# The past of a quantum particle

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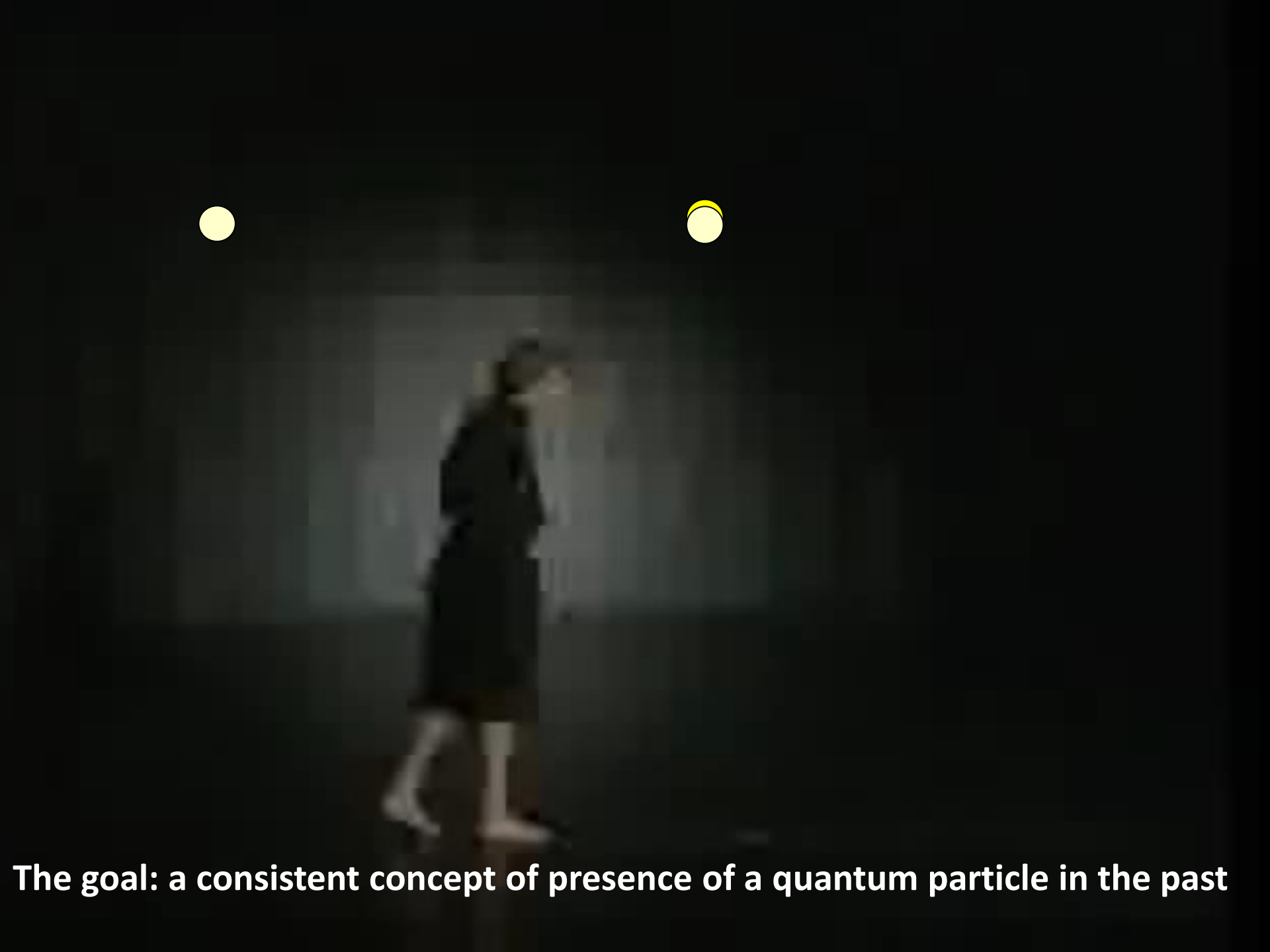
TEL AVIV UNIVERSITY אוניברסיטת תל אביב


Solstice of Foundations — ETH Zurich 2019

Quantum foundations summer school

18.6.2019



The goal: a consistent concept of presence of a quantum particle in the past

# OUTLOOK

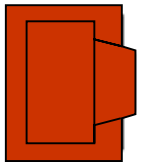
## A pre and postselected particle:

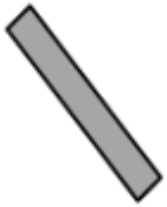
## Where it was?

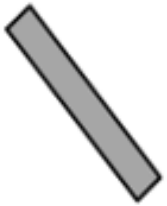
## What type of presence it had?

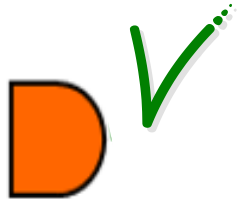
## Experimental demonstration

# Where was a pre- and post-selected particle?



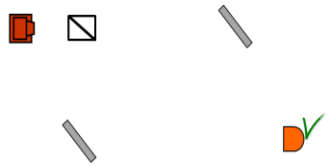




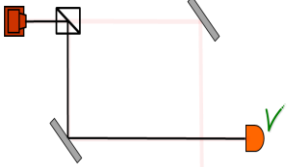


# Where was a pre- and post-selected particle?

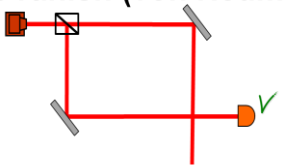
Do not ask! (Bohr)



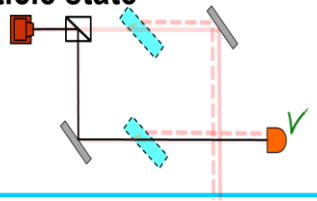
Where it could be found in a local non-demolition measurement



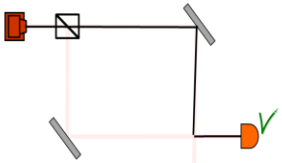
Where its Schrödinger wave did not vanish (von Neumann)



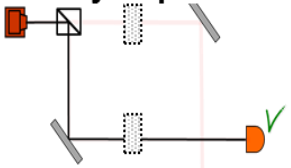
Where a local field could change the particle state



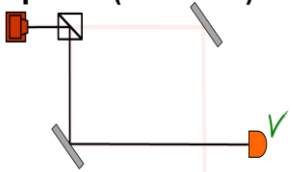
On its Bohmian trajectory



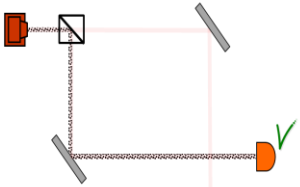
Where an absorber could change the probability of post-selection



On a trajectory through which it could pass (Wheeler)

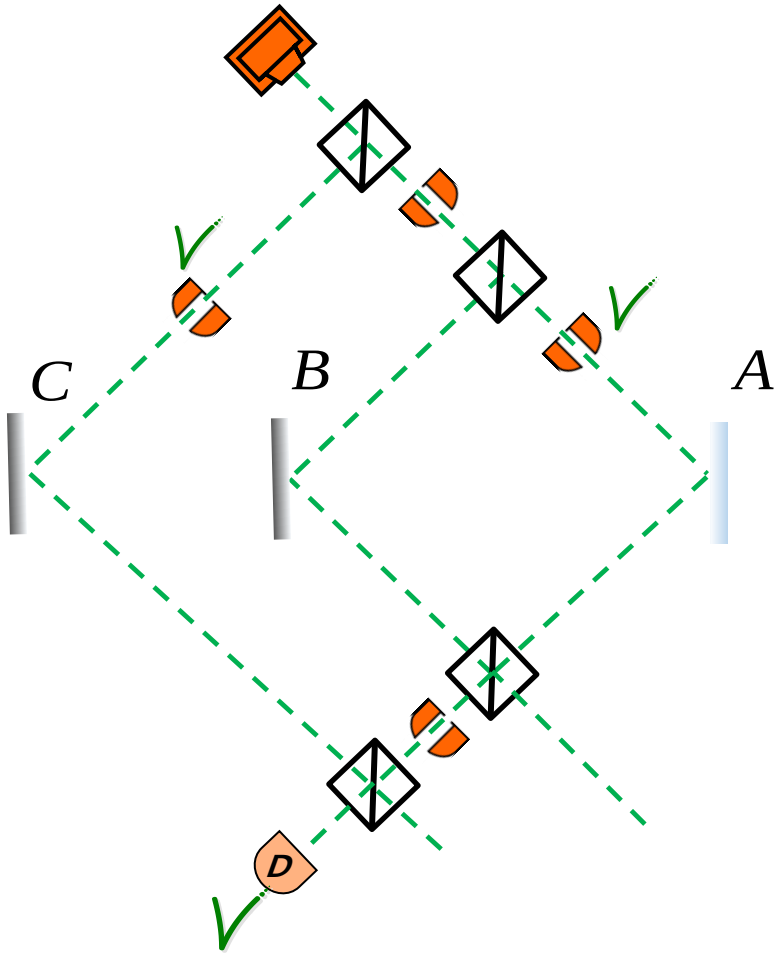


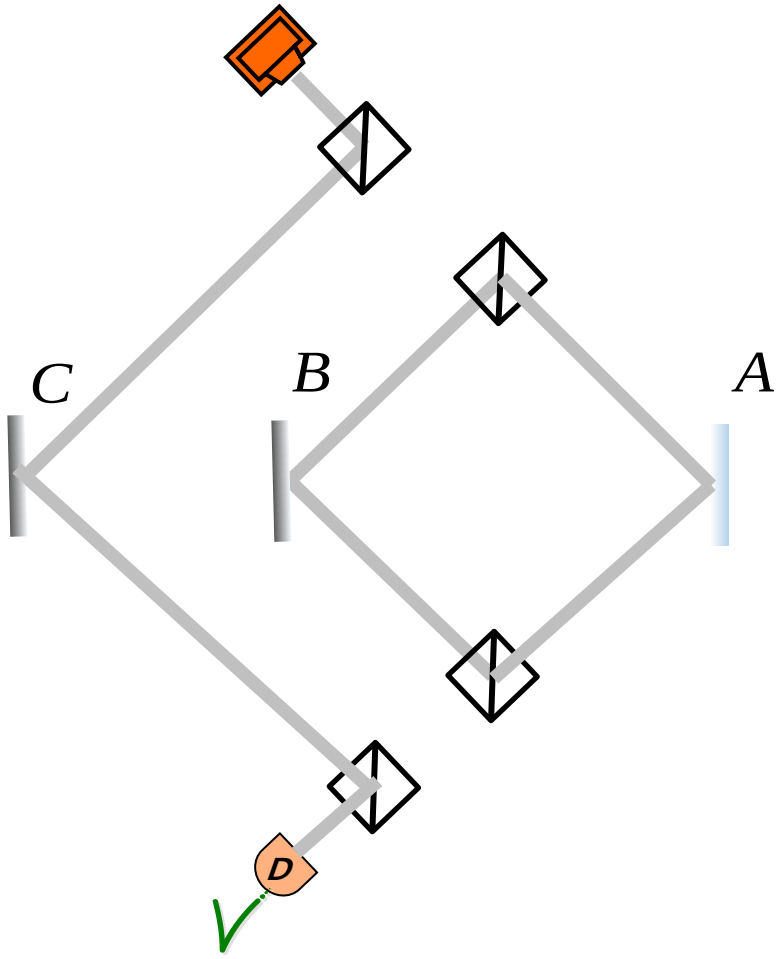
Where it left a weak trace



# Where was a pre- and post-selected particle?

**Where it could be found in a local non-demolition measurement**



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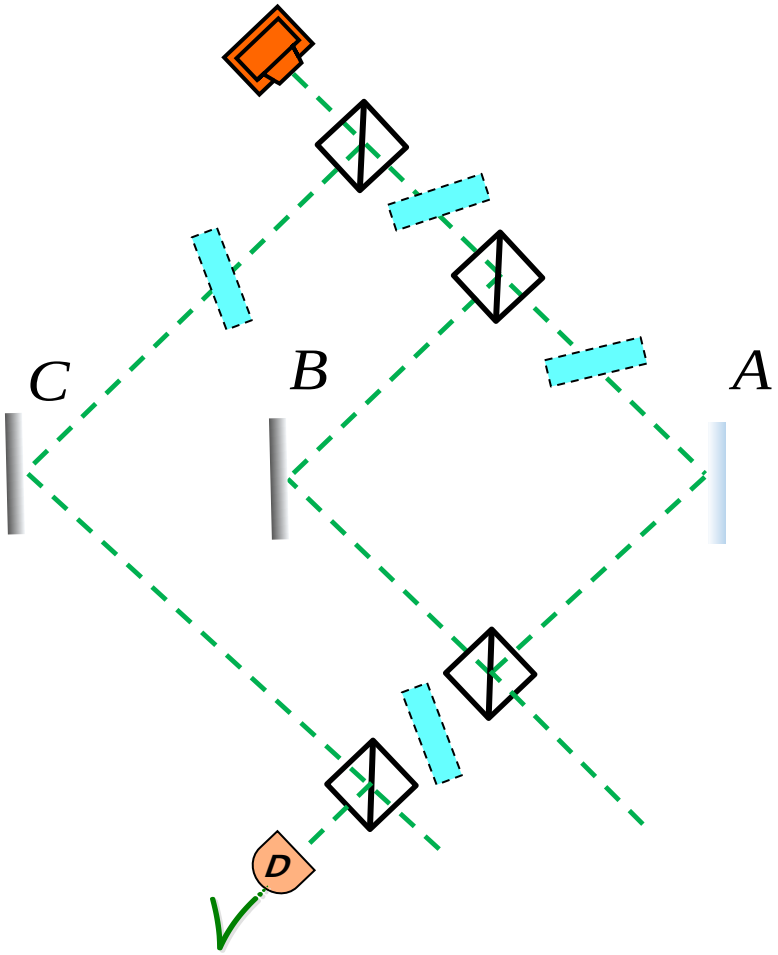
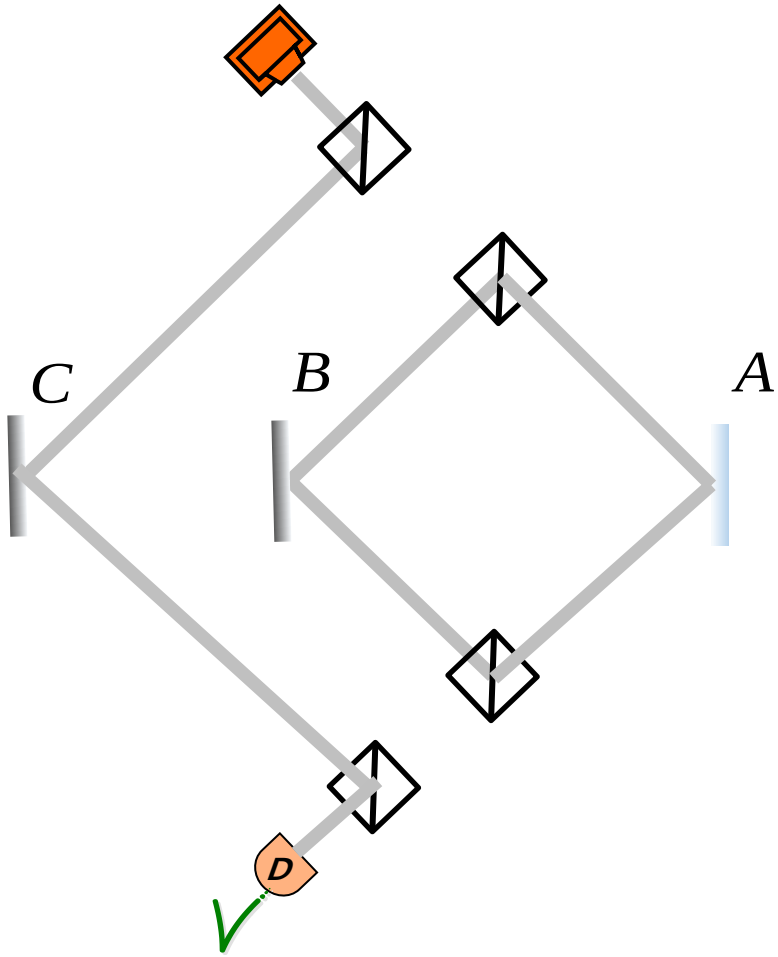
Where it could be found in a local non-demolition measurement

Where a local field could change the particle state



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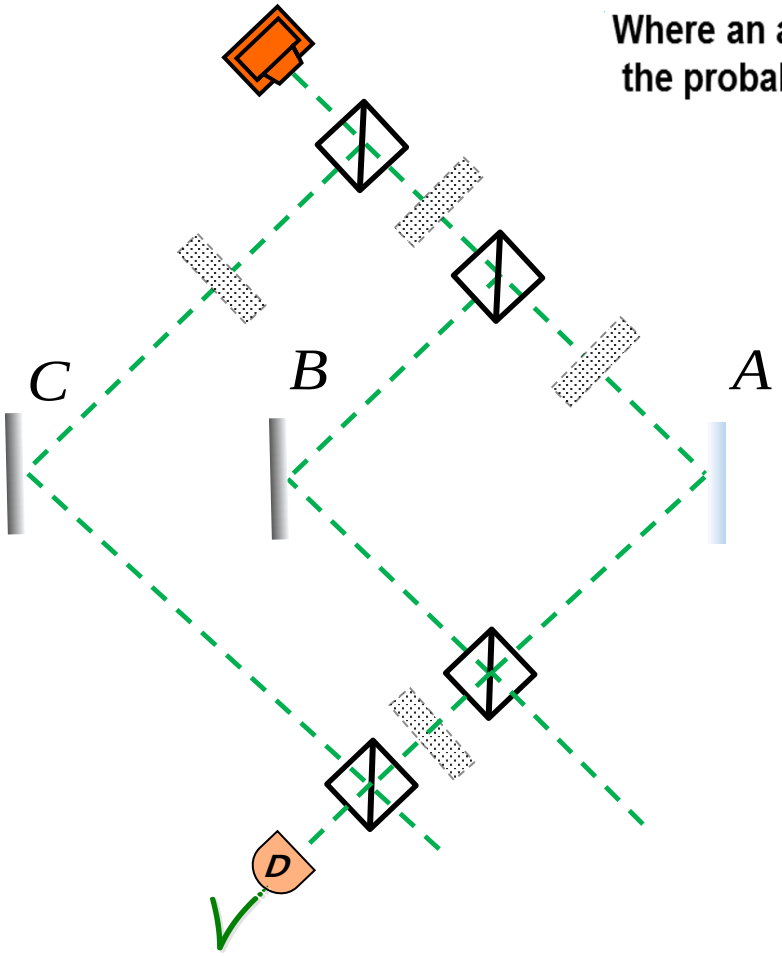
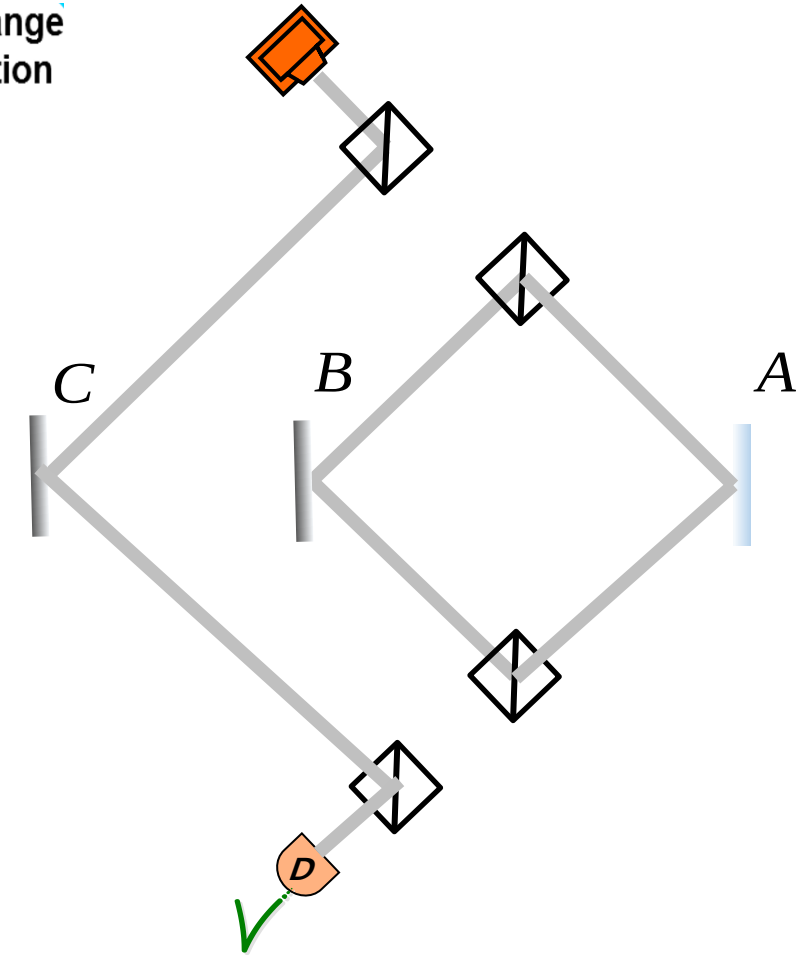


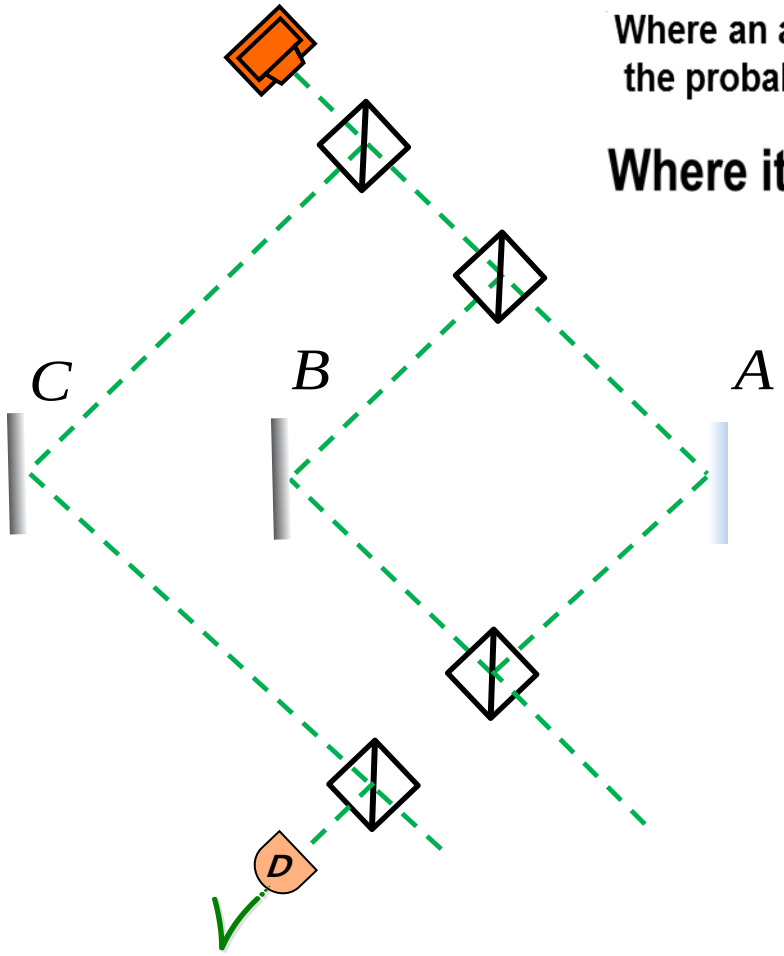
# Where was a pre- and post-selected particle?

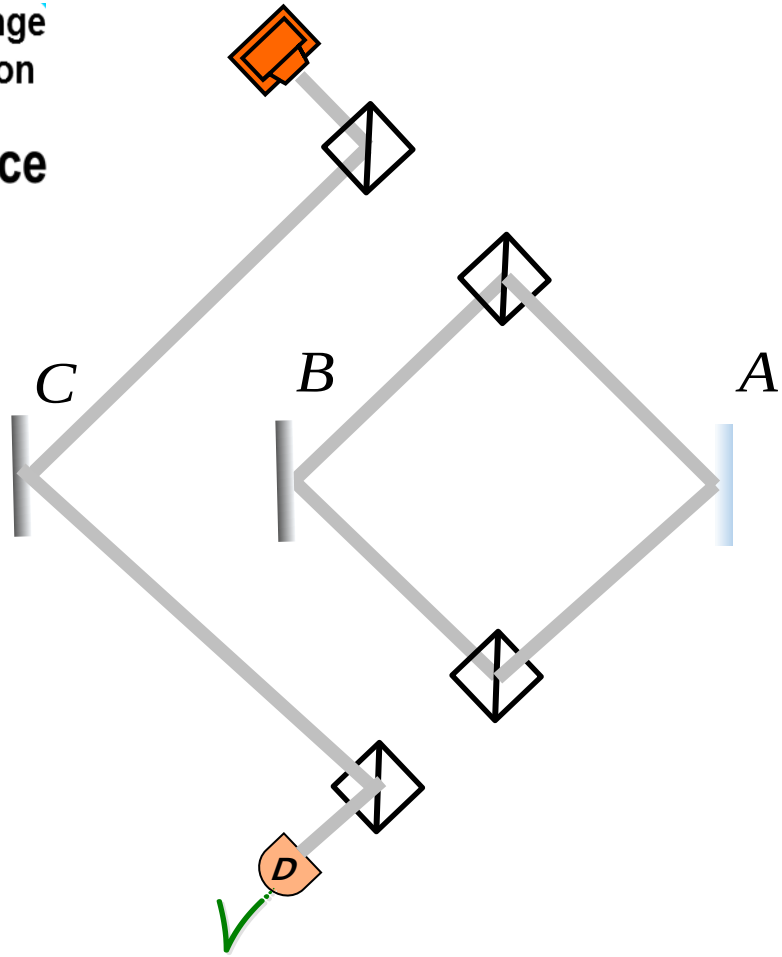
Where it could be found in a local non-demolition measurement

Where a local field could change the particle state

Where an absorber could change the probability of post-selection

Where it left a weak trace



# Where was a pre- and post-selected particle?

## Where it left a weak trace

PRL 111, 240402 (2013) Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 13 DECEMBER 2013

**Asking Photons Where They Have Been**

A. Danan, D. Farfurnik, S. Bar-Ad, and L. Vaidman

PHYSICAL REVIEW A **95**, 042121 (2017)

**Experimental observation of anomalous trajectories of single photons**

Zong-Quan Zhou,[1,2] Xiao Liu,[1,2] Yaron Kedem,[3,*] Jin-Min Cui,[1,2] Zong-Feng Li,[1,2] Yi-Lin Hua, Chuan-Feng Li,[1,2,†] and Guang-Can Guo[1,2]

PHYSICAL REVIEW A **97**, 052111 (2018)

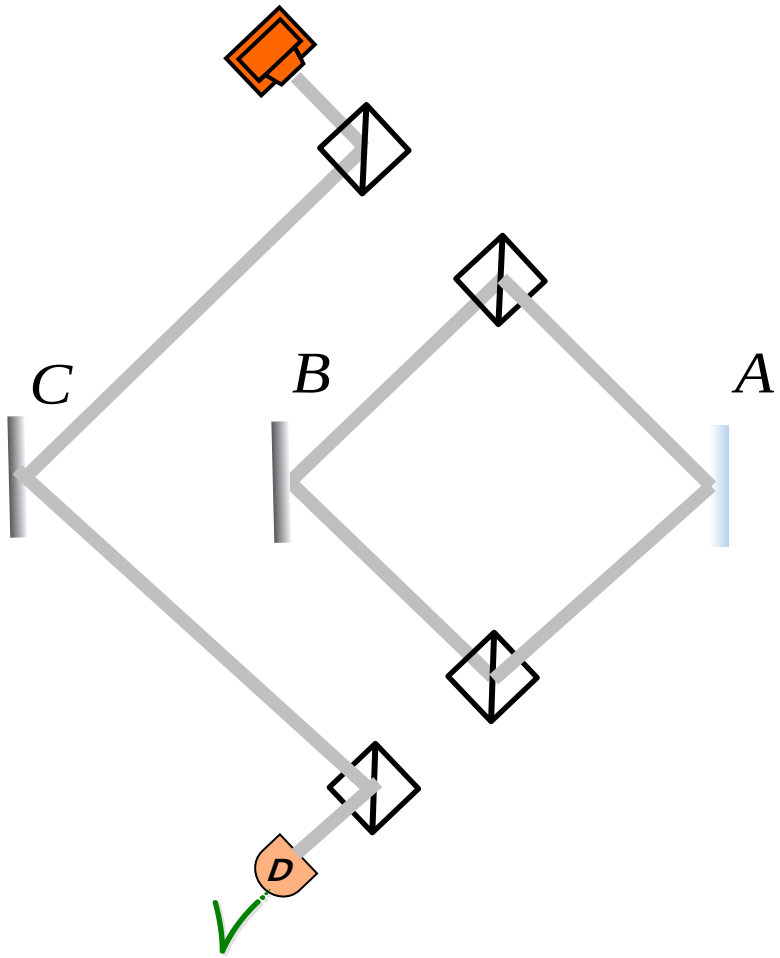
**Multifold paths of neutrons in the three-beam interferometer detected by a tiny energy kick**

Hermann Geppert-Kleinrath,[1] Tobias Denkmayr,[1] Stephan Sponar,[1] Hartmut Lemmel,[1,2] Tobias Jenke,[2] and Yuji Hasegawa[1,3,*]

arXiv:1806.01774 [pdf, other]

**Comment on "Multifold paths of neutrons in the three-beam interferometer detected by a tiny energy kick"**

Lev Vaidman



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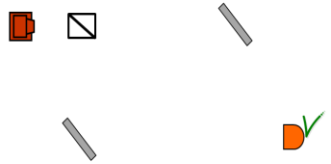

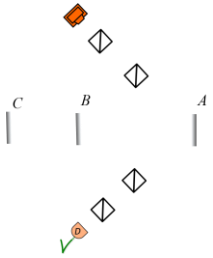


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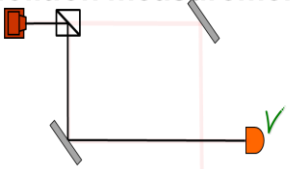

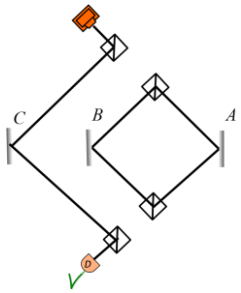


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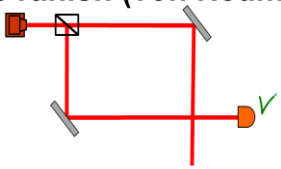

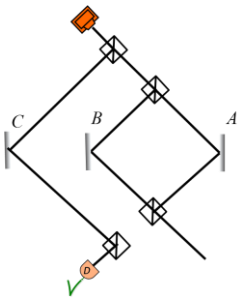


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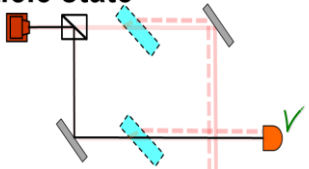

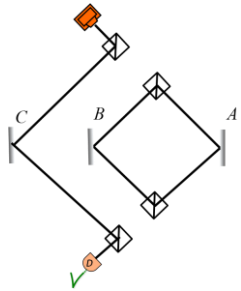


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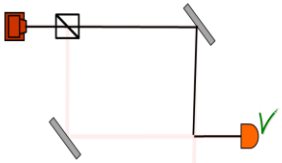

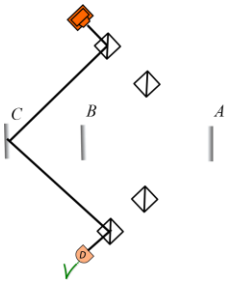


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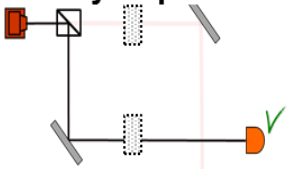

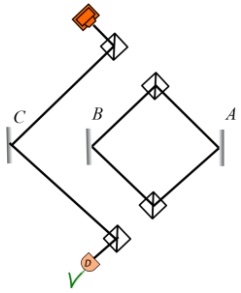


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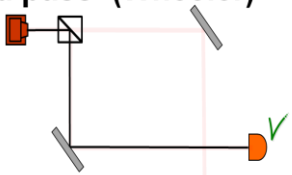
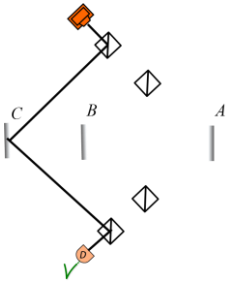
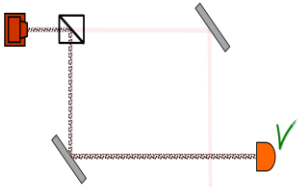
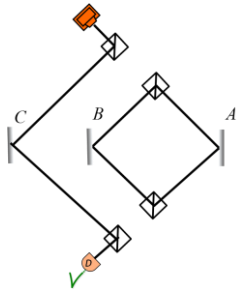





Where it left a weak trace

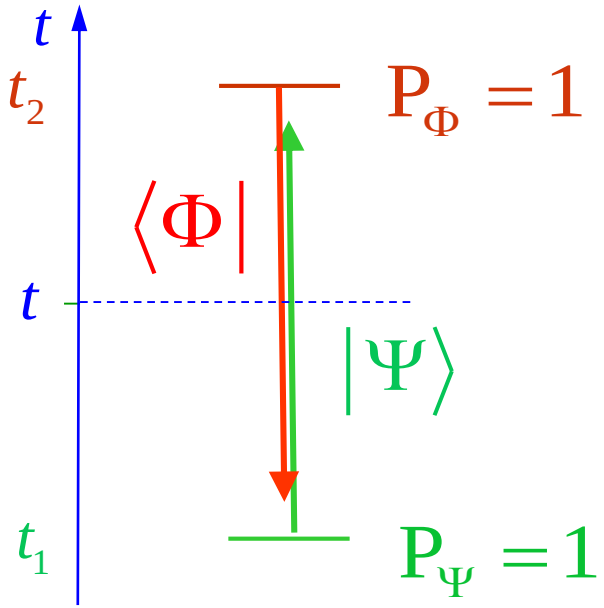




# The two-state vector formalism of quantum mechanics

**The pre- and post-selected particle is described by the two-state vector**

$$\langle \Phi | \quad | \Psi \rangle$$

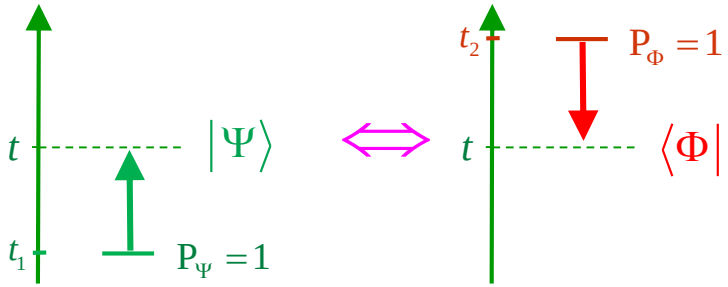



**Any coupling of a system described by $\langle \Phi | \, | \Psi \rangle$ to a variable *O* for a short enough time is a coupling to a weak value**

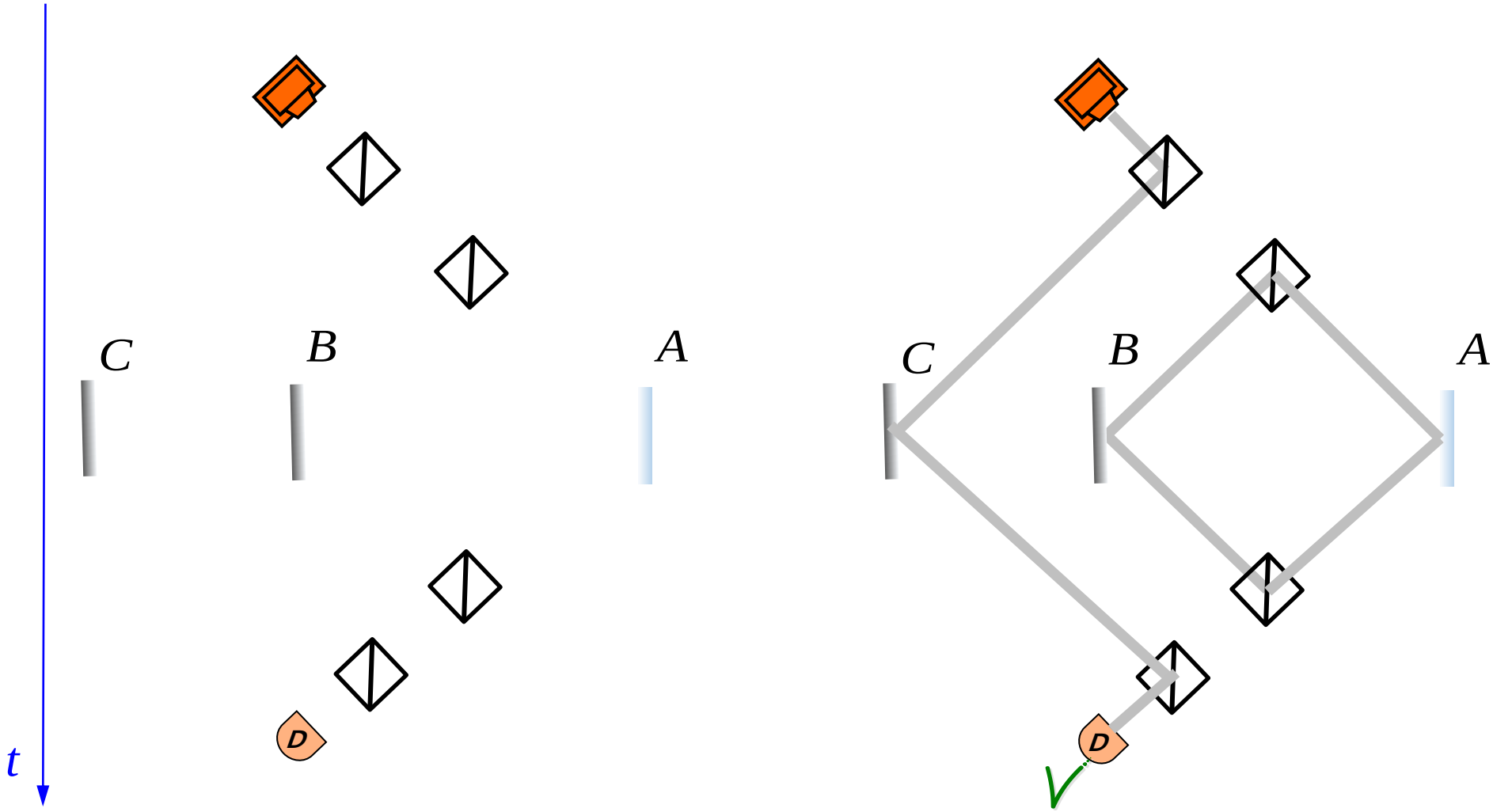
$$O_w \equiv \frac{\langle \Phi | O | \Psi \rangle}{\langle \Phi | \Psi \rangle}$$

**PRL 60, 1351 (1988)**

**PRA 96, 032114 (2017)**



# Where was a pre- and post-selected particle?



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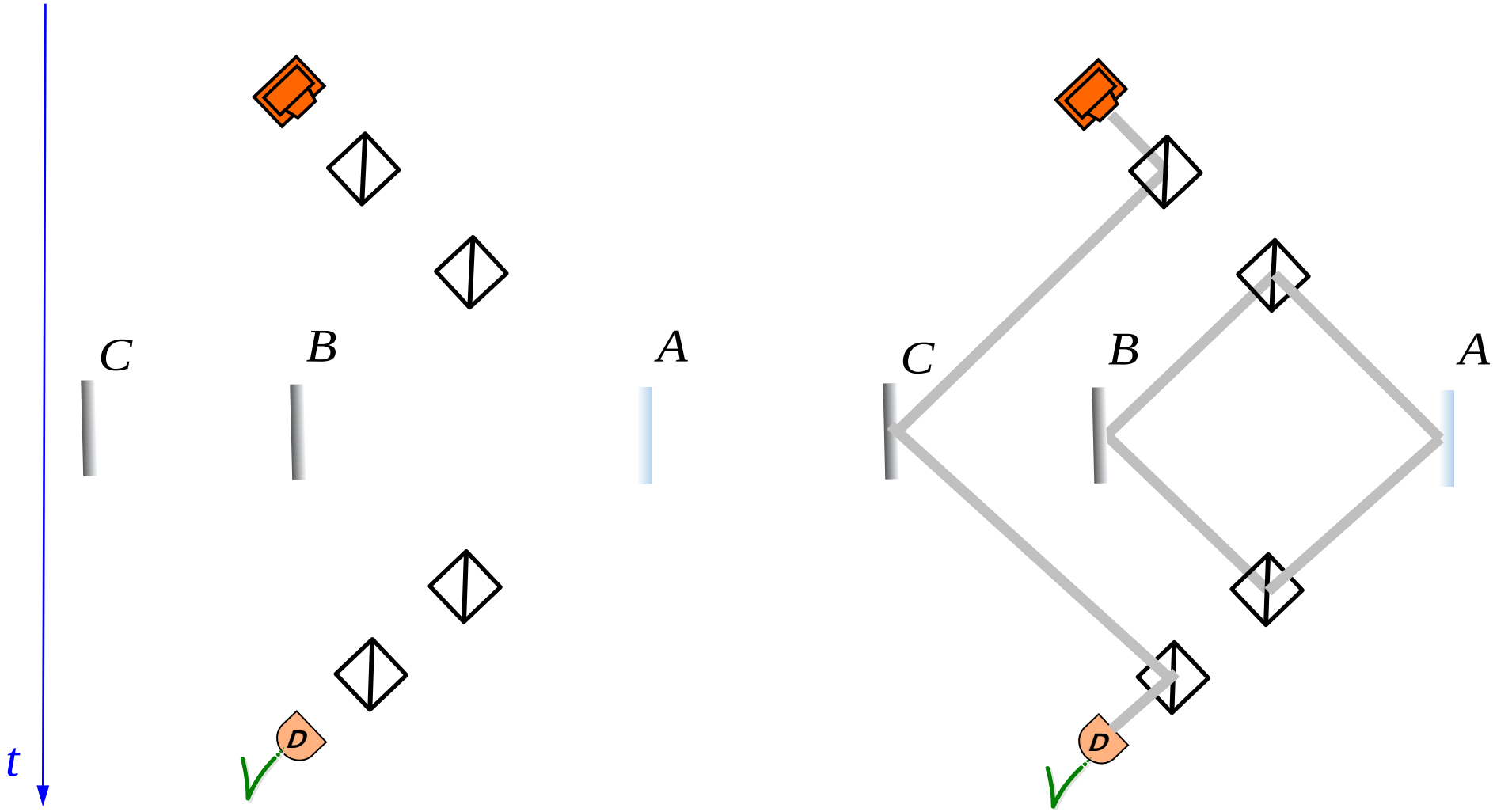
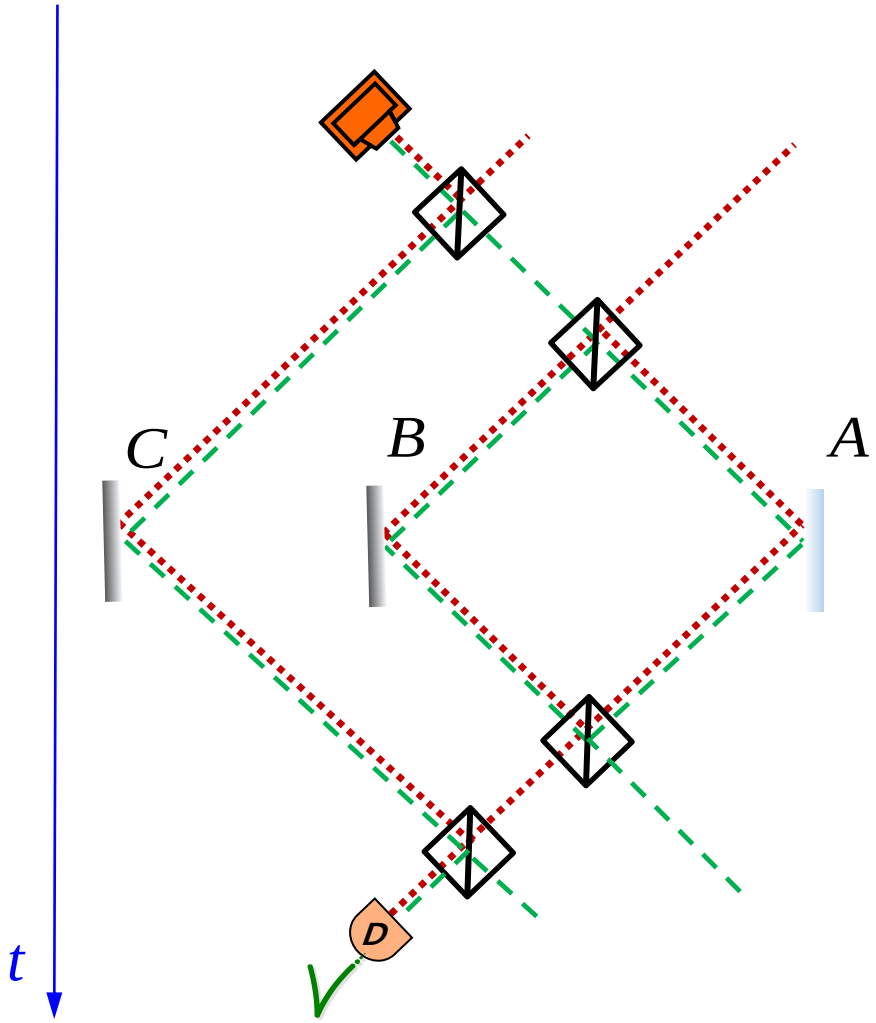
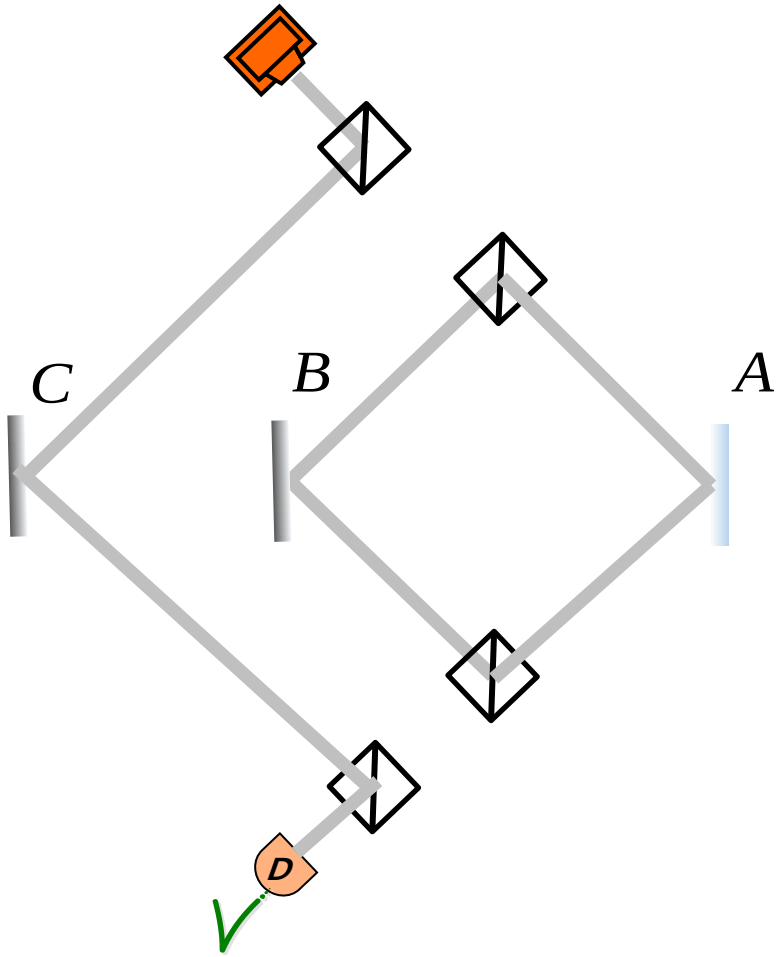


# Where was a pre- and post-selected particle?

**In the overlap of the forward and backward evolving wave functions**



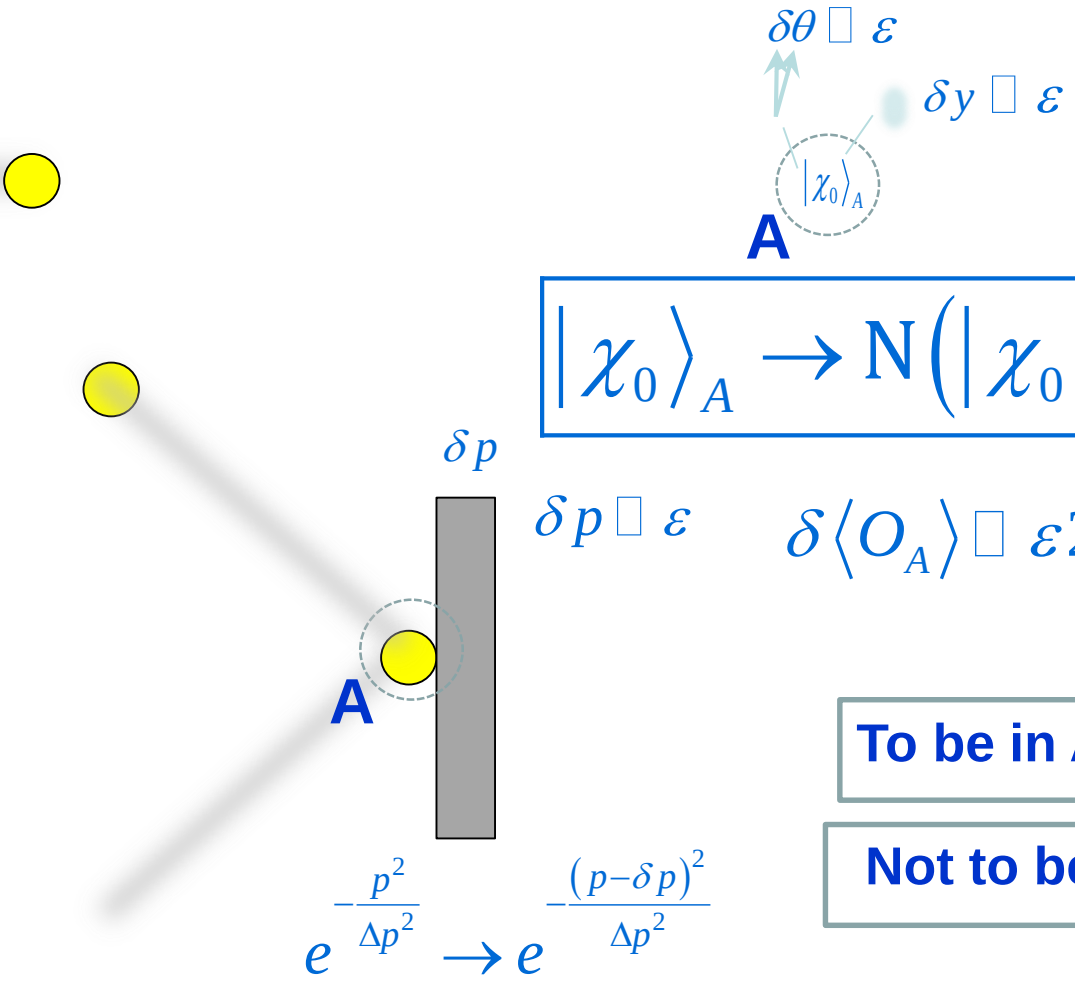

Where it left a weak trace



# Where was a pre- and post-selected particle?

**Where it left a weak trace** All interactions are local All particles have nonzero local interactions

**To be in A = to leave a local trace in A**




$$|\chi_0\rangle_A \to \mathrm{N}\left(|\chi_0\rangle_A + \varepsilon|\chi_\perp\rangle_A\right)$$

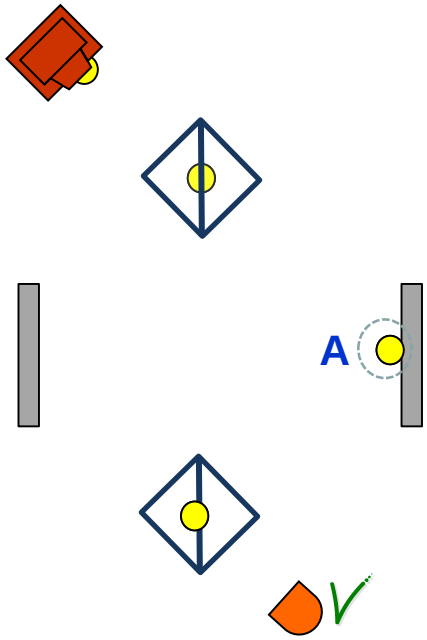
$$\delta\langle O_A\rangle \sim \varepsilon 2\,\mathrm{Re}\left[\langle\chi_0|O_A|\chi_\perp\rangle_A\right]$$

**To be in A** $|\chi_0\rangle_A \to \mathrm{N}\left(|\chi_0\rangle_A + \varepsilon|\chi_\perp\rangle_A\right)$

**Not to be in A** $|\chi_0\rangle_A \to |\chi_0\rangle_A$

# Was the particle in A or was not?

## To be in A = to leave a local trace in A



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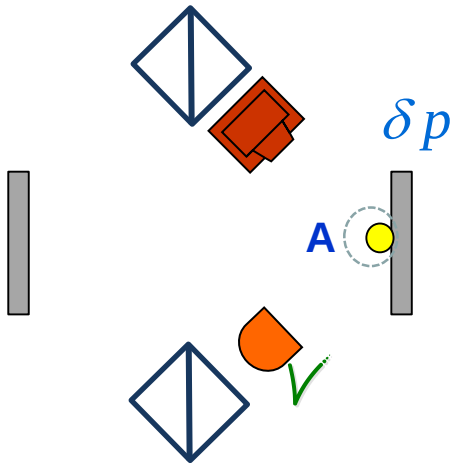
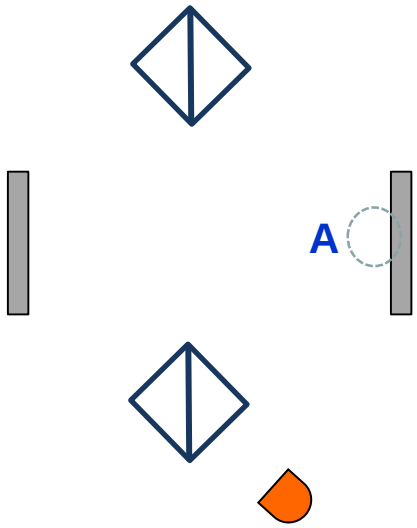



$$|\chi_0\rangle_A \to \mathrm{N}\left(|\chi_0\rangle_A + \varepsilon|\chi_\perp\rangle_A\right)$$

$$\delta p \square \varepsilon$$

**Was in A**

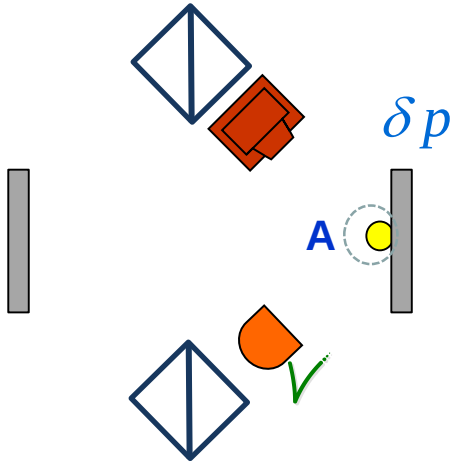



$$|\chi_0\rangle_A \to |\chi_0\rangle_A$$

$$\delta p = 0$$

**Was not in A**

# Was the particle in A or was not?

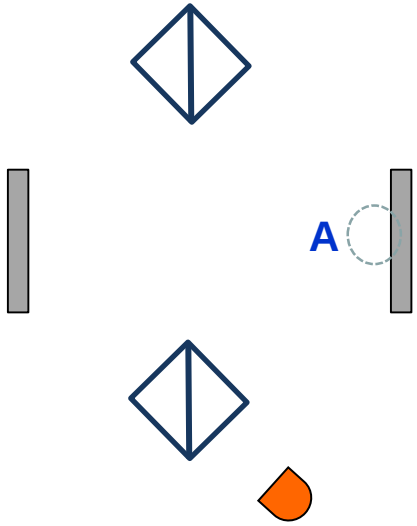



$$|\chi_0\rangle_A \to \mathrm{N}\left(|\chi_0\rangle_A + \varepsilon|\chi_\perp\rangle_A\right)$$

$$\delta p \sim \varepsilon$$

**Was in A**

$$\left(\mathbf{P}_A\right)_w = 1$$

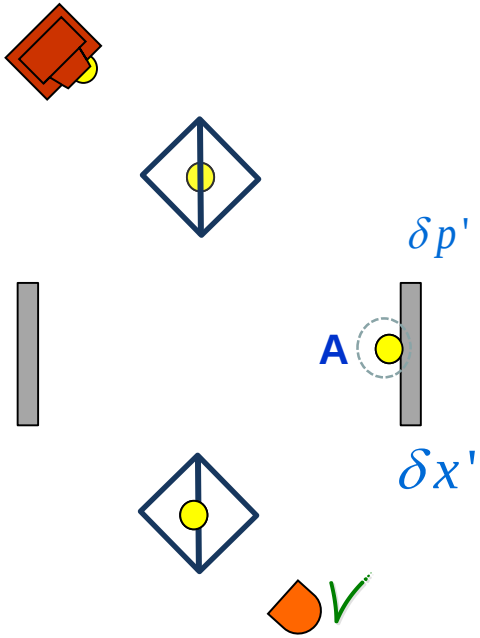



$$|\chi_0\rangle_A \to |\chi_0\rangle_A$$

$$\delta p = 0$$

**Was not in A**

$$\left(\mathbf{P}_A\right)_w = 0$$




$$|\chi_0\rangle_A \to \mathrm{N}'\left(|\chi_0\rangle_A + \left(\mathbf{P}_A\right)_w \varepsilon|\chi_\perp\rangle_A\right)$$

$$\delta p' \sim \mathrm{Re}\left(\mathbf{P}_A\right)_w \varepsilon$$

$$\delta x' \sim \mathrm{Im}\left(\mathbf{P}_A\right)_w \varepsilon$$

**Was in A with "presence"** $\left(\mathbf{P}_A\right)_w$

# What type of presence the particle had?

**Weak value of the local projection operator** $\left(\mathbf{P}_A\right)_w = \dfrac{\langle \Phi | \mathbf{P}_A | \Psi \rangle}{\langle \Phi | \Psi \rangle}$

**is the description of the presence of a quantum particle in a particular place in the past**

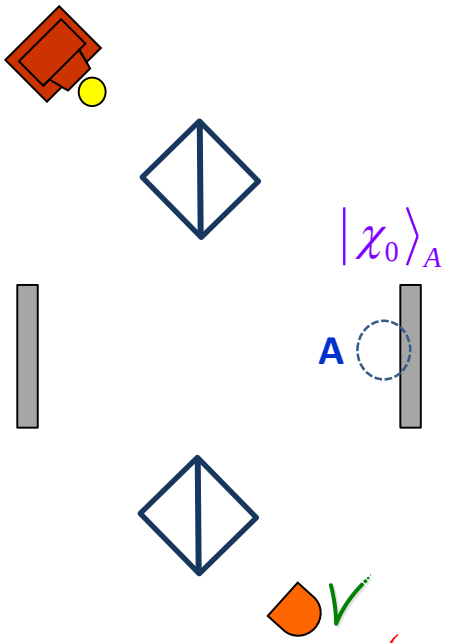
$\left(\mathbf{P}_A\right)_w$ **tells us how the trace in A is modified**

**relative to the trace of a particle well localized in A**

$$|\chi_0\rangle_A \rightarrow \mathrm{N}'\left(|\chi_0\rangle_A + \left(\mathbf{P}_A\right)_w \varepsilon |\chi_\perp\rangle_A\right)$$

$\left(\mathbf{P}_A\right)_w$ **tells us how effects of all weak (or short) interactions in A are modified**

**relative to the effects of a particle well localized in A**




**Not to be in A**

$$|\chi_0\rangle_A \rightarrow |\chi_0\rangle_A$$
$$Q \rightarrow Q$$
$$P_Q \rightarrow P_Q$$

**To be well localized in A**

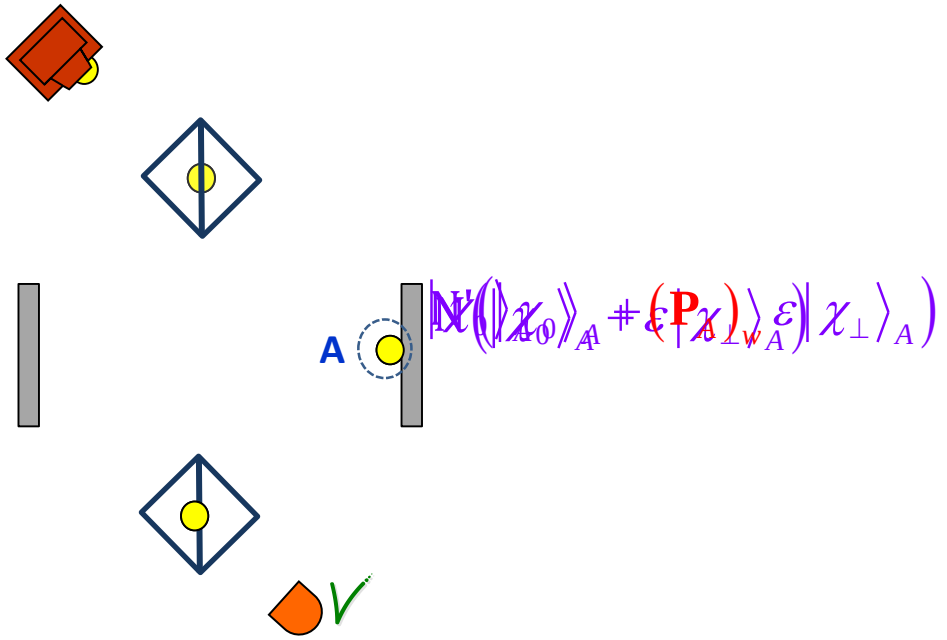
$$|\chi_0\rangle_A \rightarrow \mathrm{N}\left(|\chi_0\rangle_A + \varepsilon |\chi_\perp\rangle_A\right)$$
$$Q \rightarrow Q + \delta Q$$
$$P_Q \rightarrow P_Q$$

**To be with "presence"** $\left(\mathbf{P}_A\right)_w$

$$|\chi_0\rangle_A \rightarrow \mathrm{N}'\left(|\chi_0\rangle_A + \left(\mathbf{P}_A\right)_w \varepsilon |\chi_\perp\rangle_A\right)$$
$$Q \rightarrow Q + \mathrm{Re}\left(\mathbf{P}_A\right)_w \delta Q$$
$$P_Q \rightarrow P_Q + 2\left(\Delta P_Q\right)^2 \mathrm{Im}\left(\mathbf{P}_A\right)_w \delta Q$$

# Experiment: observing local trace in A

Dziewior, Knips, Farfurnik, Senkalla, Benshalom, Efroni, Meinecke, Bar-Ad, Weinfurter, Vaidman, **PNAS,** 116 288 (2019)



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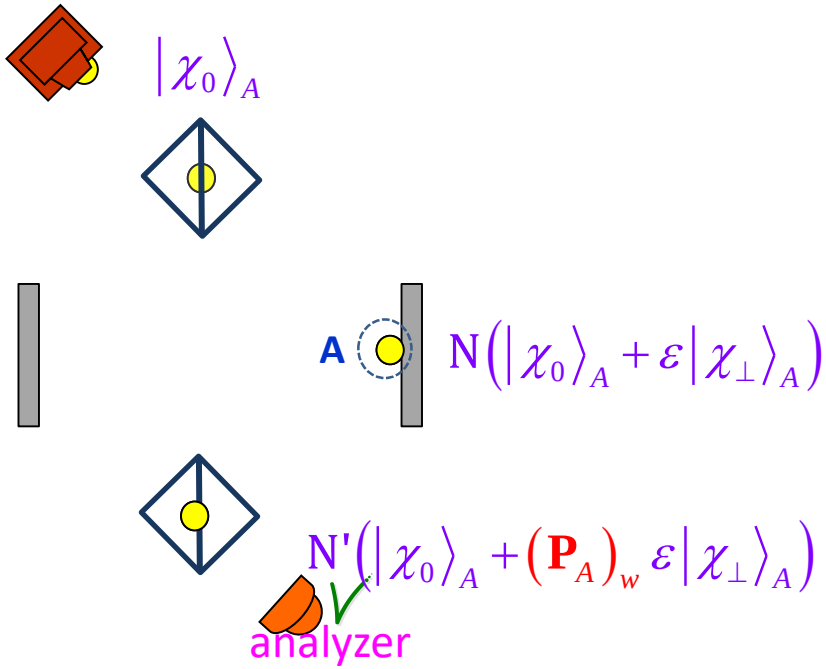
Dziewior, Knips, Farfurnik, Senkalla, Benshalom, Efroni, Meinecke, Bar-Ad, Weinfurter, Vaidman, **PNAS,** 116 288 (2019)

## The particle is the measuring device



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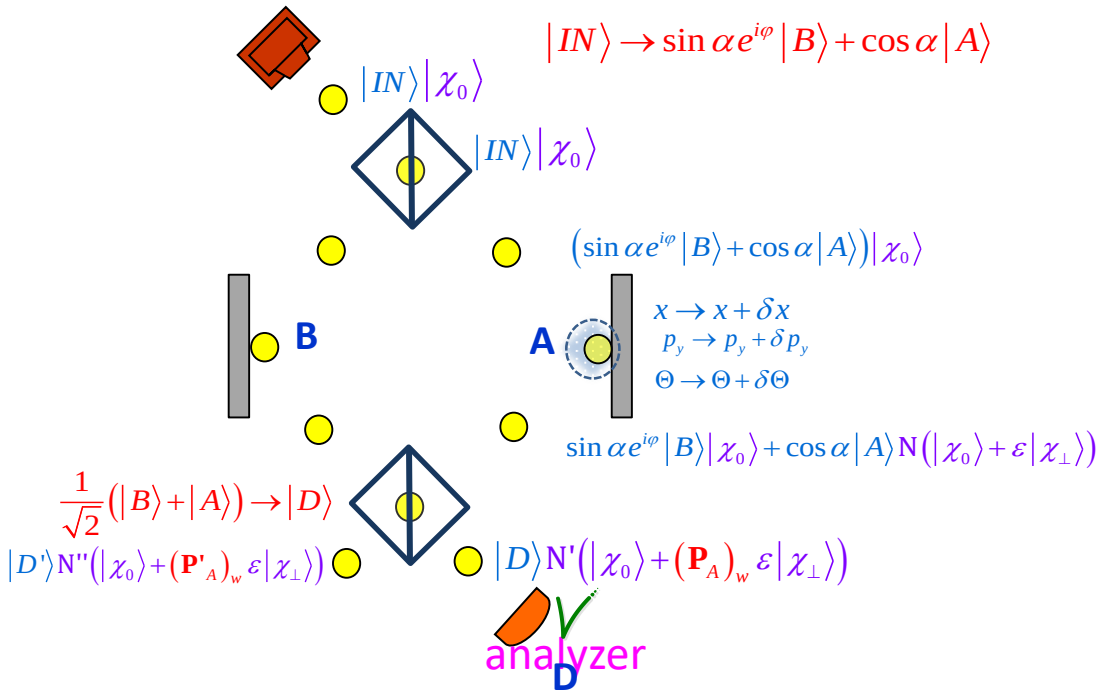
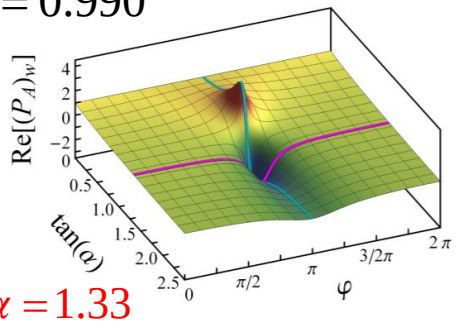
## The particle is the measuring device

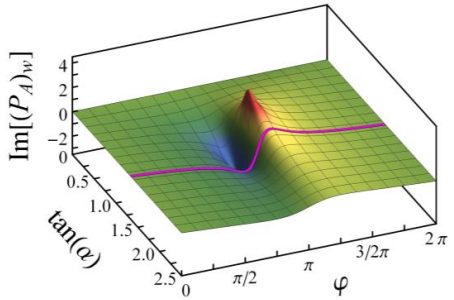



$$(\mathbf{P}_A)_w = \frac{1+\eta\tan\alpha e^{i\varphi}}{1+\tan^2\alpha + 2\eta\tan\alpha\cos\varphi}$$

$$\eta = 0.990$$




$$\tan\alpha = 1.33$$




**To be well localized in A**

$$|\chi_0\rangle_A \to \mathrm{N}(|\chi_0\rangle_A + \varepsilon|\chi_\perp\rangle_A)$$

$$x \to x + \delta x$$

$$p_y \to p_y + \delta p_y$$

$$\Theta \to \Theta + \delta\Theta$$

**To be with "presence" $(\mathbf{P}_A)_w$**

$$|\chi_0\rangle_A \to \mathrm{N}'(|\chi_0\rangle_A + (\mathbf{P}_A)_w \varepsilon|\chi_\perp\rangle_A)$$

$$x \to x + \mathrm{Re}(\mathbf{P}_A)_w \delta x \qquad p_x \to p_x + 2(\Delta p_x)^2 \,\mathrm{Im}(\mathbf{P}_A)_w \delta x$$

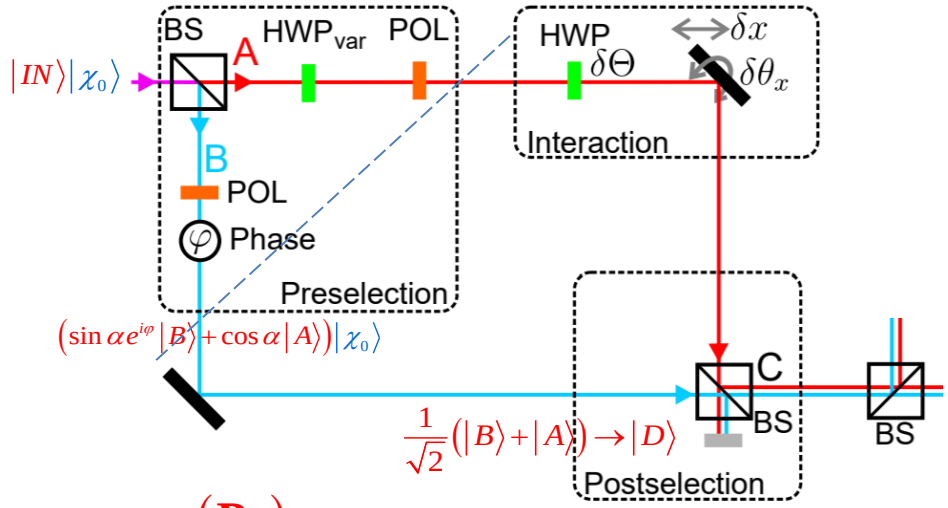
$$p_y \to p_y + \mathrm{Re}(\mathbf{P}_A)_w \delta p_y \qquad y \to y - 2(\Delta y)^2 \,\mathrm{Im}(\mathbf{P}_A)_w \delta p_y$$

$$\Theta \to \Theta + \mathrm{Re}(\mathbf{P}_A)_w \delta\Theta \qquad \Upsilon \to \Upsilon + \mathrm{Im}(\mathbf{P}_A)_w \delta\Theta$$

# Experiment: observing local trace in A

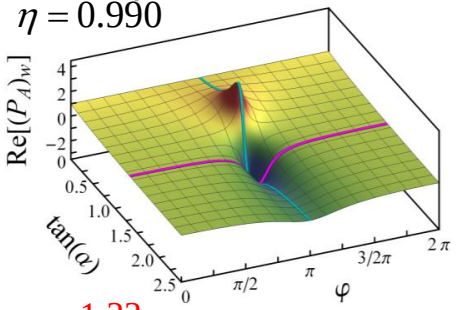
**Dziewior, Knips, Farfurnik, Senkalla, Benshalom, Efroni, Meinecke, Bar-Ad, Weinfurter, Vaidman, PNAS,** 116 288 (2019)

$$|\chi_0\rangle_A \to \mathrm{N}\left(|\chi_0\rangle_A + (\mathbf{P}_A)_w\, \varepsilon |\chi_\perp\rangle_A\right)$$

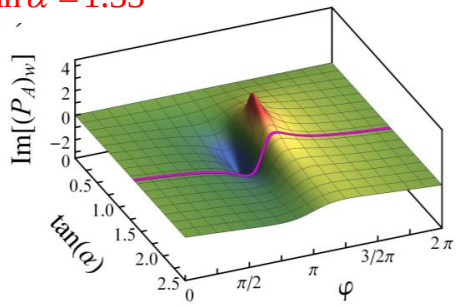



$(\mathbf{P}_A)_w$

$\eta = 0.990$




$\tan\alpha = 1.33$



# Summary

## A pre and postselected particle:

**Where it was?**

**Where it left a local trace** $|\chi_0\rangle_A \to \mathrm{N}\left(|\chi_0\rangle_A + \varepsilon|\chi_\perp\rangle_A\right)$

**In the overlap of forward and backward evolving states**

**What type of presence it had?**

$\left(\mathbf{P}_A\right)_w$ **describes the presence in A for a spatially pre- and postselected systems** $|\chi_0\rangle_A \to \mathrm{N}'\left(|\chi_0\rangle_A + \left(\mathbf{P}_A\right)_w \varepsilon|\chi_\perp\rangle_A\right)$

**All weak interactions in A are modified in the same way:**

$x \to x + \delta x$ $\quad x \to x + \mathrm{Re}\left(\mathbf{P}_A\right)_w \delta x$ $\quad p_x \to p_x + 2\left(\Delta p_x\right)^2 \mathrm{Im}\left(\mathbf{P}_A\right)_w \delta x$

**The effects are multiplied by** $\mathrm{Re}\left(\mathbf{P}_A\right)_w$ **(and change direction if** $\mathrm{Re}\left(\mathbf{P}_A\right)_w < 0$ **)**

**The conjugate variables are affected in proportion to** $\mathrm{Im}\left(\mathbf{P}_A\right)_w$ **.**