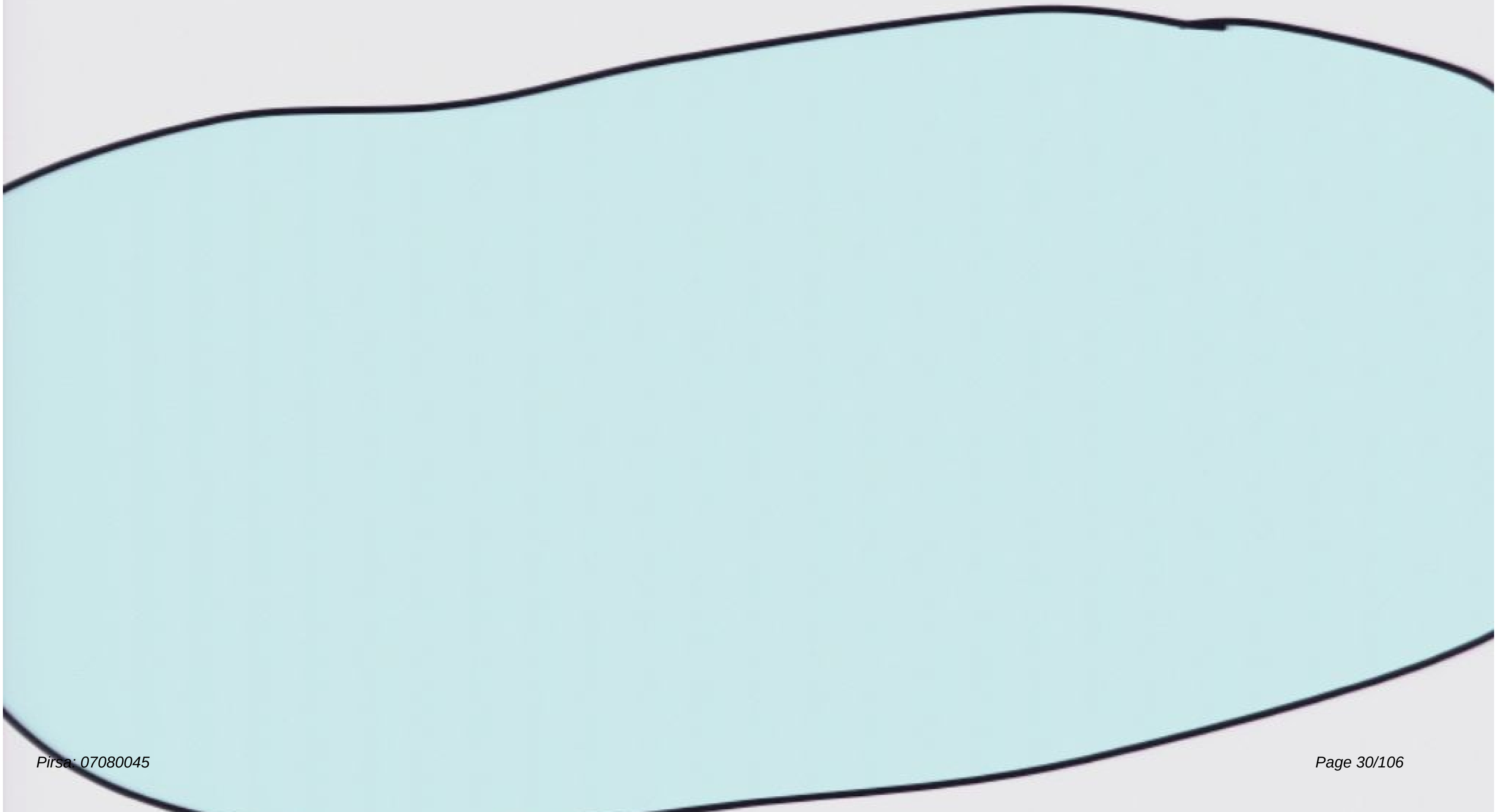

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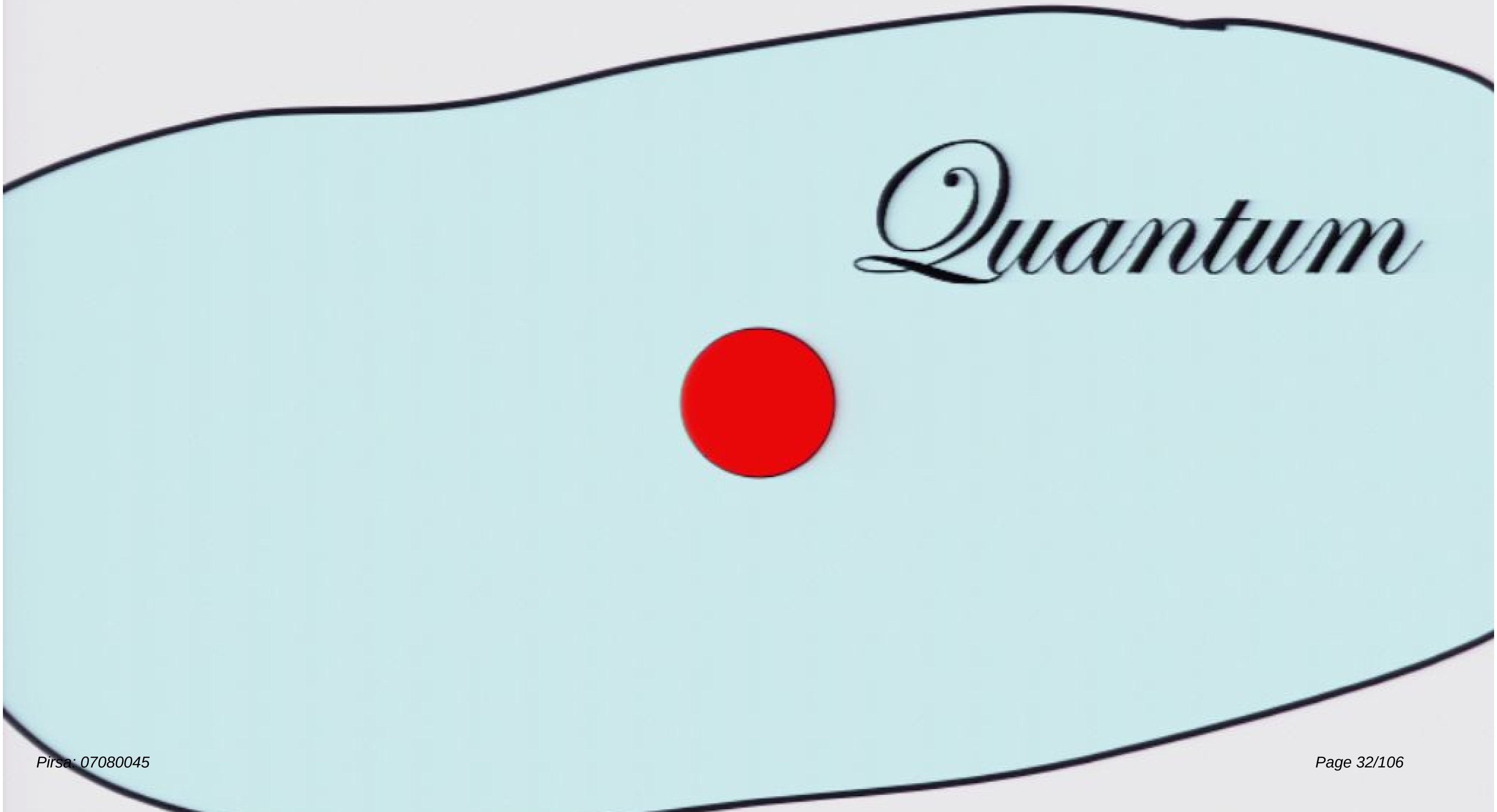

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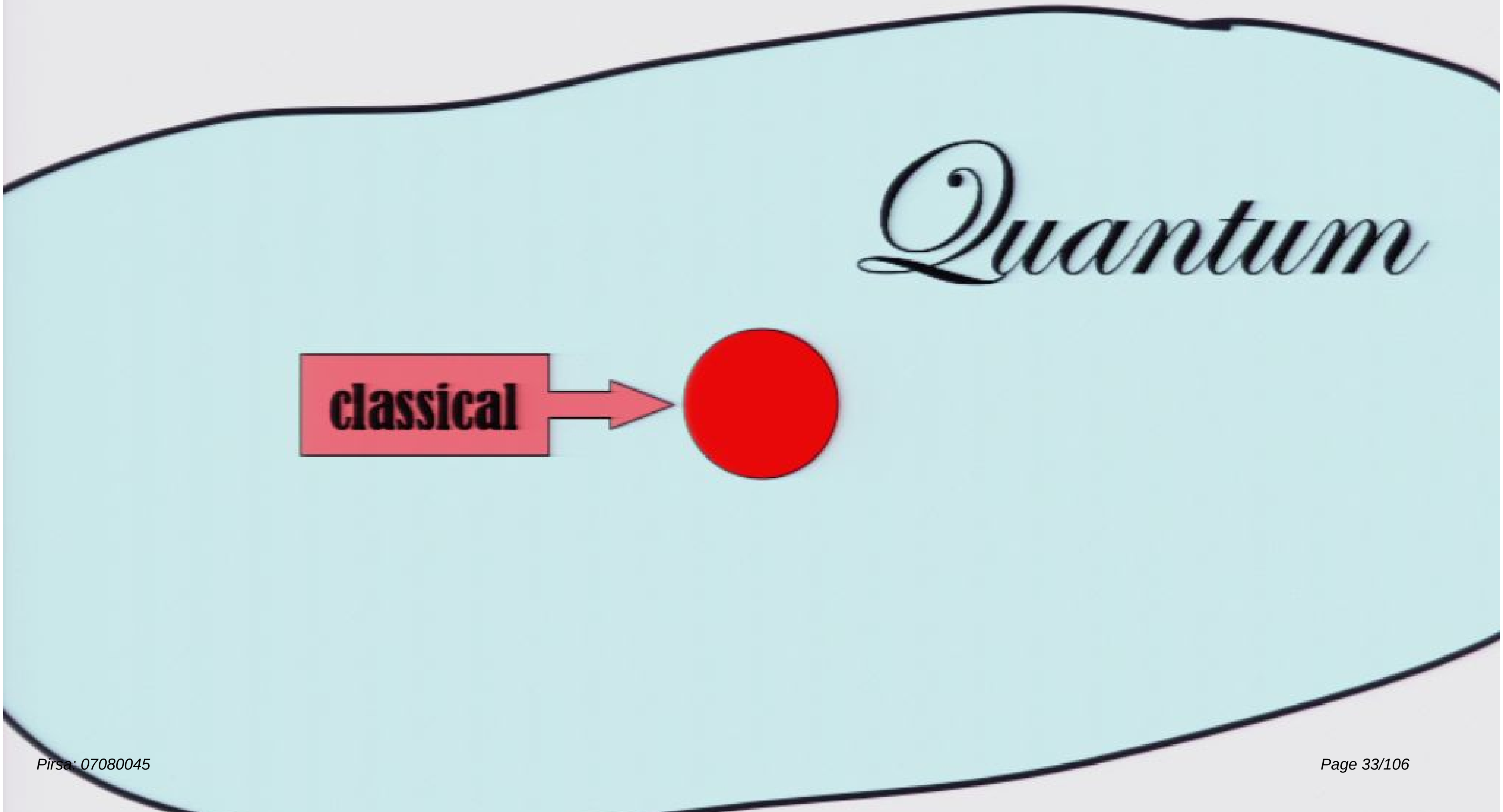

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Superposition Begets Entanglement

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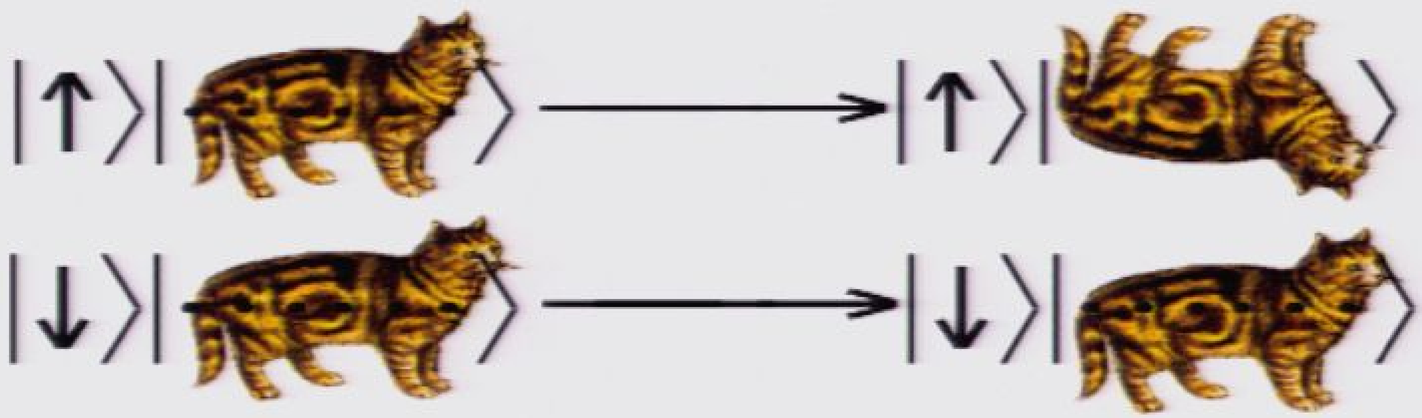
Cat in a box with a gun set of by the spin "up" (nothing happens when the spin is "down"). So:



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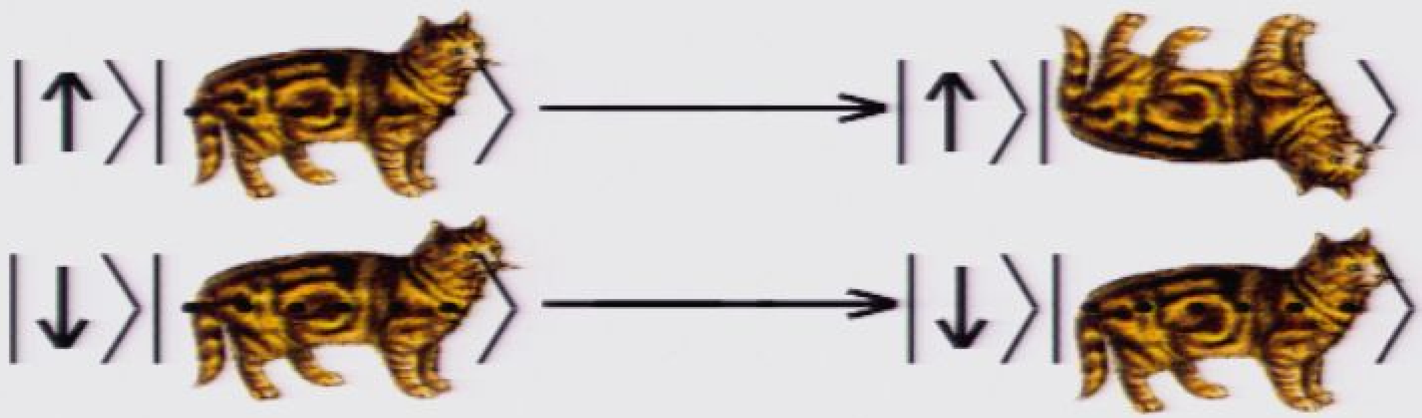

Therefore:

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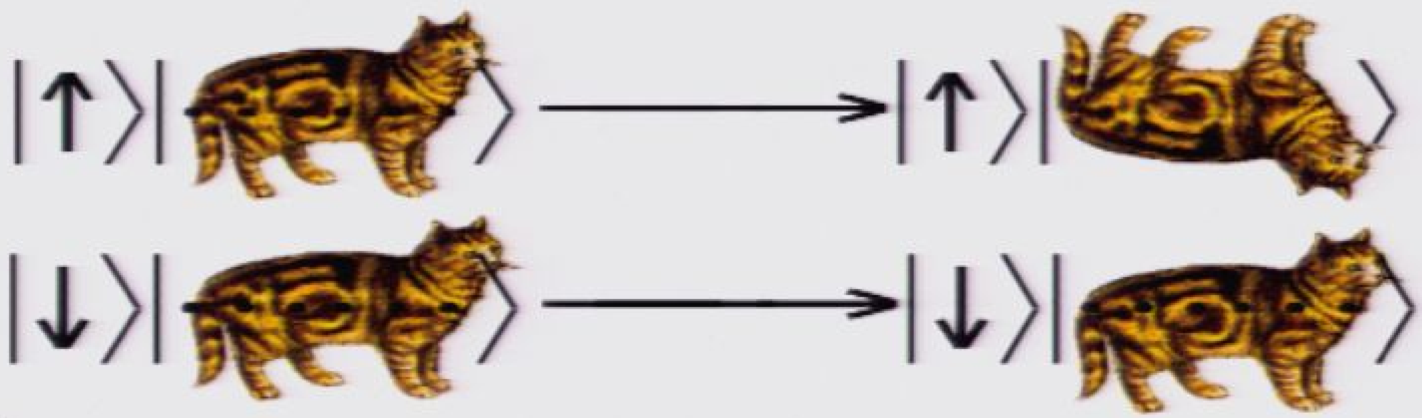

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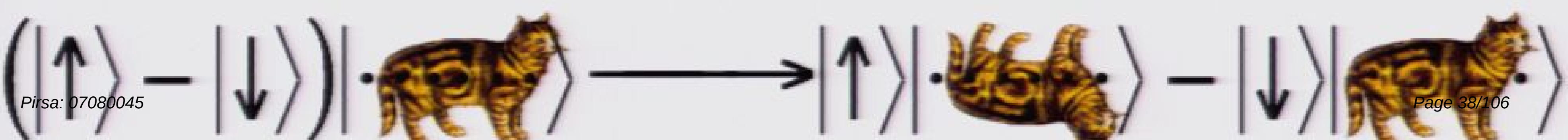
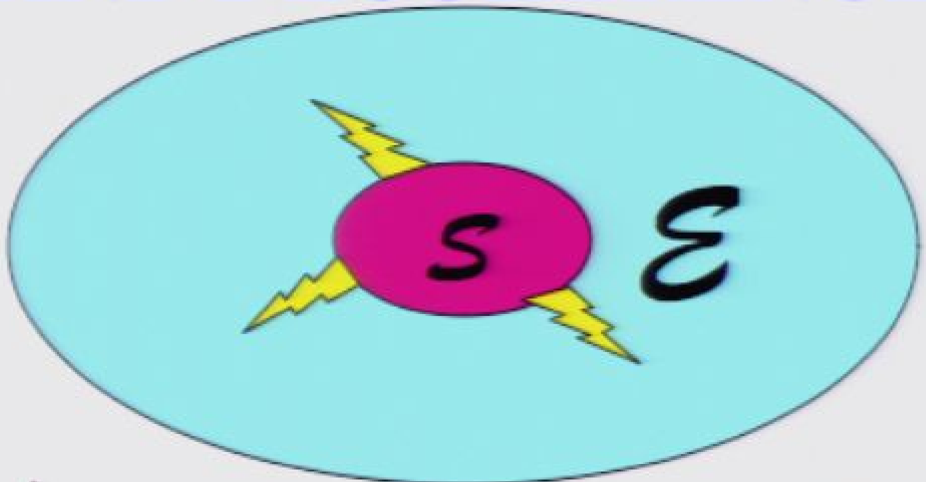
As well as:



EINSELECTION*, POINTER BASIS, AND DECOHERENCE



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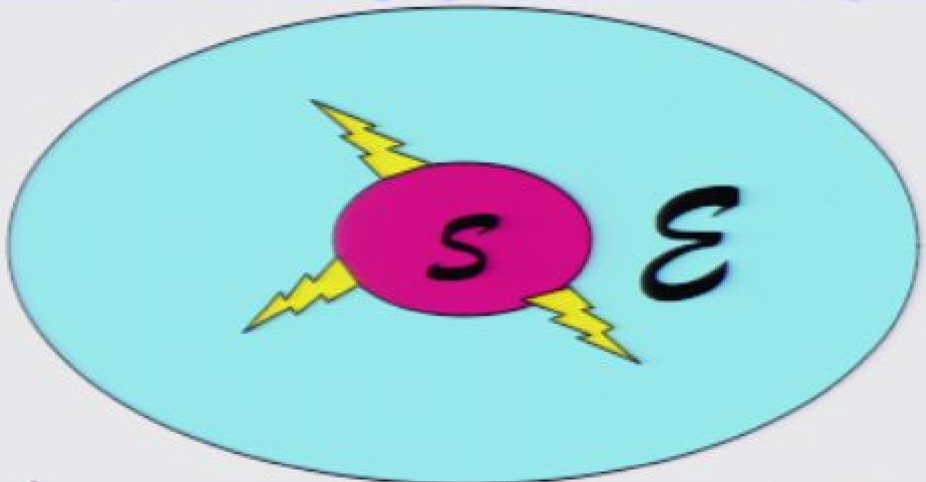

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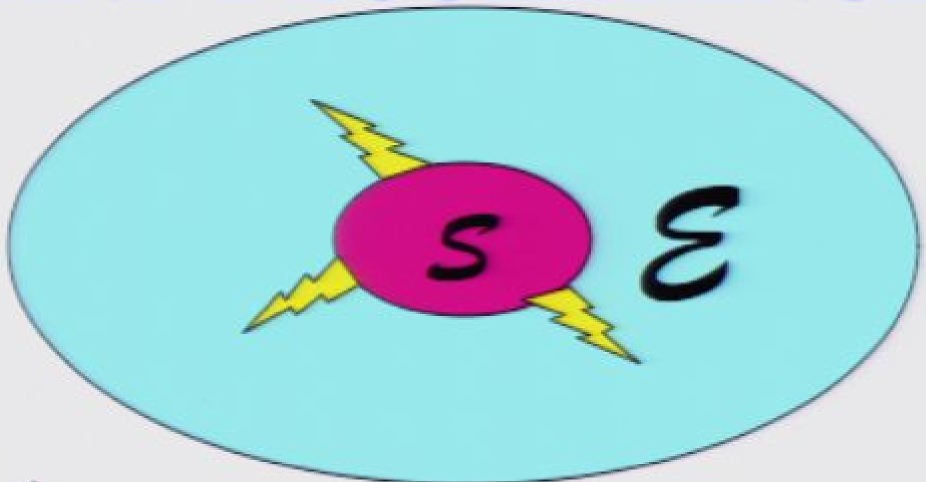

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EINSELECTION* leads to POINTER STATES

(same states appear on the diagonal of $\rho_S(t)$ for times long compared to the decoherence time; **pointer states** are effectively classical!)

Pointer states **left unperturbed** by the "environmental monitoring".

***Environment INduced superSELECTION**

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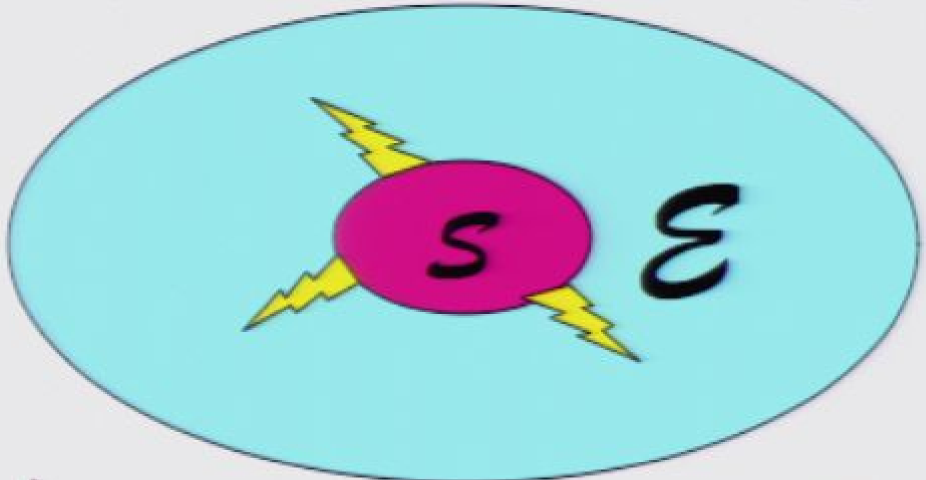

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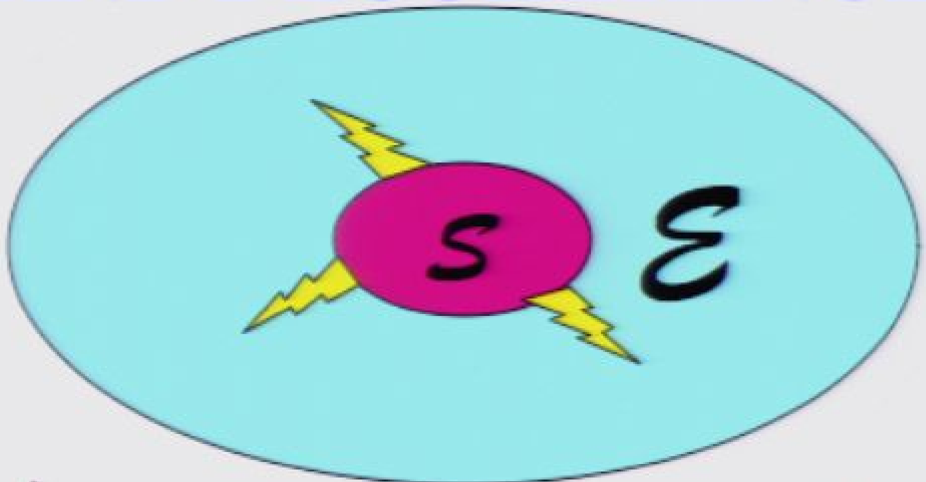

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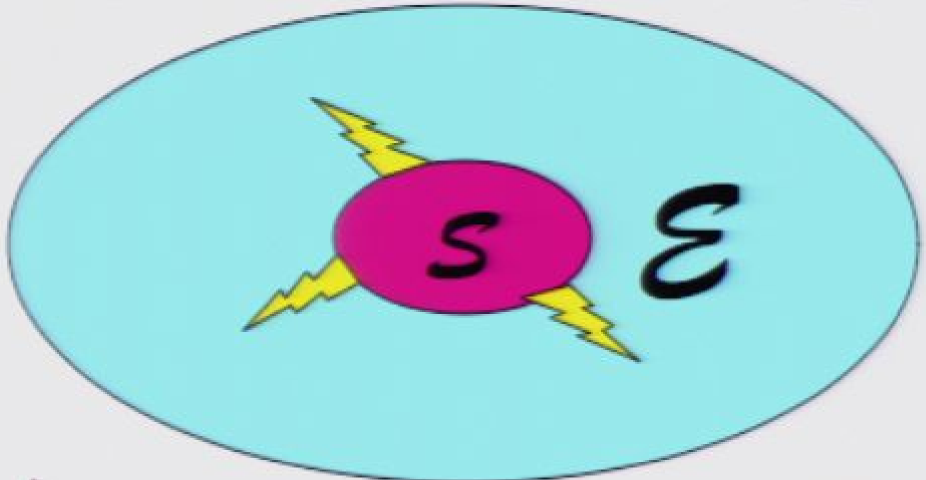

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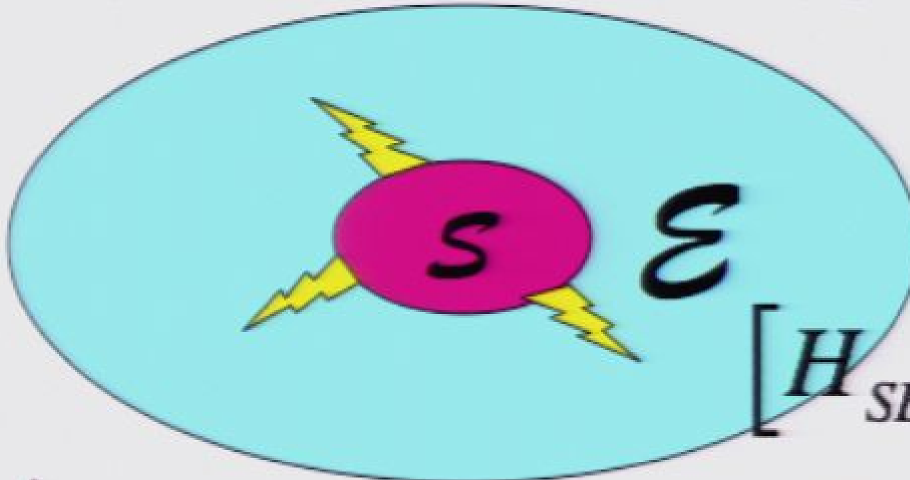

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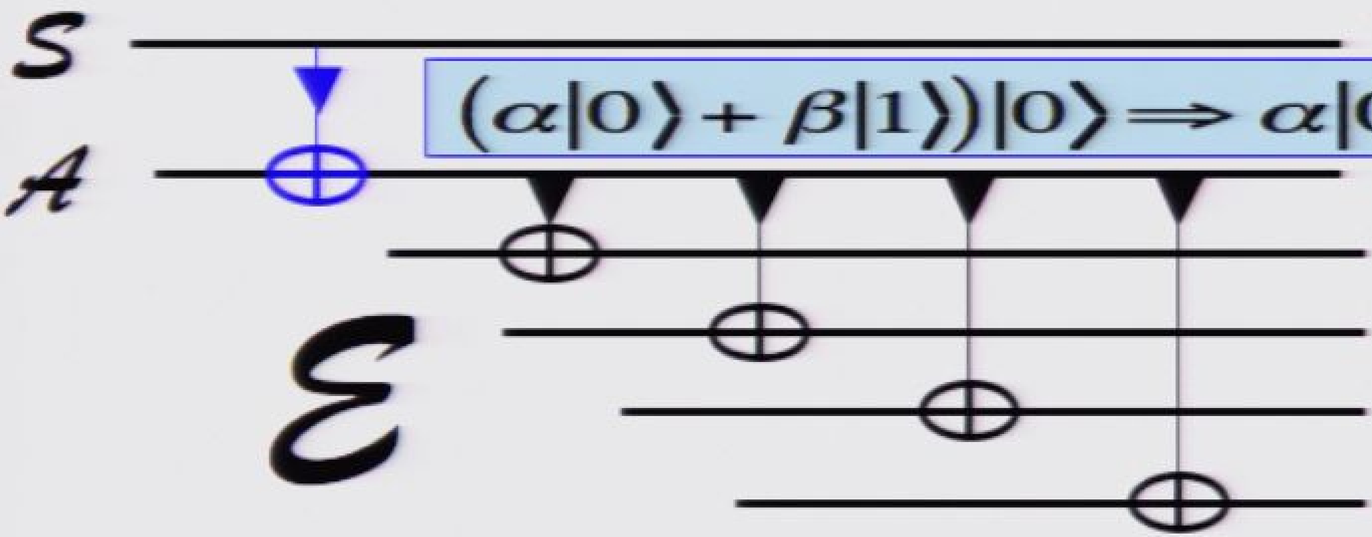
***Environment INduced superSELECTION**

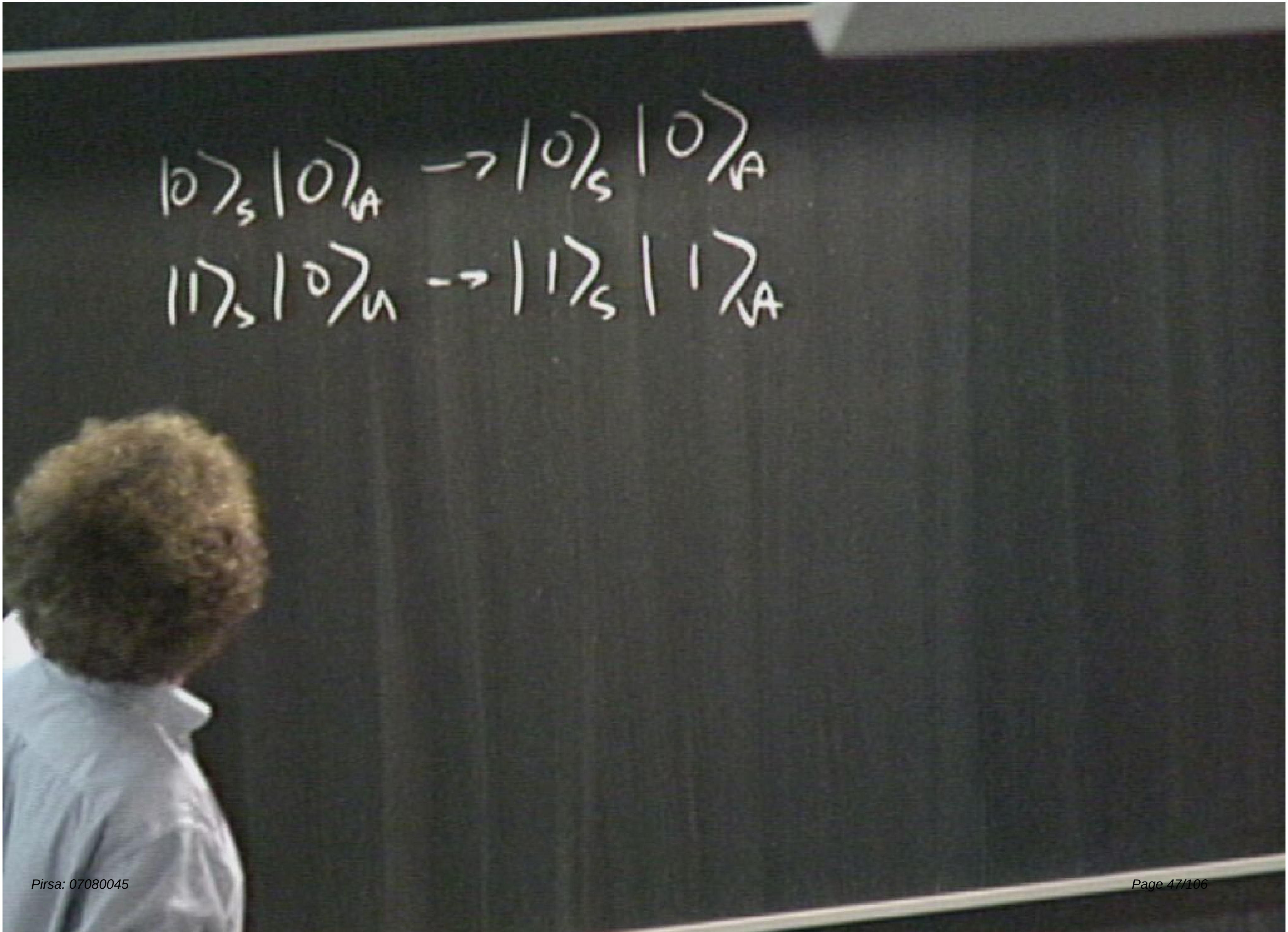
DECOHERENCE AS A MEASUREMENT BY THE ENVIRONMENT



$$(\alpha|0\rangle + \beta|1\rangle)|0\rangle \Rightarrow \alpha|00\rangle + \beta|11\rangle$$

In presence of decoherence, classical correlations remain, but entanglement disappears.

$$|\alpha|^2|00\rangle\langle 00| + \alpha\beta^*|00\rangle\langle 11| + \alpha^*\beta|11\rangle\langle 00| + |\beta|^2|11\rangle\langle 11| \rightarrow |\alpha|^2|00\rangle\langle 00| + |\beta|^2|11\rangle\langle 11|$$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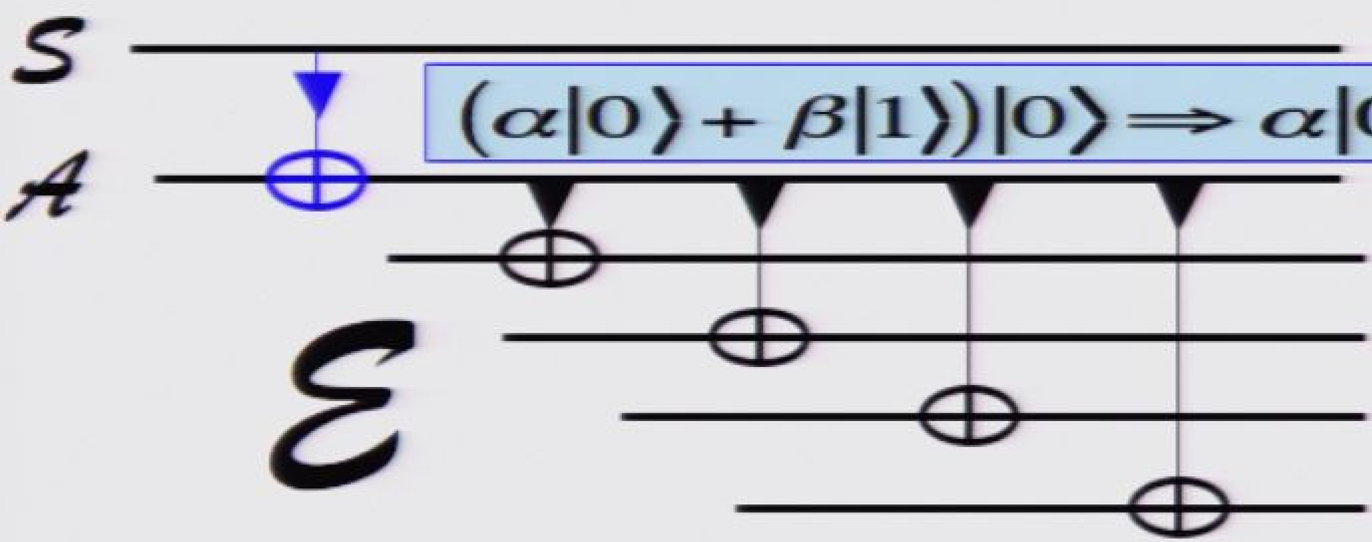

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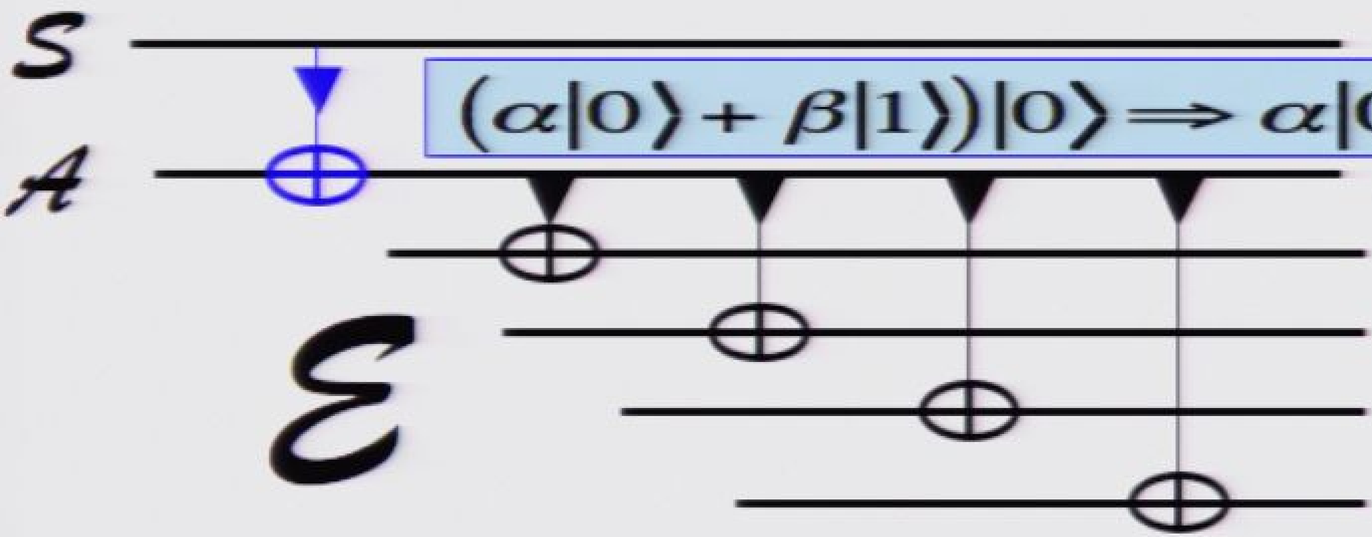

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Simple model of decoherence

A single spin–system $\mathcal{S}$ (with states $\{|0\rangle, |1\rangle\}$) interacting with an environment $\mathcal{E}$ of many independent spins ($\{|\uparrow_k\rangle, |\downarrow_k\rangle\}$, $k = 1..N$) through the Hamiltonian

$$\mathcal{H}_{\mathcal{S}\mathcal{E}} = (|0\rangle\langle 0| - |1\rangle\langle 1|) \sum_{k=1}^{N} \frac{g_k}{2} (|\uparrow_k\rangle\langle\uparrow_k| - |\downarrow_k\rangle\langle\downarrow_k|)$$

Initial state involves a superposition of “0” and “1” of $\mathcal{S}$:

$$|\Psi_{\mathcal{S}\mathcal{E}}(0)\rangle = (a|0\rangle + b|1\rangle) \bigotimes_{k=1}^{N} (\alpha_k |\uparrow_k\rangle + \beta_k |\downarrow_k\rangle)$$

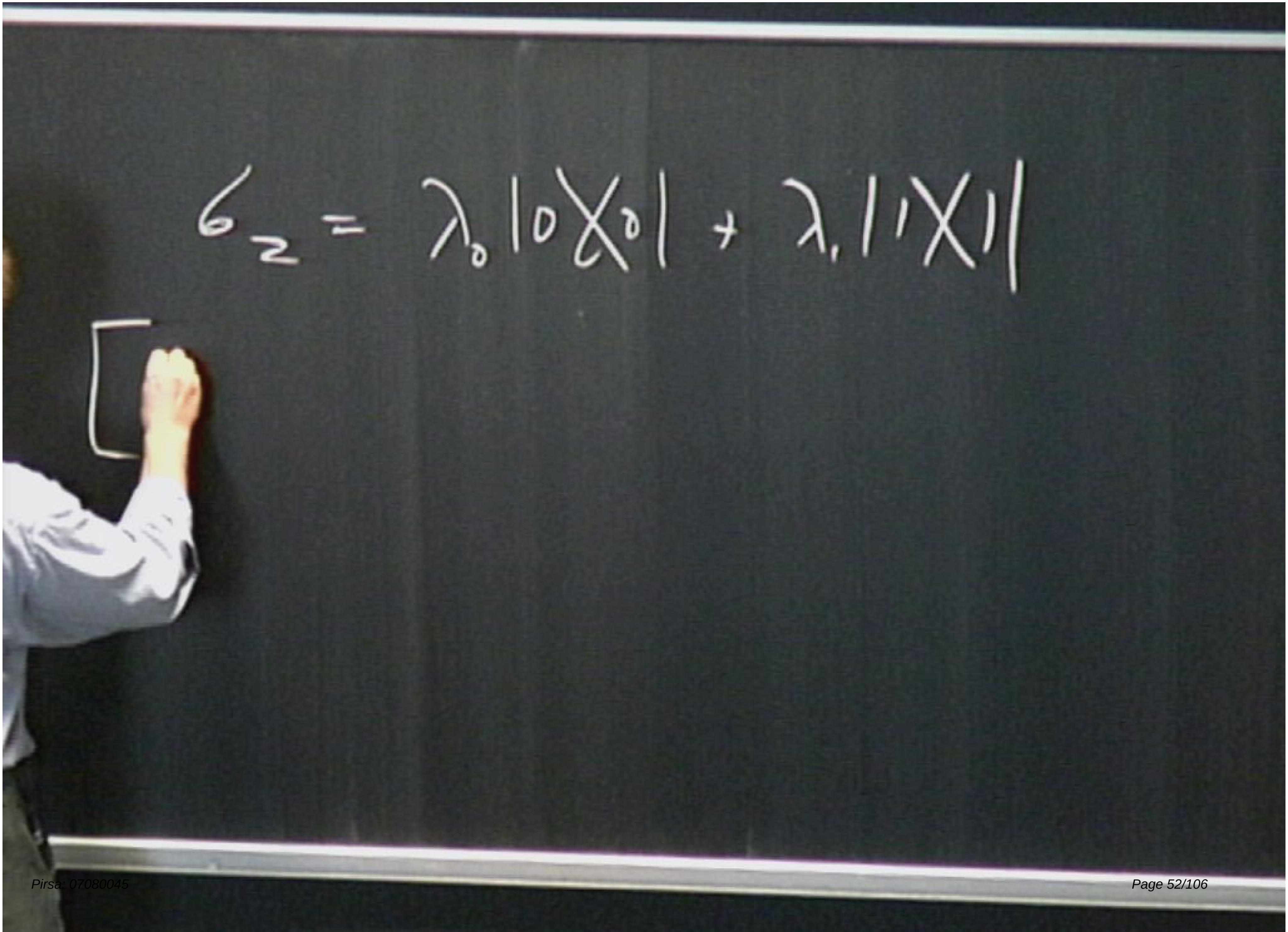
This is (of course) exactly solvable:

$$|\Psi_{\mathcal{S}\mathcal{E}}(t)\rangle = a|0\rangle|\mathcal{E}_0(t)\rangle + b|1\rangle|\mathcal{E}_1(t)\rangle$$

where;

$$|\mathcal{E}_0(t)\rangle = \bigotimes_{k=1}^{N} \left(\alpha_k e^{i g_k t/2} |\uparrow_k\rangle + \beta_k e^{-i g_k t/2} |\downarrow_k\rangle\right) = |\mathcal{E}_1(-t)\rangle$$

WHZ, Phys. Rev. D '82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IOTE: NO "FRICTION", UST DECOHERENCE"

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Decoherence factor "quickly" decays to the long time average:

$$\langle |r(t)|^2 \rangle = 2^{-N} \prod_{k=1}^{N} \left(1 + (|\alpha_k|^2 - |\beta_k|^2)^2\right)$$

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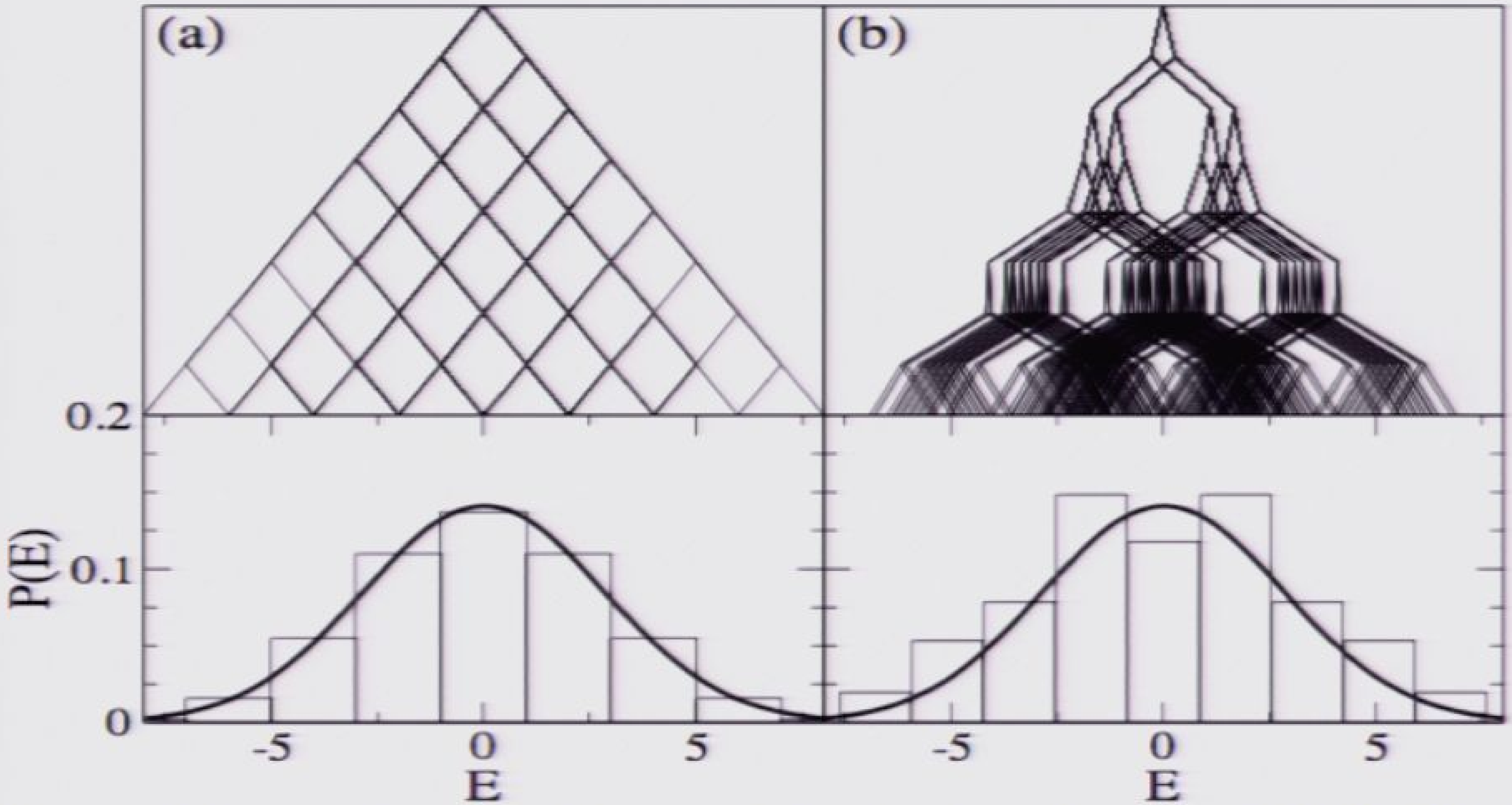
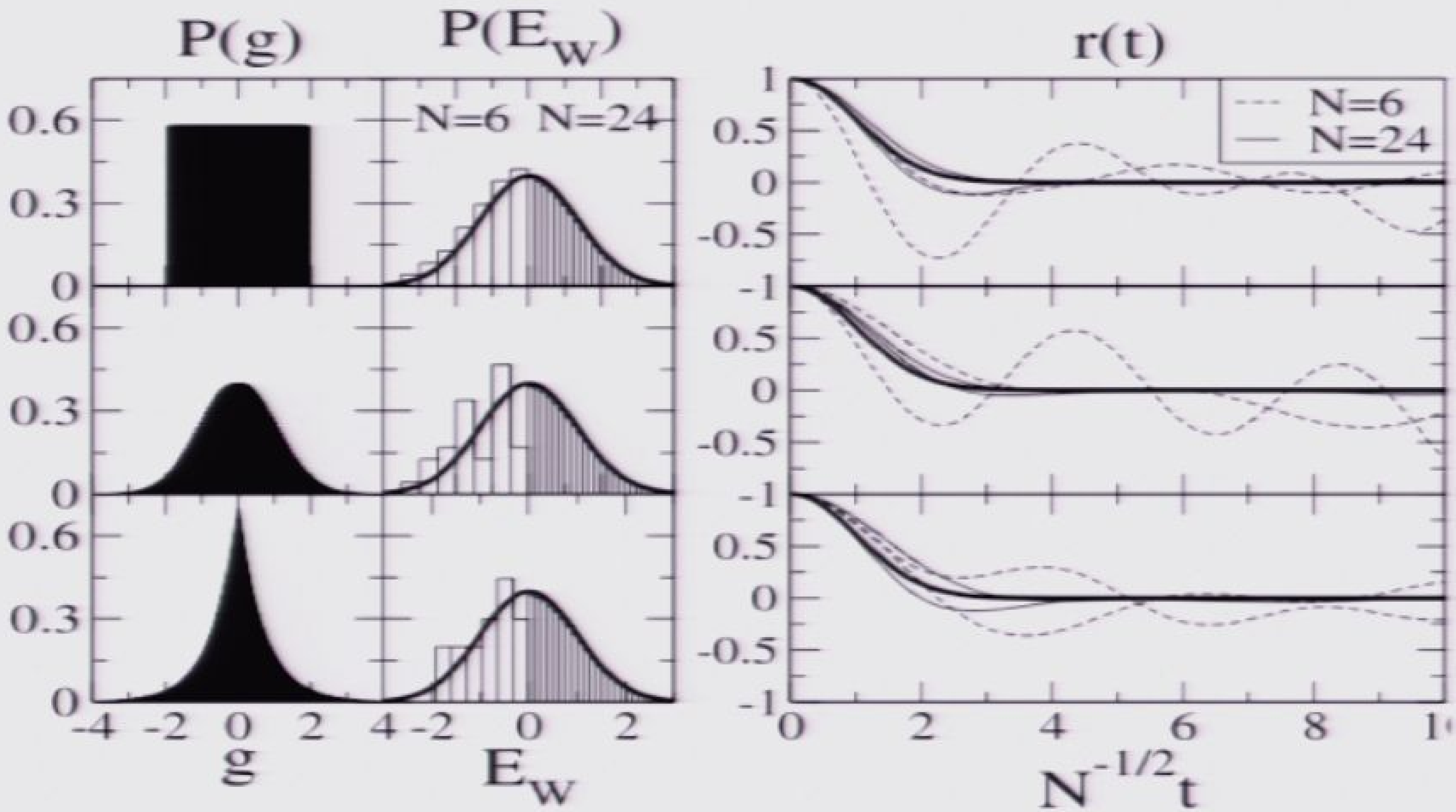
This Gaussian time dependence is "generic". It arises because he distribution of energies responsible for the time-dependence of *r(t)* is a collection of terminal points of all "random walks" taken with the steps equal to the coupling constants:



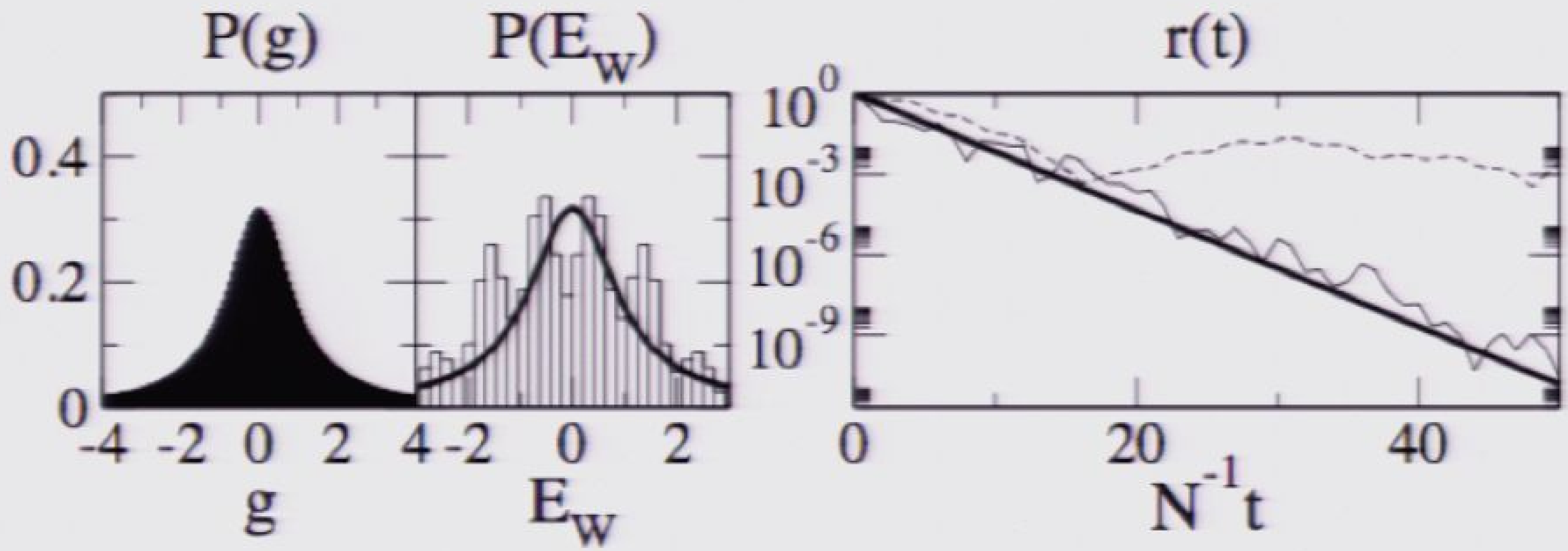
All possible random walks contribute simultaneosly!!!!!! This is he spectrum of the Hamiltonian responsible for decoherence

Convergence to Gaussian time dependence is rapid (as for N spins of the environment there will be 2^N contributing to $r(t)$. The condition for convergence to a Gaussian is the existence of a **finite** variance of the couplings $\langle (g_k - \langle g \rangle)^2 \rangle$ (so called "Lindeberg condition"). Indeed:



Note rapid convergence!

Other time-dependences for *r(t)* are possible only when Lindeberg condition is not met. For example, when distribution of couplings is Lorentzian (infinite variance!), exponential time dependence for the decoherence factor obtains:

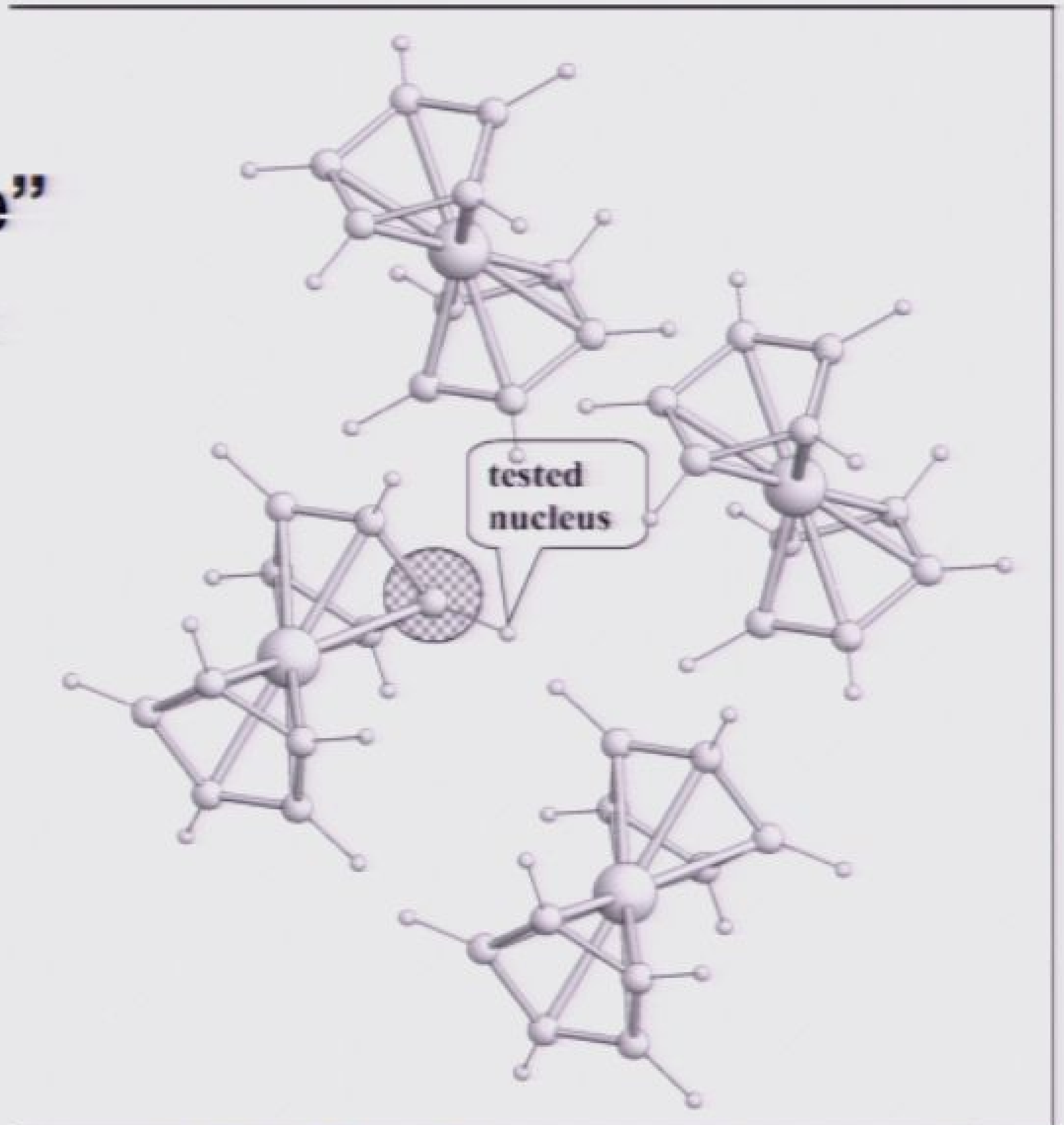


The convergence in this Lorentzian case is (understandably) much worse: Above right the two numerical simulation lines correspond to *N=20* and *N=100* spins.

“Quantum Chaos: an answer to the Boltzmann-Loschmidt controversy?”

“ferrocene”

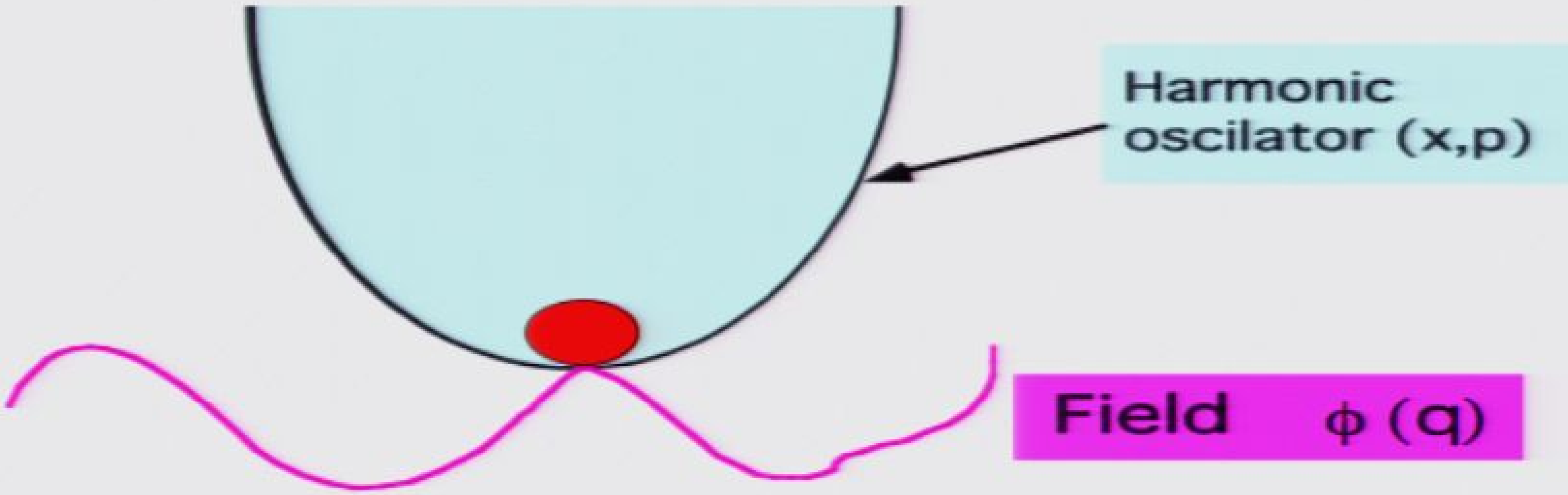
$Fe(C_5H_5)_2$



Crystalline structure of ferrocene, Fe(C5H5)2 in its (room temperature) monoclinic form with space group $P2_1/a$: Two unit cells are included to give a better idea of the 1H network. A rare 13C nucleus (spin S), (marked with a circle) serves to probe the

Reduction of the Wavepacket in Quantum Brownian Motion

Harmonic oscillator system coupled to a free field environment via H_{int}.



$$H_{int} = \varepsilon\, x\, \partial_t \phi(q)$$

To obtain the effective equation of motion for the density matrix of the harmonic oscillator:

1. Obtain the exact solution of the whole problem.

2. Trace out the field.

MASTER EQUATION*#

(in the position representation)

Von Neumann   relaxation/damping

$$\dot{\rho}(x,x') = -\frac{i}{\hbar}\left[H_{R,}\rho\right] - \gamma(x-x')(\partial_x - \partial_{x'})\rho$$

$$-\frac{2m\gamma k_B T}{\hbar^2}(x-x')^2\rho$$

DECOHERENCE

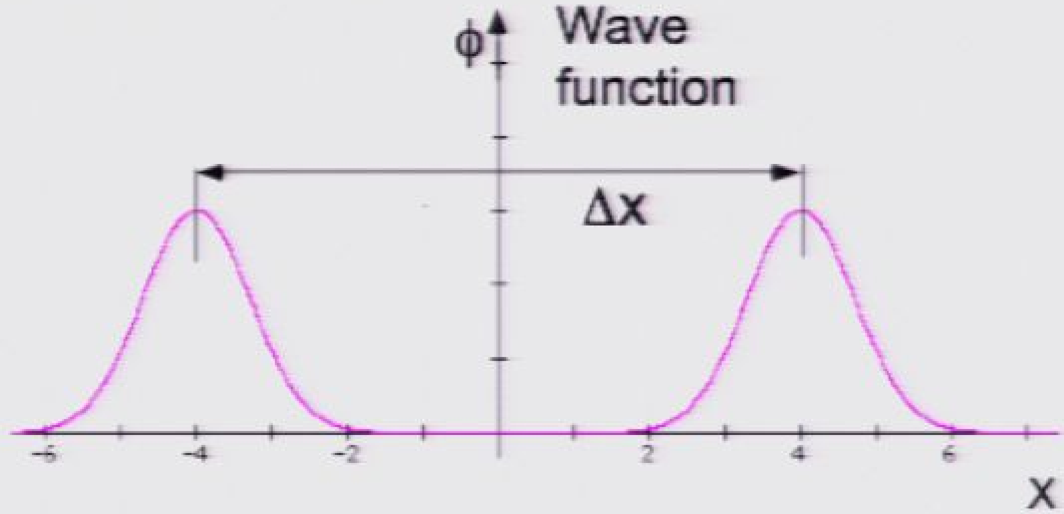
$\gamma = \dfrac{\eta}{2M}$, viscosity $\eta = \dfrac{\varepsilon^2}{2}$, where ε is the coupling constant in $\mathrm{H}_{\mathrm{int}} = \varepsilon\, \mathrm{x}\dot{\varphi}$.

A solution (to a leading order "for small Planck constant").

$$\rho(x,x';t) = \rho(x,x';0)\exp\left\{-\frac{\eta k_B T(x-x')^2}{\hbar^2}\, t\right\}$$

***High temperature limit. Master equations for arbitrary temperatures, non- ohmic spectral densities, *etc.* also can be derived and predict decoherence.**

 # ... Feyman and Vernon; Caldeira and Leggett; Unruh and Zurek; Hu, Paz and



X'

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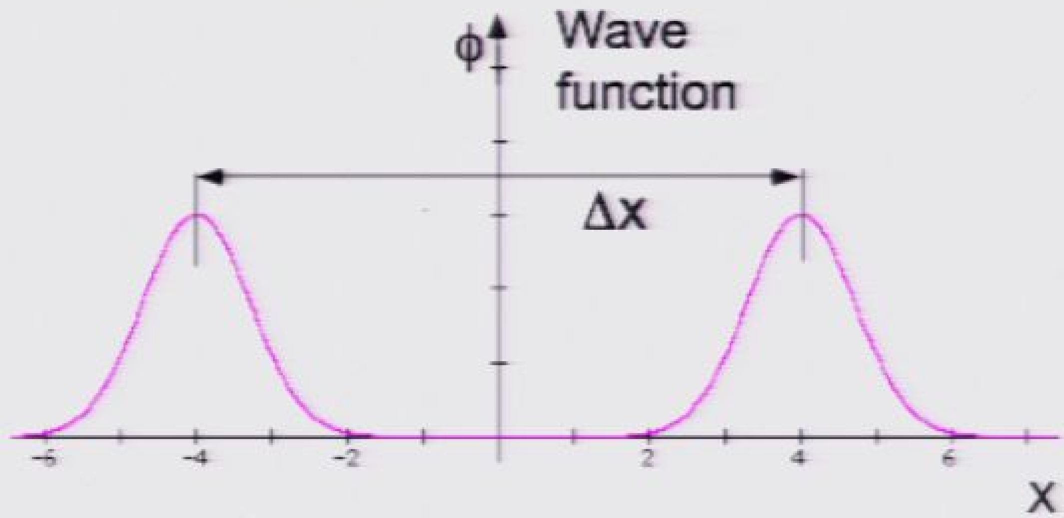
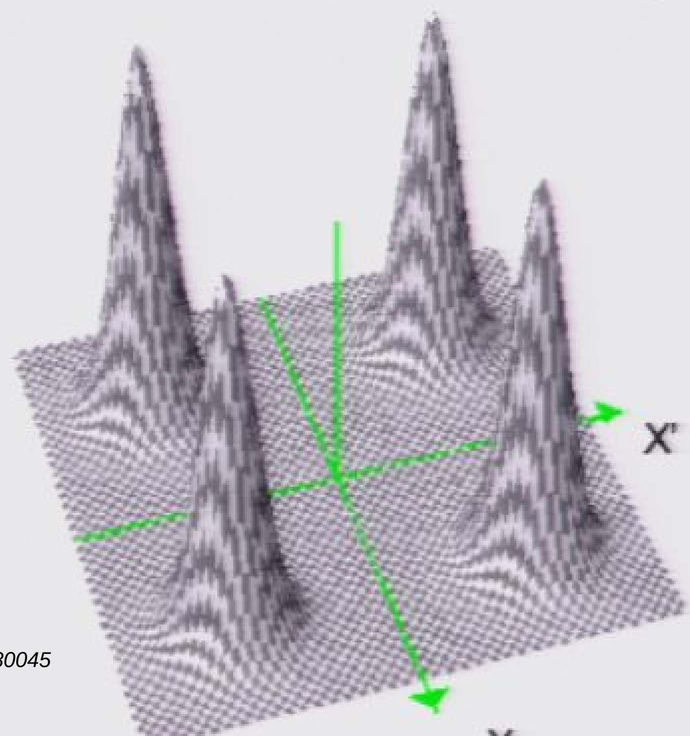


Density Matrix ρ (x, x')



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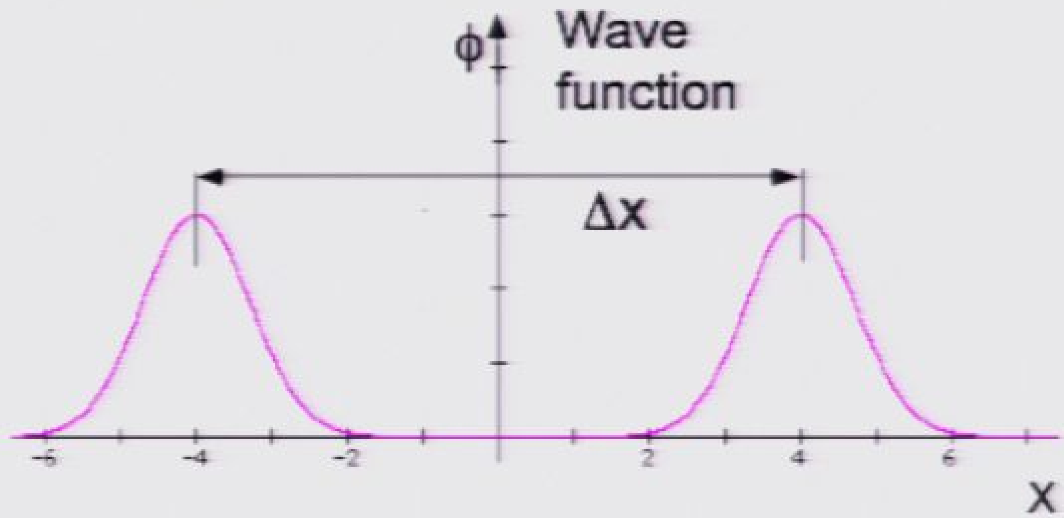

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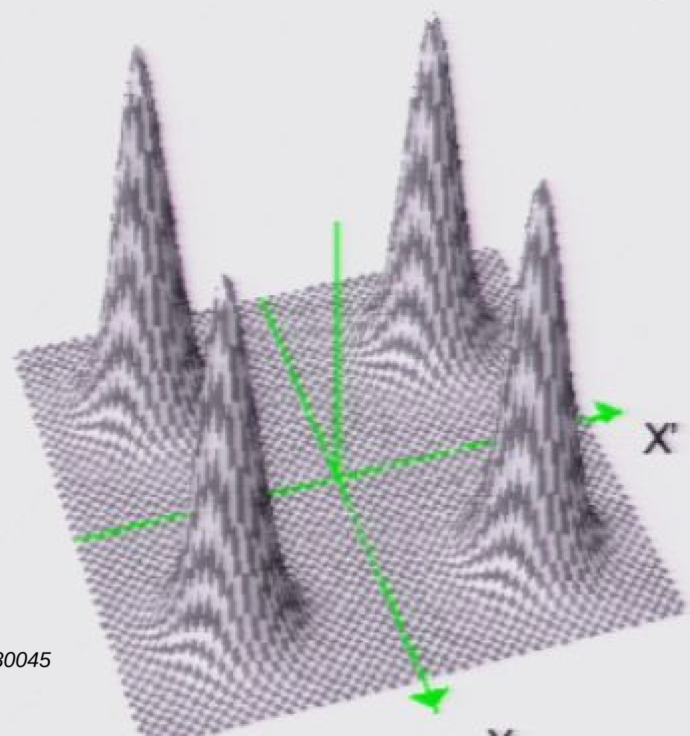
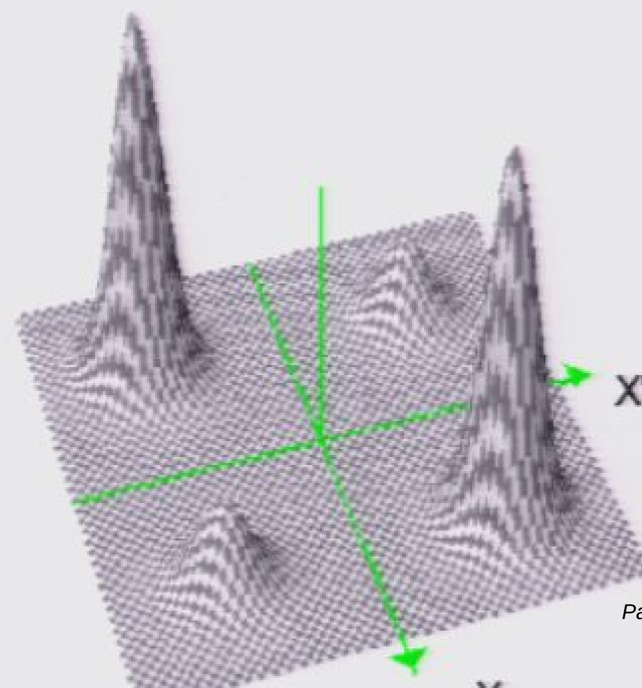
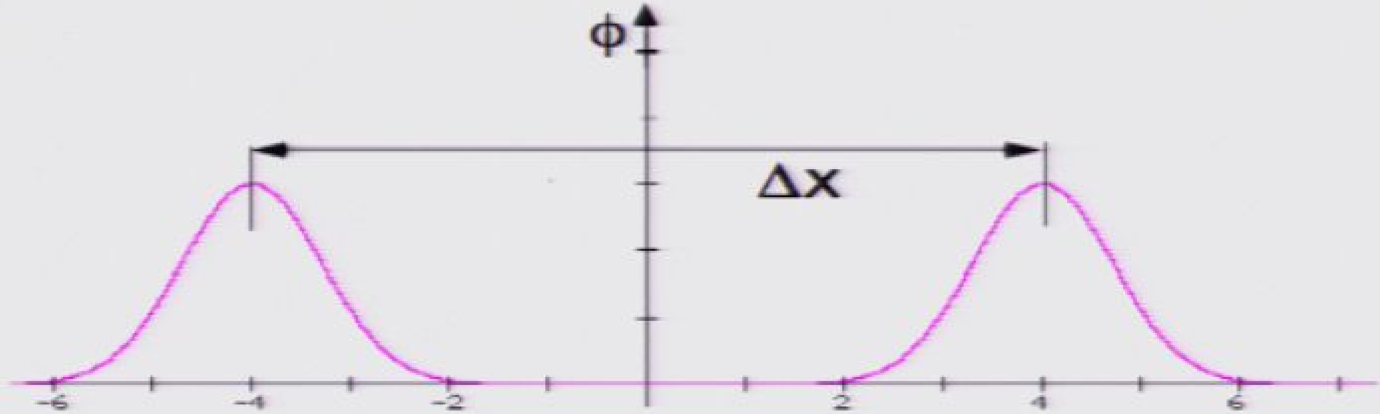




Decoherence Time Scale and the Role of Position



RELAXATION:

$$\dot{p} = -\gamma p$$

DECOHERENCE RATE:

$$\delta = \tau_D^{-1} \cong \gamma \left(\frac{\Delta x}{\lambda_{dB}(T)} \right)^2$$

Where thermal de Broglie length is:

$$\lambda_{dB} = \hbar / \sqrt{2mk_B T}$$

Zurek '84-86; Joos & Zeh '85
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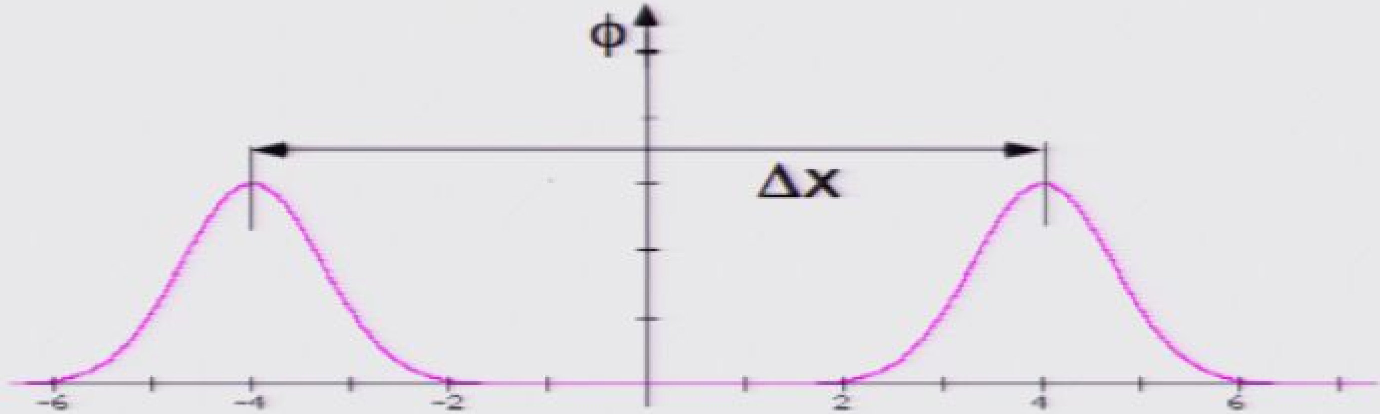

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Experimental confirmation: '96, ENS group (Brune, Haroche, Raimond…)

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Measurement of Decoherence of Electron Waves and Visualization of the Quantum-Classical Transition

Peter Sonnentag and Franz Hasselbach

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(Received 8 December 2006; published 16 May 2007)

Controlled decoherence of free electrons due to Coulomb interaction with a truly macroscopic environment, the electron (and phonon) gas inside a semiconducting plate, is studied experimentally. The quantitative results are compared with different theoretical models. The experiment confirms the main features of the theory of decoherence and can be interpreted in terms of which-path information. In contrast to previous model experiments on decoherence, the obtained interferograms directly visualize the transition from quantum to classical.

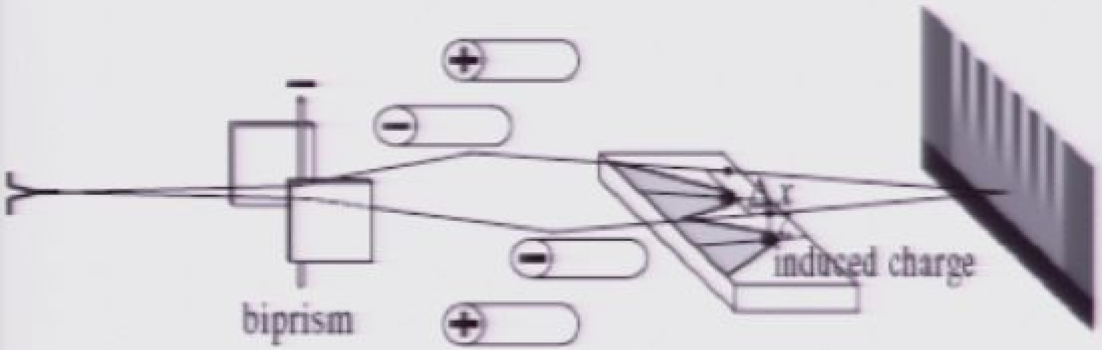

FIG. 1. Sketch of the decoherence experiment. Electron waves emerging from the source are split by the negatively charged biprism filament, placed between earthed plates, and deflected apart from each other. The electrostatic quadrupole directs them toward each other again. Before they meet, they travel over a resistive plate at the same, small height z, but with a lateral separation Δx. The induced charges moving with the beam electron lead to a disturbance in the electron (and phonon) gas inside the plate. For the two electron trajectories, the corresponding disturbance (shaded areas) is located in different regions.

Waves and Visualization Transition

asselbach
'orgenstelle 10, 72076 Tübingen, Germany
d 16 May 2007)

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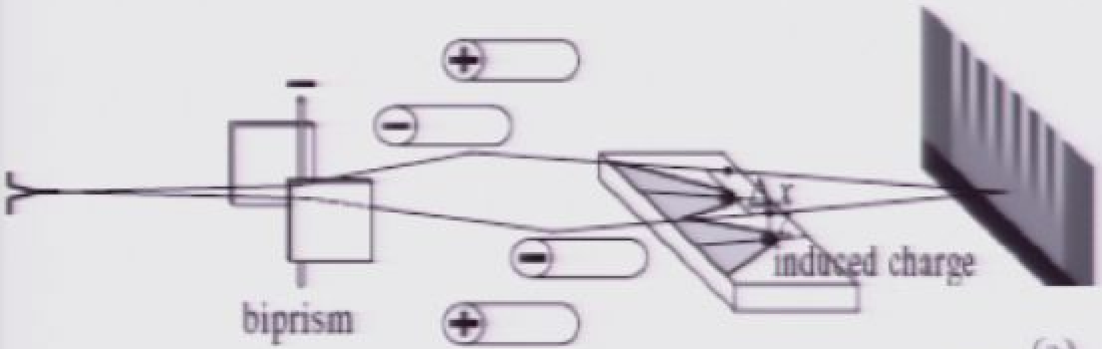

Waves and Visualization
Transition

asselbach
'orgenstelle 10, 72076 Tübingen, Germany

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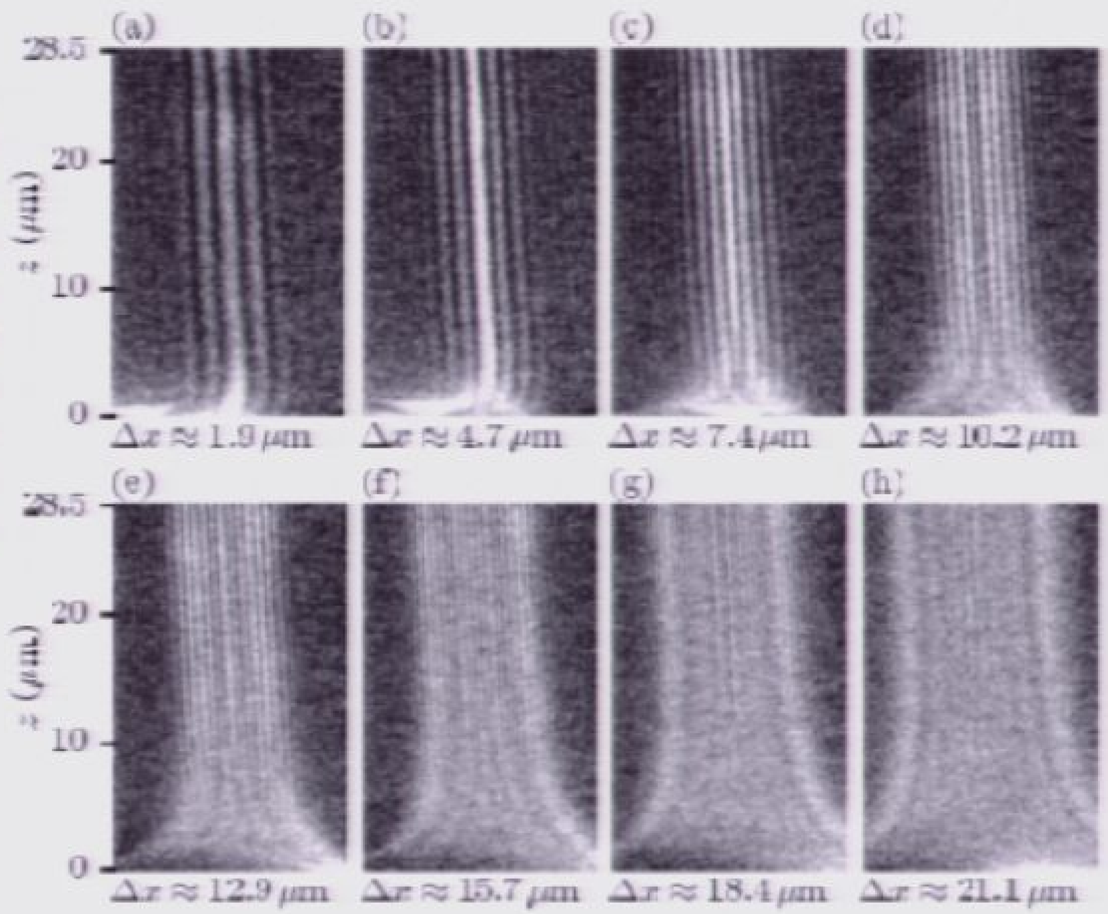
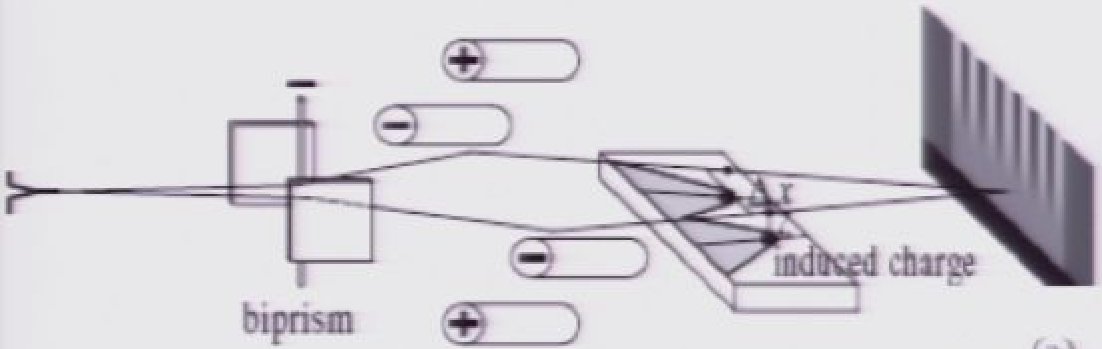


FIG. 2. Electron interferograms showing continuously increas-



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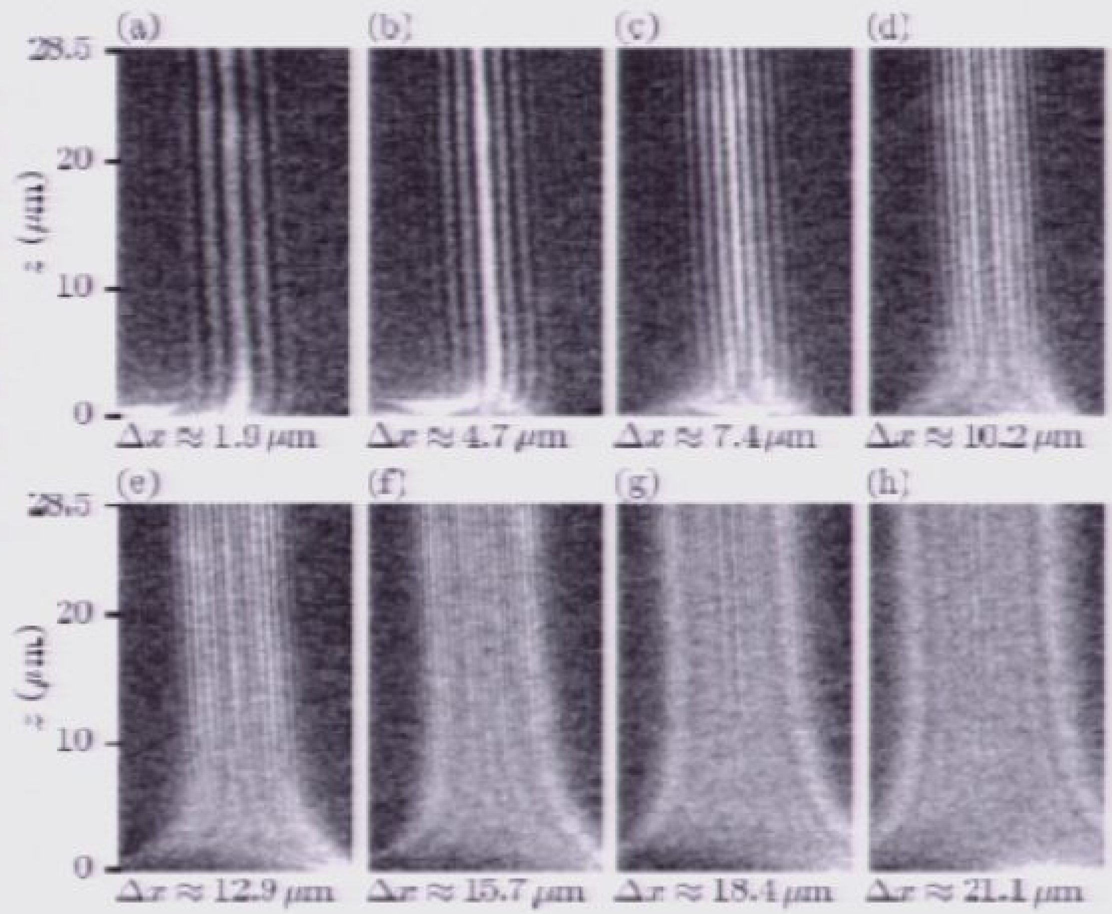

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WHAT ARE PREFERRED POINTER STATES?

POINTER STATES FROM THE PREDICTABILITY SIEVE

States in the Hilbert space of the open system evolve from pure into mixed under the influence of both the self-Hamiltonian and the interaction Hamiltonian. They can be sorted according to predictability (*e.g*. measured by entropy or by purity *h(r)*).

$$|\psi\rangle \Rightarrow \rho_\psi(t) \;\ldots\ldots\; h(\rho_\psi(t)) = Tr\rho_\psi^2(t)$$

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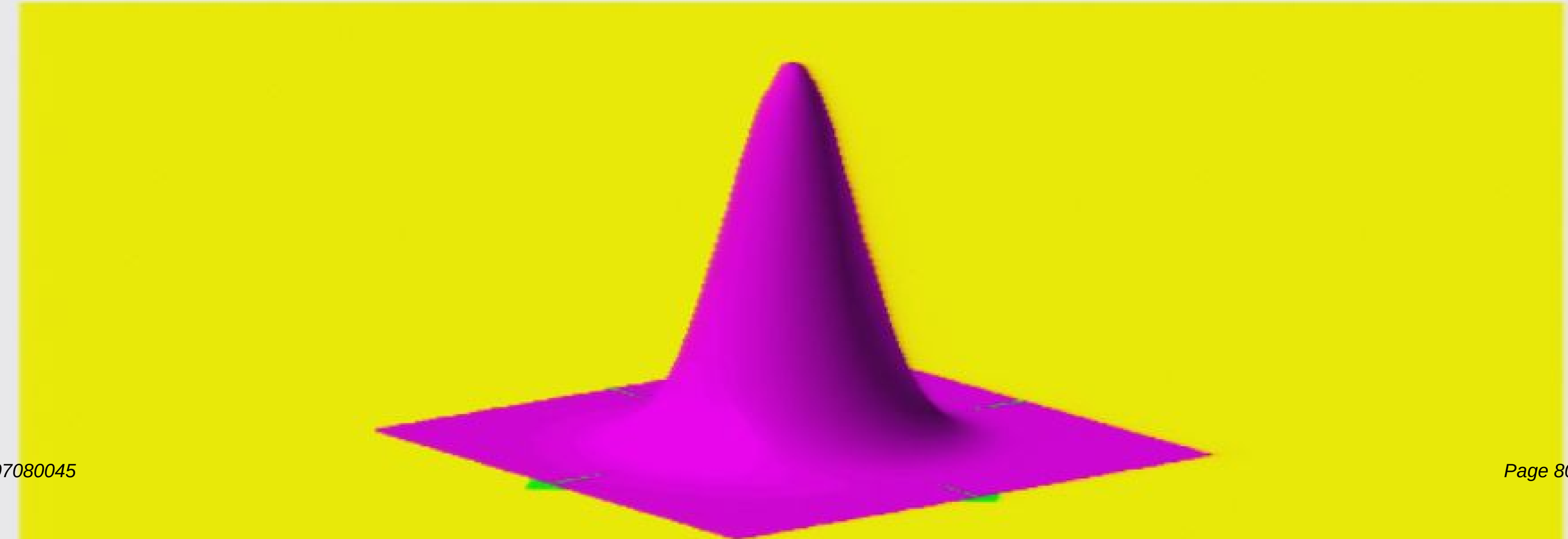

Predictability Sieve

(a) Interaction with the environment dominates -- pointer states given by: $\left[H_{SE}, |\sigma_i\rangle\langle\sigma_i|\right] = 0$

(b) System self-Hamiltonian dominates -- pointer states are its eigenstates ("quantum limit of einselection")

(c) Both H_S and H_{SE} are important (underdamped harmonic oscillator) -- pointer states are minimum uncertainty Gaussians.

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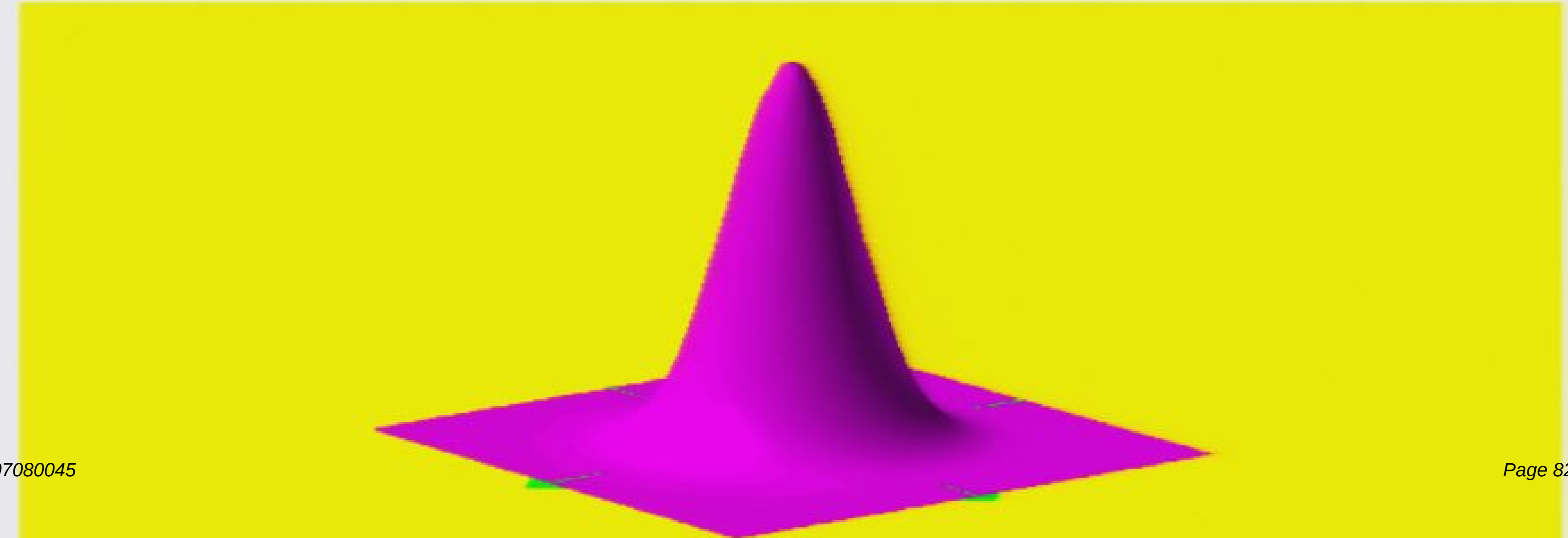

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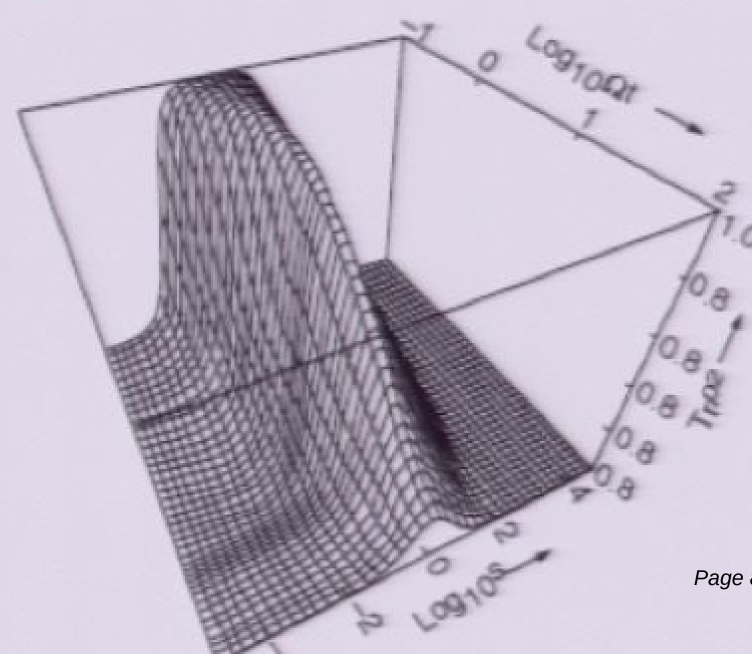

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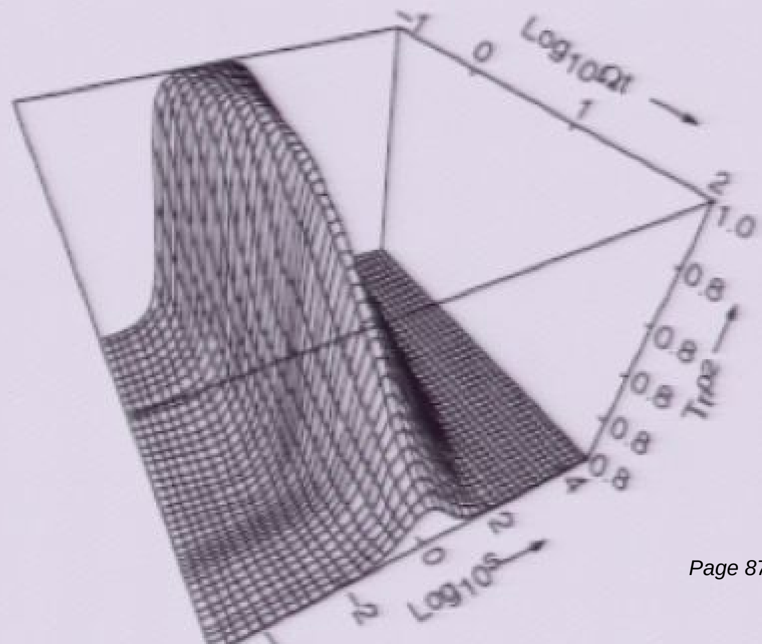

"POINTS" IN PHASE SPACE

DECOHERENCE AND EINSELECTION

Thesis: Quantum theory can explain emergence of the classical.

Principle of superposition loses its validity in "open" systems, that is, systems interacting with their environments.

Decoherence restricts stable states (states that can persist, and, therefore, "exist") to the exceptional…

Pointer states that exist or evolve predictably in spite of the immersion of the system in the environment.

Predictability sieve can be used to 'sift' through the Hilbert space of the open system in search of these pointer states.

EINSELECTION (or Environment INduced superSELECTION) is the process of selection of these preferred pointer states.

For macroscopic systems, decoherence and einselection can be very effective, enforcing ban on Schroedinger cats.

Einselection enforces an effective border that divides quantum from classical, making a point of view similar to Bohr's Copenhagen Interpretation possible, although starting from a rather different standpoint (i. e., no *ab initio* classical domain of the universe).

Zeh, Joos, Paz, Caldeira, Leggett, Kiefer, Gell-Mann, Hartle, Omnes, …

Plan

Derive controversial axioms 4&5 from the noncontroversial 0-3.
Understand emergence of “objective classical reality” -- how real states that can be found out by us arise from quantum substrate.

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- Why does "**Born's rule**" yield probabilities?

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- Why does "**Born's rule**" yield probabilities?
- How can "objective classical reality" -- states we can find out -- arise from the fragile quantum states that are perturbed by measurements? ("**Quantum Darwinism**")

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Quantum Darwinism

The imprint left by the system S in the environment E is the cause of decoherence

The focus of decoherence is the information that is left in S in spite of E. ("reduced density matrix" of S)

Quantum Darwinism is focused instead on the information about S that can be found out indirectly from E !!!

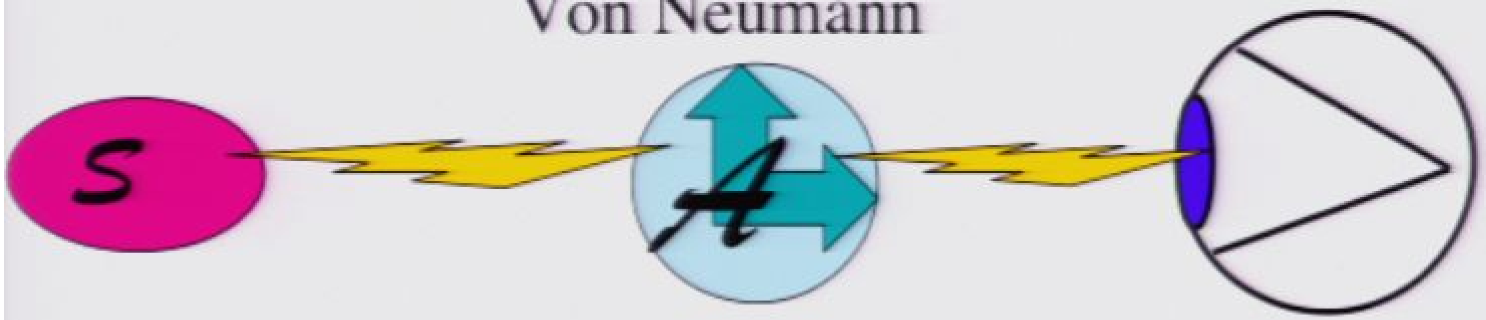
(i) How many copies of the information about S can be extracted from E? (Redundancy)

(ii) What is this information about? (i.e., what observable of S gets redundantly imprinted in E?)

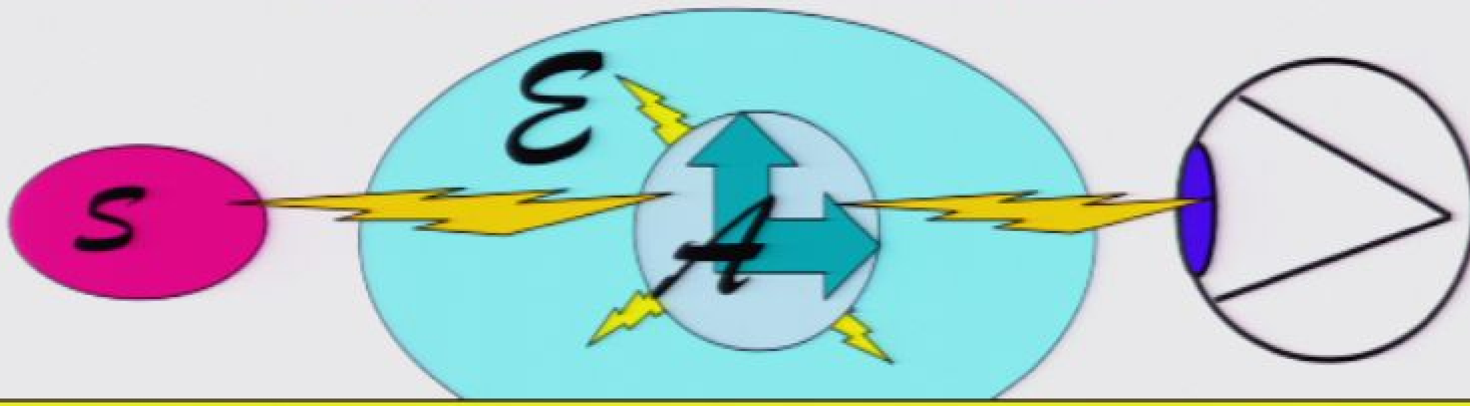
(iii) Why does this matter?

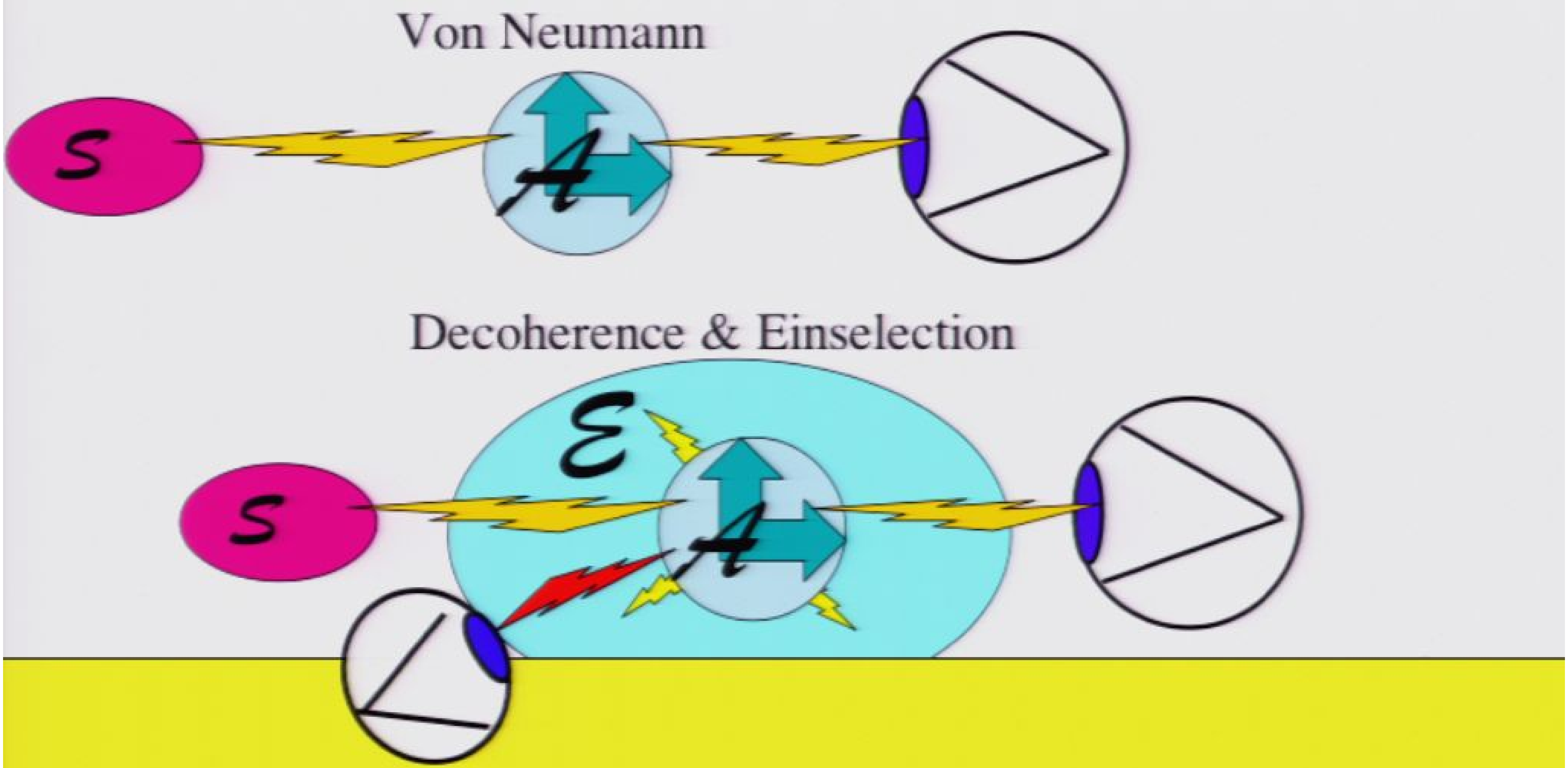
Robin Blume-Kohout (Cal Tech/PI)
Harold Ollivier (Paris)
David Poulin (Cal Tech...?)

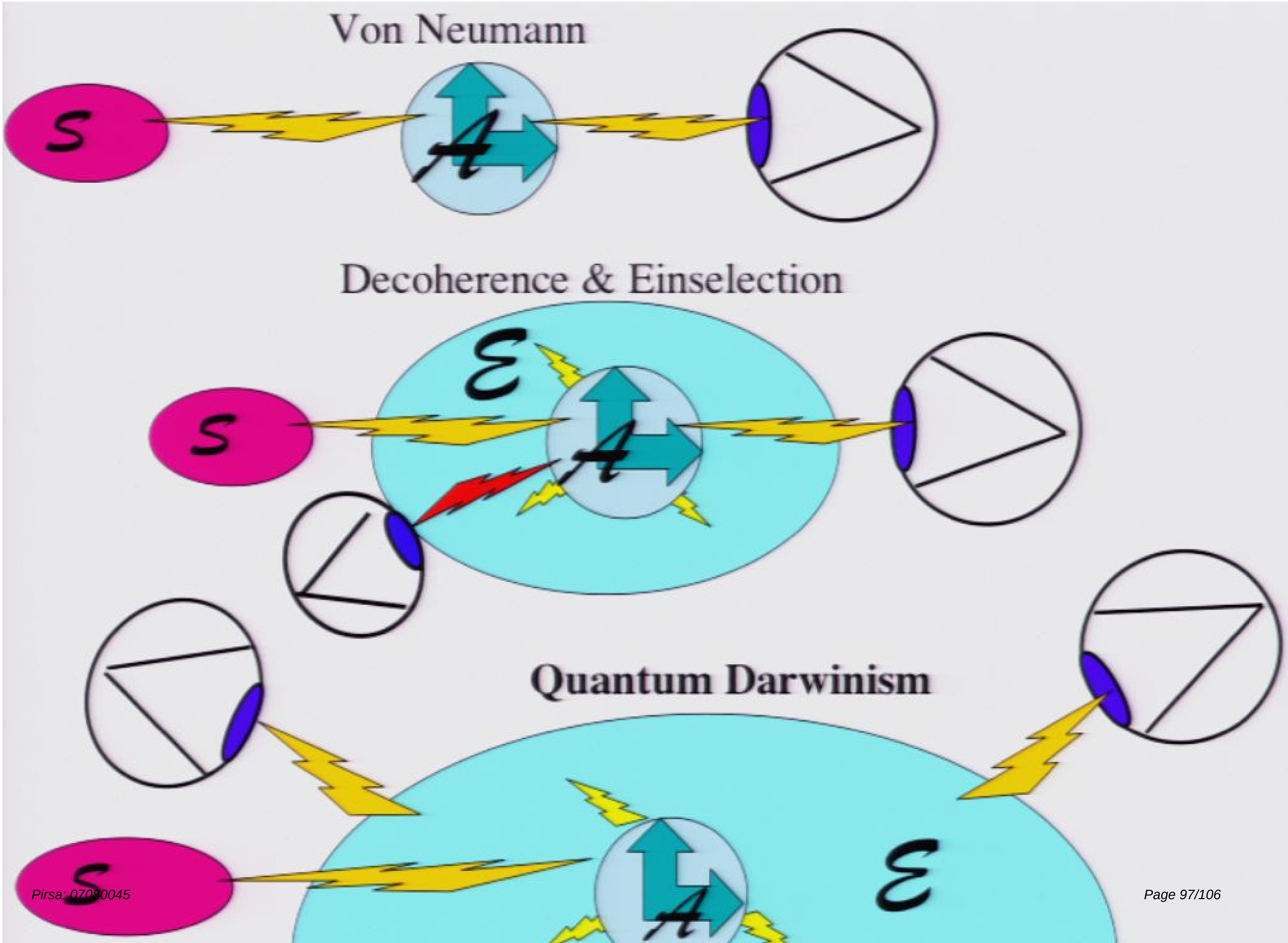
Von Neumann



Decoherence & Einselection




Von Neumann
S
A
Decoherence & Einselection
E
S
A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Quantum Darwinism
S
A
E

Quantum Darwinism -- "The Big Picture"

- Certain **"fittest" information** about S proliferates -- it is recorded in E in many copies
- **Complementary information** is diluted -- effectively **obliterated**
- The **fittest information is about the einselected pointer states** that can "survive" decoherence
- Information that can be obtained indirectly and independently by many is in effect **objective. (OPERATIONAL DEFINITION)**
- Its acquisition **does not endanger preexisting state** of the system (which can be "found out" as if it were classical). ("**Environment as a witness**")

How do we analyze this?

Measuring what $\mathcal{E}$ knows about $\mathcal{S}$

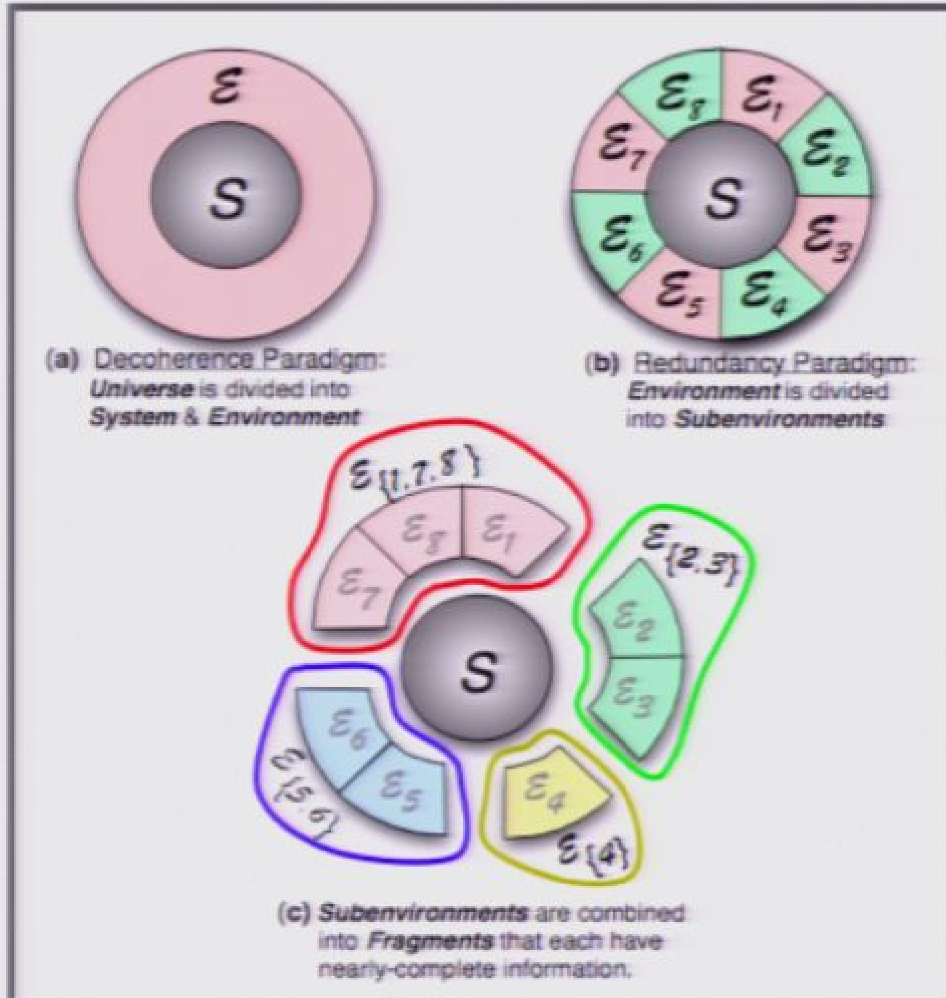
Mutual Information

$$\mathcal{I}_{\mathcal{S}:\mathcal{E}} = H_{\mathcal{S}} + H_{\mathcal{E}} - H_{\mathcal{S}\mathcal{E}}$$

where

$$H \equiv -\mathrm{Tr}\,(\rho \ln \rho)$$

- Measures the increase in entropy from eliminating correlations between $\mathcal{S}$ and $\mathcal{E}$.
- No reference to observables or measurements.
- Bounded by $\mathcal{I}_{\mathcal{S}:\mathcal{E}} \leq 2H_{\mathcal{S}}$



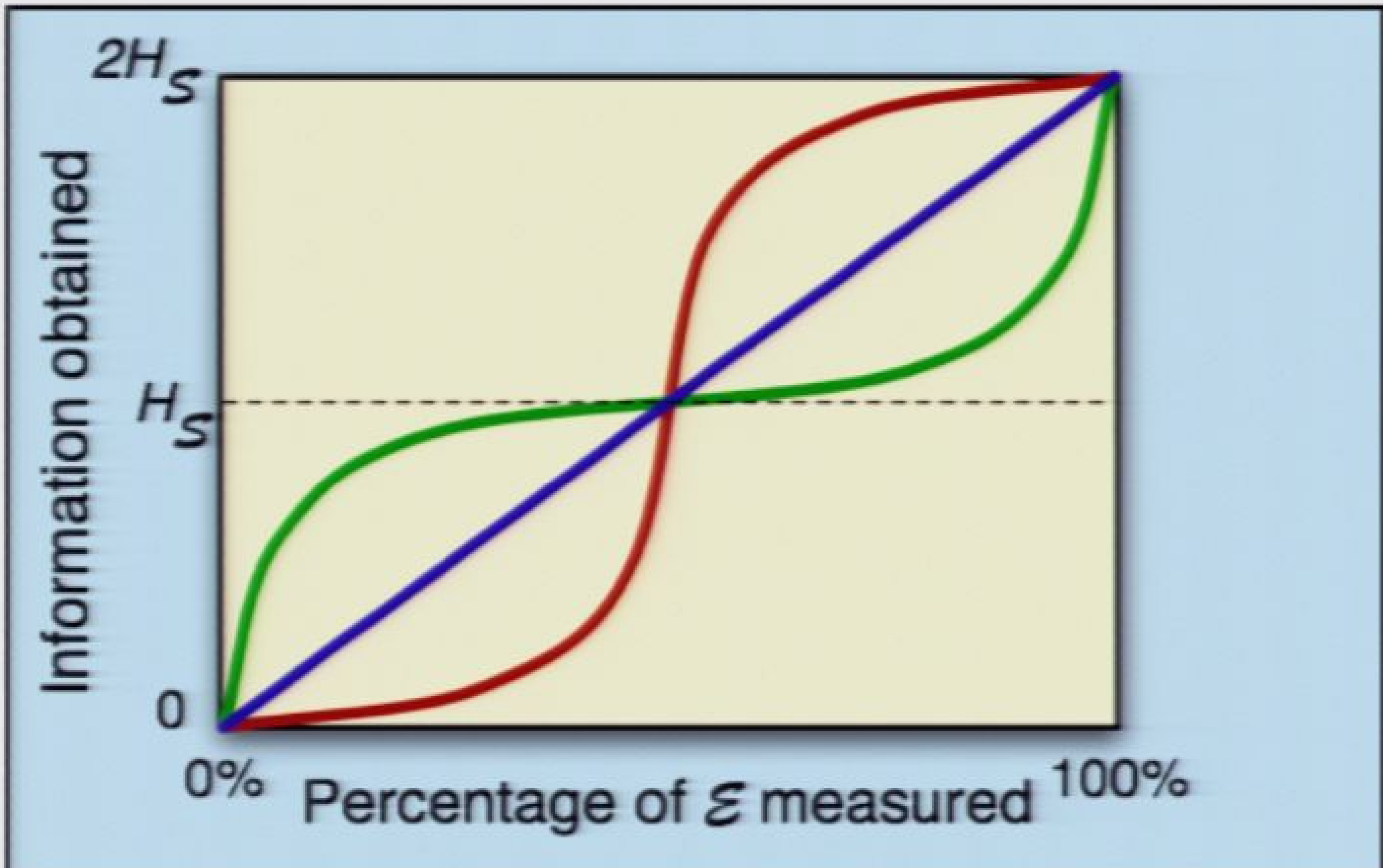
1. **Partial Info**: How much $\mathcal{I}_{\mathcal{S}:\mathcal{F}}$ does a fragment supply?
2. **Redundancy**: How many disjoint fragments supply $(1-\delta)H_S$?

Partial Information Plots

(a visual characterization of information storage)

- Plot size of a fragment (F) vs. amount of info it provides.
- We average over all fragments of a given size.
- 3 info profiles:
  - redundant
  - distributed
  - encoded

R_δ



* Blume-Kohout & Zurek, Foundations of Physics (~Nov. 2005), quant-ph/0408147

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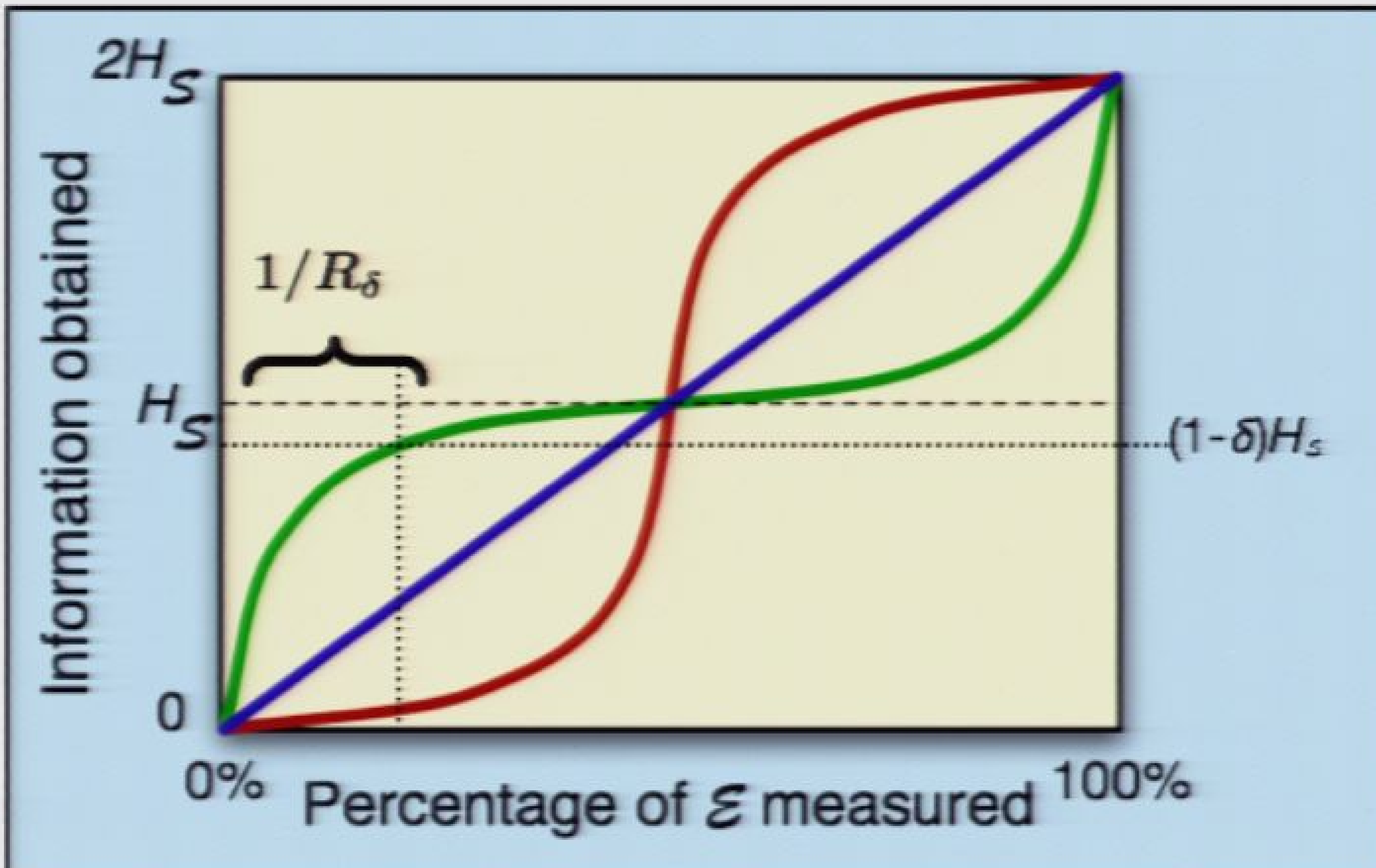
- R_δ = Redundancy of "all but δ" of the available info



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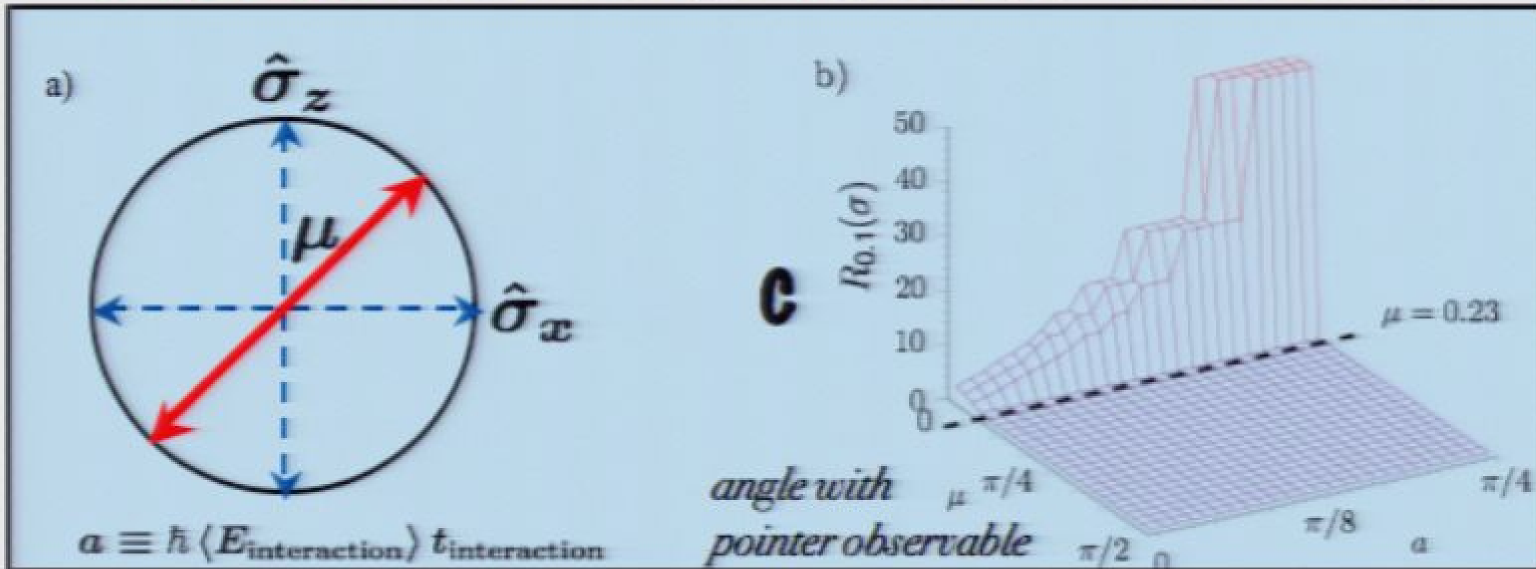
What does $\mathcal{E}$ know about?



Q: What observables can be inferred from $\mathcal{E}$?

- Consider GHZ: $|\psi\rangle \propto |0\rangle_S |00...0\rangle + |1\rangle_S |11...1\rangle$

- "Ising" model -> "singly branching states"

$$|\Psi\rangle = \sum_n s_n \left(|n\rangle_S \otimes \left|\mathcal{E}_n^{(1)}\right\rangle \otimes \left|\mathcal{E}_n^{(2)}\right\rangle \otimes \dots \left|\mathcal{E}_n^{(\mathrm{N}_{env})}\right\rangle \right)$$

A: Only the pointer observable recorded redundantly!

Ollivier, Poulin, & Zurek, *Phys. Rev. Lett.* 2004.

Quantum Darwinism -- brief summary of results

- Environment knows about the system.
- Every fragment of the environment knows the same thing about the system.
- They all know about the pointer observable.
- Many observers can extract that information without disturbing the state of the system.
- Pointer states / observables become “objective”.
- The ability of a state to survive decoherence without getting perturbed (1st part of the talk) is the key.

Existential Interpretation

- States **exist** when they can be found out without getting disrupted by observation.
- Environment - as - a - witness / quantum Darwinism allows for existence in this sense.
- Operationally, this is in effect “classical existence” (can find out the state without disrupting it).
- There is no evidence that “objective classical reality” exists in any other sense!

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