Title: On Grandma Quantum's Nonexistent Wheels: The Causal Efficacy of Quantum Non-Events and their Significance

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Abstract: Among QM's (in)famous oddities, perhaps the most intriguing is the capability of an event that did not occur, only could have, to exert a causal effect. How can a non-event leave a trace as concrete as a detector's click? I discuss this question and a novel insight into it offered by Cohen and Elitzur's "Quantum Oblivion" (20014).

On Grandma Quantum's Nonexistent Wheels: The Causal Efficacy of Quantum Non-Events and their Significance

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Outline

1. Oblivion as a Fundamental Quantum Oddity
2. Insights
3. Applications
4. Surprises

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If Grandma had Wheels, she would be a Wagon

(Yiddish proverb)

אויב די באָבע וואָלט געהאַט רעדער
וואָלט זי געווען אַ וואָגן.

If grandma had wheels, she would be a wagon.

Oyb di bobe volt gehat reder,
volt zi geven a vogn.

If Grandma had Wheels, she would be a Wagon

(Yiddish proverb)

How is it, then, that a *quantum-mechanical* grandma, although having no wheels, can sometimes outrace police cars?

If Grandma had Wheels, she would be a Wagon

(Yiddish proverb)

How is it, then, that a *quantum-mechanical* grandma, although having no wheels, can sometimes outrace police cars?

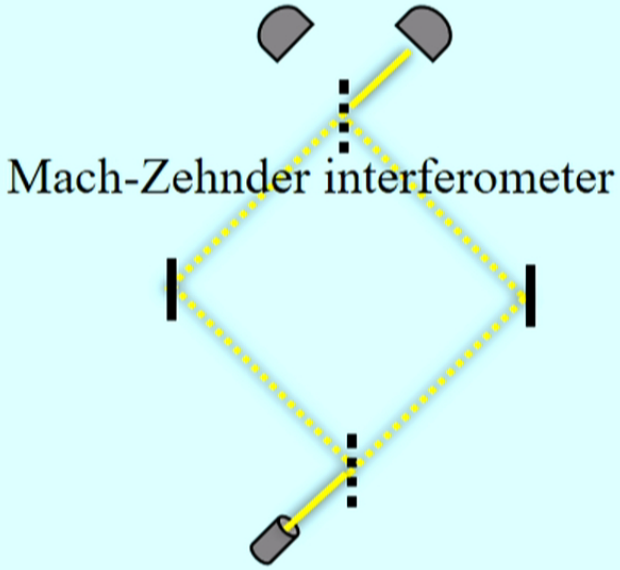
Perhaps due to a less happy sign of old age – forgetfulness.

1. Oblivion as a Fundamental Quantum Oddity

Definition

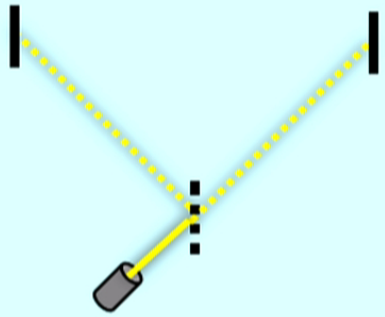
Quantum oblivion is the result of an interaction, of which one or more bodies' physical states are observably altered while the other(s) exhibit no consequence of the interaction.

Preface: Uncertainty relations and reversibility



Preface: Uncertainty relations and reversibility

Michelson interferometer



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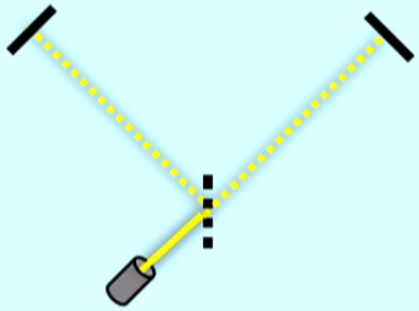

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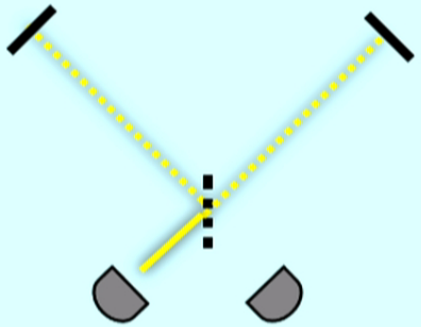

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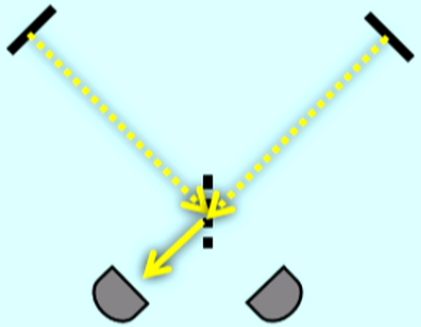

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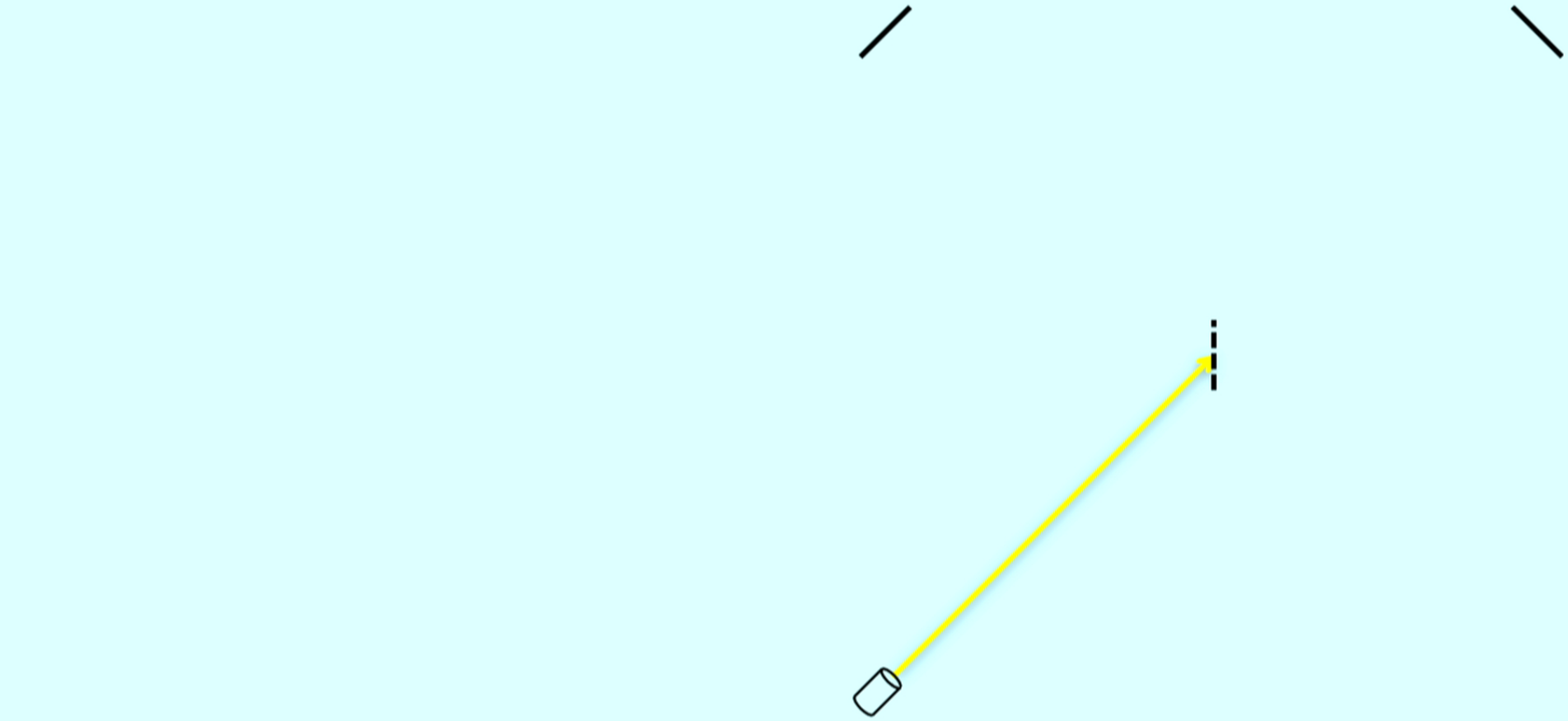

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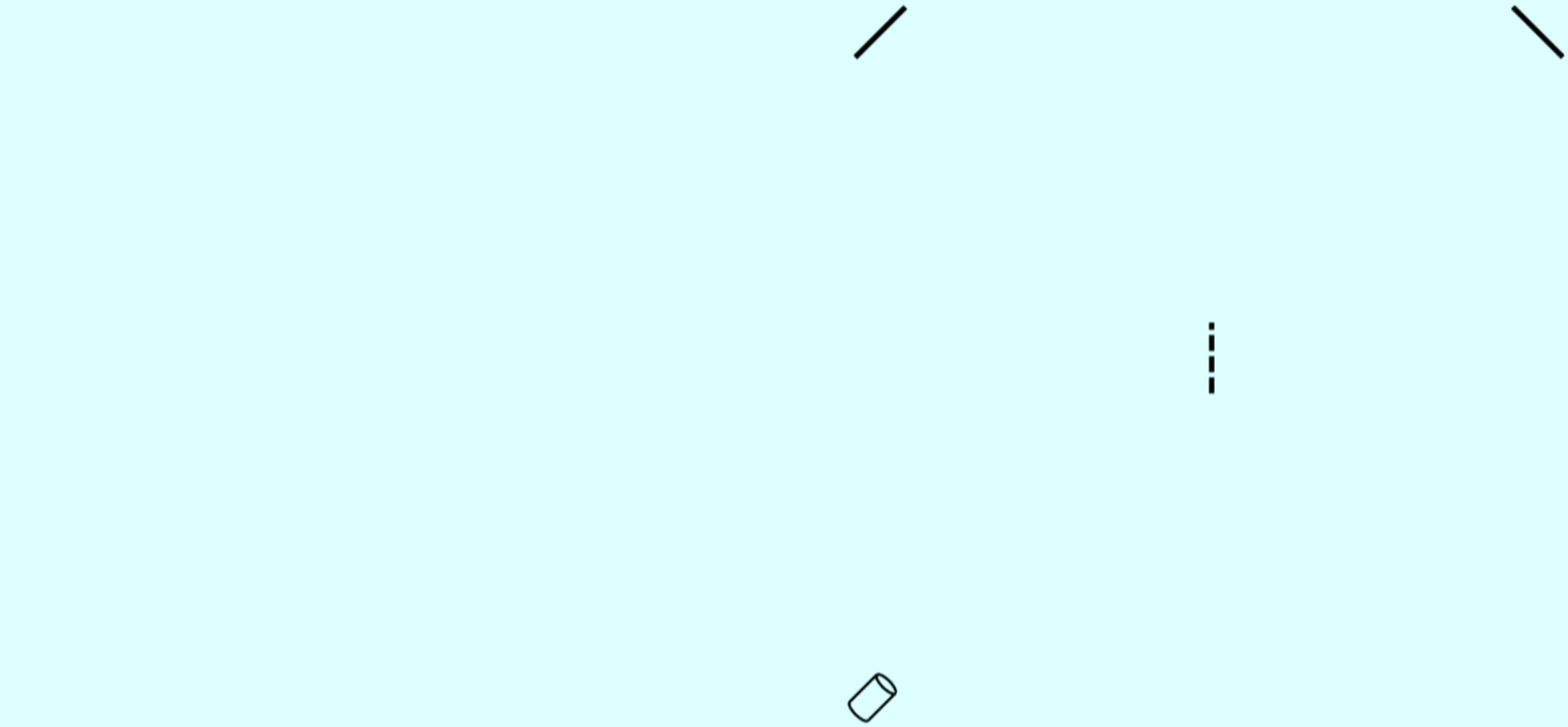

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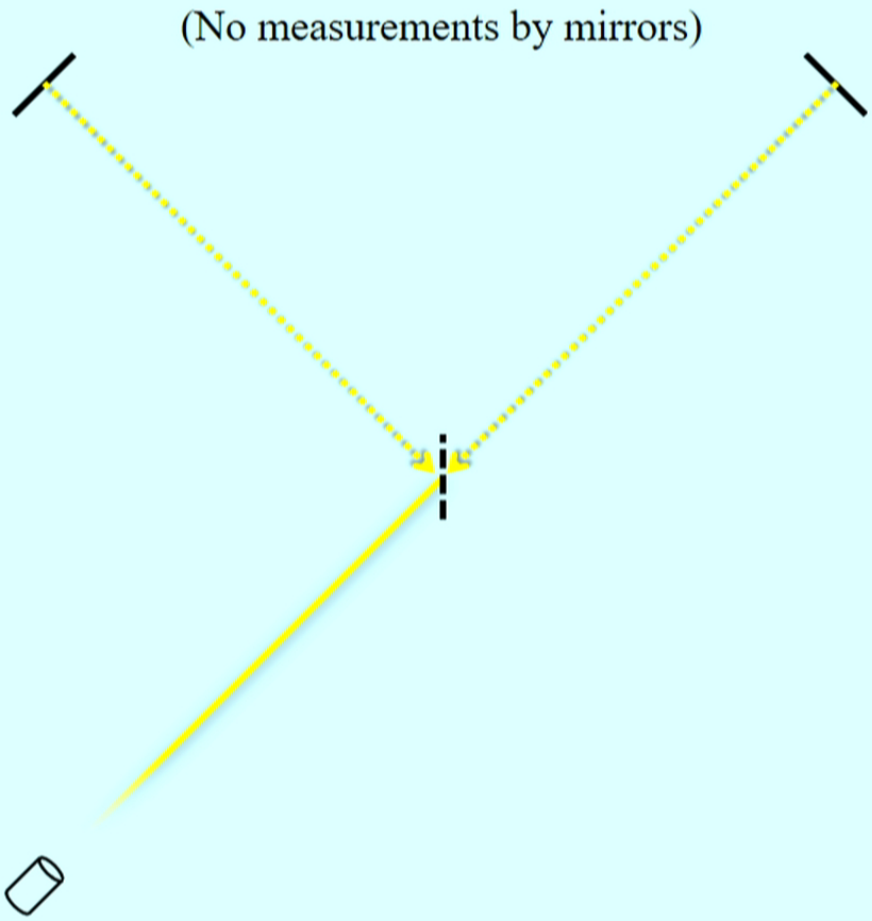

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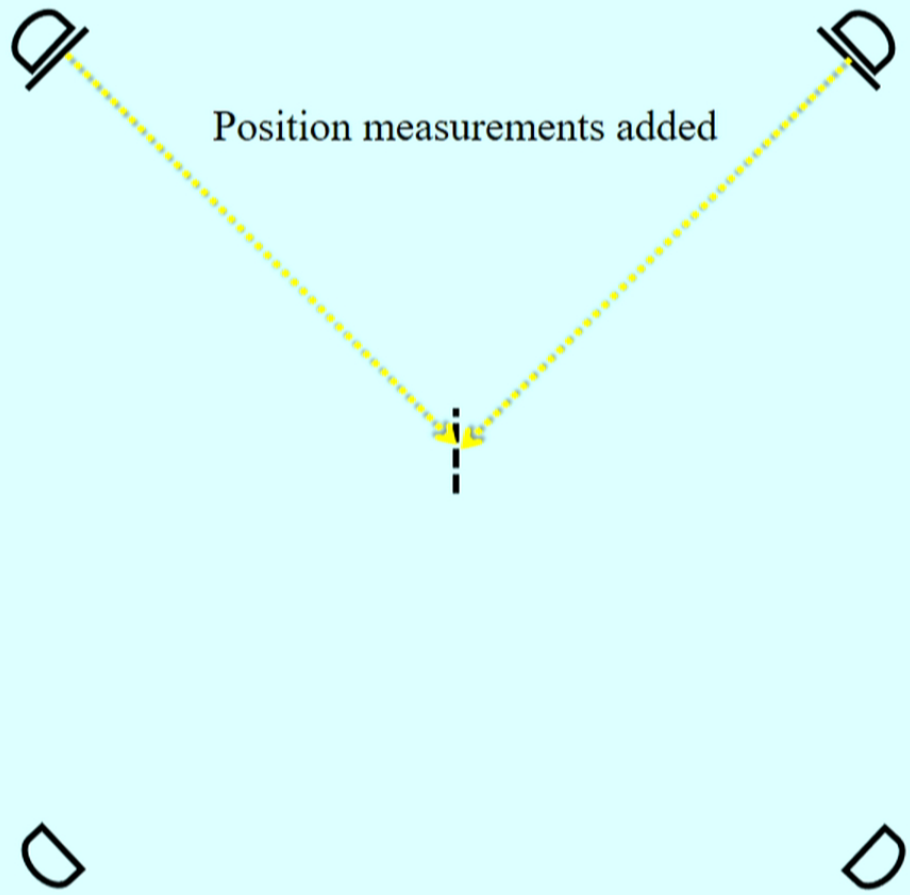

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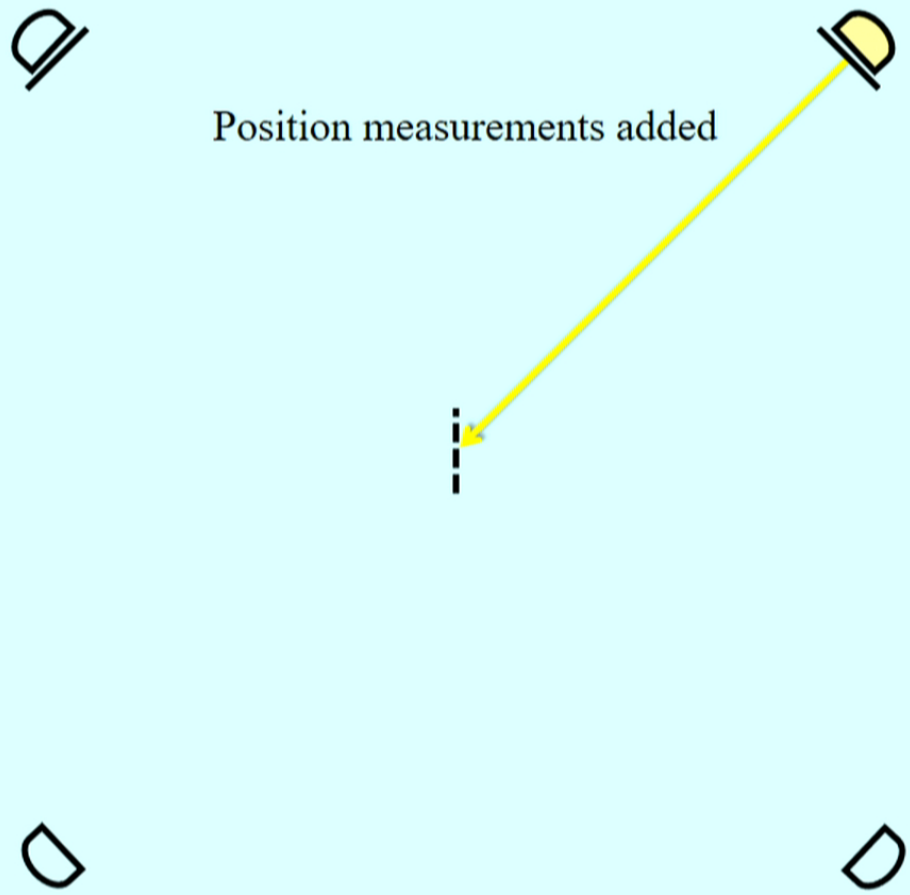

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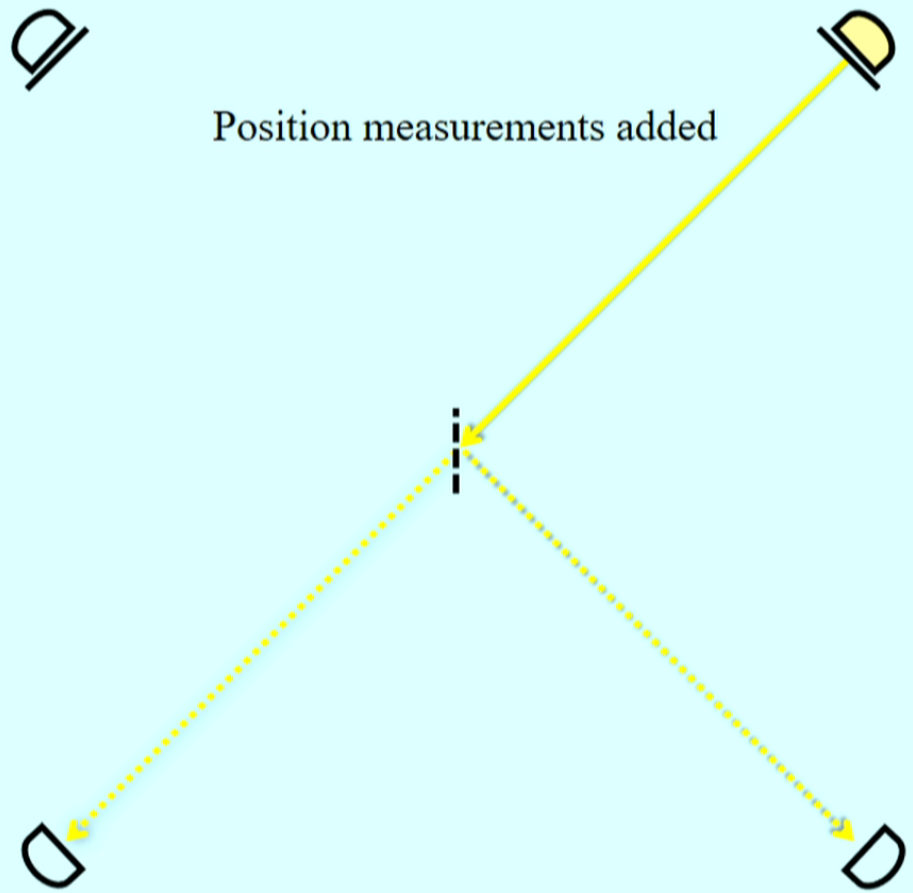

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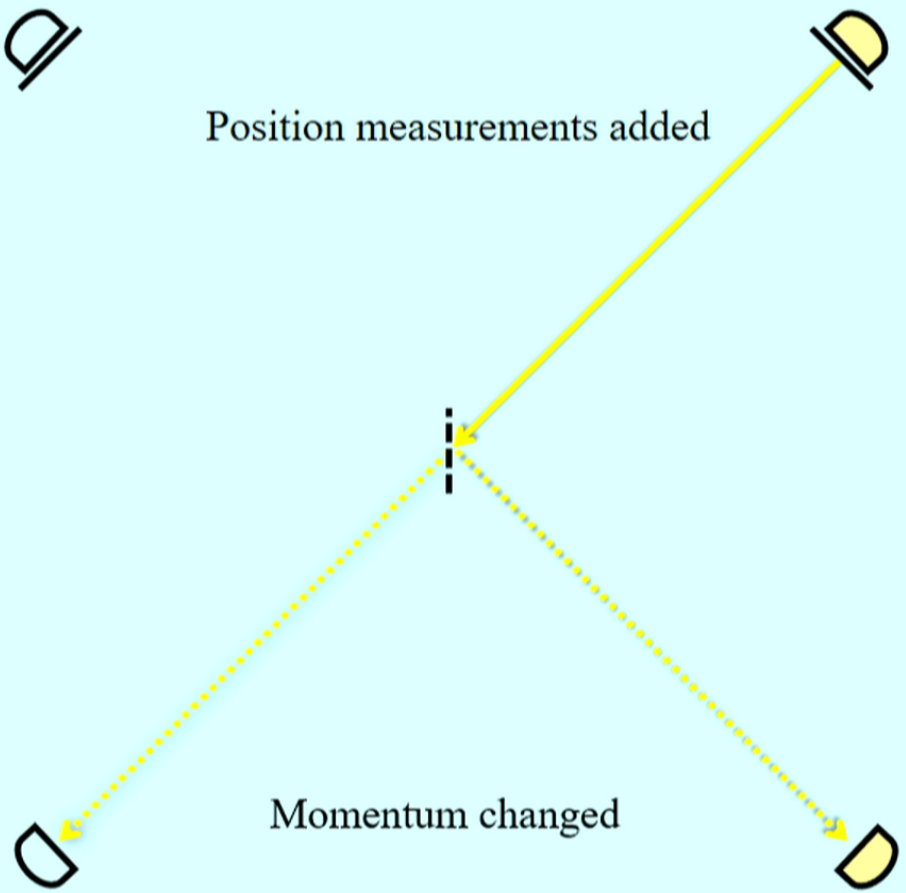

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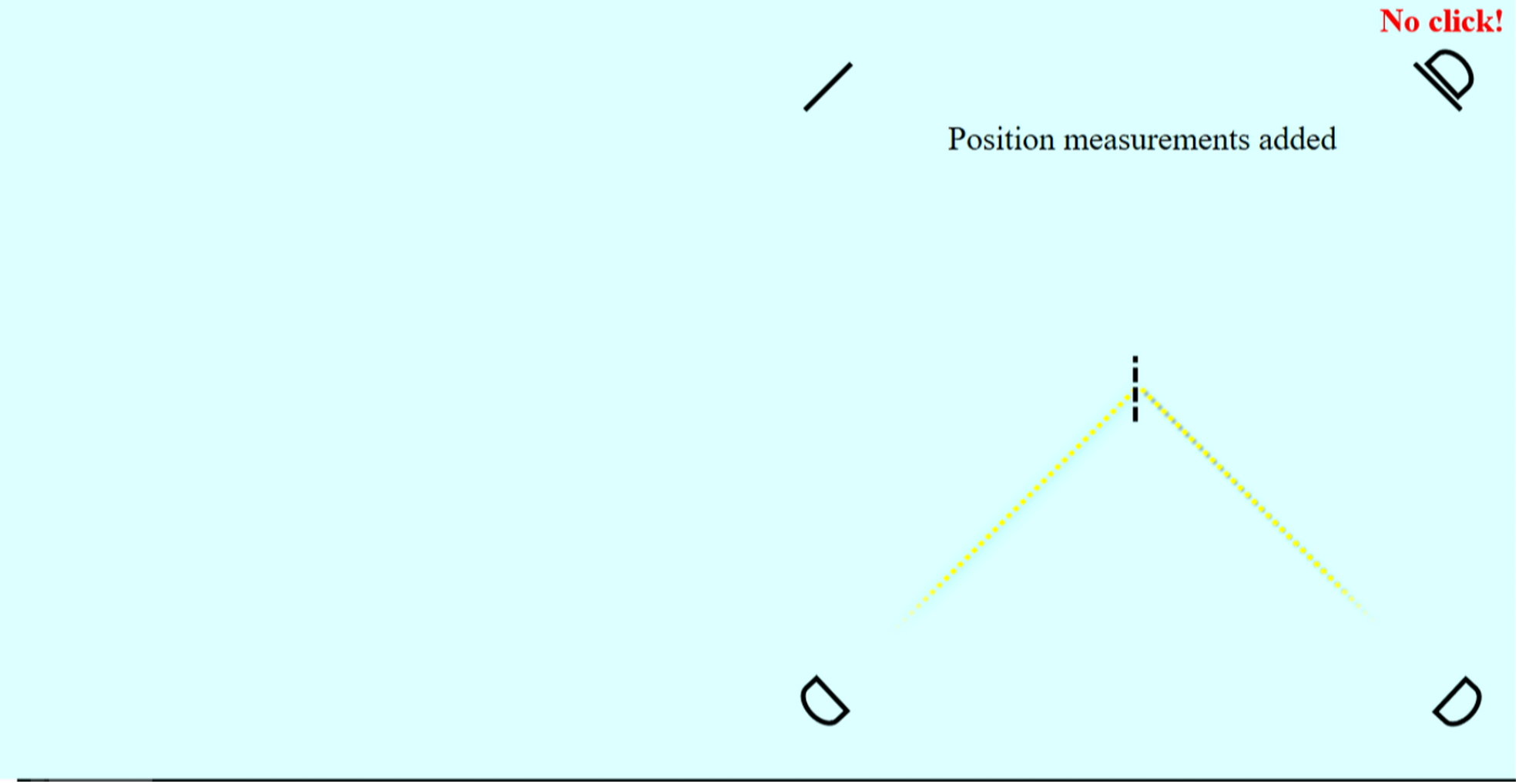

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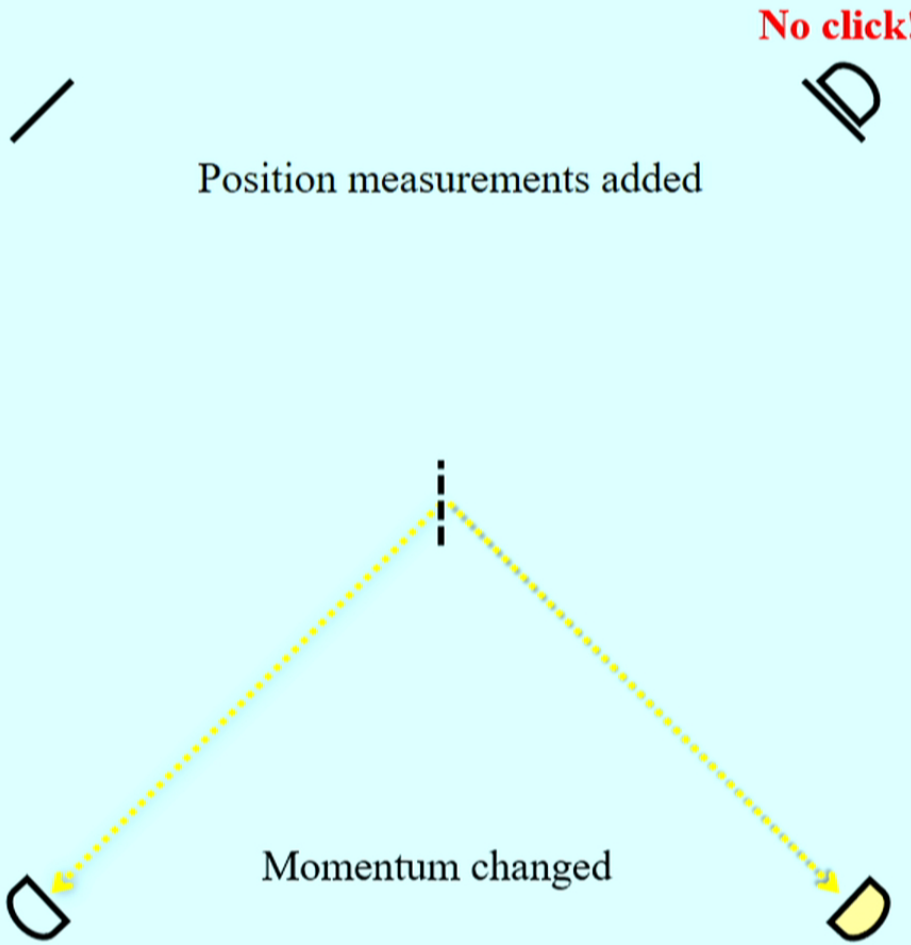
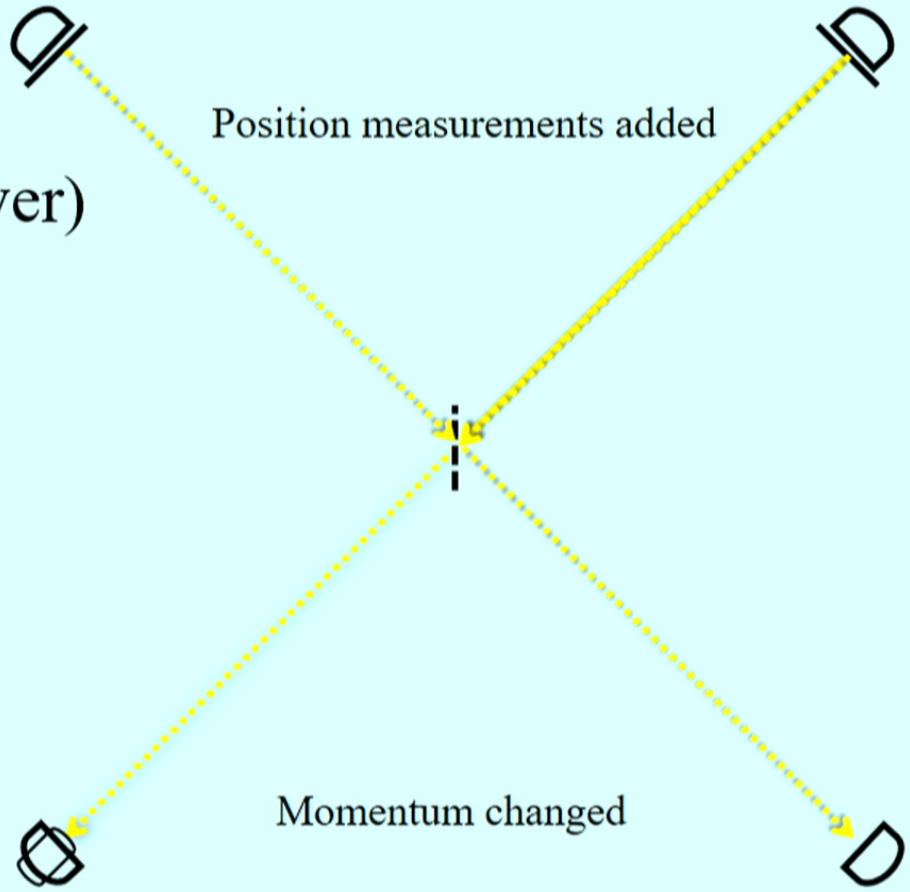


Preface: Uncertainty relations and reversibility

Classical physics:

Scientia potestas est (knowledge is power)

(Francis Bacon)



Preface: Uncertainty relations and reversibility

Classical physics:

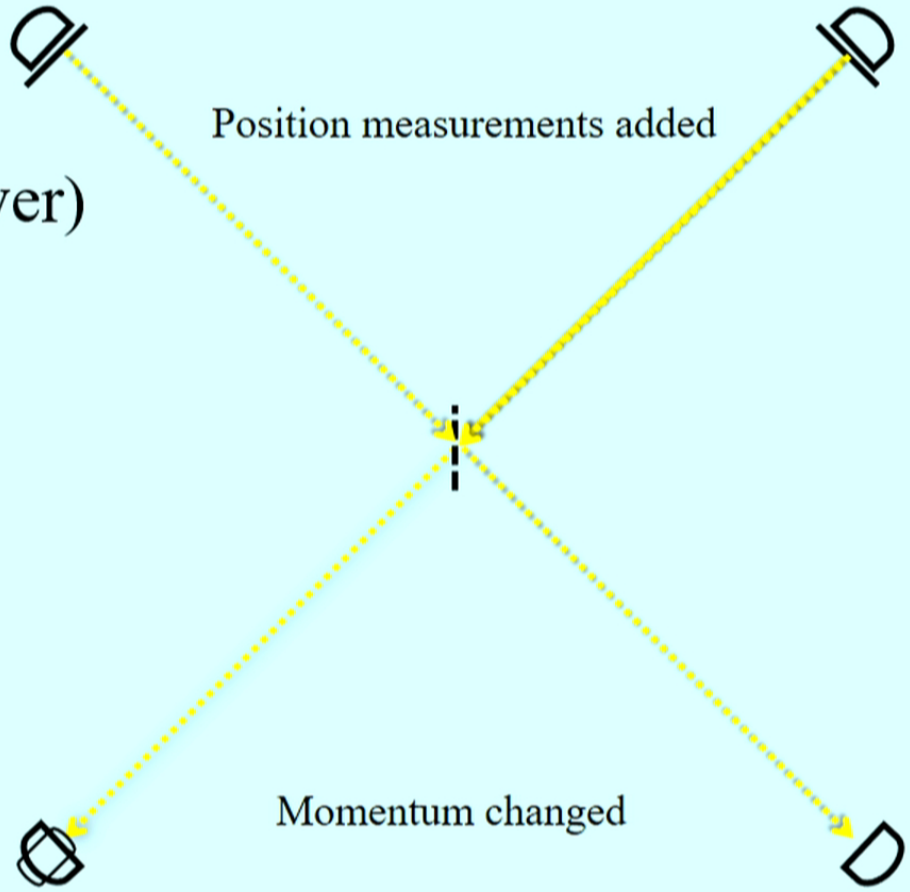
Scientia potestas est (knowledge is power)

(Francis Bacon)

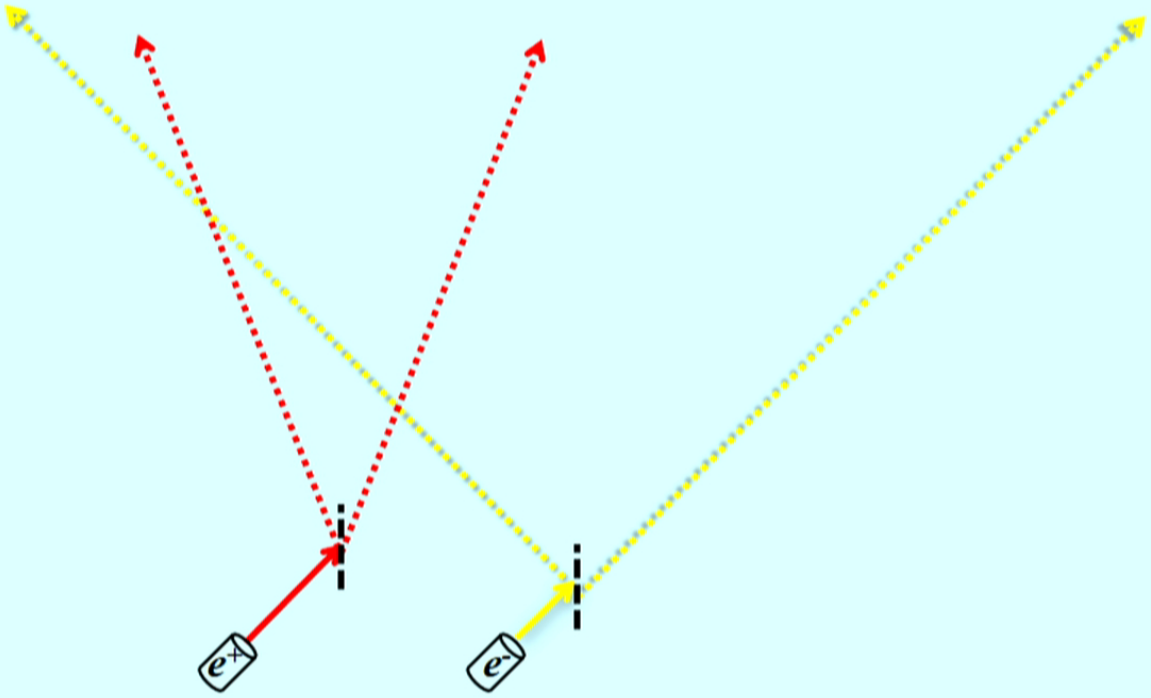
Quantum mechanics:

Ignorance is power

(George Orwell, "*1984*")



The setting: Asymmetric interaction between two wave-functions



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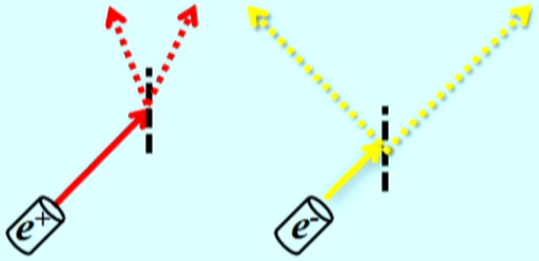
Pre-interaction state

$$\left|\psi_{e^+}\right\rangle = \frac{1}{\sqrt{2}}\left(\left|L_{e^+}\right\rangle + \left|R_{e^+}\right\rangle\right)$$

$$\left|\psi_{e^-}\right\rangle = \frac{1}{\sqrt{2}}\left(\left|L_{e^-}\right\rangle + \left|R_{e^-}\right\rangle\right)$$



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Mutual IFM: Annihilation? (1)

$$\left|\psi_{e^+}\right\rangle = \frac{1}{\sqrt{2}}\left(\left|L_{e^+}\right\rangle + \left|R_{e^+}\right\rangle\right)$$

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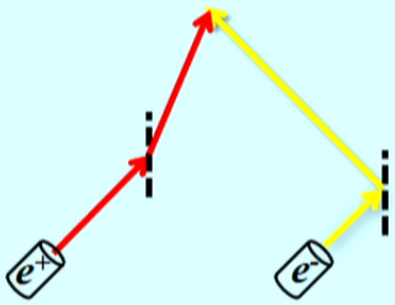

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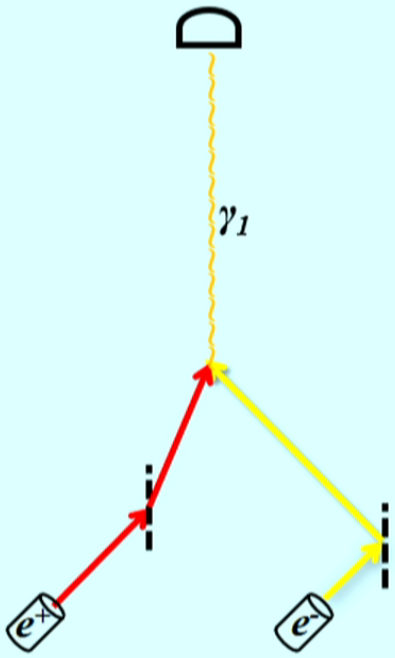
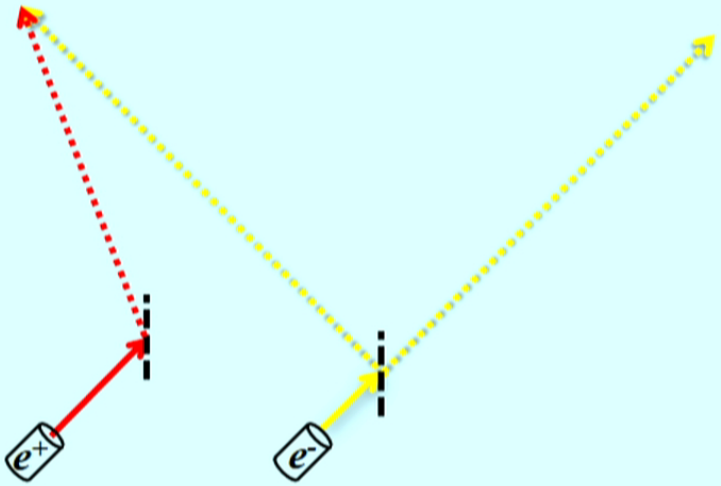


$$\left|\psi_{e^-}\right\rangle = \frac{1}{\sqrt{2}}\left(\left|L_{e^-}\right\rangle + \left|R_{e^-}\right\rangle\right)$$

13

Mutual IFM: Annihilation? (2)

$$\left|\psi_{e^+}\right\rangle = \frac{1}{\sqrt{2}}\left(\left|L_{e^+}\right\rangle + \left|R_{e^+}\right\rangle\right)$$

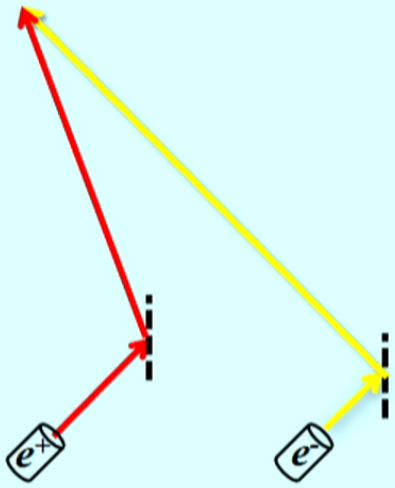


$$\left|\psi_{e^-}\right\rangle = \frac{1}{\sqrt{2}}\left(\left|L_{e^-}\right\rangle + \left|R_{e^-}\right\rangle\right)$$

14

Mutual IFM: Annihilation? (2)

$$\left|\psi_{e^+}\right\rangle = \frac{1}{\sqrt{2}}\left(\left|L_{e^+}\right\rangle + \left|R_{e^+}\right\rangle\right)$$



$$\left|\psi_{e^-}\right\rangle = \frac{1}{\sqrt{2}}\left(\left|L_{e^-}\right\rangle + \left|R_{e^-}\right\rangle\right)$$

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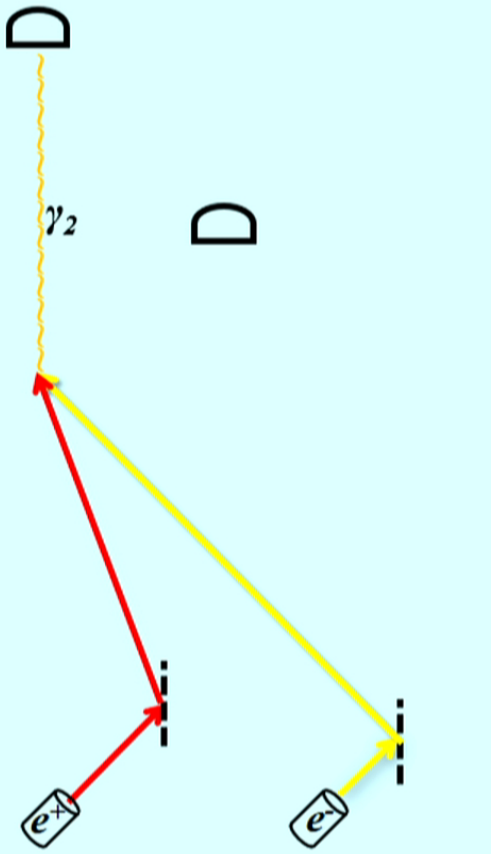
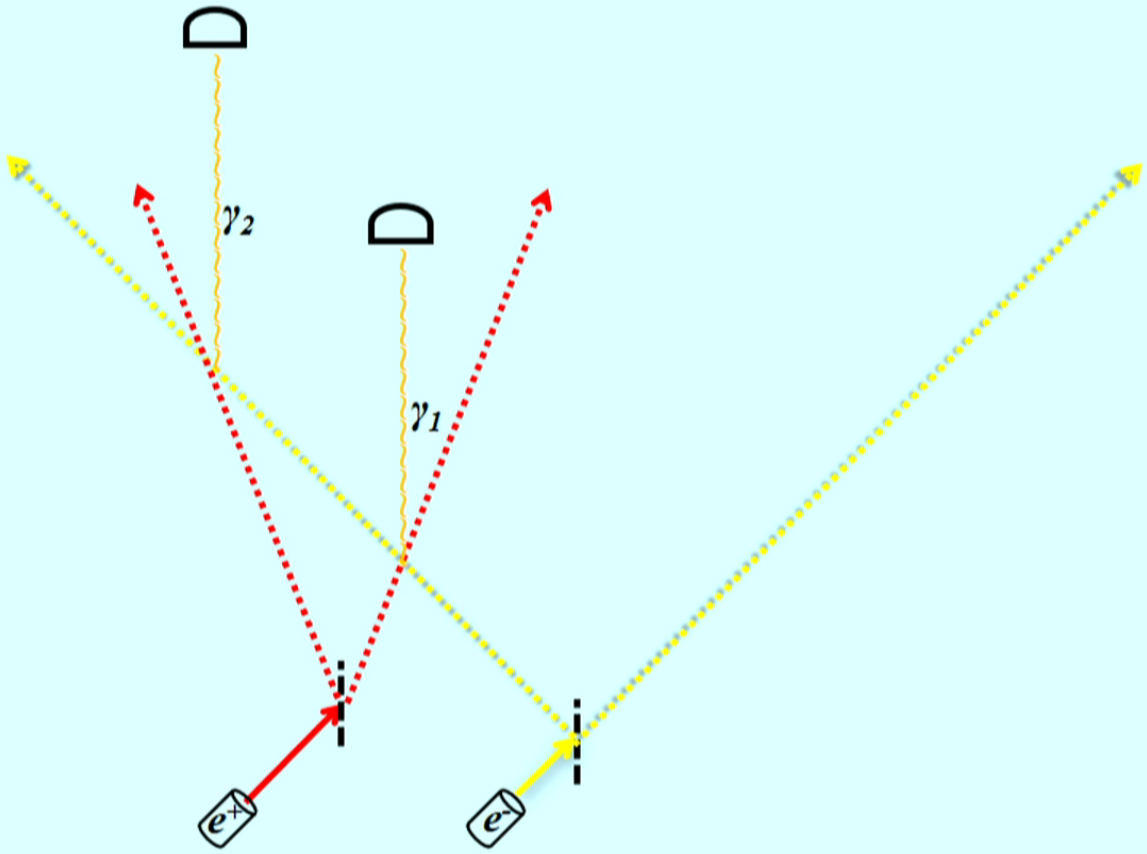
Mutual IFM: Annihilation? (2)



$$\left|\psi_{tot}\right\rangle = \left|L_{e^+}\right\rangle \left|L_{e^-}\right\rangle$$

Notice the unique role played by "counterfactual photons"

$$|\psi\gamma_1\rangle, |\psi\gamma_2\rangle = \frac{1}{\sqrt{2}}(|emitted\rangle + |never\ emitted\rangle)$$



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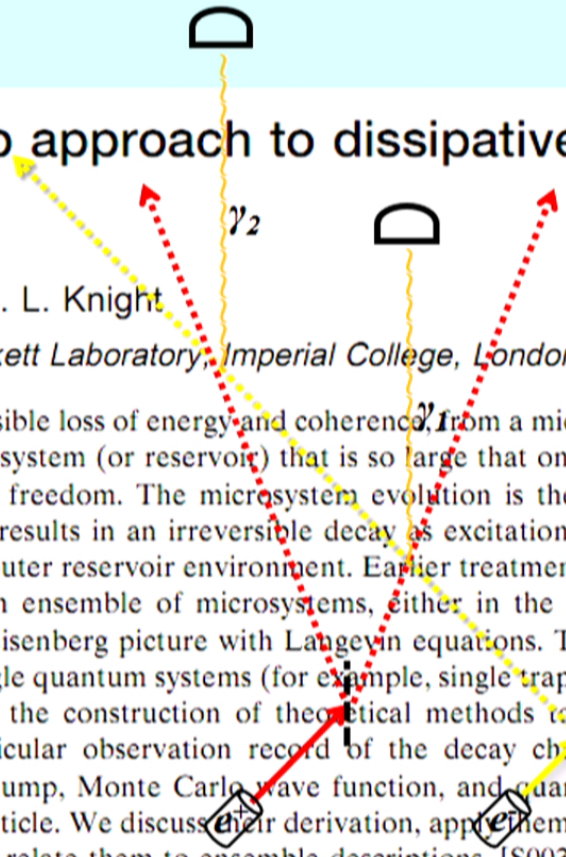
Notice the unique role played by "counterfactal photons"



To reassure ourselves that this is all true, we note that the history splits into two alternatives in a time Δt:

$$|\Psi\rangle = \begin{cases} |\Psi_{\text{emit}}\rangle & \text{with probability } \Delta P, \\ |\Psi_{\text{no emission}}\rangle & \text{with probability } 1-\Delta P. \end{cases} \quad (129)$$

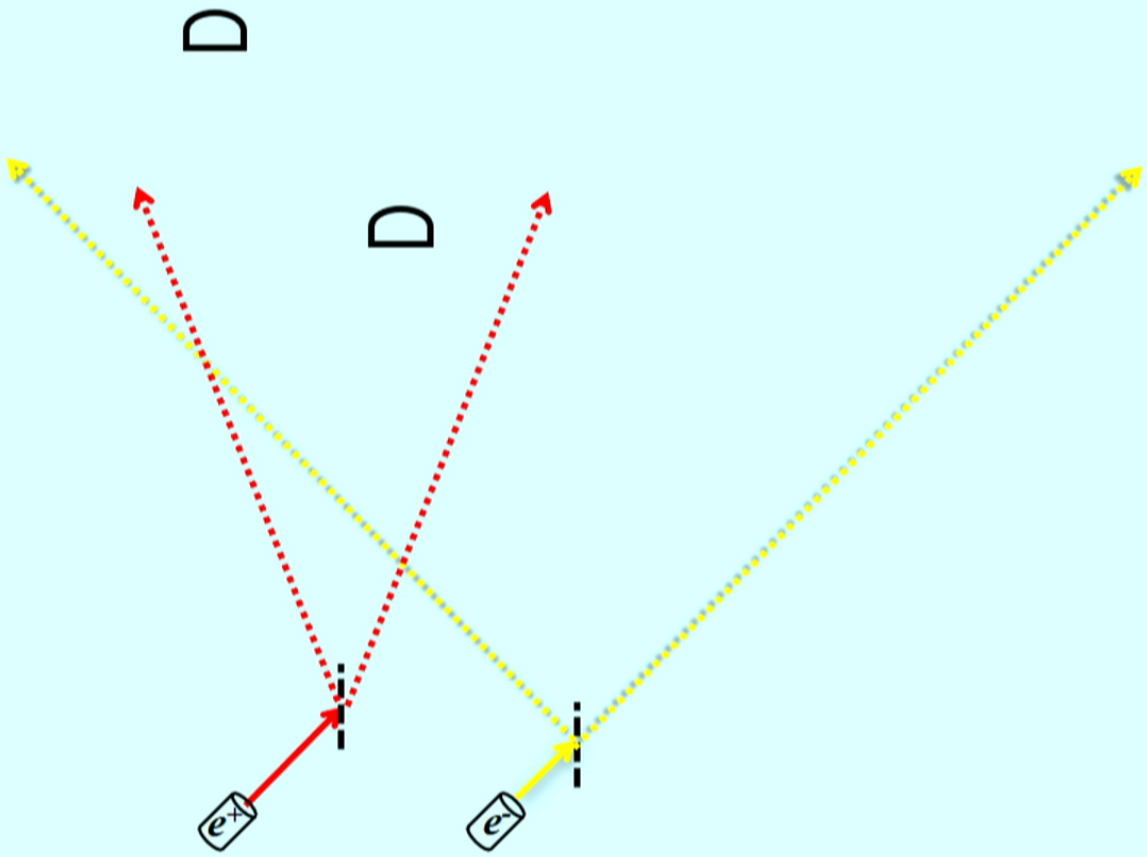
The quantum-jump approach to dissipative dynamics in quantum optics

M. B. Plenio and P. L. Knight

Optics Section, Blackett Laboratory, Imperial College, London SW7 2BZ, United Kingdom

Dissipation, the irreversible loss of energy and coherence from a microsystem is the result of coupling to a much larger macrosystem (or reservoir) that is so large that one has no chance of keeping track of all of its degrees of freedom. The microsystem evolution is then described by tracing over the reservoir states, which results in an irreversible decay as excitation leaks out of the initially excited microsystems into the outer reservoir environment. Earlier treatments of this dissipation used density matrices to describe an ensemble of microsystems, either in the Schrödinger picture with master equations, or in the Heisenberg picture with Langevin equations. The development of experimental techniques to study single quantum systems (for example, single trapped ions, or cavity-radiation-field modes) has stimulated the construction of theoretical methods to describe individual realizations conditioned on a particular observation record of the decay channel. These methods, variously described as quantum-jump, Monte Carlo wave function, and quantum-trajectory methods, are the subject of this review article. We discuss their derivation, apply them to a number of current problems in quantum optics, and relate them to ensemble descriptions. [S0034-6861(98)00601-1]

Annihilation?



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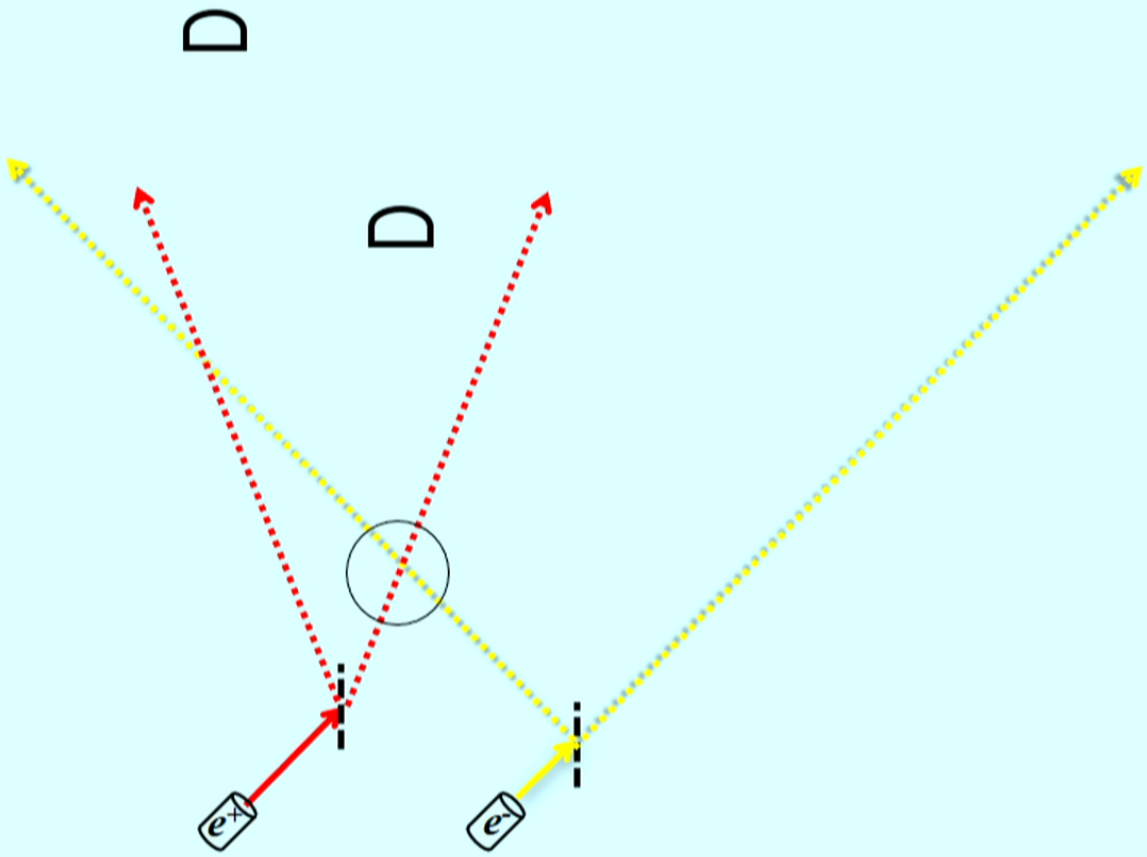
No Annihilation



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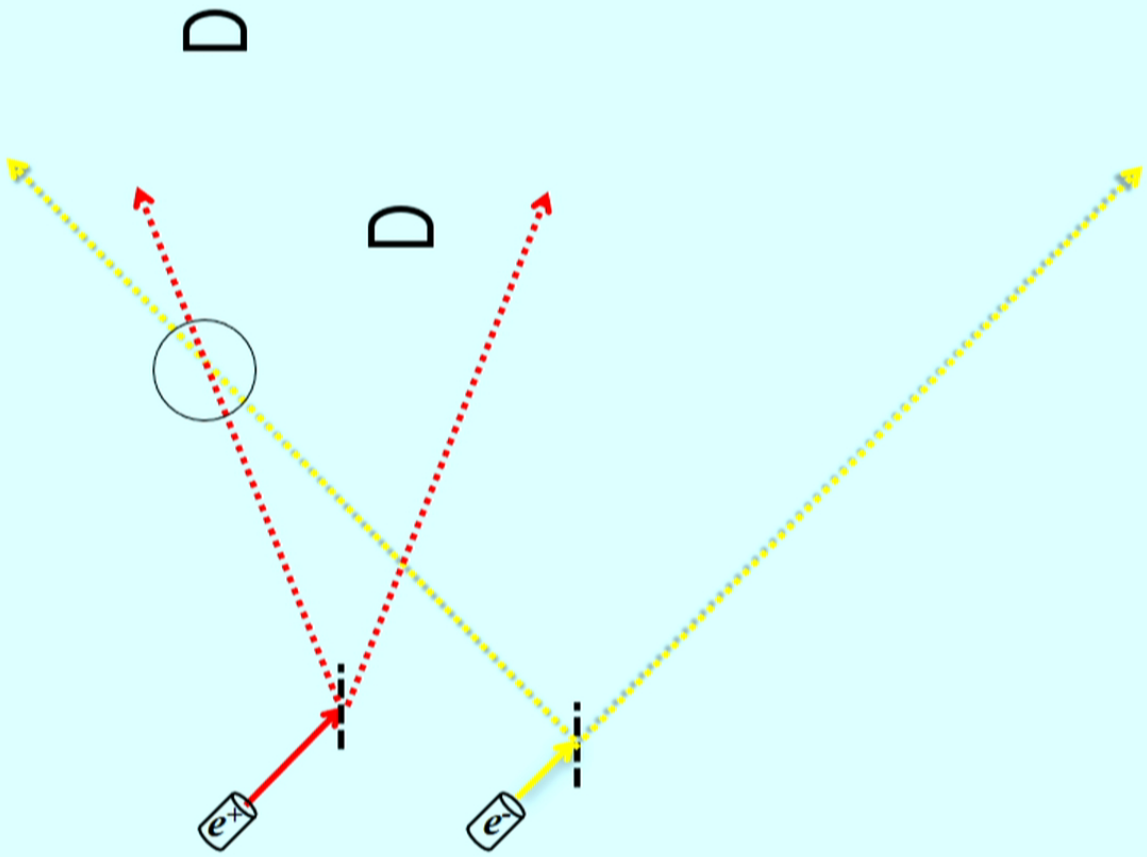
No Annihilation



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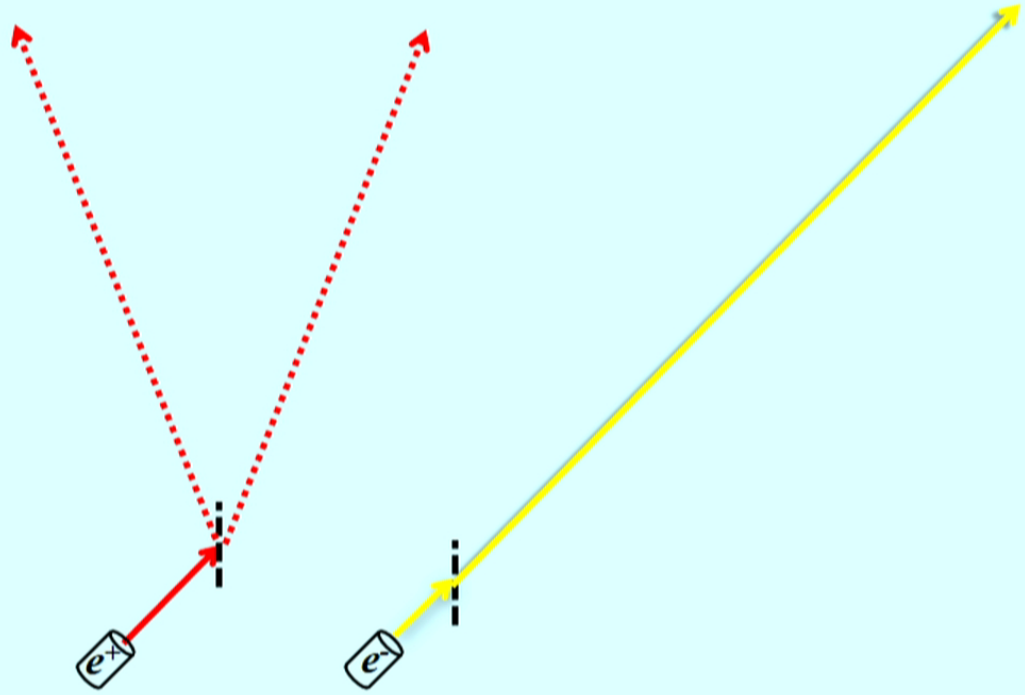
No Annihilation – then what?



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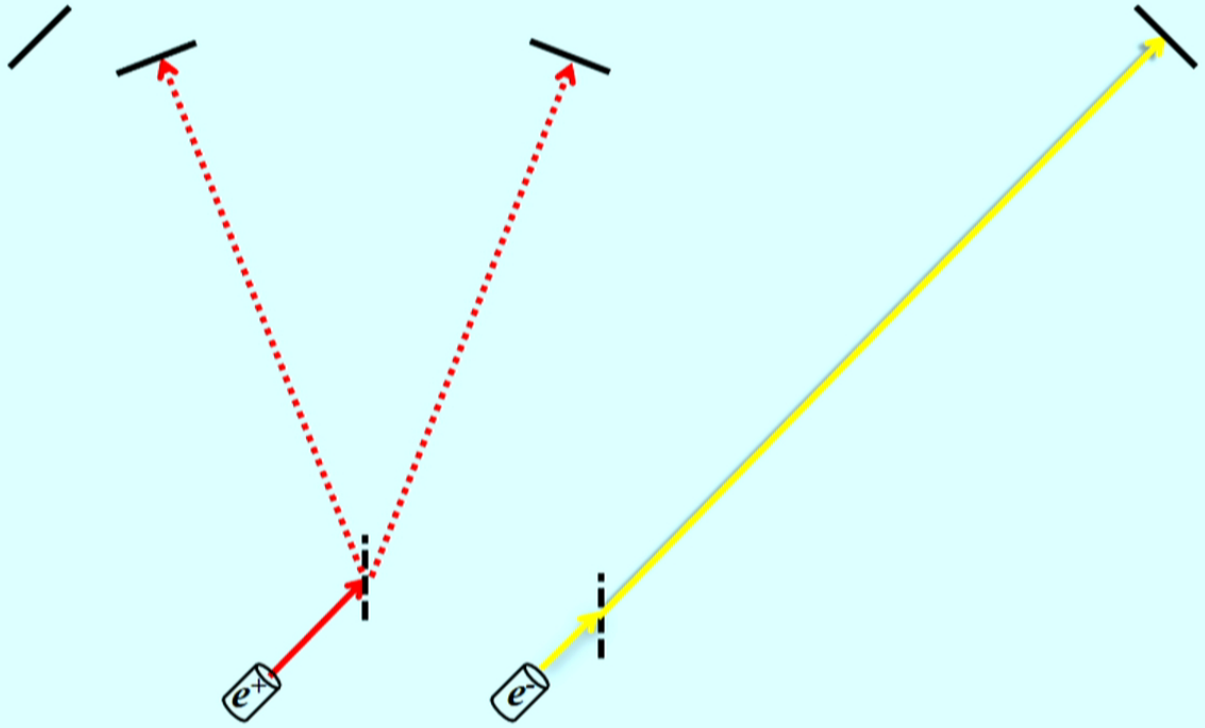
Then – an odd lack of reciprocity



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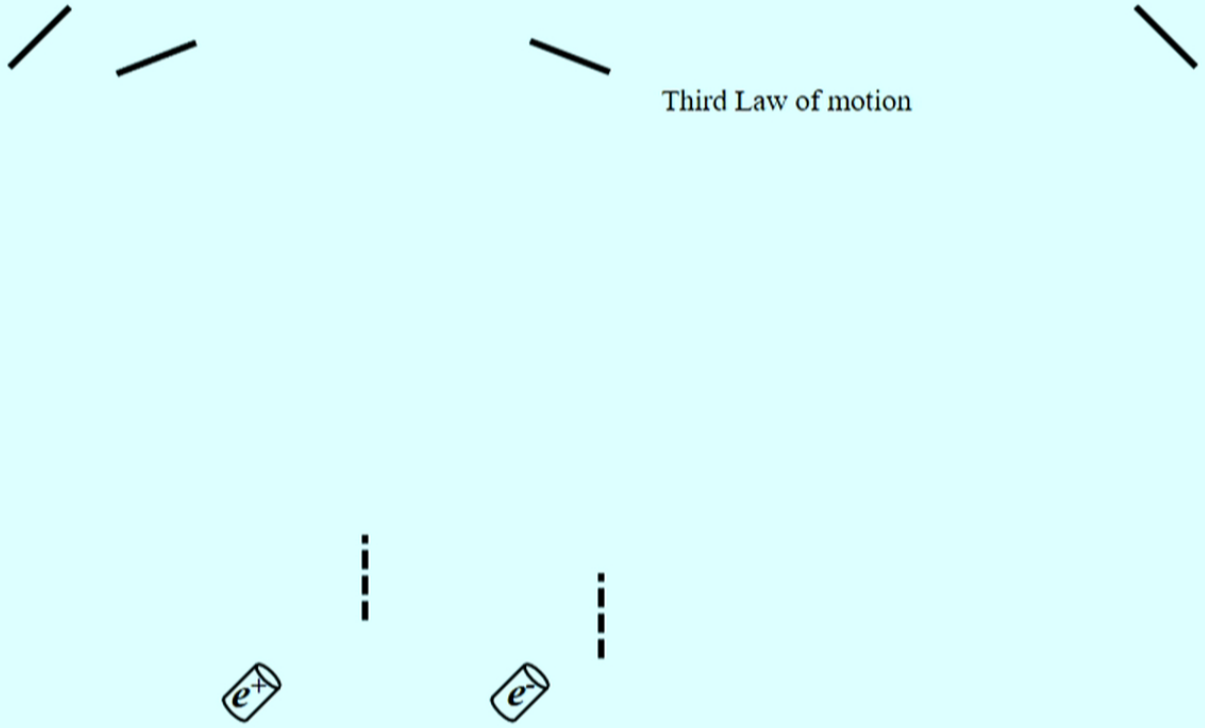
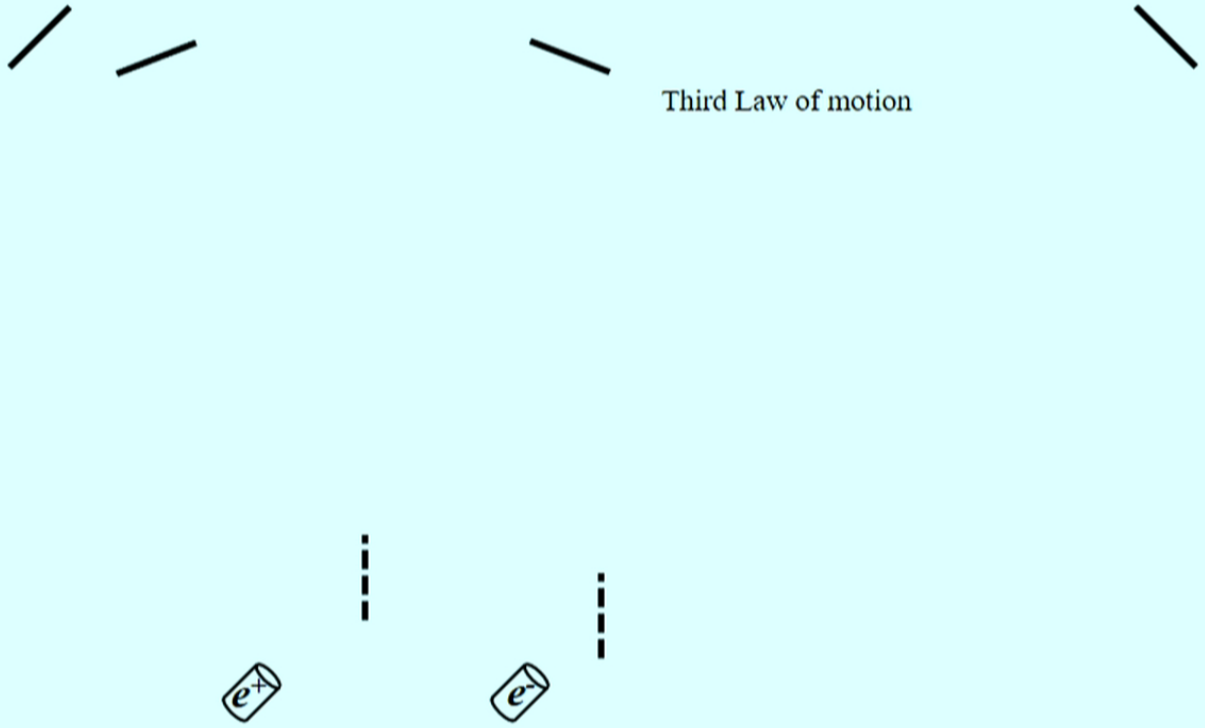


Then – an odd lack of reciprocity
i.e., **quantum oblivion**



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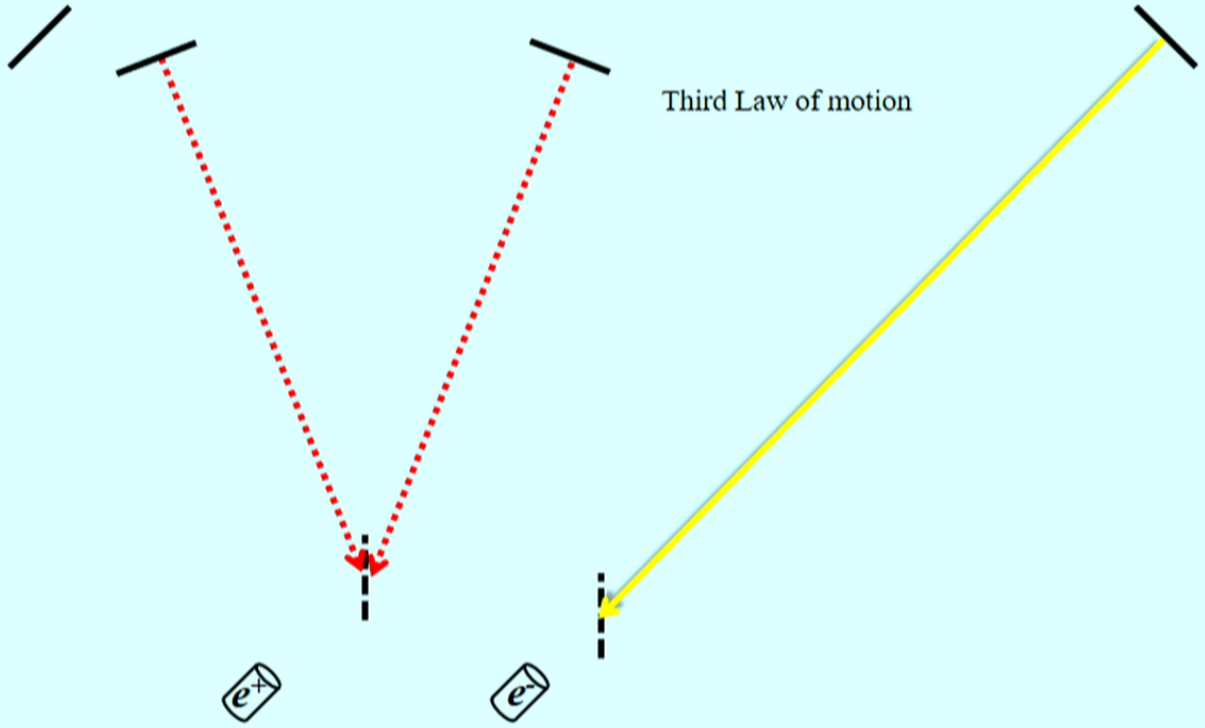

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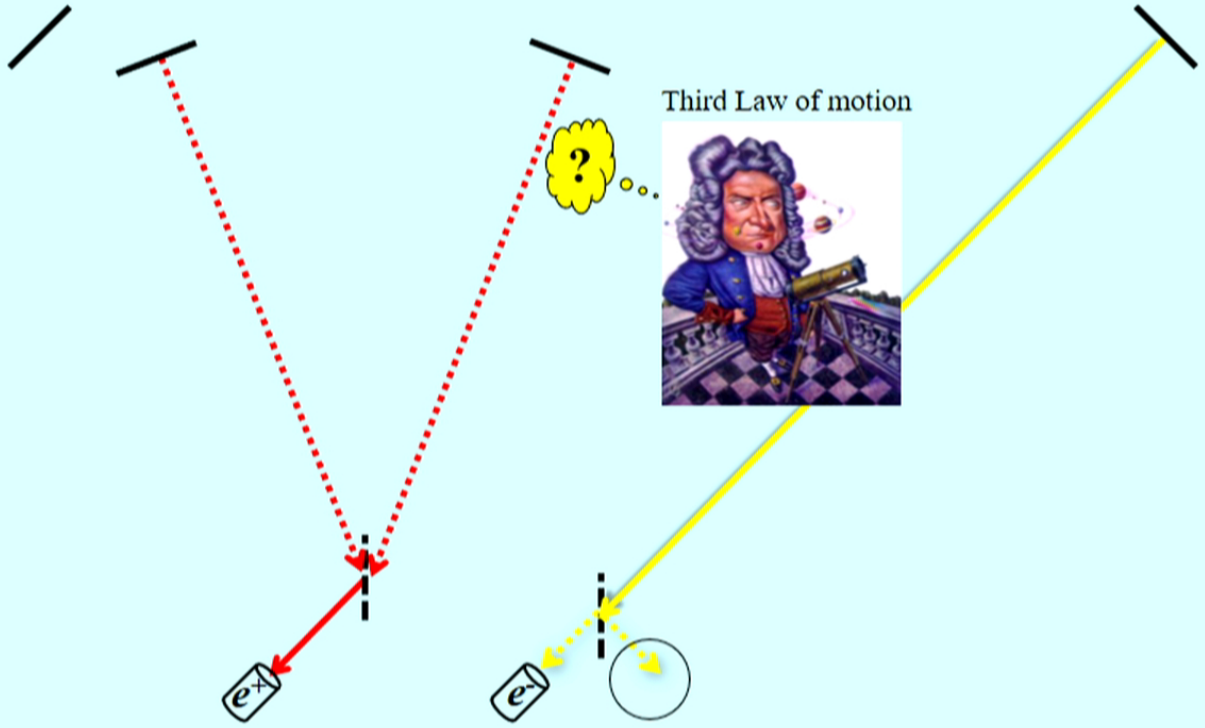

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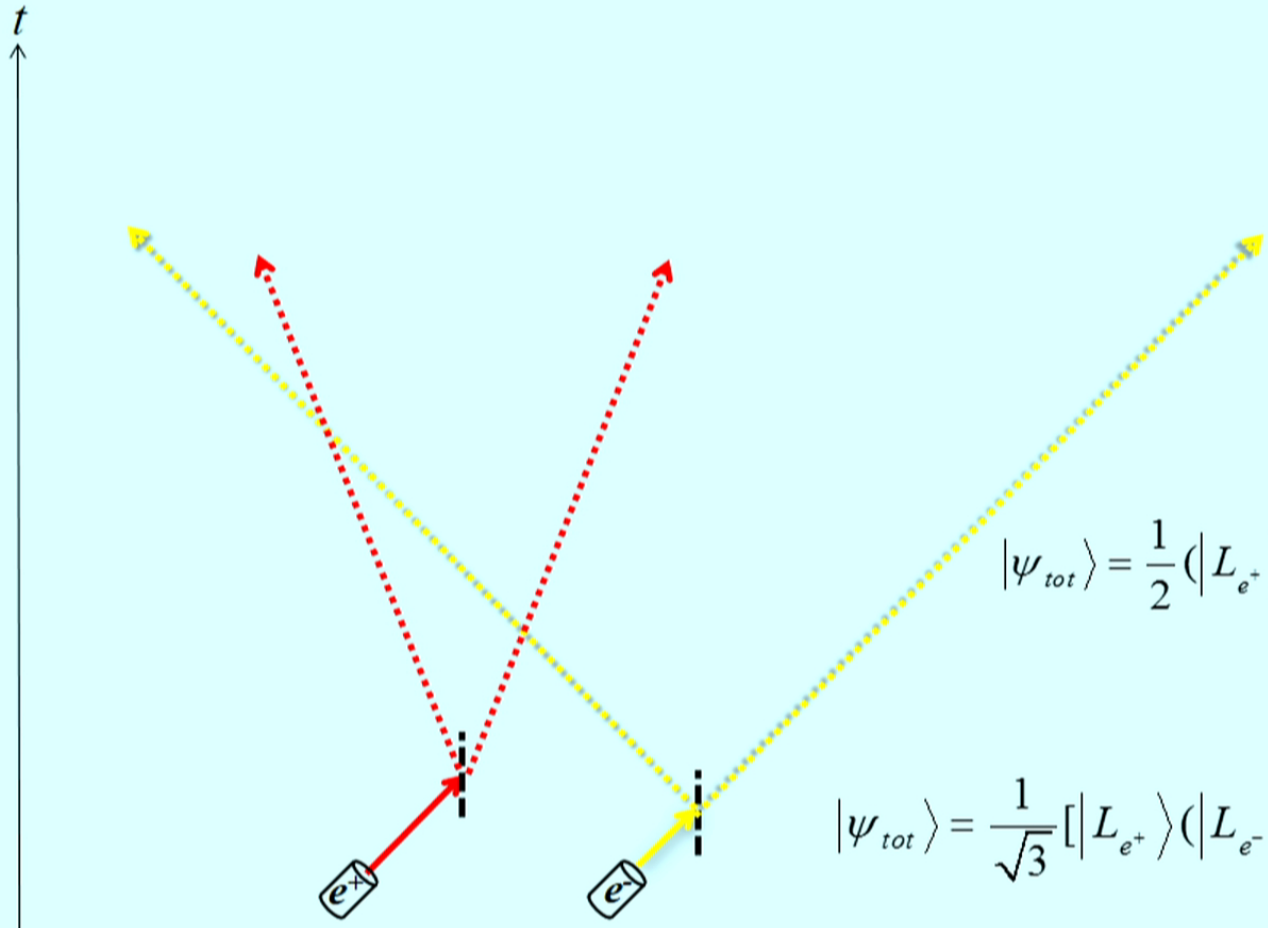
The critical interval



$$|\psi_{tot}\rangle = \frac{1}{2}(|L_{e^+}\rangle + |R_{e^+}\rangle)(|L_{e^-}\rangle + |R_{e^-}\rangle)$$

$$|\psi_{tot}\rangle = \frac{1}{\sqrt{3}}[|L_{e^+}\rangle(|L_{e^-}\rangle + |R_{e^-}\rangle) + |R_{e^+}\rangle|R_{e^-}\rangle]$$

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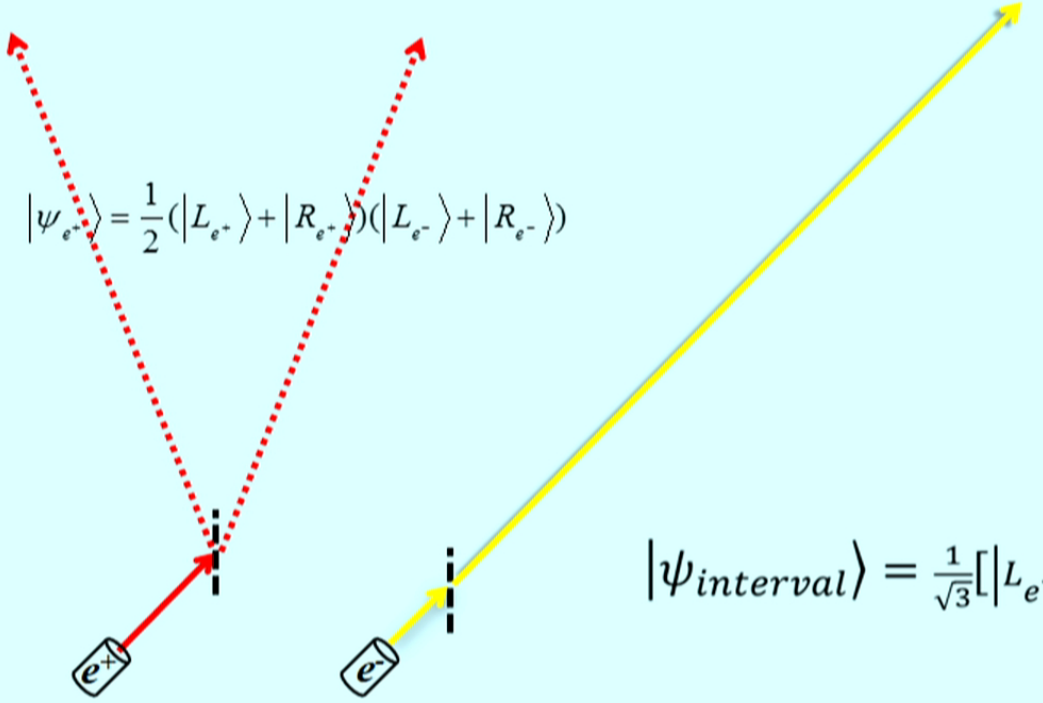
The critical interval prior to quantum oblivion

$$|\psi_{interval}\rangle = \frac{1}{\sqrt{3}}[|L_{e+}\rangle(|L_{e-}\rangle+|R_{e-}\rangle)+|R_{e+}\rangle|R_{e-}\rangle]$$



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23

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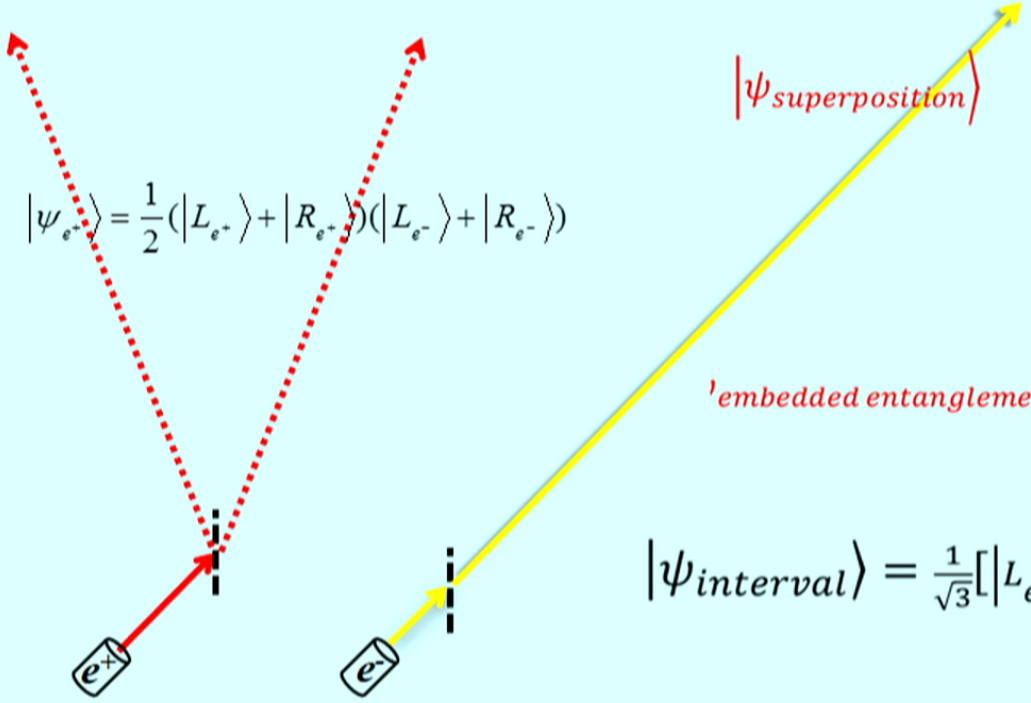

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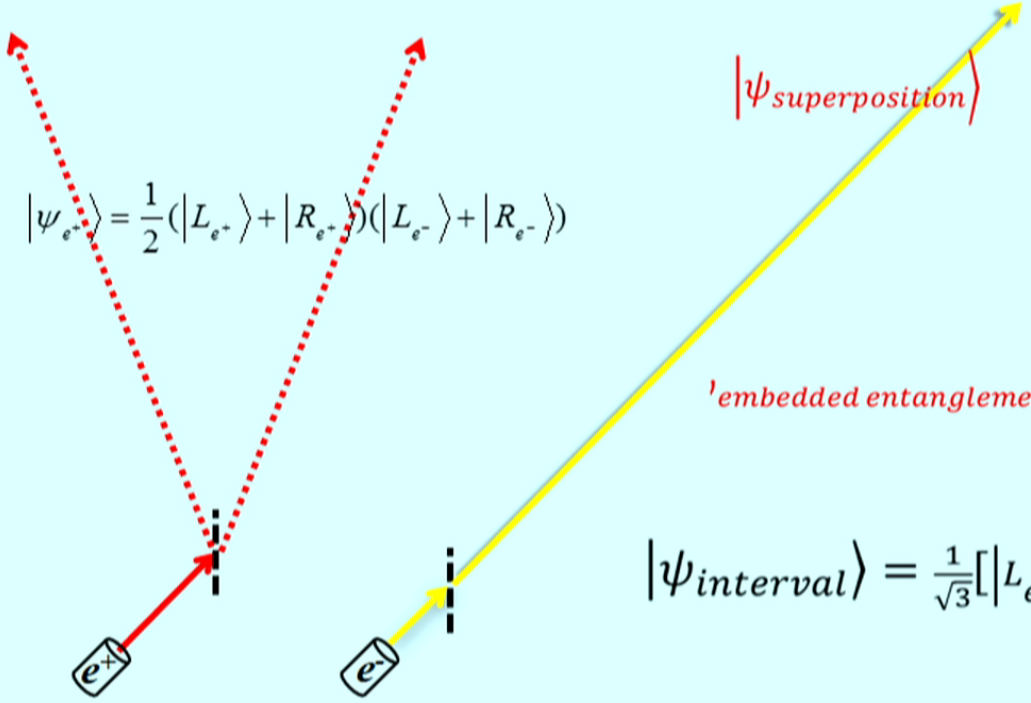

$|\psi_{superposition}\rangle$ = $e^+_{localized}$ $e^-_{superposed}$

'embedded entanglemen = *entangled state*

$$|\psi_{interval}\rangle = \frac{1}{\sqrt{3}}[|L_{e+}\rangle(|L_{e-}\rangle+|R_{e-}\rangle)+|R_{e+}\rangle|R_{e-}\rangle]$$

23

The critical interval prior to quantum oblivion

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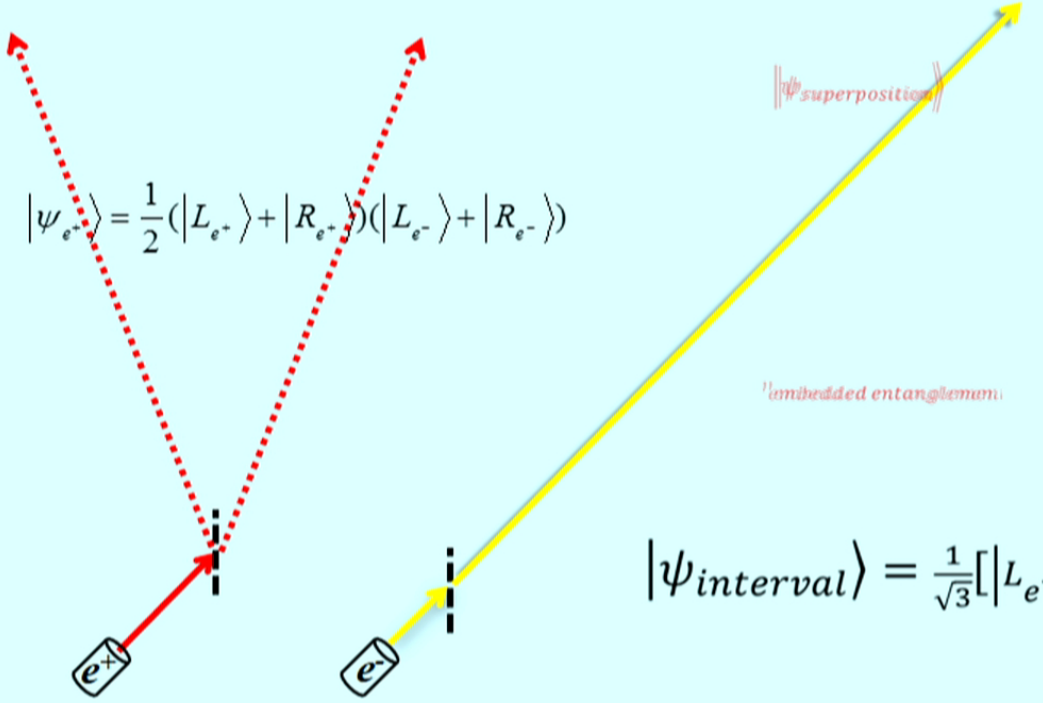

$|\psi_{superposition}\rangle$ = $e^+_{localized}$ $e^-_{superposed}$ + $e^+_{localized}$

"embedded entanglement" = entangled state + non-entangled state

$$|\psi_{interval}\rangle = \frac{1}{\sqrt{3}}[|L_{e+}\rangle(|L_{e-}\rangle+|R_{e-}\rangle)+|R_{e+}\rangle|R_{e-}\rangle]$$

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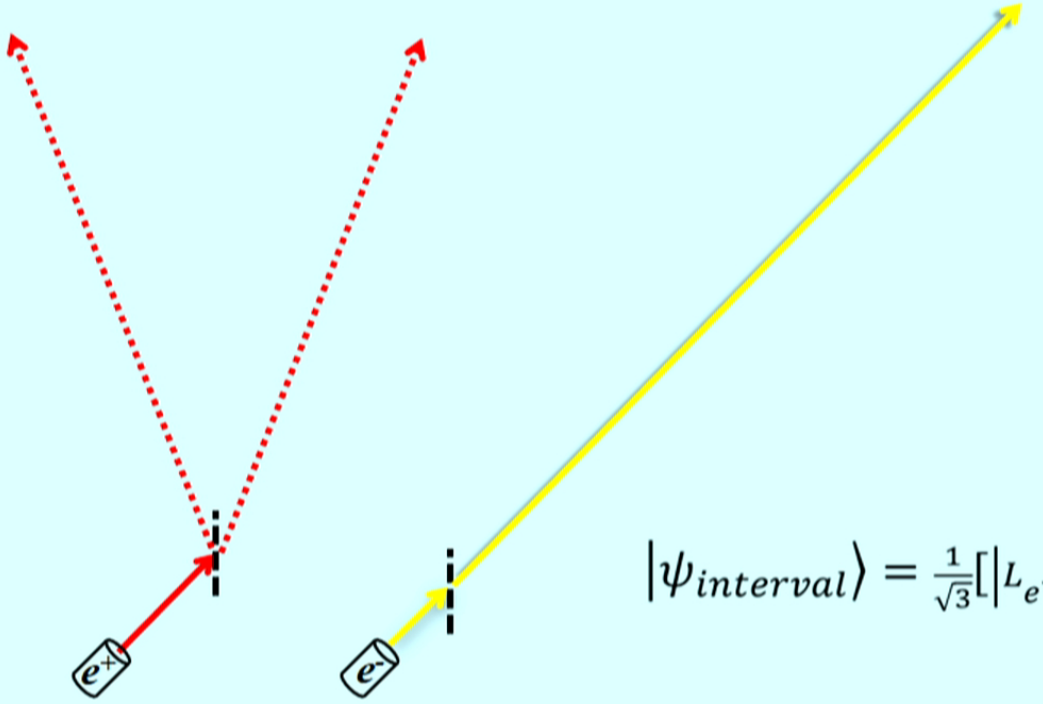

non-entangled state

$$|\psi_{interval}\rangle = \frac{1}{\sqrt{3}}[|L_{e+}\rangle(|L_{e-}\rangle+|R_{e-}\rangle)+|R_{e+}\rangle|R_{e-}\rangle] \qquad |\psi_{tot}\rangle = |R_{e^+}\rangle|L_{e^-}\rangle$$

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The critical interval and high-order entanglement

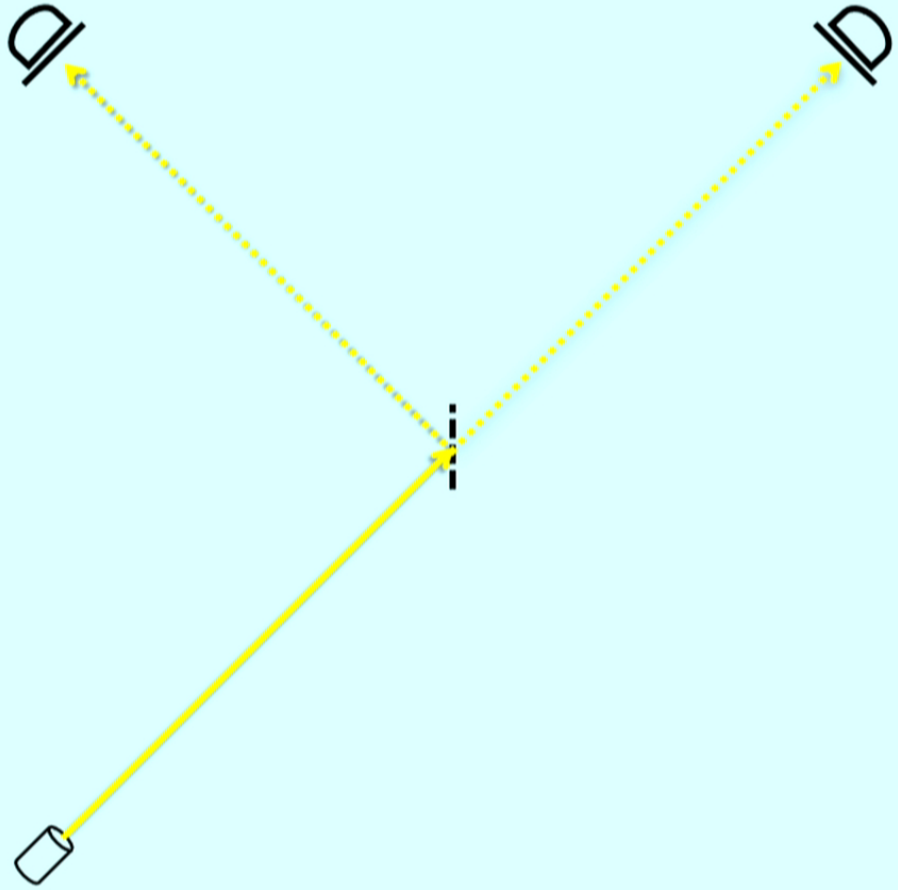
A. Zeilinger, M.A. Horne and D.M. Greenberger, Higher-order quantum entanglement, in *"Squeezed States and Quantum Uncertainty"*, D. Han, Y.S. Kim, W.W. Zachary (Eds.), NASA Conference Publication 3135, National Aeronautics and Space Administration, (1992).

G. Krenn, and A. Zeilinger, Entangled entanglement, *Phys. Rev.* A 54 , 1793 (1996).

Superposition and entanglement can be embedded within complex states, such that measurement ("collapse") gives a superposed/entangled state.

Oblivion: Just an interesting rare interaction?

No, rather a ubiquitous ingredient of all quantum measurements!



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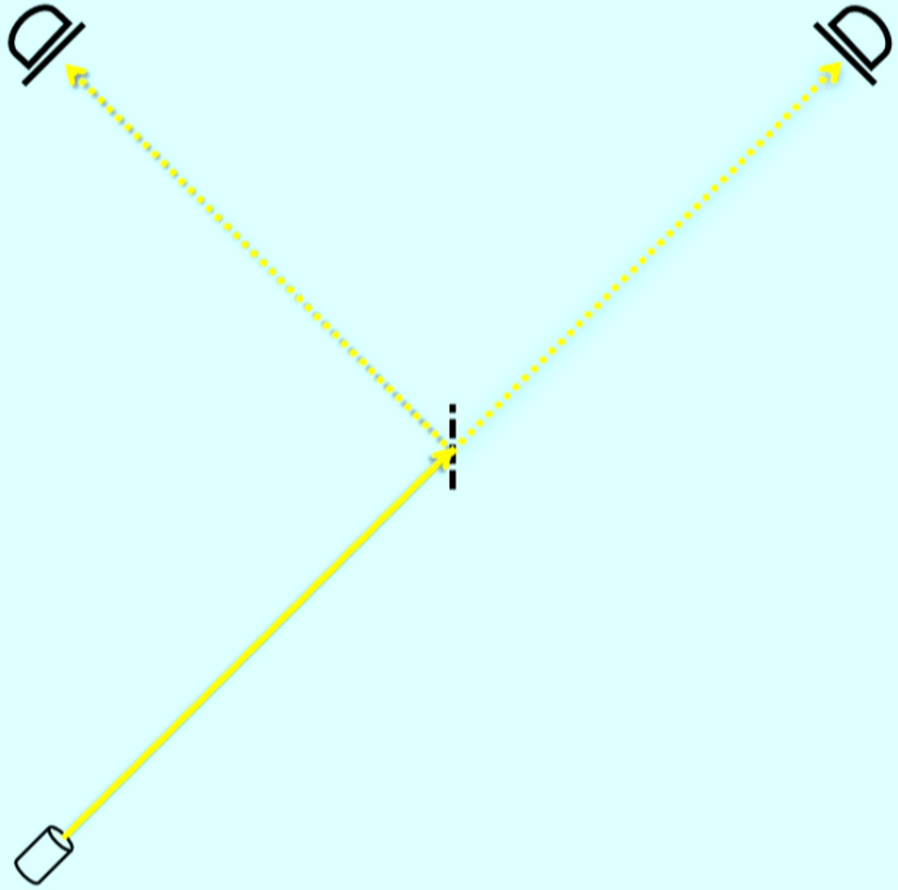

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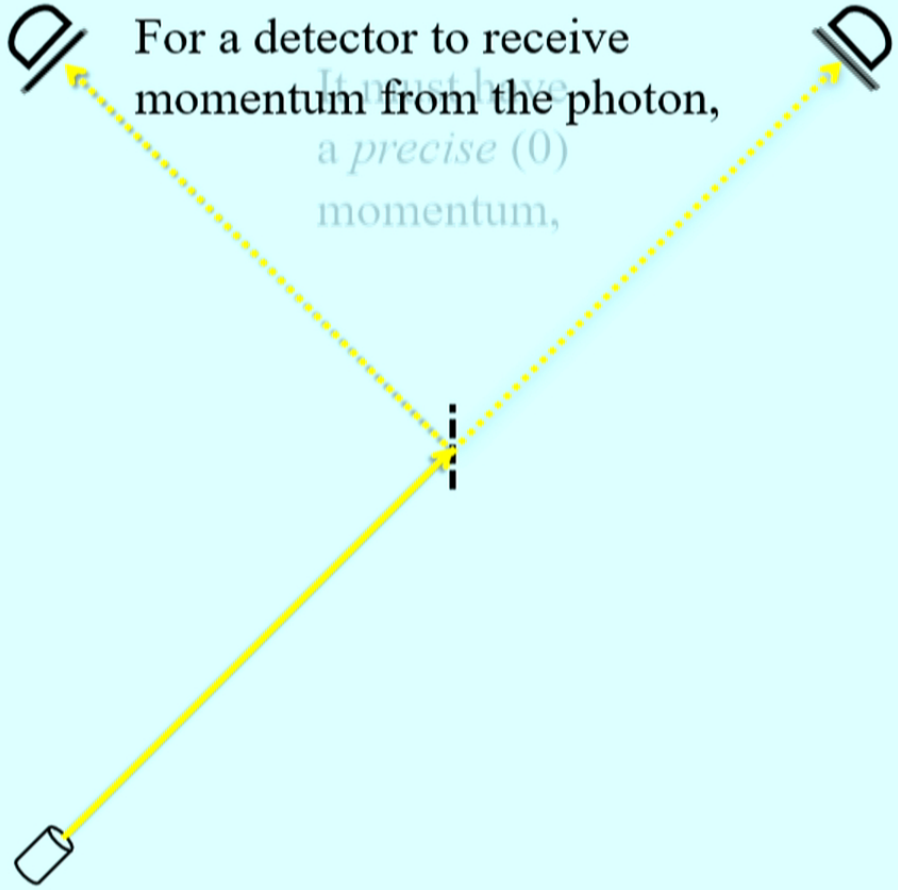

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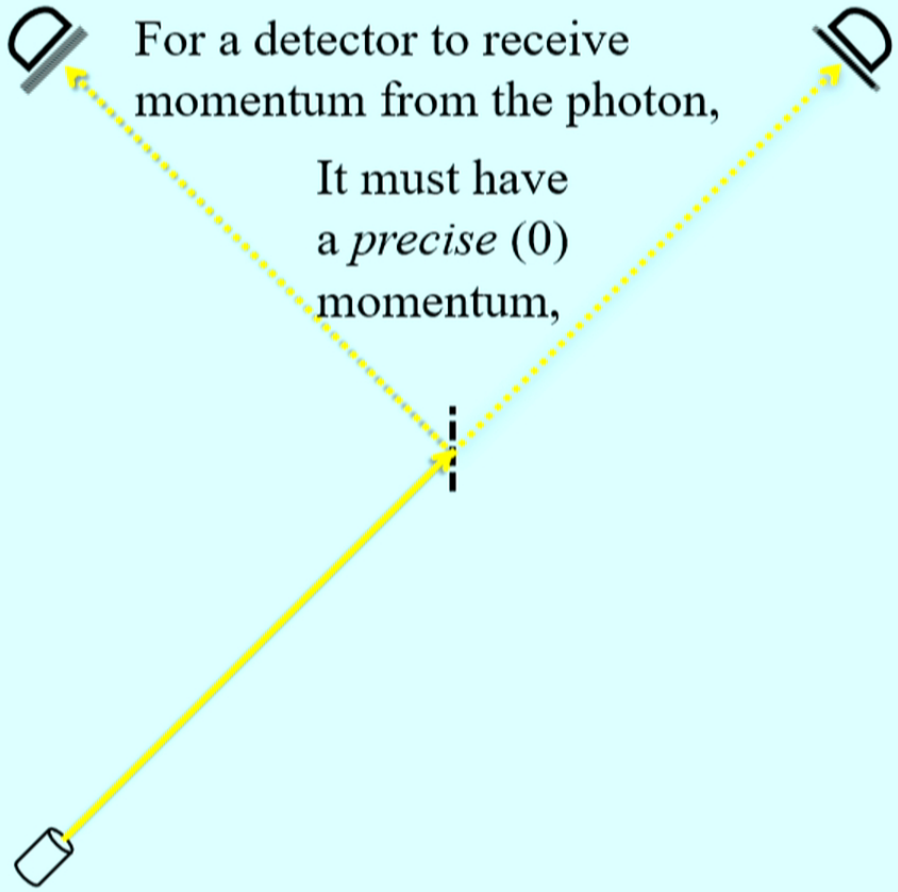

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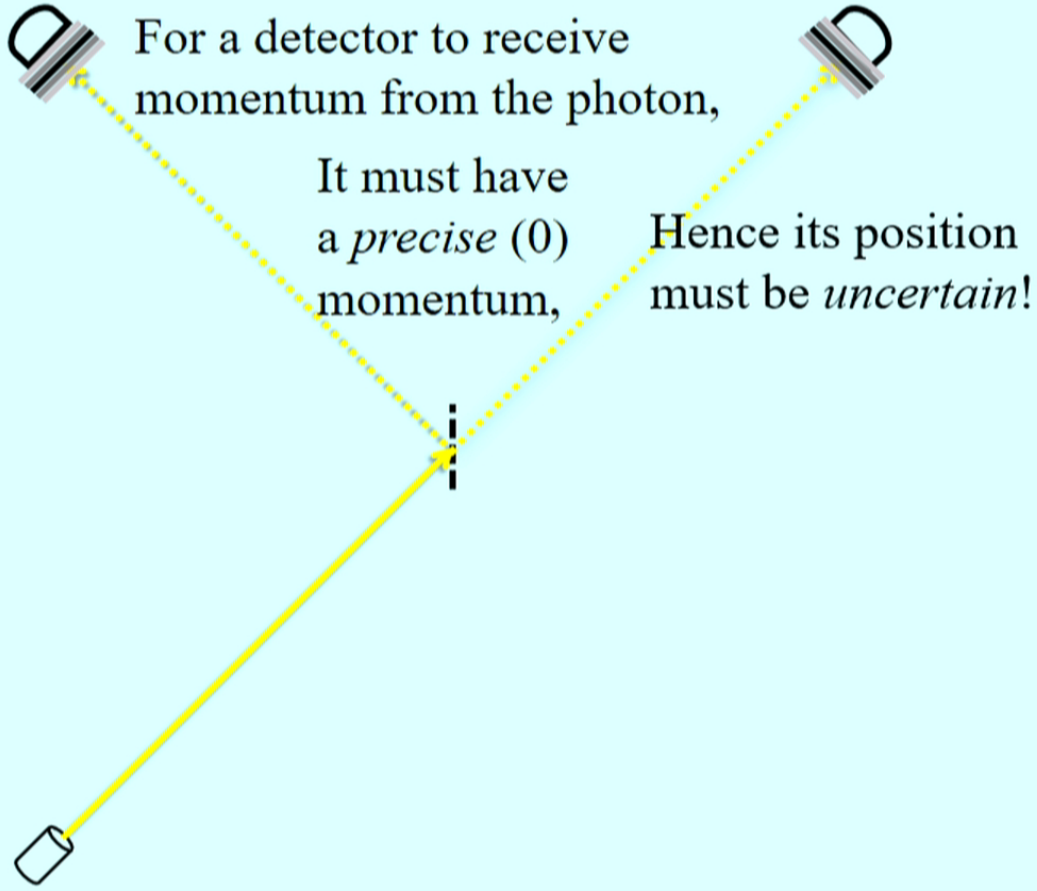
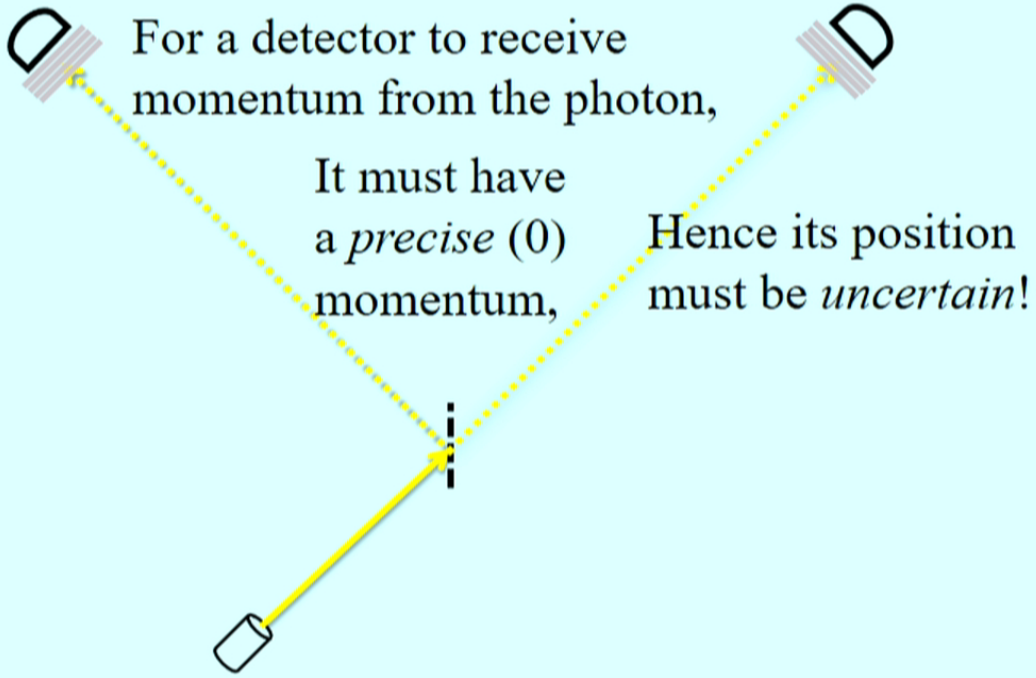


This, then, is quantum position measurement:



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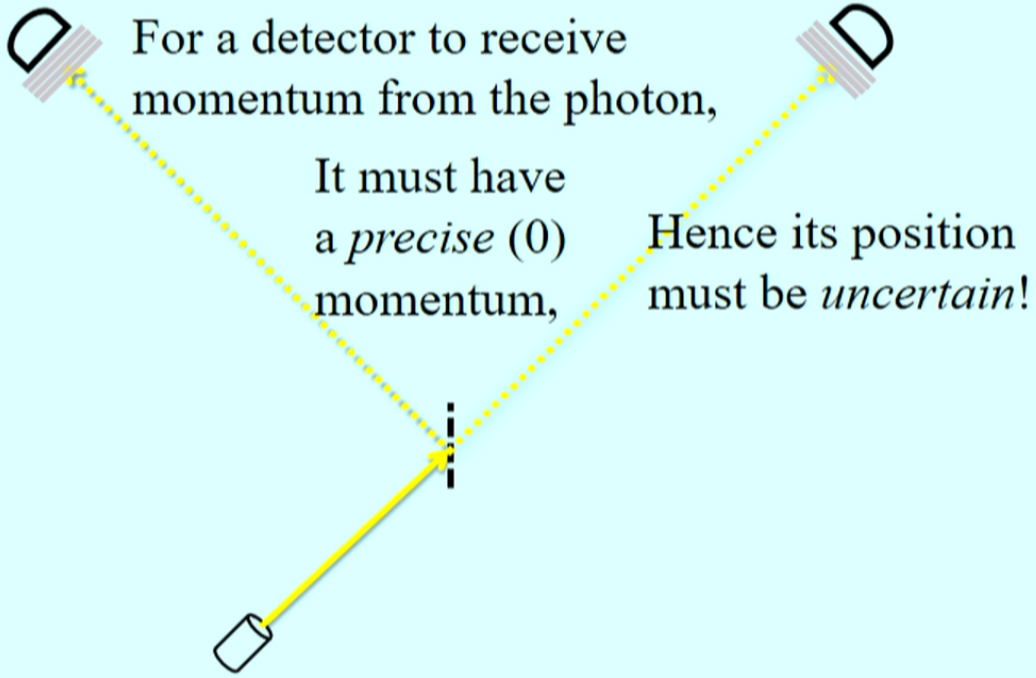
This, then, is quantum position measurement:

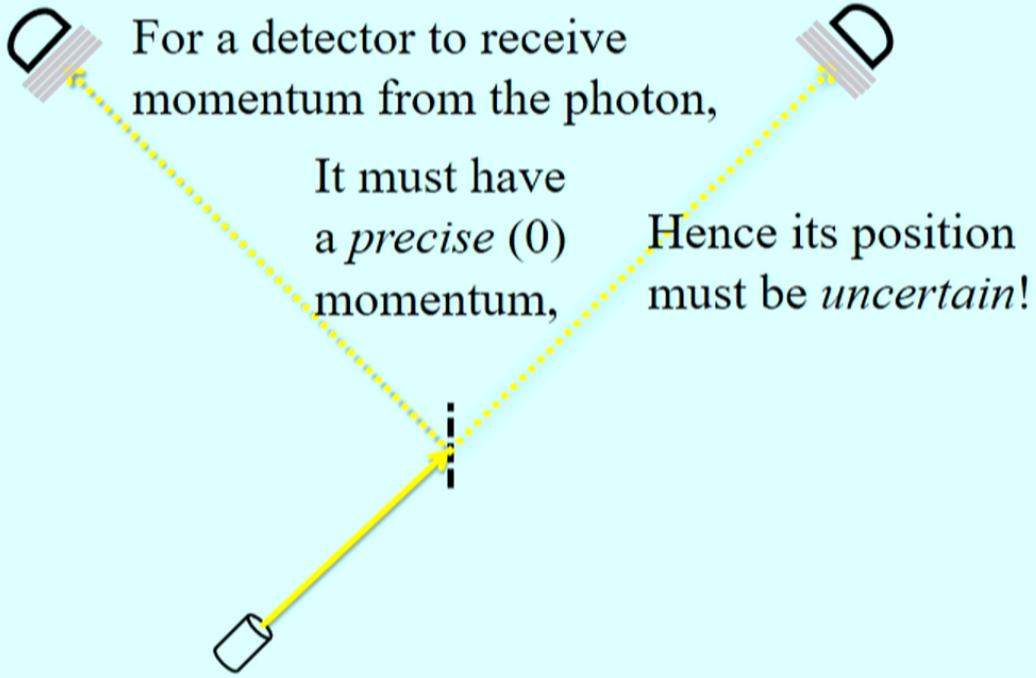
Part of the measured object's wave-function



28

This, then, is quantum position measurement:

Part of the measured object's wave-function interacts with *all* the probe's wave-function



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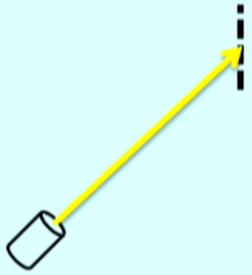
This, then, is quantum position measurement:

Part of the measured object's wave-function interacts with *all* the probe's wave-function

Mirror's momentum gain is recorded, *leaving its position unknown*.



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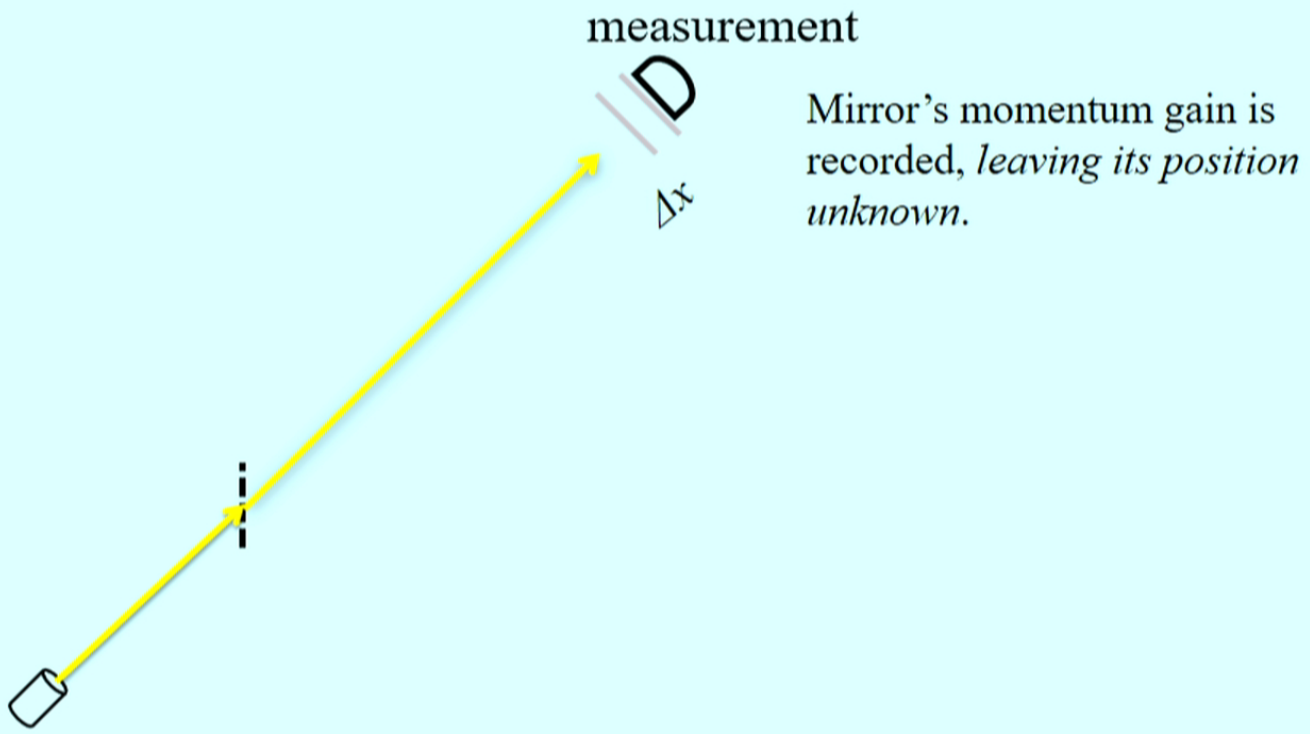

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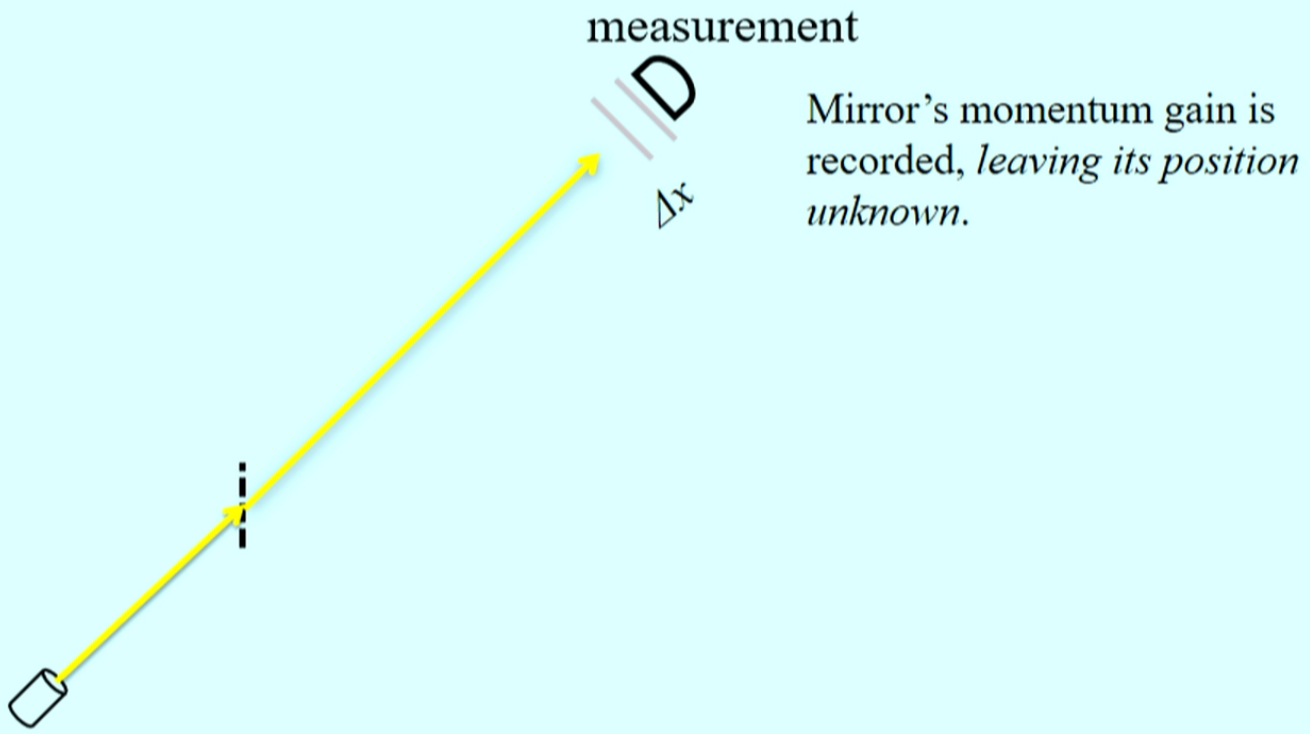

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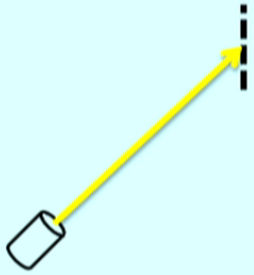
measurement

Mirror's momentum gain (0) is recorded, *leaving its position unknown*.



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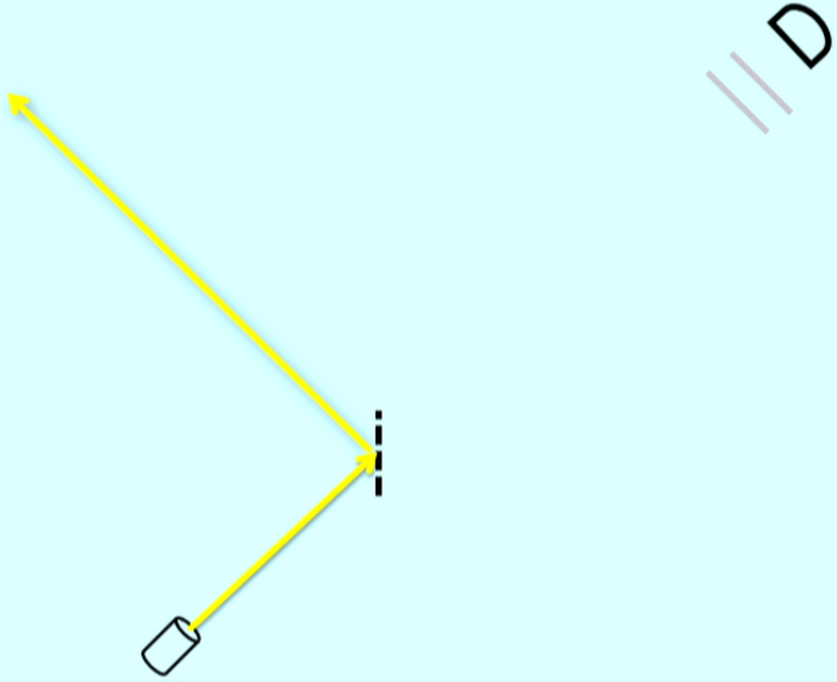
Interaction-free measurement



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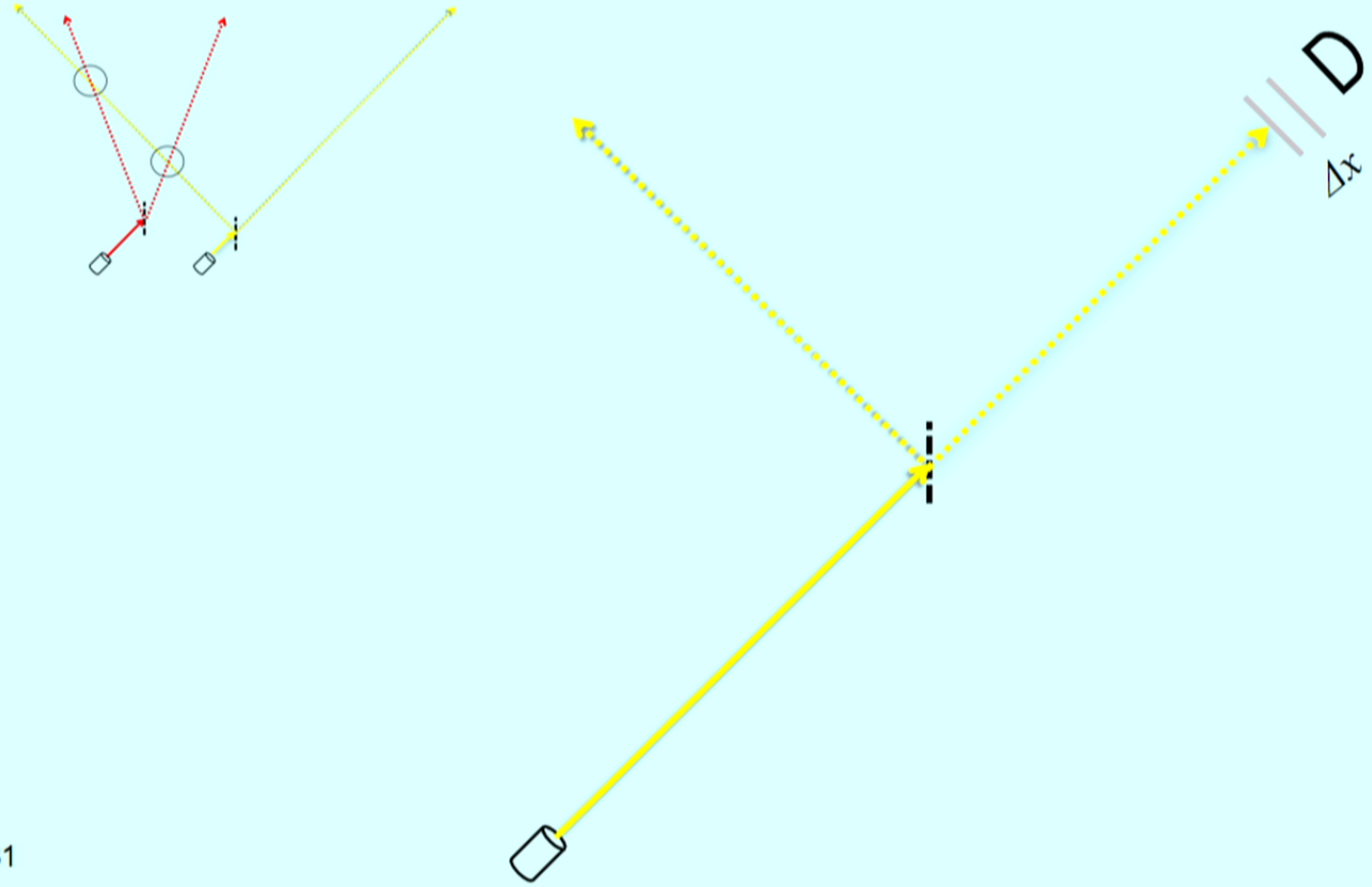
30

The critical interval



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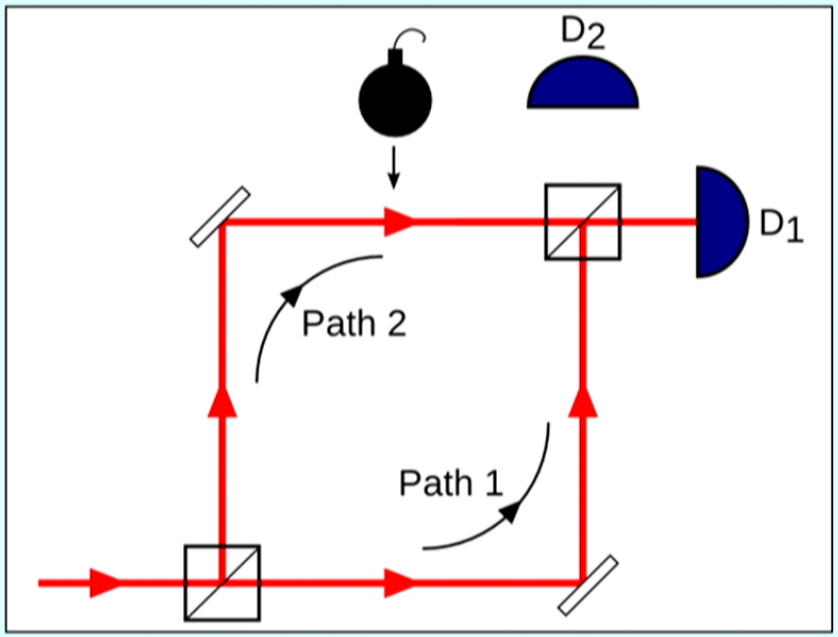
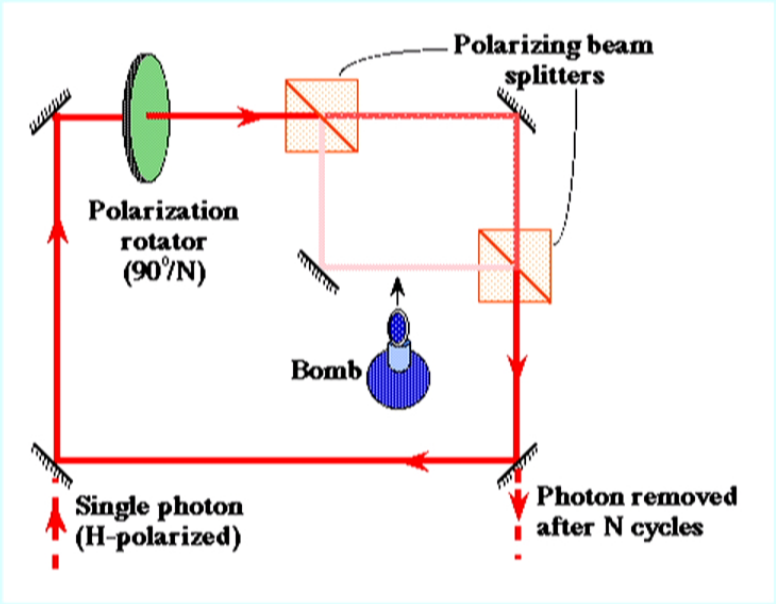
The critical interval

31

IFM (Reninger, 1953 ; Dicke, 1981; Elitzur & Vaidman, 1993) and IFM + Zeno (Kwiat *et al*. 1995) Revisited





IFM (Reninger, 1953 ; Dicke, 1981; Elitzur & Vaidman, 1993) and IFM + Zeno (Kwiat *et al*. 1995) – which interpretation?

Copenhagen (information)

Quantum Oblivion

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*or *could* gain

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- Nothing more to it!

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Quantum Oblivion

- Recall the physics of measurement: The detector's probe has been superposed.

*or *could* gain

Oblivion, then, underlies

- **IFM** – the "mirror" is first localized by the photon in one or more of its possible locations, its momentum being proportionately disturbed; then regains its superposition, loosing again the momentum noise, thereby "forgetting" all about its interaction with the photon.

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In all cases, a critical interval ensues, during which entanglement is formed, giving its place to unentanglement, as opposed to disentanglement.

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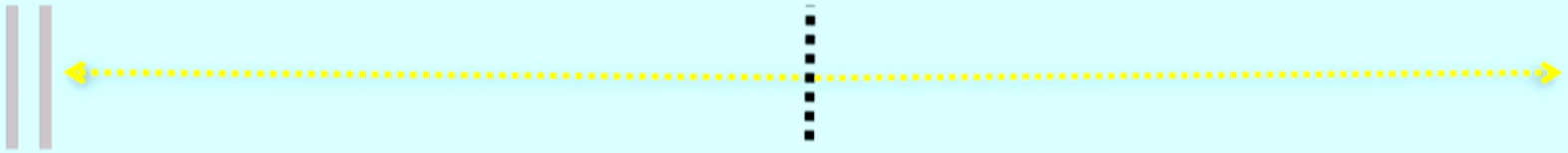
In all cases, a critical interval ensues, during which entanglement is formed, giving its place to unentanglement, as opposed to disentanglement.

Put differently: during the critical interval the parties undergo decoherence, and then one undergoes recoherence.

A new question:

What if measurement is performed *within* the crucial interval?



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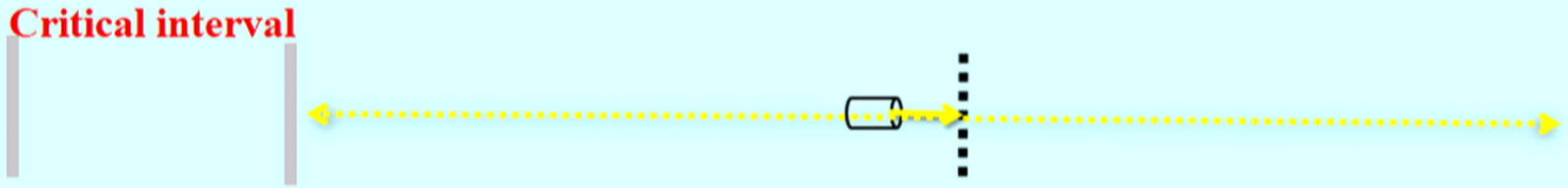

We enter the realm of incomplete measurement:

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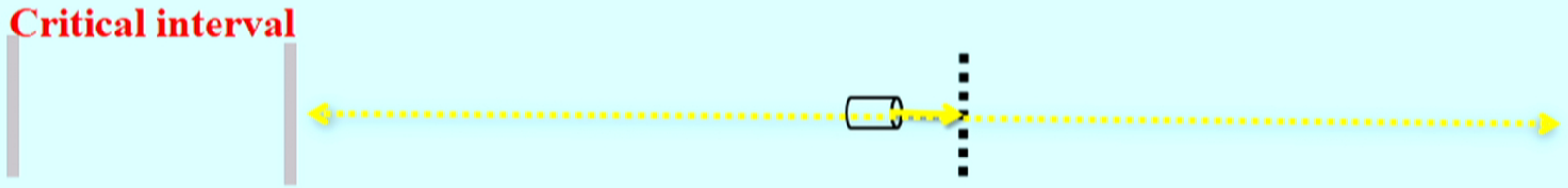

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- Weak measurement (Aharonov, Albert & Vaidman, 1988; Aharonov, Cohen & Elitzur, 2014)

- Partial measurement (Elitzur & Dolev, 2000; Cohen & Elitzur, 2011)

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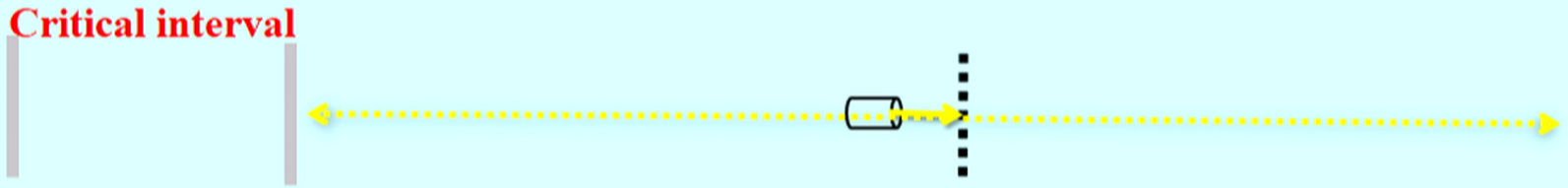

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4. Surprises

1. The Ghostly Mirror

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A mirror becomes superposed

38

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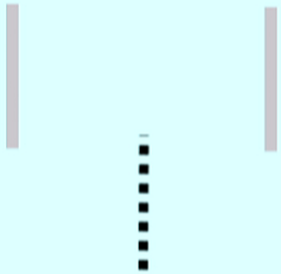
A mirror becomes superposed

38

1. The Ghostly Mirror

A photon becomes
superposed



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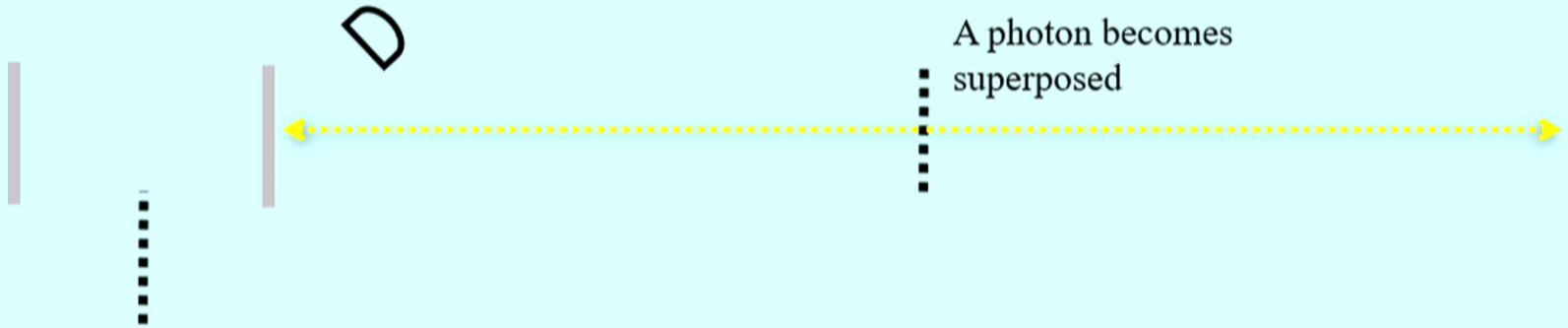

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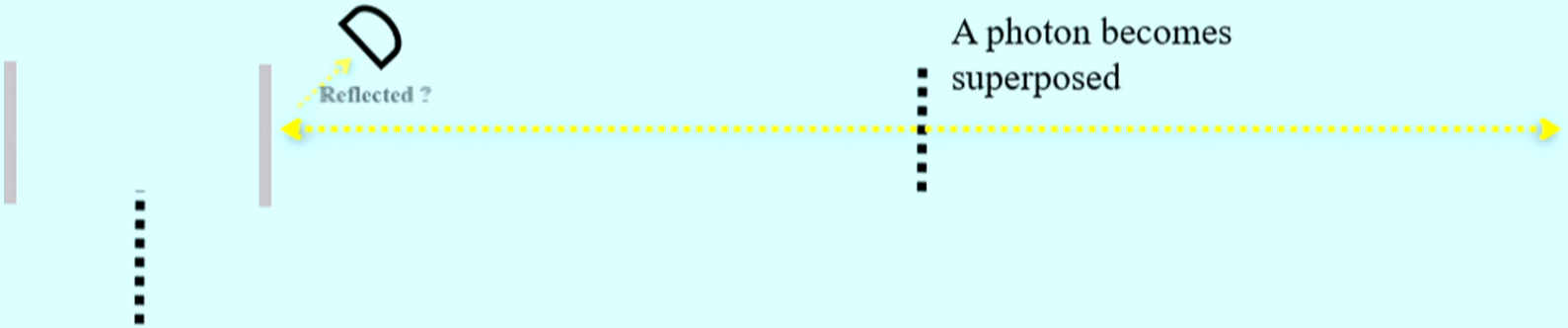

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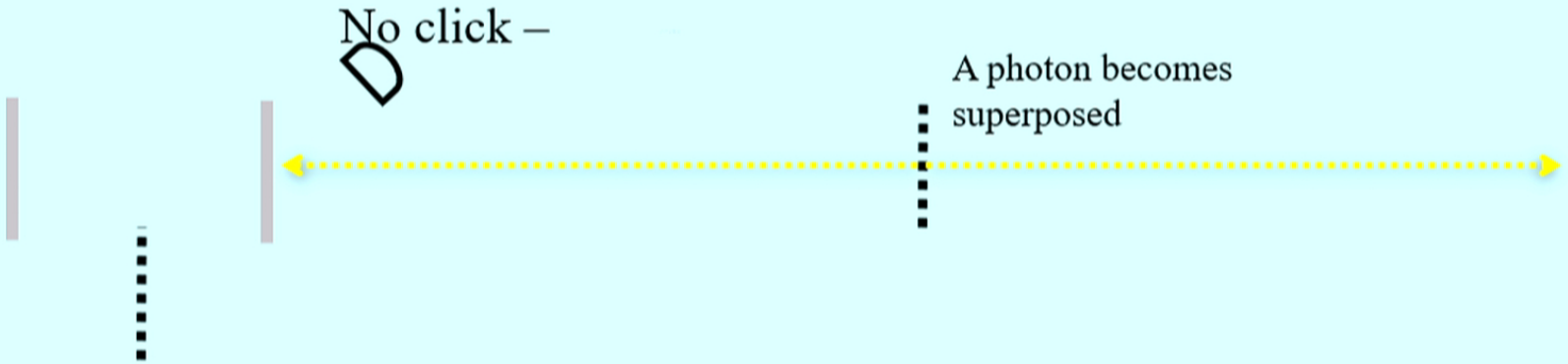

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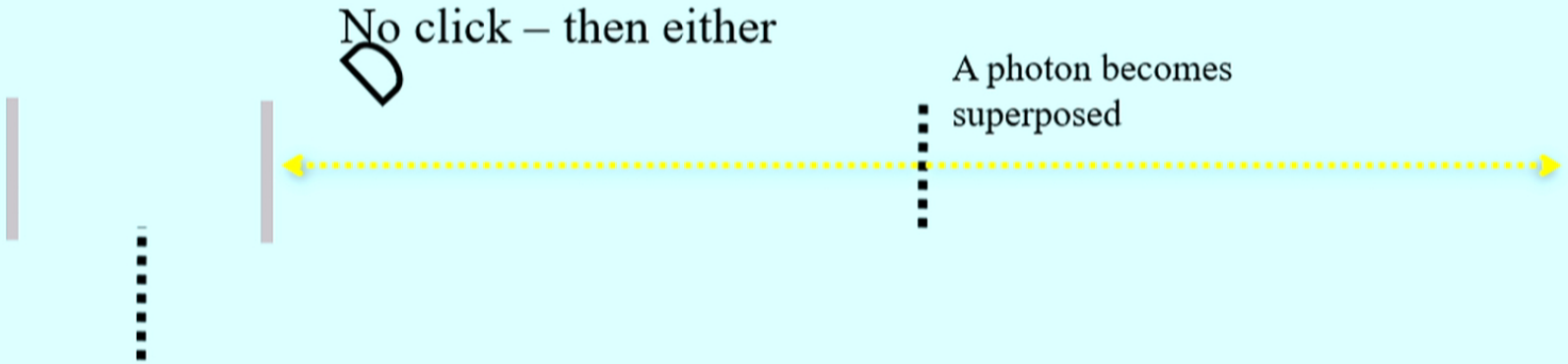

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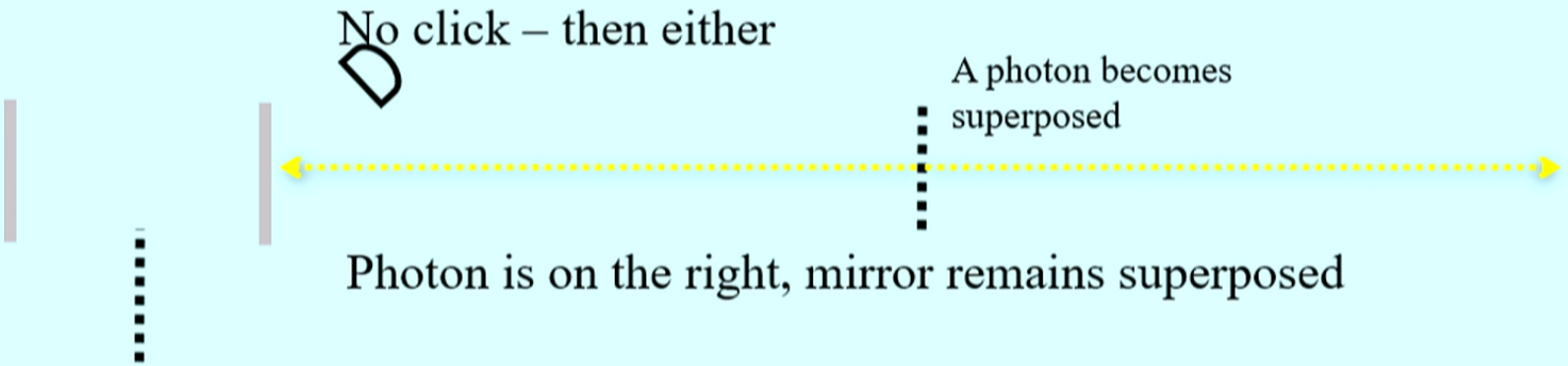

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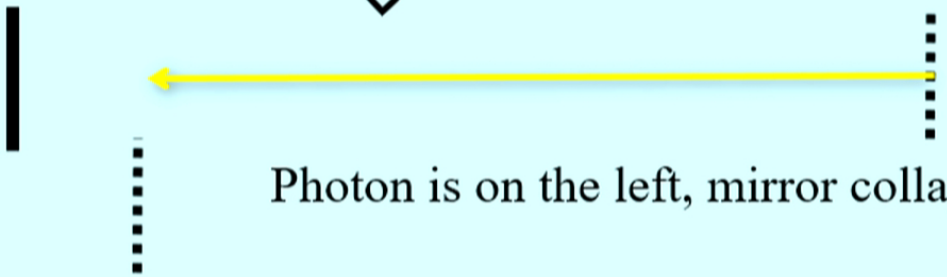
1. The Ghostly Mirror

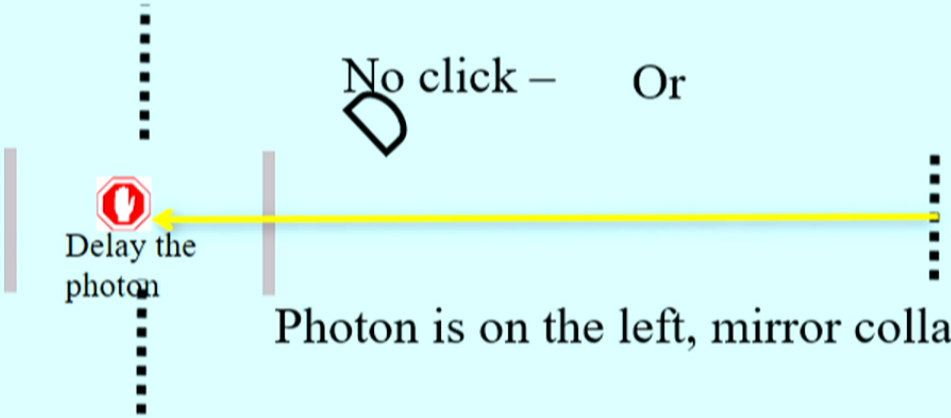
No click – Or



Photon is on the left, mirror collapses on the leftmost position

38

1. The Ghostly Mirror



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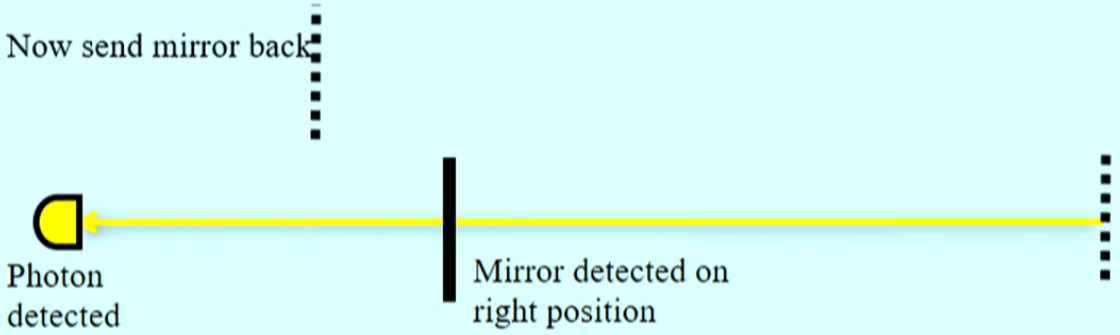
1. The Ghostly Mirror

Now send mirror back

39

1. The Ghostly Mirror



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1. The Ghostly Mirror

Preparation: $$|\psi(t=0)\rangle_{tot} = \frac{1}{\sqrt{2}}(|Z+\rangle_M (|L_{e^-}\rangle + |R_{e^-}\rangle)$$

Hardy split: $$|\psi(t=t_0)\rangle_{tot} = \frac{1}{2}(|X+\rangle_M + |X-\rangle_M)(|L_{e^-}\rangle + |R_{e^-}\rangle)$$

No reflection : $$|\psi(t_1 < t < t_2)\rangle_{tot} = \frac{1}{\sqrt{3}}[|X+\rangle_M (|L_{e^-}\rangle + |R_{e^-}\rangle) + |X-\rangle_M |R_{e^-}\rangle]$$

If a Spin Z measurement within the critical interval

$$|\psi_{meas}\rangle_{tot} = \frac{1}{\sqrt{6}}[|Z+\rangle_M (|L_{e^-}\rangle + 2|R_{e^-}\rangle) + |Z-\rangle_M |L_{e^-}\rangle]$$

results in Z-,

$$|\psi_{proj}\rangle_{tot} = |Z-\rangle_M |L_{e^-}\rangle$$

40

1. The Ghostly Mirror

Interrogation after the clash

Ms. Mirror: I stood quietly, superposed, when this rude photon ran into me. He spoiled my delicate superposition and localized me merely on the right position, trembling with uncertainty!

Mr. Photon: She's lying, I hastily crossed the street (can't make it slower) to the left side, encountering no mirror whatsoever.

Interrogator: ?…

But where is the missing momentum?

A Two-State-Vector Formalism (TSVF) proposal:

Although the interacting bodies have initially possessed definite momenta, their interaction may introduce uncertainties not only to their future but to their past states as well.