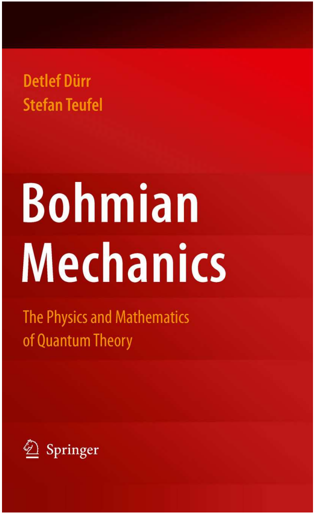
On the role of Decoherence in Bohmian Mechanics

Detlef Dürr

Mathematisches Institut
LMU München

June 8, 2009

My talk is based on my new book on Bohmian mechanics



and on a new book coming out next year

Sheldon Goldstein, Nino Zanghì, D.D.:
Quantum Physics without Quantum Philosophy
Springer 2010

What are the sources of and what is decoherence?

1. Schrödinger's wave function lives on configuration space (entanglement)
2. Boltzmann's irreversibility (applied to Bohmian mechanics)
3. the ever growing diminishment of the possibility of interference due to the ubiquitous and ever growing entanglement with "the environment" which separates wave functions parts in configuration space

What are the sources of and what is decoherence?

1. Schrödinger's wave function lives on configuration space (entanglement)
2. Boltzmann's irreversibility (applied to Bohmian mechanics)
3. the ever growing diminishment of the possibility of interference due to the ubiquitous and ever growing entanglement with "the environment" which separates wave functions parts in configuration space

What are the sources of and what is decoherence?

1. Schrödinger's wave function lives on configuration space (entanglement)
2. Boltzmann's irreversibility (applied to Bohmian mechanics)
3. the ever growing diminishment of the possibility of interference due to the ubiquitous and ever growing entanglement with "the environment" which separates wave functions parts in configuration space

The problem of the missing ontology

Schrödinger's cat

One can even set up quite ridiculous cases. A cat is penned up in a steel chamber, along with the following device (which must be secured against direct interference by the cat): in a Geiger counter there is a tiny bit of radioactive substance, so small, that perhaps in the course of the hour one of the atoms decays, but also, with equal probability, perhaps none; if it happens, the counter tube discharges and through a relay releases a hammer which shatters a small flask of hydrocyanic acid. If one has left this entire system to itself for an hour, one would say that the cat still lives if meanwhile no atom has decayed. The psi-function of the entire system would express this by having in it the living and dead cat (pardon the expression) mixed or smeared out in equal parts.

The problem of the missing ontology

Schrödinger's cat

One can even set up quite ridiculous cases. A cat is penned up in a steel chamber, along with the following device (which must be secured against direct interference by the cat): in a Geiger counter there is a tiny bit of radioactive substance, so small, that perhaps in the course of the hour one of the atoms decays, but also, with equal probability, perhaps none; if it happens, the counter tube discharges and through a relay releases a hammer which shatters a small flask of hydrocyanic acid. If one has left this entire system to itself for an hour, one would say that the cat still lives if meanwhile no atom has decayed. The psi-function of the entire system would express this by having in it the living and dead cat (pardon the expression) mixed or smeared out in equal parts.

Schrödinger continued

It is typical of these cases that an indeterminacy originally restricted to the atomic domain becomes transformed into macroscopic indeterminacy, which can then be resolved by direct observation. That prevents us from so naively accepting as valid a "blurred model" for representing reality. In itself it would not embody anything unclear or contradictory. There is a difference between a shaky or out-of-focus photograph and a snapshot of clouds and fog banks.
E. Schrödinger, "Die gegenwärtige Situation in der Quantenmechanik" Naturwissenschaften 23: pp.807-849 (1935).

Feynman on Observation

Does this mean that my observations become real only when I observe an observer observing something as it happens? This is a horrible viewpoint. Do you seriously entertain the thought that without observer there is no reality? Which observer? Any observer? Is a fly an observer? Is a star an observer? Was there no reality before 10^9 B.C. before life began? Or are you the observer? Then there is no reality to the world after you are dead? I know a number of otherwise respectable physicists who have bought life insurance. By what philosophy will the universe without man be understood?
Richard Feynman: Lecture Notes on Graviation

Feynman on Observation

Does this mean that my observations become real only when I observe an observer observing something as it happens? This is a horrible viewpoint. Do you seriously entertain the thought that without observer there is no reality? Which observer? Any observer? Is a fly an observer? Is a star an observer? Was there no reality before 10^9 B.C. before life began? Or are you the observer? Then there is no reality to the world after you are dead? I know a number of otherwise respectable physicists who have bought life insurance. By what philosophy will the universe without man be understood?
Richard Feynman: Lecture Notes on Graviation

the measurement problem

1. Schrödinger's wave function is function on **configuration space** = **entanglement**
2. Schrödinger evolution of the wave function is **linear**

$\Longrightarrow$

3. Measurement Problem: *the theory does not describe what is*

the measurement problem

1. Schrödinger's wave function is function on **configuration space** = **entanglement**
2. Schrödinger evolution of the wave function is **linear**

$\Longrightarrow$

3. Measurement Problem: *the theory does not describe what is*

the measurement problem

1. Schrödinger's wave function is function on **configuration space** = **entanglement**
2. Schrödinger evolution of the wave function is **linear**

$\Longrightarrow$

3. Measurement Problem: *the theory does not describe what is*

the measurement problem

1. Schrödinger's wave function is function on **configuration space** = **entanglement**
2. Schrödinger evolution of the wave function is **linear**

$$\Longrightarrow$$

3. Measurement Problem: *the theory does not describe what is*

the measurement problem

1. Schrödinger's wave function is function on **configuration space** = **entanglement**
2. Schrödinger evolution of the wave function is **linear**

$$\Longrightarrow$$

3. Measurement Problem: *the theory does not describe what is*

experiment called measurement

an apparatus is *devised* in such a way that Schrödinger evolution of system in state ψ_k and apparatus in ready state Φ_0 yields

$$\psi_k(x)\Phi_0(y) \Longrightarrow \psi_k(x)\Phi_k(y), k = 1, 2, ..., n$$

Linearity: for system state in superposition $\sum_k \psi_k$

$$\sum_k \psi_k(x)\Phi_0(y) \Longrightarrow \sum_k \psi_k(x)\Phi_k(y)$$

wave functions are entangled $\neq$ A pointer always points either this or that way $\Longrightarrow$ "Observer" observes and collapses the wave function

When does the measurement end?

experiment called measurement

an apparatus is *devised* in such a way that Schrödinger evolution of system in state ψ_k and apparatus in ready state Φ_0 yields

$$\psi_k(x)\Phi_0(y) \Longrightarrow \psi_k(x)\Phi_k(y), k = 1, 2, ..., n$$

Linearity: for system state in superposition $\sum_k \psi_k$

$$\sum_k \psi_k(x)\Phi_0(y) \Longrightarrow \sum_k \psi_k(x)\Phi_k(y)$$

wave functions are entangled $\neq$ A pointer always points either this or that way $\Longrightarrow$ "Observer" observes and collapses the wave function

When does the measurement end?

experiment called measurement

an apparatus is *devised* in such a way that Schrödinger evolution of system in state ψ_k and apparatus in ready state Φ_0 yields

$$\psi_k(x)\Phi_0(y) \Longrightarrow \psi_k(x)\Phi_k(y), k = 1, 2, ..., n$$

Linearity: for system state in superposition $\sum_k \psi_k$

$$\sum_k \psi_k(x)\Phi_0(y) \Longrightarrow \sum_k \psi_k(x)\Phi_k(y)$$

wave functions are entangled $\neq$ A pointer always points either this or that way $\Longrightarrow$ "Observer" observes and collapses the wave function

When does the measurement end?

experiment called measurement

an apparatus is *devised* in such a way that Schrödinger evolution of system in state ψ_k and apparatus in ready state Φ_0 yields

$$\psi_k(x)\Phi_0(y) \Longrightarrow \psi_k(x)\Phi_k(y), k = 1, 2, ..., n$$

Linearity: for system state in superposition $\sum_k \psi_k$

$$\sum_k \psi_k(x)\Phi_0(y) \Longrightarrow \sum_k \psi_k(x)\Phi_k(y)$$

wave functions are entangled $\neq$ A pointer always points either this or that way $\Longrightarrow$ “Observer” observes and collapses the wave function

When does the measurement end?

experiment called measurement

an apparatus is *devised* in such a way that Schrödinger evolution of system in state ψ_k and apparatus in ready state Φ_0 yields

$$\psi_k(x)\Phi_0(y) \Longrightarrow \psi_k(x)\Phi_k(y), k = 1, 2, ..., n$$

Linearity: for system state in superposition $\sum_k \psi_k$

$$\sum_k \psi_k(x)\Phi_0(y) \Longrightarrow \sum_k \psi_k(x)\Phi_k(y)$$

wave functions are entangled $\neq$ A pointer always points either this or that way $\Longrightarrow$ "Observer" observes and collapses the wave function

When does the measurement end?

Bell on Quantum Mechanics

It would seem that the theory is exclusively concerned about 'results of measurement', and has nothing to say about anything else. What exactly qualifies some physical systems to play the role of 'measurer'? Was the wave function of the world waiting to jump for thousands of years until a single-celled living creature appeared? Or did it have to wait a little longer, for some better qualified system...with a Ph.D.? If the theory is to apply to anything but highly idealized laboratory operations, are we not obliged to admit that more or less 'measurement-like' processes are going on more or less all the time, more or less everywhere? Do we not have jumping then all the time?

"Against 'measurement' John S. Bell

Bell on Quantum Mechanics

It would seem that the theory is exclusively concerned about ‘results of measurement’, and has nothing to say about anything else. What exactly qualifies some physical systems to play the role of ‘measurer’? Was the wave function of the world waiting to jump for thousands of years until a single-celled living creature appeared? Or did it have to wait a little longer, for some better qualified system...with a Ph.D.? If the theory is to apply to anything but highly idealized laboratory operations, are we not obliged to admit that more or less ‘measurement-like’ processes are going on more or less all the time, more or less everywhere? Do we not have jumping then all the time?
“Against ‘measurement’ John S. Bell

Decoherence

"If the theory is to apply to anything but highly idealized laboratory operations, are we not obliged to admit that more or less 'measurement-like' processes are going on more or less all the time, more or less everywhere?"

In

$$\sum_k \psi_k(x)\Phi_0(y) \Longrightarrow \sum_k \psi_k(x)\Phi_k(y)$$

$$\mathrm{supp}\Phi_\mathrm{k} \cap \mathrm{supp}\Phi_\mathrm{j} \approx \emptyset$$

supports are macroscopically disjoint in pointer-**configuration space**

Decoherence

"If the theory is to apply to anything but highly idealized laboratory operations, are we not obliged to admit that more or less 'measurement-like' processes are going on more or less all the time, more or less everywhere?"

In

$$\sum_k \psi_k(x)\Phi_0(y) \Longrightarrow \sum_k \psi_k(x)\Phi_k(y)$$

$$\mathrm{supp}\Phi_\mathrm{k} \cap \mathrm{supp}\Phi_\mathrm{j} \approx \emptyset$$

supports are macroscopically disjoint in pointer-**configuration space**

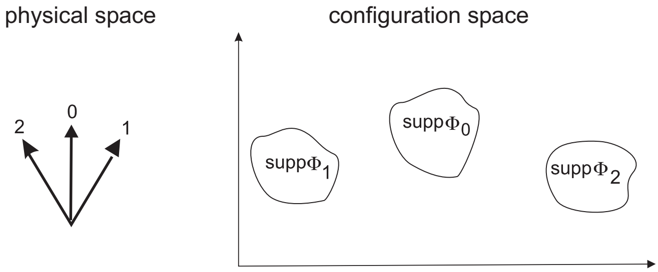
Decoherence

“If the theory is to apply to anything but highly idealized laboratory operations, are we not obliged to admit that more or less ‘measurement-like’ processes are going on more or less all the time, more or less everywhere?”
In

$$\sum_k \psi_k(x)\Phi_0(y) \Longrightarrow \sum_k \psi_k(x)\Phi_k(y)$$

$$\mathrm{supp}\Phi_\mathrm{k} \cap \mathrm{supp}\Phi_\mathrm{j} \approx \emptyset$$

supports are macroscopically disjoint in pointer-**configuration space**



physical and configuration space - both are physical in Quantum Mechanics

fapp=for all practical purposes

- entanglement lifts physical description to higher dimensional configuration space $\longrightarrow$ **decoherence**
- macroscopic wave functions with disjoint supports in **configuration space** fapp-never interfere in the future.
  Therefore

1. the pointer wave functions "decohere" the superposition $\psi = \sum_k \psi_k(x)$
2. "pointer" stands for anything macroscopic the system's wave function gets **entangled** with
3. environment "reads" where the particle is and decoheres the particles wave function
4. possible loss of interference in the two slit experiment

fapp=for all practical purposes

- entanglement lifts physical description to higher dimensional configuration space $\longrightarrow$ **decoherence**
- macroscopic wave functions with disjoint supports in **configuration space** fapp-never interfere in the future.
  Therefore

1. the pointer wave functions "decohere" the superposition $\psi = \sum_k \psi_k(x)$
2. "pointer" stands for anything macroscopic the system's wave function gets **entangled** with
3. environment "reads" where the particle is and decoheres the particles wave function
4. possible loss of interference in the two slit experiment

fapp=for all practical purposes

- entanglement lifts physical description to higher dimensional configuration space $\longrightarrow$ **decoherence**
- macroscopic wave functions with disjoint supports in **configuration space** fapp-never interfere in the future.
  Therefore

1. the pointer wave functions "decohere" the superposition $\psi = \sum_k \psi_k(x)$
2. "pointer" stands for anything macroscopic the system's wave function gets **entangled** with
3. environment "reads" where the particle is and decoheres the particles wave function
4. possible loss of interference in the two slit experiment

fapp=for all practical purposes

- entanglement lifts physical description to higher dimensional configuration space $\longrightarrow$ **decoherence**
- macroscopic wave functions with disjoint supports in **configuration space** fapp-never interfere in the future.
  Therefore

1. the pointer wave functions “decohere” the superposition $\psi = \sum_k \psi_k(x)$
2. “pointer” stands for anything macroscopic the system’s wave function gets **entangled** with
3. environment “reads” where the particle is and decoheres the particles wave function
4. possible loss of interference in the two slit experiment

fapp=for all practical purposes

- entanglement lifts physical description to higher dimensional configuration space $\rightarrow$ **decoherence**
- macroscopic wave functions with disjoint supports in **configuration space** fapp-never interfere in the future.
  Therefore

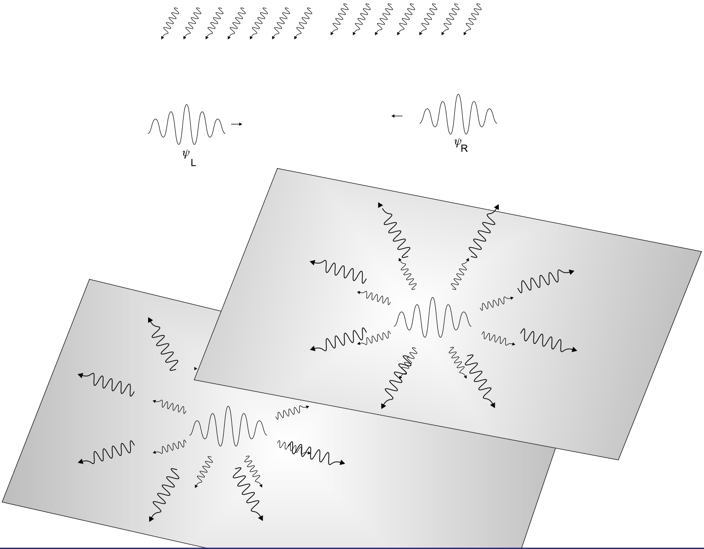
1. the pointer wave functions "decohere" the superposition $\psi = \sum_k \psi_k(x)$
2. "pointer" stands for anything macroscopic the system's wave function gets **entangled** with
3. environment "reads" where the particle is and decoheres the particles wave function
4. possible loss of interference in the two slit experiment

fapp=for all practical purposes

- entanglement lifts physical description to higher dimensional configuration space $\longrightarrow$ **decoherence**
- macroscopic wave functions with disjoint supports in **configuration space** fapp-never interfere in the future.
  Therefore

1. the pointer wave functions “decohere” the superposition $\psi = \sum_k \psi_k(x)$
2. “pointer” stands for anything macroscopic the system’s wave function gets **entangled** with
3. environment “reads” where the particle is and decoheres the particles wave function
4. possible loss of interference in the two slit experiment

light (as far as we understand it) decoheres a wave function



fapp-redundancies

Schrödinger's cat decoheres the atomic wave function
"observer" decoheres the cat that decoheres the atomic wave function
environment decoheres observer that decoheres the cat that decoheres the atomic wave function
universe decoheres the environment that....

What decoheres the universe?

fapp-redundancies

Schrödinger's cat decoheres the atomic wave function
"observer" decoheres the cat that decoheres the atomic wave function
environment decoheres observer that decoheres the cat that decoheres the atomic wave function
universe decoheres the environment that....

What decoheres the universe?

fapp-redundancies

Schrödinger's cat decoheres the atomic wave function
"observer" decoheres the cat that decoheres the atomic wave function
environment decoheres observer that decoheres the cat that decoheres the atomic wave function
universe decoheres the environment that....

What decoheres the universe?

fapp-redundancies

Schrödinger's cat decoheres the atomic wave function
"observer" decoheres the cat that decoheres the atomic wave function
environment decoheres observer that decoheres the cat that decoheres the atomic wave function
universe decoheres the environment that....

What decoheres the universe?

fapp-redundancies

Schrödinger's cat decoheres the atomic wave function
"observer" decoheres the cat that decoheres the atomic wave function
environment decoheres observer that decoheres the cat that decoheres the atomic wave function
universe decoheres the environment that....

What decoheres the universe?

fapp-redundancies

Schrödinger's cat decoheres the atomic wave function
"observer" decoheres the cat that decoheres the atomic wave function
environment decoheres observer that decoheres the cat that decoheres the atomic wave function
universe decoheres the environment that....

What decoheres the universe?

decoherence does not yield facts

Schrödinger again:
"...which can then be resolved by direct observation. That prevents us from so naively accepting as valid a "blurred model" for representing reality. In itself it would not embody anything unclear or contradictory. **There is a difference between a shaky or out-of-focus photograph and a snapshot of clouds and fog banks.**"

IT IS: Bohmian Mechanics

Ontology: N-particle system, positions $Q_1, ..., Q_N$, $Q_i \in \mathbb{R}^3$
mathematical formulation of the law is on configuration space:
$Q = (Q_1, ..., Q_N) \in \mathbb{R}^{3N}$
guiding field $\psi : \mathbb{R}^{3N} \times \mathbb{R} \mapsto \mathbb{C}$

$$(q, t) \mapsto \psi(q, t)$$

generates vector field $v^\psi(q, t)$ on configuration space

$$v^\psi(q, t) = \hbar m^{-1} \Im \frac{\nabla \psi}{\psi}(q, t)$$

the Bohmian law

$$i\hbar\frac{\partial\psi}{\partial t}(q,t) = -\sum\frac{\hbar^2}{2m_k}\Delta_k\psi(q,t) + V(q)\psi(q,t),$$

$$\frac{dQ}{dt} = v^{\psi}(Q(t),t)\,.$$

$k-$th particle's trajectory $Q_k(t)$

$$\frac{dQ_k}{dt} = \frac{\hbar}{m_k}\Im\frac{\nabla_k\psi}{\psi}(Q,t), \quad k = 1,\ldots,N$$

Bohmian Mechanics is straightforward, its analysis is not

Born's statistical law: $\rho = |\psi|^2$ is "justified" by the quantum flux equation (identity for solution of Schrödinger's equation)

$$\frac{\partial|\psi|^2}{\partial t} = -\nabla \cdot j^\psi$$

by interpreting this as continuity equation. It is the continuity equation of the Bohmian flow, i.e.

$$v^\psi = \frac{j^\psi}{|\psi|^2}$$

Analogy for analysis:
Bohmian mechanics $\doteq$ Hamiltonian mechanics
Born's law $\doteq$ Gibbs distribution
quantum measurement formalism $\doteq$ thermodynamic formalism

Bohmian Mechanics is straightforward, its analysis is not

Born's statistical law: $\rho = |\psi|^2$ is "justified" by the quantum flux equation (identity for solution of Schrödinger's equation)

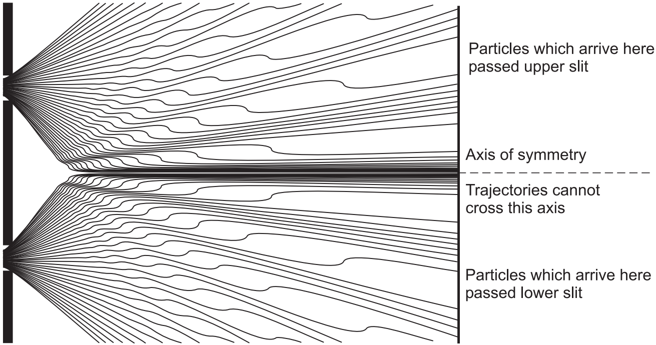
$$\frac{\partial |\psi|^2}{\partial t} = -\nabla \cdot j^{\psi}$$

by interpreting this as continuity equation. It is the continuity equation of the Bohmian flow, i.e.

$$v^{\psi} = \frac{j^{\psi}}{|\psi|^2}$$

Analogy for analysis:
Bohmian mechanics $\doteq$ Hamiltonian mechanics
Born's law $\doteq$ Gibbs distribution
quantum measurement formalism $\doteq$ thermodynamic formalism

two slit experiment: N=1



measurement-experiment

$$(\psi_1(x) + \psi_2(x))\Phi_0(y) \Longrightarrow \psi_1(x)\Phi_1(y) + \psi_2(x)\Phi_2(y)$$

$$\mathrm{supp}\Phi_1 \cap \mathrm{supp}\Phi_2 \approx \emptyset$$

What IS?

$$(X(0), Y(0)) \longrightarrow (X(T), Y(T))$$

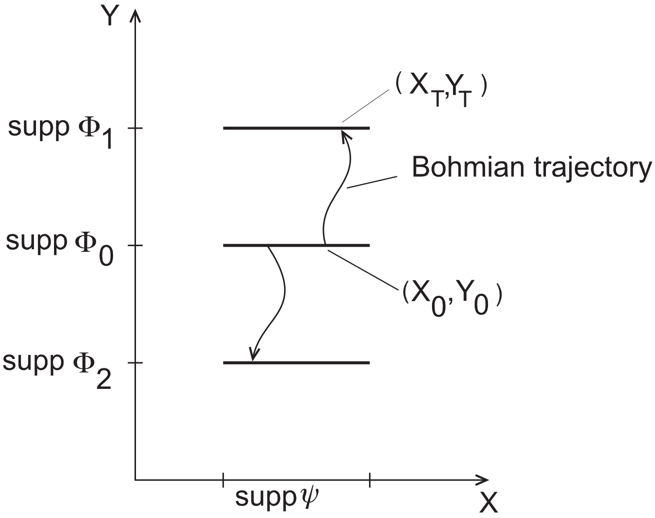
$$Y(0) \in \mathrm{supp}\Phi_0 \longrightarrow \mathrm{Y(T)} \in \mathrm{supp}\Phi_1 \vee \mathrm{supp}\Phi_2$$

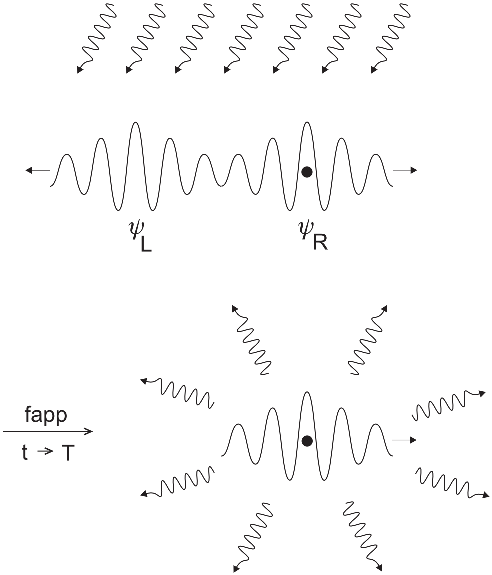
IF $Y_T \in \mathrm{supp}\Phi_1$ forget fapp Φ_2-packet in Bohmian universe:

$$\psi_1(x)\Phi_1(y) + \cancel{\psi_2(x)\Phi_2(y)}$$

$\psi_1(x)\Phi_1(y)$ is effective: guides the Bohmian trajectories

configuration space





ψ_L
ψ_R
fapp
t → T

Bohmian mechanics analysed: wave function for subsystem with coordinates X

$Q = (X, Y) \Longrightarrow$

$$\dot{X}(t) = v_x^{\Psi}(X(t), Y(t)) \sim \Im \frac{\nabla_x \Psi(x, Y(t))}{\Psi(x, Y(t))}\Bigg|_{x=X(t)}$$

$\longrightarrow$ **conditional wave function of x-system**

$$\varphi^Y(x) = \frac{\Psi(x, Y)}{\|\Psi(Y)\|}$$

not autonomous!

decoherence yields an effective autonomous description

φ is **effective wave function** if

$$\Psi(x,y) = \varphi(x)\Phi(y) + \Psi^{\perp}(x,y),$$

Φ and $\Psi^{\perp}$ have *macroscopically disjoint* y-supports = **decoherent** wave packets
and

$$Y \in \operatorname{supp} \Phi.$$

effective wave function= fapp-collapsed wave function

Quantum-Equilibrium

Bohmian mechanics is deterministic: How does randomness enter?
Like in classical mechanics!
Boltzmann's statistical analysis applied to Bohmian mechanics yields Quantum-Equilibrium typicality
Typicality yields Born's law: If the system has effective wave function φ then the empirical distribution of particle positions approximates $|\varphi|^2$

Quantum-Equilibrium

Bohmian mechanics is deterministic: How does randomness enter?
Like in classical mechanics!
Boltzmann's statistical analysis applied to Bohmian mechanics yields Quantum-Equilibrium typicality
Typicality yields Born's law: If the system has effective wave function φ then the empirical distribution of particle positions approximates $|\varphi|^2$

Quantum-Equilibrium

Bohmian mechanics is deterministic: How does randomness enter?
Like in classical mechanics!
Boltzmann's statistical analysis applied to Bohmian mechanics yields Quantum-Equilibrium typicality
Typicality yields Born's law: If the system has effective wave function φ then the empirical distribution of particle positions approximates $|\varphi|^2$

Quantum Equilibrium analysis of Bohmian Mechanics

the equilibrium statistical description of Bohmian mechanics and decoherence yields

1. macroscopic locality from microscopic non locality
2. quantum formalism (POVMs and PVMs)
3. Heisenberg uncertainty
4. arrival time statistics, scattering theory, tracks in a cloud chamber, the classical world

Quantum Equilibrium analysis of Bohmian Mechanics

the equilibrium statistical description of Bohmian mechanics and decoherence yields

1. macroscopic locality from microscopic non locality
2. quantum formalism (POVMs and PVMs)
3. Heisenberg uncertainty
4. arrival time statistics, scattering theory, tracks in a cloud chamber, the classical world

Quantum Equilibrium analysis of Bohmian Mechanics

the equilibrium statistical description of Bohmian mechanics and decoherence yields

1. macroscopic locality from microscopic non locality
2. quantum formalism (POVMs and PVMs)
3. Heisenberg uncertainty
4. arrival time statistics, scattering theory, tracks in a cloud chamber, the classical world

Quantum Equilibrium analysis of Bohmian Mechanics

the equilibrium statistical description of Bohmian mechanics and decoherence yields

1. macroscopic locality from microscopic non locality
2. quantum formalism (POVMs and PVMs)
3. Heisenberg uncertainty
4. arrival time statistics, scattering theory, tracks in a cloud chamber, the classical world

Quantum Equilibrium analysis of Bohmian Mechanics

the equilibrium statistical description of Bohmian mechanics and decoherence yields

1. macroscopic locality from microscopic non locality
2. quantum formalism (POVMs and PVMs)
3. Heisenberg uncertainty
4. arrival time statistics, scattering theory, tracks in a cloud chamber, the classical world

physics must be about ontology

2500 years ago in Elea in Campania Parmenides wrote:
The Poem, The way of truth:
Come now, I will tell thee - and do thou hearken to my saying and carry it away - the only two ways of search that can be thought of. The first, namely, that It is, and that it is impossible for it not to be, is the way of belief, for truth is its companion. The other, namely, that It is not, and that it must needs not be, - that, I tell thee, is a path that none can learn of at all. For thou canst not know what is not - that is impossible - nor utter it; for it is the same thing that can be thought and that can be. ...For this shall never be proved, that the things that are not are; and do thou restrain thy thought from this way of inquiry.