Quantum Control of Wave-Particle Duality

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science.uwaterloo.ca

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Real or Predictive?

After 1 hour:

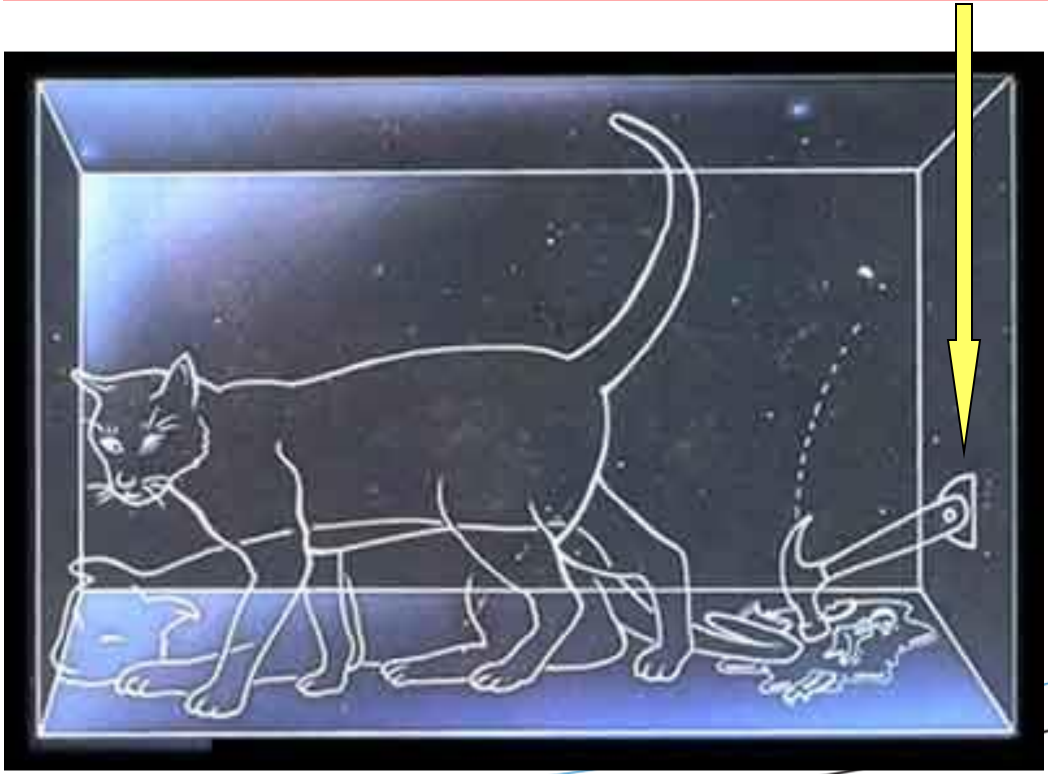
Either

If the cat is really dead or really alive, we can't predict which

Or

If we predict the state of the cat, it isn't really dead or alive

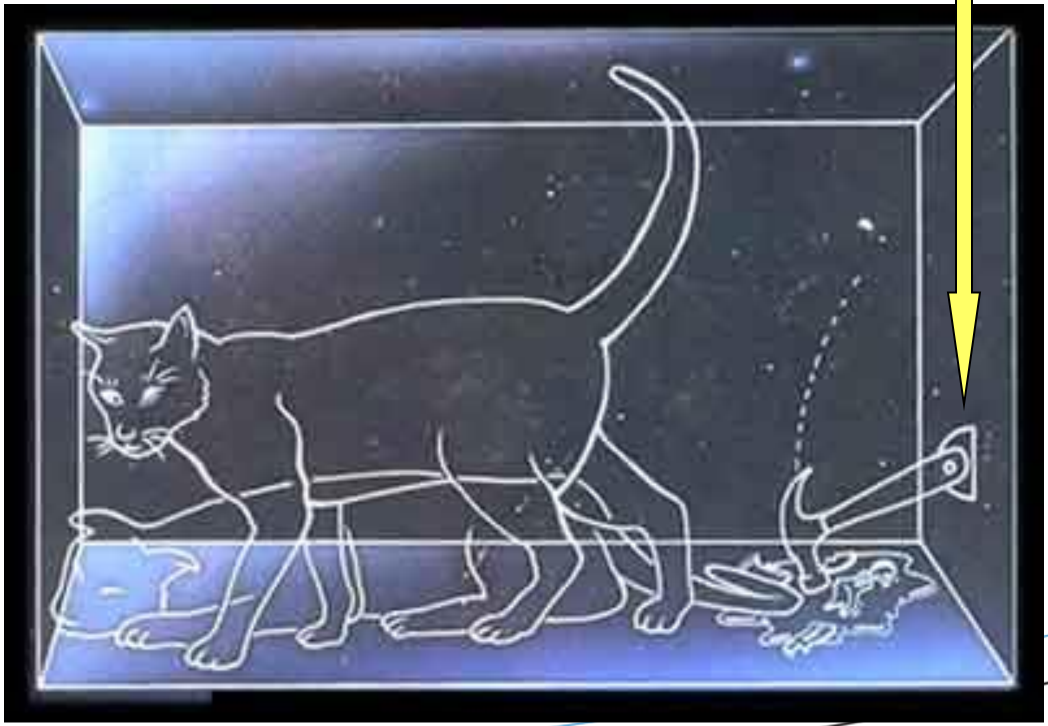
Quantum Decay of a radioactive nucleus triggers hammer
After 1 hour: 50% chance of decay



Hidden Variable Theories

Perhaps the radioactive nucleus has some (as yet) unseen physical properties (hidden variables) that DEFINITELY PREDICT the REAL state (dead or alive) of the cat

Our forced choice between reality and prediction might be because we don't (yet) know what these hidden variables are



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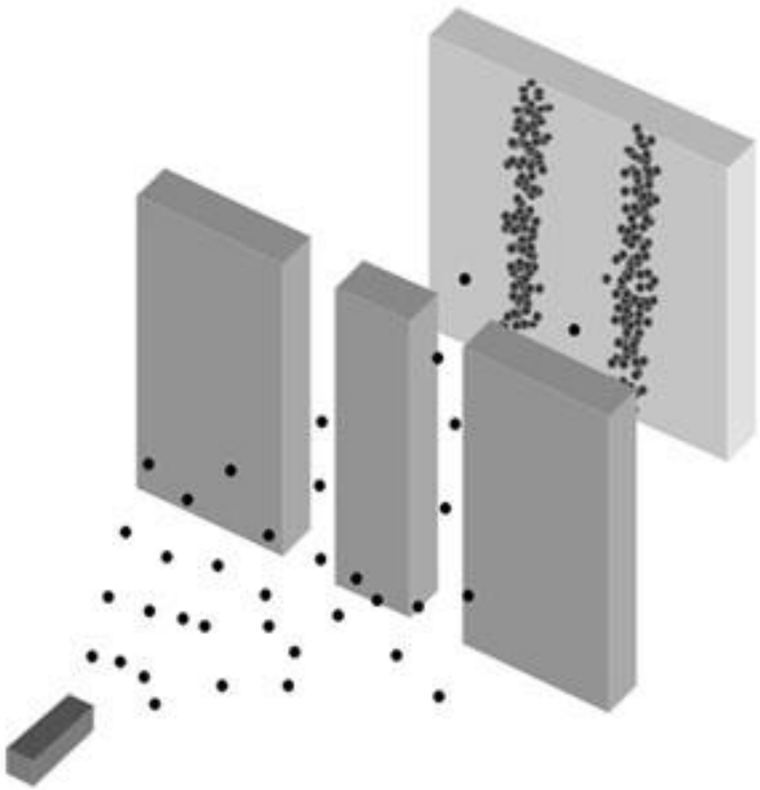
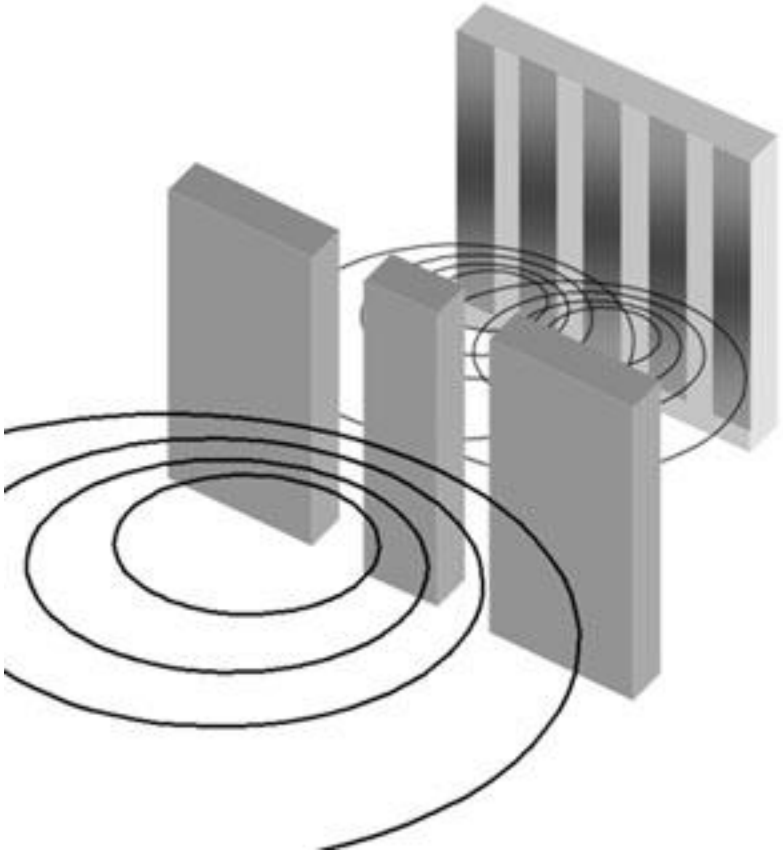
Can we test this?





Knowledge of the hidden variables will tell us which of these situations occur for any given setup

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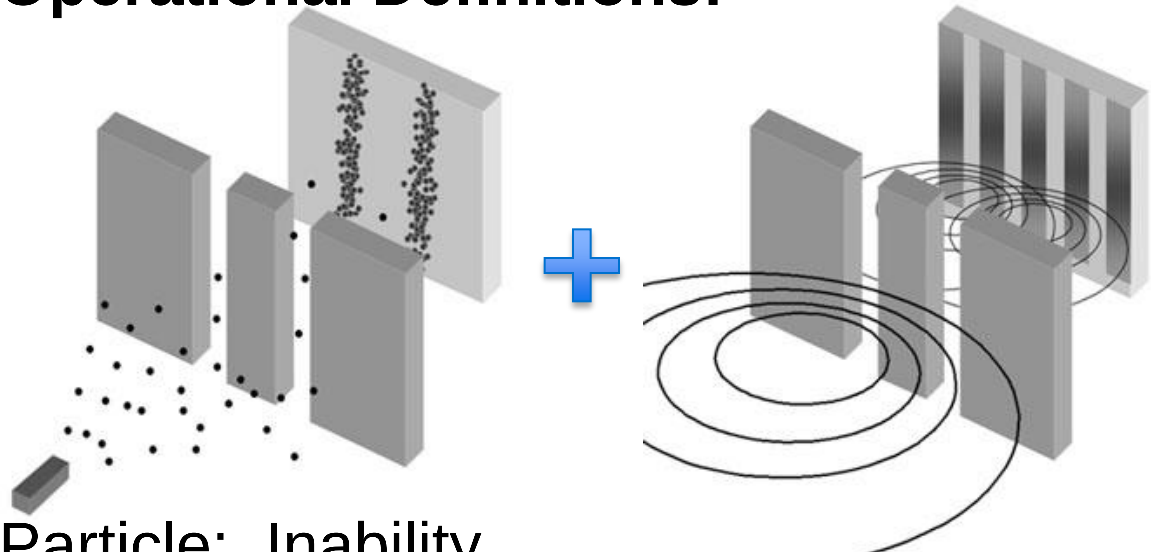
Operational Definitions:

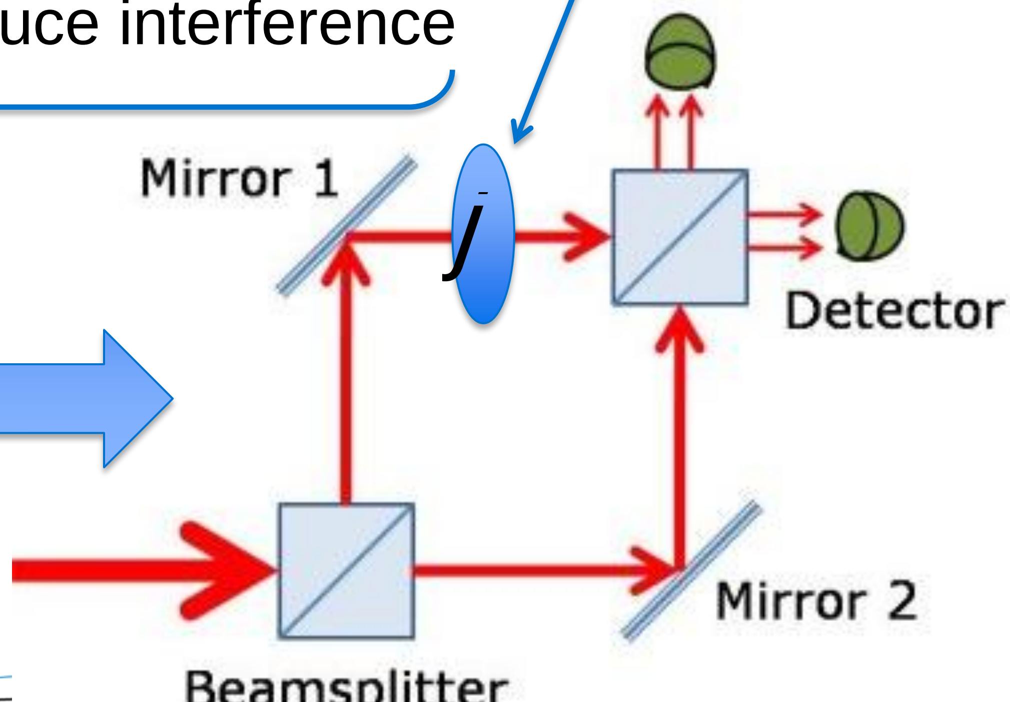


Particle: Inability to produce interference

Wave: Ability to produce interference

phase shift

Mach-Zender Interferometer



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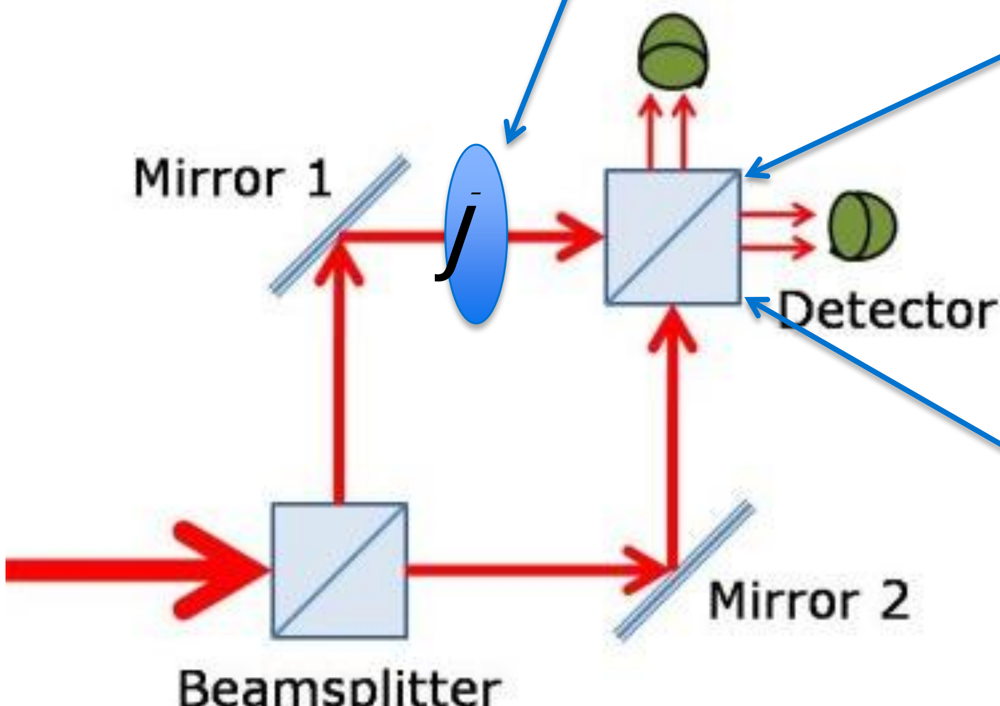
Mach-Zender Interferometer

phase shift

If this beamsplitter is present then the detectors register an phase-dependent interference pattern ➔ photon is a wave



If this beamsplitter is absent then the detectors each click half the time ➔ photon is a particle

(a half-silvered mirror)

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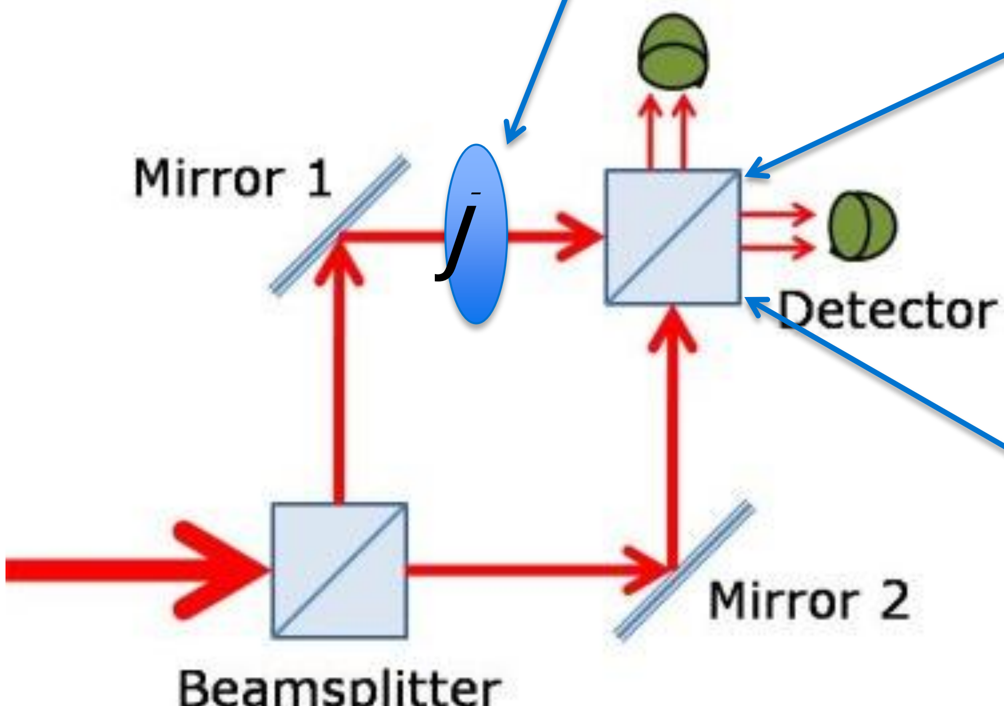
Delayed Choice Experiment

phase shift

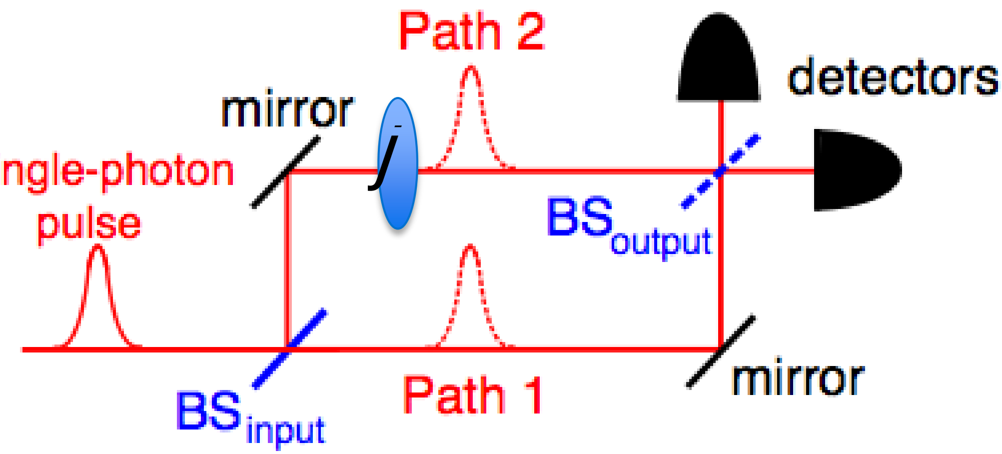


(a half-silvered mirror)

Randomly decide whether or not to insert this 2nd beamsplitter AFTER the photon has gone through the 1st beamsplitter

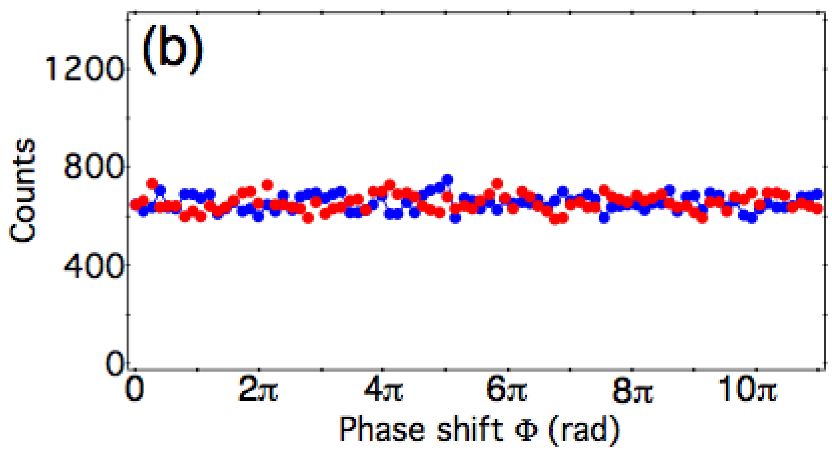
Photon can't "know" beforehand if it is a wave or a particle

Delayed Choice Results

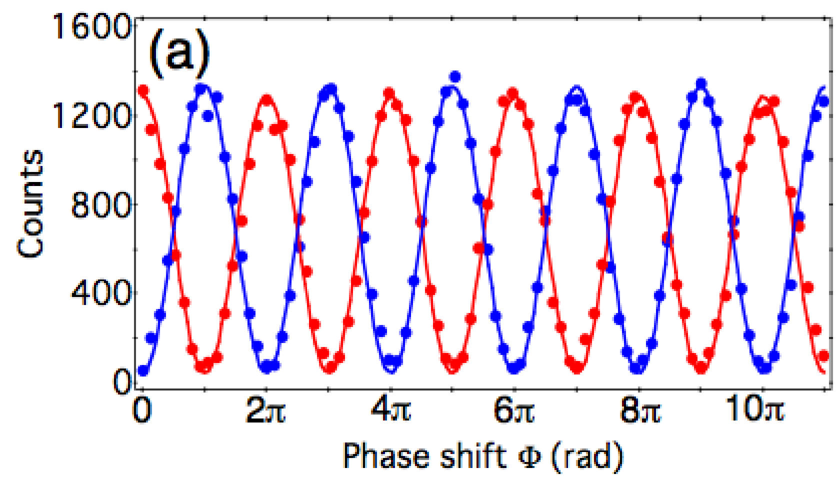


Jacques, Vincent; et al. (2007) "Experimental Realization of Wheeler's Delayed-Choice Gedanken Experiment". *Science* **315**: 966–968.

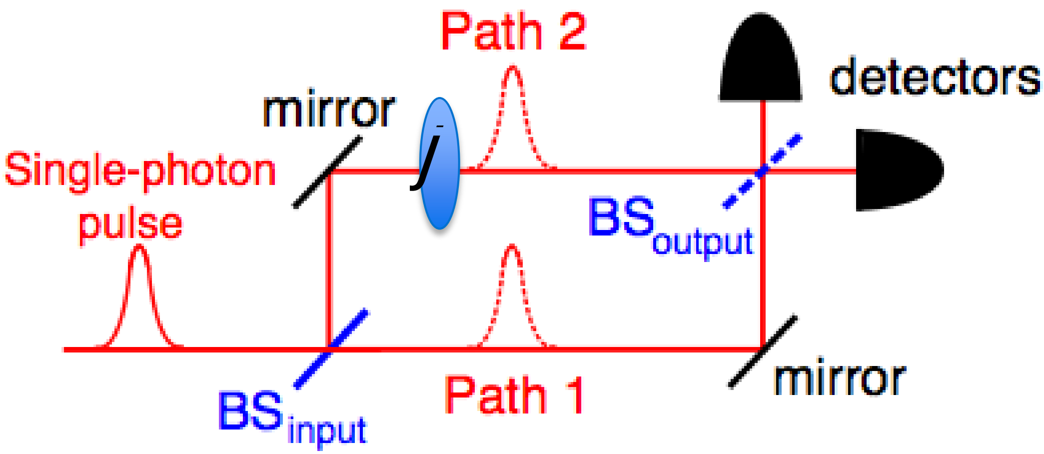
2nd Beamsplitter removed



2nd Beamsplitter inserted

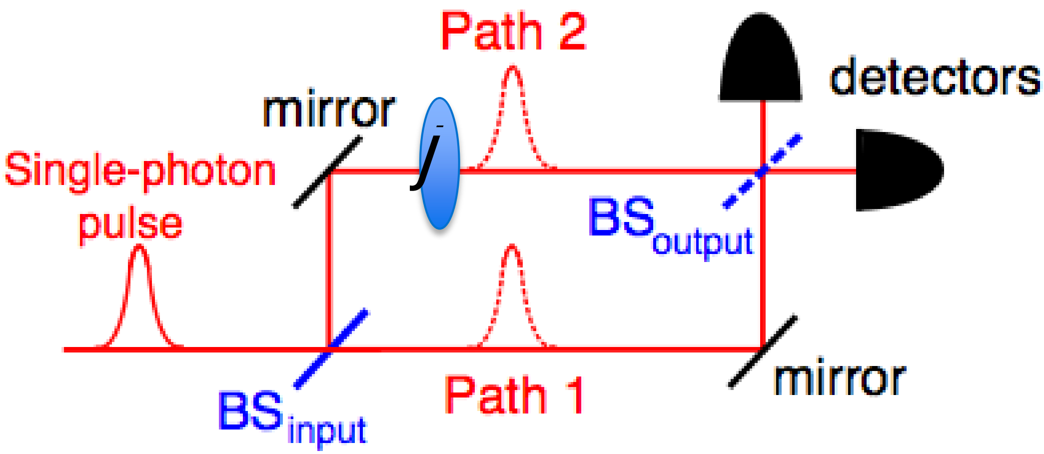


Not So Fast!



Maybe the insertion (or removal) of the 2nd beamsplitter modifies the hidden variable of the photon, telling it whether or not it is a wave or a particle BEFORE it reaches the detectors!

Quantum Delayed Choice



What if the 2nd beamsplitter itself is a quantum object?

In other words, what would happen if the state of a quantum object (like another photon) determined if the 2nd beamsplitter were inserted or not?

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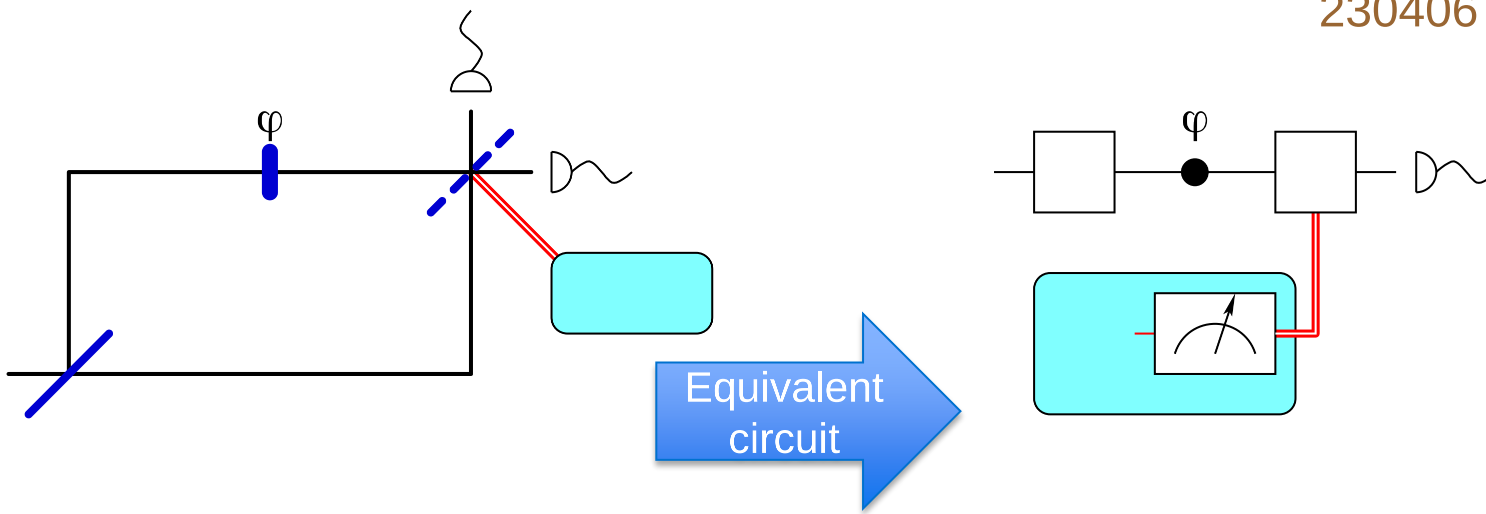
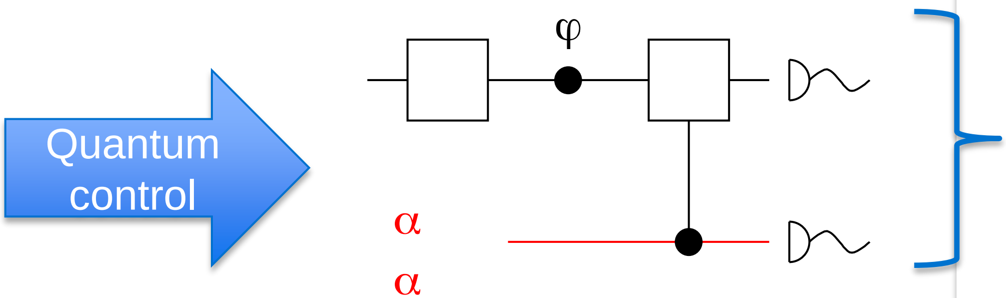
Quantum Delayed Choice Experiment

R. Ionicioiu & D. Terno
Phys. Rev. Lett. 107, 230406 (2011)





$$|\text{photon+control}\rangle$$

$$= \frac{1}{\sqrt{2}}\Big[|\text{particle}\rangle|0\rangle + |\text{wave}\rangle|1\rangle\Big]$$

$$|\text{particle}\rangle = \frac{1}{\sqrt{2}}\Big[|0\rangle + e^{ij}|1\rangle\Big]$$

$$|\text{wave}\rangle = \frac{e^{ij/2}}{\sqrt{2}}\left[\cos\frac{j}{2}|0\rangle - i\sin\frac{j}{2}|1\rangle\right]$$

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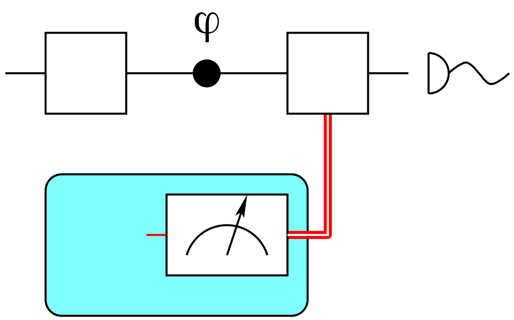
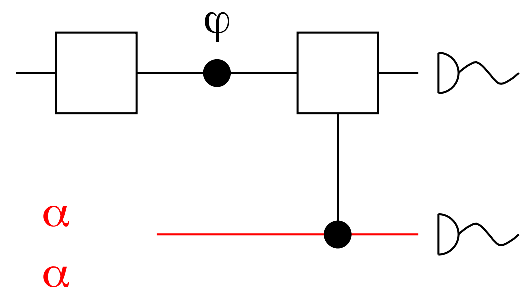
Implications of Quantum Control





Classical control after = Quantum control before

- Beamsplitter is in an open/closed superposition
- Temporal order reversed
  - Photon detected *before* learning if beamsplitter is open |0> or closed |1>
  - Wave/particle selection is made *after* detection

$$|\text{photon+control}\rangle = \frac{1}{\sqrt{2}}\left[|\text{particle}\rangle|0\rangle + |\text{wave}\rangle|1\rangle\right]$$

$$|\text{particle}\rangle = \frac{1}{\sqrt{2}}\left[|0\rangle + e^{ij}|1\rangle\right] \qquad |\text{wave}\rangle = \frac{e^{ij/2}}{\sqrt{2}}\left[\cos\frac{j}{2}|0\rangle - i\sin\frac{j}{2}|1\rangle\right]$$

Hidden Variable Explanation?

Hidden Variable theories

➔ Photon is "really" a wave or "really" a particle

$$\lambda = \begin{cases} p \Rightarrow |\text{particle}\rangle \\ w \Rightarrow |\text{wave}\rangle \end{cases}$$

$$p(\det, BS) = \sum_{\lambda} p(\det \mid BS, \lambda)\, p(BS \mid \lambda)\, p(\lambda)$$

Probability detector registers and BS is either open or closed

Probability detector registers, given state of beamsplitter and λ

Probability beamsplitter is open or closed, given λ

Probability photon is really a particle or really a wave

HV requires

$$p(\det \mid BS = \text{open}, \lambda = p) = \left(\frac{1}{2}, \frac{1}{2}\right)$$

$$p(\det \mid BS = \text{closed}, \lambda = w) = \left(\cos^2\frac{\varphi}{2}, \sin^2\frac{\varphi}{2}\right)$$

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No (good) HV Explanation

$$p(\det \mid BS = \text{open}, \lambda = p) = \left(\frac{1}{2}, \frac{1}{2}\right)$$

$$p(\det \mid BS = \text{closed}, \lambda = w) = \left(\cos^2\frac{\phi}{2}, \sin^2\frac{\phi}{2}\right)$$

$$\lambda = \begin{cases} p \Rightarrow |\text{particle}\rangle \\ w \Rightarrow |\text{wave}\rangle \end{cases}$$

The only way this works is if

$$p(BS \mid \lambda) = \delta_{\lambda,p}\,\delta_{\text{BS,open}} + \delta_{\lambda,w}\,\delta_{\text{BS,closed}}$$

- Hidden variable must be PERFECTLY correlated with the beamsplitter!
- Source randomly emits waves or particles with a probability distribution identical to the ancilla

R. Ionicioiu & D. Terno
Phys. Rev. Lett. 107, 230406 (2011)

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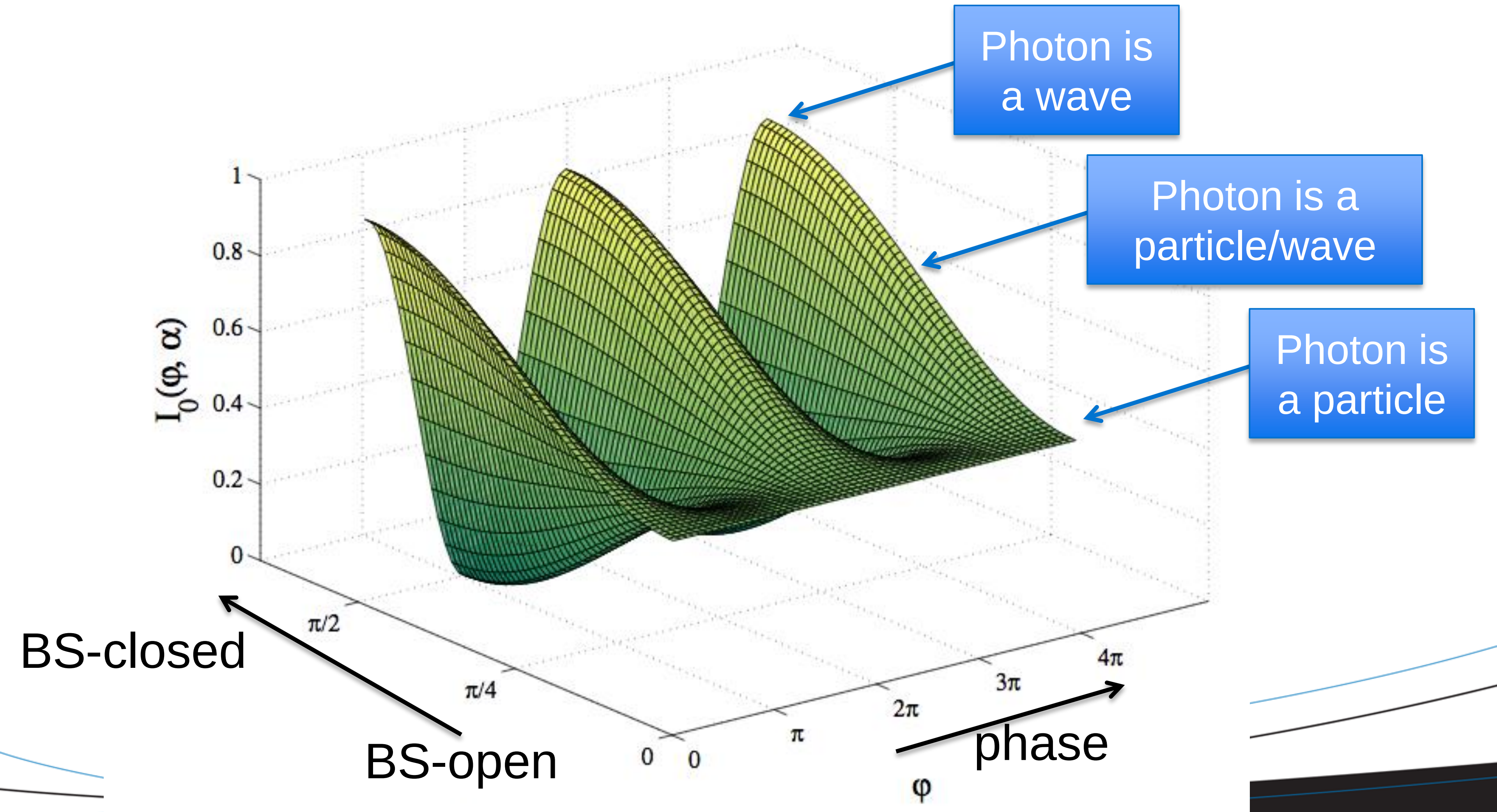
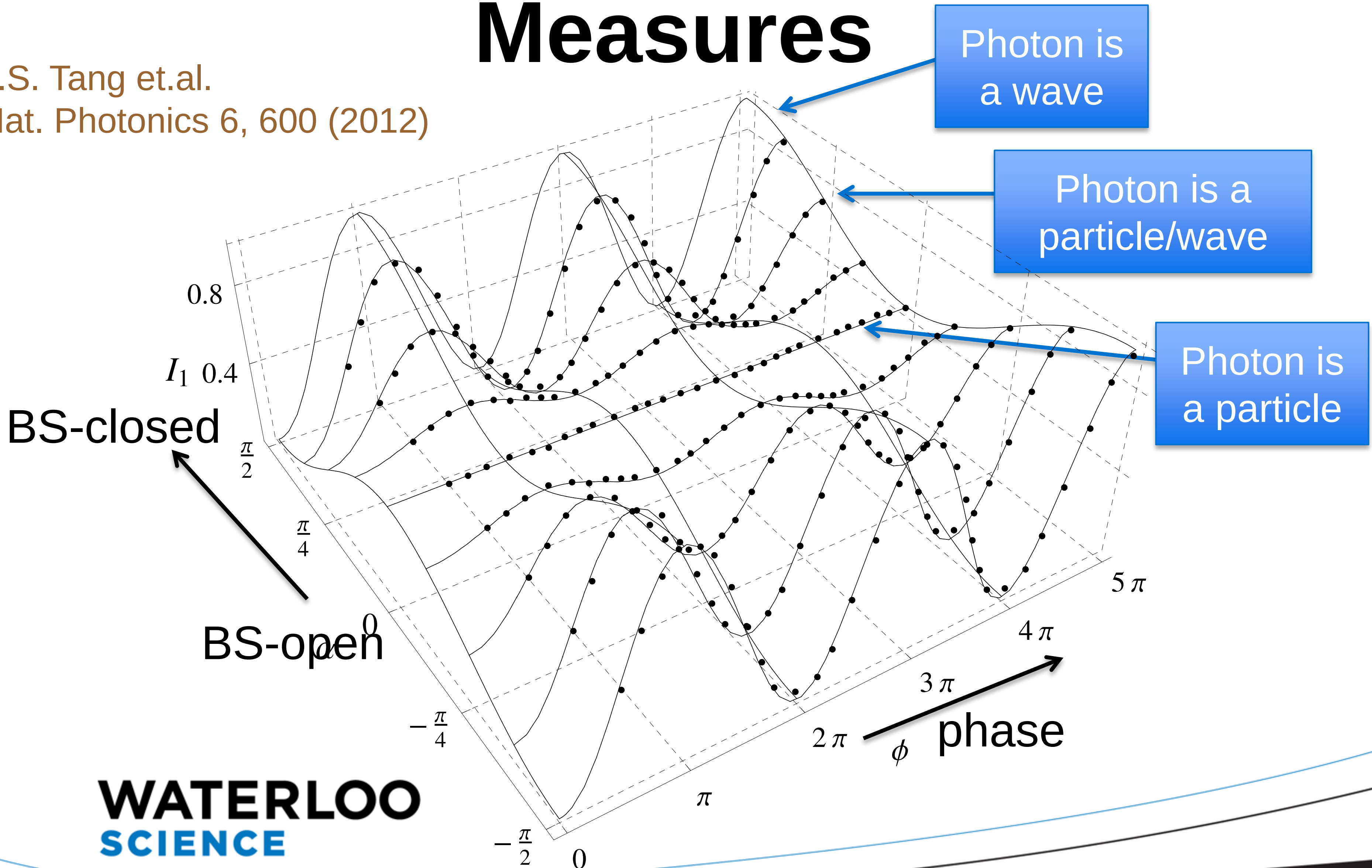
What the Quantum DC Expt Predicts



What the Quantum DC Expt Measures

J.S. Tang et.al.
Nat. Photonics 6, 600 (2012)



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(Un)Predictable (Un)Reality

Realism: Photons are either particles or waves
(hidden variables determine which is the case)

Determinism: The future can be predicted from the past
(hidden variables determine how detectors will click)

We show

Realism and Determinism are NOT compatible!

R. Ionicioiu, T. Jennewein, R.B. Mann & D. Terno
arXiv 1211.0979
L. Celeri, R. GomesR. Ionicioiu, T. Jennewein,
R.B. Mann & D. Terno Fnd Phys (in press)

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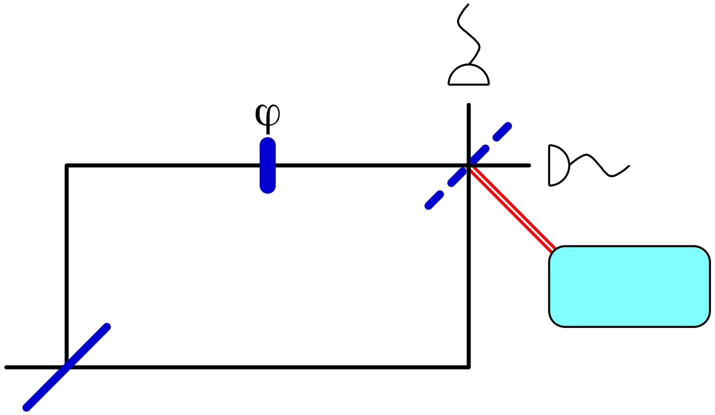
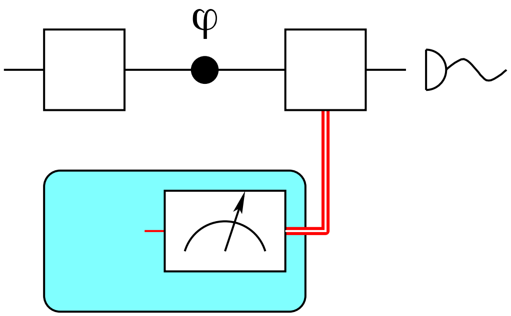
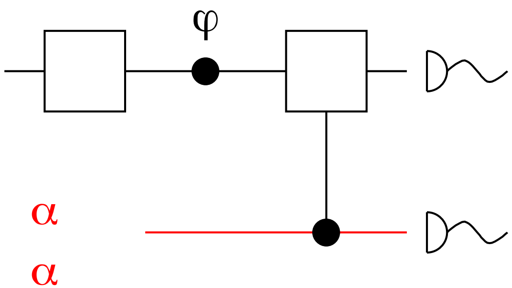
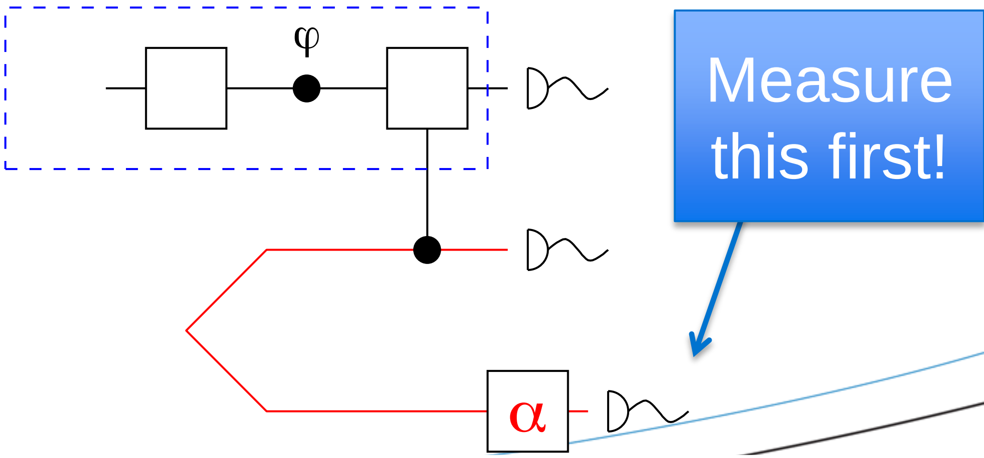
Realism vs. Determinism









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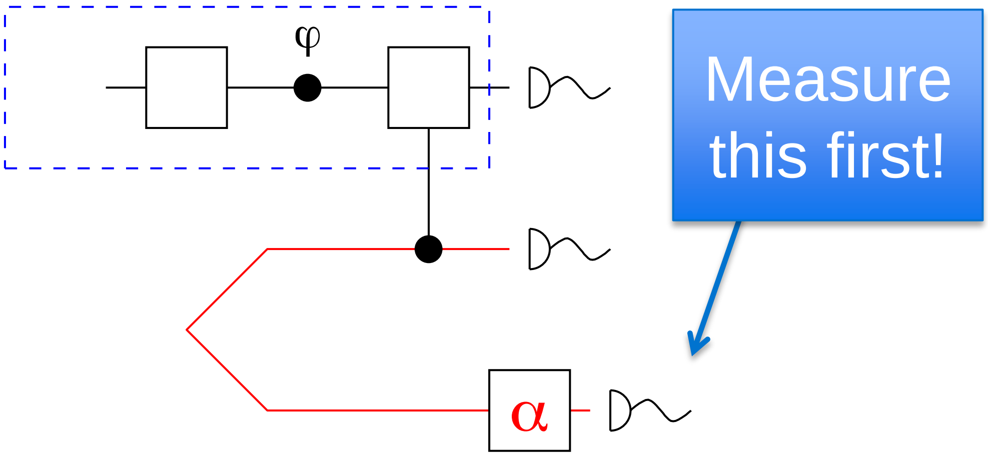
Ancilla “has no state” before interacting

EPR Control



Our result:
There are NO HV models that allow a deterministic AND real solution to the probability requirements

$$|f\rangle_{AB} = \frac{1}{\sqrt{2}}\left(|0\rangle_1^A |1\rangle_2^B + |1\rangle_1^A |0\rangle_2^B\right)$$

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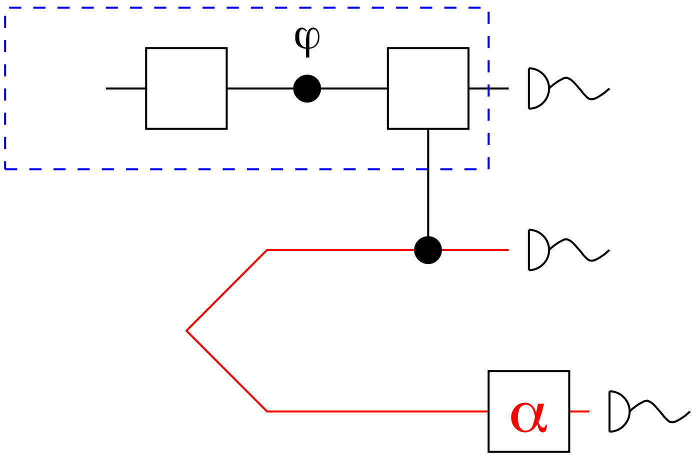
Squeezing out HV Theories?

- Objective: An HV Theory that is



  - Deterministic

    predicts outcomes of (D_a, D_b) based on HVs $\{/_A, /_B\}$

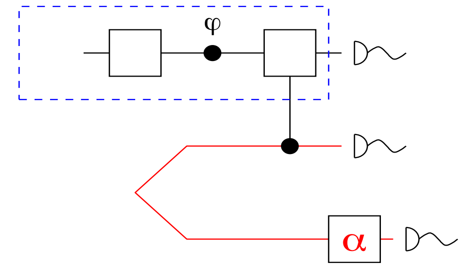
    (or a single underlying HV L)

  - WPR

    photons are either p or w: type determined by $/_A$ (or by L)

Deterministic WPR theory exists

1) Must reproduce QM predictions



$$q(a,b) = \left(\tfrac{1}{2}\cos^2\alpha,\ \sin^2\alpha\cos^2\tfrac{\varphi}{2},\ \tfrac{1}{2}\cos^2\alpha,\ \sin^2\alpha\sin^2\tfrac{\varphi}{2}\right)$$

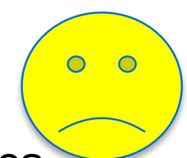
(0,0) (0,1) (1,0) (1,1)

2) Adequacy: $q(a,b) = P_{ab} = \sum_{\lambda = \mathrm{p,w}} P_{ab\lambda}$ $\quad P_{ab\lambda} = \int dL\, p(a,b,\lambda \mid L)\, p(L)$

3) WPR:

$p(\det \mid BS = \text{open}, \lambda = p) = \left(\tfrac{1}{2}, \tfrac{1}{2}\right)$ $\quad p(\det \mid BS = \text{closed}, \lambda = w) = \left(\cos^2\tfrac{\varphi}{2}, \sin^2\tfrac{\varphi}{2}\right)$

$\Rightarrow$ $P_{00\mathrm{p}} = P_{10\mathrm{p}},$ $\quad P_{01\mathrm{w}}\sin^2\tfrac{\varphi}{2} = P_{11\mathrm{w}}\cos^2\tfrac{\varphi}{2}$



4) WPR + Adequacy:

$\Rightarrow$ $p(a = 0 \mid b = 0, \lambda = \mathrm{w}) = \tfrac{1}{2},$ $\quad p(a = 0 \mid b = 1, \lambda = \mathrm{p}) = \cos^2\tfrac{\varphi}{2}$

Statistics determined by interferometer

5) Alternative? Conspiracy!

$$\Rightarrow\ p(b \mid \lambda) = \delta_{\lambda,p}\,\delta_{\mathrm{b},0} + \delta_{\lambda,w}\,\delta_{\mathrm{b},1} \equiv p(\lambda \mid b)$$

Conspiratorial Determinism → QM Statistics

$$p(b\,|\,\lambda) = \delta_{\lambda,p}\delta_{b,0} + \delta_{\lambda,w}\delta_{b,1} \equiv p(\lambda\,|\,b)$$

Suppose other statistics:

$$P_{00p} = P_{10p} = x$$

HV→ particle

$$P_{01w} = y\cos^2\tfrac{\varphi}{2} \quad P_{11w} = y\sin^2\tfrac{\varphi}{2}$$

HV → wave

Adequacy

$$x = \tfrac{1}{2}\cos^2\theta$$

$$y = \sin^2\theta$$

$$P_{ab\lambda} = q(a,b)\,p(\lambda\,|\,b)$$

Quantum Statistics are reproduced!

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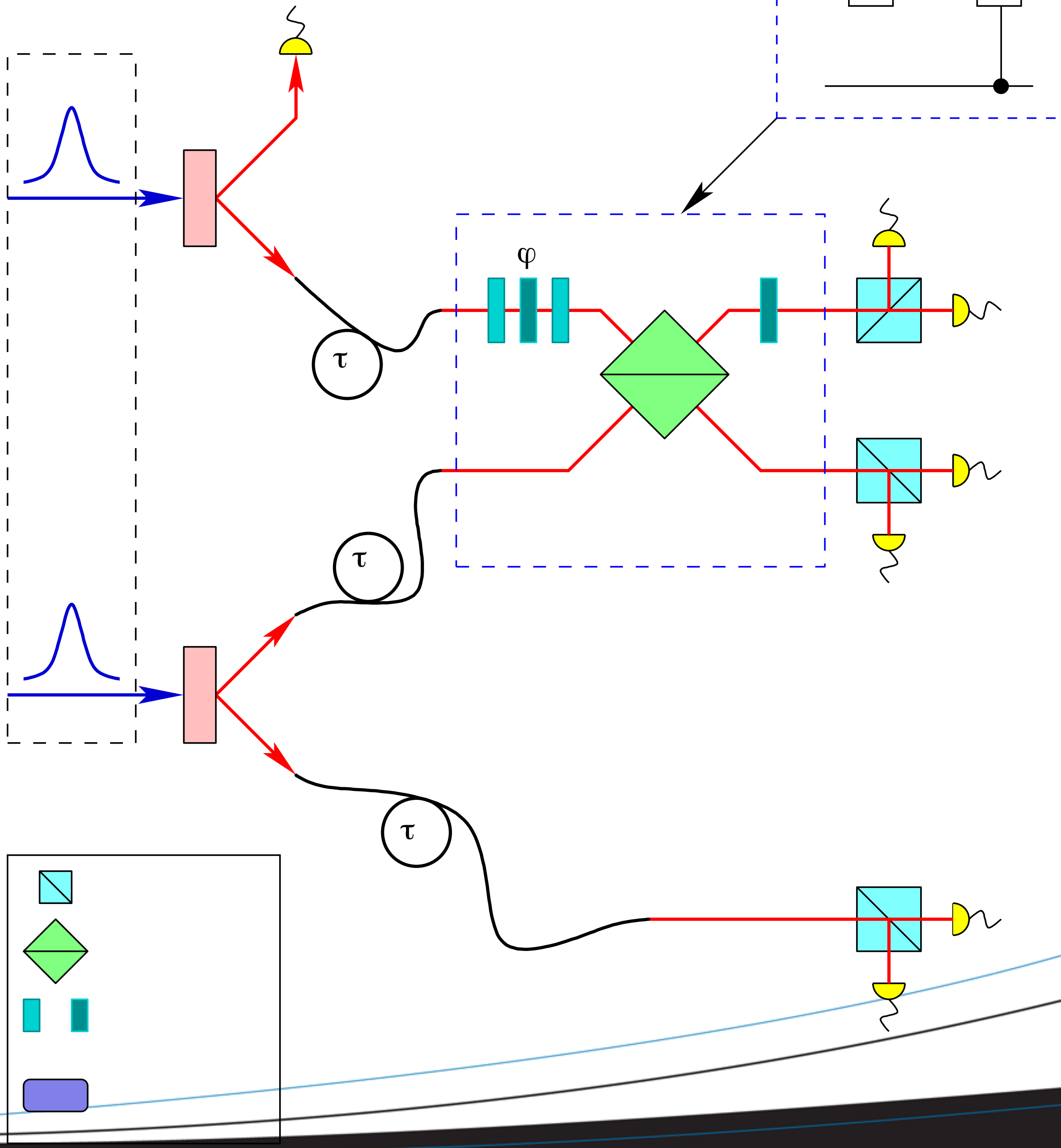
Testing Conspiratorial Determinism



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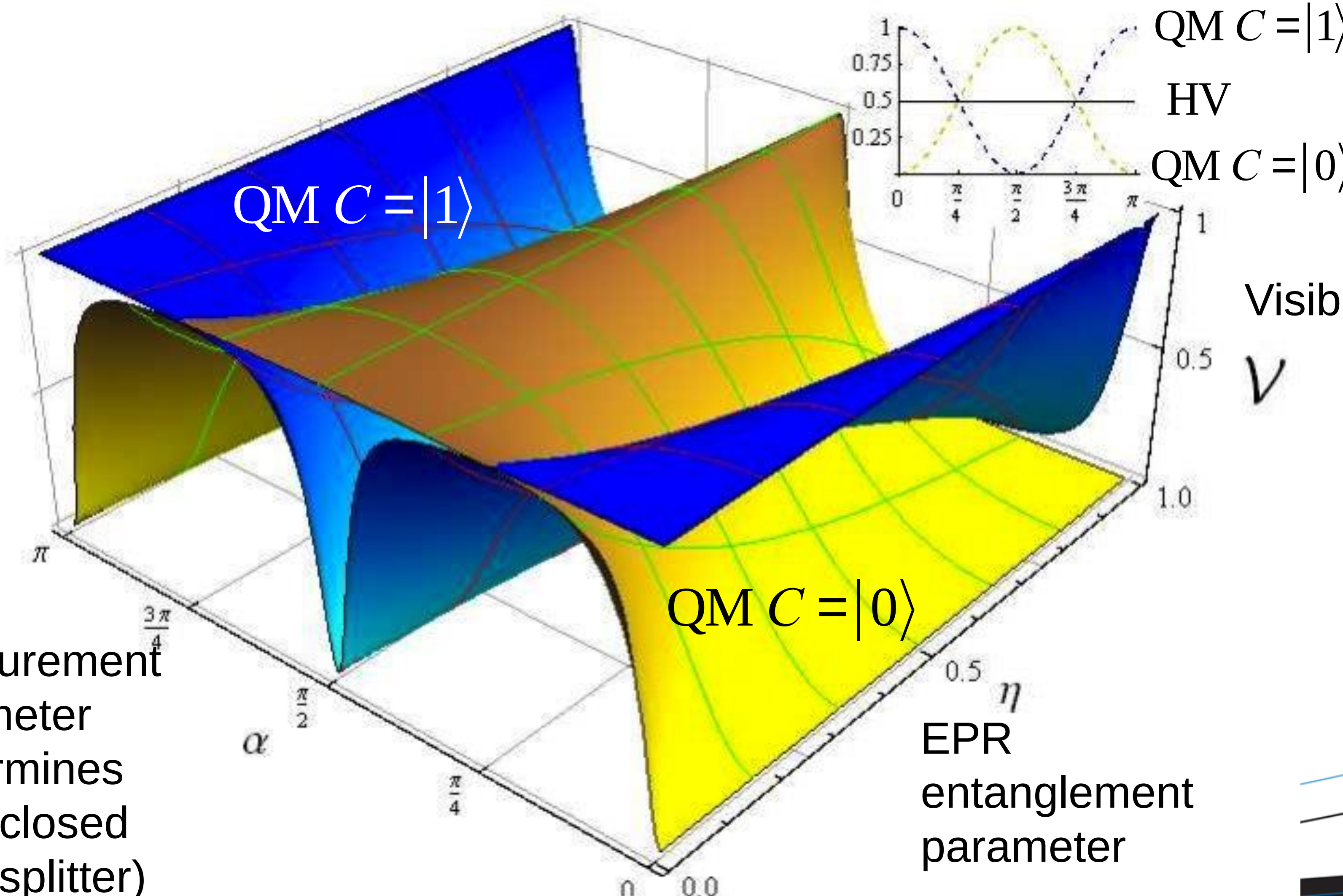
Possible Experimental Outcomes



Visibility

EPR measurement parameter (determines open/closed beamsplitter)

EPR entanglement parameter

Additional Applications

- CHSH Experiment
  - Measure the entangled Photons before the choice of direction is made
- Position/Momentum Complementarity
  - Fourier transform a continuous-variable state contingent on measurement of entangled ancillae
- Gravitational Quantum Control
  - Quantum-controlled COW expt?

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Summary

- Quantum Physics forces a choice between
  - Realism (objects are definitely waves or particles at any given time)
  - Predictability (given initial conditions unambiguously determine how detectors will register
- Is there a way out?
  - Superluminal communication (signals go faster than light)
  - Infinite regression (hidden variables for the hidden variables for the hidden variables ...)

My Research Group + Friends

- Aida Ahmadzadegan
- Wilson Brenna
- Eric Brown
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- Keith Ng
- Marvellous Onuma-Kalu
- Alexander Smith

- Aharon Brodutch
- Eduardo Martin-Martinez
- Marco Piani

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IQC Institute for Quantum Computing