Title: Quantum Darwinism: Classicality via Objectivity

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Abstract:

Quantum Darwinism:
Classicality via Objectivity

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Wojciech H. Zurek (LANL)

1. Reality as emergent phenomenon.
2. The "environment as a witness" approach.
3. Redundancy ➡ Objectivity ➡ "Reality"
4. Tools of the trade -- how to analyze models.
5. Some results -- exploring models.

RBK & WHZ, quant-ph/0408147
RBK & WHZ, quant-ph/0505031
RBK & WHZ, arxiv/0705.4282

Framework & Foundations

- **Operational Classicality & Decoherence.** Suppose we take quantum mechanics seriously. How much of classical behavior *emerges* from the dynamics?

- **Reality is in the eye of the beholder (1)** (a) Old approach: Why a decohering system is always "found" in a pointer basis state.

- **Environment as a Witness.** We observe indirectly -- through the environment. What does it make accessible to us?

- **Reality is in the eye of the beholder (2)** (b) New approach: Why some of a system's properties are *objective** -- and the rest effectively don't exist.

- **Quantum Darwinism.** The selection and propagation of *certain* properties of a system (by the environment), at the expense of incompatible observables.

* or "inter-subjective", if you prefer

Operational Classicality

* **Problem: quantum theory ≠ classical theory.**
  - epistemic & ontic states are different
  - measurements disturb the system
  - we can't duplicate information
  - etc, etc, etc... quantum is not ***realistic***.

* **This really bothers some people.**
  ➡ hidden variable theories...
  - *goal*: show that quantum behavior could emerge from an underlying realistic substrate.

* **Or, we could try it the other way...**
  ➡ can reality emerge from a quantum substrate?
  - *goal*: show that *operational* classicality can exist.

Decoherence

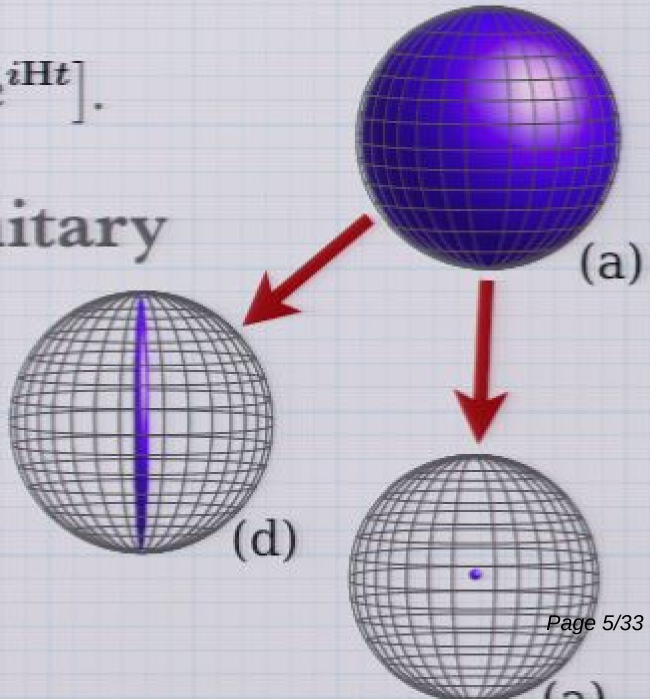
* **A two-headed beast:**
  - helps explain why the world looks classical
  - the major obstacle to QIP.

* **System interacts with its environment.**
  - Instead of $\rho_{\mathcal{S}} \to e^{-i\mathrm{H}t}\rho_{\mathcal{S}}e^{i\mathrm{H}t}$,
  we get $\rho_{\mathcal{S}} \to \mathrm{Tr}_{\mathcal{E}}\left[e^{-i\mathrm{H}t}(\rho_{\mathcal{S}} \otimes \rho_{\mathcal{E}})e^{i\mathrm{H}t}\right]$.

* **System's evolution is nonunitary**

* Typically, there is a *pointer basis*.

* Sometimes, there isn't.



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Zurek, *Phys. Rev. D* 24, 1516 (1981)

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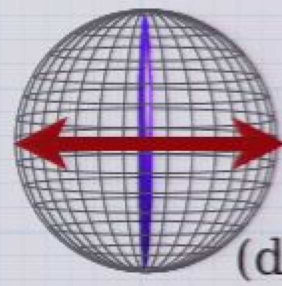

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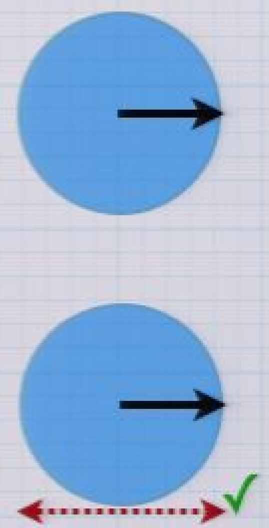

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➡ correlation verifies observation.

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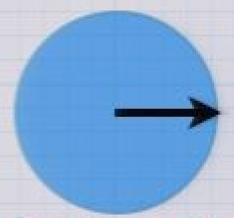

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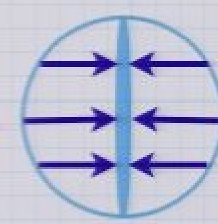

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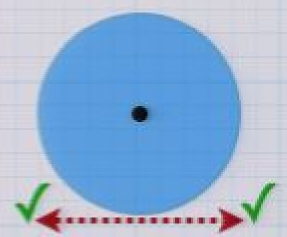

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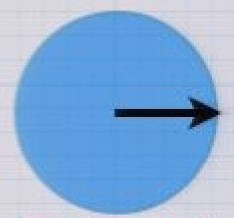

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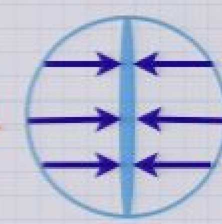

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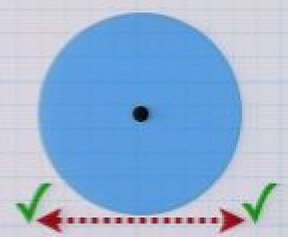

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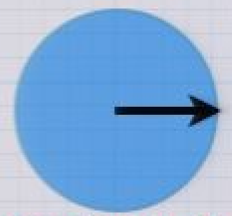

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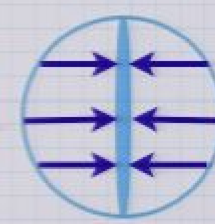

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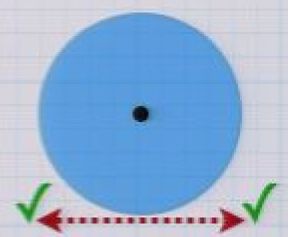

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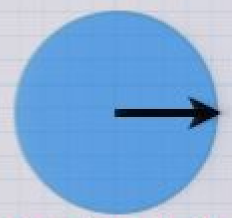

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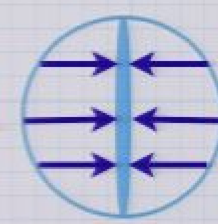

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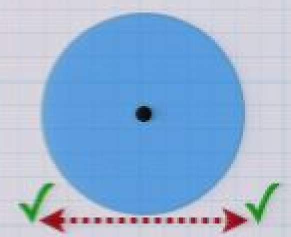

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- Dynamics constrain reality.

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* **Limitations of the decoherence approach.**
  - Measurement is still a magical process.
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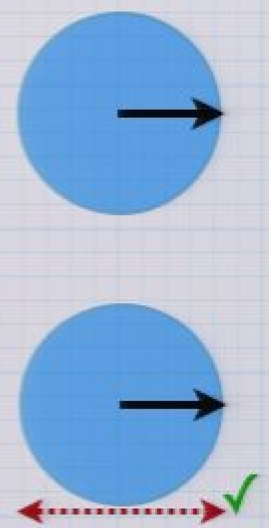

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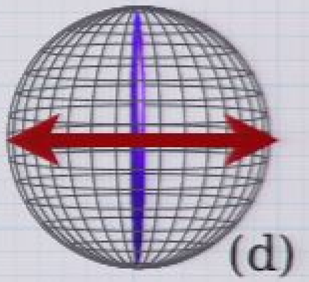

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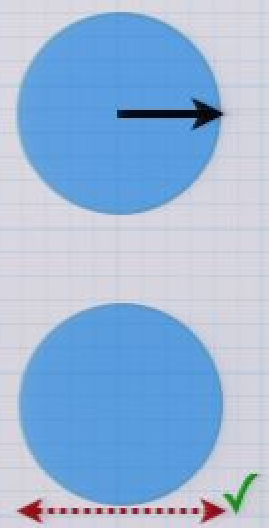

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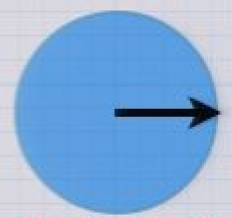

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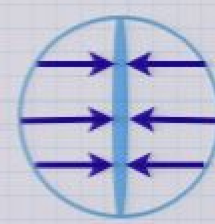

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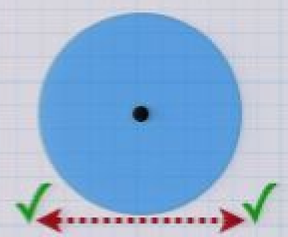

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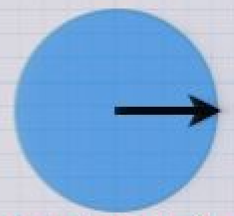

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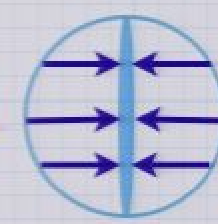

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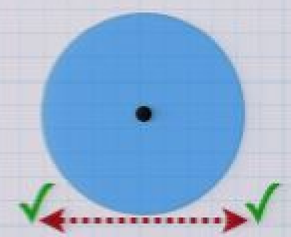

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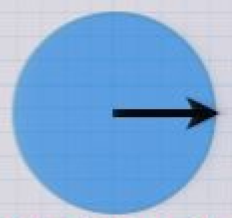

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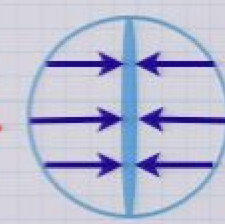

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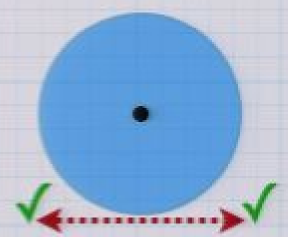

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Objectivity & Reality

* **What can I observe?**
  - I can only capture a small fragment of $\mathcal{E}$.
  - I can reliably observe *only* properties that are recorded *redundantly* throughout the environment.

* **Sufficiently redundant records are objective.**
  (1) The same information is available to many observers.
  (2) One measurement does not disturb other copies (no-signaling).

* **Redundant = Objective = Real**
  - Decoherence *creates* objectivity
  (a closed system is invisible... e.g., doesn't exist!)

Quantum Darwinism

* **Need a name for the spreading of information**
  * Some properties (the only ones that can be observed!) get spammed all over $\mathcal{E}$.
  * No-cloning implies not *all* properties can be redundant.
  * Environment selects at most one observable to be propagated all over the place.
* **Complementary observables are kaput!**
  - Measuring them requires capturing *all* of $\mathcal{E}$.
* **Quantum Darwinism**: the process by which *one* property is propagated throughout $\mathcal{E}$, and becomes objective, at the expense of complementary observables.

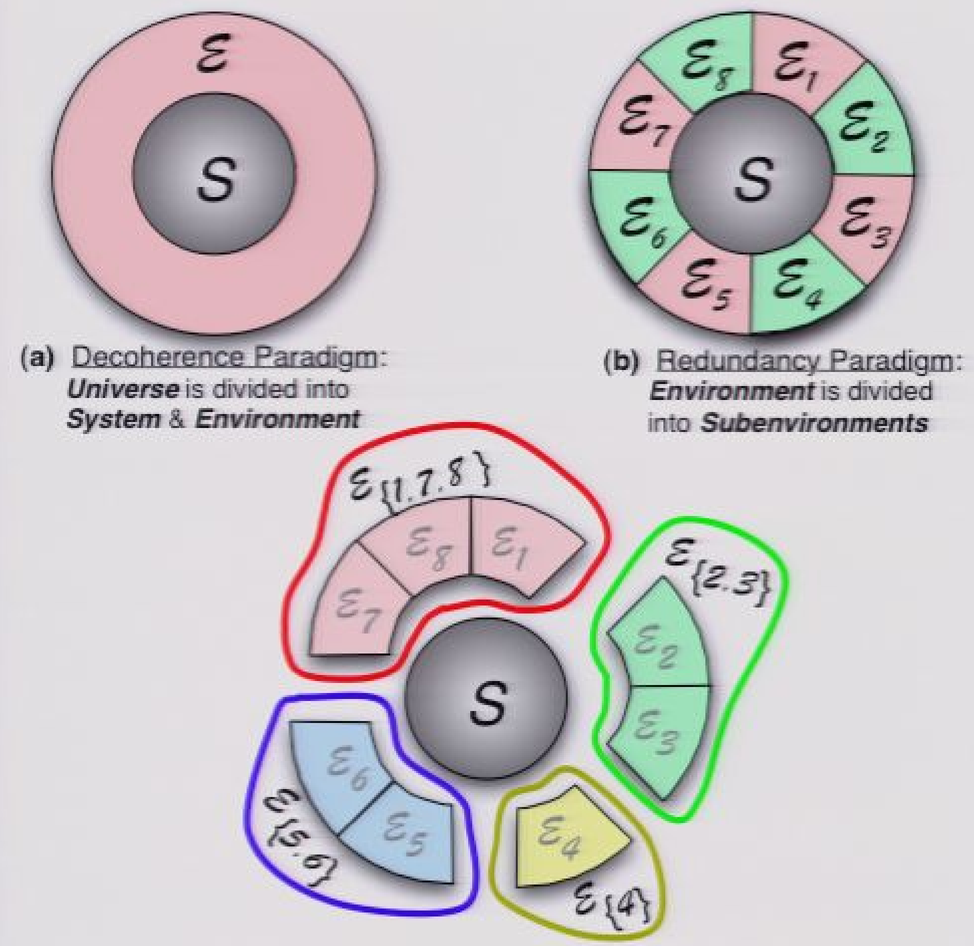
The Environment-as-a-witness Toolkit

- Observers learn about systems by measuring the environment ($\mathcal{E}$).
- Information lost to $\mathcal{E}$ implies decoherence *unless it is recaptured*.
- Measurements we can make on $\mathcal{E}$ are limited by its *locality structure*.
- A measure of "What information does $\mathcal{E}_i$ provide about $\mathcal{S}$?" is the *Quantum Mutual Information:*

$$I_{\mathcal{S}\mathcal{E}} = H_{\mathcal{S}} + H_{\mathcal{E}} - H_{\mathcal{S}\mathcal{E}}$$

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

- Quantum MI can rise to $I_{\mathcal{S}\mathcal{E}} = 2H_{\mathcal{S}}$ (whereas $I_{\text{classical}} < H_{\mathcal{S}}$).



(a) Decoherence Paradigm: ***Universe*** is divided into ***System*** & ***Environment***

(b) Redundancy Paradigm: ***Environment*** is divided into ***Subenvironments***

(c) ***Subenvironments*** are combined into ***Fragments*** that each have nearly-complete information.

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Partial Information Plots

(a visual approach to information storage)

* Plot ***how much of $\mathcal{E}$ is captured***
  vs.
  how much information can be inferred.

* Three distinct profiles:
  - *redundant* information
  - *distributed* information
  - *encoded* information

* For pure states of $\mathcal{SE}$, PIPS have reflection symmetry

Typical Examples

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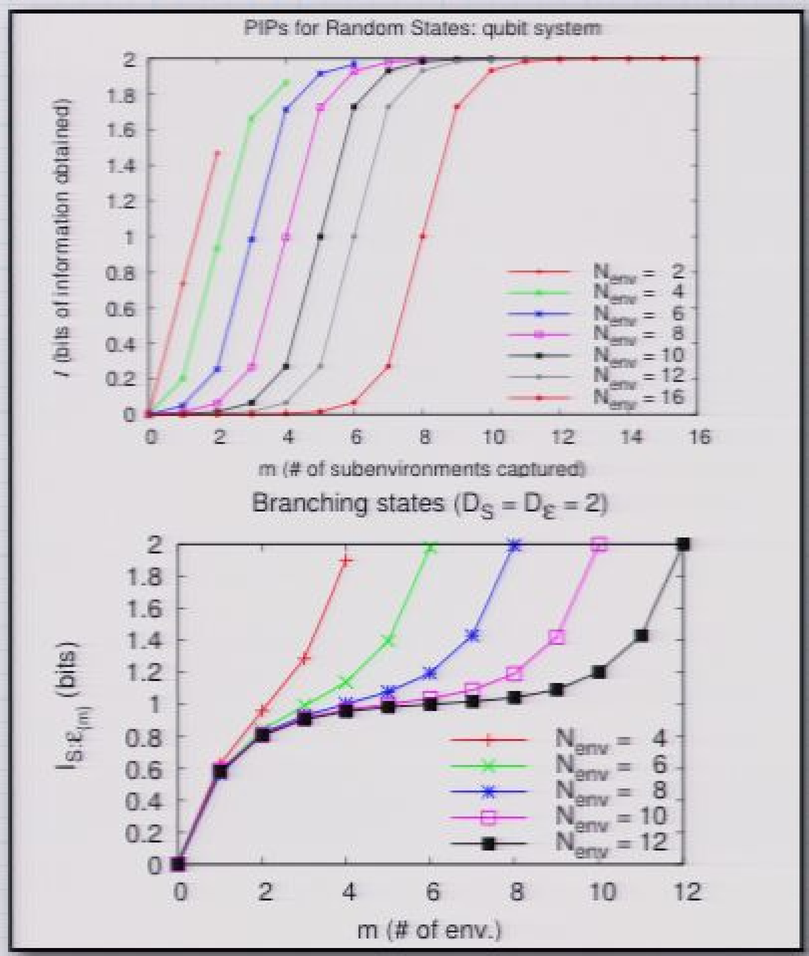
Random vs. *Singly-branching* States

- Randomly selected states for $\mathcal{S}\otimes\mathcal{E}$ display encoding:
  - No redundant information
  - Not representative of the universe we live in.



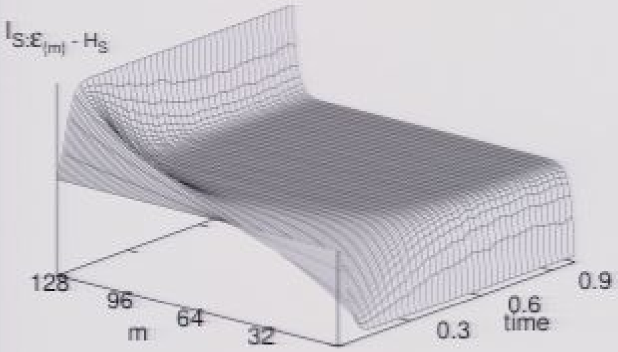
- Singly-branching states* of $\mathcal{S}\otimes\mathcal{E}$ display redundancy:
  - Simple model of decoherence
  - Results agree with ubiquitous observations of real universe.

*Singly-branching states: Each ***pointer state*** of $\mathcal{S}$ is correlated w/a random ***product state*** of $\mathcal{E}$

$$|\Psi\rangle = \sum_n s_n \left(|n\rangle_{\mathcal{S}} \otimes \overbrace{\left|\mathcal{E}_n^{(1)}\right\rangle \otimes \left|\mathcal{E}_n^{(2)}\right\rangle \otimes \ldots \left|\mathcal{E}_n^{(N\mathrm{env})}\right\rangle}\right)$$

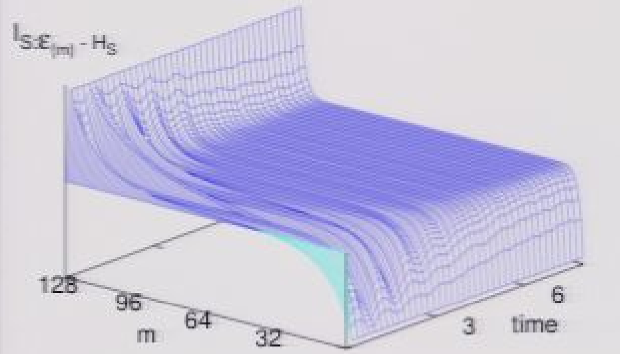
Dynamical evolution of PIPs
(Spin bath models of decoherence)

Interaction-only model



Each part of $\mathcal{E}$ interacts with ("measures") $\mathcal{S}$ independently. No other dynamics.

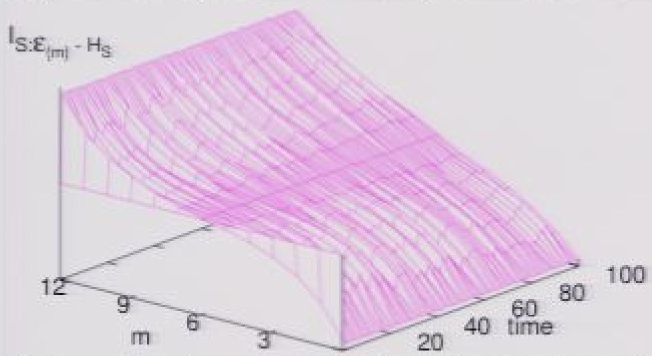
Quantum-measurement model



Each part of $\mathcal{E}$ evolves on its own, *while* it measures $\mathcal{S}$. The system has no dynamics.

These models yield *singly-branching* states

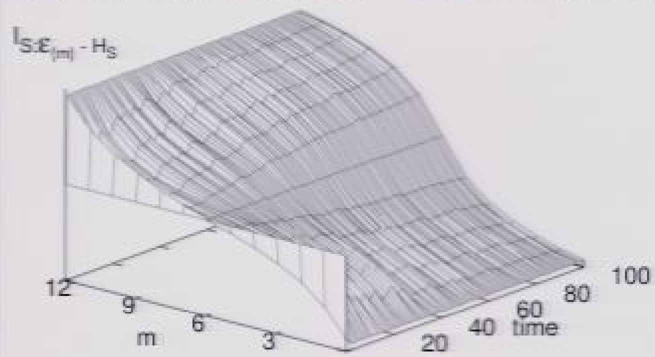
Dynamical-system & *Multiple-measurement*



D-S: $\mathcal{S}$ evolves, mediating $\mathcal{E}_i$-$\mathcal{E}_j$ interaction.

M-M: Multiple noncommuting interactions between $\mathcal{S}$ and each $\mathcal{E}_i \Rightarrow$ same effect.

Dissipative models (assorted)



Starting with the *D-S* or *M-M* model, we add independent dynamics for each part of $\mathcal{E}$.

More general models explore a much wider range of states... ...eventually, states appear *randomly distributed*.

Quantifying Redundancy

- Goal 1: Quantify how many independent observers could obtain "nearly all" the information available about $\mathcal{S}$.
- Goal 2: Distill out the most important features of a PIP, for easier analysis.
- Basic Idea: Compute $N_\delta = \{\#$ of random fragments that provide "all but δ" of the classical information$\}$; $R_\delta \approx N_\delta$.
- Caveats: Presence of entanglement yields extra information; large values of δ cause overestimation of R_δ.

$$R_\delta \geq (1-\delta)N_\delta - 1$$

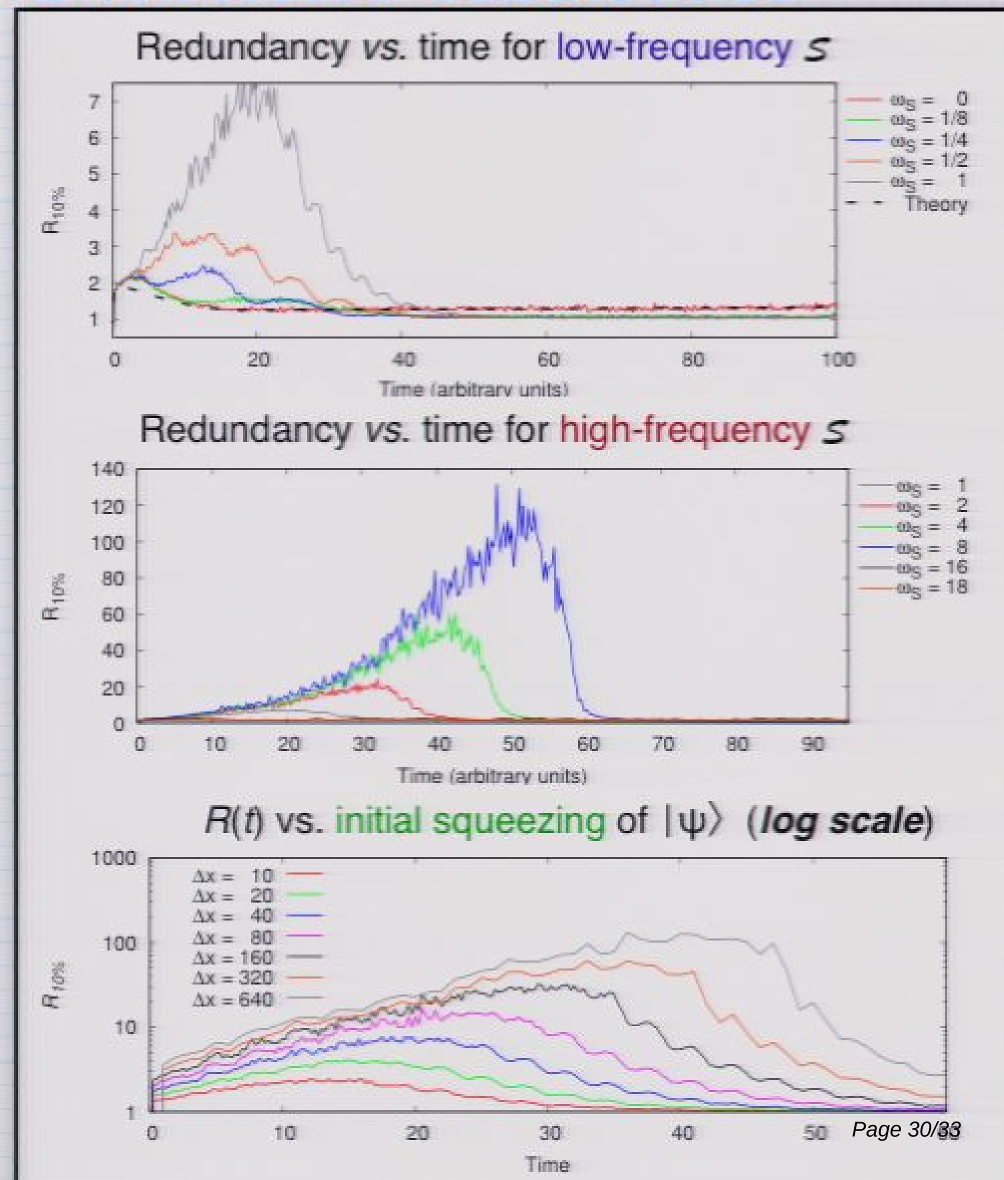
Dynamics of Redundancy Quantum Brownian motion

- Most important parameters:
  - Central system's frequency, $\omega_{\mathcal{S}}$. *Determines how much of $\mathcal{E}$ actually interacts with $\mathcal{S}$.*
  - Squeezing of $\mathcal{S}$'s initial state, Δx. *Determines how "classical" the system's state is.*

- R increases sharply as $\omega_{\mathcal{S}}$ and Δx are increased.

- Dissipation eventually destroys redundancy (& all information).

- Dissipation is also crucial for *enhancing* redundancy in QBM!



Summary & Conclusions

* Classical reality emerges from quantum theory.
    * Operationally, the unobservable doesn't exist.
    * So, we can construct self-consistent, objective "reality" as the set of properties selected & broadcast by the environment (this is Q.D.)
* Environment-as-a-witness is a useful paradigm & toolset for tracing information flow from system to observer.
    * Models show that Q.D. really *does* happen.
    * ...but there's more complex behavior, too.

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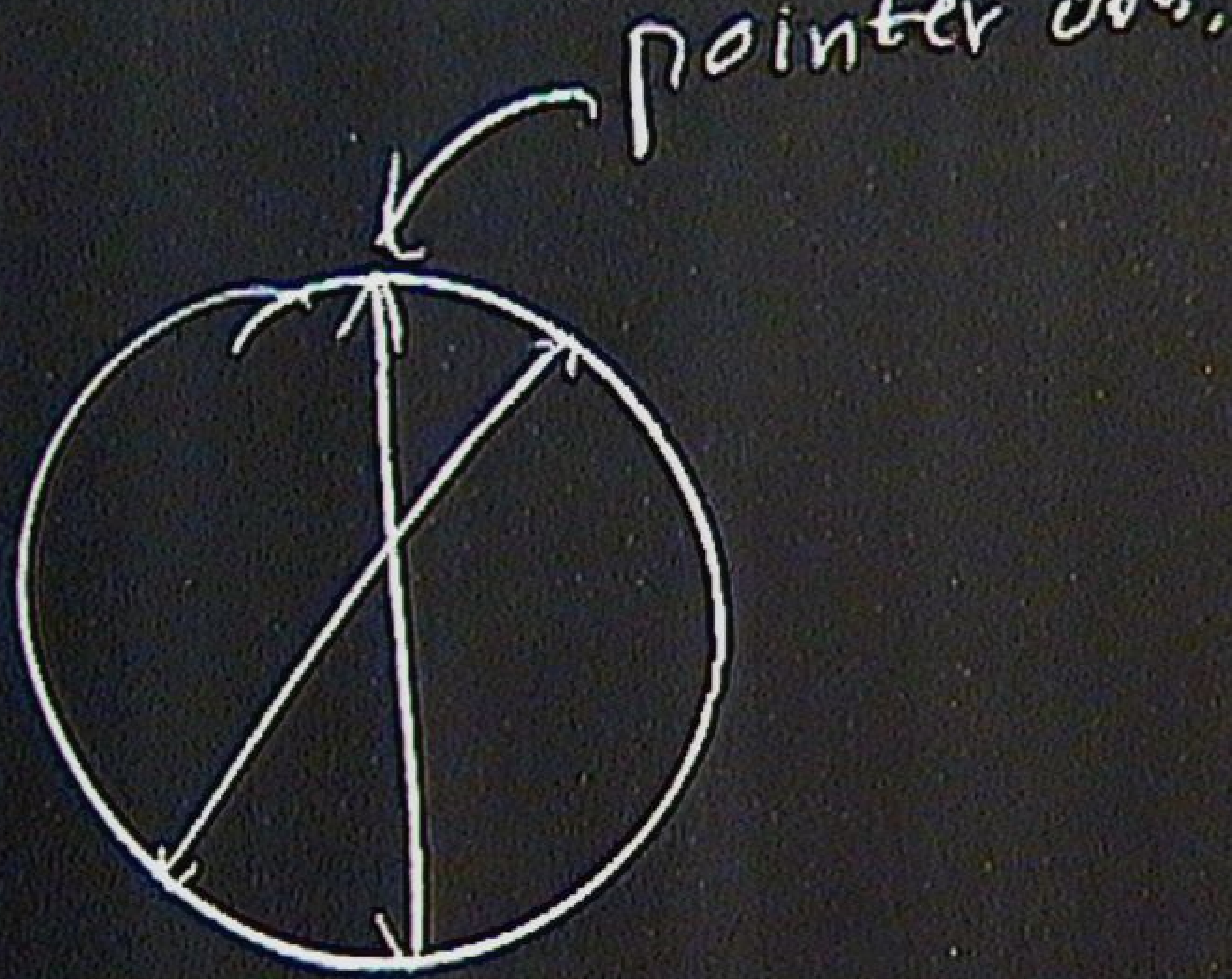
* Classical reality emerges from quantum theory.
  * Operationally, the unobservable doesn't exist.
  * So, we can construct self-consistent, objective "reality" as the set of properties selected & broadcast by the environment (this is Q.D.)
* Environment-as-a-witness is a useful paradigm & toolset for tracing information flow from system to observer.
  * Models show that Q.D. really *does* happen.
  * ...but there's more complex behavior, too.


pointer obs.