Can Decoherence make quantum theories unfalsifiable? Understanding the quantum-to-classical transition without it

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What does **decoherence** mean?

Does it appears when dealing with open systems ?

- Diagonalize "reduced" density matrix
- Continuous monitoring by the environment.
- Environment induced superselection

Or it is also present in closed systems ?

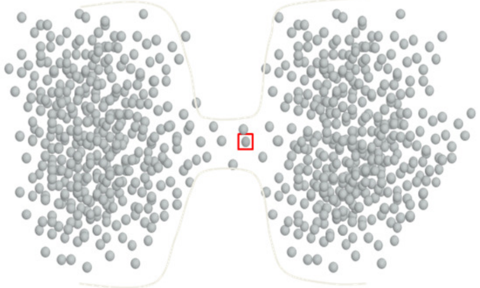
- Plank constant to zero
- Large number of particles
- Ehrenfest theorem

Does it appears at an ontological level of the theory ? Or not?

- GRW "spontaneous" collapse
- Decoherent(consistent) histories

Decoherence is somehow a "fuzzy" concept!

How decoherence is modelled "FAPP" ?



Phenomenologic

$$\frac{d\hat{\rho}_S}{dt} = \frac{-i}{\hbar}\left[\hat{H}_S, \hat{\rho}_S\right] + \hat{D}\left[\hat{\rho}_S\right]$$

Quantum-to-classical
Dissipation,...
Irreversability,...

FAPP, decoherence (+ the many-body problem) make quantum theories universal and unfalsifiable

Good news for a quantum engineers ! They can easily put the dissipation and irreversibility into their models.

Bad news for foundations of quantum mechanics ! Unless they clarify or eliminate decoherence, it is difficult to test the universality of quantum theories.

Can decoherence make quantum theories unfalsifiable?
Understanding the quantum-to-classical transition without it

Within Bohmian mechanics:



1.- Dissipation by invoking the fuzzy concept of decoherence

1.1- The Bohmian conditional wave function

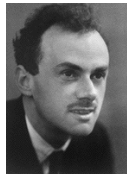
1.2- Electron-phonon dissipation within Bohmian mechanics

2.- Quantum-to-classical transition without invoking decoherence

1.1.- Conditional (Bohmian) wave function

Orthodox quantum theory:

An object cannot be a wave and a particle simultaneously !




Bohmian quantum theory:

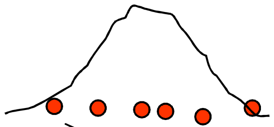
But two objects can !
Specially, if one is a wave and the other is a particle.



Waves

$$\Phi(x_1,..,x_N,t) = R(x_1,..,x_N,t)\,e^{iS(x_1,..,x_N,t)/\hbar}$$

$$i\hbar\frac{\partial\Phi(x_1,..,x_N,t)}{\partial t} = \left\{\sum_{a=1}^{N} -\frac{\hbar^2}{2\cdot m}\frac{\partial^2}{\partial x_a^2} + U(x_1,..,x_N,t)\right\}\Phi(x_1,..,x_N,t)$$



Particles

$$X_1[t] \rightarrow v_i(x_1,..,x_N,t) = \frac{J_i(x_1,..,x_N,t)}{|\Psi(x_1,..,x_N,t)|^2} = \frac{1}{m}\partial S(x_1,..,x_N,t)/\partial x_i$$

Non-Local | Contextual | unpredicatble and deterministic

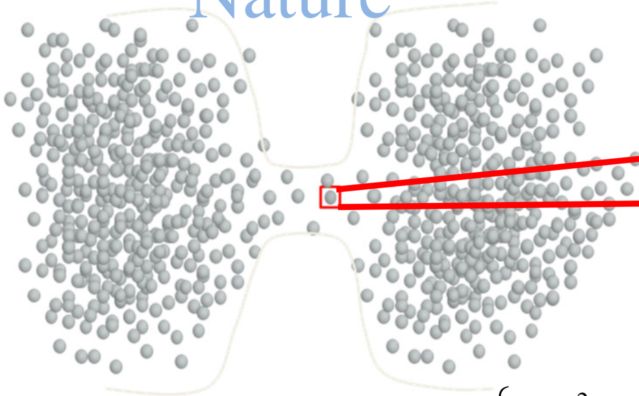
1.1.- Conditional (Bohmian) wave function

The **many-particle** wave function

The many-body problem

$$i\hbar\frac{\partial\Phi(x_1,x_2,\dots,x_N,t)}{\partial t}=\left\{\sum_{a=1}^{N}-\frac{\hbar^2}{2\cdot m}\frac{\partial^2}{\partial x_a^2}+U(x_1,x_2,\dots,x_N,t)\right\}\Phi(x_1,x_2,\dots,x_N,t)$$

Nature



Linear | Unitary | "lives" in R^{3N}

$$\Phi(x_1,x_2,\dots,x_N,t)$$

(Point) Particle

$$\Psi(x_a,t)=\Phi(x_1(t),x_2(t),\dots x_a\dots,x_N(t),t)$$

Non-Linear | Non-Unitary | "lives" in R

$$i\hbar\frac{\partial\Psi(x_a,t)}{\partial t}=\left\{-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x_a^2}+U(x_a,\vec{x}_b[t],t)+G(x_a,\vec{x}_b[t],t)+i\cdot J(x_a,\vec{x}_b[t],t)\right\}\Psi(x_a,t)$$

[X. Oriols, Phys. Rev. Lett. 98, 066803 (2007)]

[T.Norsen, Found. Phys 40, 1858 (2010)]

The **conditional** wave function

1.2.- Single-particle (conditional) dissipative wave functions

Usual single-particle Schrodinger equation:

$$i\hbar\frac{\partial\Psi(x,t)}{\partial t}=\left\{-\frac{\hbar^2}{2m^*}\frac{\partial^2}{\partial x^2}+U(x,t)\right\}\Psi(x,t)$$

"Conditional" single-particle Schrodinger equation:

$$i\hbar\frac{\partial\Psi(x,t)}{\partial t}=\left\{-\frac{\hbar^2}{2m^*}\frac{\partial^2}{\partial x^2}+U(x,t)+G(x,t)+i\cdot J(x,,t)\right\}\Psi(x,t)$$

[X. Oriols, Phys. Rev. Lett. 98, 066803 (2007)]

Our goal:

Use G(x,t) and i·J(x,t) to produce an electron changes from the state {E,k} to {E',k'}

$$i\hbar\frac{\partial\Psi(x,t)}{\partial t}=\left\{\frac{1}{2m^*}\left(-i\hbar\frac{\partial}{\partial x}+\lambda\Phi(t_1)\right)^2+U(x,t)\right\}\Psi(x,t)$$

Hermitian Hamiltonian

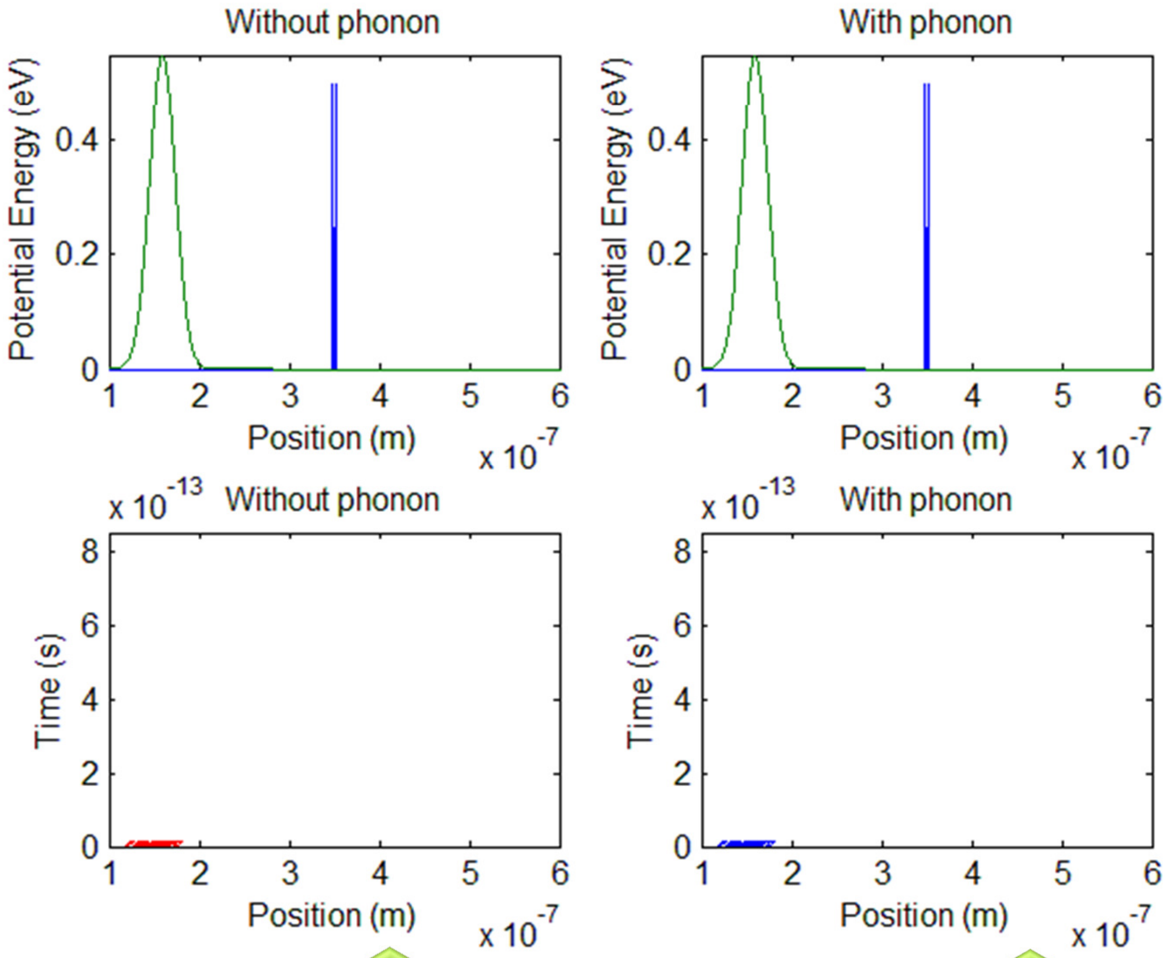
$$i\hbar\frac{\partial\Psi(x,t)}{\partial t}=\left\{-\frac{\hbar^2}{2m^*}\frac{\partial^2}{\partial x^2}+U(x,t)+i\frac{\hbar\lambda\Phi(t_1)}{m^*}\frac{\partial}{\partial x}+\frac{\lambda^2\Phi^2(t_1)}{2m^*}\right\}\Psi(x,t)$$

1.2.- Single-particle (conditional) dissipative wave functions

Eo=0.18 eV
K_λ=-2,2e^8 m^{-1}

T=0.85 ps
T_1= 0.21 ps

well = 4 nm
barr = 0.8 nm
Height= 0.5 eV



(quantum) Wave

(Point) Particle

$$i\hbar\frac{\partial\Psi(x,t)}{\partial t}=\left\{-\frac{\hbar^2}{2m^*}\frac{\partial^2}{\partial x^2}+U(x,t)\right\}\Psi(x,t)$$

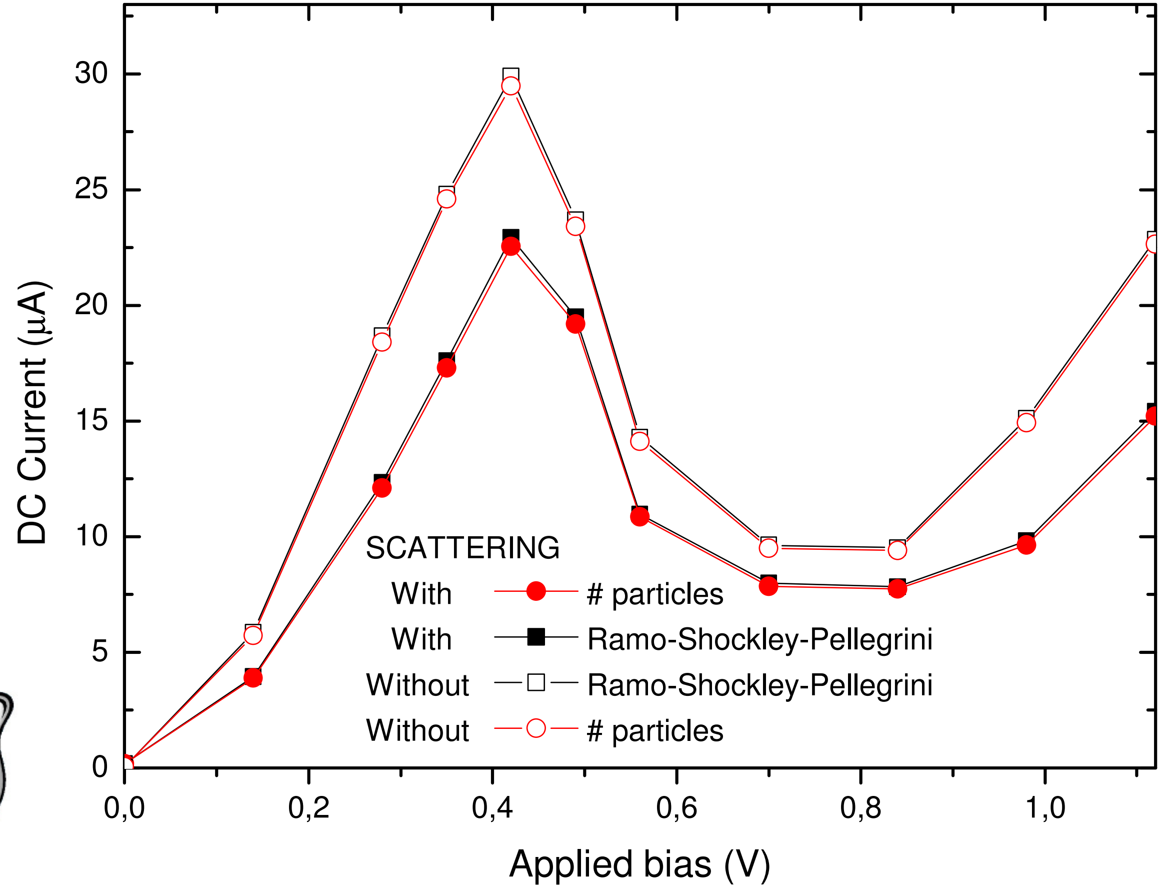
$$i\hbar\frac{\partial\Psi(x,t)}{\partial t}=\left\{-\frac{\hbar^2}{2m^*}\frac{\partial^2}{\partial x^2}+U(x,t)+i\frac{\hbar\lambda\Phi(t_1)}{m^*}\frac{\partial}{\partial x}+\frac{\lambda^2\Phi^2(t_1)}{2m^*}\right\}\Psi(x,t)$$

1.3.- Single-particle (conditional) dissipative wave functions

Scattering mechanisms
(Fermi Golden Rule)

1.- Acustic Phonons.
2.- Optial phonons (0.036 eV)
3.- Optial phonons (-0.036 eV),
4.- Impurities (N_D=10^{17} cm^{-3})

BITLLES:



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Can decoherence make quantum theories unfalsifiable?
Understanding the quantum-to-classical transition without it

Within Bohmian mechanics:



1.- Dissipation by invoking the fuzzy concept of decoherence

2.- Quantum-to-classical transition without invoking decoherence

2.1.- A "frustrating" single-particle Bohmian attempt

2.2.- A natural many-particle Bohmian attempt for the center of mass

2.3.- A conditional wave function for the center of mass

2.1.- A “frustrating” single-particle Bohmian attempt

Classical and Bohmian similarities

.- Both deal with particles.
.- Both deal with single-experiments (not ensemble of experiments).
.- Both have no measurement postulate (it is just a type of interaction).

Rosen’s criteria:

$$i\hbar\frac{\partial\Phi(x,t)}{\partial t}=\left\{-\frac{\hbar^2}{2\cdot m}\frac{\partial^2}{\partial x_a^2}+U(x,t)\right\}\Phi(x,t)$$

[1] N. Rosen, Am. J. Phys. 32, 377 (1964).

$$\Phi(\vec{x},t)=\mathrm{R}(\vec{x},t)\,\mathrm{e}^{iS(\vec{x},t)/\hbar}$$

3 equations and only
2 unknowns: $R(\vec{x},t)$ $S(\vec{x},t)$

1.- Continuity equation:

$$\frac{\partial R^2(x,t)}{\partial t}+\frac{\partial}{\partial x}\Big(R^2(x,t)\cdot v(x,t)\Big)=0$$

2.- Quantum Hamilton-Jacobi:

$$\frac{\partial S(x,t)}{\partial t}+U(x)+\frac{1}{2m}\cdot\left(\frac{\partial S(x,t)}{\partial x}\right)^2+Q(\vec{x},t)=0$$

3.- Matemathical condition:

$$Q(x,t)=0$$

2.2.- A natural many-particle Bohmian attempt for the center of mass

The reason of the previous bad results is because and apple is not a single-particle system! **We Try a many-particle system !**

1.- Many body system:

$$i\hbar\frac{\partial\Phi(x_1,x_2,...,x_N,t)}{\partial t}=\left\{\sum_{a=1}^{N}-\frac{\hbar^2}{2\cdot m}\frac{\partial^2}{\partial x_a^2}+U(x_1,x_2,...,x_N,t)\right\}\Phi(x_1,x_2,...,x_N,t)$$

We study the transition for the center of mass ! (not for an individual electron)

2.- Center of mass:

$$y_1=x_{cm}=\frac{1}{N}\sum_{i=1}^{N}x_i$$

$$y_j=x_j-\frac{\left(\sqrt{N}x_{cm}+x_1\right)}{\sqrt{N}+1}\qquad j=2,...N$$

$$i\hbar\frac{\partial\Psi(x_{cm},y_2,...,y_N,t)}{\partial t}=\left\{-\frac{\hbar^2}{2\cdot N\cdot m}\frac{\partial^2}{\partial x_{cm}^2}-\frac{\hbar^2}{2\cdot m}\sum_{a=2}^{N}\frac{\partial^2}{\partial y_a^2}+U(x_{cm},y_2,...,y_N,t)\right\}\Psi(x_1,x_2,...,x_N,t)$$

[1] D. Tena, A. Benseny, X.Oriols, submitted (2015).

2.2.- A natural many-particle Bohmian attempt for the center of mass

1.- Wave-equation for the center of mass of a many body system:

$$i\hbar \frac{\partial \Psi(x_{cm}, y_2,...,y_N,t)}{\partial t} = \left\{ -\frac{\hbar^2}{2\cdot N\cdot m}\frac{\partial^2}{\partial x_{cm}^2} - \frac{\hbar^2}{2\cdot m}\sum_{a=2}^{N}\frac{\partial^2}{\partial y_a^2} + U(x_{cm},y_2,...,y_N,t)\right\}\Psi(x_1,x_2,...,x_N,t)$$

2.- Quantum Hamilton-Jacobi:

$$0 = \frac{\partial S}{\partial t} + U + \frac{1}{2}M\cdot v_{cm}^2 + Q_{cm} + \sum_{j=2}^{N}\left(\frac{1}{2}m\cdot v_j^2 + Q_j\right)$$

$$M = N\cdot m$$

$$v_j(x_{cm},\vec{y},t) = \frac{1}{m}\frac{\partial S(x_{cm},y_2,...,y_N,t)}{\partial x_j}$$

$$v_{cm}(x_{cm},\vec{y},t) = \frac{1}{N\cdot m}\frac{\partial S(x_{cm},y_2,...,y_N,t)}{\partial x_{cm}}$$

3.- Quantum Newton like equation for X_{CM}

$$N\cdot m\frac{dX_{cm}[t]}{dt} = -\frac{\partial}{\partial x_{cm}}\left(U + Q_{cm} + \sum_{j=2}^{N}Q_j\right)$$

[1] D. Tena, A. Benseny, X.Oriols, submitted (2015).

3.- Conditions for the Quantum-to-Classical transition of the center of mass:

$$M\frac{dX_{cm}[t]}{dt} = -\frac{\partial}{\partial x_{cm}}\left(U + Q_{cm} + \sum_{j=2}^{N} Q_j\right) \Rightarrow M\frac{dX_{cm}[t]}{dt} \approx -\frac{\partial}{\partial x_{cm}}U$$

$$\frac{\partial}{\partial x_{cm}}U \; ? \; \frac{\partial}{\partial x_{cm}}Q_{cm} + \sum_{j=2}^{N}\frac{\partial}{\partial x_{cm}}Q_j$$

$$\lim_{N\to\infty}\frac{\partial}{\partial x_{cm}}U \propto N \qquad \lim_{N\to\infty}\frac{\partial}{\partial x_{cm}}Q_{cm} \propto \sqrt{N}$$

For particles with exchange interaction

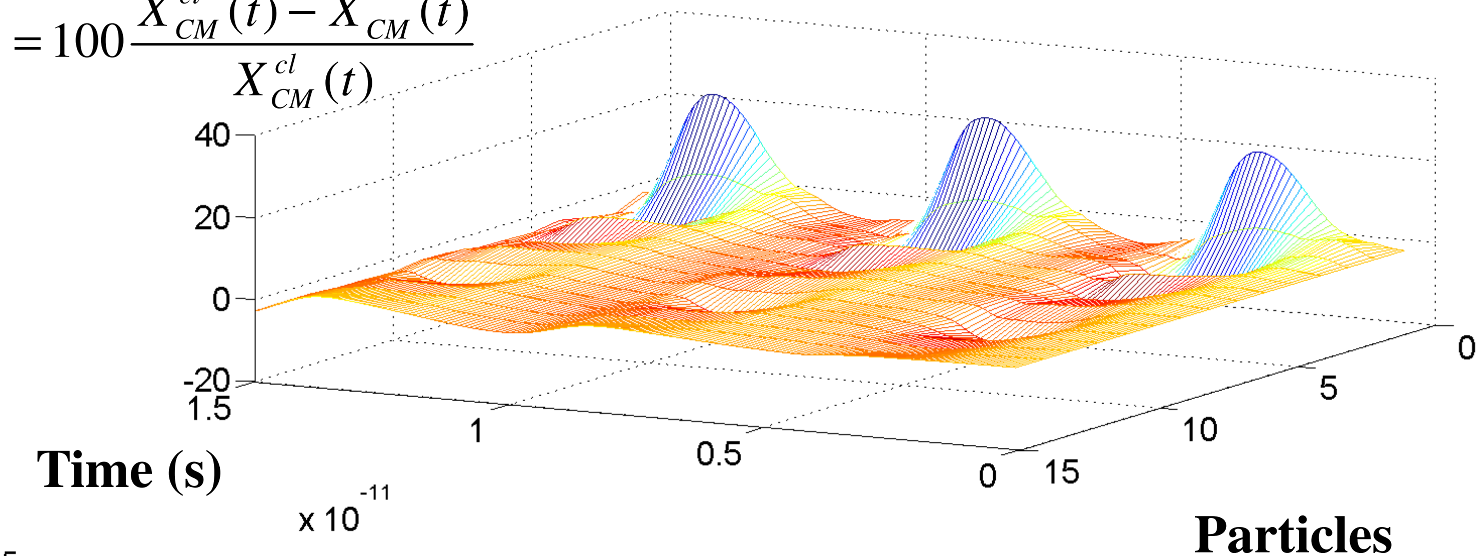
$$\lim_{N\to\infty}\sum_{j=2}^{N}\frac{\partial}{\partial x_{cm}}Q_j \approx \int_{-\infty}^{\infty}\frac{\partial}{\partial x_{cm}}Q_2 dx_2 \to 0$$

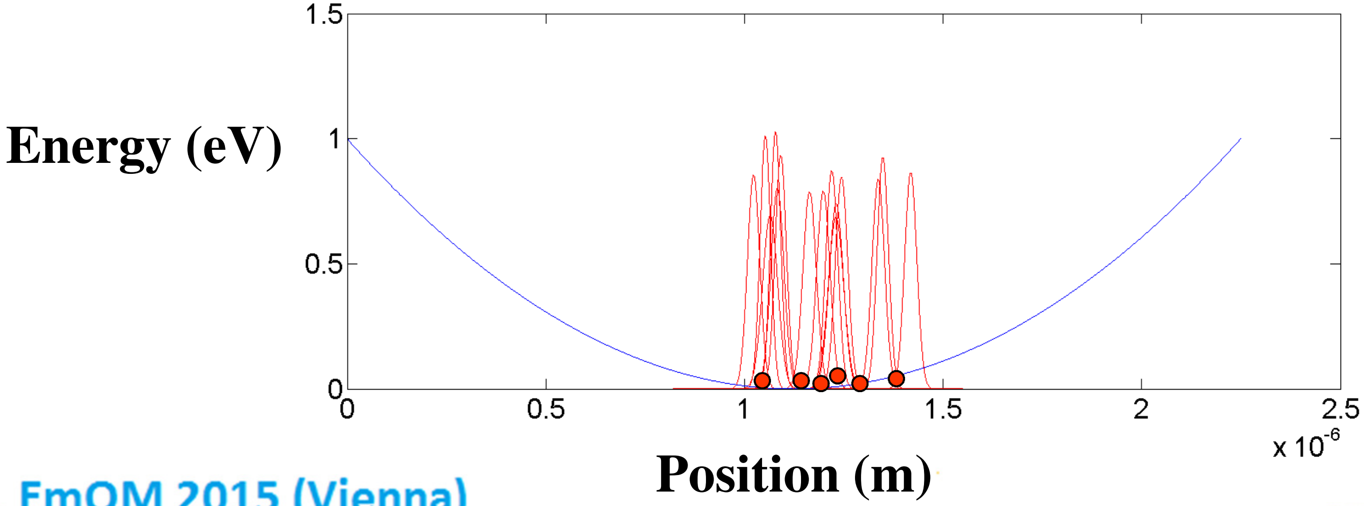
Clear evidences for the ontological goal of quantum and classical re-unification

2.2.- A natural many-particle Bohmian attempt for the center of mass

$$Error(\%) = 100\frac{X_{CM}^{cl}(t) - X_{CM}(t)}{X_{CM}^{cl}(t)}$$

Bosons



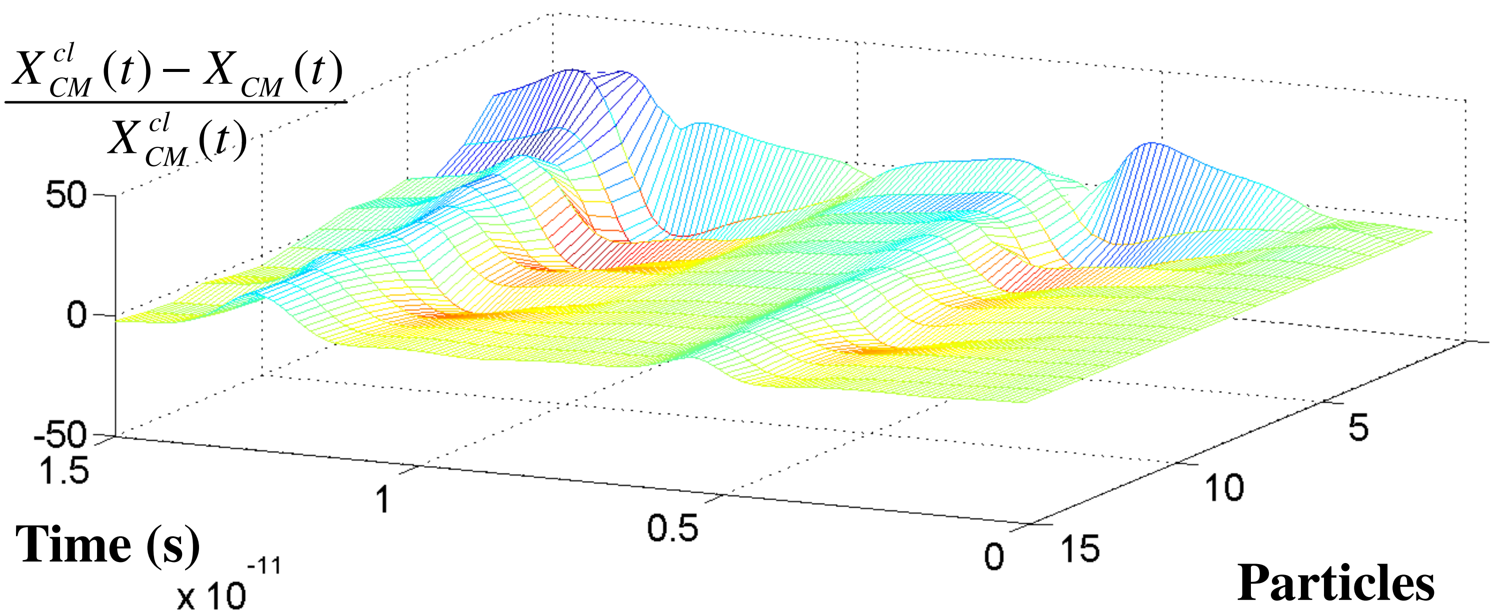


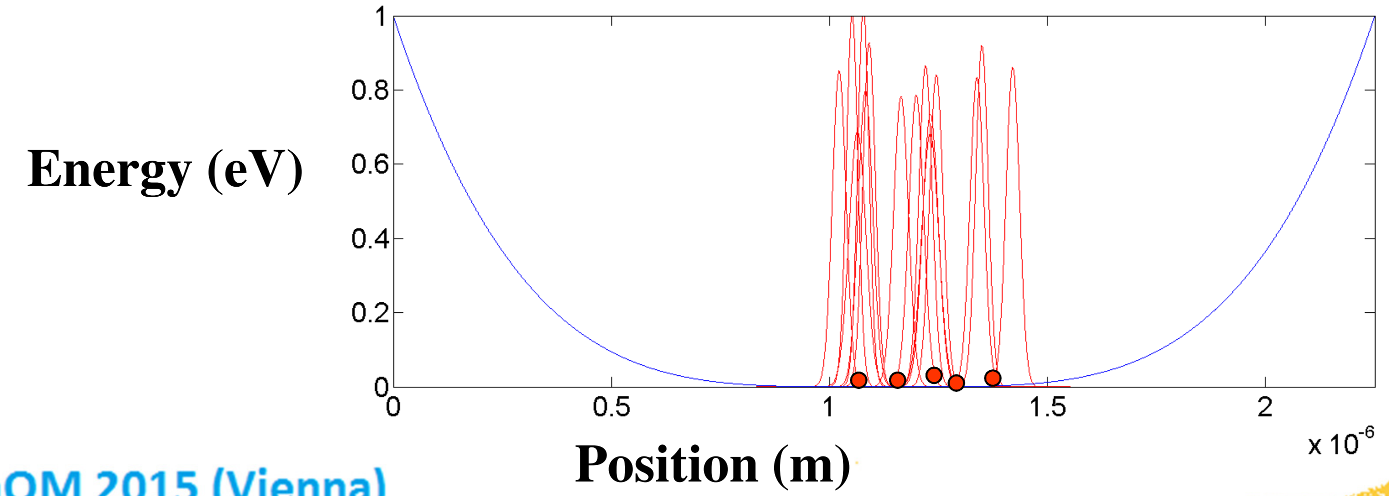
Parabolic potential

2.2.- A natural many-particle Bohmian attempt for the center of mass

$$Error(\%) = 100\frac{X_{CM}^{cl}(t) - X_{CM}(t)}{X_{CM}^{cl}(t)}$$

Bosons





quadratic potential

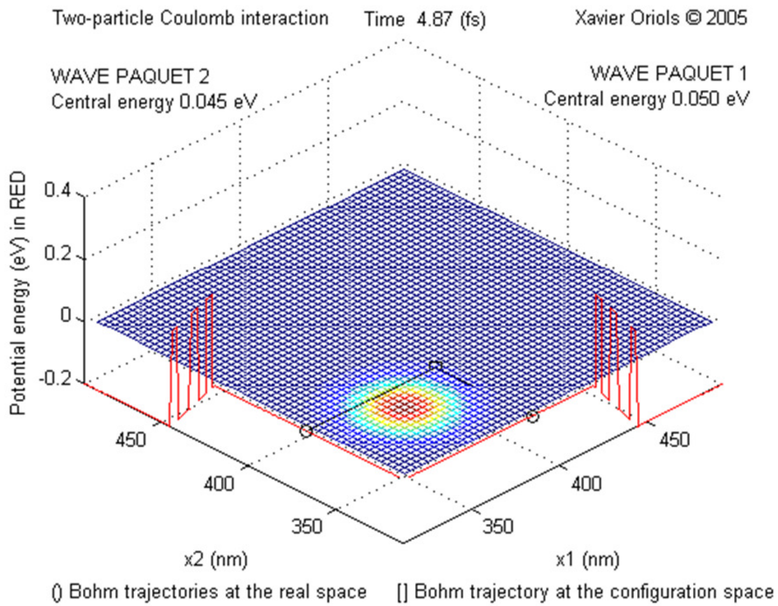
2.3.- A conditional wave function for the center of mass

How the quantum non-locality disappears ?

Bohmian quantum theory: Non-local

.- **Bohmian trajectories lives in physical space R^3**

.- **Many-particle wave function lives in configuration space R^{3N}**



$$N \cdot m \frac{dX_{cm}[t]}{dt} = -\frac{\partial}{\partial x_{cm}}\left(U + Q_{cm} + \sum_{j=2}^{N} Q_j\right) \Rightarrow N \cdot m \frac{dX_{cm}[t]}{dt} \approx -\frac{\partial}{\partial x_{cm}} U$$

2.3.- A conditional wave function for the center of mass

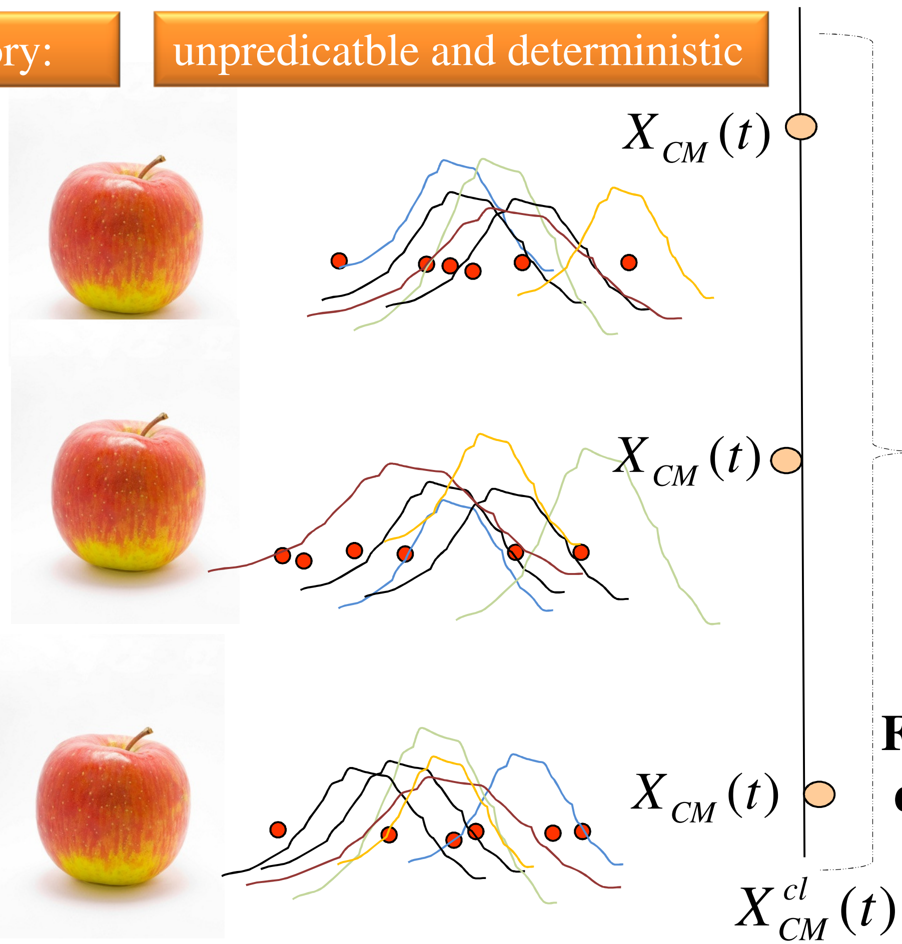
How the quantum randomness disappears ?

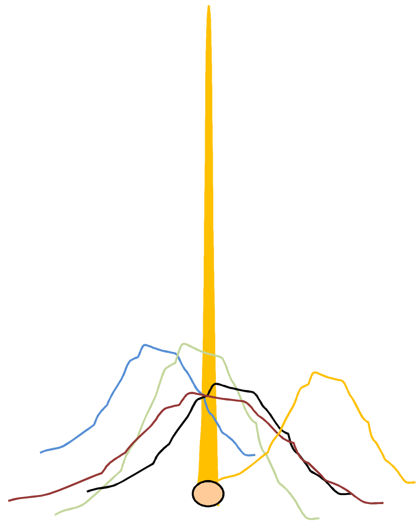
Bohmian quantum theory: unpredicatble and deterministic

1st experiment:

2nd experiment:

3rd experiment:

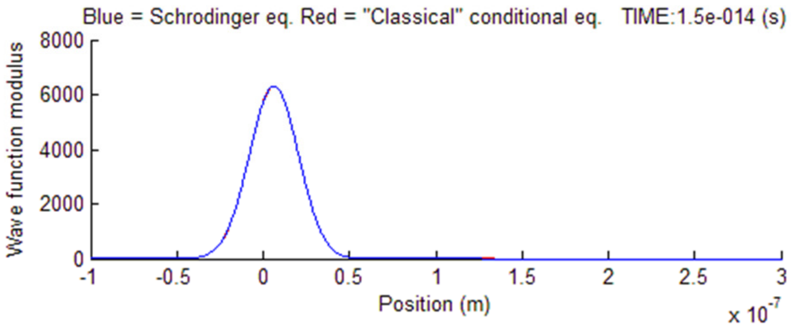




FAPP, predictable and deterministic evolution.

2.3.- A conditional wave function for the center of mass

$$i\hbar \frac{\partial \Psi(x_a,t)}{\partial t} = \left\{ -\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x_a^2} + U(x_a,\vec{x}_b[t],t) \quad - Q(x_a,\vec{x}_b[t],t) \right\} \Psi(x_a,t)$$



nº of equations:

3 equations

nº of unknowns:

$R(\vec{x},t)$ $S(\vec{x},t)$ $G(x_a,\vec{x}_b[t],t)+i\cdot J(x_a,\vec{x}_b[t],t)$

A new equation for an intermediate domain of physics where the behavior of the system is neither purely quantum nor classical.

3.- Conclusions

Two main messages:

Message 1.- Decoherence and the many-body problem makes quantum theories universal and unfalsifiable FAPP. This is a very attractive feature for a quantum engineer (http:\europe.uab.es\bitlles), but a disgusting one for those interesting on foundations of quantum mechanics.

Message 2.- (main result)- Classical mechanics appears in a very natural way from Bohmian mechanics, when dealing with the center of masses of a very large number of particles with exchange symmetry.

Thank you very much for your attention