Title: Bell's Theorem and Stochastic Quantization

Date: Nov 22, 2006 04:00 AM

URL: http://pirsa.org/06110017

Abstract: Most modern discussions of Bell's theorem take microscopic causality (the arrow of time) for granted, and raise serious doubts concerning realism and/or relativity. Alternatively, one may allow a weak form of backwards-in-time causation, by considering "causes" to have not only "effects" at later times but also "influences" at earlier times. These "influences" generate the correlations of quantum entanglement, but do not enable information to be transmitted to the past. Can one realize this scenario in a mathematical model? If macroscopic time-asymmetry is introduced by imposing initial conditions, such a model can not be deterministic. Stochastic Quantization (Parisi and Wu,1981) is a non-deterministic approach known to reproduce quantum field theory. Based on this, a search for models displaying quantum nonlocal correlations, while maintaining the principles of realism, relativity and macroscopic causality, is proposed.

Bell's Theorem and Stochastic Quantization

Nathan Argaman

- Bell's theorem: QM vs. the scientific method
- Is there a microscopic arrow of time?
- Stochastic Quantization with initial conditions
- Summary

Bell's Theorem and Stochastic Quantization

Nathan Argaman

- Bell's theorem: QM vs. the scientific method
- Is there a microscopic arrow of time?
- Stochastic Quantization with initial conditions
- Summary

No one understands quantum mechanics.

"There was a time when the newspapers said that only twelve men understood the theory of relativity. I do not believe that there ever was such a time. . . . On the other hand, I think it is safe to say that no one understands quantum mechanics. . . . Do not keep saying to yourself, if you can possibly avoid it, 'But how can it be like that?' because you will get 'down the drain' into a blind alley from which nobody has yet escaped. Nobody knows how it can be like that."

R. P. Feynman
The Character of Physical Law
(1967a, p. 129)

38 PHYSICS TODAY / APRIL 1985

Is the moon there when nobody looks? Reality and the quantum theory

Einstein maintained that quantum metaphysics entails spooky actions at a distance; experiments have now shown that what bothered Einstein is not a debatable point but the observed behavior of the real world.

N. David Mermin

Shut up and calculate!

Intelligent Design in the Physics Classroom?

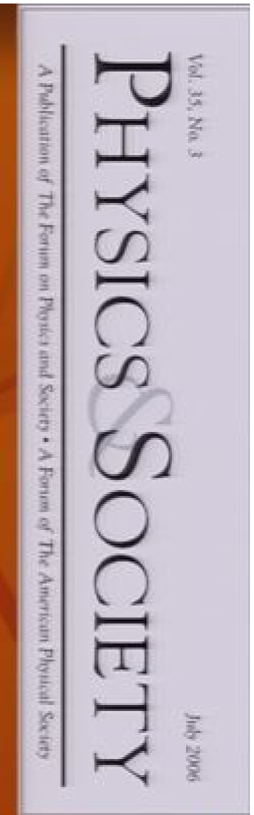
Travis Norsen

A dangerous enemy has infiltrated our science classrooms and is infecting our students' minds. …blurs the distinction between real science and arbitrary dogma and "makes students stupid" by leaving them less able to distinguish reasonable ideas from unreasonable ones

Bohr's approach was not so much to resolve the paradox as to embrace it. Naming his philosophy "complementarity,"

Heisenberg explains …"science no longer confronts nature as an objective observer, but sees itself as an actor in this interplay between man and nature."[3]

shouldn't the obviously more rational alternative theory of de Broglie and Bohm also be taught — "not as the only way, but as an antidote to the prevailing complacency? To show that vagueness, subjectivity, and indeterminism are not forced on us by experimental facts, but by deliberate theoreti-



QM has many formulations:

- Matrix mechanics (1925)
- Wave mechanics (1926)
- Path integrals (1948)
- Bohmian mechanics (1952)

} deterministic evolution

- Stochastic Mechanics (1966)
- …

QM has been superceded by QFT:

- Experimental input has led to the SM, involving non-Abelian gauge fields.

EPR's EPRs (1935)

Einstein, Podolsky and Rosen's Elements of Physical Reality – a sufficient condition:

"If, without in any way disturbing a system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity."

Requirements: **Locality** + **Realism** + **Completeness** → QM is "incomplete."

"God does not play dice" is not the issue!

Spooky actions at a distance

That which really exists in B should … not depend on what kind of measurement is carried out in part of space A; it should also be independent of whether or not any measurement at all is carried out in space A.

If one adheres to this program, one can hardly consider the quantum-theoretical description as a complete representation of the physically real.

If one tries to do so in spite of this, one has to assume that the physically real in B suffers a sudden change as a result of a measurement in A.

My instinct for physics bristles at this.

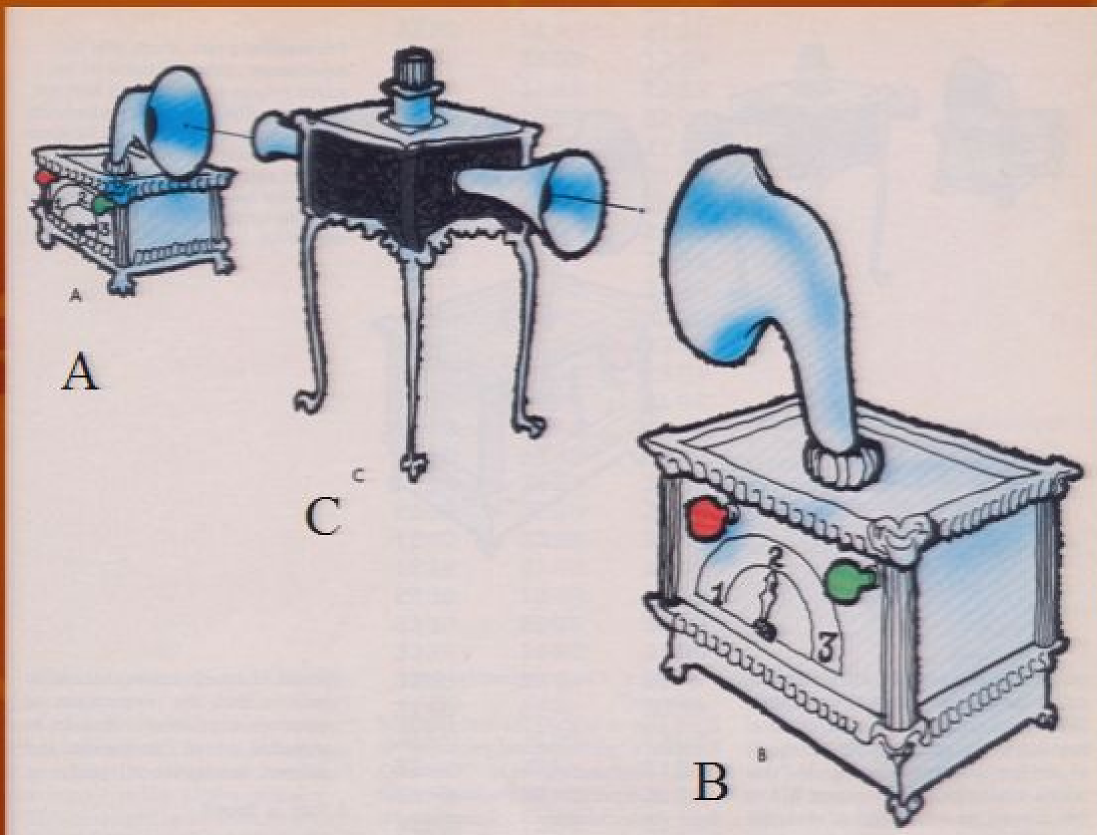
Einstein to Born (1948)

Those physicists who regard the descriptive properties of quantum mechanics as definitive … drop the requirement for the independent existence of the physical reality present in different parts of space;

… When I consider the physical phenomena known to me, and especially those which are being so successfully encompassed by quantum mechanics, I still cannot find any fact anywhere which would make it appear likely that [the] requirement will have to be abandoned.

Einstein to Born (1948)

John S. Bell (1964) – A fact is found



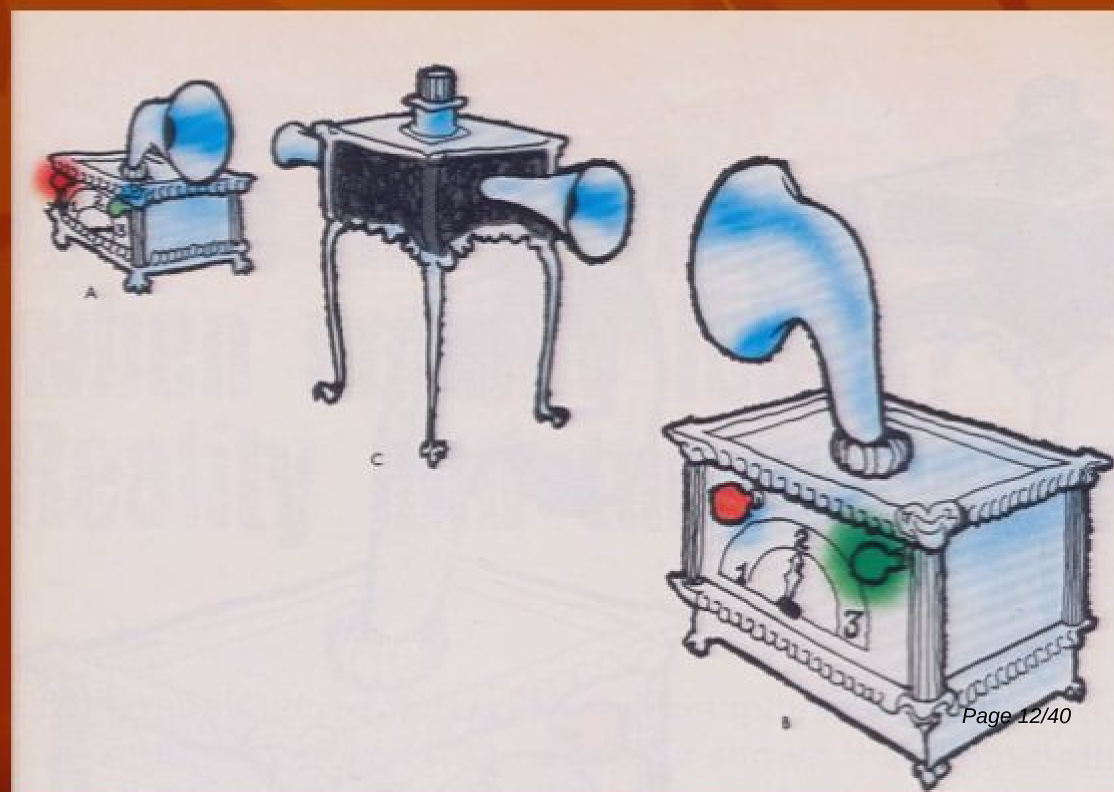
A. Aspect
(1981)

Bell's inequality (Mermin's description)

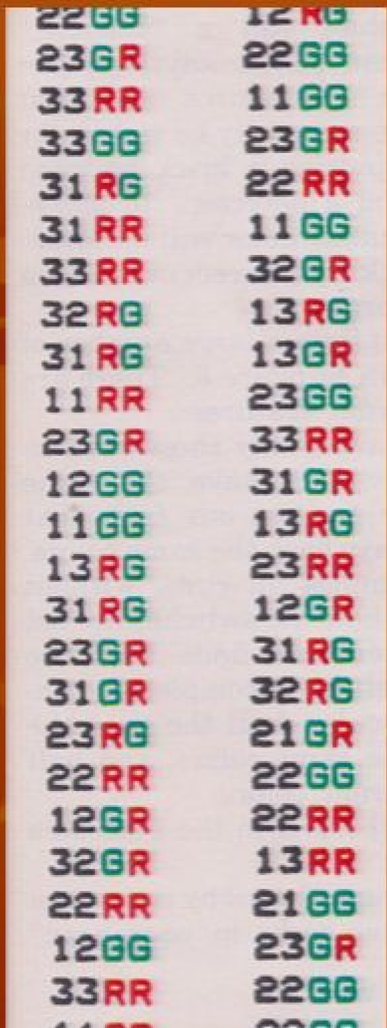
- Black box approach: detectors A and B, source C.
- C has button. A and B have switches and lights.
- No communication except through "particles."

To perform a run, randomize switch settings, push and record, e.g.:

32RG



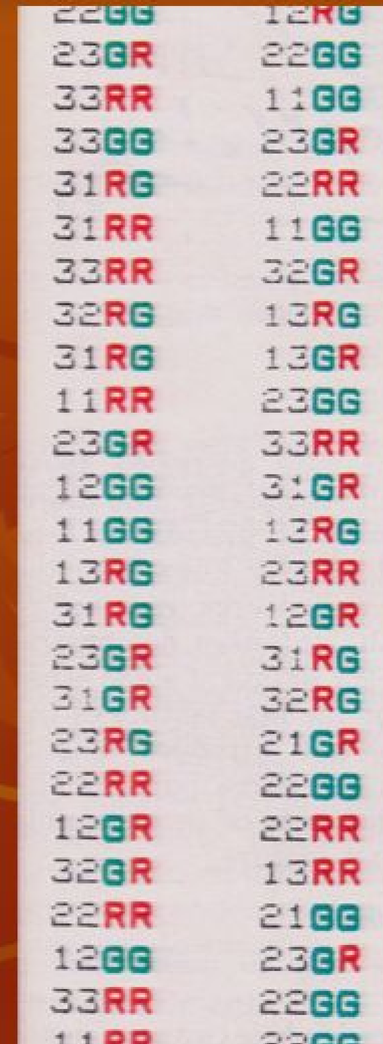
Data generated by repetition:



23GR	22GG
33RR	11GG
33GG	23GR
31RG	22RR
31RR	11GG
33RR	32GR
32RG	13RG
31RG	13GR
11RR	23GG
23GR	33RR
12GG	31GR
11GG	13RG
13RG	23RR
31RG	12GR
23GR	31RG
31GR	32RG
23RG	21GR
22RR	22GG
12GR	22RR
32GR	13RR
22RR	21GG
12GG	23GR
33RR	22GG

Analysis:

23GR	22GG
33RR	11GG
33GG	23GR
31RG	22RR
31RR	11GG
33RR	32GR
32RG	13RG
31RG	13GR
11RR	23GG
23GR	33RR
12GG	31GR
11GG	13RG
13RG	23RR
31RG	12GR
23GR	31RG
31GR	32RG
23RG	21GR
22RR	22GG
12GR	22RR
32GR	13RR
22RR	21GG
12GG	23GR
33RR	22GG

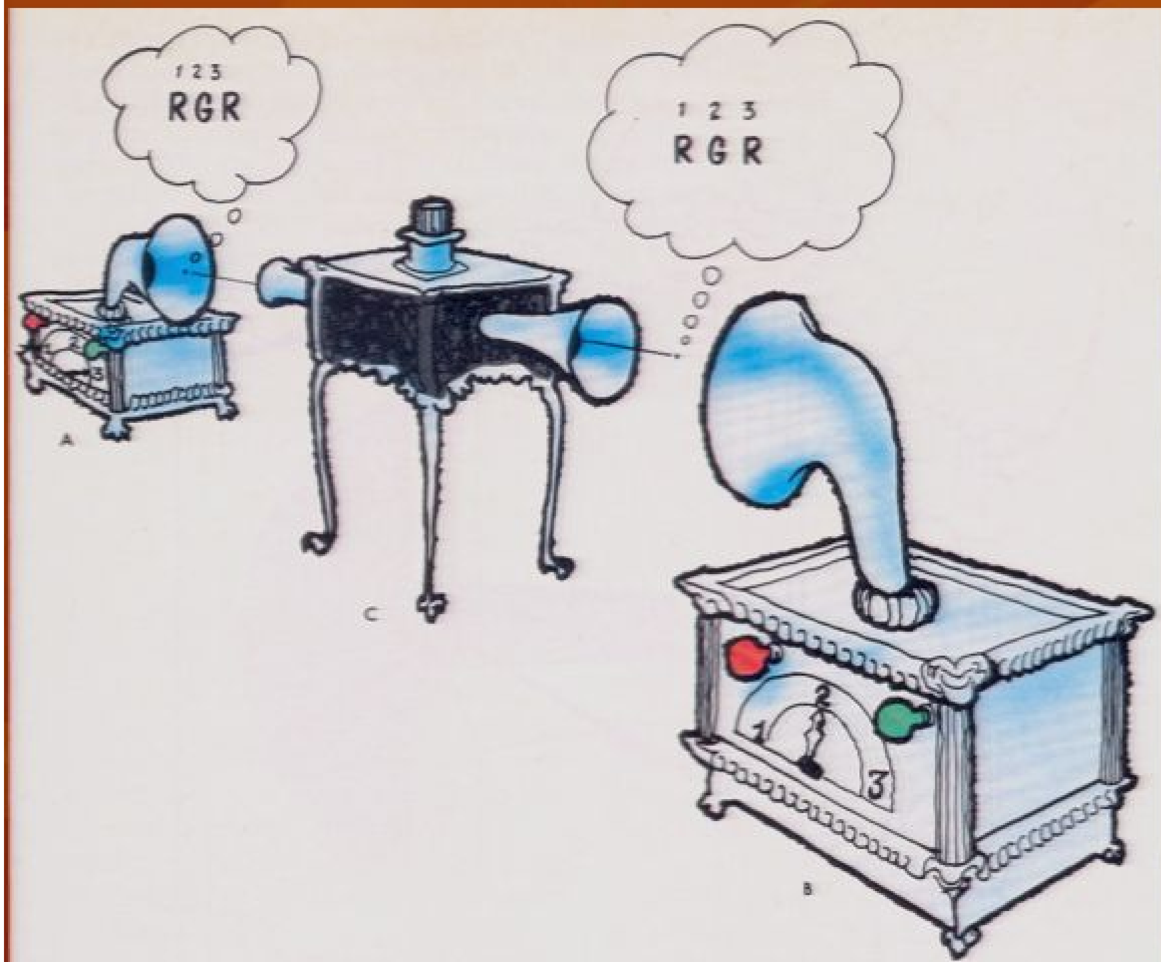


23GR	22GG
33RR	11GG
33GG	23GR
31RG	22RR
31RR	11GG
33RR	32GR
32RG	13RG
31RG	13GR
11RR	23GG
23GR	33RR
12GG	31GR
11GG	13RG
13RG	23RR
31RG	12GR
23GR	31RG
31GR	32RG
23RG	21GR
22RR	22GG
12GR	22RR
32GR	13RR
22RR	21GG
12GG	23GR
33RR	22GG

Same switch settings → Same result

Random switch settings → Random results

Same settings → hidden variables. Hidden variables → correlations.



For hidden instruction sets such as "RGR," the same colors flash 5/9 of the time (for switch settings 11, 22, 33, 13, and 31). For "RRR" or "GGG," same colors flash *all* the time. Thus,

$$P(\text{same color}) \geq \frac{5}{9}.$$

But QM says they flash the same color only ½ of the time!

Aspect's experiments

- Photon pairs emitted by calcium atoms in a radiative cascade. Detectors measure polarization in directions θ_A, θ_B.
- Initial and final states have J=0.
- Polarization measurements at 120° give same result ¼ = $\cos^2(120°)$ of the time.
- For random settings, same colors flash $\frac{1}{3}\cdot 1+\frac{2}{3}\cdot\frac{1}{4}=\frac{1}{2}$ of the time – no correlations.
- No instruction sets, no hidden variables.
- A and B 13 meters apart; Delayed choice…

"Local Realism" vs. QM

What do Bell's theorem, and its generalizations/amplifications, assume?

- Realism
- Logic
- Local causality
- Genuine randomness (no conspiracies)

The scientific method is under attack!

Contemporary Physics, Vol. 47, No. 2, March–April 2006, 79–88

From Einstein's theorem to Bell's theorem: a history of quantum non-locality

H. M. WISEMAN*

To conclude, the results of the Bell-experiments leave only two possibilities:

(i) the world is non-local—events happen which violate the principles of relativity;
(ii) objective reality does not exist—there is no matter of fact about distant events.

†To be scrupulous, there are perhaps four other ways that the correlations in such an experiment could be explained away. (1) One could simply "refuse to consider the correlations mysterious" [57]. (2) One could deny that the experimenters have free will to choose the settings of their measurement devices at random, as required for a statistically valid Bell-experiment [54]. (3) One could entertain the idea of backward-in-time causation [58]. (4) One could conclude that ordinary (Boolean) logic is not valid in our Universe [59]. I do not consider these escape routes because

But…

- Relativity is time-reversal symmetric
- Causality is not!

Local causality follows from

relativity + an arrow of time.

Can we cast doubt on time's arrow?

- – Revolutionary, but not inappropriate!
- – Much closer in spirit to relativity!

We must choose between "telepathy" and "foresight."

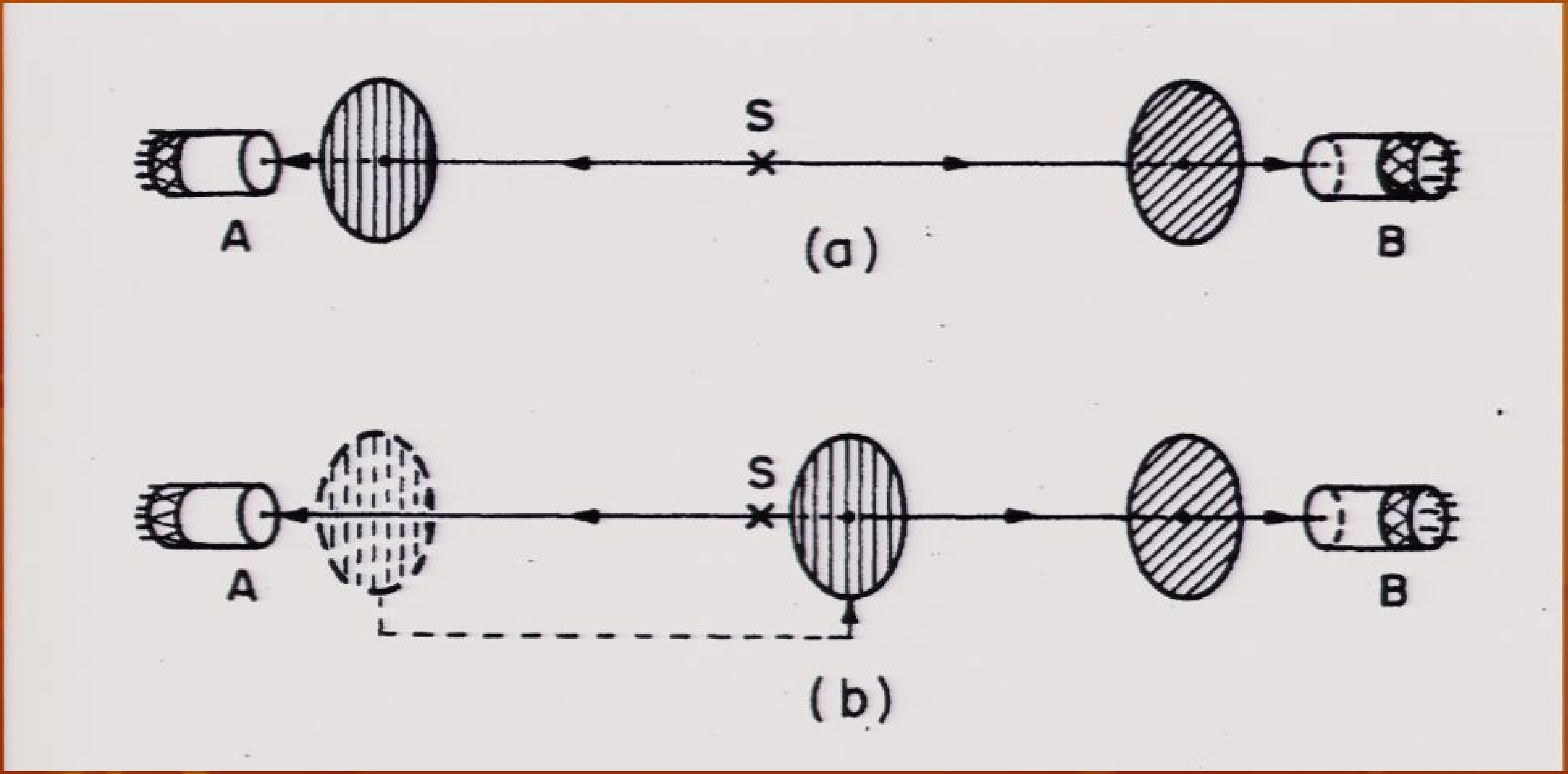
A plausible model for Aspect's experiments:

The radiative cascade involves an intermediate state with J=1, identified with a direction θ.

Assuming θ takes one of the values θ_A, $\theta_A+\pi/2$, θ_B, $\theta_B+\pi/2$ with equal probabilities, and the photons pass the polarizers with probabilities $\cos^2(\theta - \theta_A)$, $\cos^2(\theta - \theta_B)$, reproduces the results.

- Measuring θ changes results…
- This model differs from Bell's nonlocal counter-example.

→ "Local Realism" without causality



$$\cos^2(\theta_{rel})$$

Cramer (1986): "The transactional interpretation of quantum mechanics"

Why do we believe in time's arrows?

- 2nd law of thermodynamics.
- Paradoxes associated with causality loops.
- …   (Time has many arrows).

However:

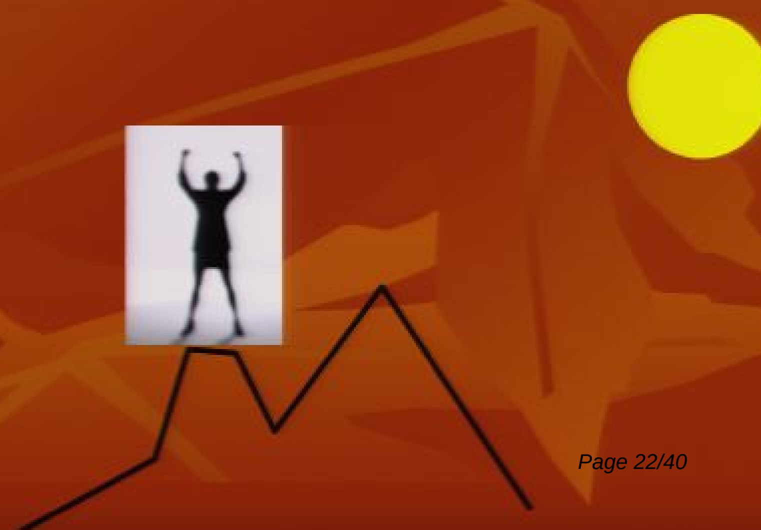
- Microscopic systems are not thermodynamic.
- Quantum correlations can not be used to transmit information.

Could all arrows emerge from initial conditions?

An analogy

Imagine a world in which, for some astronomical reason, the sun always hangs in the east. Inhabitants of that world will naturally come to see “East” as fundamentally different from “West,” because of this “high temperature boundary condition.”

Possibly, in our universe, “Past” is different from “Future” only because of the low-entropy boundary condition imposed by the Big Bang.



valid in our Universe [59]. I do not consider these escape routes because they seem to undercut the core assumptions necessary to undertake scientific experiments. Bell expressed similar sentiments: with regard to option (1) he said "Outside [the] peculiar context [of quantum philosophy], such an attitude would be dismissed as unscientific. The scientific attitude is that correlations cry out for explanation." [56]. With regard to option (2) he thought it was not worth considering unless it could be shown to have some theoretical justification: "When a theory ... in which such conspiracies inevitably occur ... is announced, I will not refuse to listen ..." [60]. In Bell's opinion, option (3) was the same as option (2): "I have not myself been able to make sense of backward causation. When I try to think of it I lapse quickly into fatalism", as quoted in [58]. Finally, of option (4), Bell said that "When one remembers the role of the apparatus, ordinary logic is just fine." [61], and thought that a "full appreciation of this [role] would have aborted ... most of 'quantum logic'." [62] (p. vii).

Huw Price: retro-causality is possible if, when we say "a causes b," we do not hold fixed *all* the past of a, but rather only the *accessible* past of a.

Local causality fails

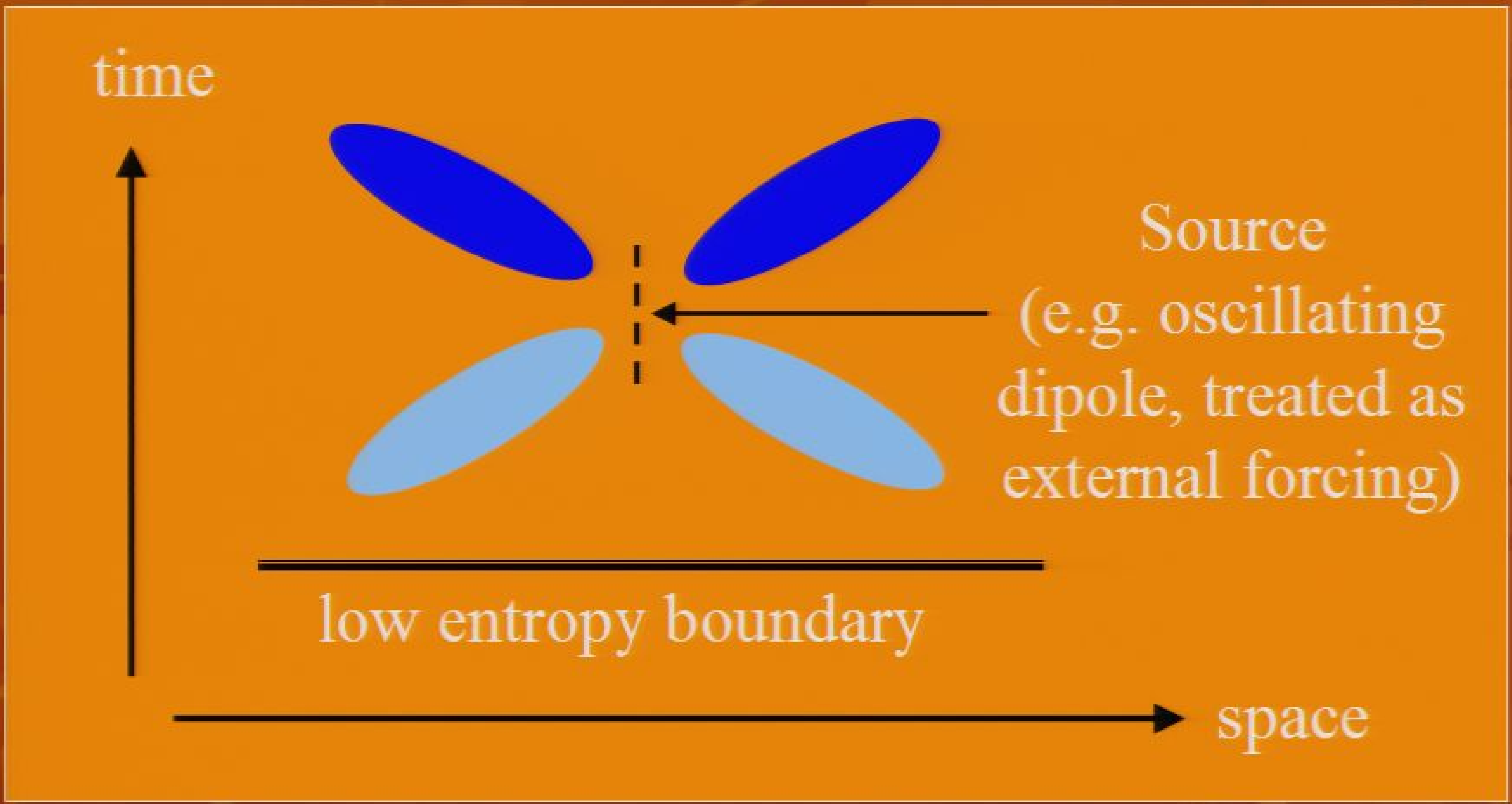
- Bohmian mechanics describes quantum phenomena using non-local causality – the wavefunctions guide the particles, providing a mechanism for nonlocality.
- Can these phenomena alternatively be described with non-causal locality? Possibly.
- Would such a description require an even more elaborate mechanism? No! (prejudice with respect to time's arrows).

Philosophy

Bohr: It is wrong to think that the task of physics is to find out how Nature is. Physics concerns what we can say about Nature."[4]

Theoretical physics

Causality due to initial conditions:



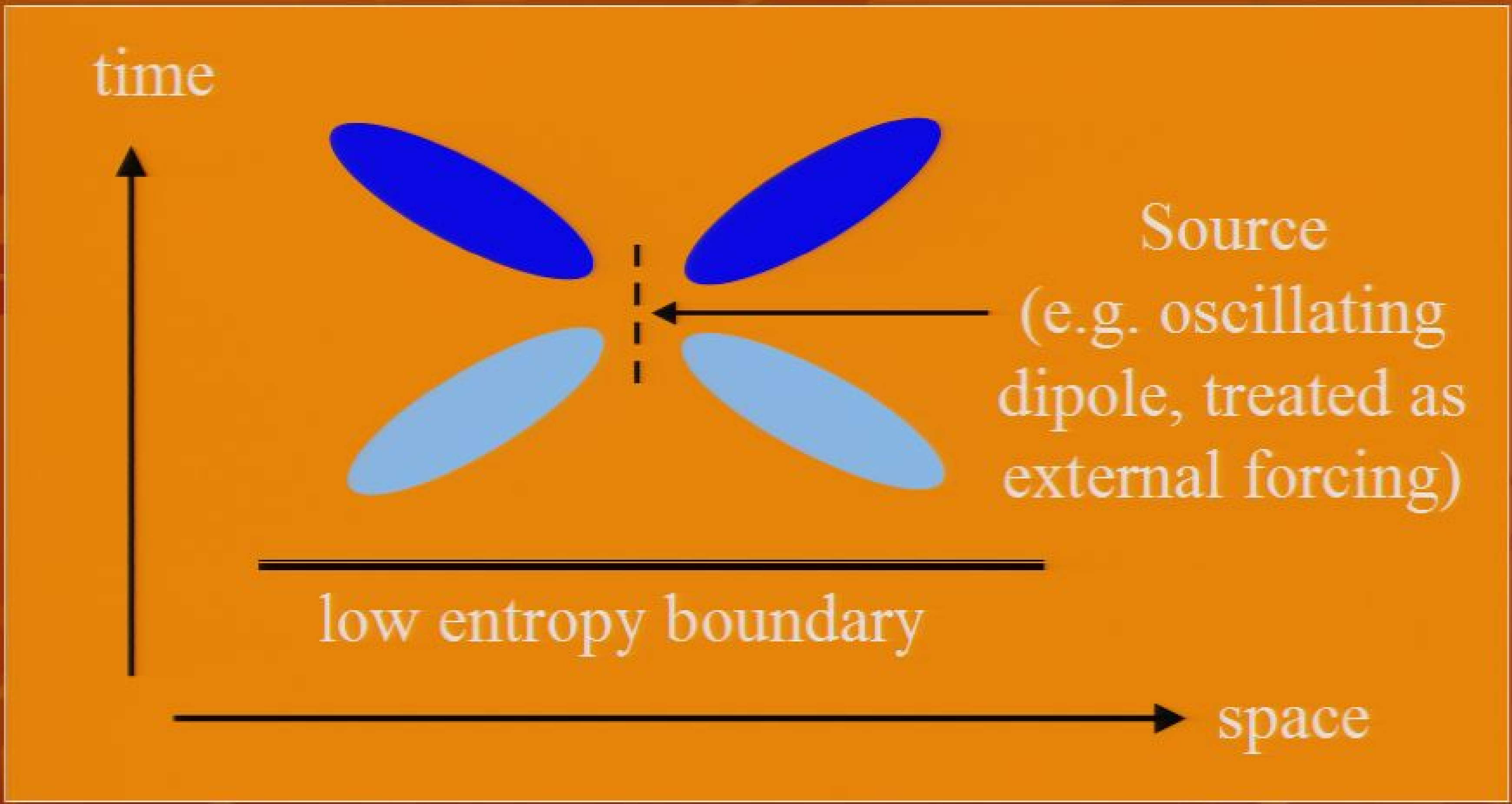
- Source causes waves in blue regions = causality.
- Deterministic vs. Stochastic fields…

Stochastic models…

- A theory can describe a set of discrete components (beam splitters etc.), with corresponding "elements of reality," or describe continuous fields $\Phi_i(\bar{x})$, with a probability distribution denoted $P[\{\Phi_i(\bar{x})\}]$.
- A distribution $P[\{\Phi_i(\bar{x})\}]$ which reproduces quantum field theory already exists in Parisi-Wu stochastic quantization (1981).

For references and recent numerical results, see:
J. Berges and I.-O. Stamatescu, P.R.L. **95**, 202003 (2005).

Causality due to initial conditions:



- Source causes waves in blue regions = causality.
- Deterministic vs. Stochastic fields…

Stochastic models…

- A theory can describe a set of discrete components (beam splitters etc.), with corresponding "elements of reality," or describe continuous fields $\Phi_i(\bar{x})$, with a probability distribution denoted $P[\{\Phi_i(\bar{x})\}]$.
- A distribution $P[\{\Phi_i(\bar{x})\}]$ which reproduces quantum field theory already exists in Parisi-Wu stochastic quantization (1981).

For references and recent numerical results, see:
J. Berges and I.-O. Stamatescu, P.R.L. **95**, 202003 (2005).

Stochastic Quantization

1. Wick rotation

4. Back to Minkowski

2. Imaginary time

3. Langevin time

Stochastic Quantization

1. Wick rotation

$$e^{-it\hat{H}} \rightarrow e^{-\beta\hat{H}}$$

$$t \rightarrow -i\beta$$

4. Back to Minkowski

2. Imaginary time

3. Langevin time

Stochastic Quantization

1. Wick rotation

$$e^{-it\hat{H}} \rightarrow e^{-\beta\hat{H}}$$

$$t \rightarrow -i\beta$$

2. Imaginary time

$$\mathrm{tr}\, e^{-\beta\hat{H}} = \int D\varphi\, e^{-S_E}$$

$$S_E = \int d^4x \left[\frac{1}{2}(\nabla\varphi)^2 + U(\varphi)\right]$$

$$\varphi(x_i, x_4 = 0) = \varphi(x_i, x_4 = \beta)$$

3. Langevin time

4. Back to Minkowski

Stochastic Quantization

1. Wick rotation

$$\mathrm{e}^{-it\hat{H}} \rightarrow \mathrm{e}^{-\beta\hat{H}}$$

$$t \rightarrow -i\beta$$

2. Imaginary time

$$\mathrm{tr}\,\mathrm{e}^{-\beta\hat{H}} = \int \mathrm{D}\varphi\, \mathrm{e}^{-S_E}$$

$$S_E = \int \mathrm{d}^4x \left[\frac{1}{2}(\nabla\varphi)^2 + U(\varphi)\right]$$

$$\varphi(x_i, x_4 = 0) = \varphi(x_i, x_4 = \beta)$$

3. Langevin time

$$\left\langle F[\varphi] \right\rangle_{S_E} = \lim_{\tau\to\infty} \frac{1}{\tau}\int_0^\tau d\tau'\, F[\varphi(\tau')]$$

$$\frac{\partial\varphi}{\partial\tau} + \frac{\delta S_E}{\delta\varphi} = \eta$$

$$\langle \eta(x,\tau)\eta(x',\tau')\rangle = 2\delta^4(x-x')\delta(\tau-\tau')$$

4. Back to Minkowski

Stochastic Quantization

1. Wick rotation

$$e^{-it\hat{H}} \rightarrow e^{-\beta\hat{H}}$$

$$t \rightarrow -i\beta$$

2. Imaginary time

$$\mathrm{tr}\, e^{-\beta\hat{H}} = \int D\varphi\, e^{-S_E}$$

$$S_E = \int d^4x \left[\frac{1}{2}(\nabla\varphi)^2 + U(\varphi)\right]$$

$$\varphi(x_i, x_4 = 0) = \varphi(x_i, x_4 = \beta)$$

3. Langevin time

$$\left\langle F[\varphi] \right\rangle_{S_E} = \lim_{\tau\to\infty} \frac{1}{\tau}\int_0^\tau d\tau'\, F[\varphi(\tau')]$$

$$\frac{\partial\varphi}{\partial\tau} + \frac{\delta S_E}{\delta\varphi} = \eta$$

$$\langle \eta(x,\tau)\eta(x',\tau')\rangle = 2\delta^4(x-x')\delta(\tau-\tau')$$

4. Back to Minkowski

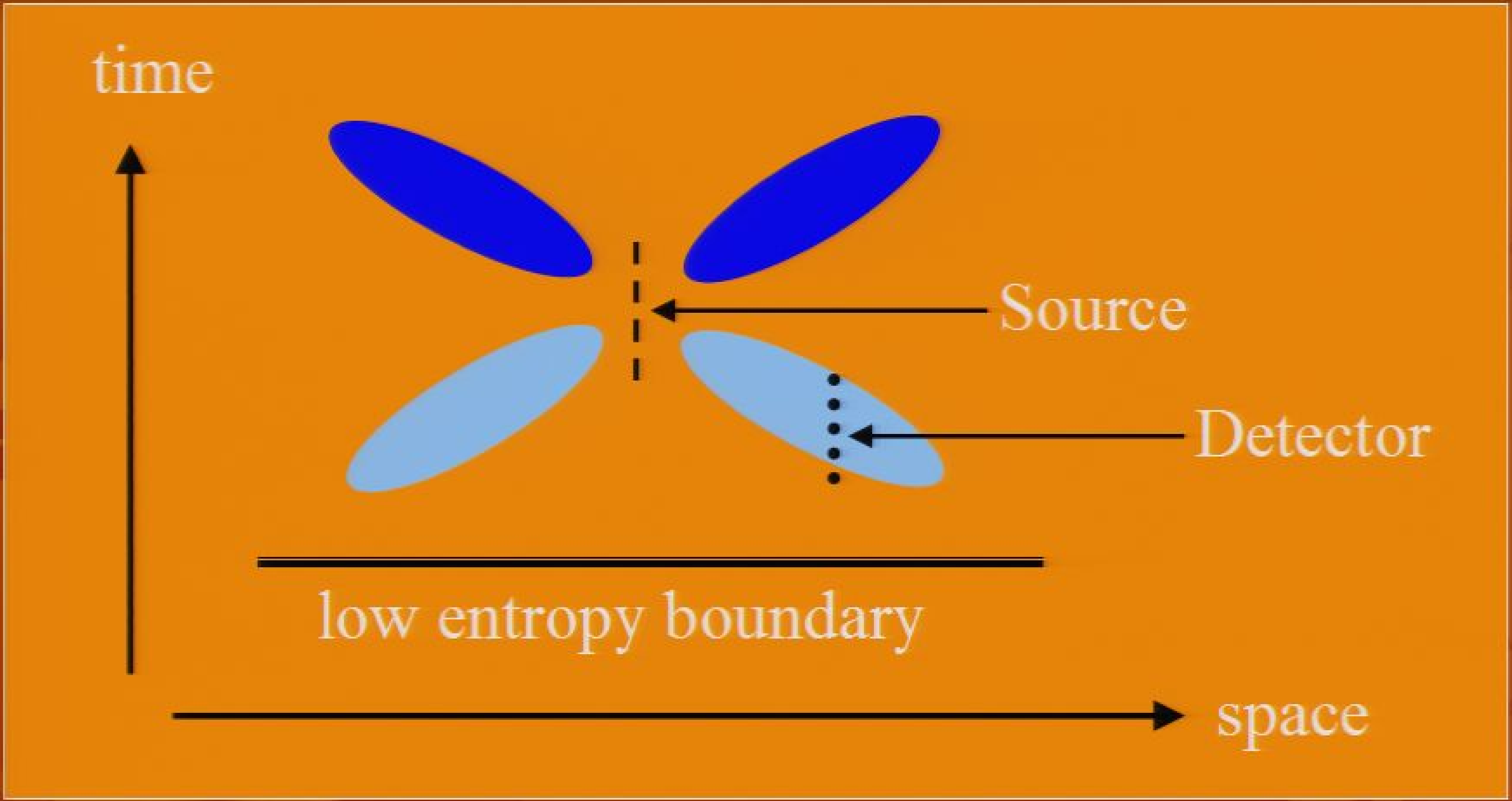
$$\frac{\partial\varphi}{\partial\theta} + i\left(m^2 - \nabla^2 + \frac{\partial^2}{\partial t^2}\right)\varphi = \eta$$

$$x_4 \rightarrow it,\ \tau \rightarrow i\theta,\ m^2 \rightarrow m^2 - i\varepsilon$$

- Parisi and Wu (1981): "Perturbation theory without gauge fixing."
- As $\theta \rightarrow \infty$, an "equilibrium distribution" is obtained.
- Fields are complex, probabilities aren't.

Stochastic Field Approach $P[\{\Phi_i(\bar{x})\}]$

- Small ($\hbar$) fluctuations around classical field.
- Need to verify that macroscopic causality arises when initial conditions are imposed.



Source is simple. Detector involves:

- internal degree of freedom
- amplification, dissipation
- initialized in metastable state → click!

If this works…

- Add double slit. Is there particle-wave duality?
- Is duality due to discreteness of information collected by the detector?

- If this fails, it will be interesting to find out how and why.

If this works…

- Application to Aspect's experiments – add source of EPR pairs – is the result similar to the "discrete model" above?
- "Lenient Causality" – a cause may have effects in the future, *and* may influence the past, but without transmitting information.

Additional Issues:

- Quantization of information
- Link between increasing entropy and information flow (arrows of time)
- Propagation vs. collapse of Ψ (paradoxes, "unitary evolution")
- Extensions (can G replace θ ?)

Conclusions:

- Quantum phenomena are incompatible with local causality. Realism is not the issue.
- Saying "local realism fails" is not legitimate.
- The arrows of time require further study.
- The stochastic field approach is promising.
- Imposing a low-entropy condition in the past can (hopefully) regain macroscopic causality.
- Let's find the way out of Feynman's blind alley.

argaman@mailaps.org