Title: Introduction to Quantum Foundations

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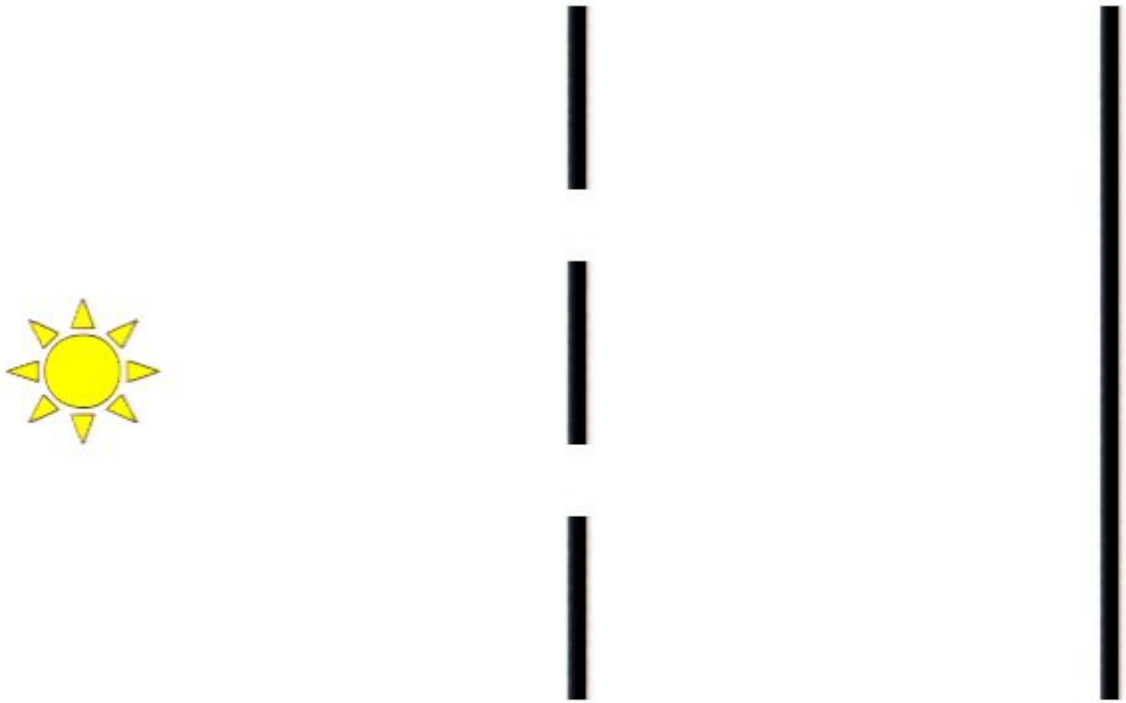
Abstract:

Introduction to the Foundations of Quantum Theory

- *Why* the quanta? How do we make sense of the occurrence of quantum phenomena.
  - What are the properties of a phenomena that makes it quantum?
  - What kind of physical process can possibly account for such properties?
  - How does the everyday classical world co-exist with quantum phenomena?
  - ...and could it be different?
- With conceptual *clarity* and *precision*!

Quantum phenomena : interferometry



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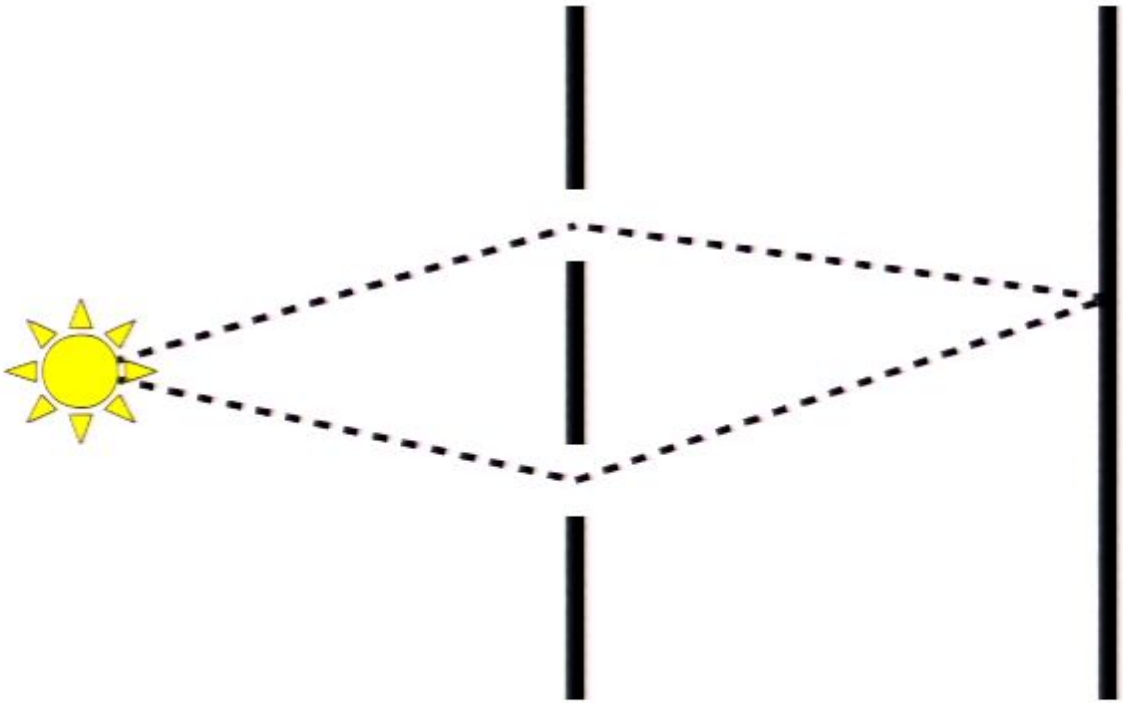

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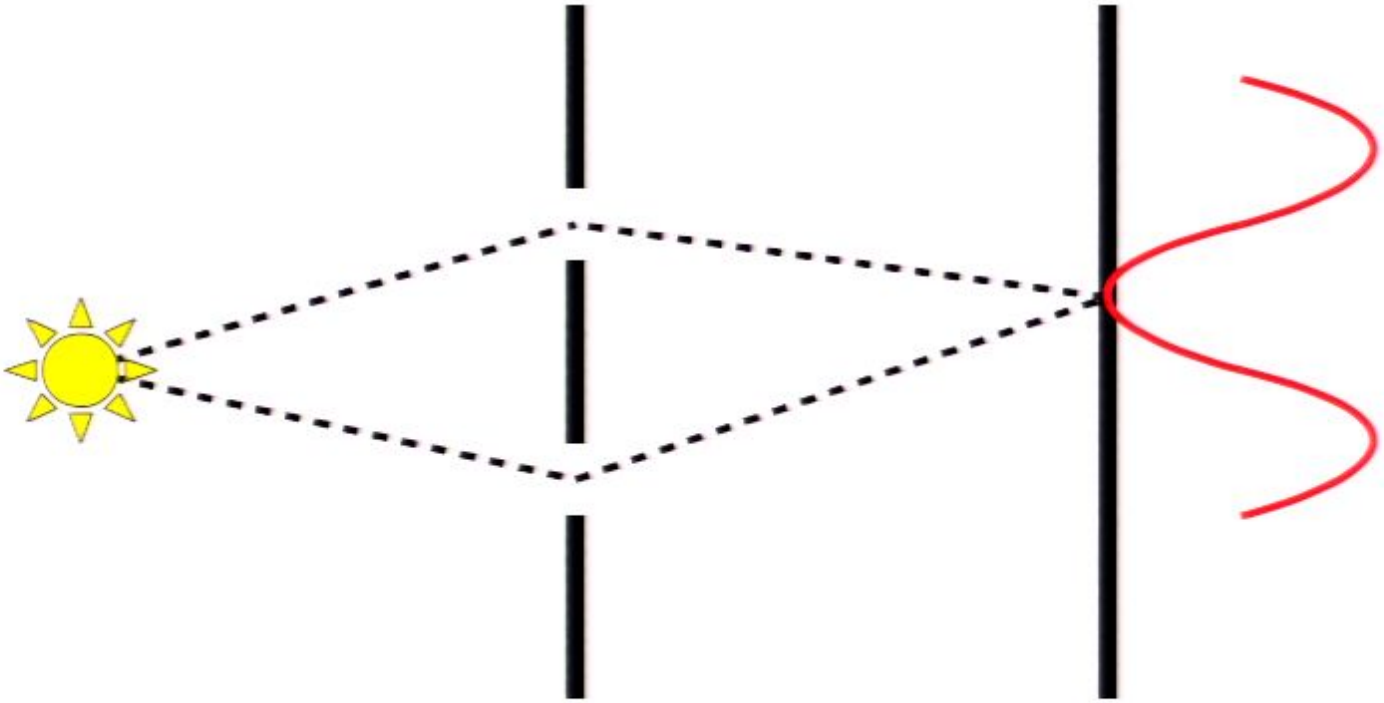

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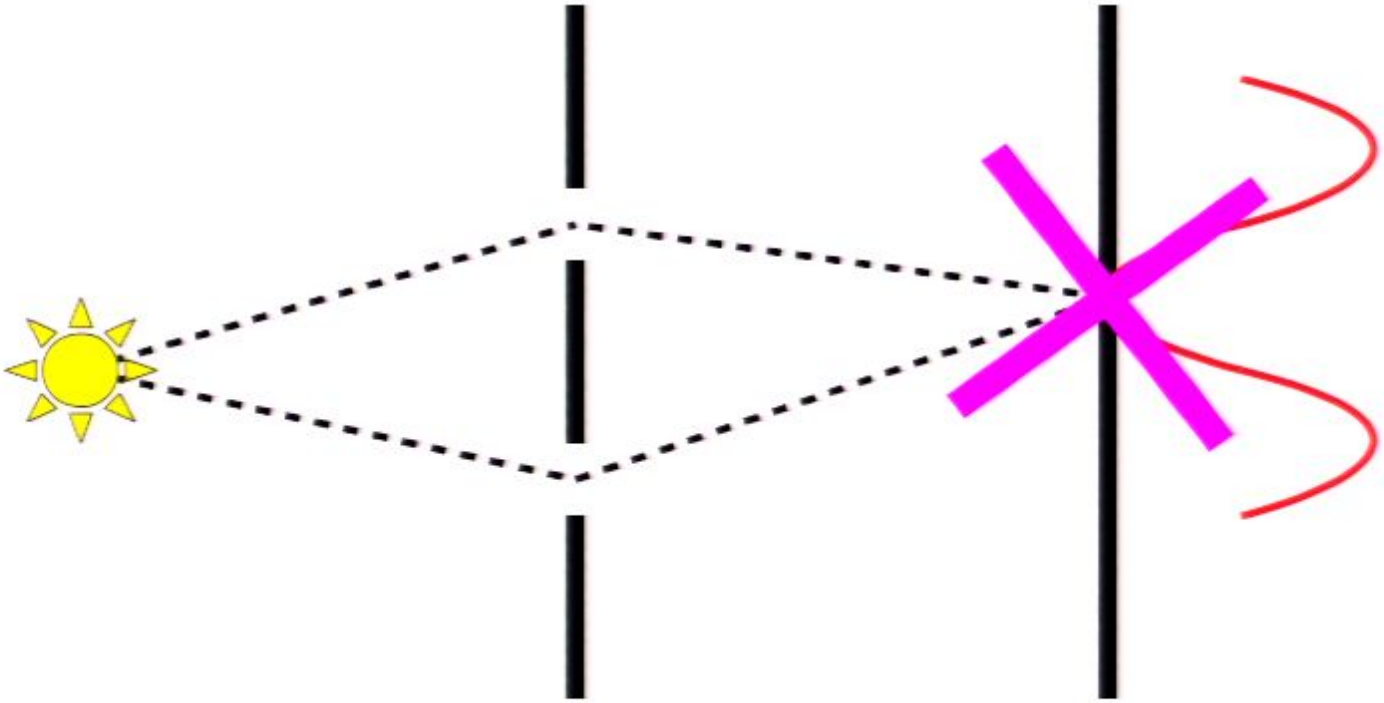

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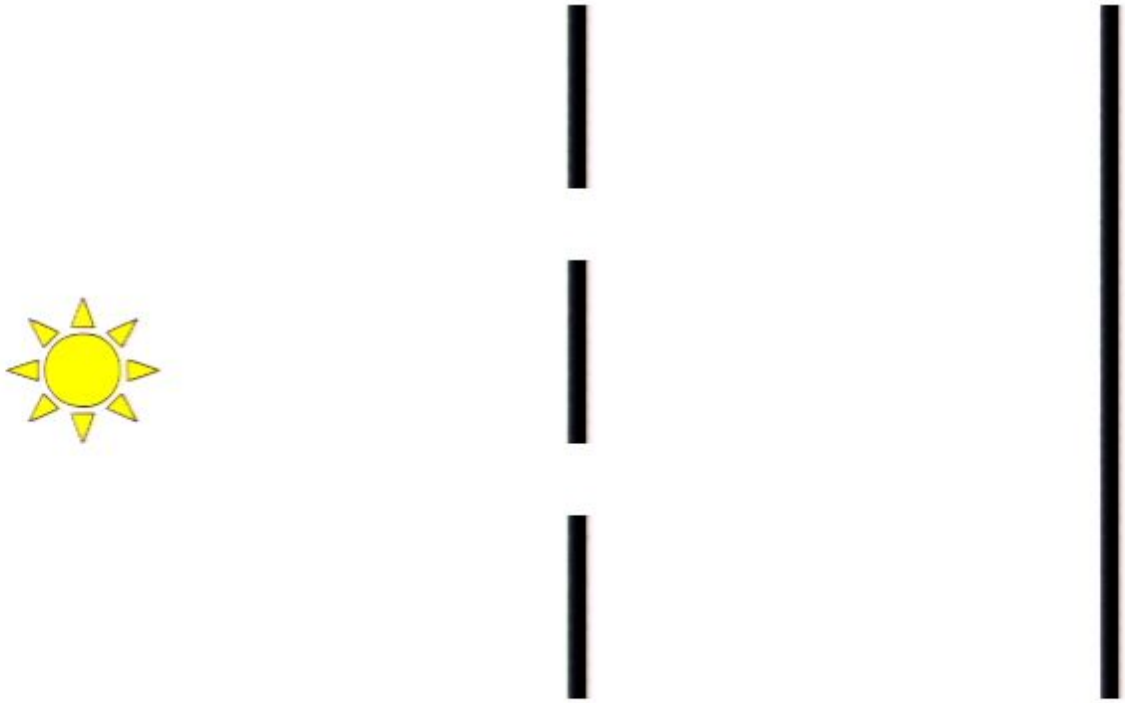

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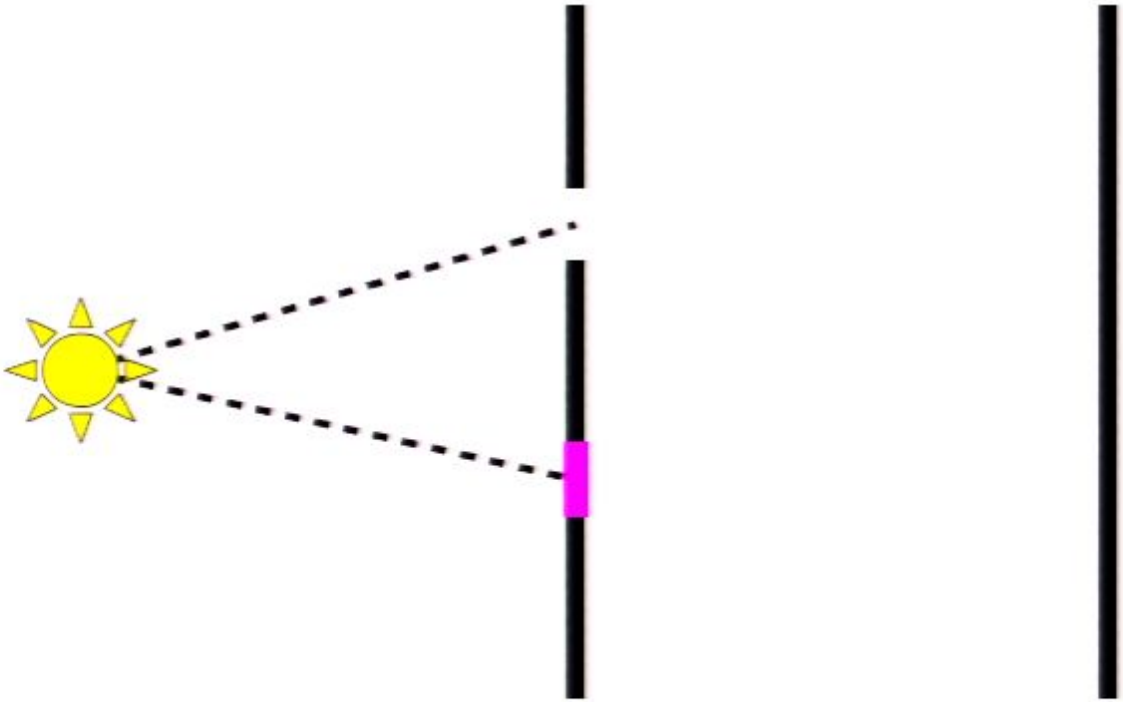

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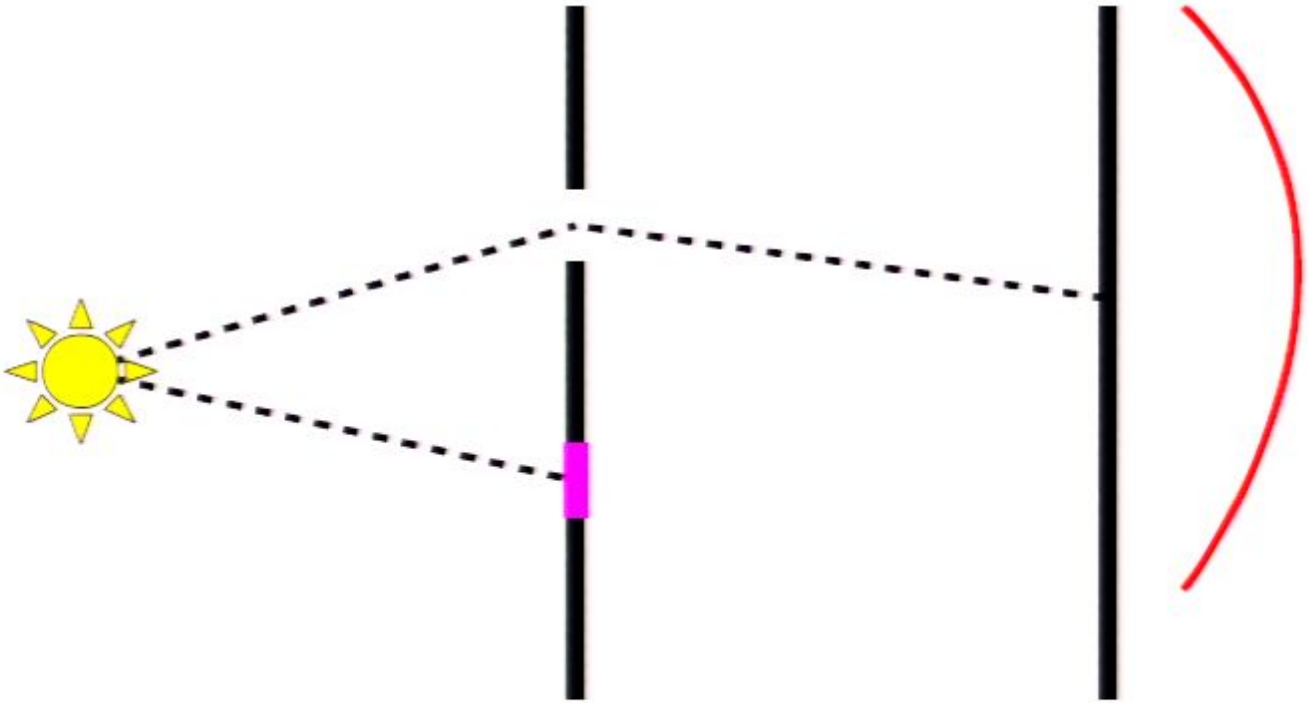

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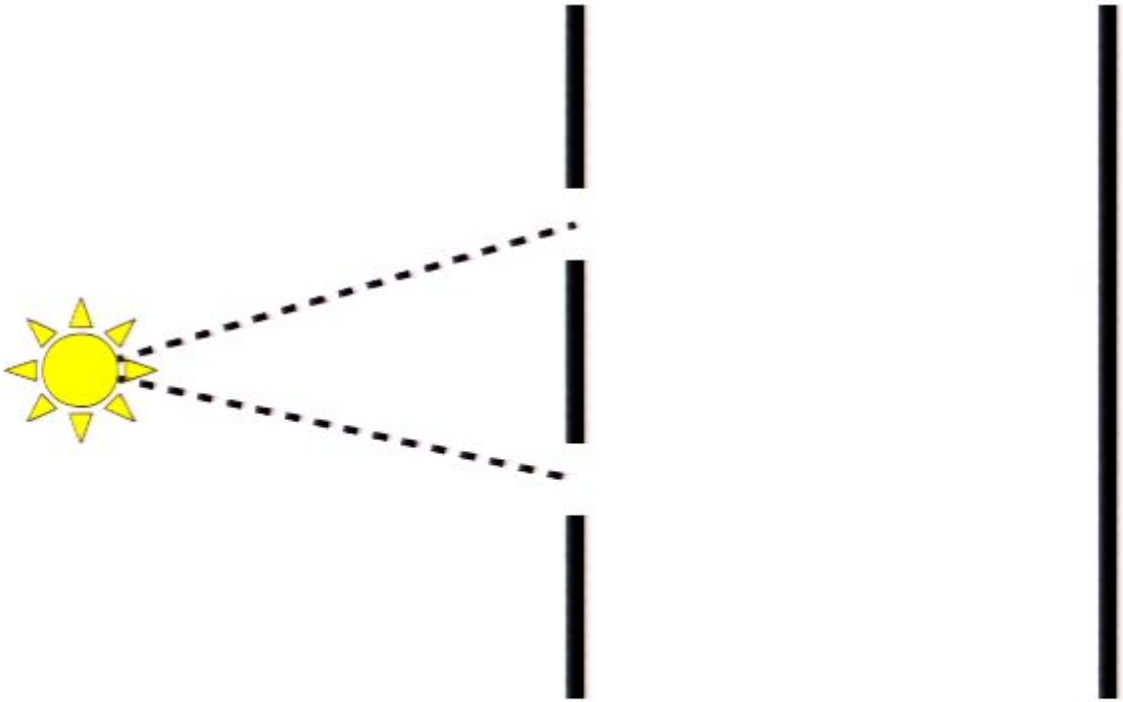

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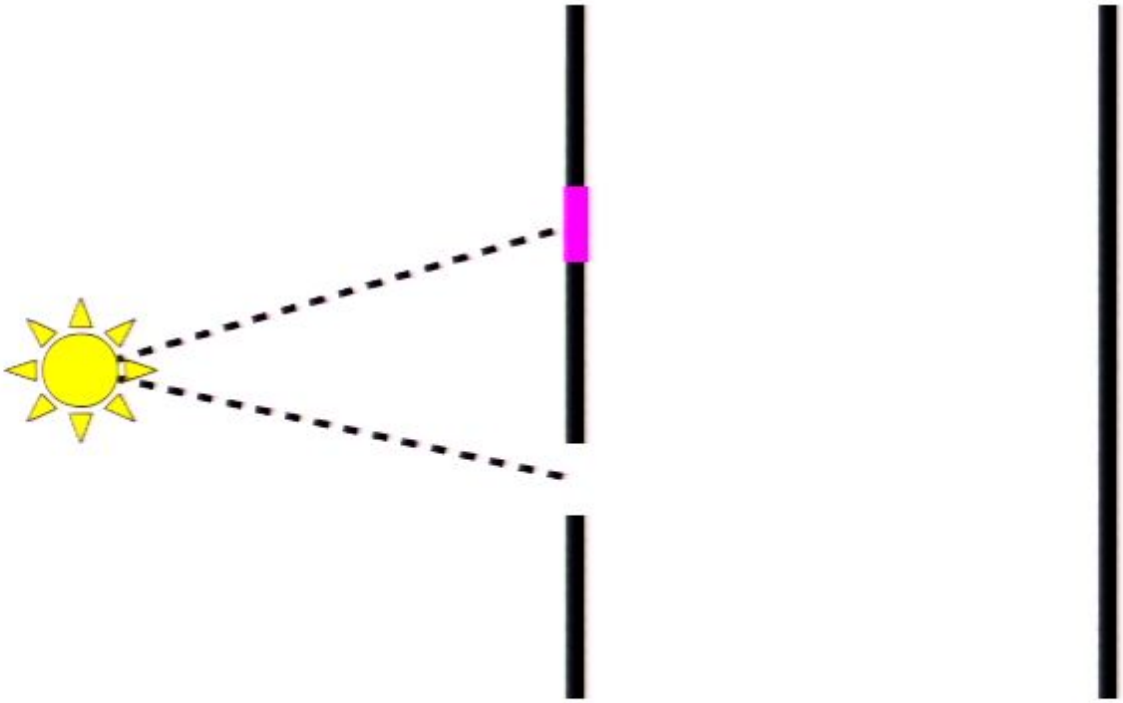

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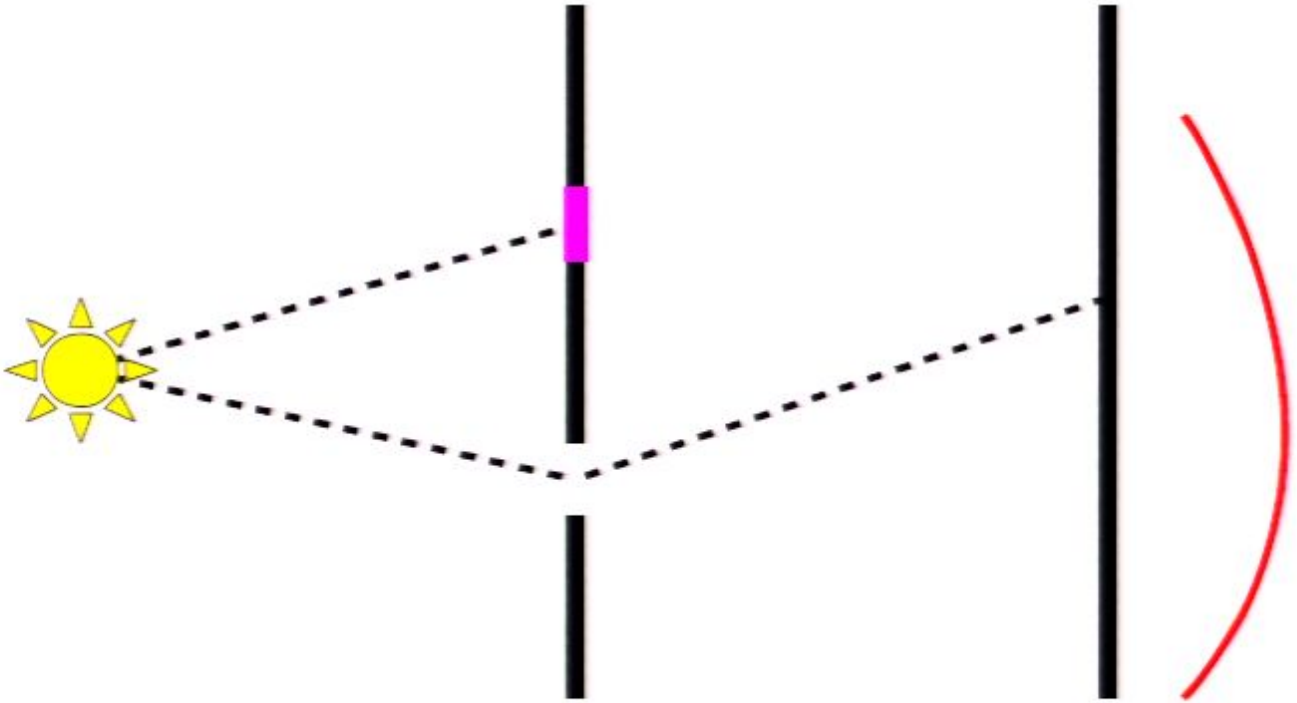

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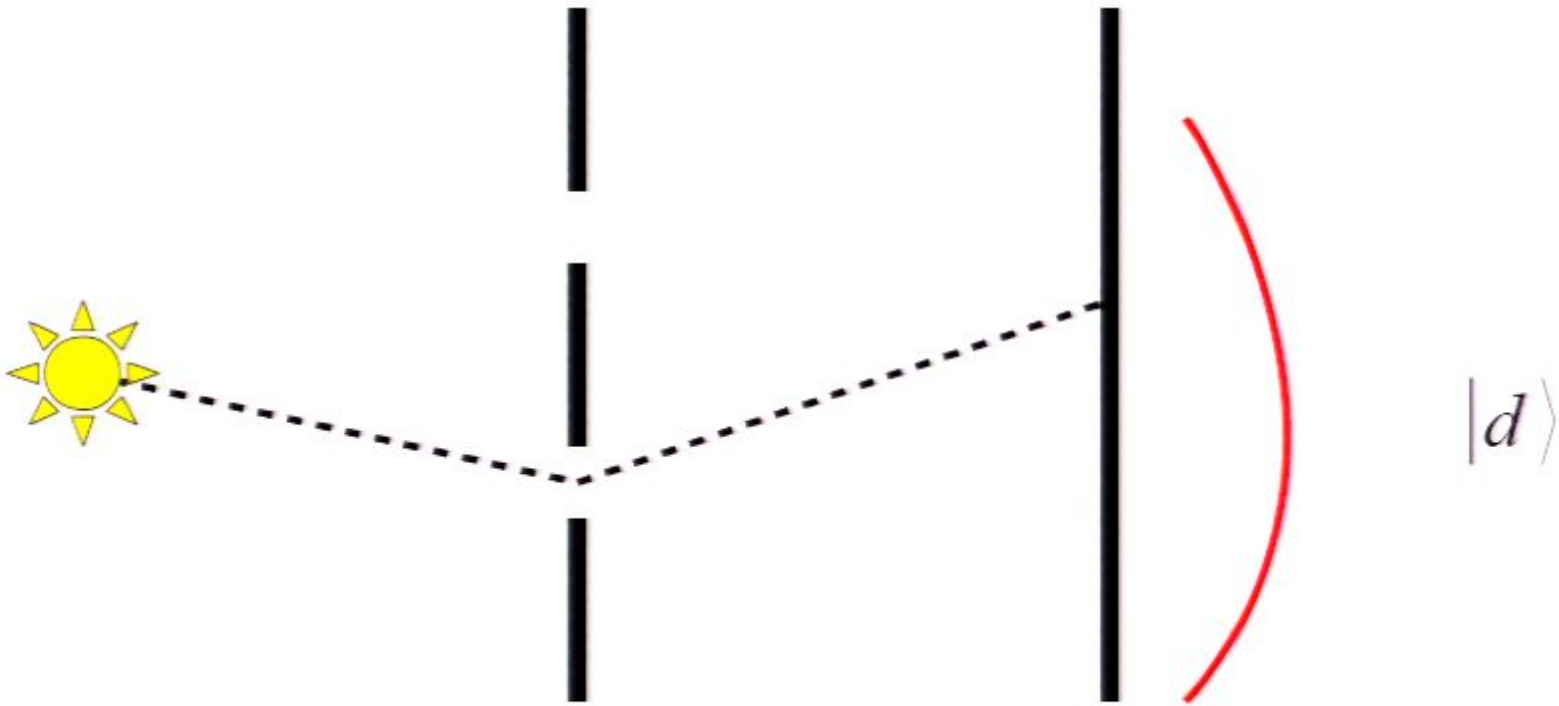

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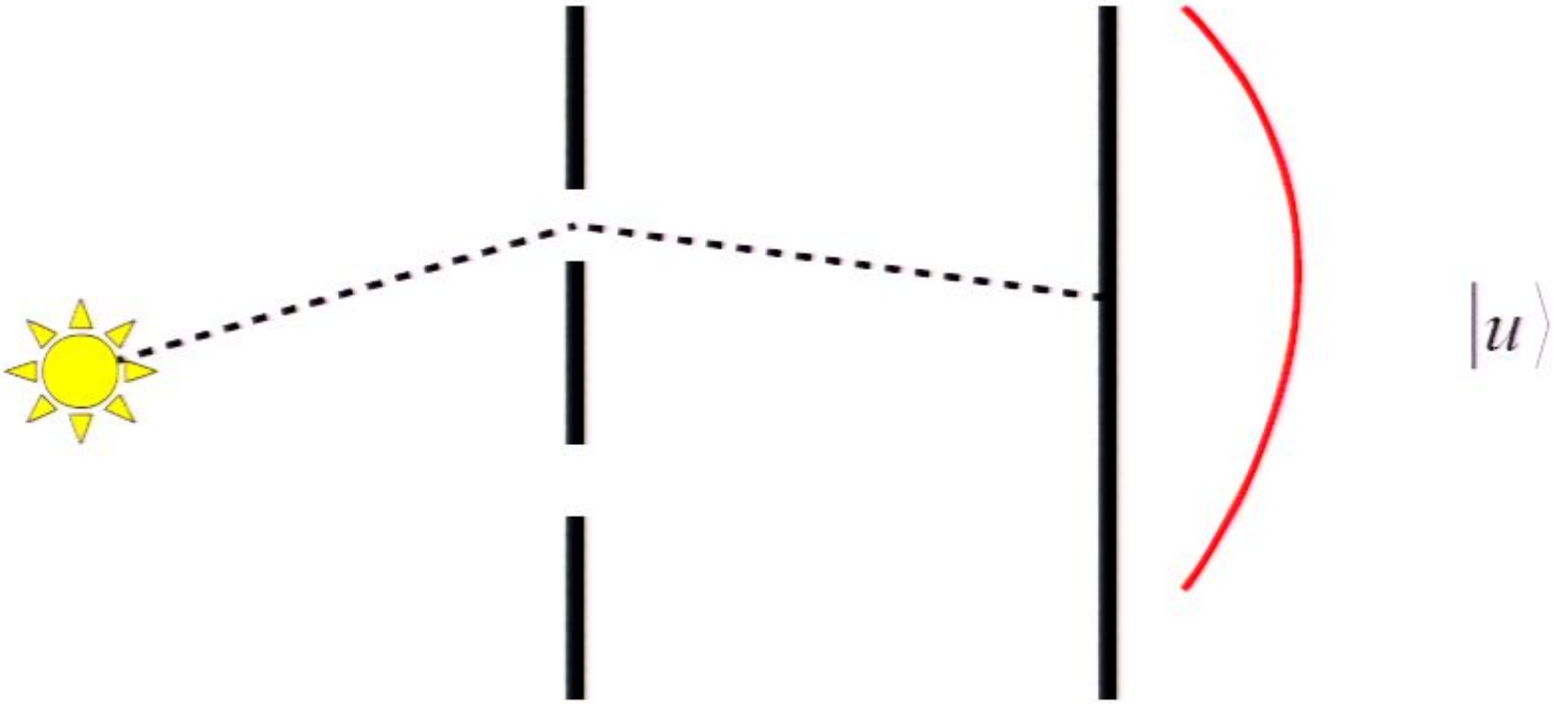

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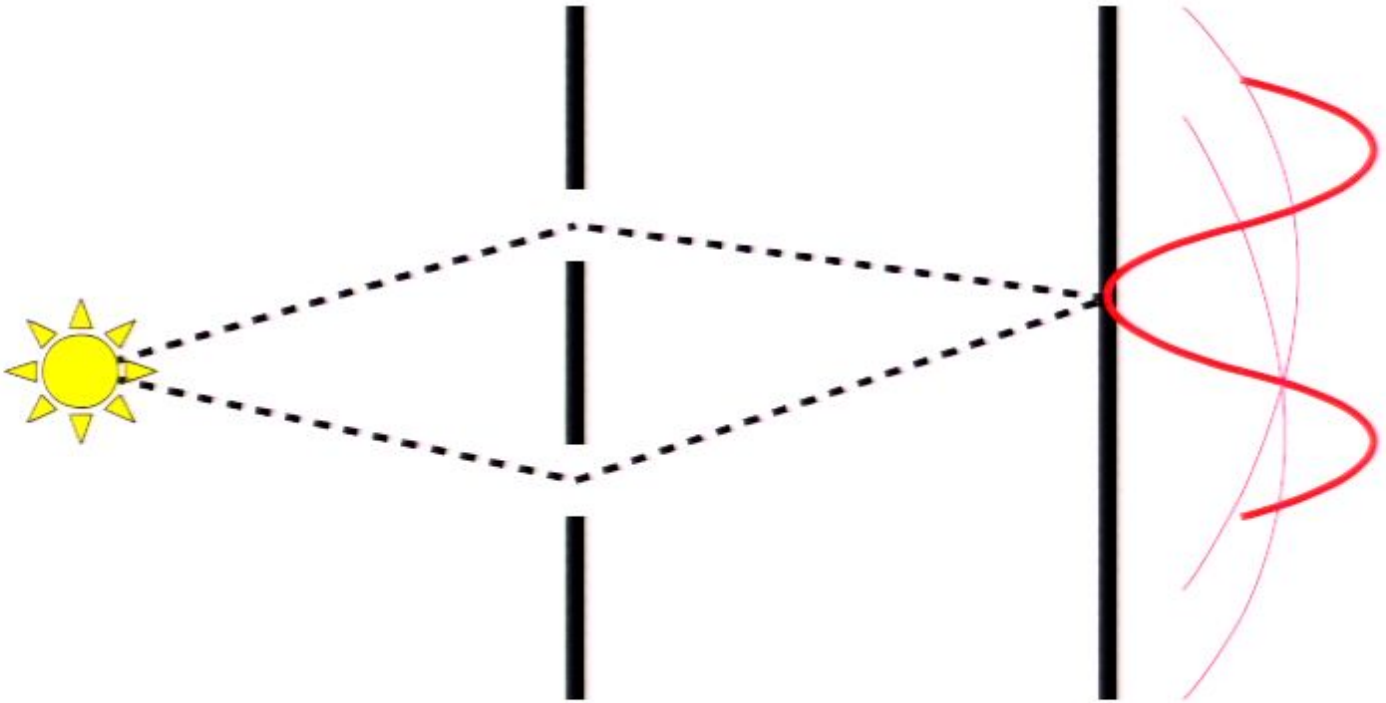
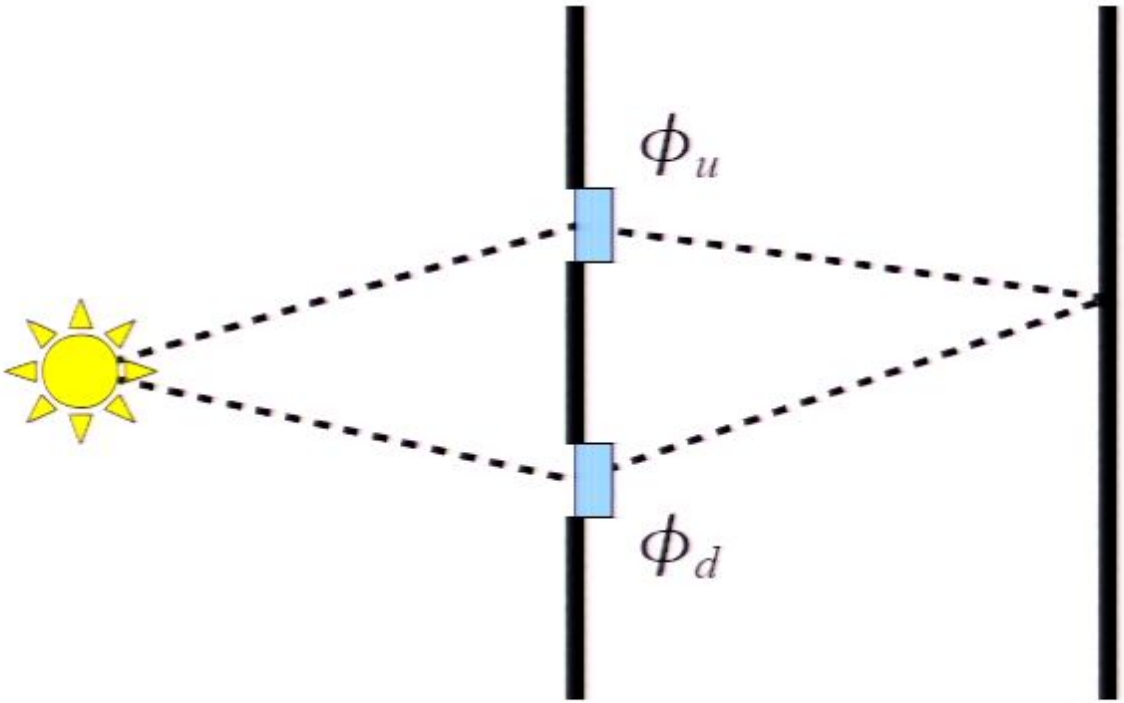


$$\frac{1}{\sqrt{2}}\left(|u\rangle + |d\rangle\right)$$

A superposition is *not* a statistical ensemble

Quantum phenomena : interferometry



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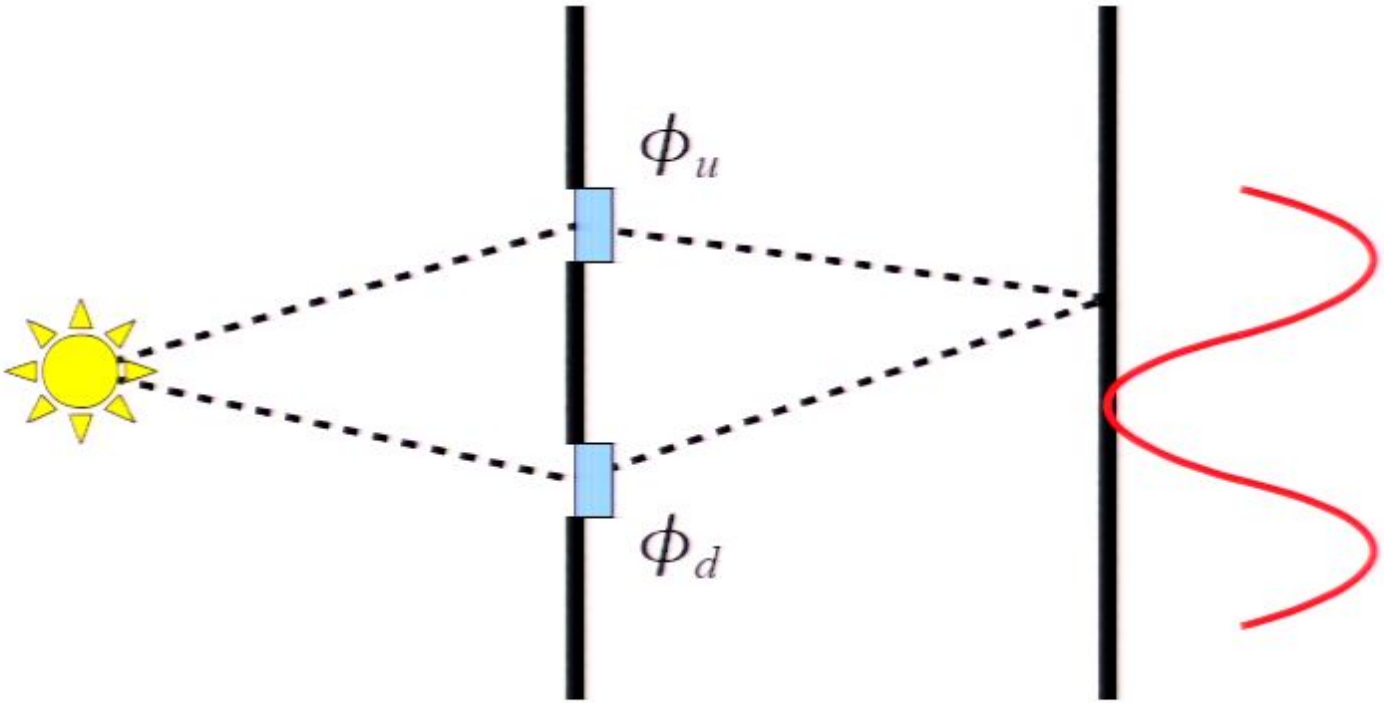

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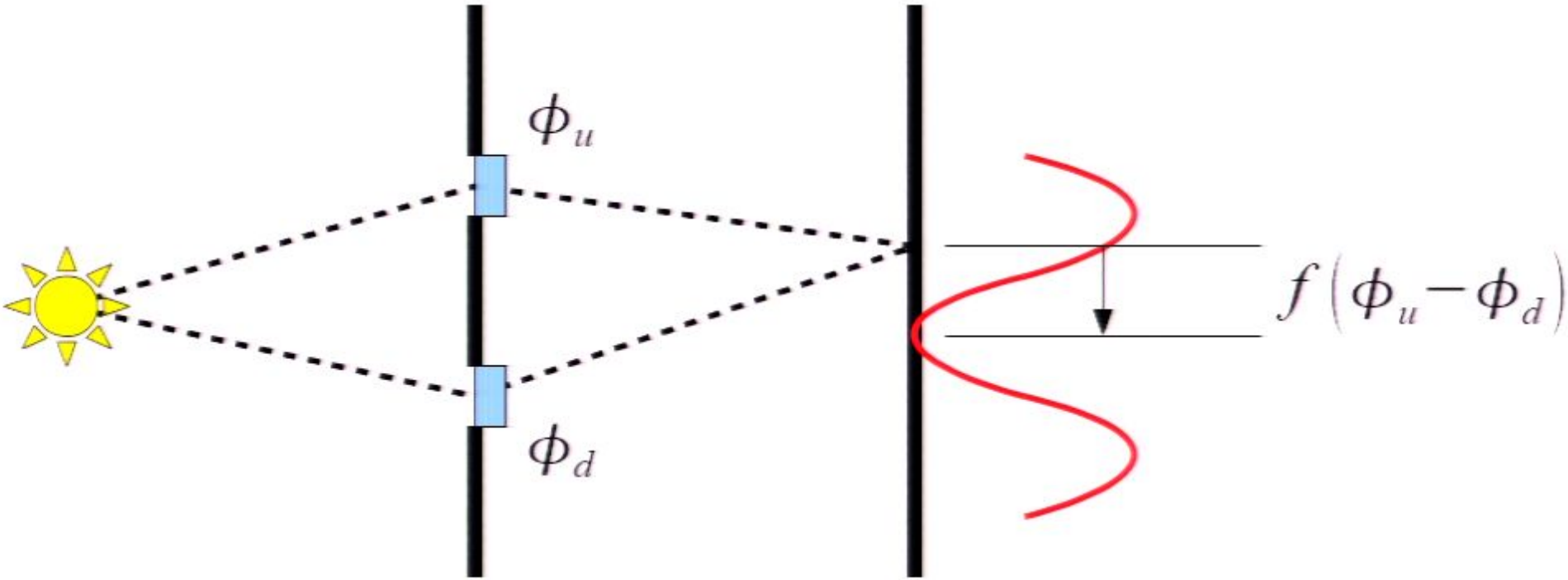

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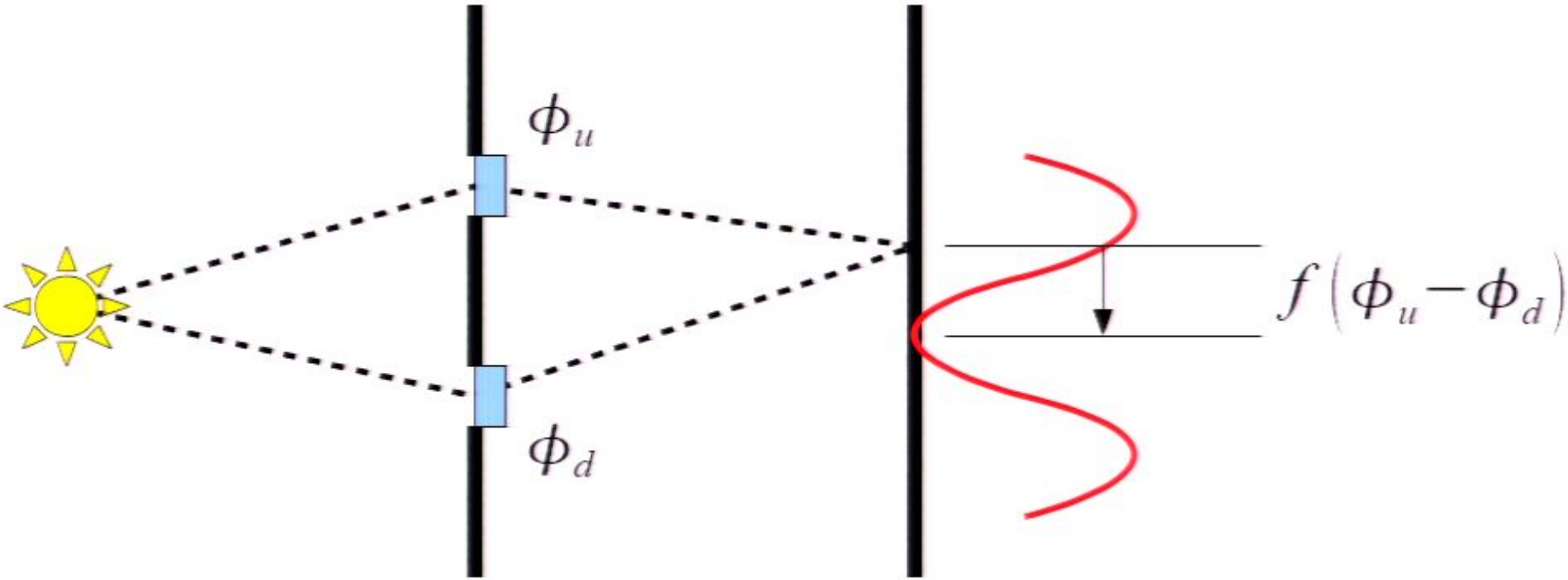
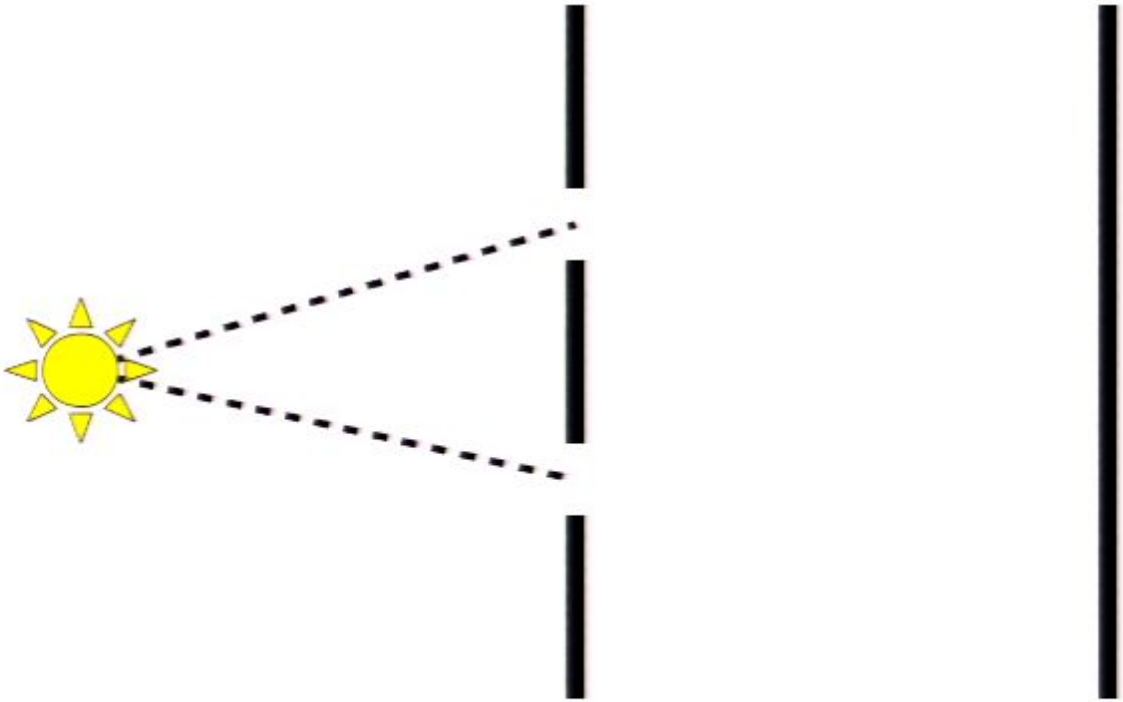


"In any attempt of a pictorial representation of the behaviour of the photon we would, thus, meet with the difficulty: to be obliged to say, on the one hand, that the photon always chooses *one* of the two ways and, on the other hand, that it behaves as if it had passed *both* ways." Bohr

Quantum phenomena : interferometry



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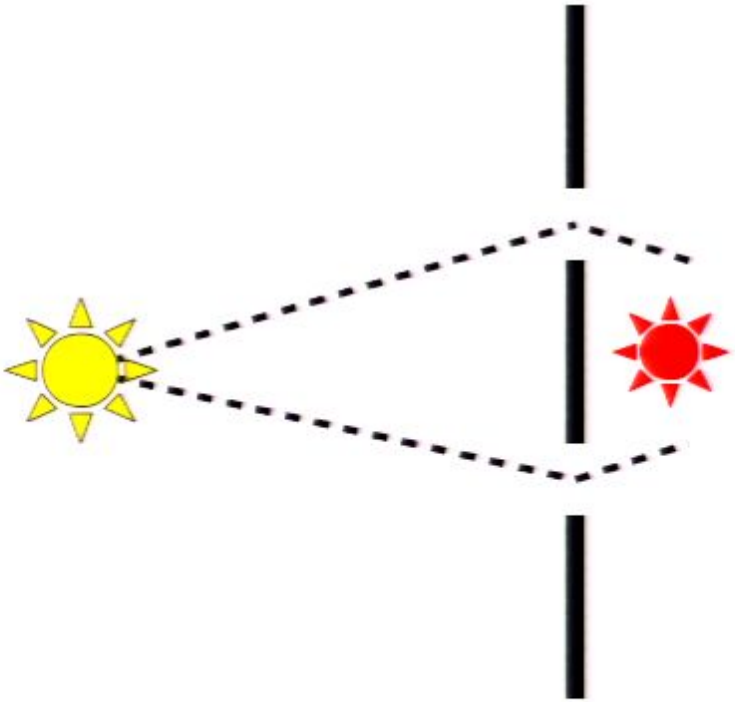
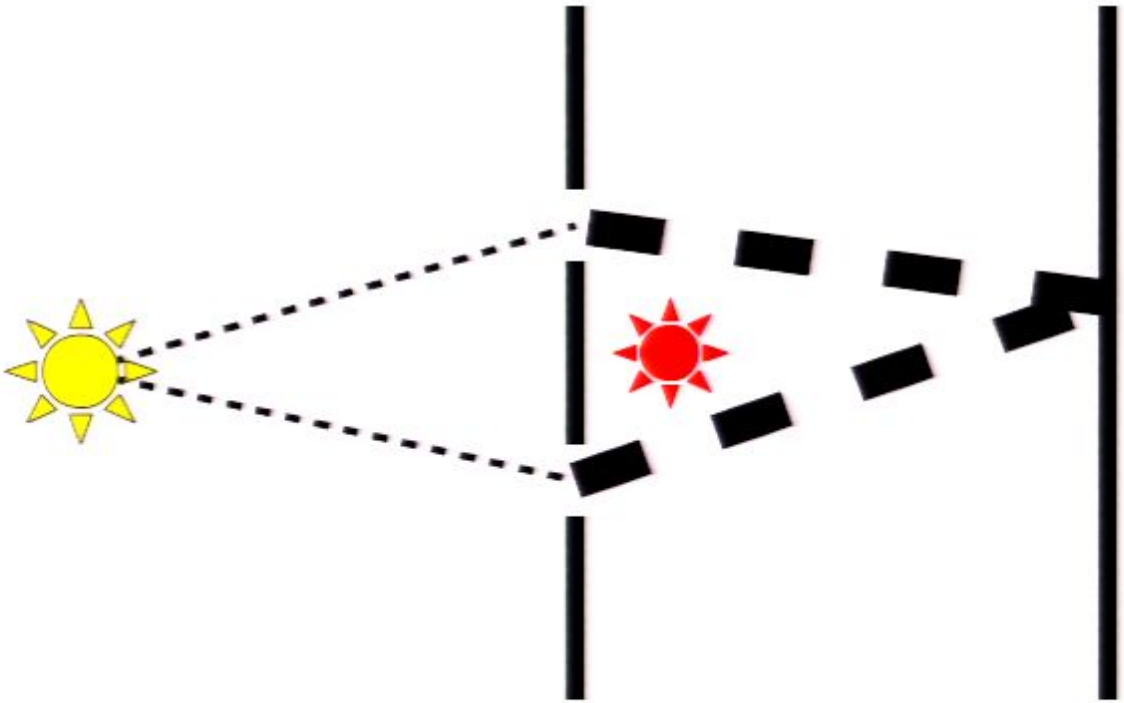


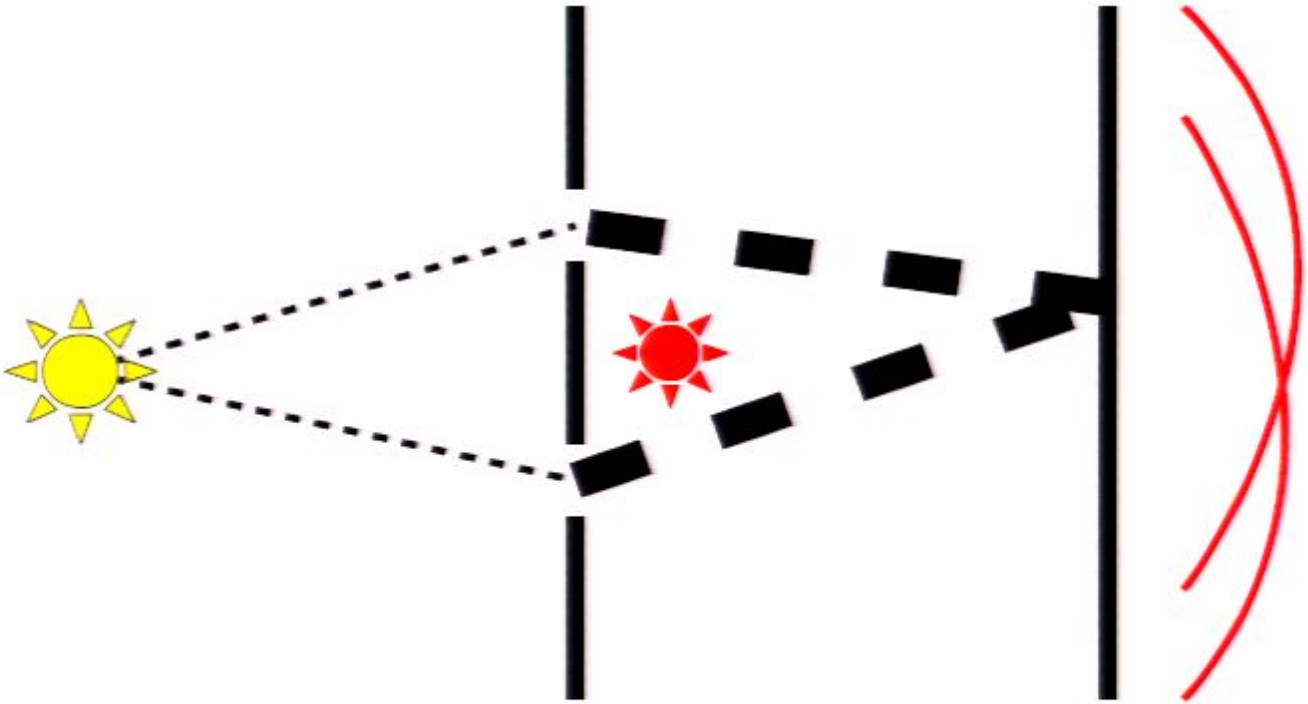
Shine a light to see where it went

Quantum phenomena : interferometry



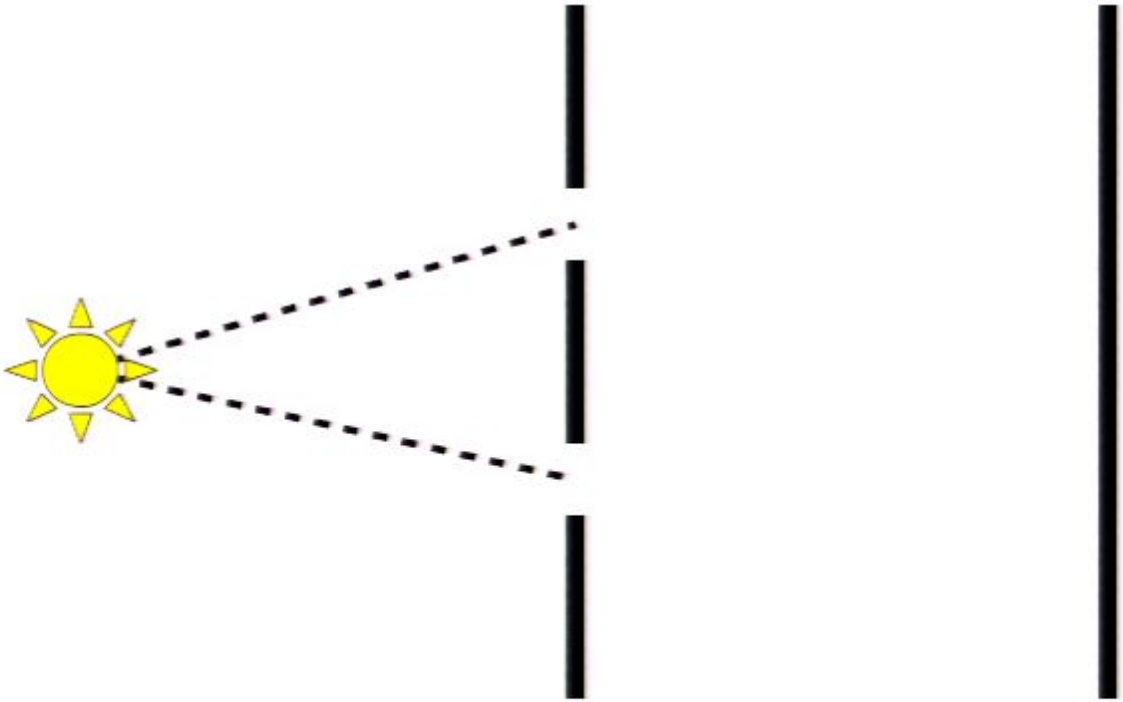
Interaction affects momentum of particle

Quantum phenomena : interferometry



Complementarity of position and momentum?

Quantum phenomena : interferometry



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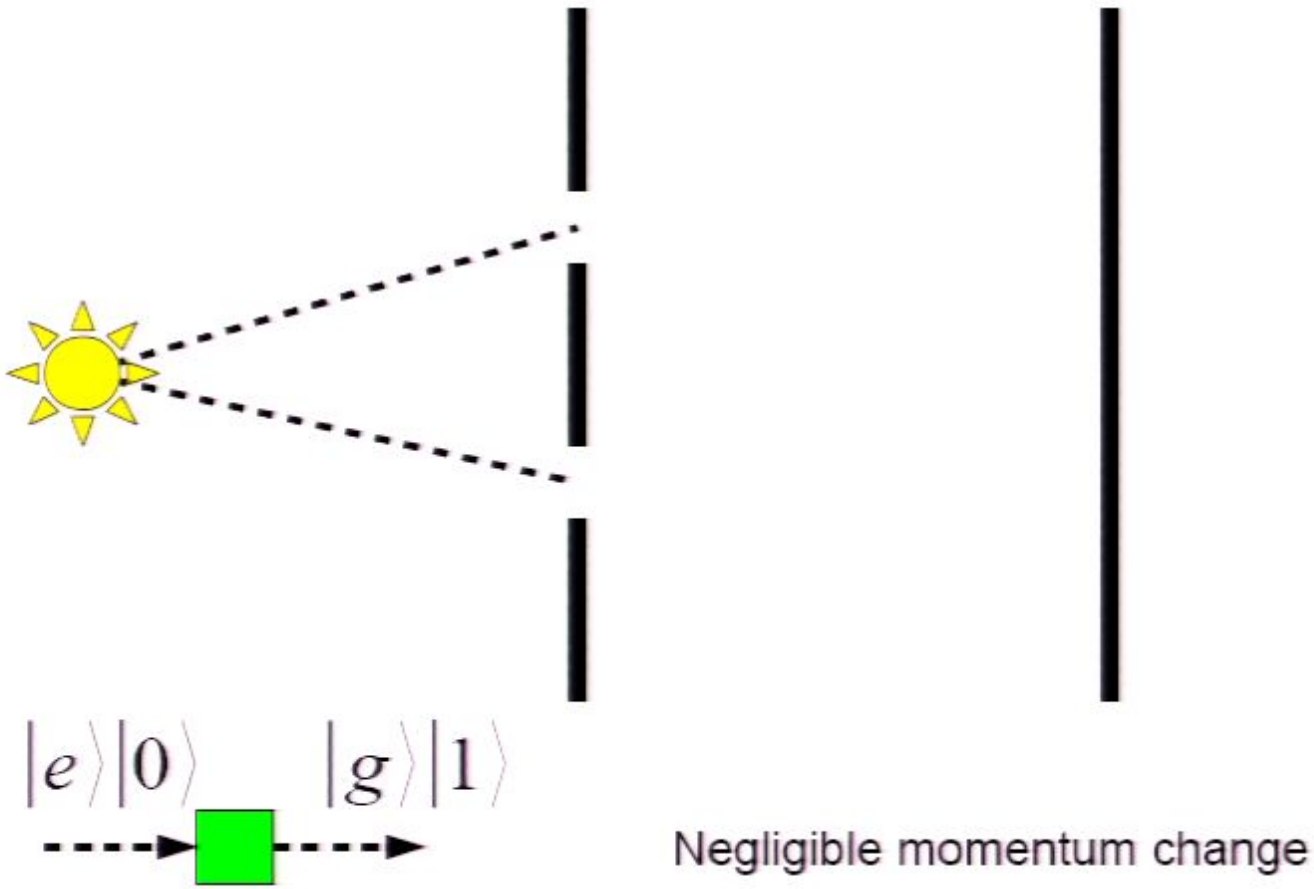

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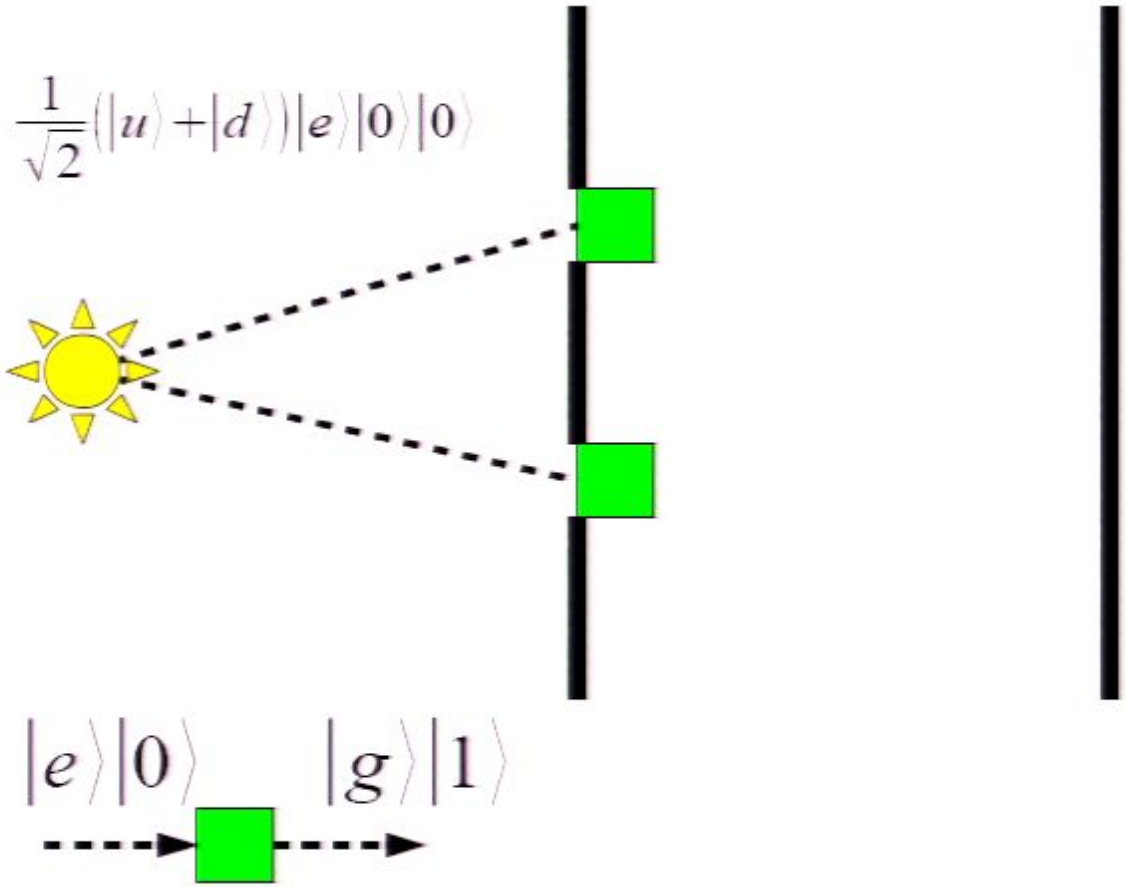

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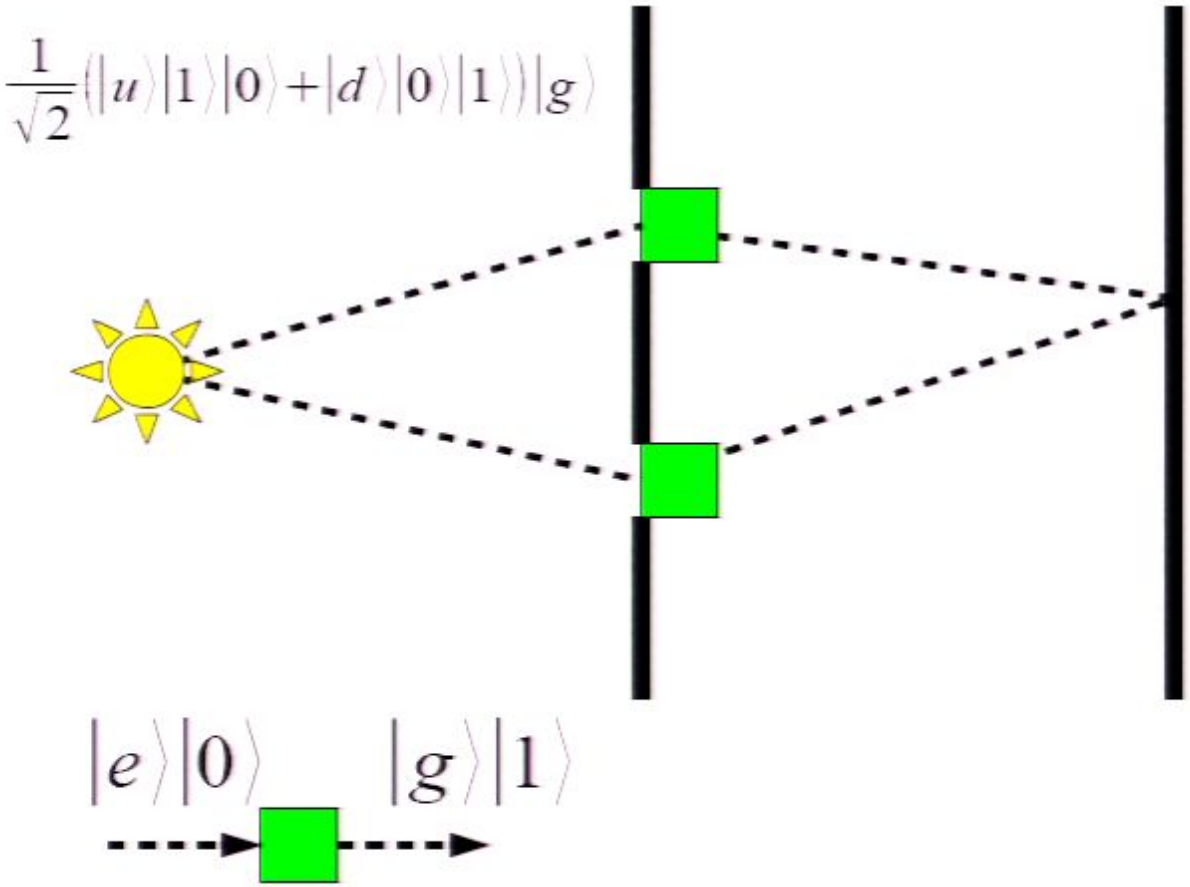

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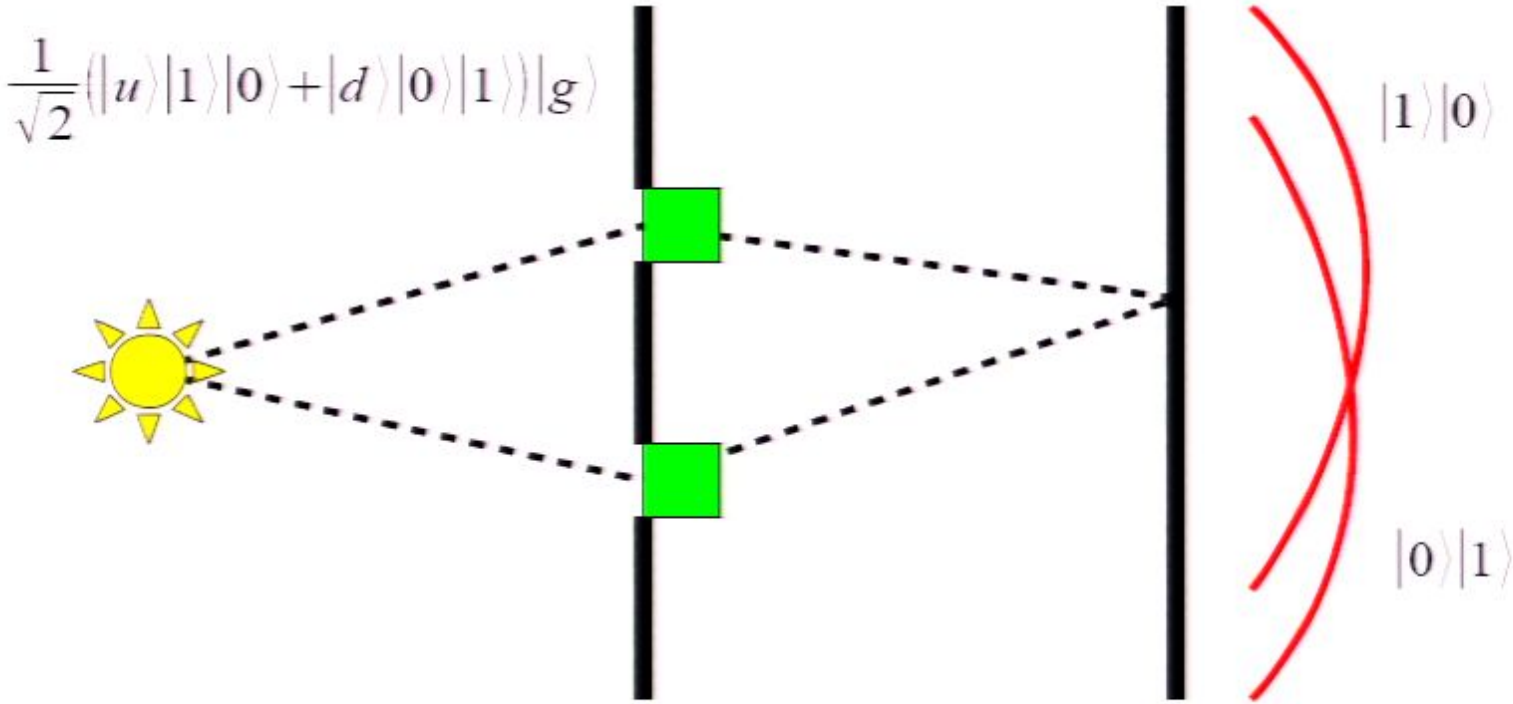
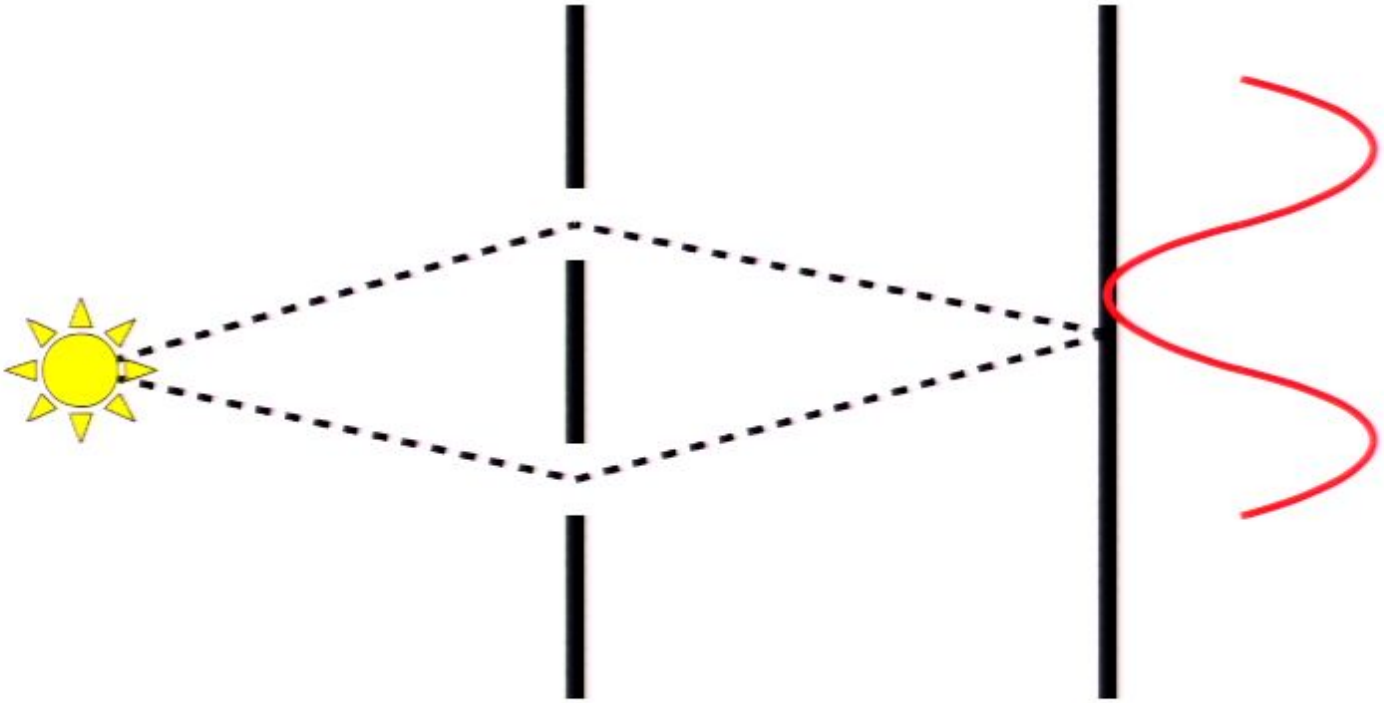


$|e\rangle|0\rangle \quad |g\rangle|1\rangle$

Optical QED Cavity

Information about which path destroys interference.
Wave-particle duality?

Quantum phenomena : interferometry



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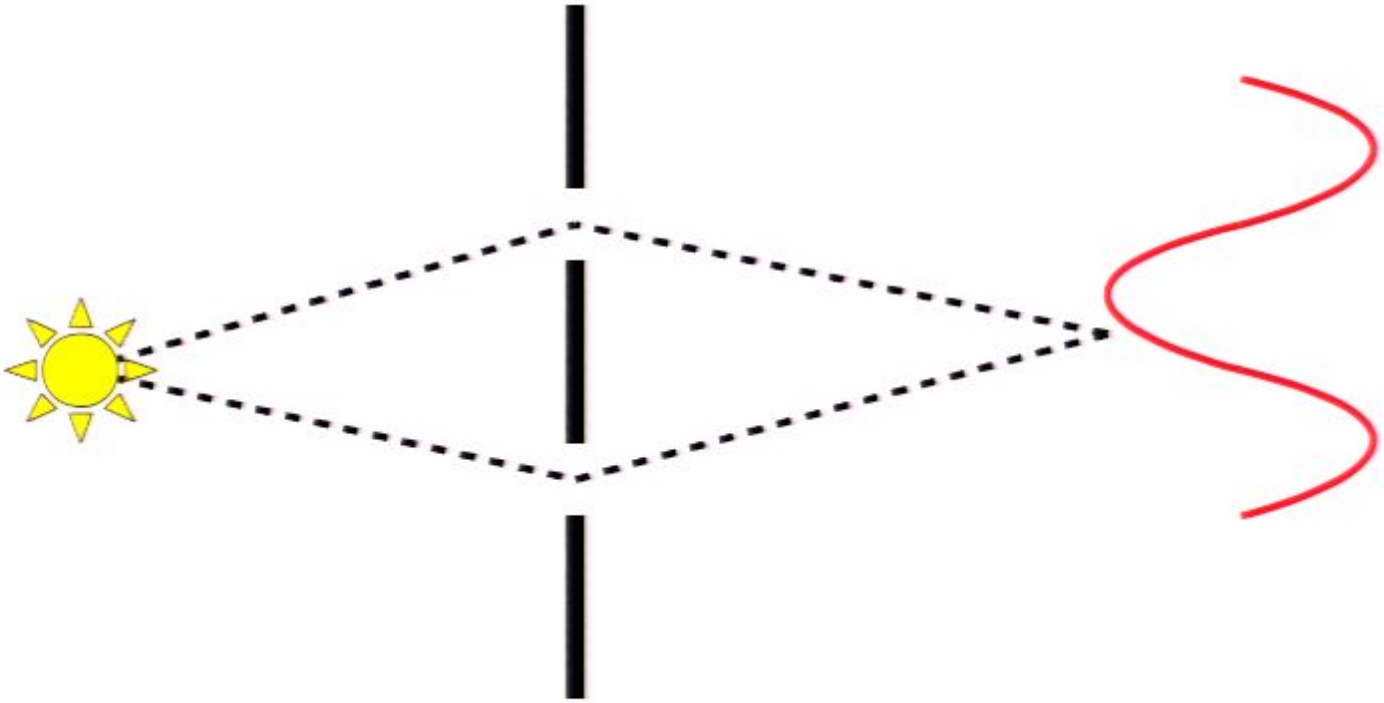

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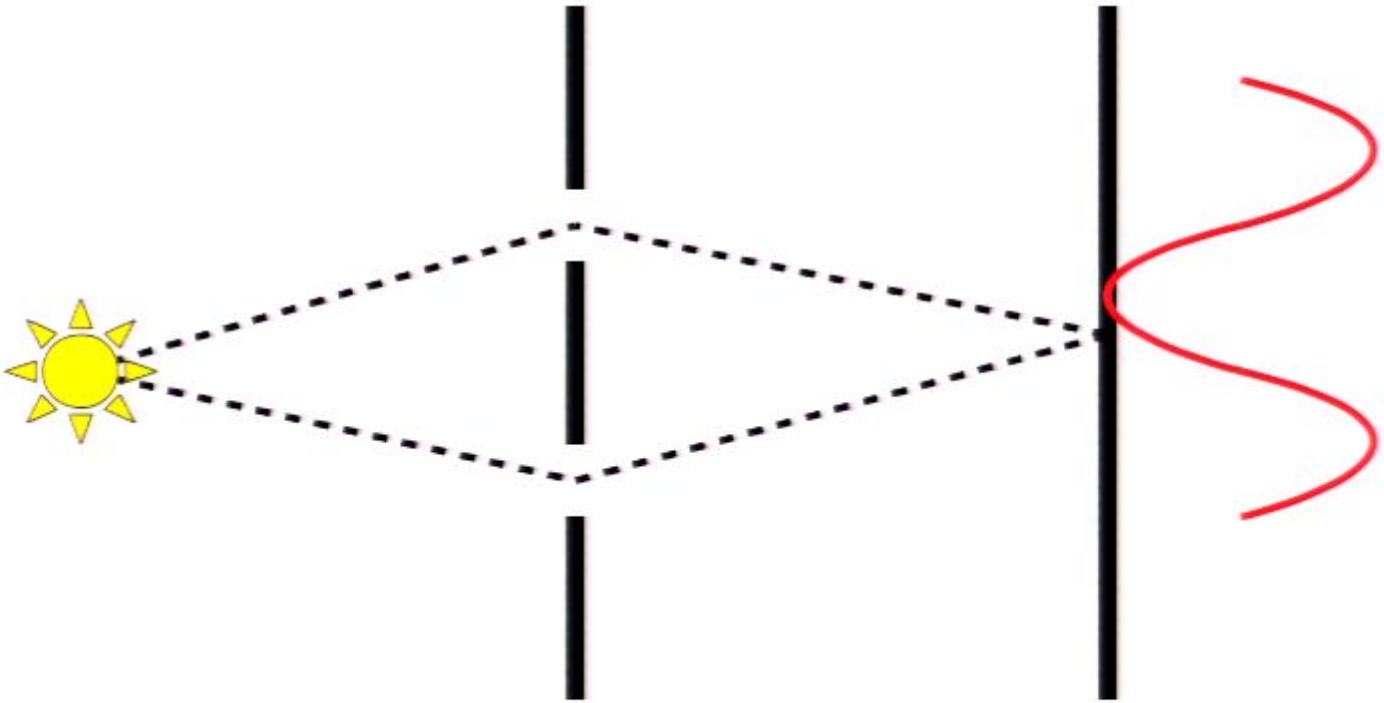

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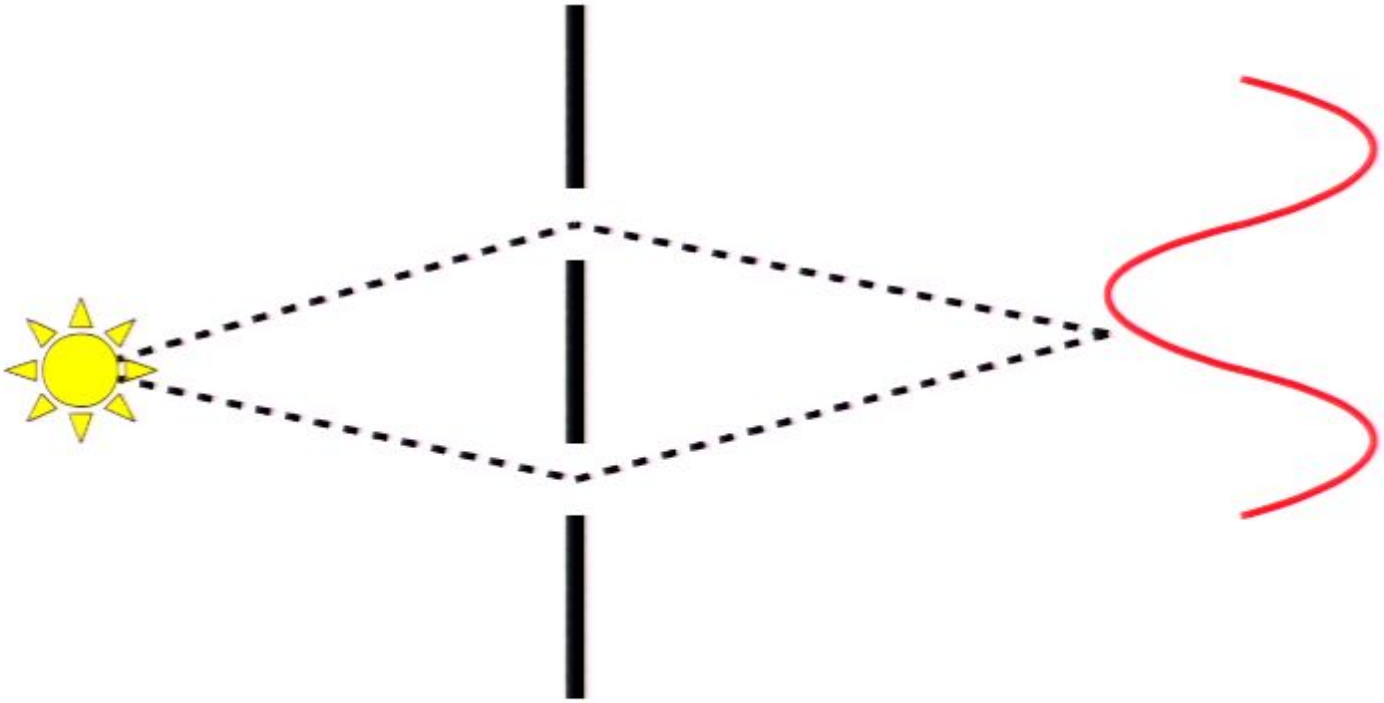

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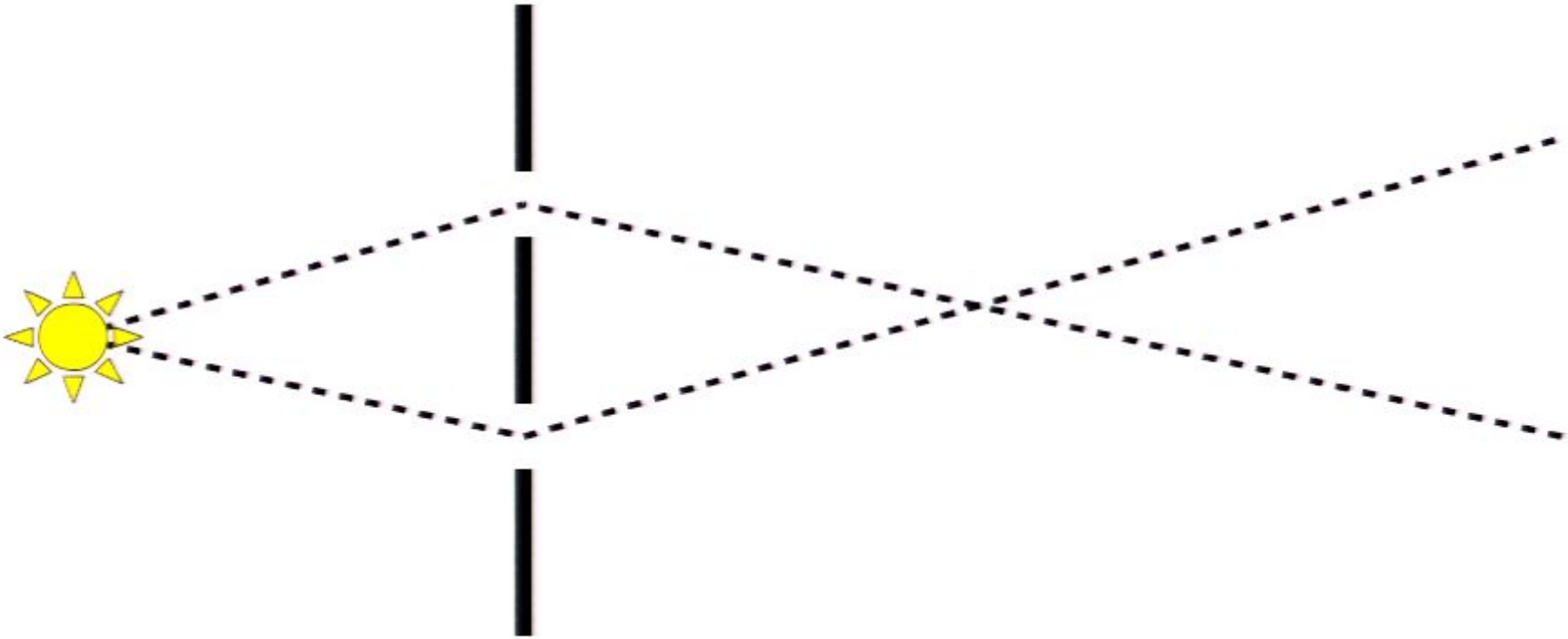

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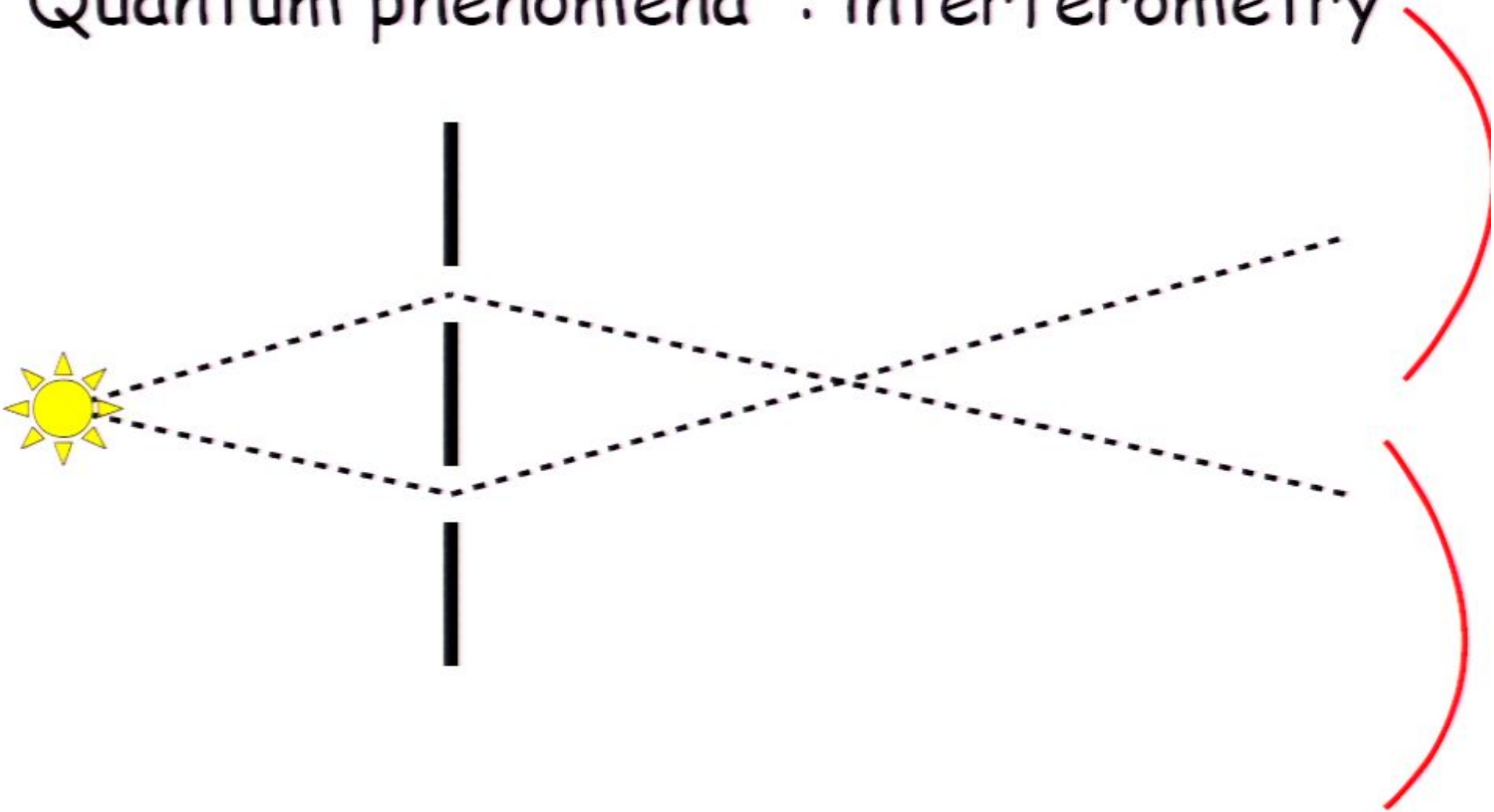

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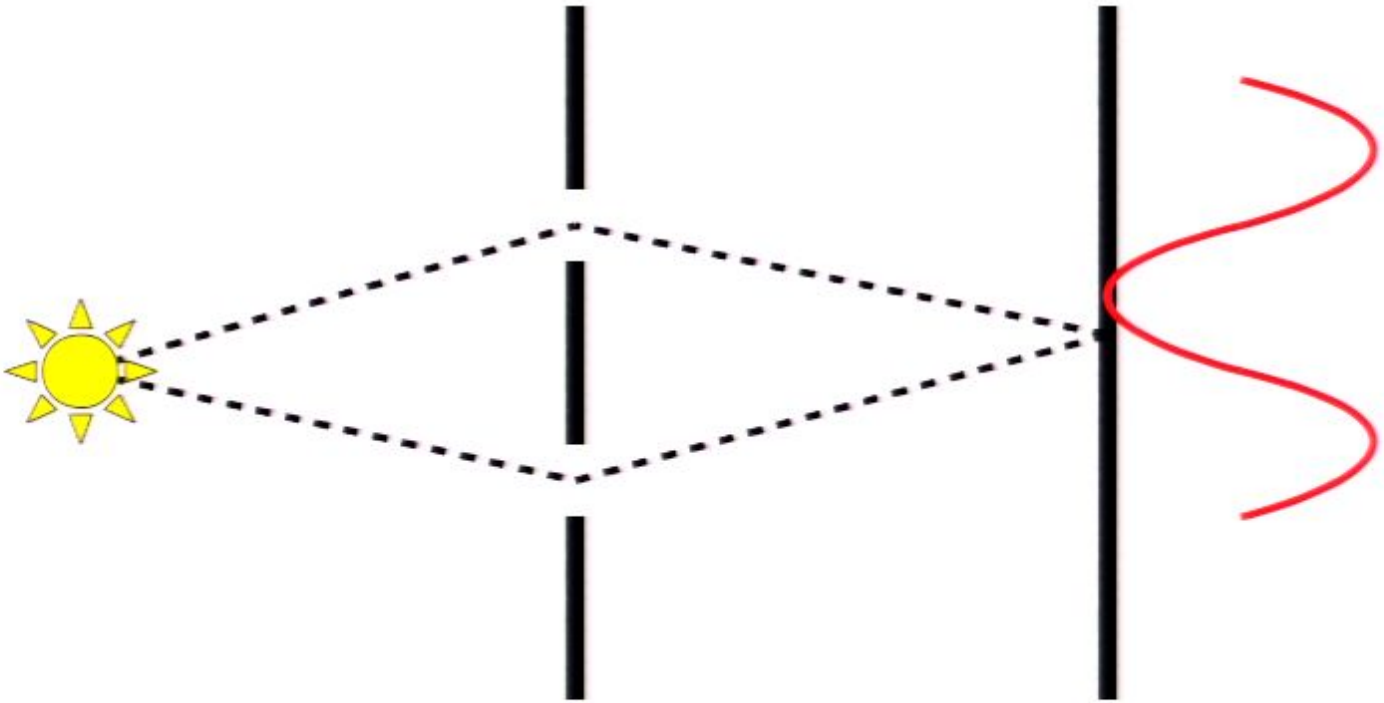
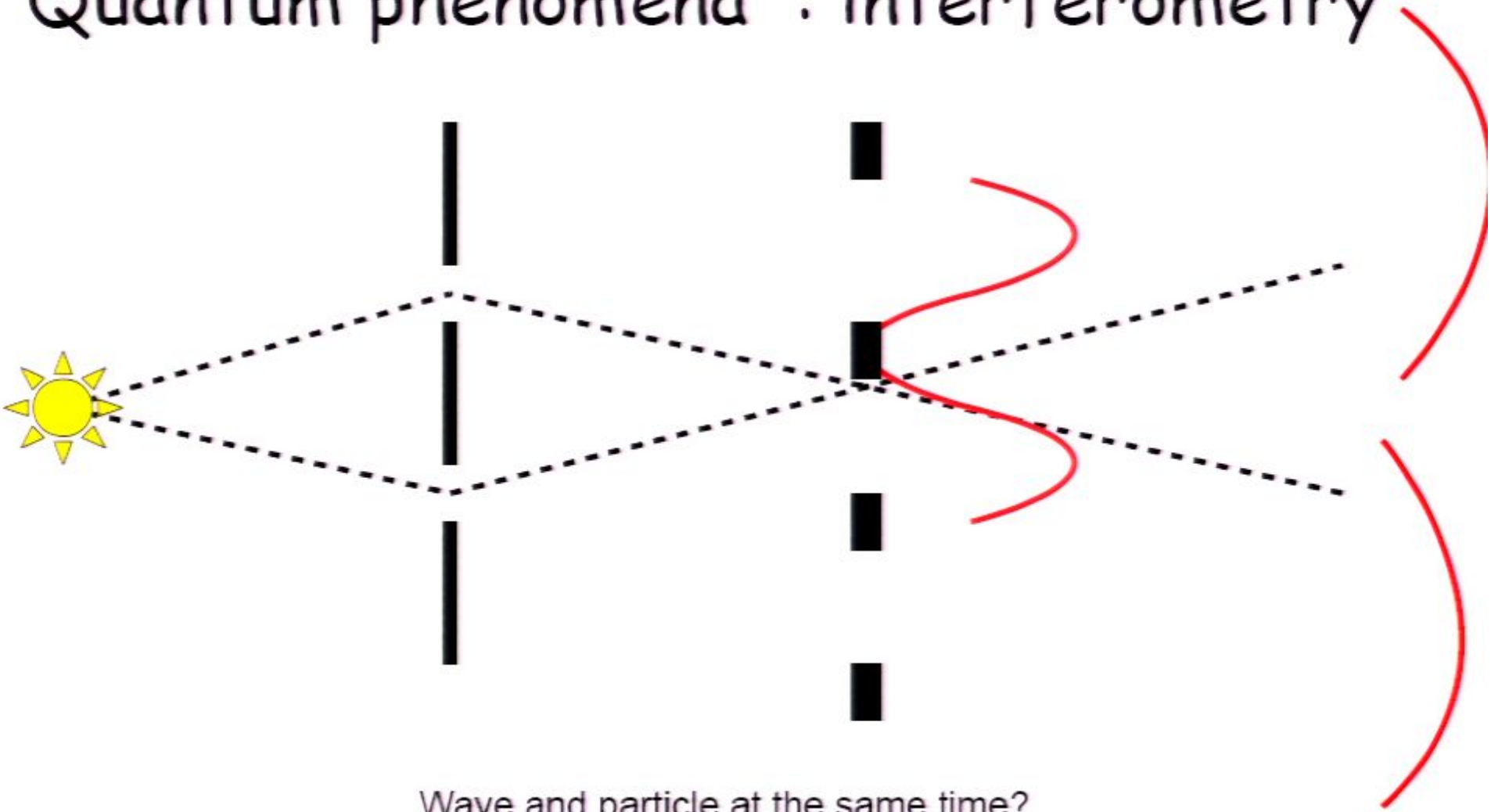


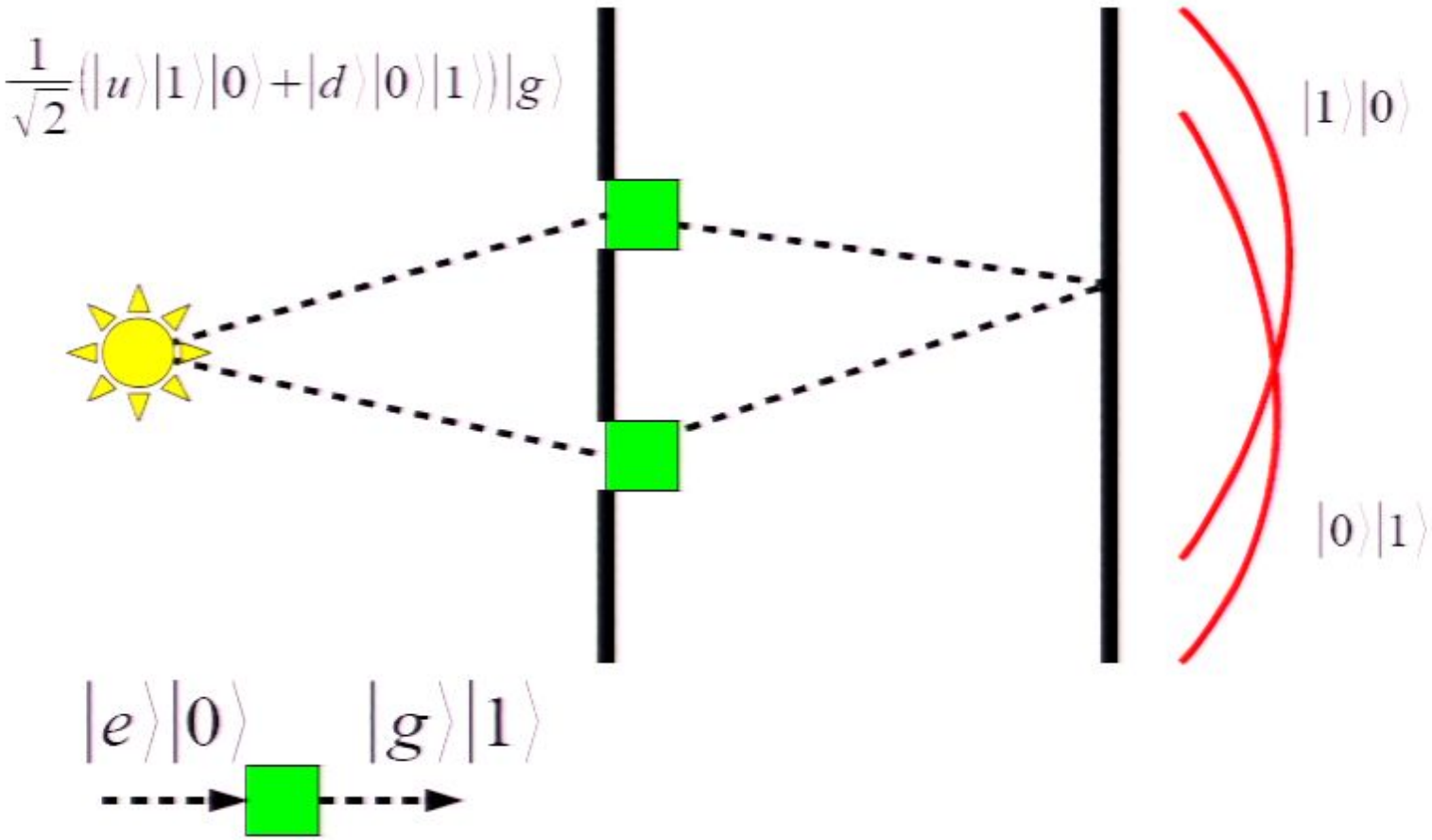
Delayed choice as to whether the quanta is a particle or wave?

Quantum phenomena : interferometry



Wave and particle at the same time?

Quantum phenomena : interferometry



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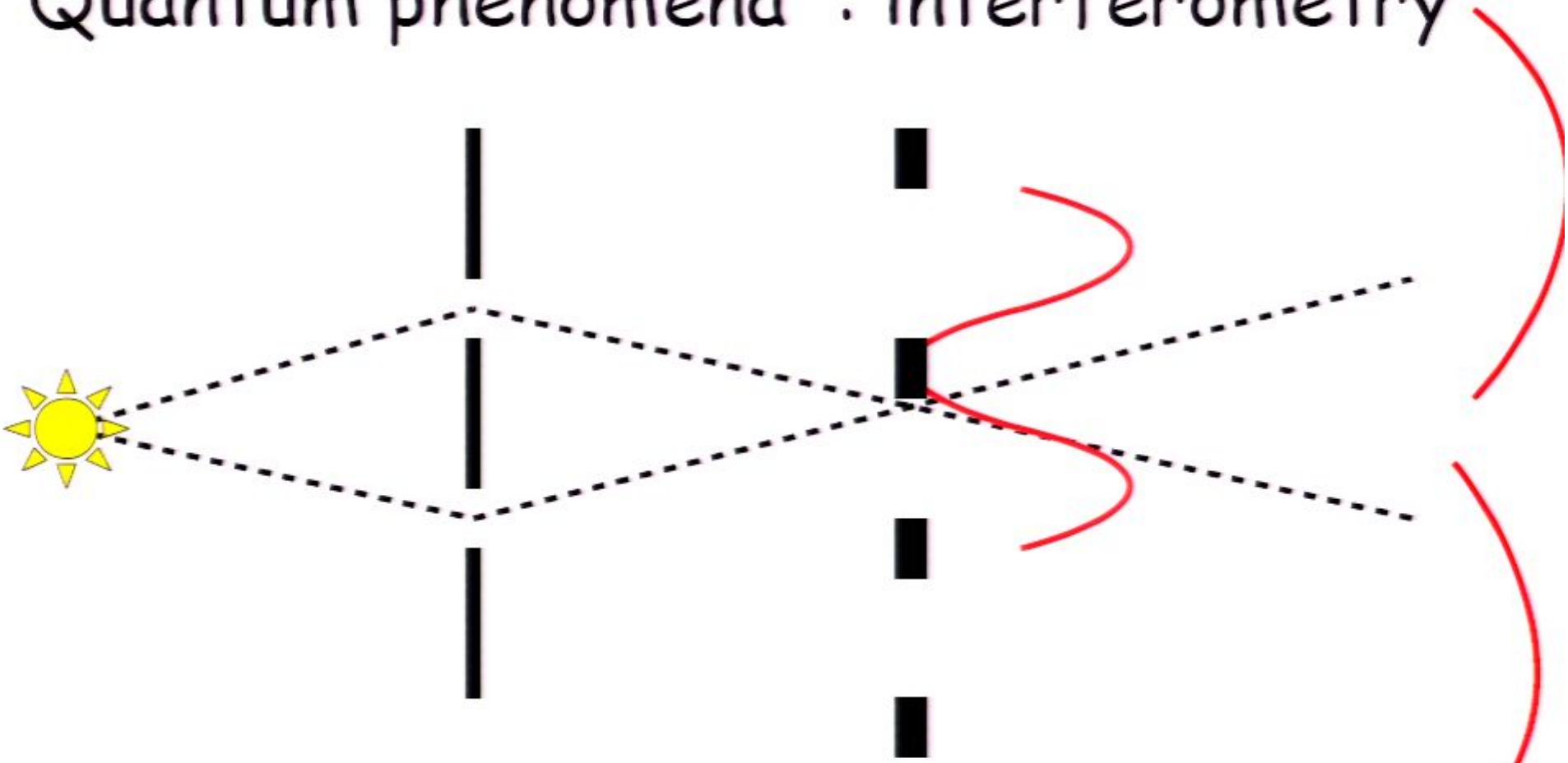

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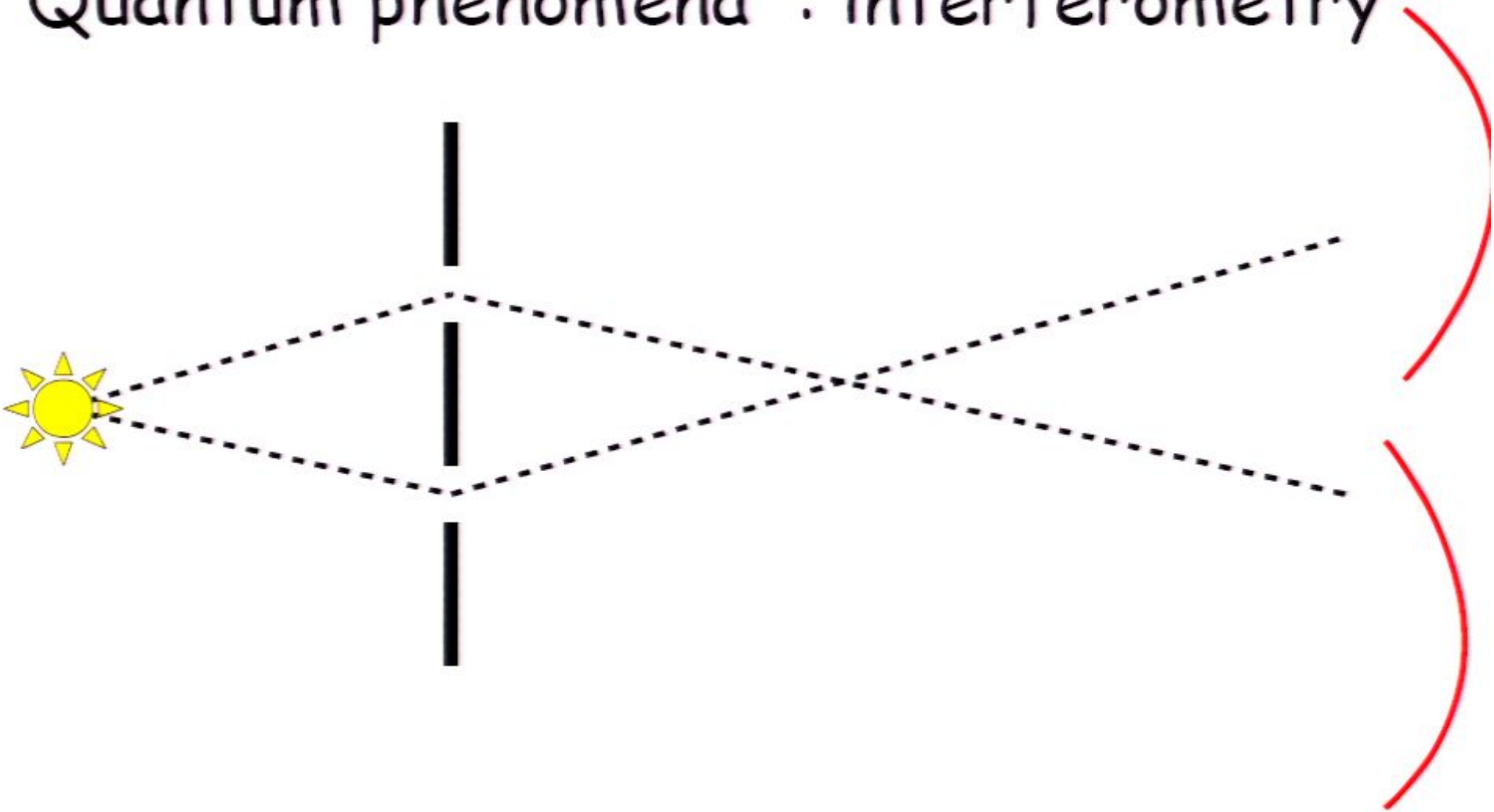

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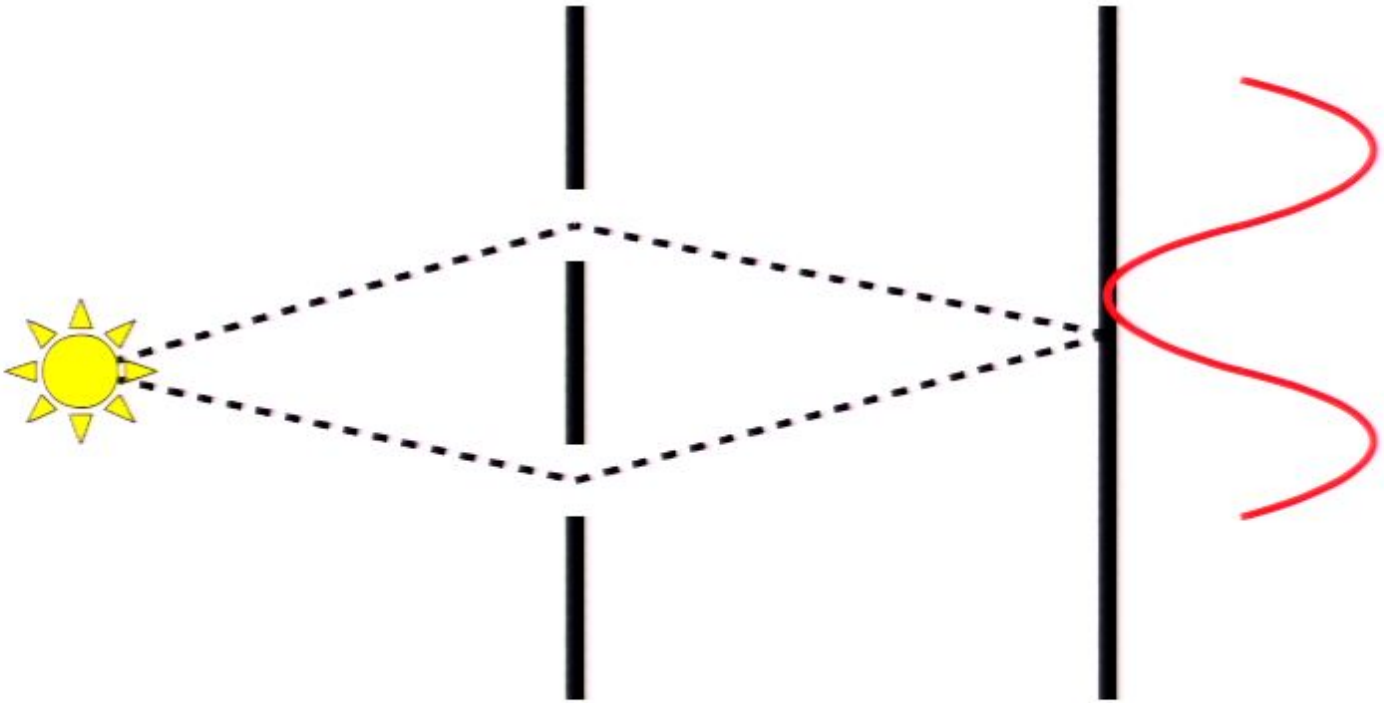

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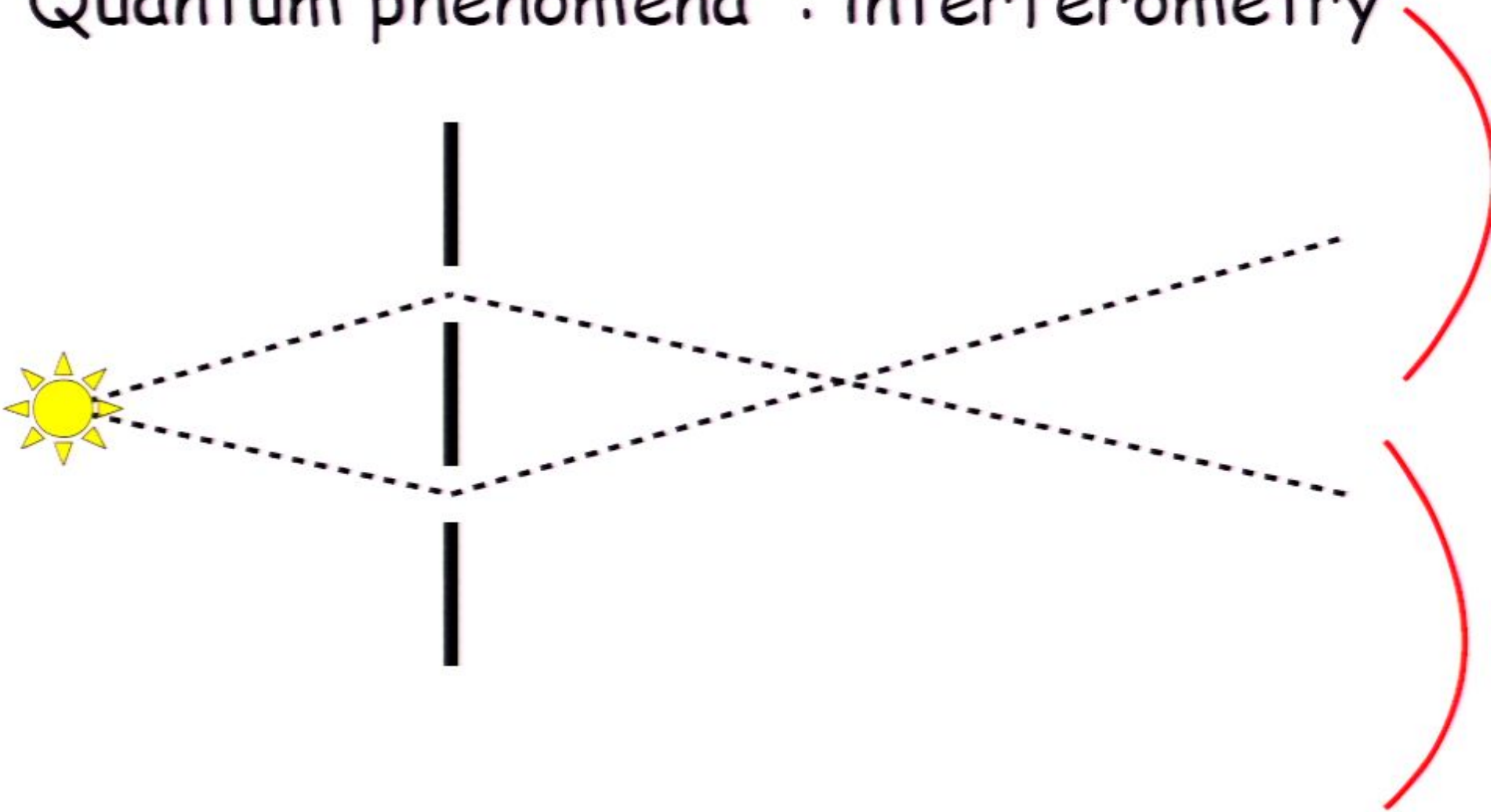

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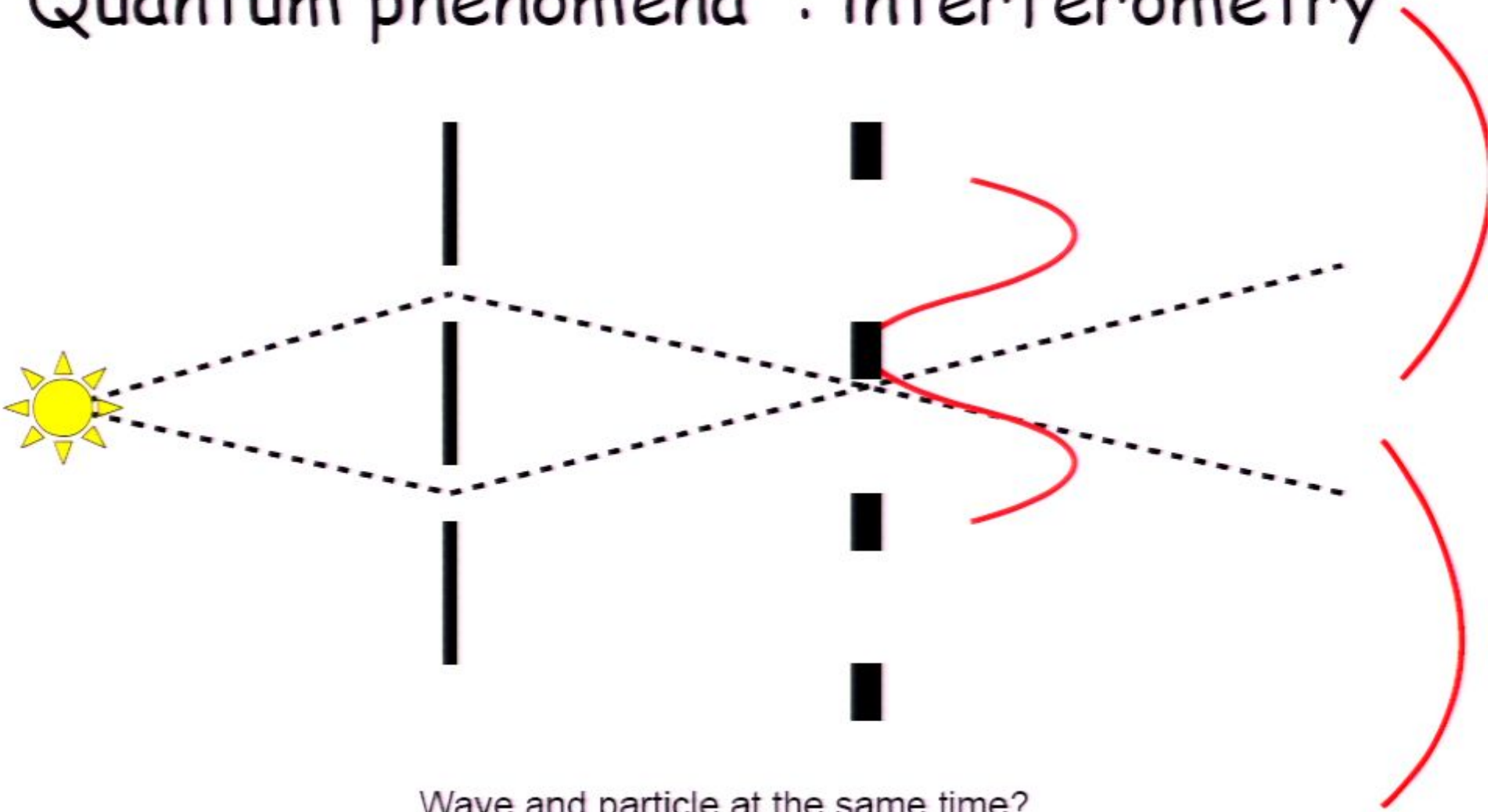

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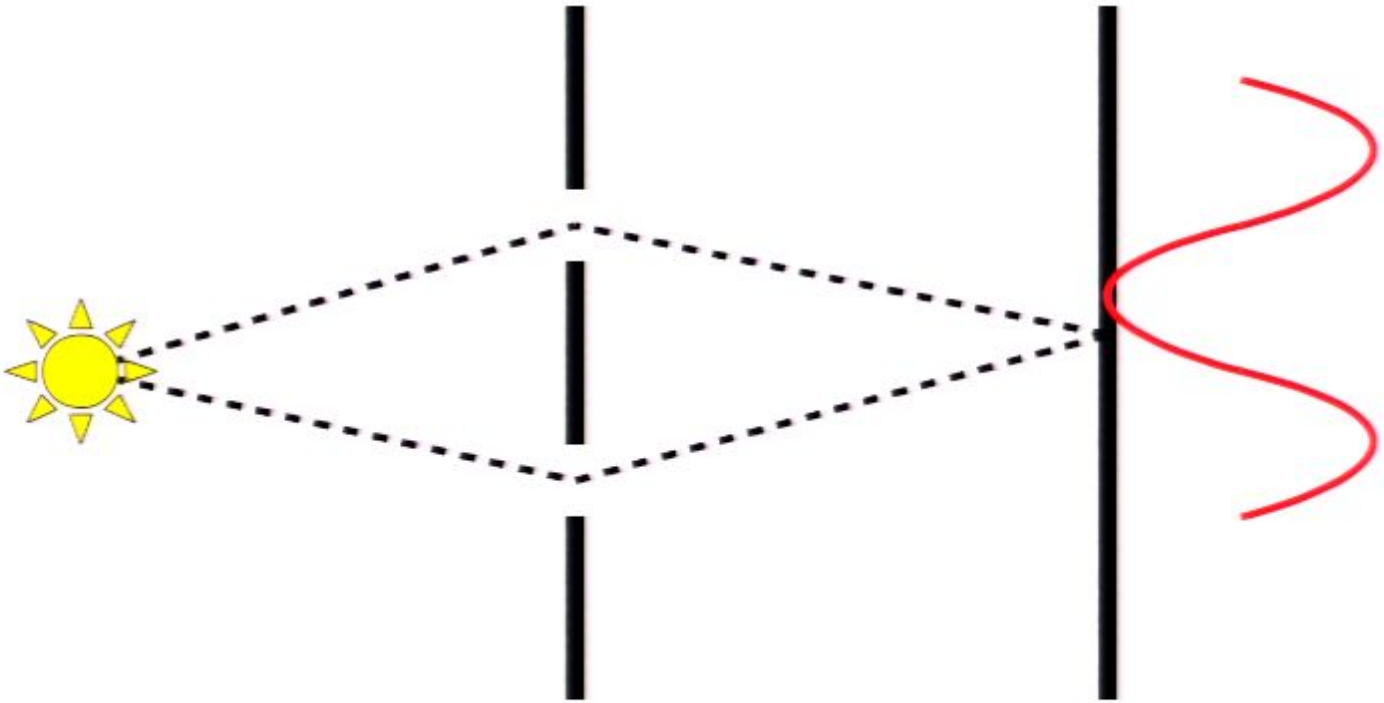

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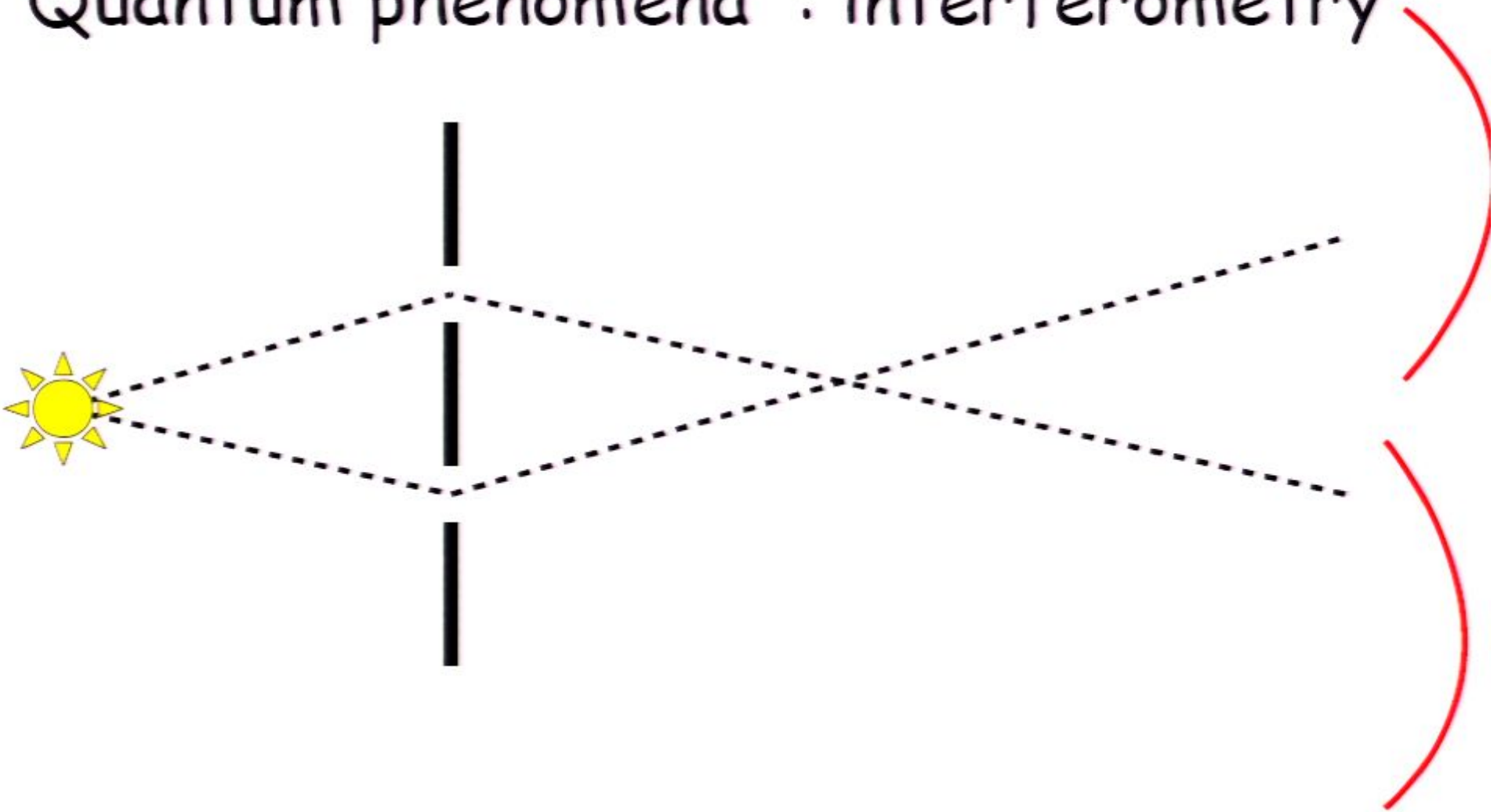

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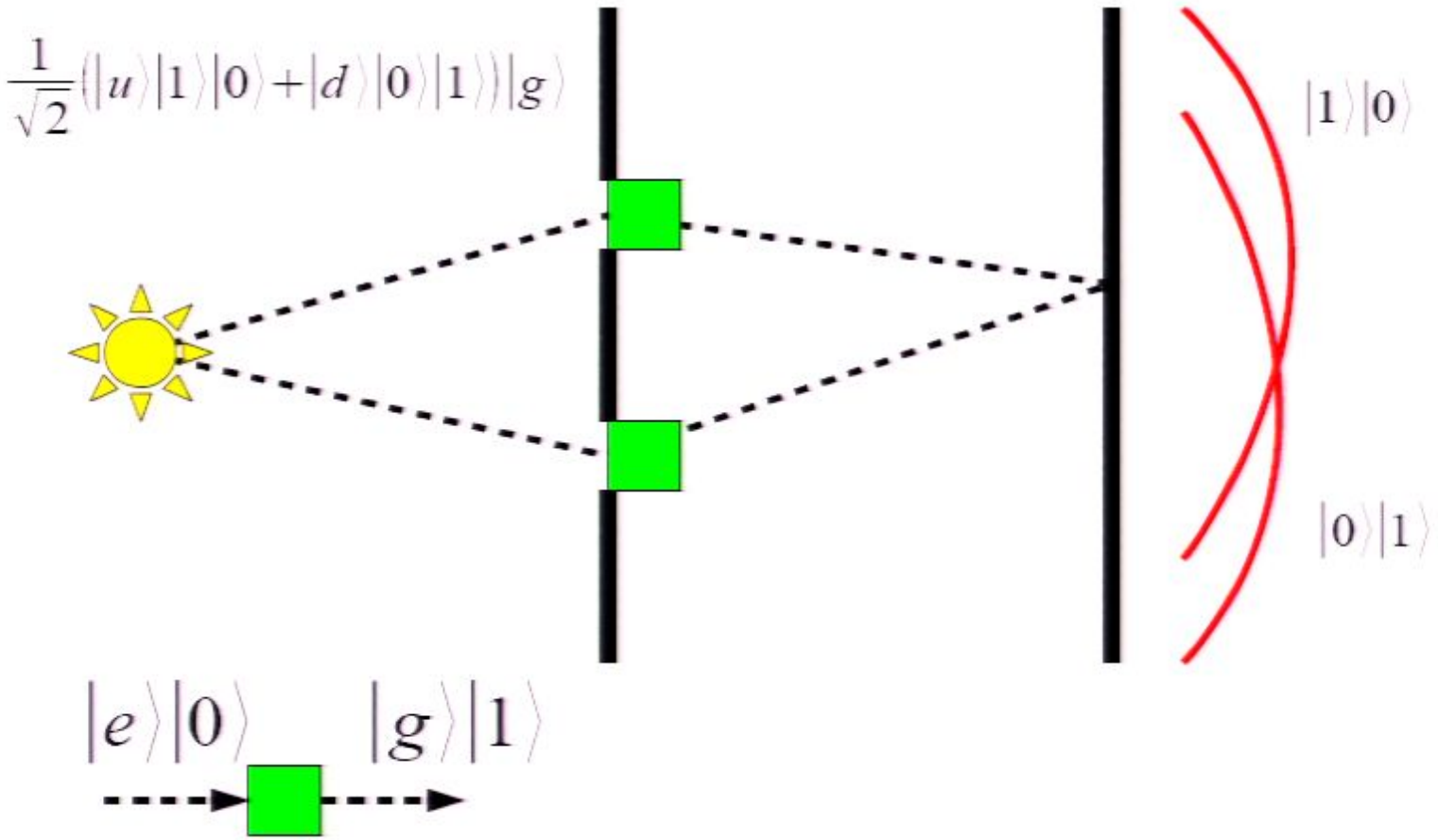

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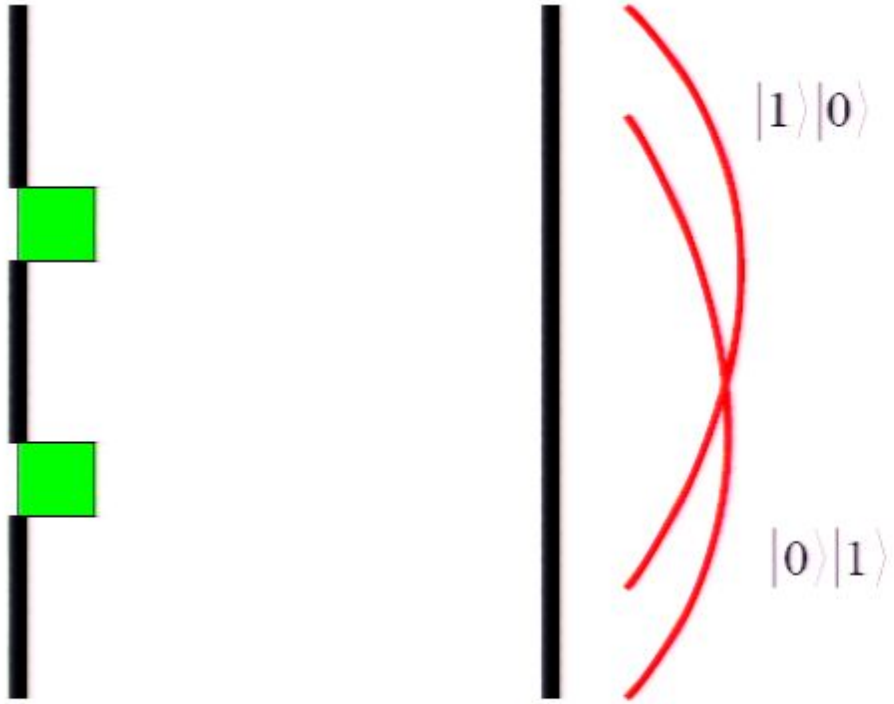

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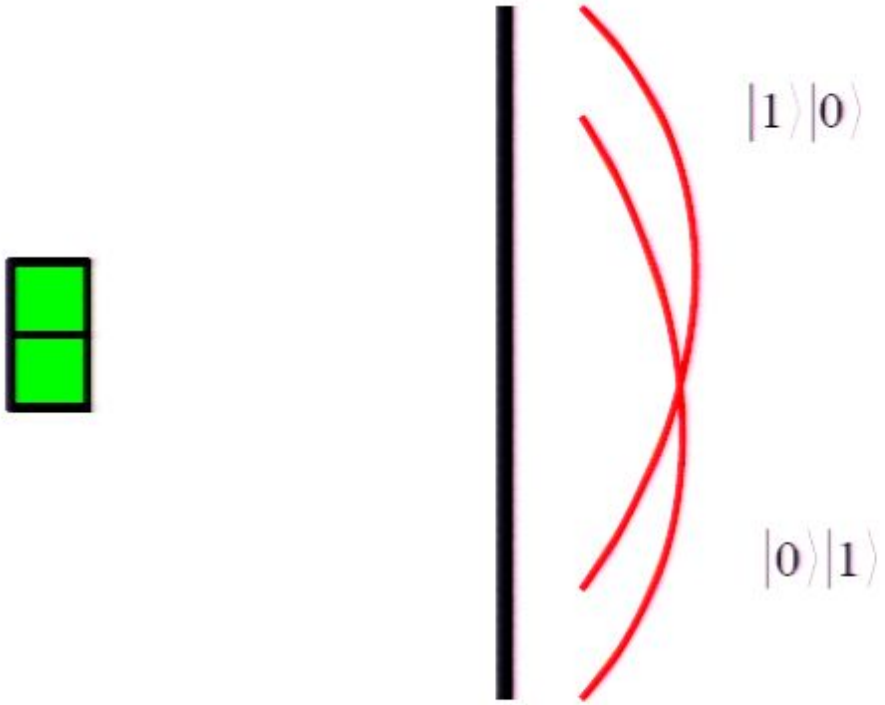

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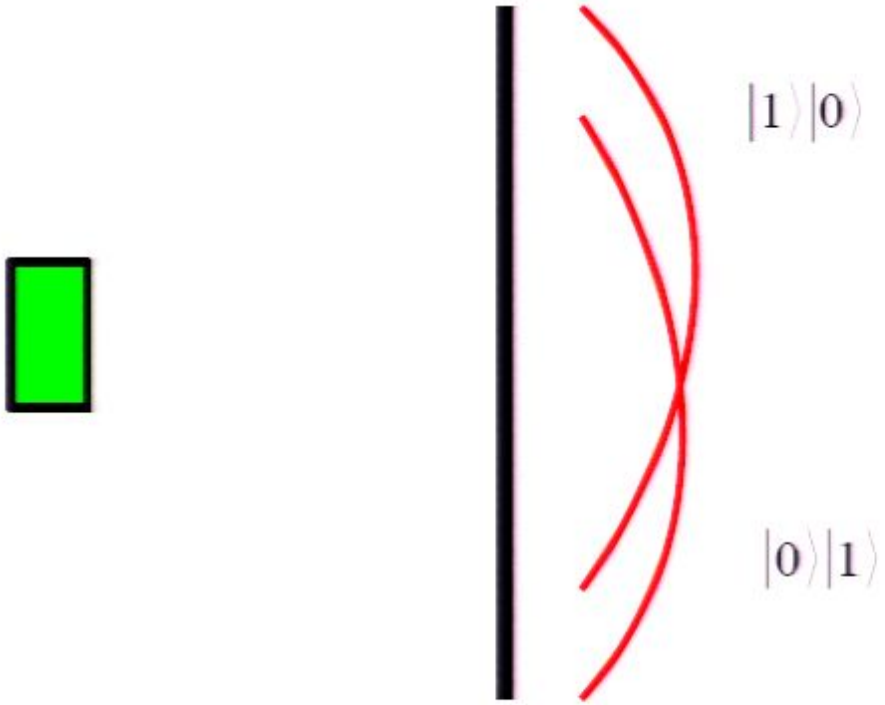
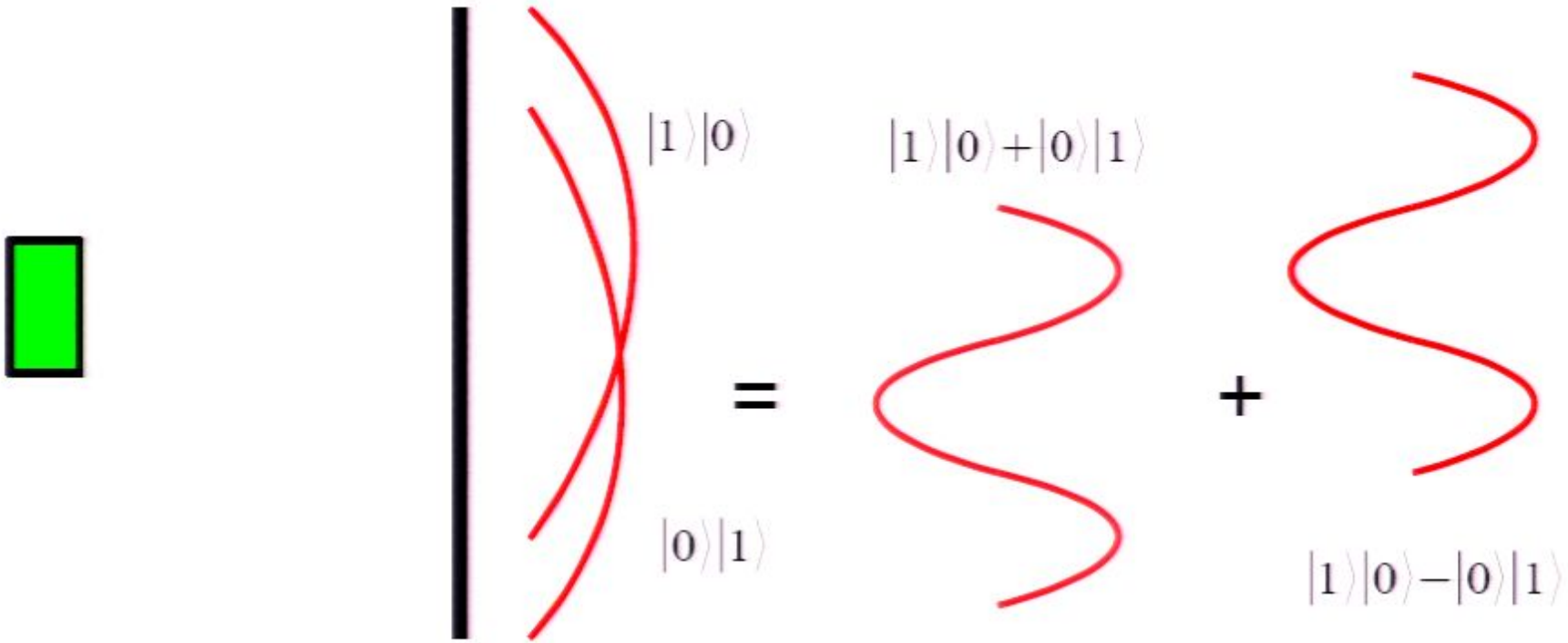


$$\frac{1}{\sqrt{2}}\left(|u\rangle|1\rangle|0\rangle+|d\rangle|0\rangle|1\rangle\right)|g\rangle=\frac{1}{\sqrt{2}}\left[\frac{\left(|u\rangle+|d\rangle\right)}{\sqrt{2}}\frac{\left(|1\rangle|0\rangle+|0\rangle|1\rangle\right)}{\sqrt{2}}+\frac{\left(|u\rangle-|d\rangle\right)}{\sqrt{2}}\frac{\left(|1\rangle|0\rangle-|0\rangle|1\rangle\right)}{\sqrt{2}}\right]|g\rangle$$

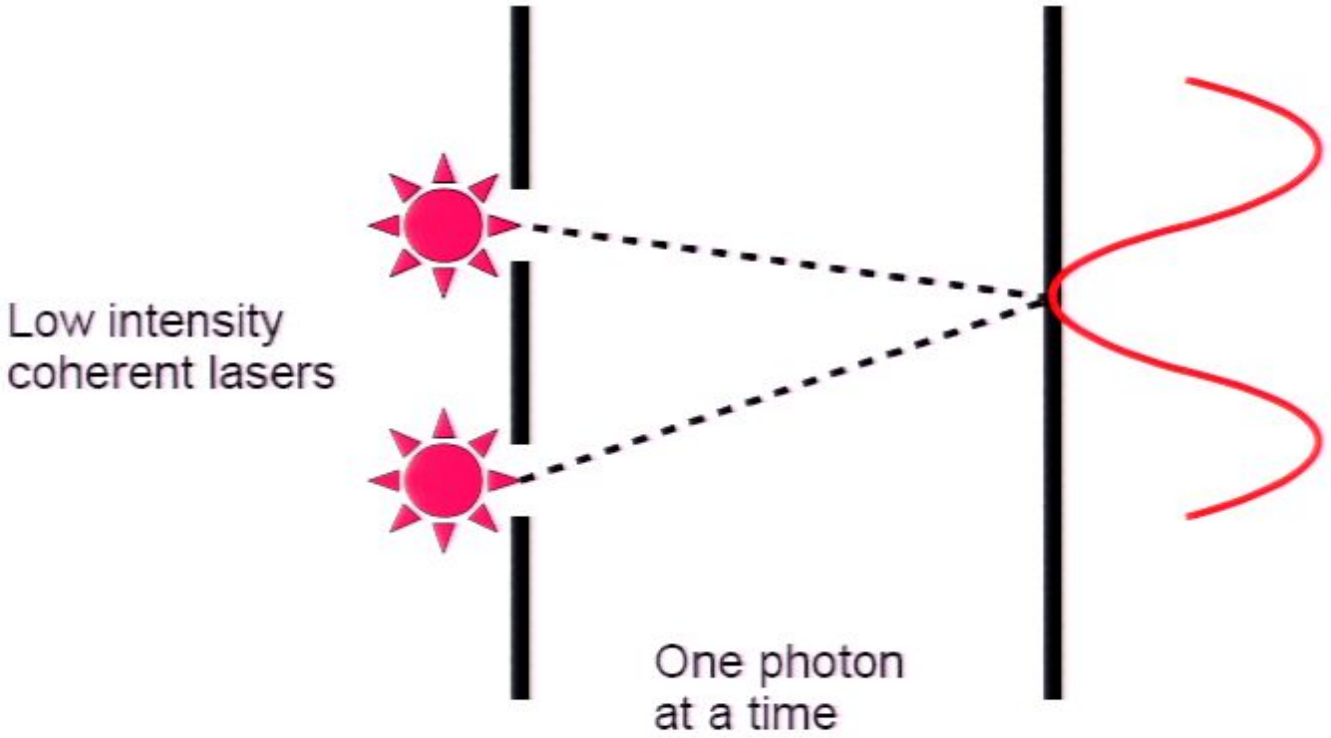
Quantum phenomena : interferometry



Erase information: recover interference?

$$\frac{1}{\sqrt{2}}\left(|u\rangle|1\rangle|0\rangle+|d\rangle|0\rangle|1\rangle\right)|g\rangle=\frac{1}{\sqrt{2}}\left[\frac{\left(|u\rangle+|d\rangle\right)}{\sqrt{2}}\frac{\left(|1\rangle|0\rangle+|0\rangle|1\rangle\right)}{\sqrt{2}}+\frac{\left(|u\rangle-|d\rangle\right)}{\sqrt{2}}\frac{\left(|1\rangle|0\rangle-|0\rangle|1\rangle\right)}{\sqrt{2}}\right]|g\rangle$$

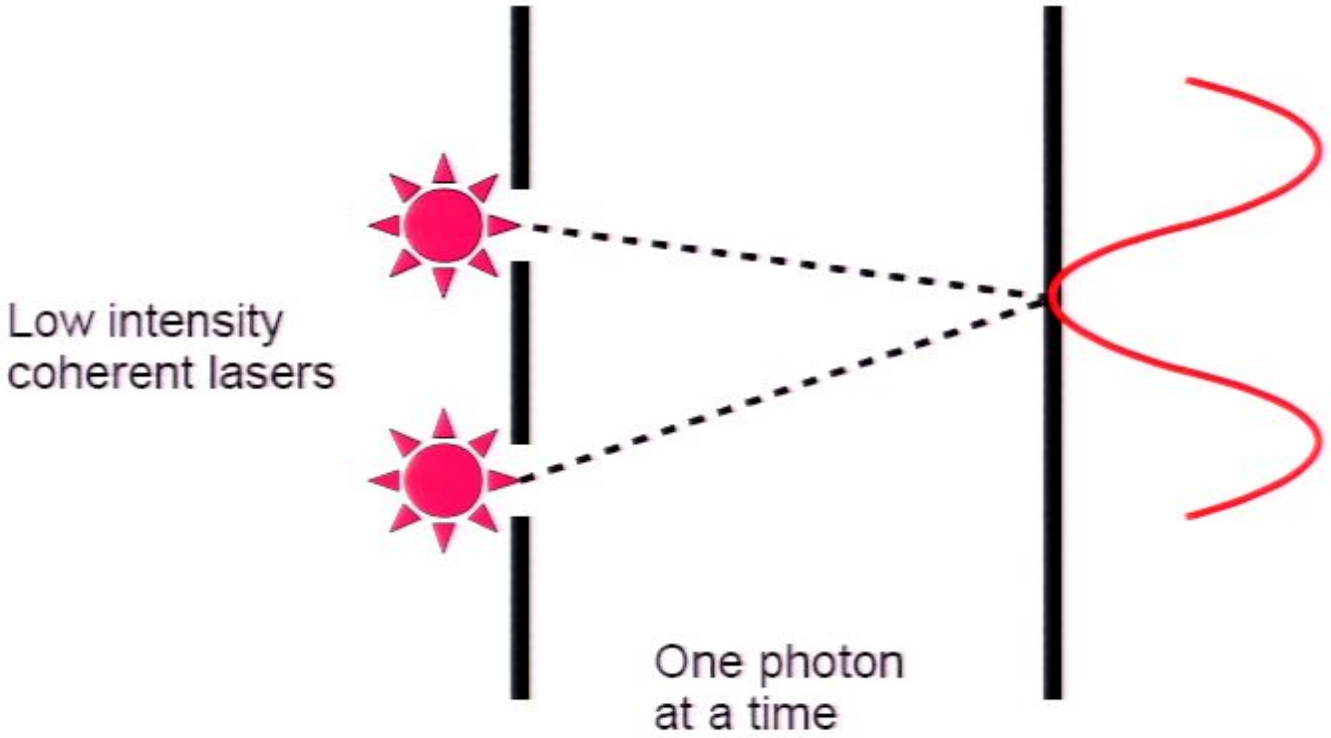
Quantum phenomena : interferometry



Quantum phenomena : interferometry

How to test a for dud bombs

Quantum phenomena : interferometry



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Quantum phenomena : interferometry

How to test a for dud bombs

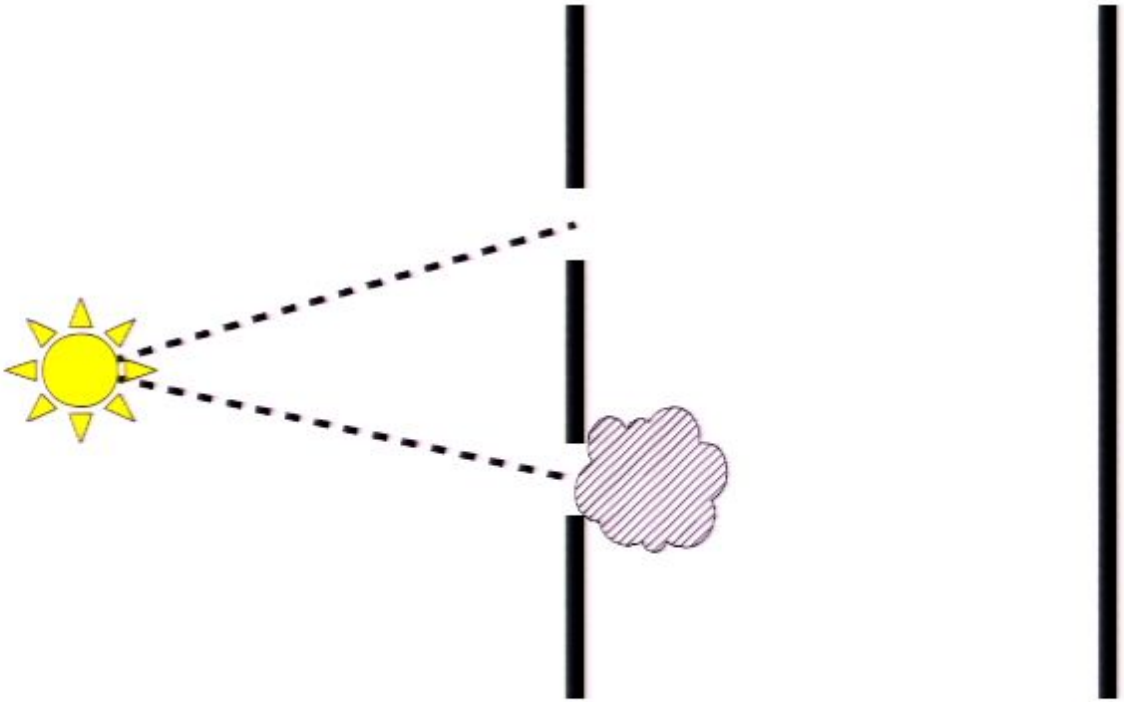
Quantum phenomena : interferometry

... *without* destroying a good bomb?

Quantum phenomena : interferometry

?

Quantum phenomena : interferometry



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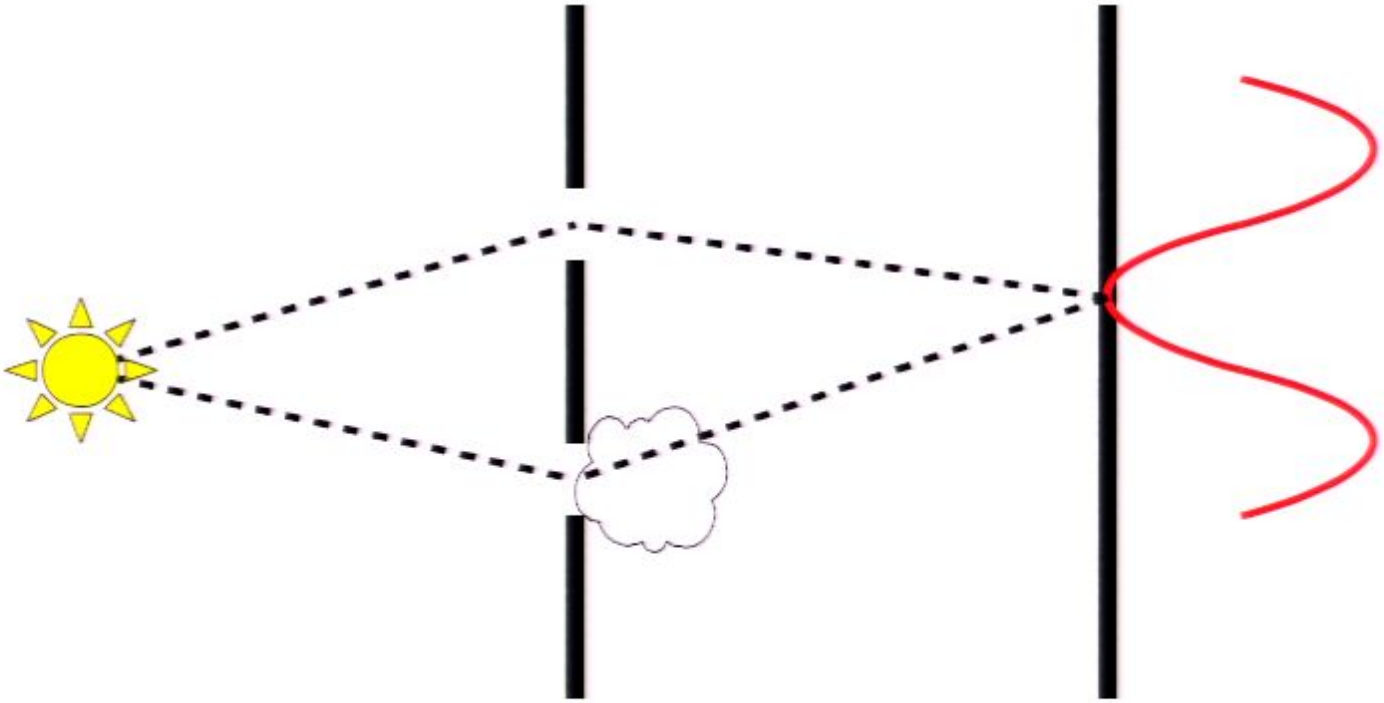

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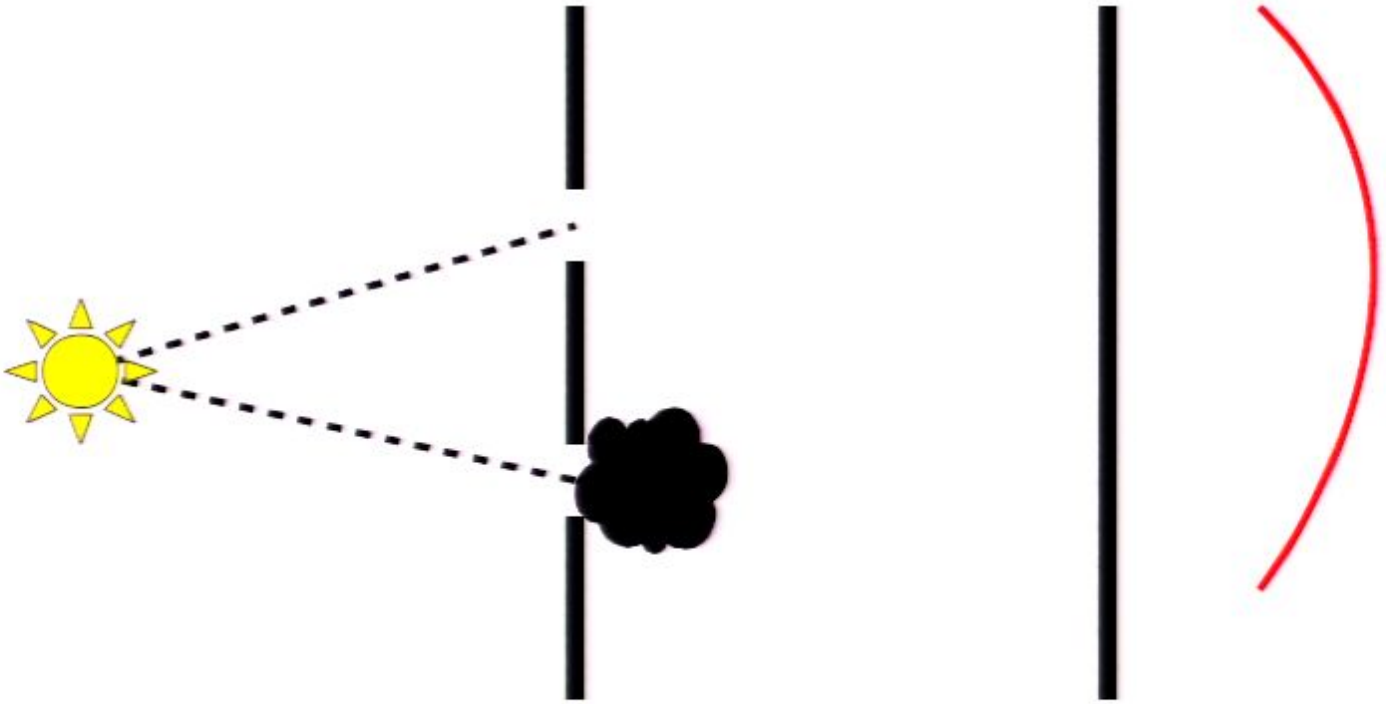

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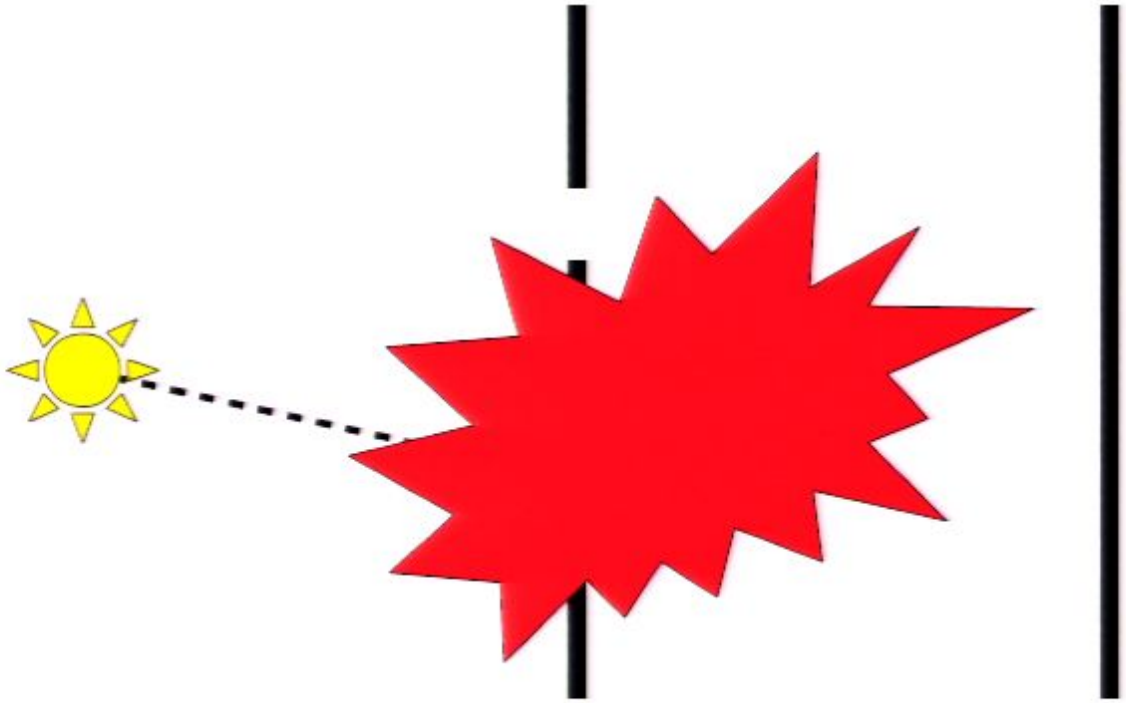

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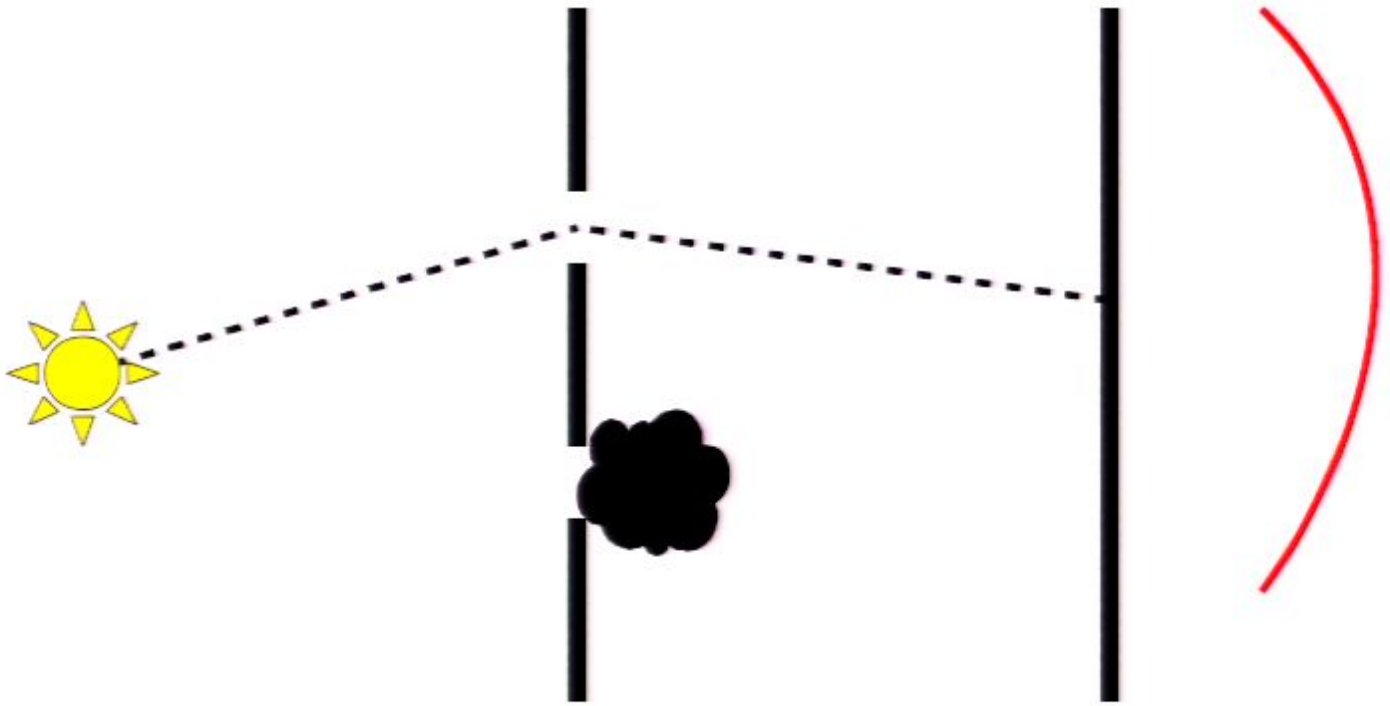

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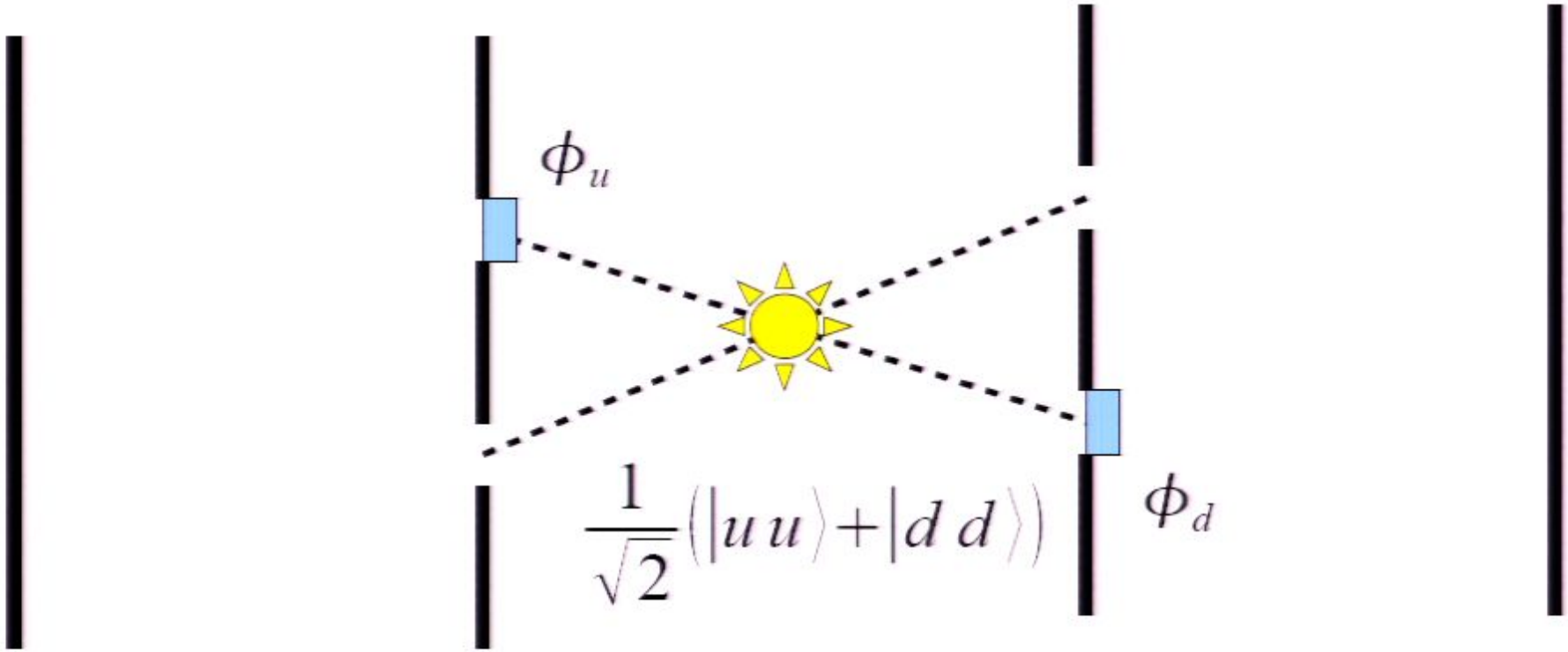

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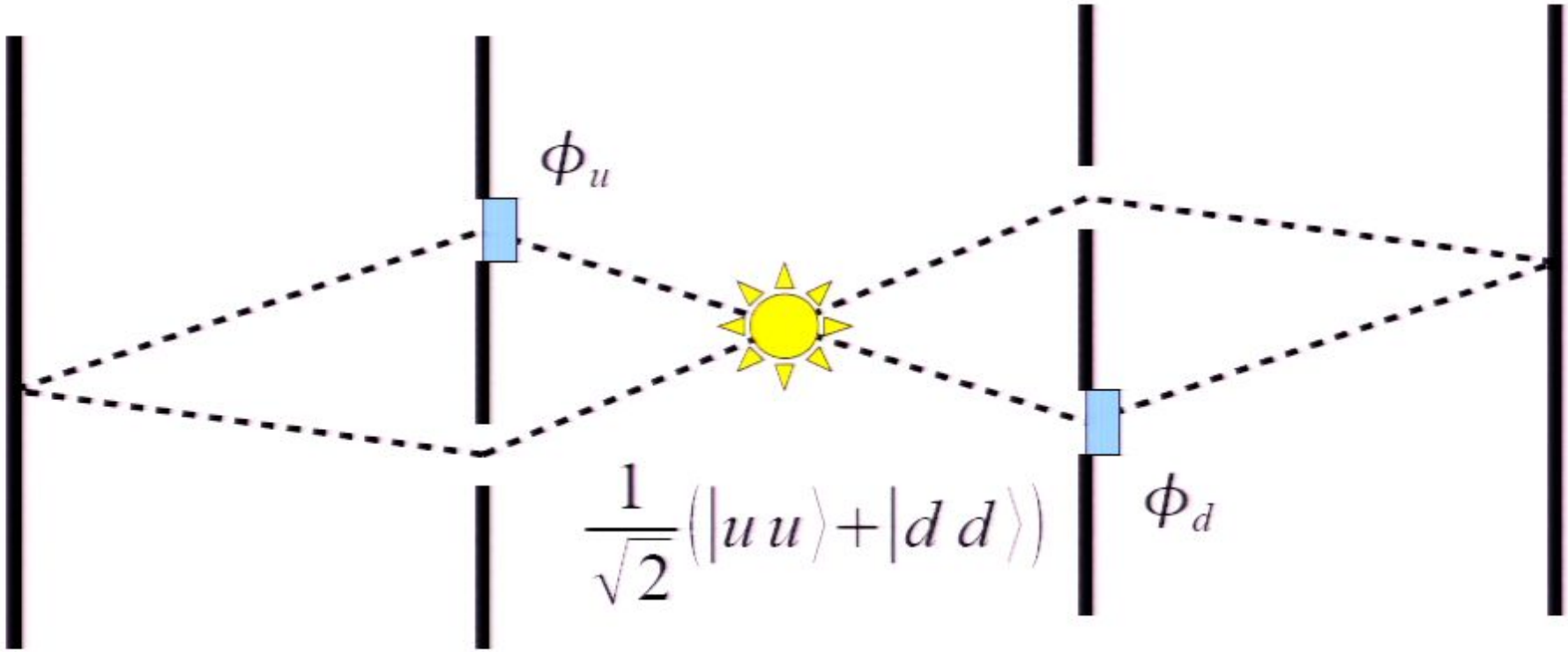

$$\frac{1}{\sqrt{2}}\left(|u\,u\rangle+|d\,d\rangle\right)$$

$$\frac{e^{i\frac{\phi_d+\phi_u}{2}}}{\sqrt{2}}\left(e^{-i\frac{\phi_d-\phi_u}{2}}|u\,u\rangle+e^{i\frac{\phi_d-\phi_u}{2}}|d\,d\rangle\right)$$

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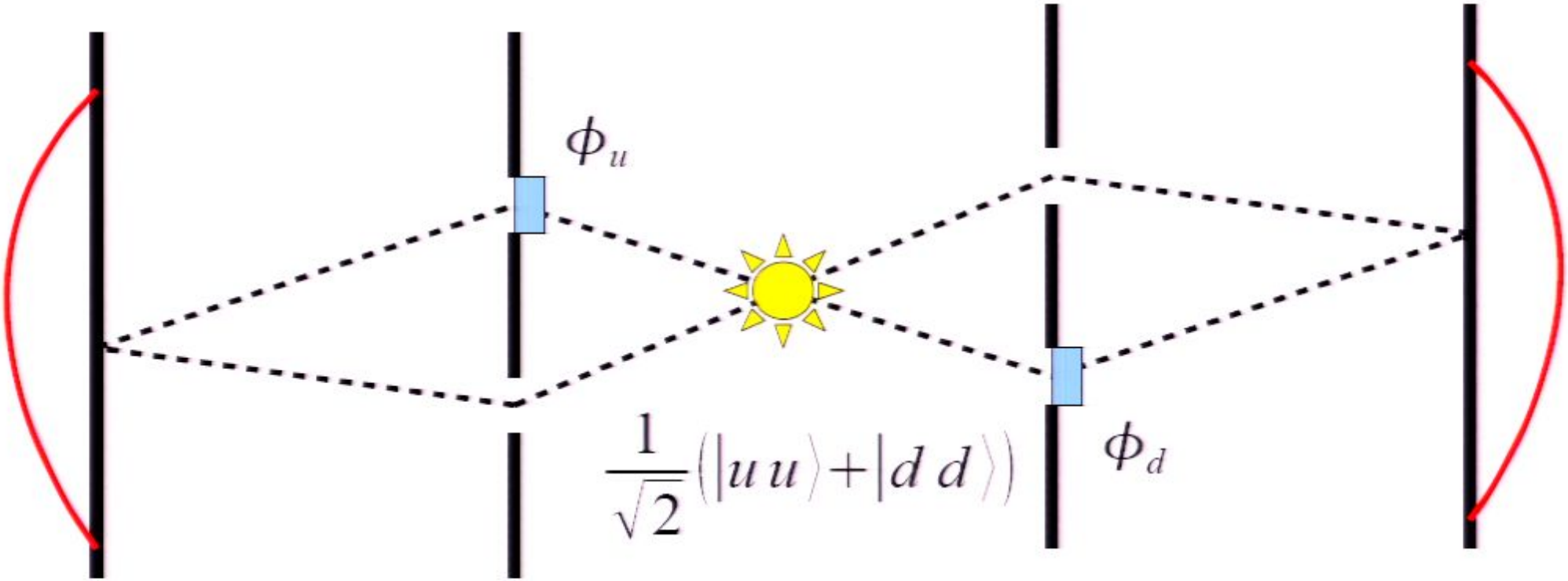

$$P(x_1) \qquad \frac{e^{i\frac{\phi_d+\phi_u}{2}}}{\sqrt{2}}\left(e^{-i\frac{\phi_d-\phi_u}{2}}|u\,u\rangle+e^{i\frac{\phi_d-\phi_u}{2}}|d\,d\rangle\right) \qquad P(x_2)$$

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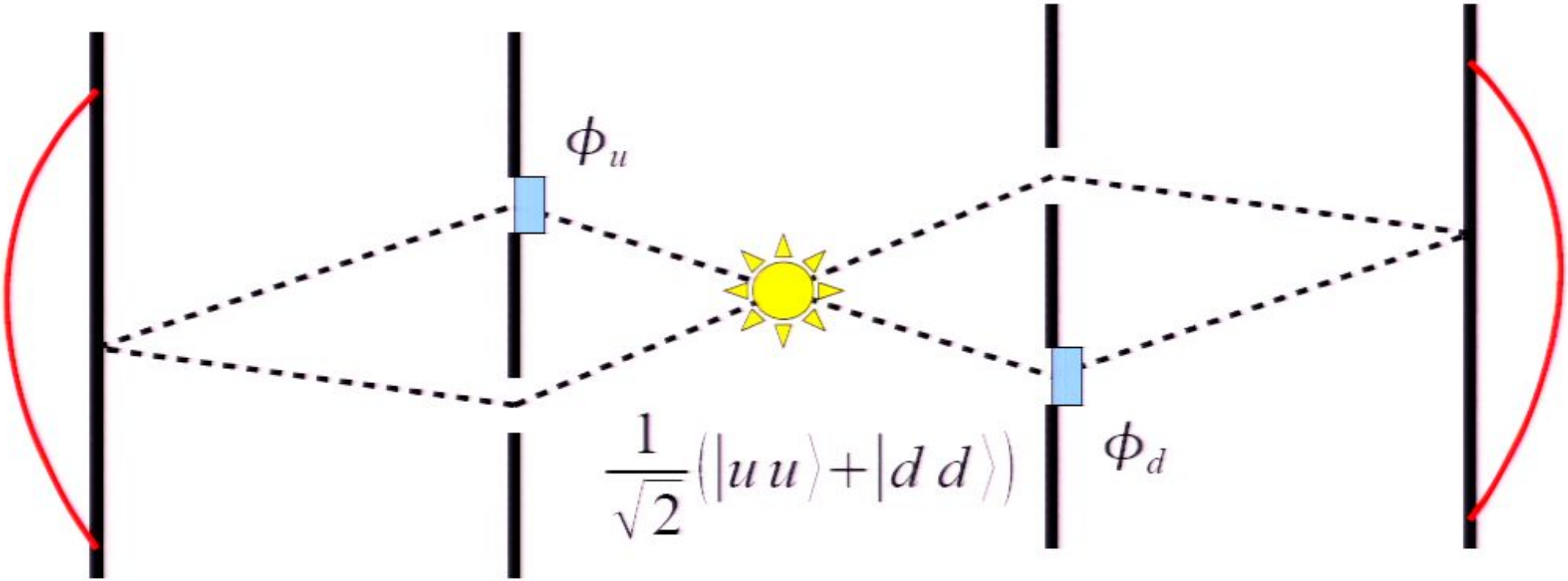

$P(x_1)$ $\quad P(x_1 . x_2) = f(\phi_u - \phi_d)$ $\quad P(x_2)$

Superposition is *still* not a statistical ensemble, even when it's an entangled superposition.

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The non-locality question

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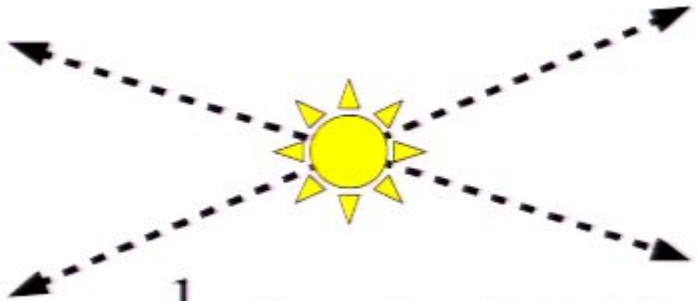

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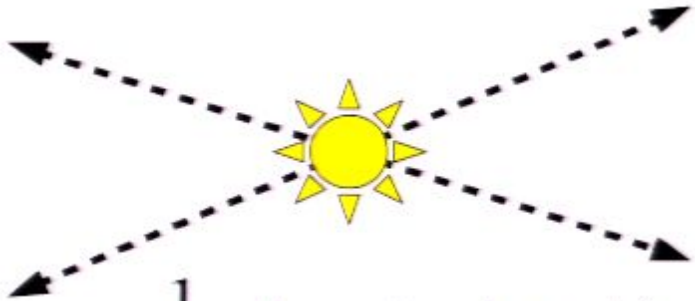

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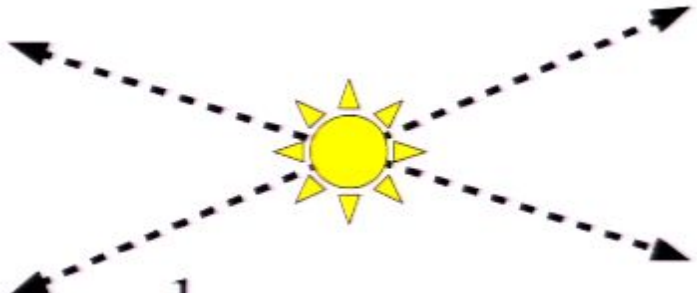

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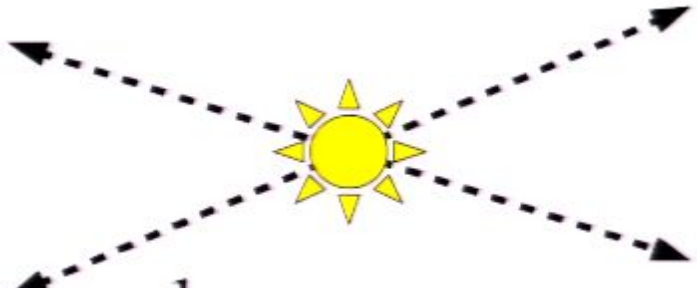

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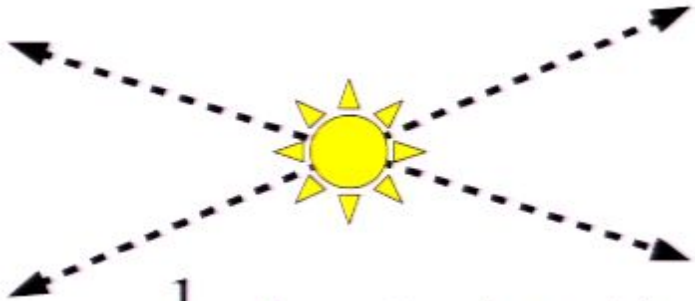

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As the second possibility is non-local, EPR opt for the first

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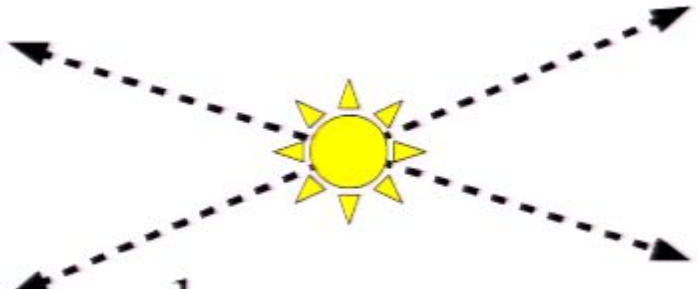

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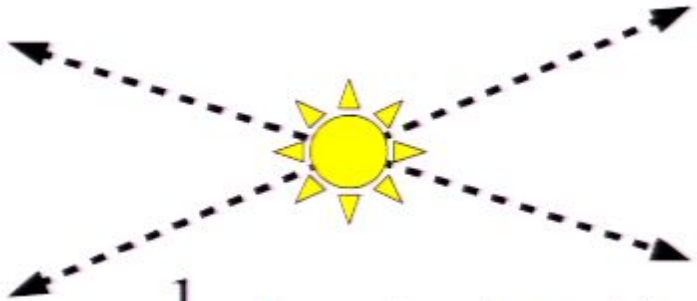

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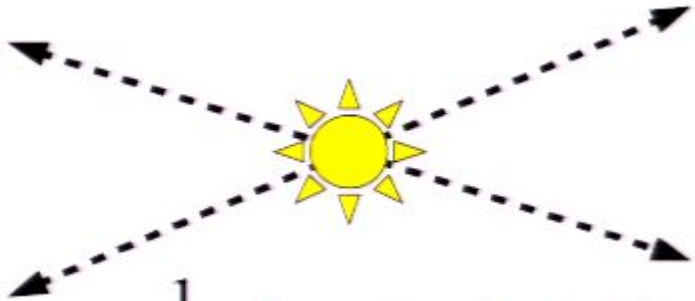

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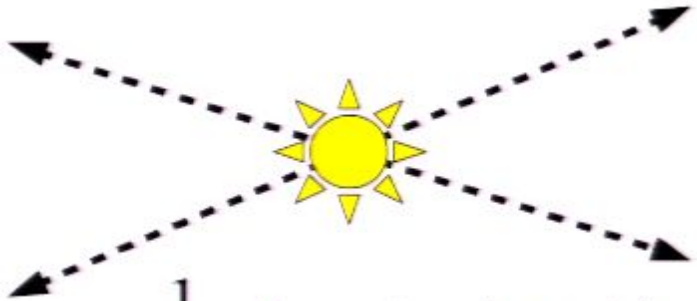

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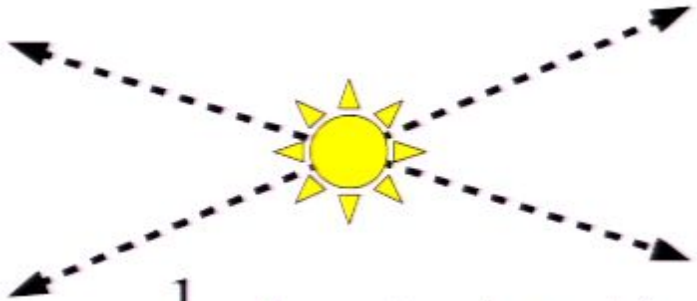

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As quantum theory does not satisfy this equality for the singlet state, Bell concludes from this and EPR that quantum theory is irreducibly, ineliminably, unequivocally *non-local*.

Pirsa 07120045

The non-locality question

1969: Clauser, Holt, Horne, Shimony derive a more general inequality, also violated by the singlet state in quantum theory:

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(Of particular note, in 1976 Bell rederived the CHSH inequality without reference to quantum theory, hidden variables or anything like that)

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  - Empirical predictions. Wavefunction collapse models generically produce situations where different predictions can be made to quantum theory. Experimentally probing these situations are hard, as environmental decoherence must be excluded.

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  - The wavefunction shares some properties with classical probability distributions. de Broglie-Bohm hidden variable models treat the wavefunction as a real entity. Is it possible to construct models in which the wavefunction is only a probability distribution over a microscopic reality?

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  - Constructs which do things quantum mechanics *cannot* do.
    - E.g. Popescu-Rohrlich non-local boxes, which are more non-local than quantum theory, although still do not permit signalling.

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  - Bell tests, entanglement, operational formulations, quantum parallelism, no-cloning, many early researchers and many early results came from the study of quantum foundations.
- Quantum gravity
  - Collapse theories, hidden variables, causal frameworks and other reformulations may help. Any quantum theory of gravity will face the same challenges for understanding observed quantum phenomena.
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- Statistical mechanics, cosmology
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