Title: Our Quantum World, Contextuality, and Bohmian Mechanics

Date: Jun 22, 2016 02:30 PM

URL: http://pirsa.org/16060057

Abstract: Our universe is at its heart quantum mechanical, yet classical behaviour is seen everywhere. I will discuss the scales that determine the quantum to classical transition and the prospects for the observation of ever more macroscopic quantum behaviour. I will then discuss how paradoxes in quantum mechanics can be understood and visualized with Bohmian trajectories, how these trajectories can be measured, and the implications for the ontology of the Bohmian picture.

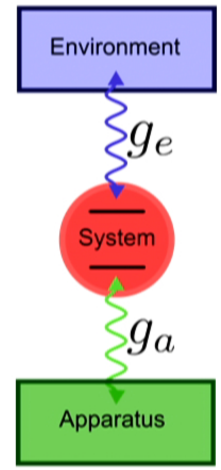
Outline

- The boundary of quantum and classical
  - The quantum computing angle
- QM paradoxes in the Bohmian picture
  - Bohm-de Broglie and Wigner
  - Surreal trajectories and contextuality
  - Hardy's paradox
- Is position special?

Our Quantum World

- The world appears classical because of decoherence
- Key parameter:

$$\frac{g_a}{g_a + g_e} \sim 1 - \varepsilon$$

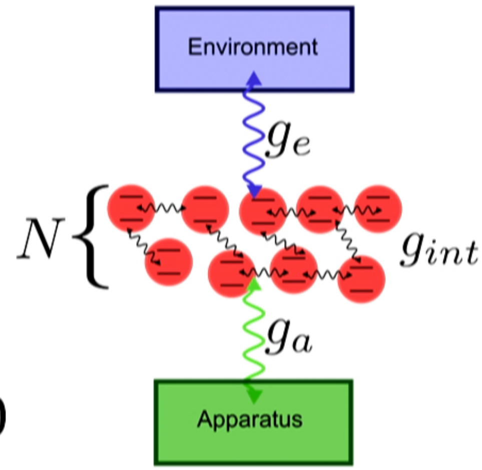


- i.e. experimenter's share of information about the system (⟶ interference visibility)
  – Quantum Bayesianism

Zurek, *RMP*, **75**, 715 (2003)

Quantum Computers

- Goals for quantum computing: creating large ($N \gg 1$), controllable, unitary systems ($\varepsilon \ll 1$)
  - Best realizations: $\varepsilon \sim 10^{-4}, N \sim 10$
- Spontaneous collapse theories suggest this is impossible (for large enough N/ε)
- Maximum coherence time: $1/N g_e$



May include g_{int}

Good Quantum Systems

- Some systems with robust quantumness:
  - Photons: mode, frequency, polarization, number
  - Atoms, atom-like systems: internal ("spin")
  - BECs, ions, macroscopic oscillators: motion
- Common features:
  - Initial state, controls effectively at $\mathrm{T} = 0$
  - Relevant degrees of freedom are uniquely decoupled

Schrödinger's Spherical Cat

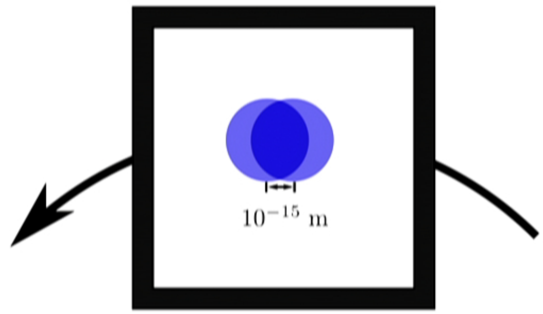
$N \sim 10^{26}$, $\Delta X = 10^{-15} m$

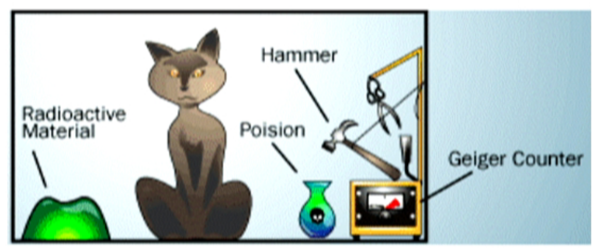
Even if the box is opaque, information is still escaping:

- Neutrinos: $g_e \sim 10^{-6}\ s^{-1}$
- Gravity: $g_e \sim 10^{17}\ s^{-1}$
- Photons: $g_e \sim 10^{20}\ s^{-1}$

The cat's internal state acts as a thermal reservoir:

$$g_e \sim 10^{38}\ s^{-1}$$



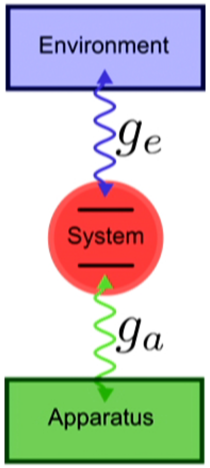


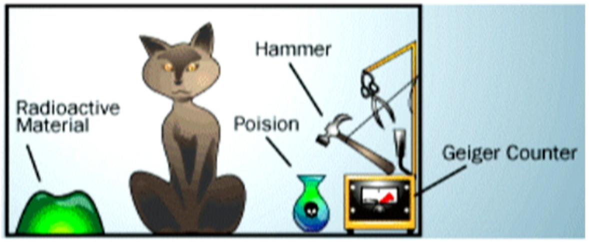
http://www.smashinglists.com/10-renonwed-thought-experiments/2/

Schrödinger's Cat Error Correction

Objection: Well, we *could* make the evolution go backwards *if* we could keep track of all the DOF's

- ~ Fault-tolerant quantum computation
- Need $\varepsilon \sim 10^{-4}$, $g_e \sim 10^{42}\ s^{-1}$





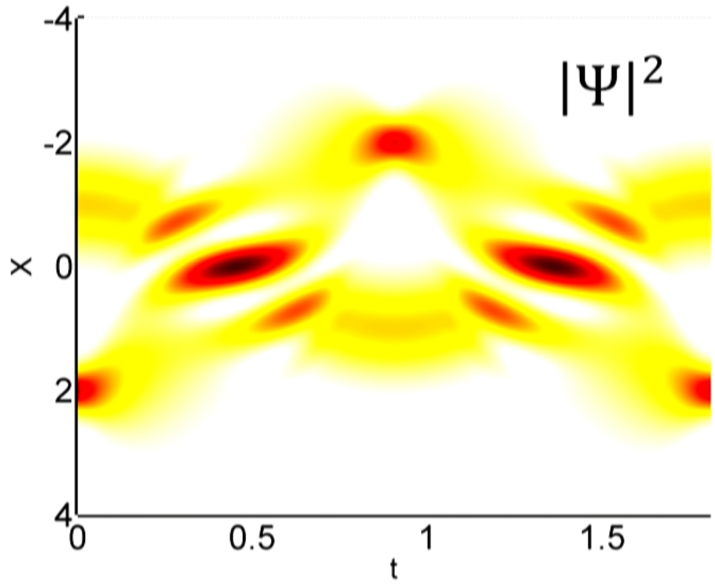
http://www.smashinglists.com/10-renonwed-thought-experiments/2/

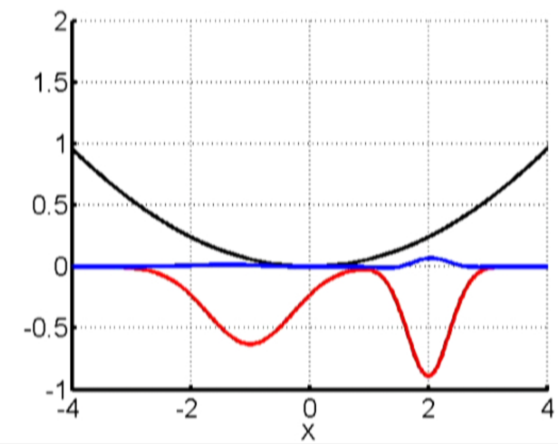
Our Quantum World

- "Classical" systems are strongly coupled a thermal environment
  - Internal *and* external DOFs, typically with g_e huge
  - Each coupled system encodes infinitesimal relative but large absolute information about each other
- "Quantum" systems have T=0 and are strongly coupled to a T=0, low-entropy environment
  - Challenge: DOF's couple equally well to both T=0 and thermal environments

Quantum Dynamics

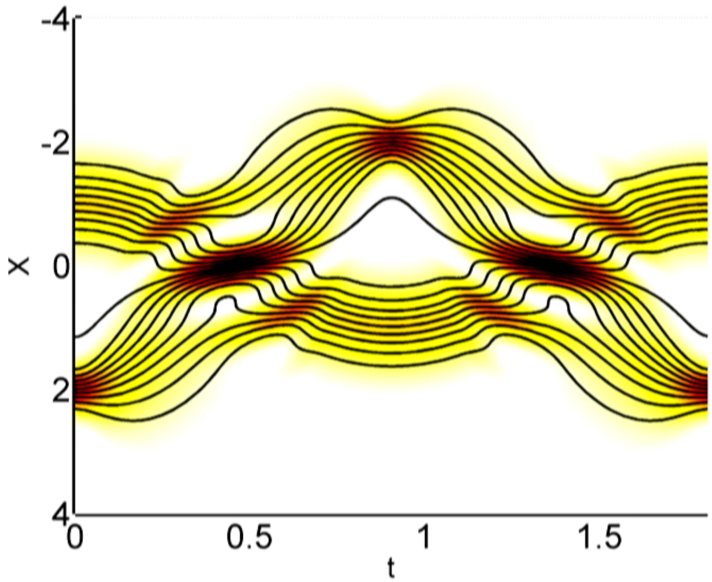
QM oscillator (with nonclassical initial state):



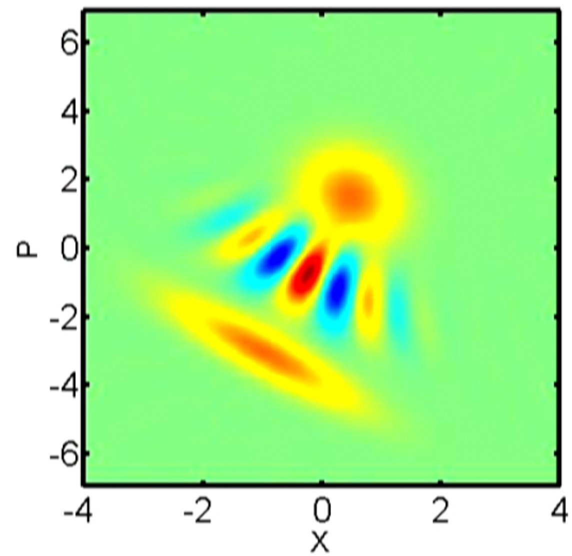


Quantum Dynamics With Realism

Bohmian Mechanics: Trajectories
QM dynamics from HV's and QM potential



Phase Space: Wigner Function
QM dynamics from –ve probabilities



Wigner & Bohm

“Wigner Velocity”: $v_W(x) = \frac{1}{m}\frac{\int W(x,p)\,p\,dp}{\int W(x,p)\,dp}$

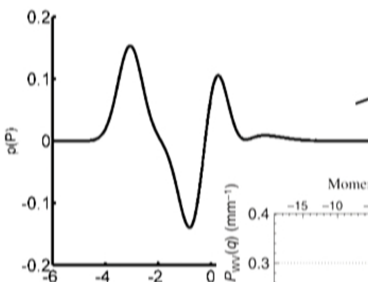
Equal!

“Bohmian Velocity”: $v_B(x) = \frac{\hbar}{2mi}\frac{\psi^*(x)\psi\prime(x) - c.c.}{\psi^*(x)\psi(x)}$

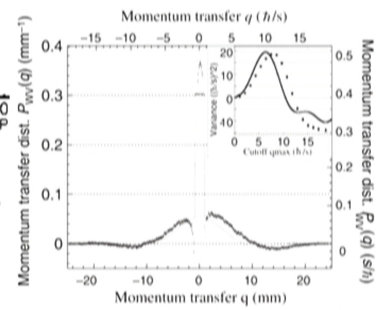
Bohm:

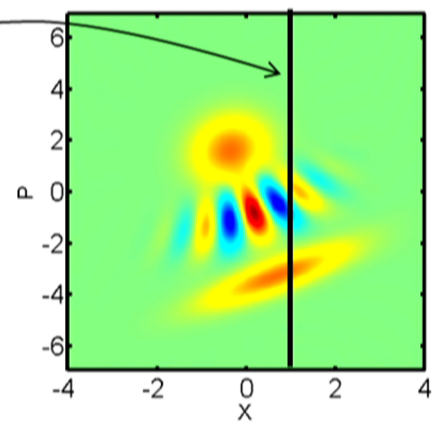
X is real,

P absorbs the “quantumness”!



Mir et al. NJP **9** 287 (2007)



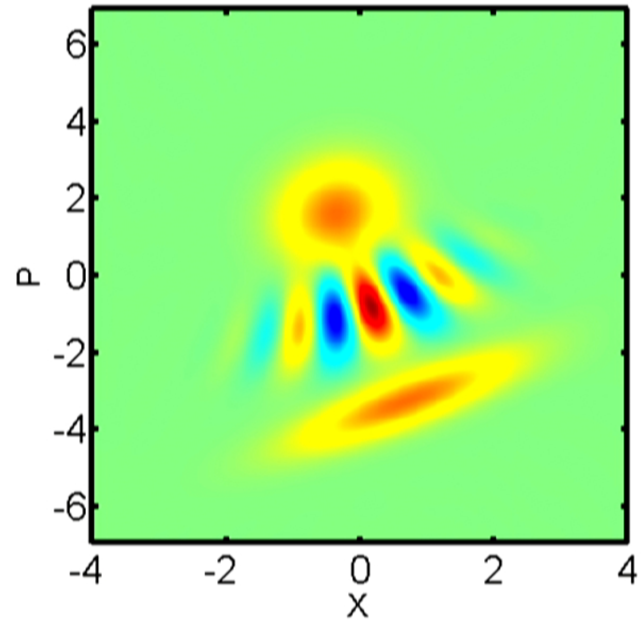


A Continuum of HV Theories

Can define a "Bohm-like theory" through a canonical transformation:

$$\begin{pmatrix} X^\theta \\ P^\theta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} X \\ P \end{pmatrix}$$

- $[X^\theta, P^\theta] = i\hbar$



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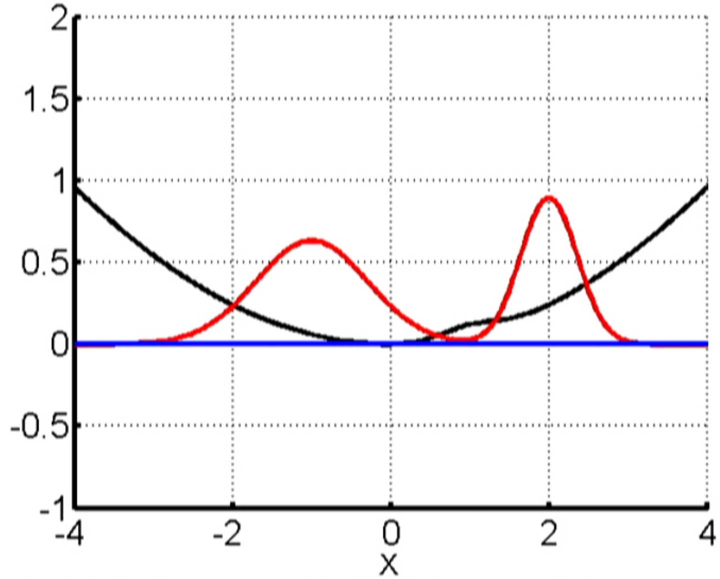
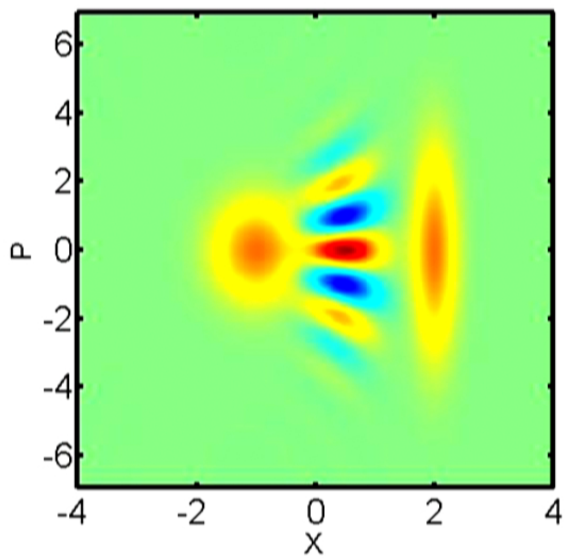
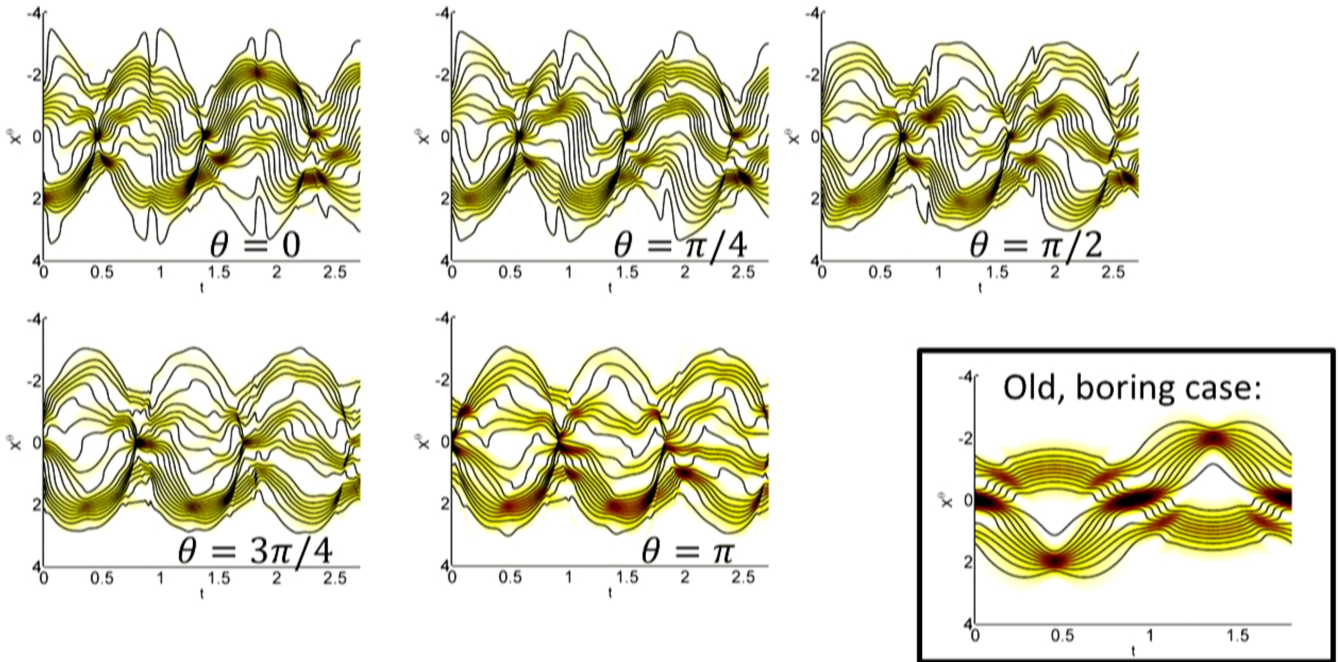
A More Interesting Case





A More Interesting Case

- Trajectories over X^{θ}



Surrealistic Bohm Trajectories

Berthold-Georg Englert[1,2], Marlan O. Scully[3], Georg Süssmann, and Herbert Walther[1,2]

[1] Sektion Physik, Universität München, Am Coulombwall 1, D-8046 Garching, Germany
[2] Max-Planck-Institut für Quantenoptik, Ludwig-Prandtl-Straße 10, W-8046 Garching.
[3] Department of Physics, Texas A & M University, College Station, TX 77843-4242.

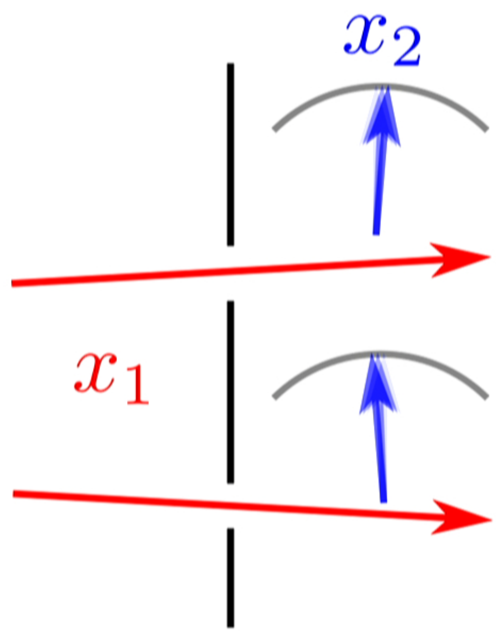
Z. Naturforsch. 47a, 1175–1186 (1992); received September 22, 1992

A study of interferometers with one-bit which-way detectors demonstrates that the trajectories, which David Bohm invented in his attempt at a *realistic* interpretation of quantum mechanics, are in fact *surrealistic*, because they may be macroscopically at variance with the observed track of the particle. We consider a two-slit interferometer and an incomplete Stern-Gerlach interferometer, and propose an experimentum crucis based on the latter.

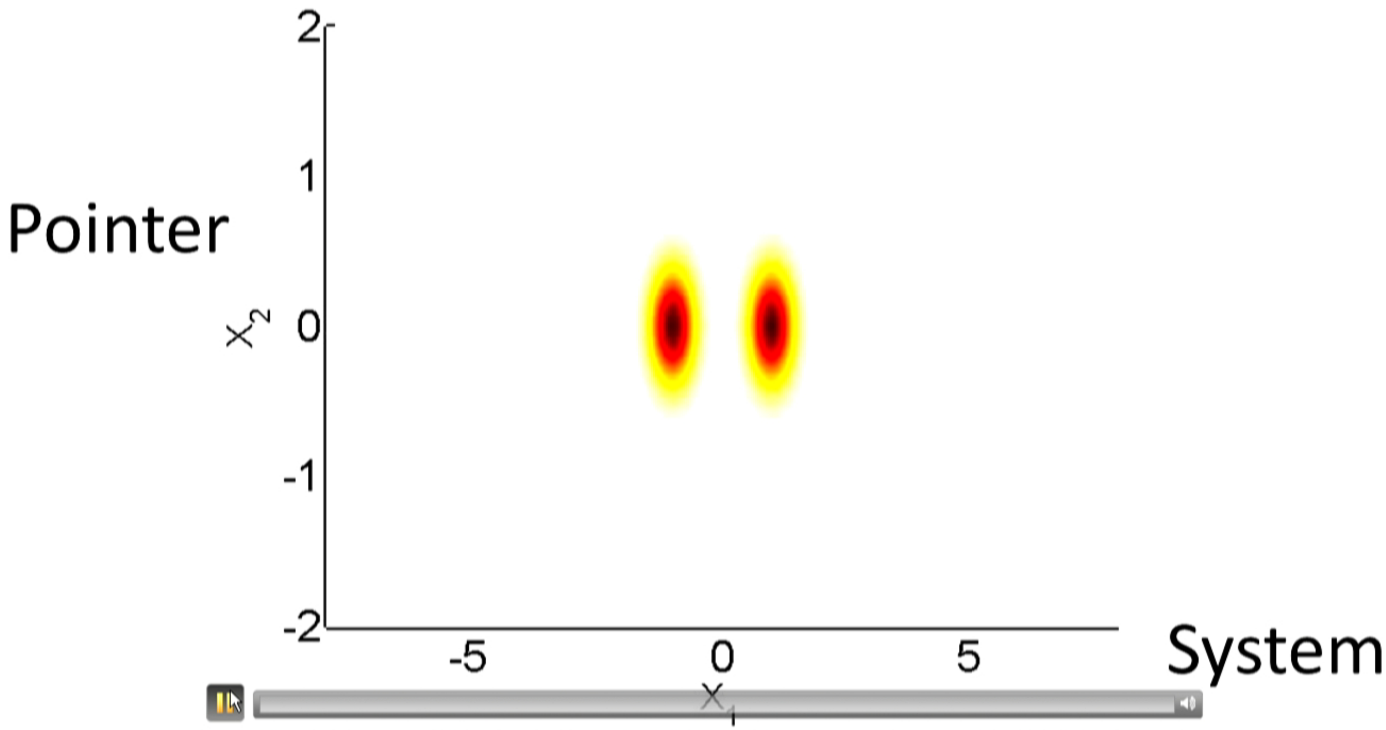
- Also known as the "empty wave" problem
- Conclusion disputed by analyzing treatment of spin (i.e. Hiley & Callaghan, Physica Scripta, **74**, 336 (2006))
- In fact, using spin is irrelevant (i.e. Aharonov & Vaidman quant-ph/9511005)

Surrealistic Trajectories Exist!

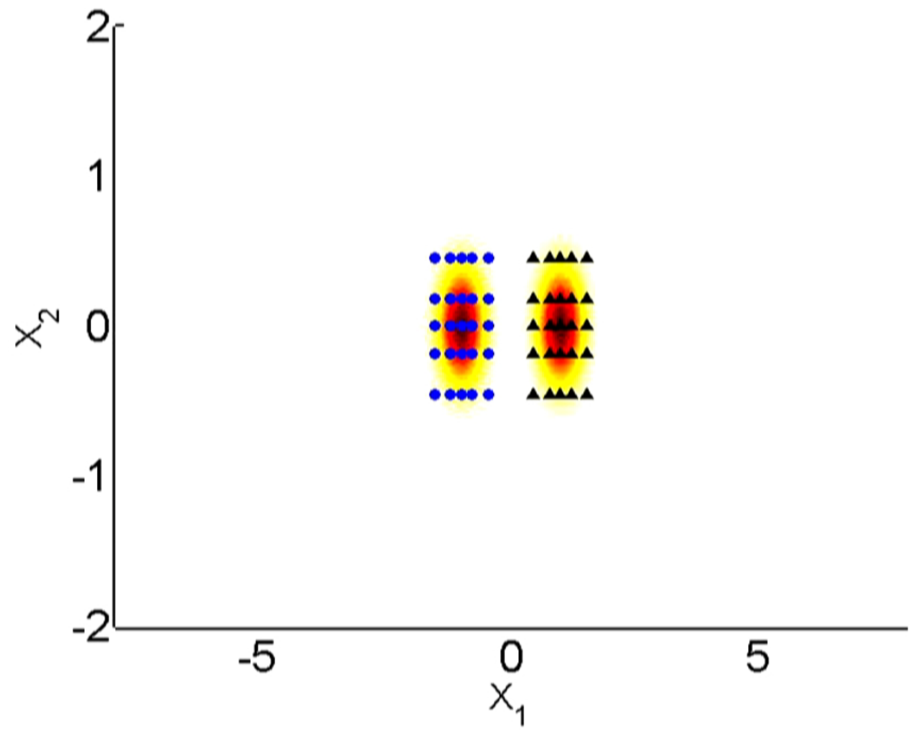
- Can formulate problem entirely in terms of position (and momentum) coordinates:
  $|\psi(x_1, x_2)\rangle =$
  $|\psi_L(x_1)\rangle \otimes |\phi(x_2)e^{ix_2p_0}\rangle$
  $+|\psi_R(x_1)\rangle \otimes |\phi(x_2)e^{-ix_2p_0}\rangle$
- $p_0 \gg \Delta P_2$ for 100% accurate detector



Stage for Surrealistic Trajectories



Surrealistic Trajectories



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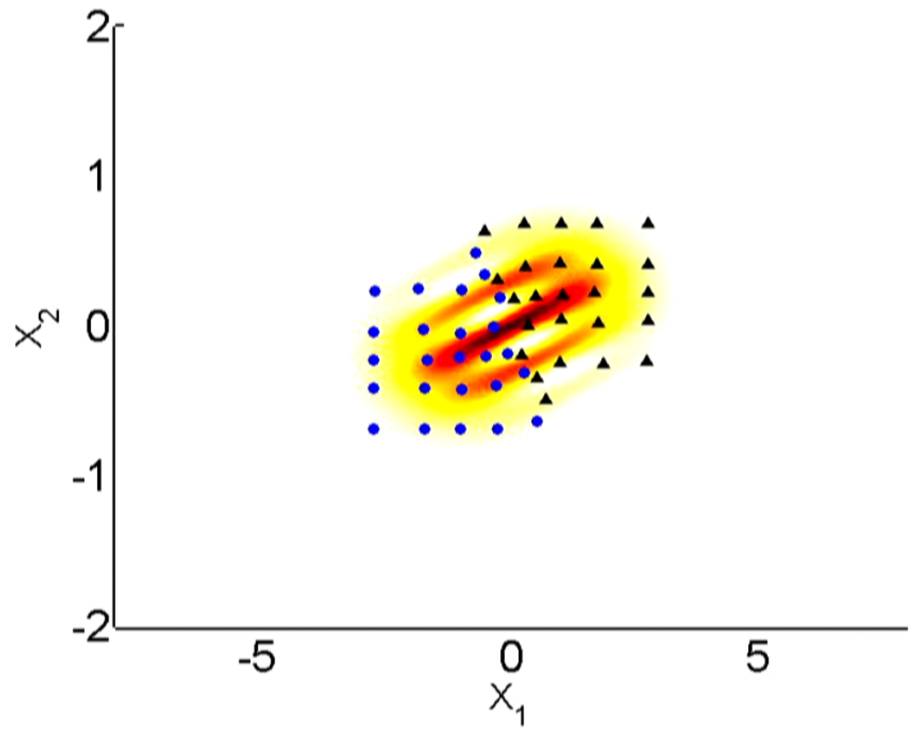

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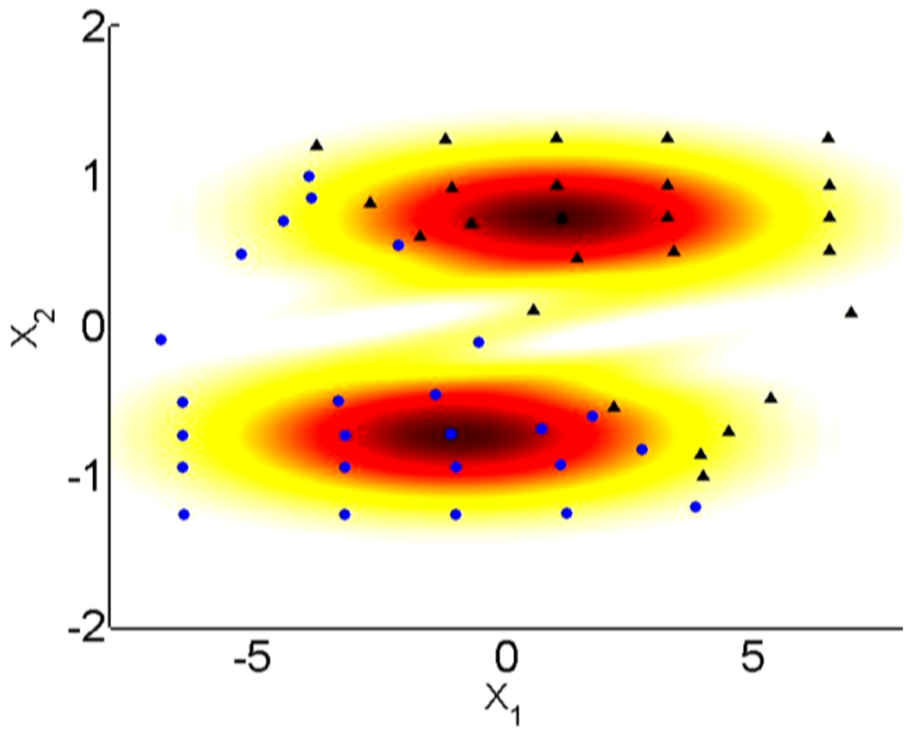
Surrealistic Trajectories

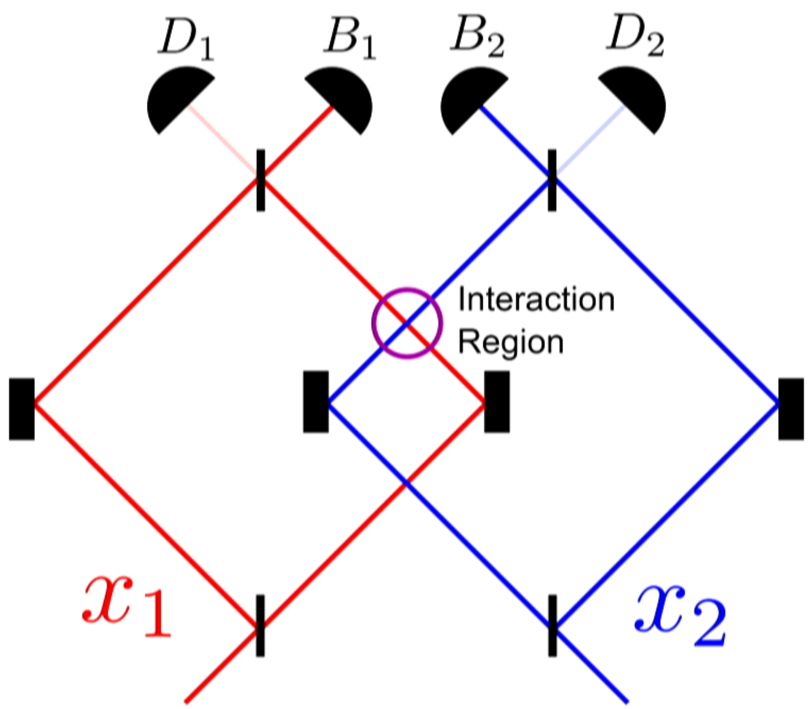


Surrealistic Trajectories: Lessons

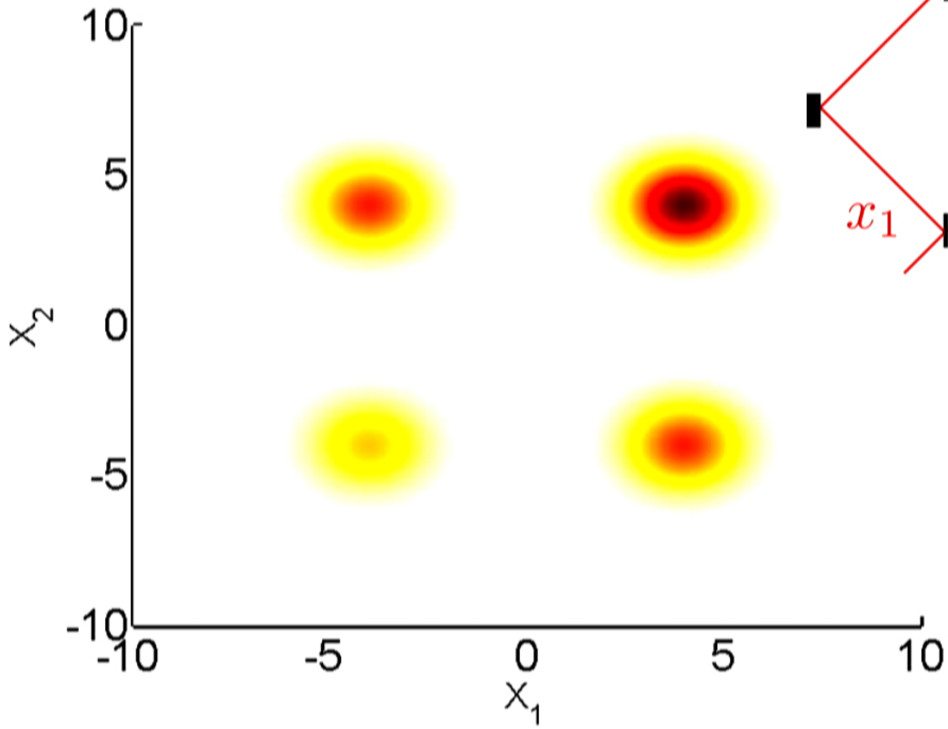
- Even *good* (100% accurate) detectors of *position* (the “preferred” coordinate) can *misfire*, depending on the measurement context
- Only classical detectors reveal the true value of the hidden position

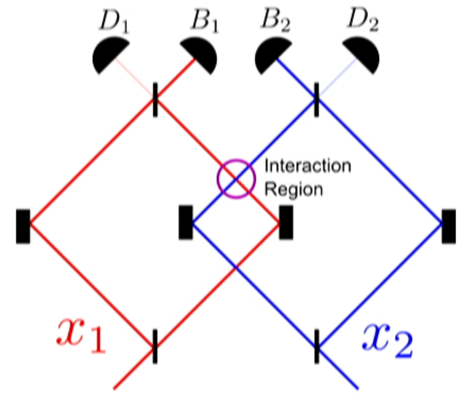
Hardy's Paradox

- Two nested interaction-free measurements



Hardy's Interferometer





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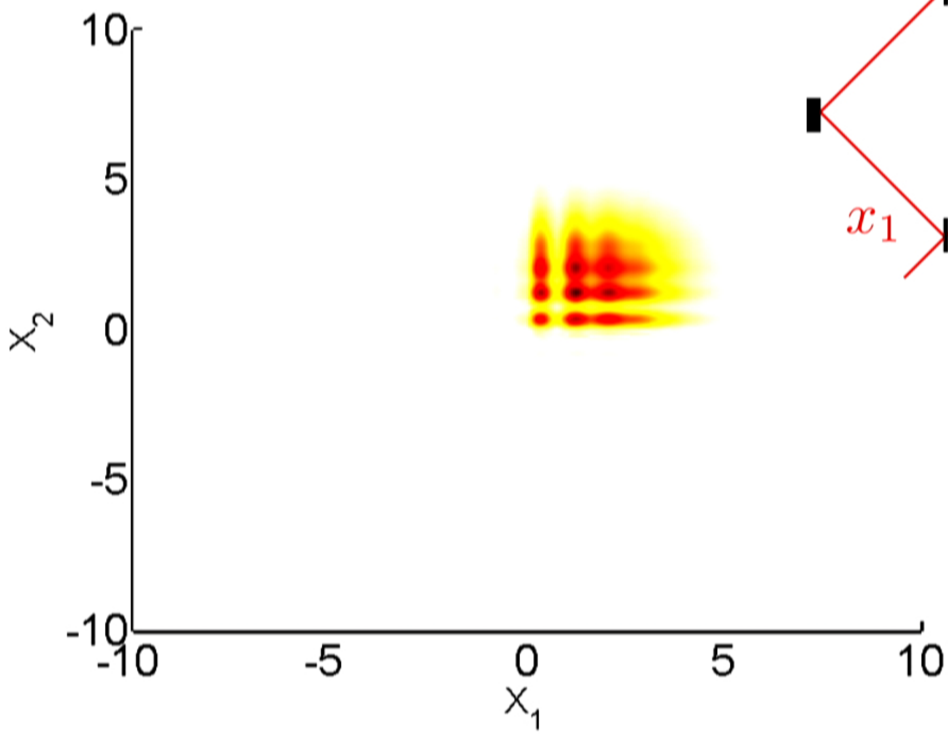

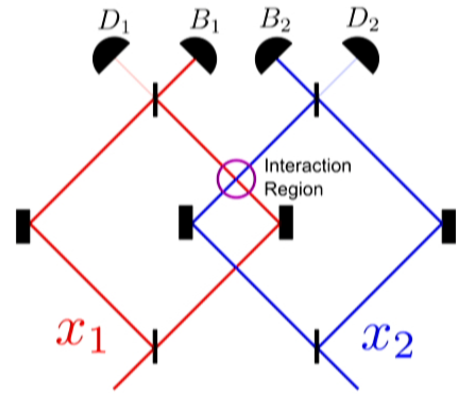

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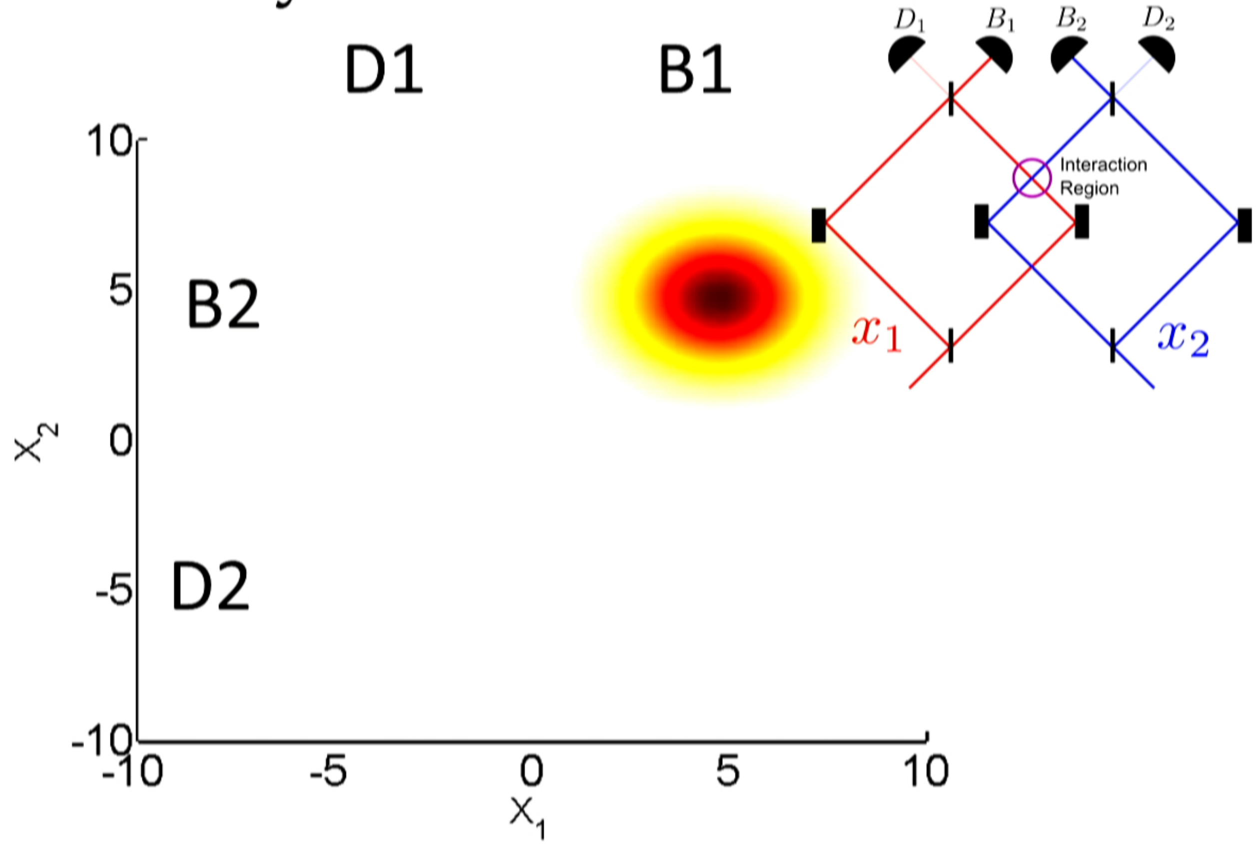
Hardy's Interferometer



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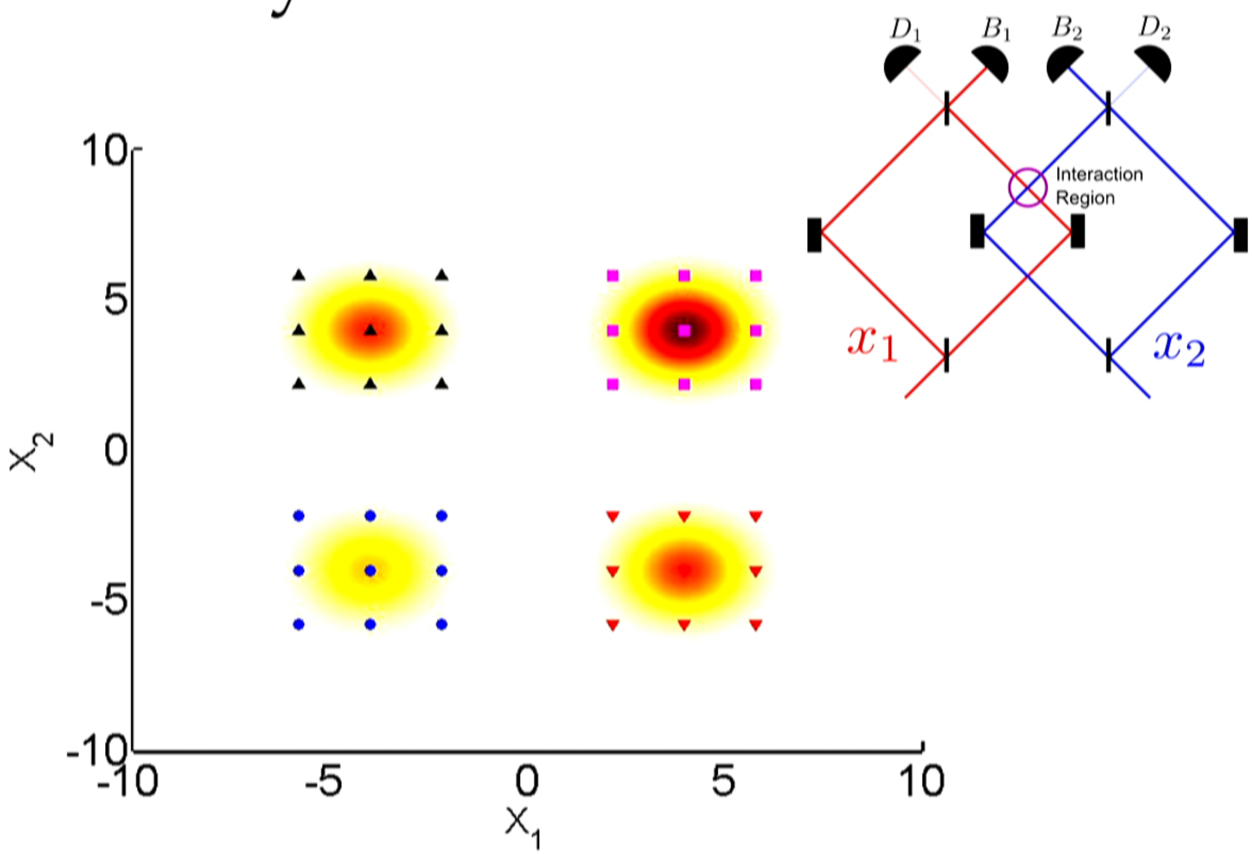

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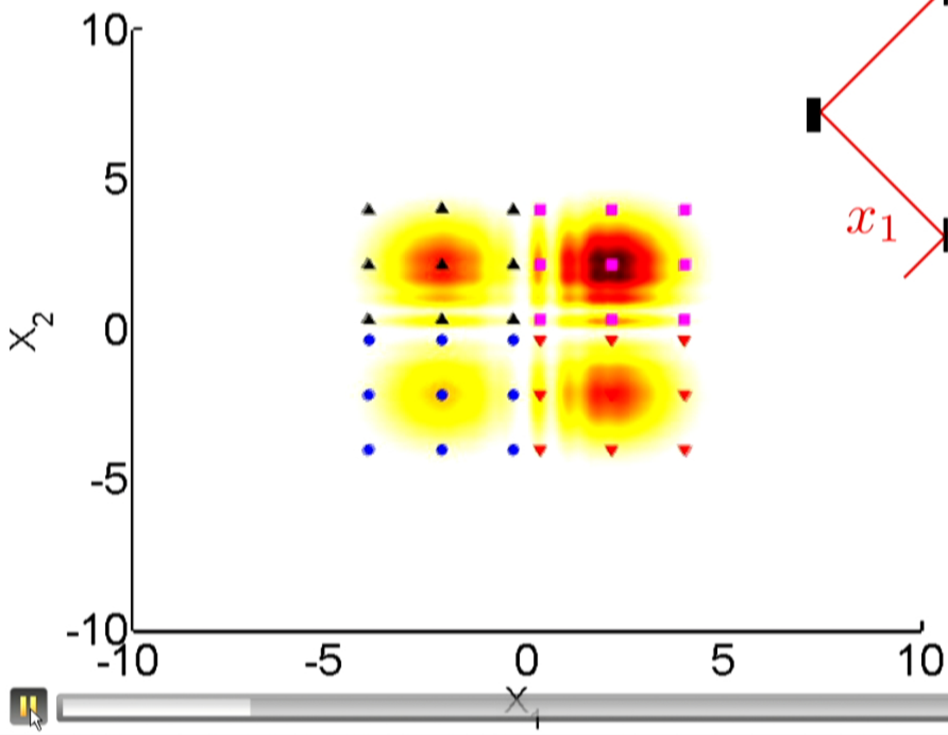

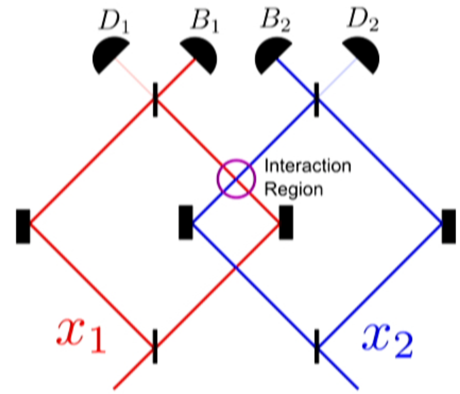

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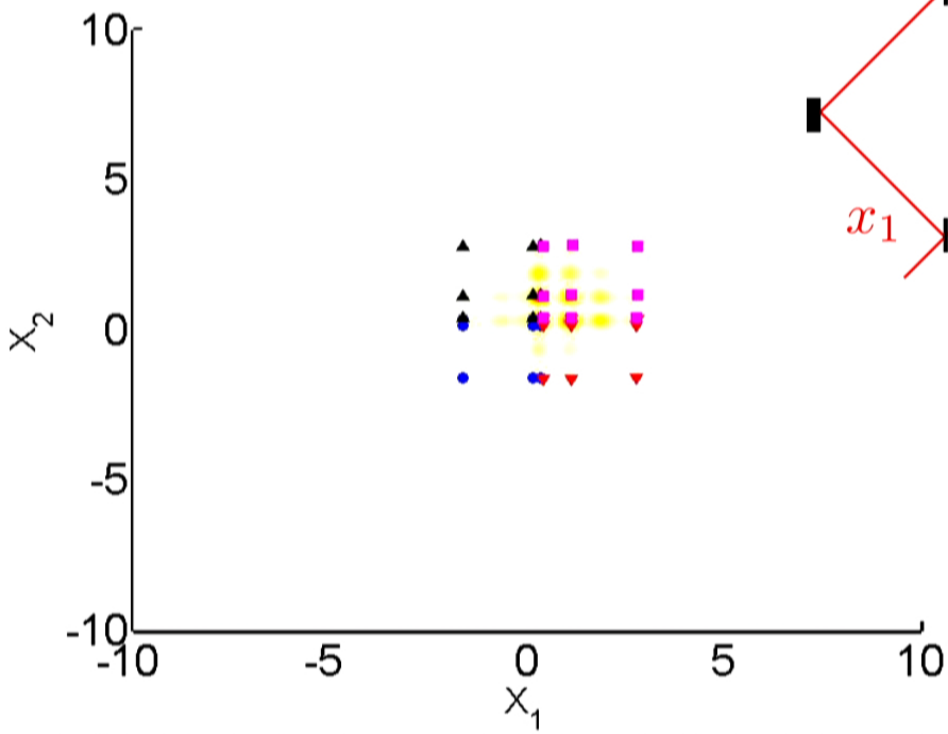

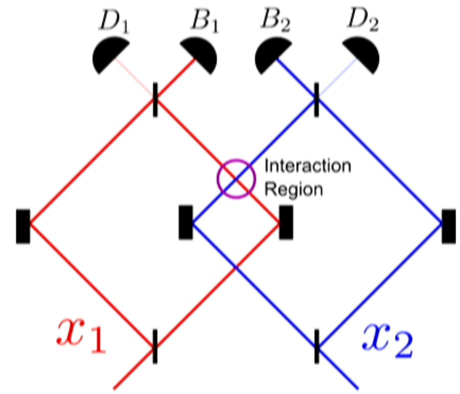

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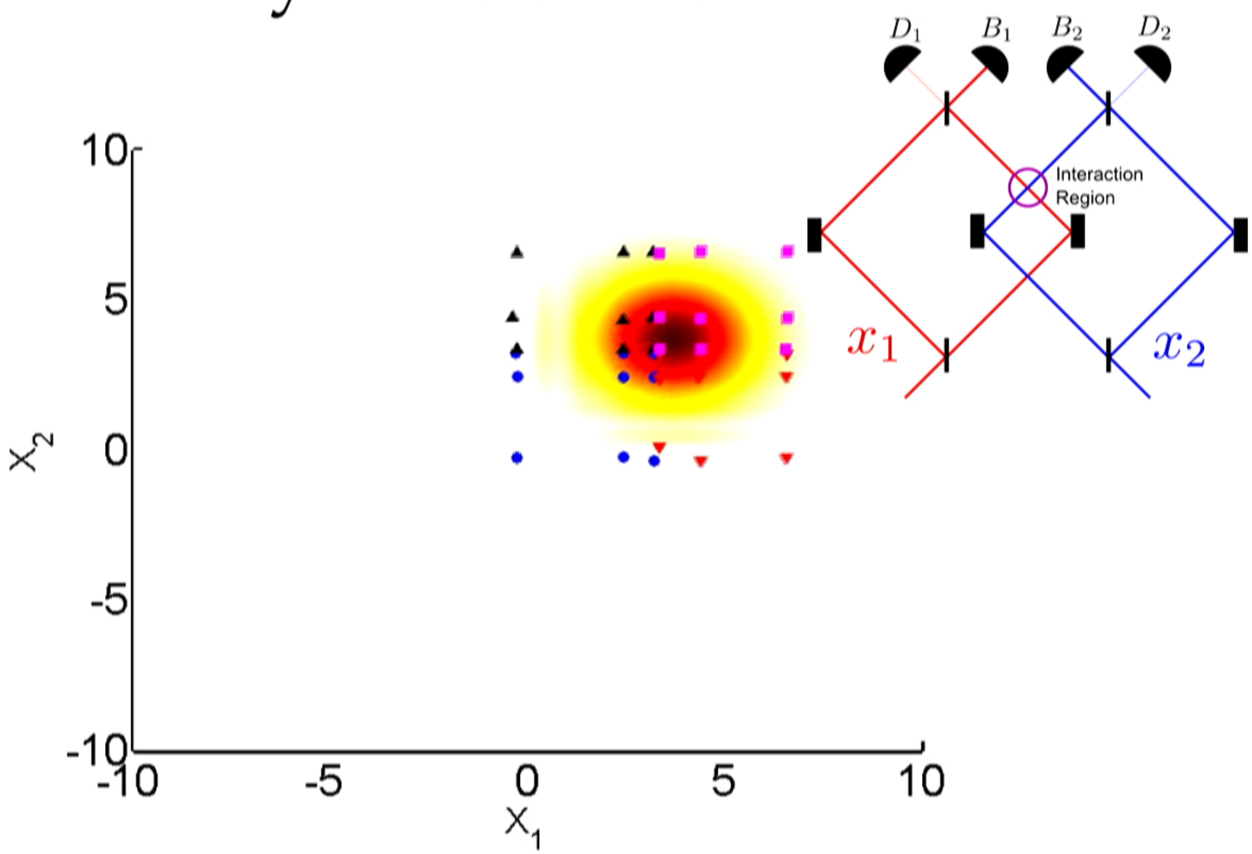

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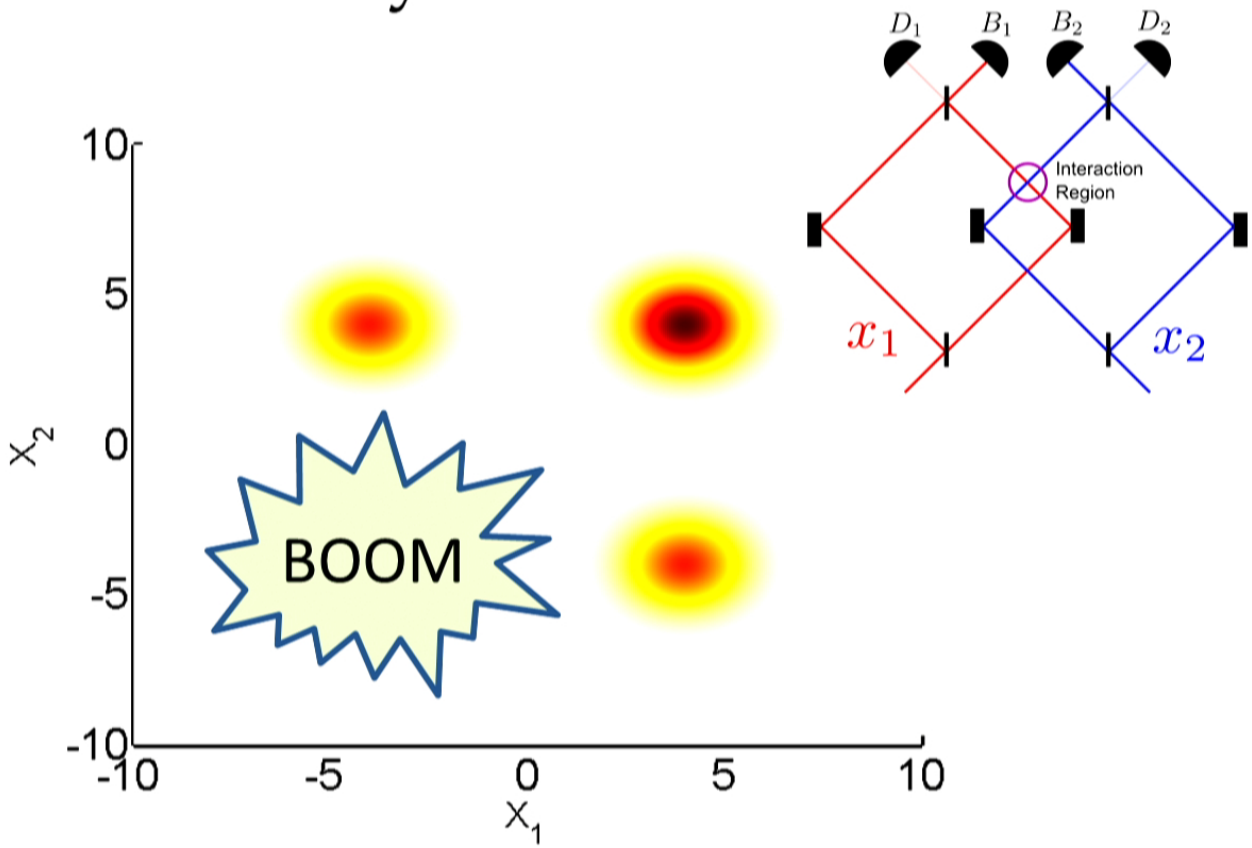
Hardy's Paradox



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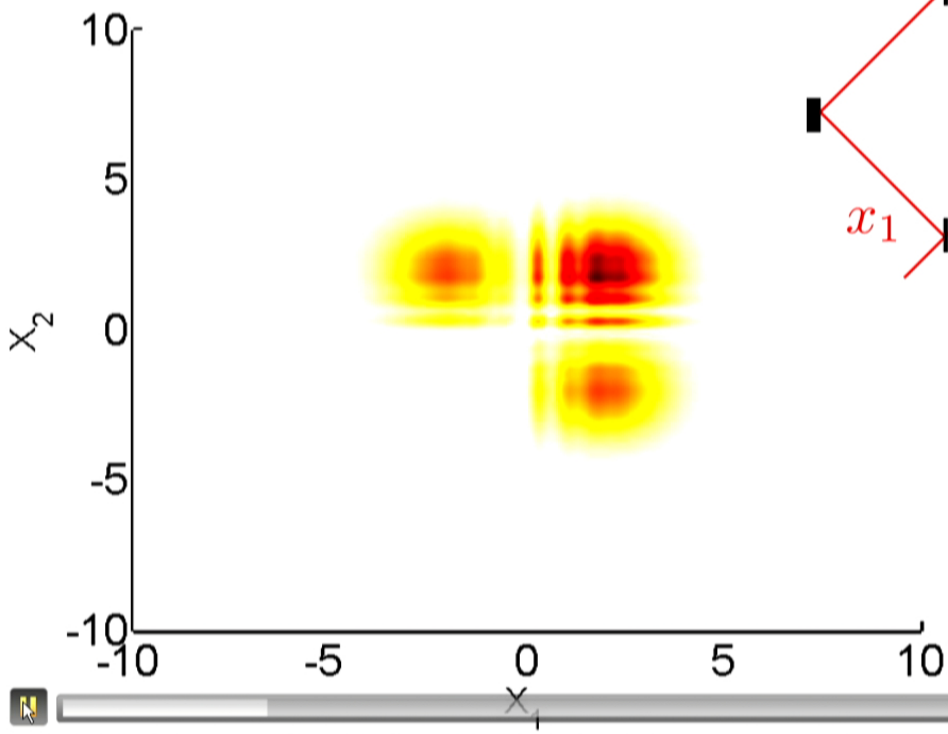

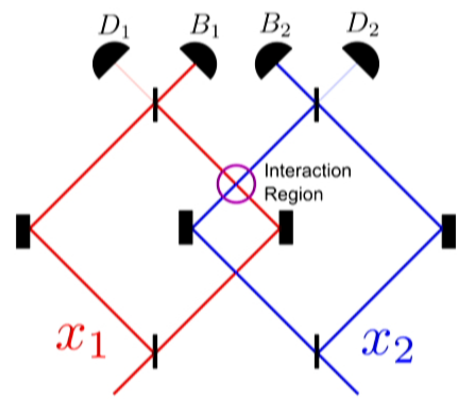

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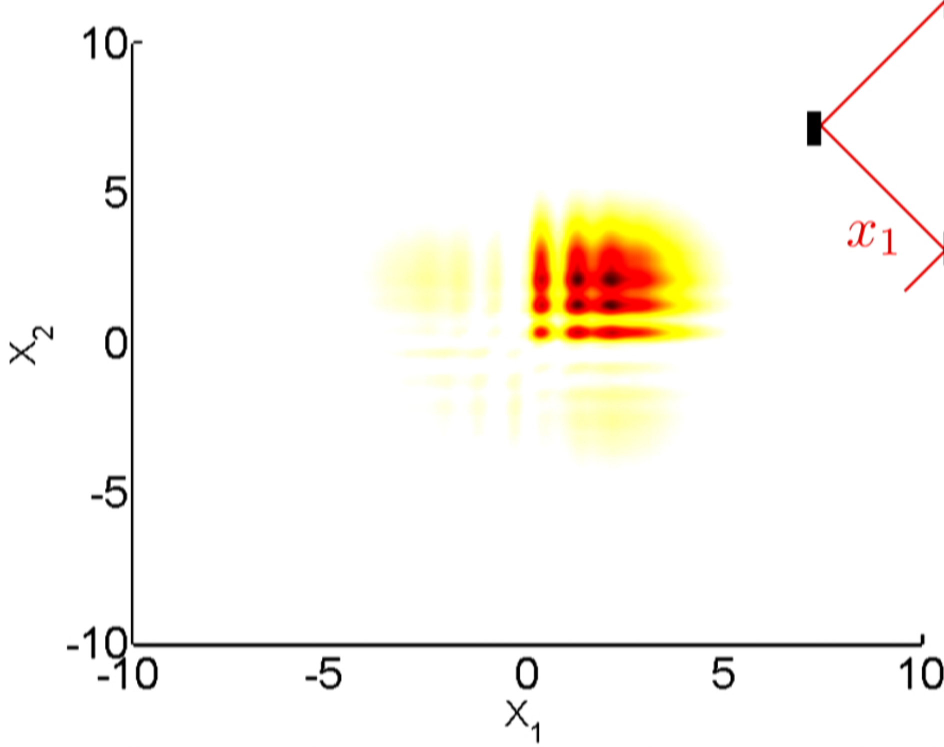
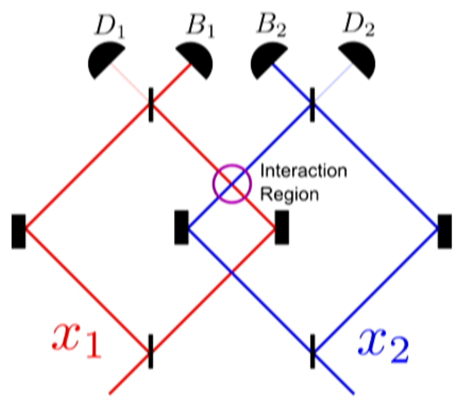
Hardy's Paradox





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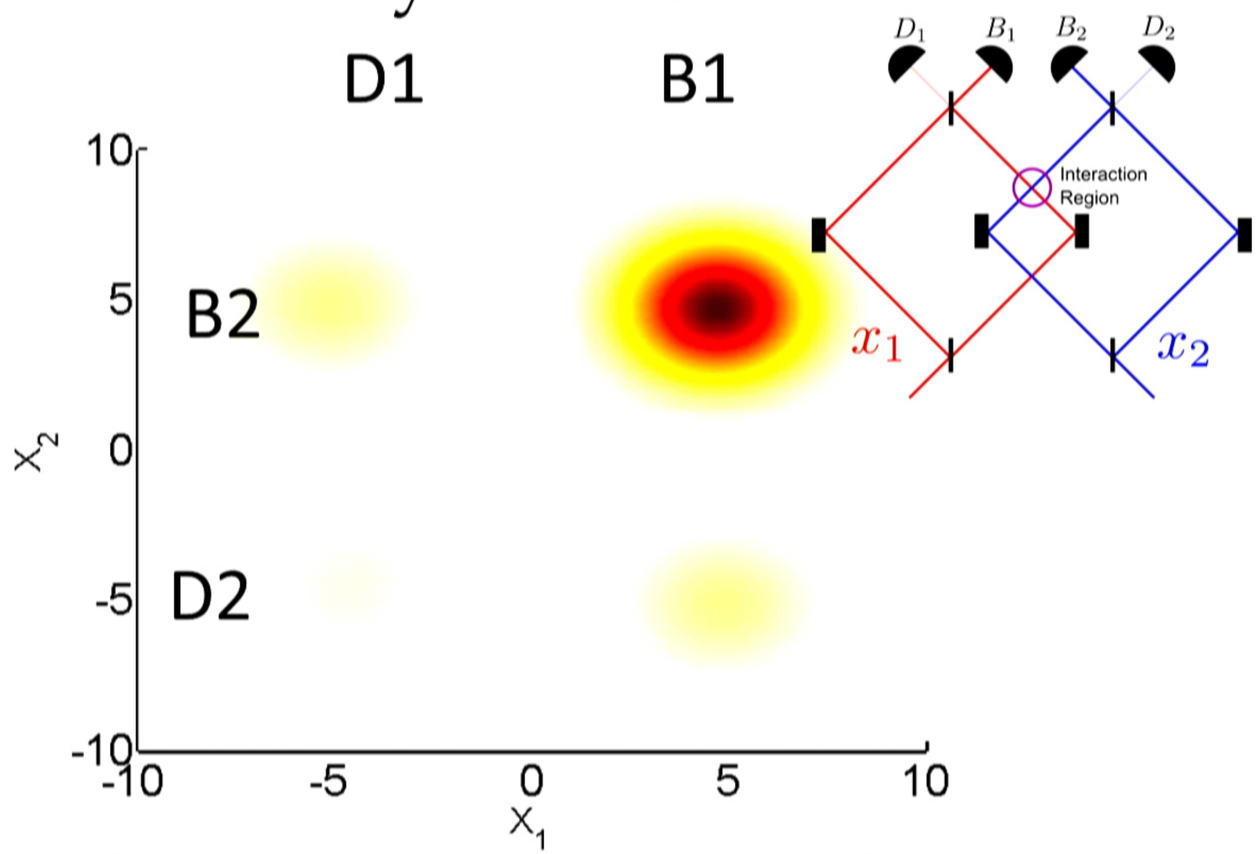

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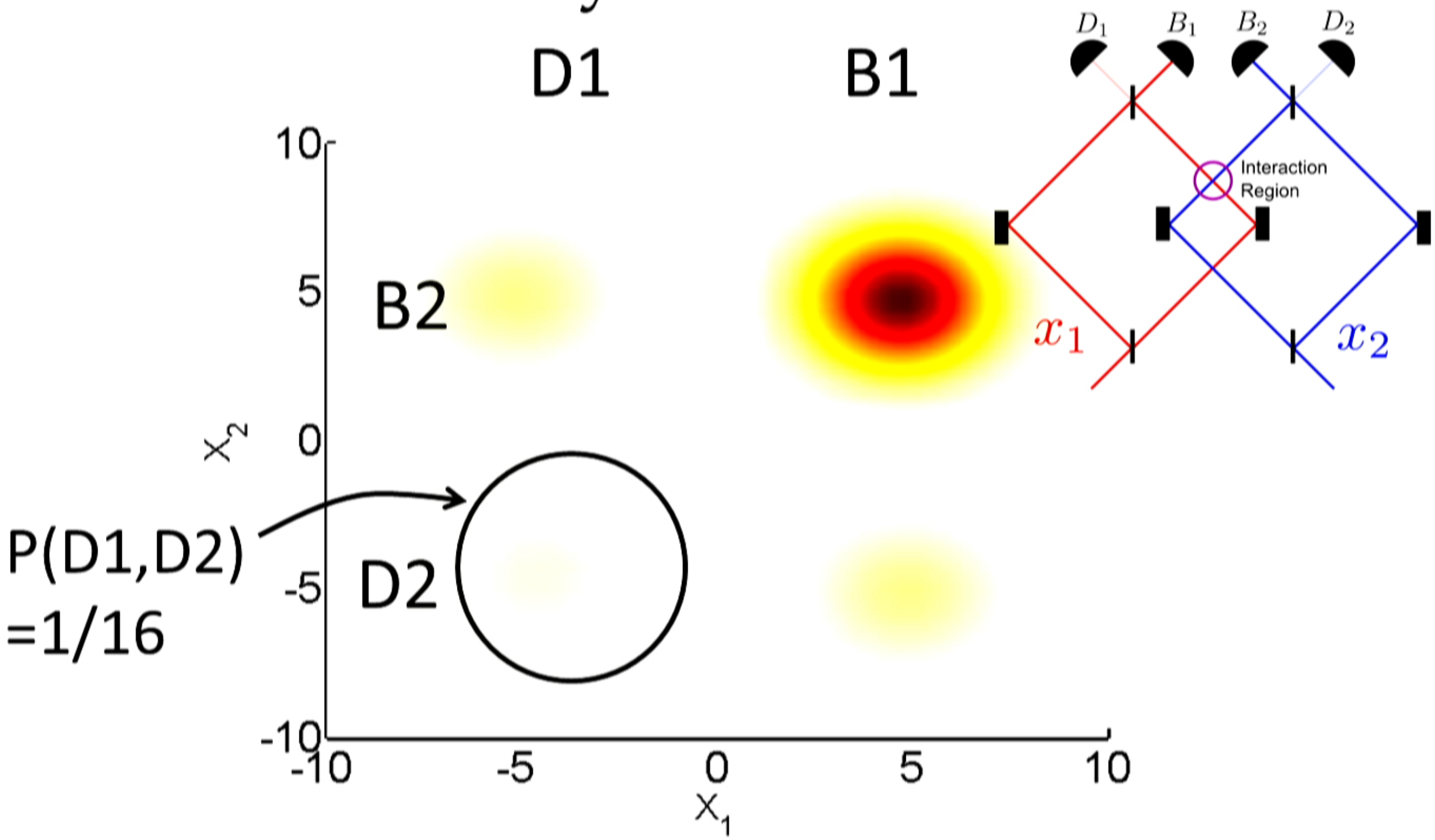

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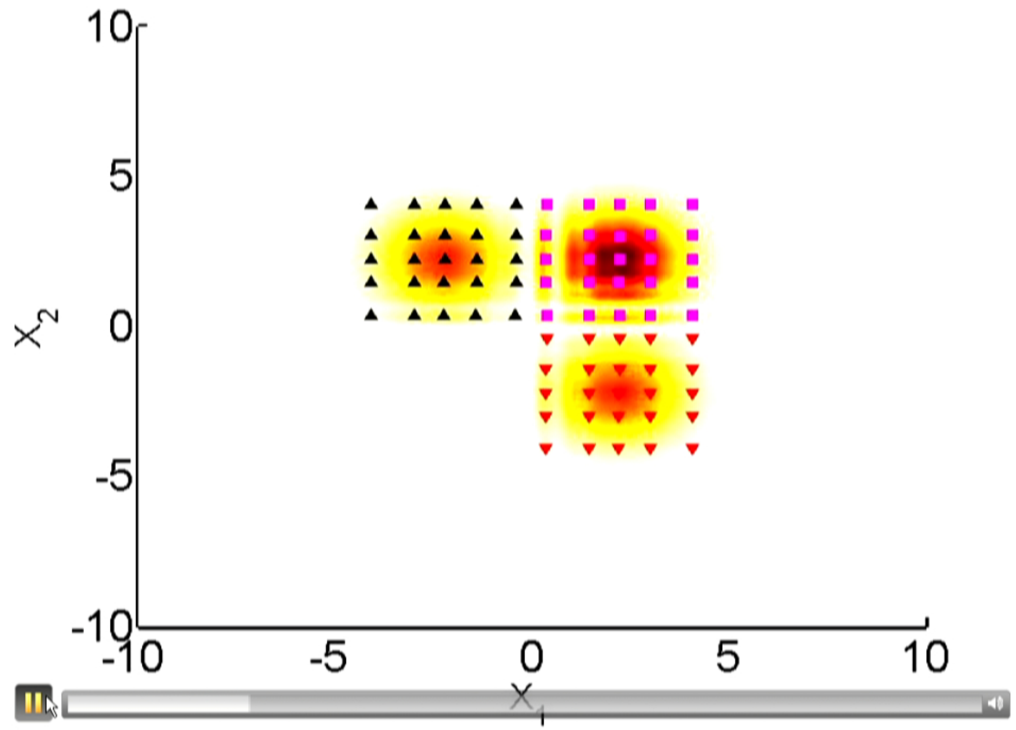

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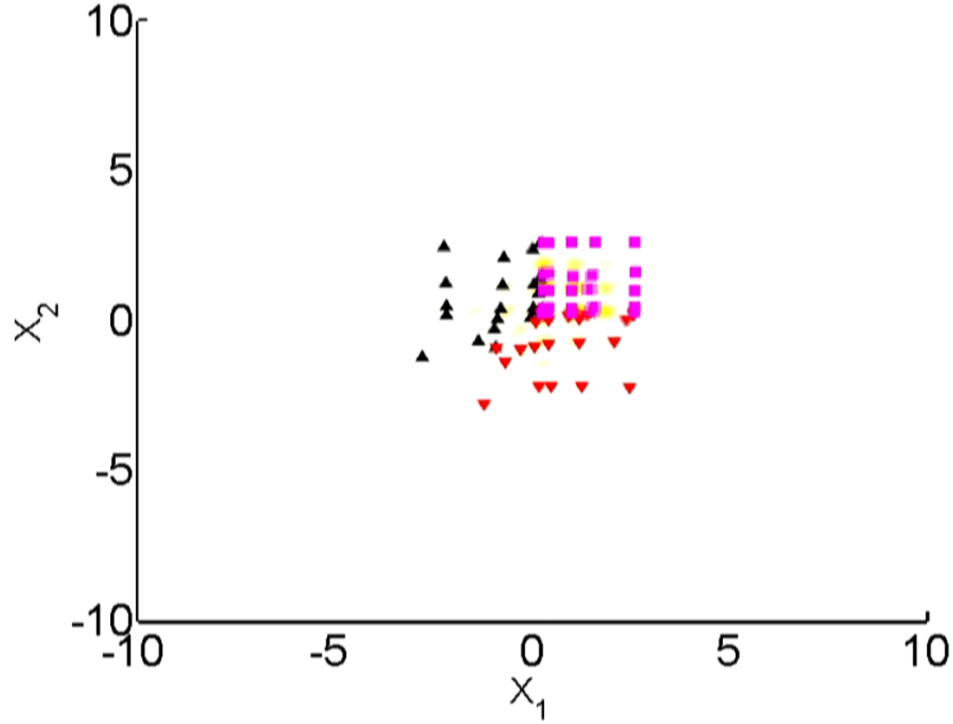

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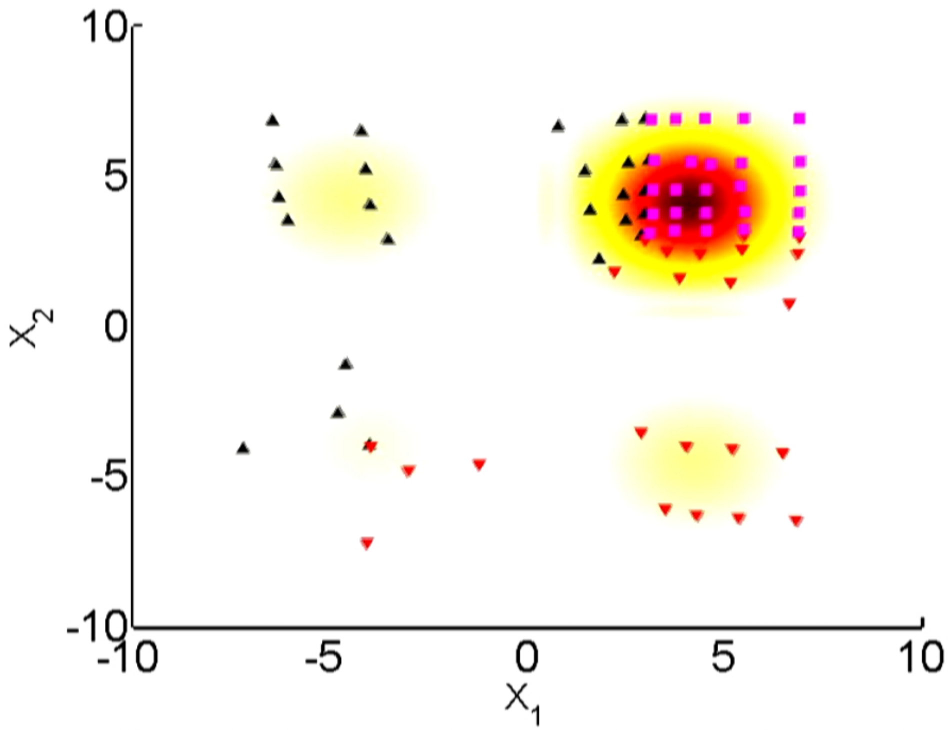

Hardy's Paradox: Lessons

- It's dangerous to use retrodiction and trying to speak about counterfactuals
- There is no such thing as "interaction-free" measurement
- The very possibility of interference is part of the measurement context
- BM: due to nonlocal quantum potential, some trajectories are surrealistic

Quantum Paradoxes and BM

- Even the most simple, reliable measurement of position *can be wrong* (i.e. empty wave) due to interference!
- Surrealistic trajectories are closely related to paradoxes, contextuality (and anomalous weak values)

(How) Is Position Special?

Yes:

- Causality: Interactions much be local in real space (in fact a postulate in QFT)
- Only when we use X as the HV, we have naïve = Bohmian = Wigner velocity
- QM objects become classical through interactions; plays a special role in decoherence

No:

- Phase space is agnostic to X vs P
- Even in pure BM, X measurements can be bad ("surrealistic")