Title: Action Duality: A Constructive Principle for Quantum Foundations

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Abstract: Ken Wharton
An analysis of the path-integral approach to quantum theory motivates the hypothesis that two experiments with the same classical action should have dual ontological descriptions. If correct, this hypothesis would not only constrain realistic interpretations of quantum theory, but would also act as a constructive principle, allowing any realistic model of one experiment to generate a corresponding model for its action-dual. Two pairs of action-dual experiments will be presented, including one experiment that violates the Bell inequality and yet is action-dual to a single particle. Demanding a consistent, realistic ontology leads to a highly restricted parameter space of possible interpretations.

Action Duality: A Constructive Principle for Quantum Foundations

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What does the Feynman Path Integral tell us about nature?

$$P\left[\psi_i(x,t_i),\psi_f(x,t_f)\right] \propto \left| \iint \left(\sum_{z,t_i \to y,t_f} e^{iS/\hbar} \right) \psi_f^*(y,t_f)\psi_i(z,t_i)dy\,dz \right|^2$$

where S is the **classical** action! $S = \int L\,dt$

Still need discrete outcomes $\psi_{n,\ f \in n}$ $P(\psi_f \mid \psi_i) = \dfrac{P(\psi_i,\psi_f)}{\sum_n P(\psi_i,\psi_n)}$

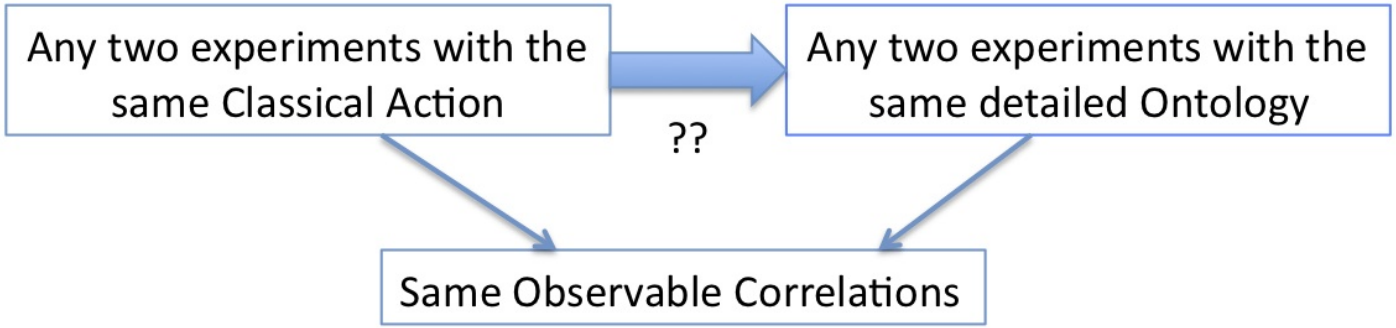
Naturally generalizes to relativistic treatments; i.e. quantum field theory (QFT)

$$P\left(\phi_i,\phi_f\right) = \left| \int D\phi\, e^{iS/\hbar} \right|^2 \qquad S=\int \mathcal{L}(\phi,\partial_\mu\phi)\, \mathrm{d}^4\mathrm{x}$$

Despite its importance, no obvious interpretation.

An indirect approach: consider symmetries of the Path Integral

Assume: "Realistic" ontology, QFT probabilities are correct.



Feynman Integral Symmetry Hypothesis (FISH):
For any two experiments with an action duality (a well-defined spacetime transformation that maps the classical Lagrangian density of one experiment onto the classical Lagrangian density of the other), any realistic ontology must also map between the two experiments under the same spacetime transformation.

Almost like a "diffeomorphism invariance" for quantum ontologies.

FISH is not trivially dismissible

- **Variants of FISH are already in widespread use.**

  - Einstein's Hole Argument; Widely accepted that ontology maps to classical Lagrangian in general relativity.

  - Crossing Symmetry in QFT (Calculation tool, without interpretation)

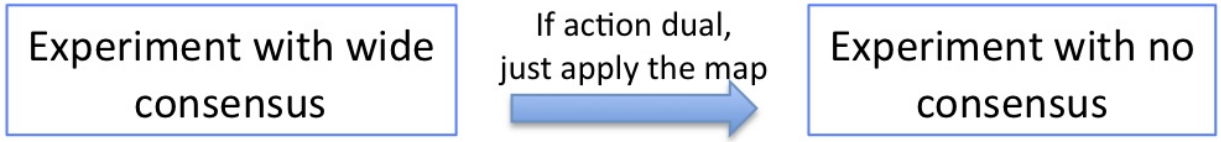
- **What if FISH were false?**

  - Action-dual experiments would still have identical probabilities, via exactly the same mathematics, but for different ontological reasons.

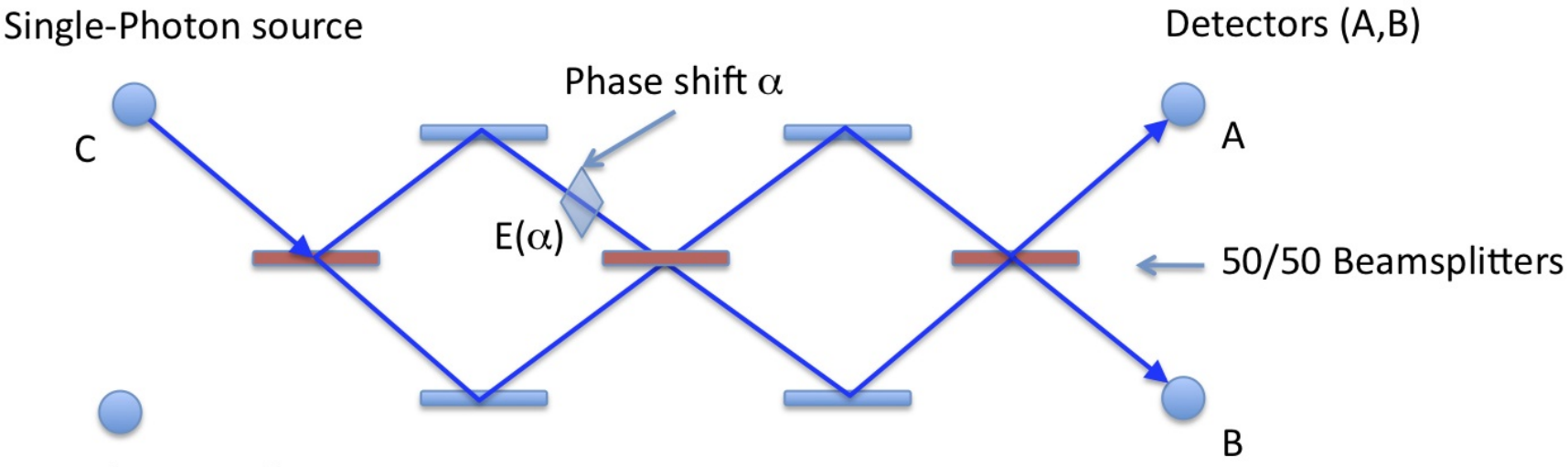
  - This would imply "asymmetries [in the ontology] which do not appear to be inherent in the phenomena." (Einstein, 1905)

FISH has many promising features

- **A constraining principle**
  - Can be used to "test" any realistic interpretation. (Examples forthcoming)
  - Naturally restricts ontology to spacetime (same as action integral)
  - Based on classical fields/particles (constrains addition of new elements)
- **A constructive principle**
  - Easy path to local and/or generally covariant ontologies (via Lagrangian)
  - Can build new ontologies (given an action-dual ontology)



Experiment A1: Double Interferometer



$$|C\rangle = \frac{1}{\sqrt{2}}\left(i|A\rangle - e^{i\alpha}|B\rangle\right)$$

A,B have 50% outcome chance, regardless of setting at E(α).

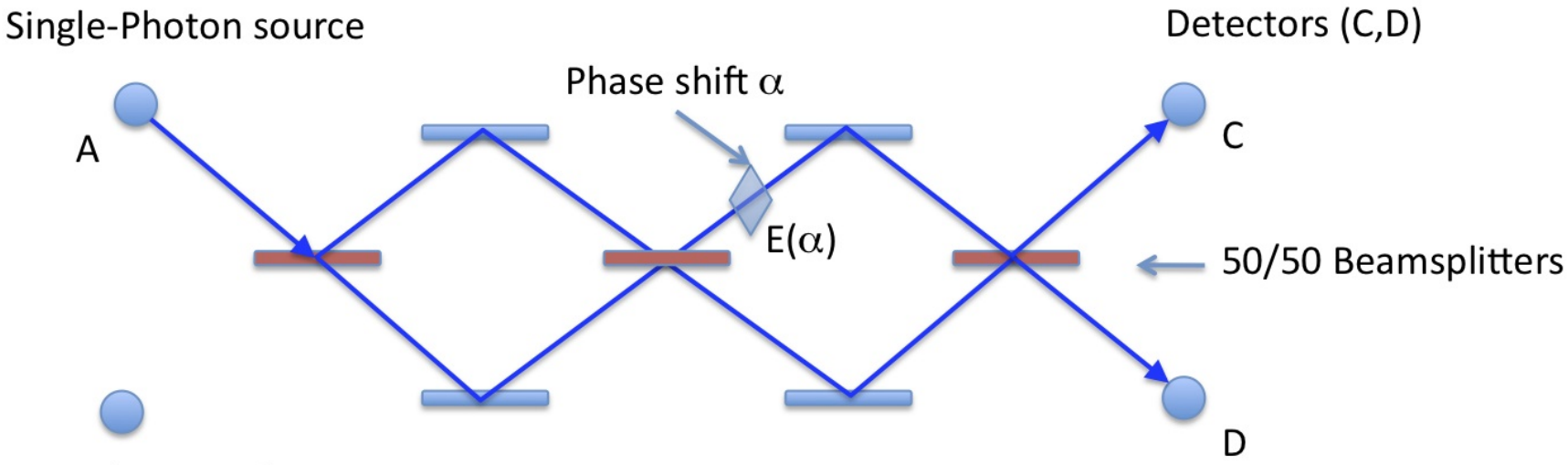
$$\sum_{C->A} e^{iS} = e^{i\left(\frac{3\pi}{2}+\alpha\right)} + e^{i\left(\frac{\pi}{2}+\alpha\right)} + e^{i\frac{\pi}{2}} + e^{i\frac{\pi}{2}} = 2i$$

$$\sum_{C->B} e^{iS} = e^{i(\pi+\alpha)} + e^{i(\pi+\alpha)} + e^{0} + e^{i\pi} = -2e^{i\alpha}$$

$$P(A,C) \propto |2i|^2$$

$$P(A\,|\,C) = \frac{|2i|^2}{|2i|^2 + \left|-2e^{i\alpha}\right|^2} = \frac{1}{2}$$

Experiment A2: Time-Reverse of A1 (trivial action duality)



$$|A\rangle = \frac{1}{\sqrt{2}}\left(i|C\rangle - |D\rangle\right)$$

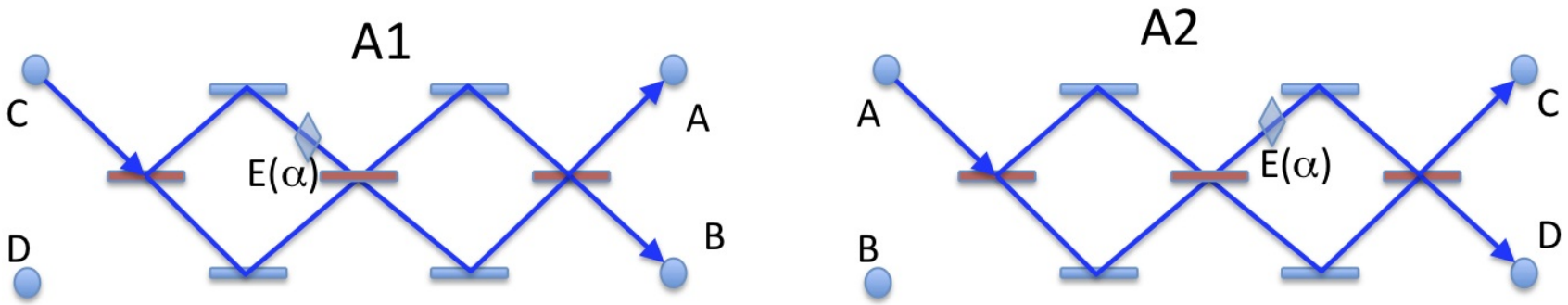
C,D have 50% outcome chance, regardless of setting at E(α).

$$\sum_{A->C} e^{iS} = e^{i\left(\frac{3\pi}{2}+\alpha\right)} + e^{i\left(\frac{\pi}{2}+\alpha\right)} + e^{i\frac{\pi}{2}} + e^{i\frac{\pi}{2}} = 2i$$

$$P(A,C) \propto |2i|^2$$

C->A path integral in "A1" explicitly identical to A->C path integral in "A2".

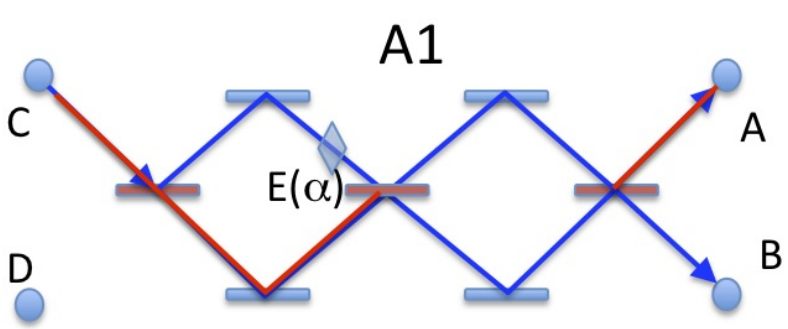
Path integral-inspired ontologies will not be ψ-ontic

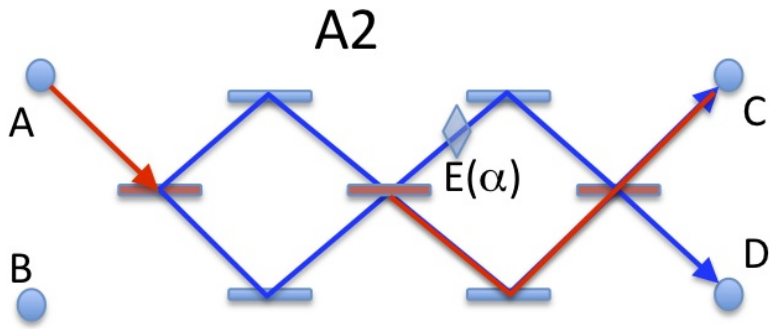


"Given C->A or A->C, does anything pass through E or not?"	A1	A2
ψ-ontic interpretation of QM: Does |ψ> =0 at E?	No	Yes
Path Integral calculation of P(A,C): Does the partial amplitude of paths through E sum to zero?	Yes	Yes

Contradicts FISH

FISH seems to require retrodiction





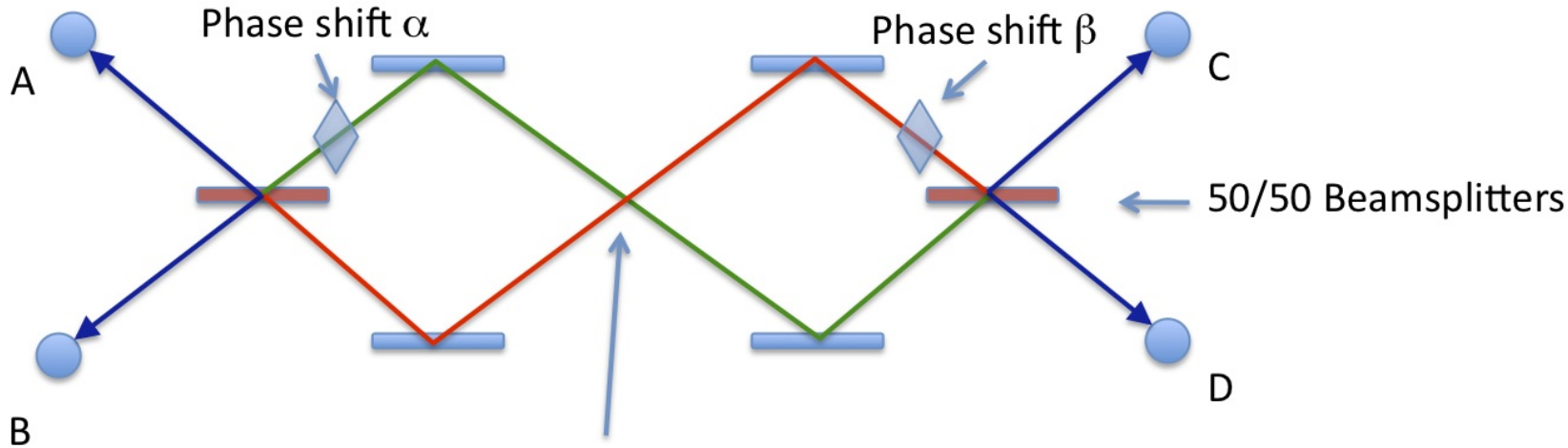
Retrodiction can give the same (action-dual) picture in Experiment A1.
(See Blasi and Hardy, Phys Lett A, 1995.)

If a given ontology says that nothing passes through E for Experiment A2...

FISH tells us the same must be true in A1

But standard QM has no "inaccessible" parameters left to retrodict; therefore FISH is pointing toward the construction of a hidden variable model.

Bell-Inequality-Violation: Experiment B1



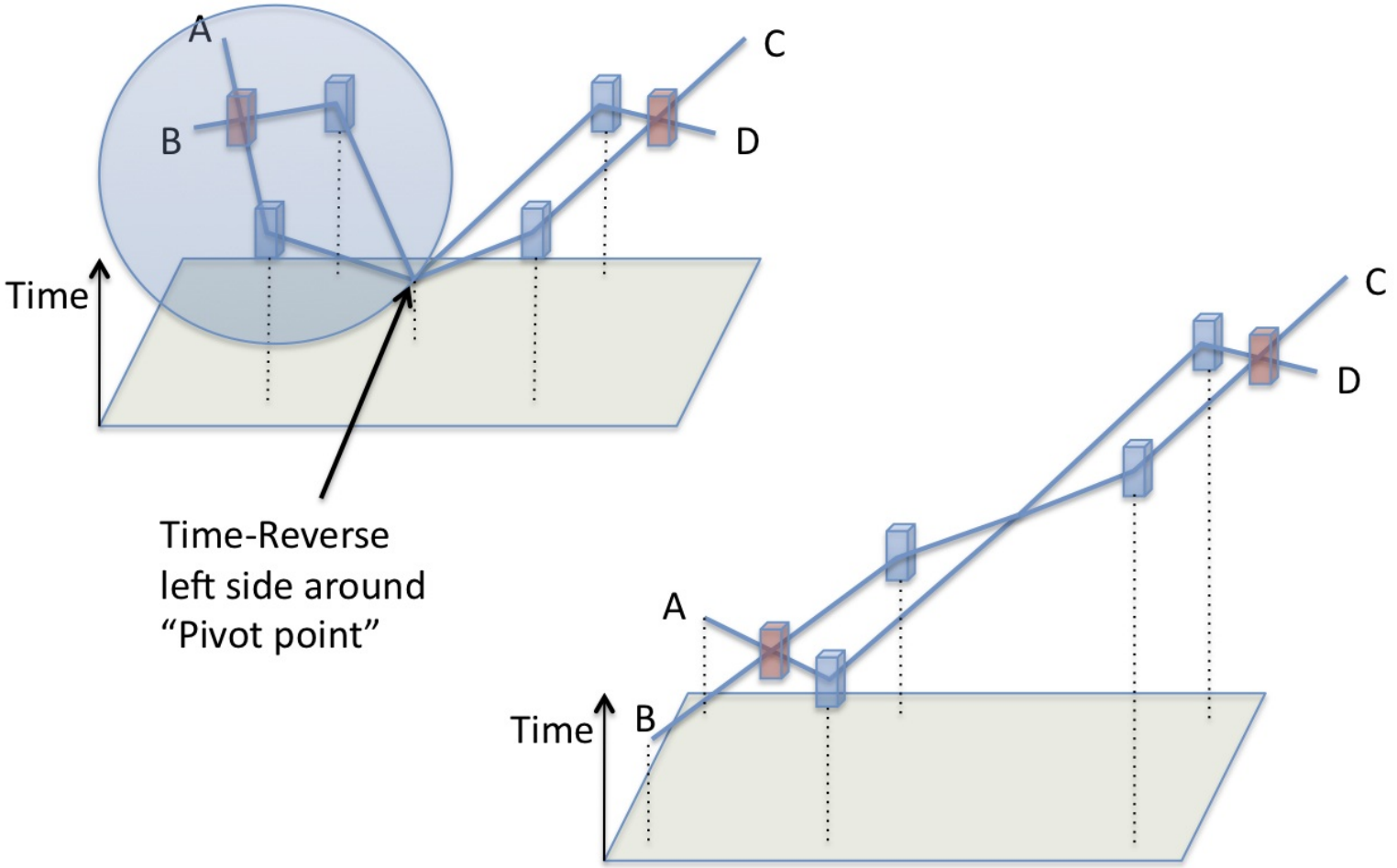
Two photon source (opposite directions)
-- No further entanglement required!

(Simplified variant of geometry from Sinha and Sorkin, Found. Phys. Lett. 1991.)

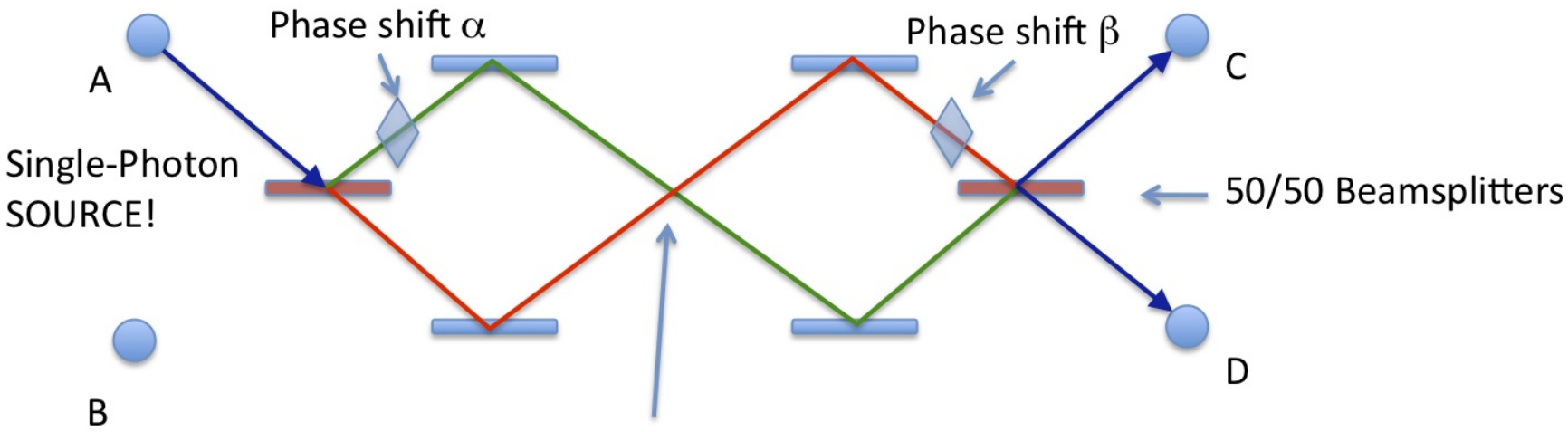
$$\sum_{toA,C} e^{iS} = e^{i\left(\frac{\pi}{2}+\alpha\right)} + e^{i\left(\frac{\pi}{2}+\beta\right)} = i\left(e^{i\alpha} + e^{i\beta}\right) \qquad P(A,C) \propto \left|e^{i\alpha} + e^{i\beta}\right|^2 \propto \cos^2\left(\frac{\alpha-\beta}{2}\right)$$

Violates Bell Inequality via local path calculations?

Spacetime transformation from 2-photon to 1-photon geometry



Single-photon action dual: Experiment B2



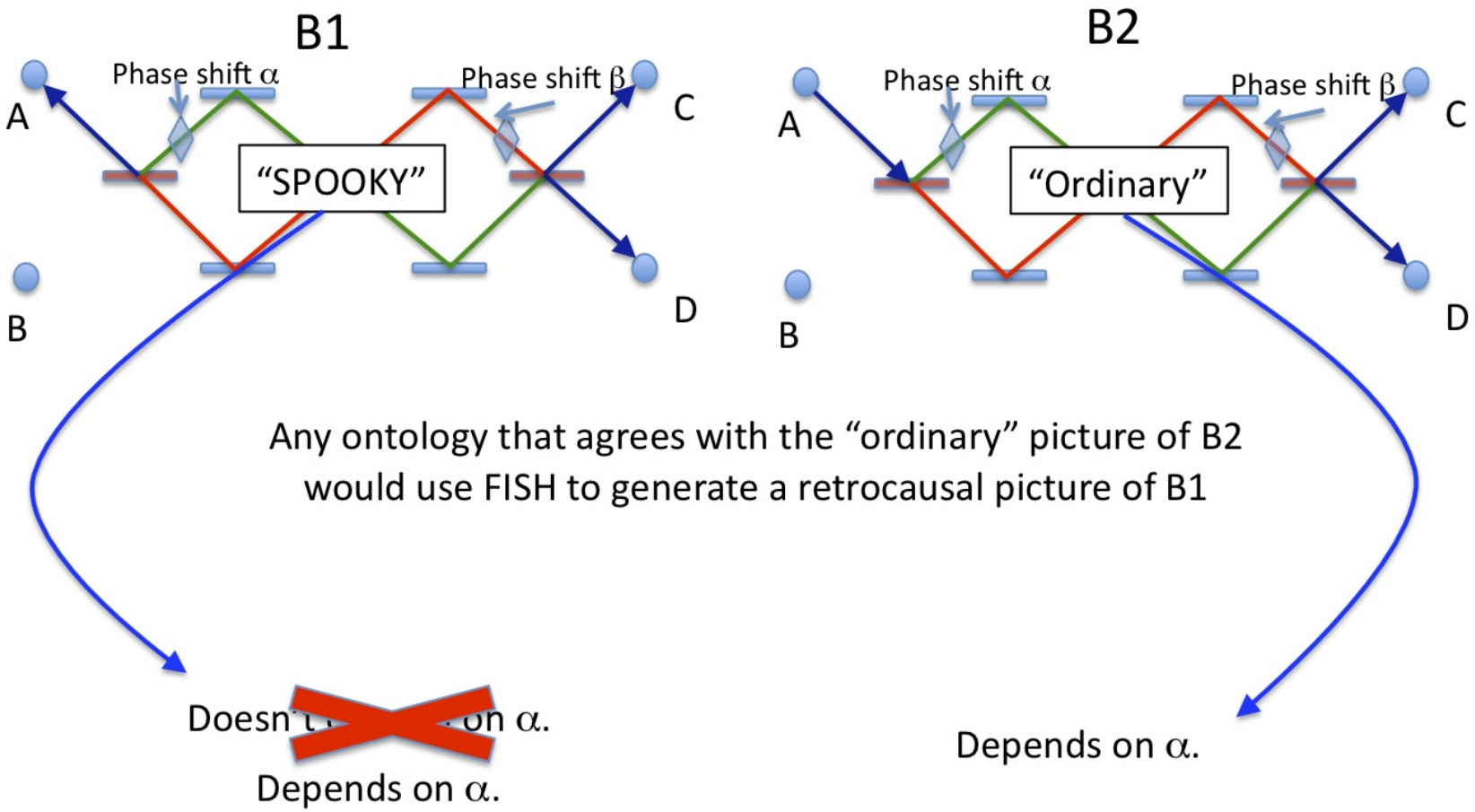
$$\sum_{A->C} e^{iS} = e^{i\left(\frac{\pi}{2}+\alpha\right)} + e^{i\left(\frac{\pi}{2}+\beta\right)} = i\left(e^{i\alpha} + e^{i\beta}\right)$$

$$P(A,C) \propto \left|e^{i\alpha} + e^{i\beta}\right|^2 \propto \cos^2\left(\frac{\alpha-\beta}{2}\right)$$

Same answer, same reason:
exactly the same mathematics!

Violation of Bell-Inequality is *expected*
if intermediate states depends on α.

FISH implies a retrocausal ontology



Seems to bolster retrocausal interpretations of Bell Inequality violations; see arXiv:1001.5057

The FISH Challenge

- **A challenge for "anti-realists":**

  - FISH provides technique to construct general realistic models, weakening impact of no-go theorems.

  - New challenge: Present an argument against FISH.

- **A challenge for "realists":**

  - The implications of FISH conflict with our intuitive causal picture.

  - Quantum Foundations needs some principle to tell us which of our intuitions may be flawed. Might FISH be that principle?