Title: Quantum Mechanics in the Presence of Time Machines

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Abstract: Tim Ralph

We consider quantum mechanical particles that traverse general relativistic wormholes in such a way that they can interact with their own past, thus forming closed timelike curves. Using a simple geometric argument we reproduce the solutions proposed by Deutsch for such systems. Deutsch's solutions have attracted considerable interest because they do not contain paradoxes, however, as originally posed, they do contain ambiguities. We show that these ambiguities are removed by following our geometric derivation.

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Quantum Mechanics in the presence of Time Mahines

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Defence Science and Technology Organization

ARC AUSTRALIAN RESEARCH COUNCIL

THE UNIVERSITY OF QUEENSLAND AUSTRALIA

Overview

* Physical model of the interaction of a quantum system with a Closed Timelike Curve formed by spacetime geometry

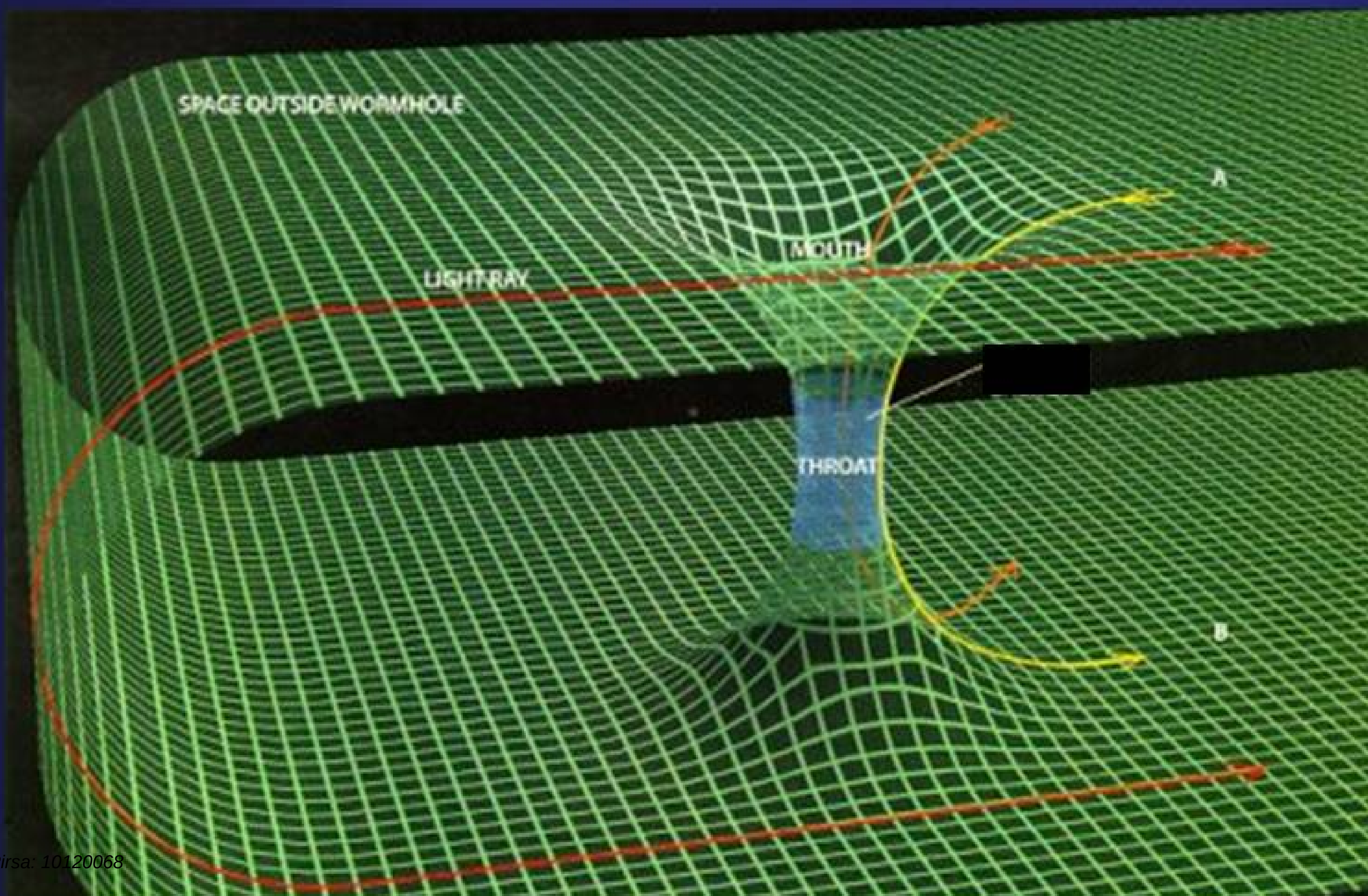
* Connection with Deutsch's model

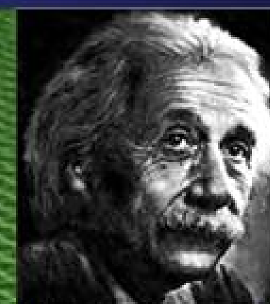
* Resolution of problems of the Deutsch model by the geometric model.

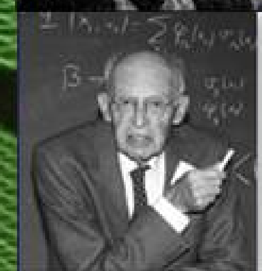
* Conclusions

Creation of a Closed Timelike Curve

Wormhole







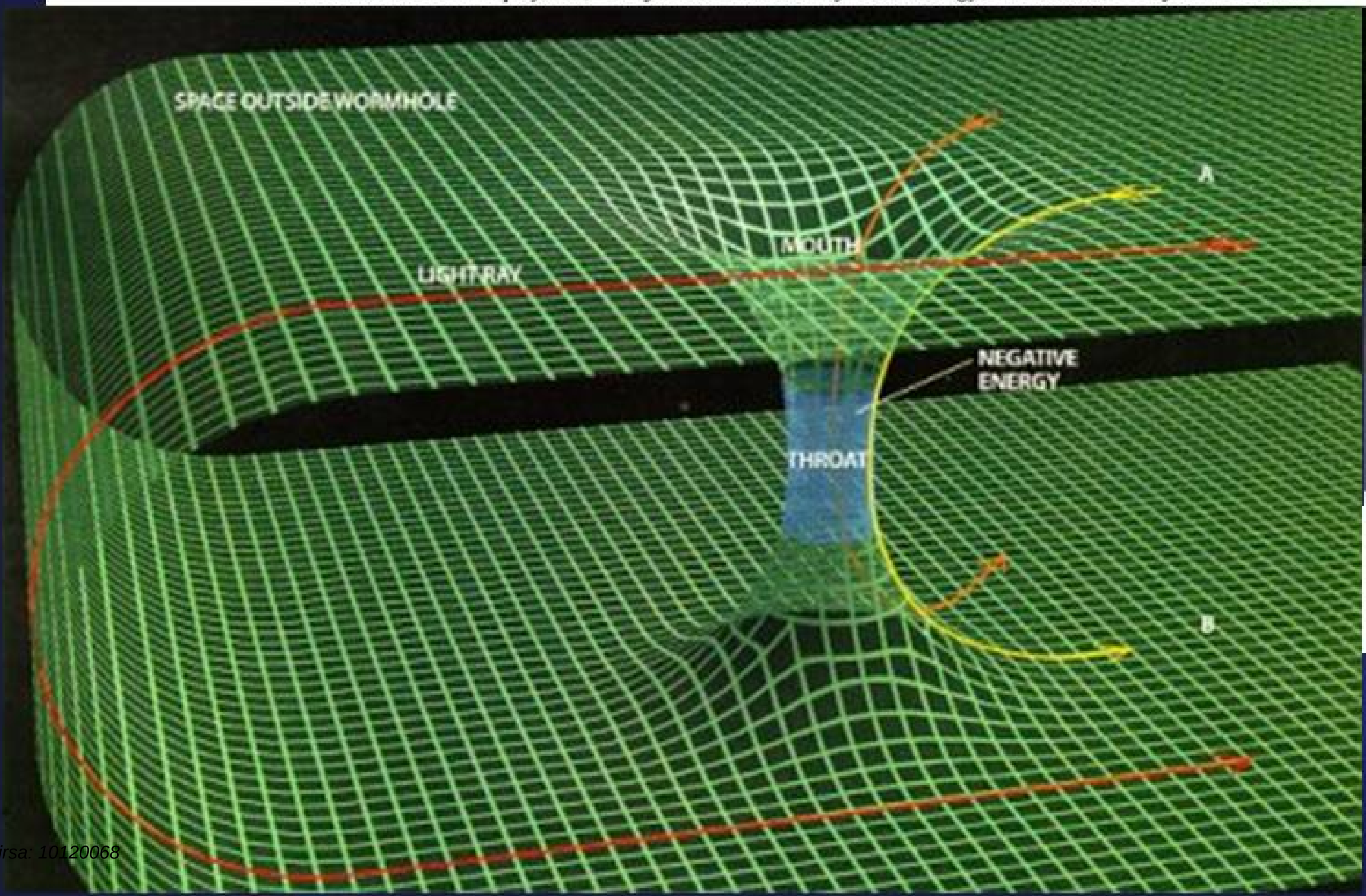
also known as Einstein-Rosen bridge

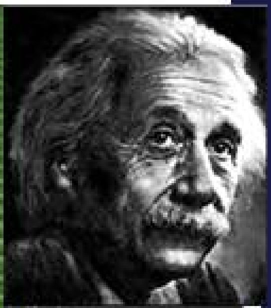
Creation of a Closed Timelike Curve

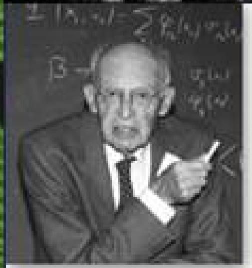
VOLUME 61, NUMBER 13 PHYSICAL REVIEW LETTERS 26 SEPTEMBER 1988

Wormholes, Time Machines, and the Weak Energy Condition

Michael S. Morris, Kip S. Thorne, and Ulvi Yurtsever
Theoretical Astrophysics, California Institute of Technology, Pasadena, California 91125







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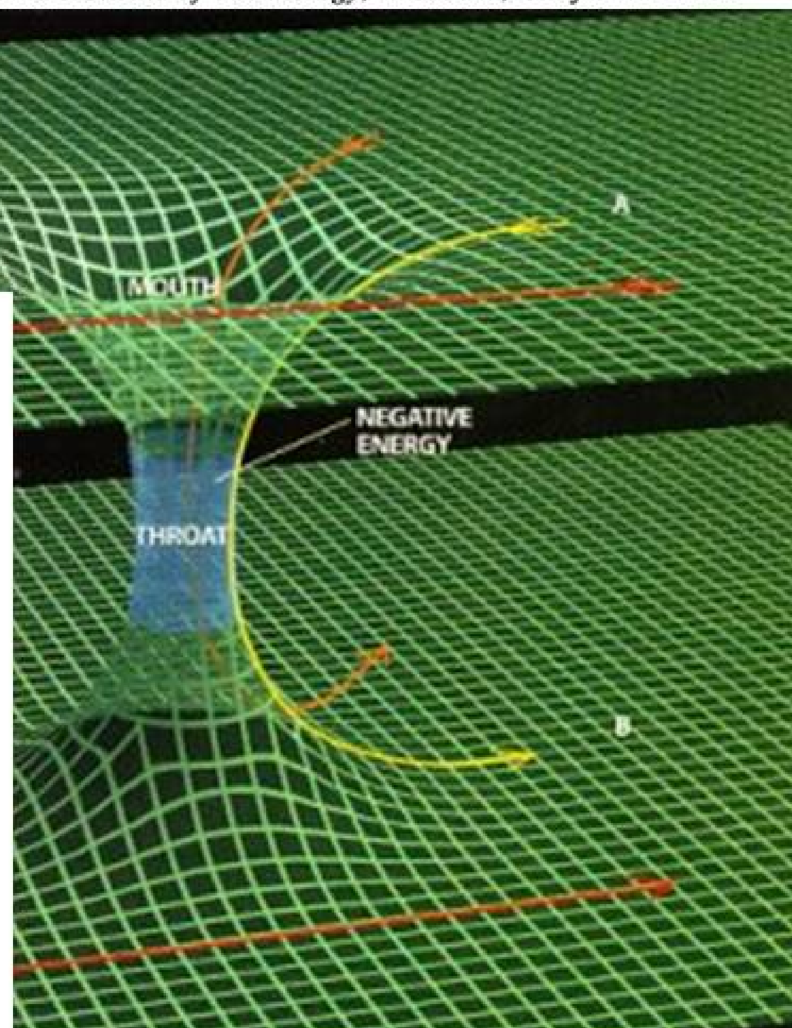

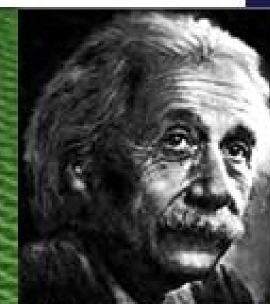

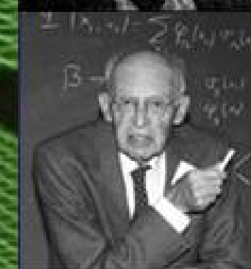

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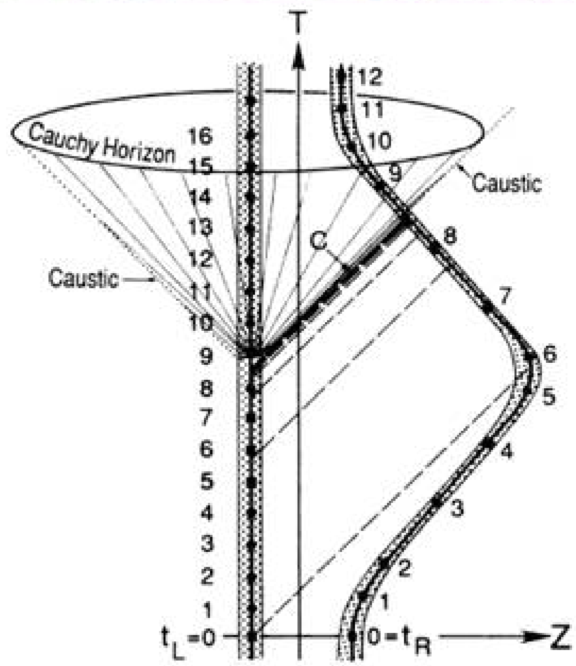
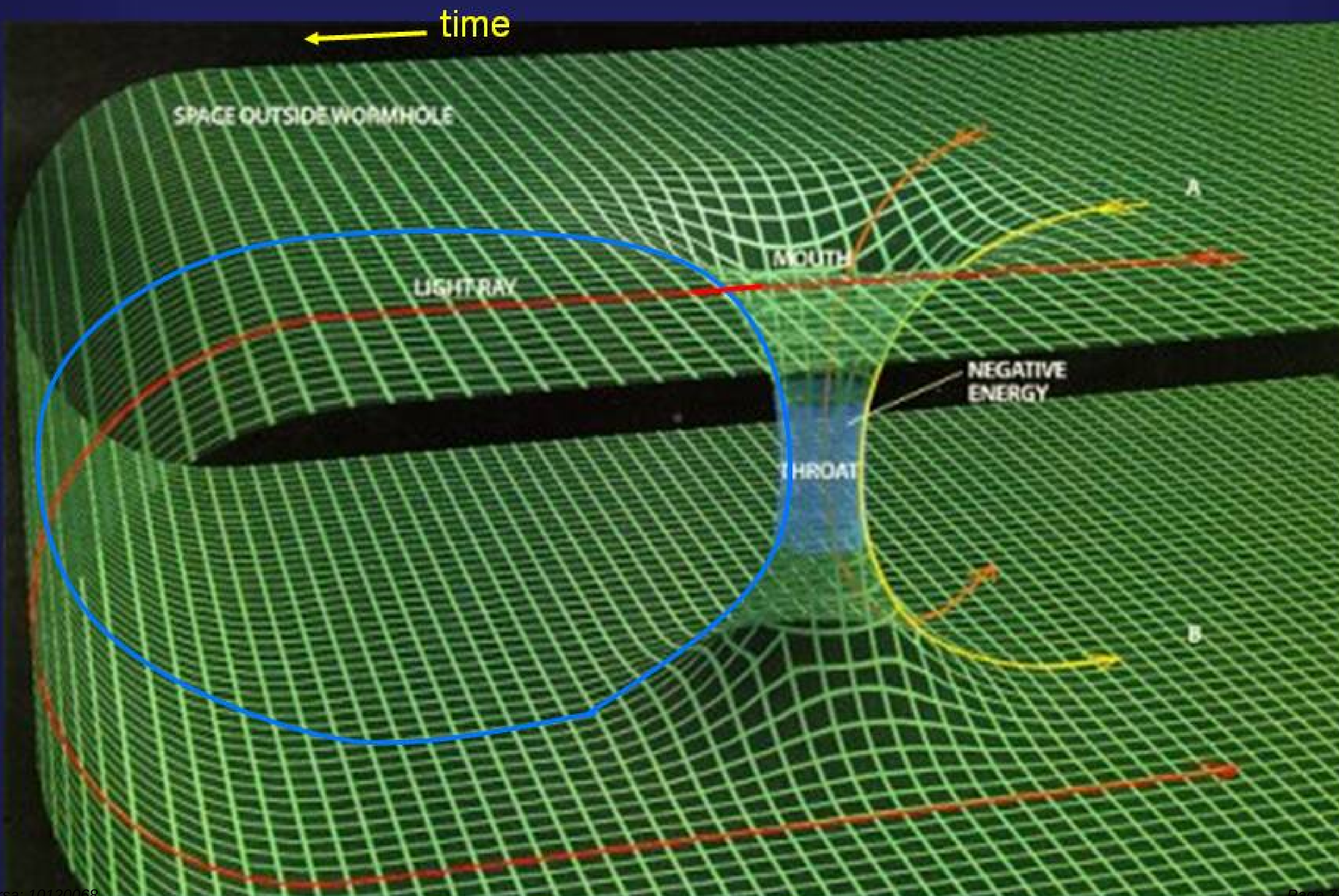
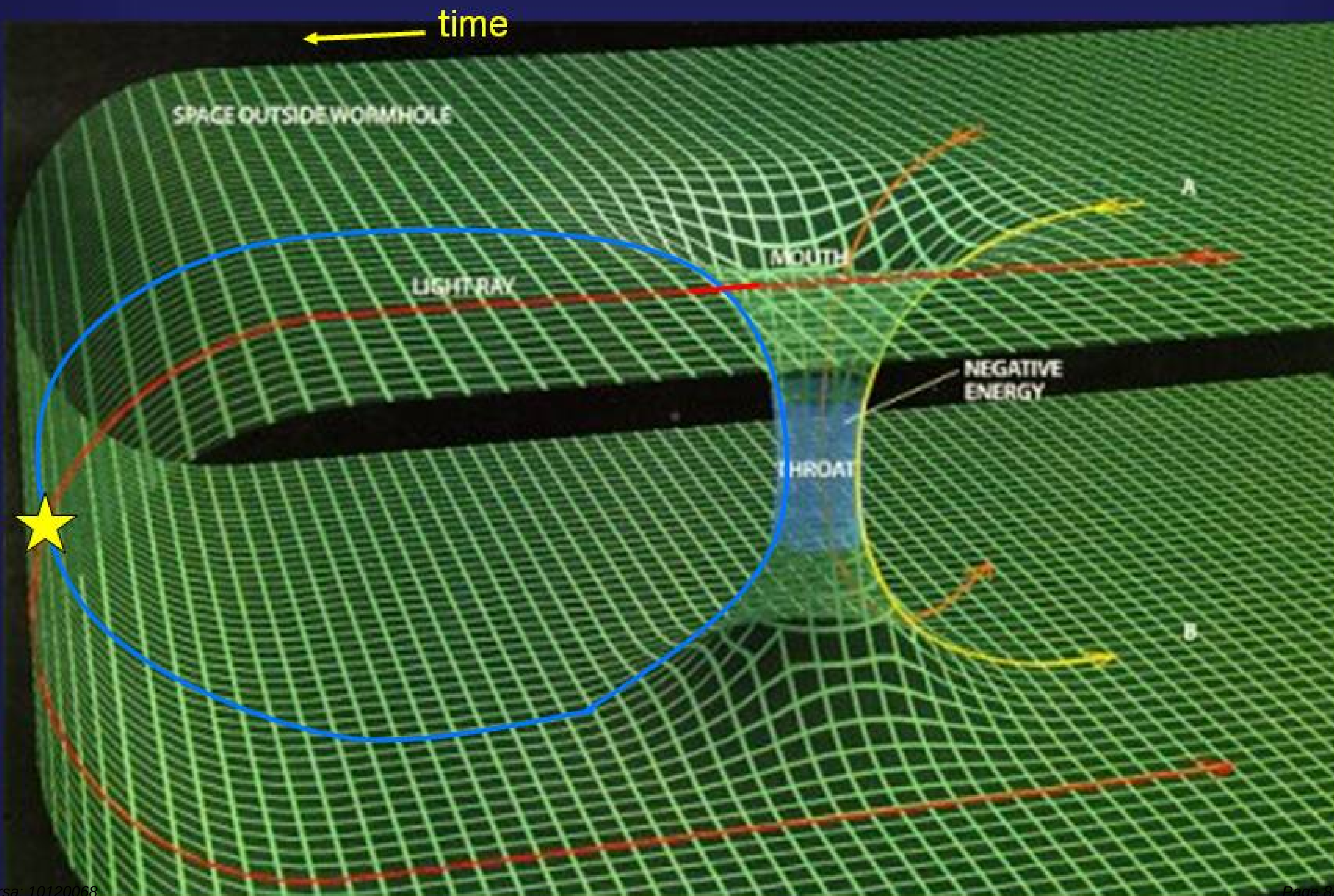


FIG. 2. Spacetime diagram for conversion of a wormhole into a time machine.

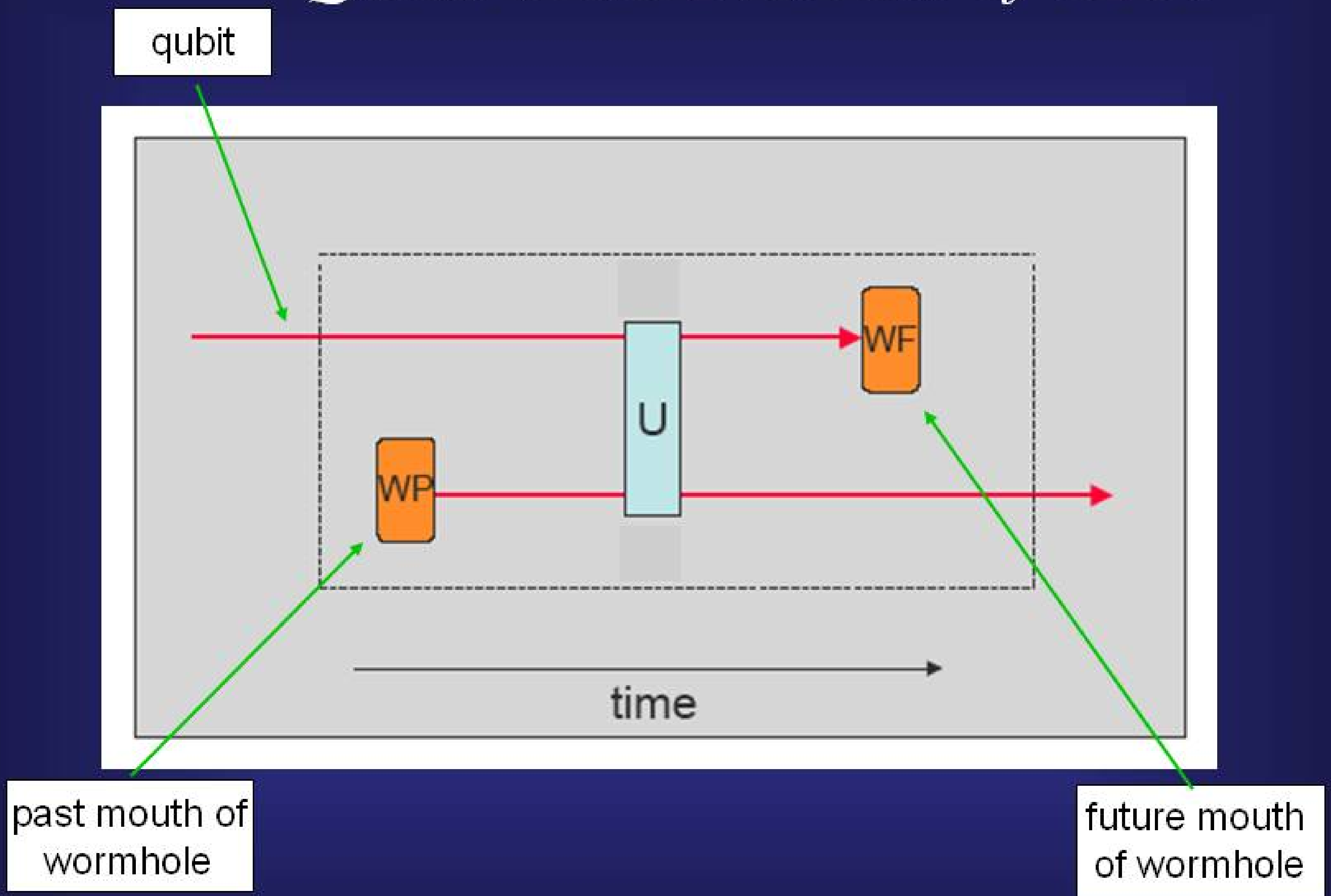
Creation of a Closed Timelike Curve



Creation of a Closed Timelike Curve



Qubits in the Presence of CTCs



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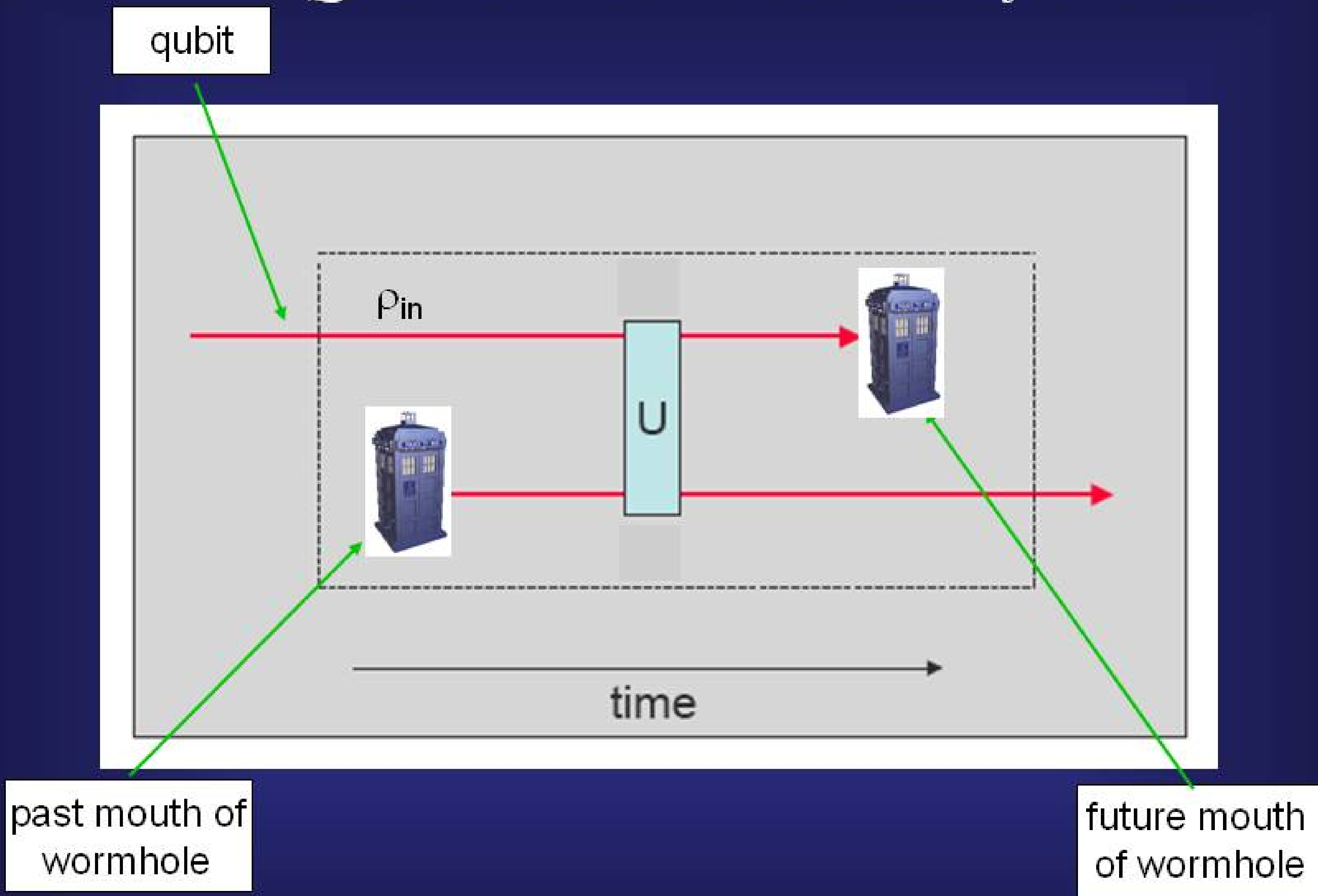

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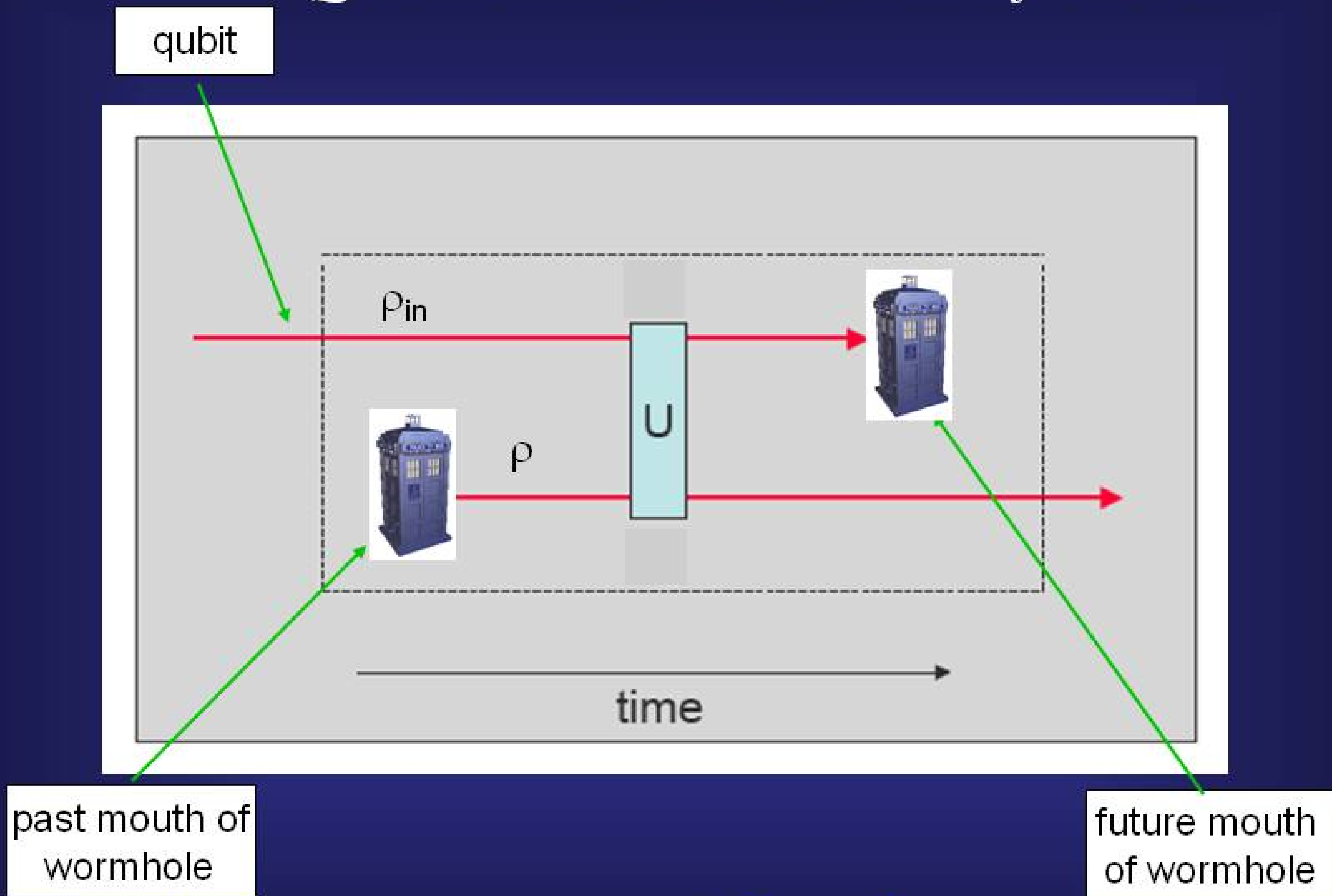

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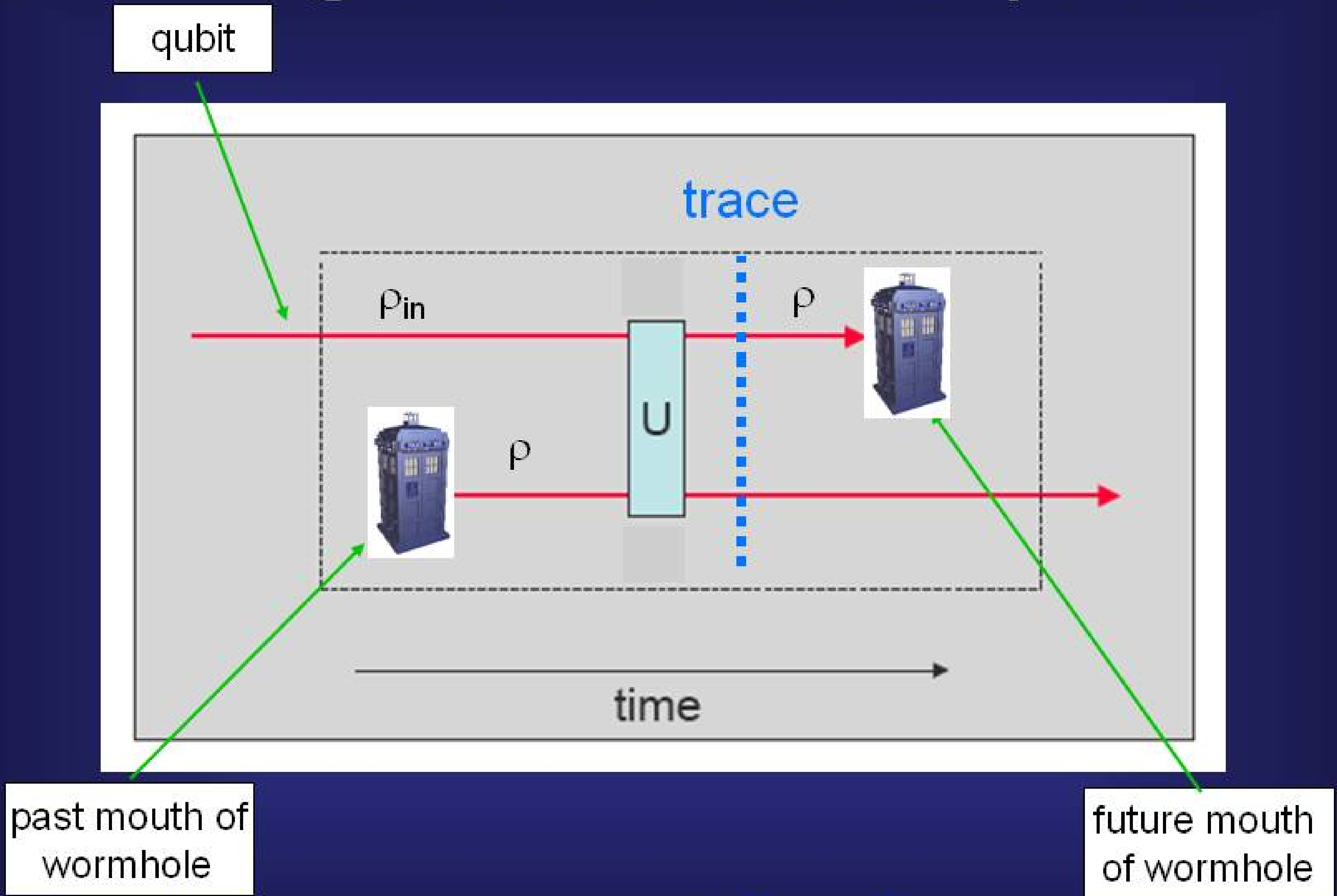

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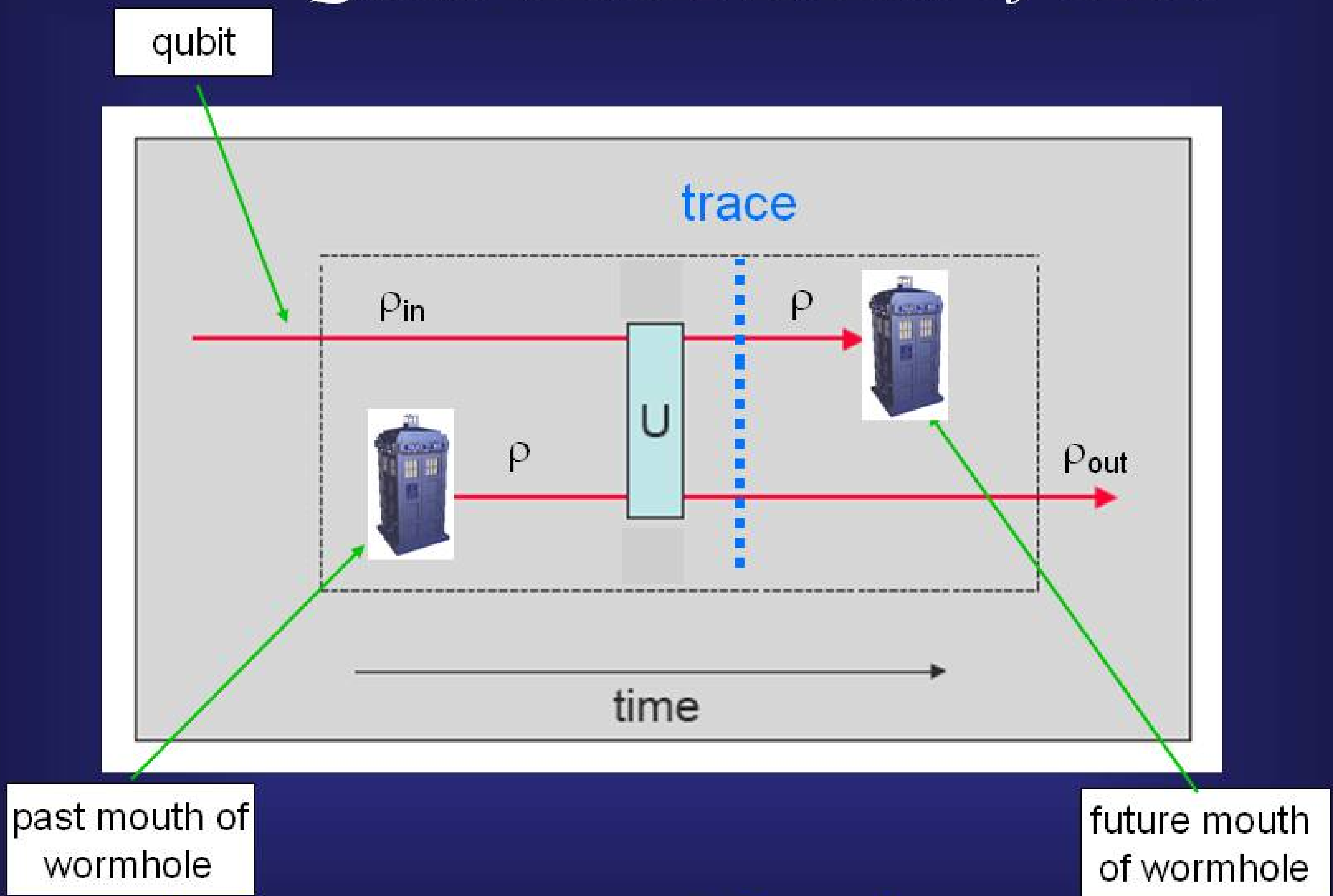

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Key results of the Deutsch Model

(i) **No Paradoxes**

(ii) Non-linear evolution

(iii) no signalling

PHYSICAL REVIEW A **70**, 032309 (2004)

Quantum computational complexity in the presence of closed timelike curves

Dave Bacon*

Institute for Quantum Information, California Institute of Technology, Pasadena, California 91125, USA and Department of Physics, California Institute of Technology, Pasadena, California 91125, USA

(Received 28 October 2003; published 13 September 2004)

PRL **102**, 210402 (2009) PHYSICAL REVIEW LETTERS week ending 29 MAY 2009

Localized Closed Timelike Curves Can Perfectly Distinguish Quantum States

Todd A. Brun,[1] Jim Harrington,[2] and Mark M. Wilde[1,3]

[1]*Communication Sciences Institute, Department of Electrical Engineering, University of Southern California, Los Angeles, California 90089, USA*

[2]*Applied Modern Physics (P-21), MS D454, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*

[3]*Centre for Quantum Technologies, National University of Singapore, 3 Science Drive 2, Singapore 117543*

(Received 7 November 2008; published 27 May 2009)

PRL **103**, 170502 (2009) PHYSICAL REVIEW LETTERS week ending 23 OCTOBER 2009

Can Closed Timelike Curves or Nonlinear Quantum Mechanics Improve Quantum State Discrimination or Help Solve Hard Problems?

Charles H. Bennett,[1,*] Debbie Leung,[2,†] Graeme Smith,[1,‡] and John A. Smolin[1,§]

[1]*IBM T.J. Watson Research Center, Yorktown Heights, New York 10598, USA*

[2]*Institute for Quantum Computing, University of Waterloo, Waterloo, Ontario, N2L 3G1, Canada*

(Received 2 September 2009; published 21 October 2009)

Problems with the Deutsch Model

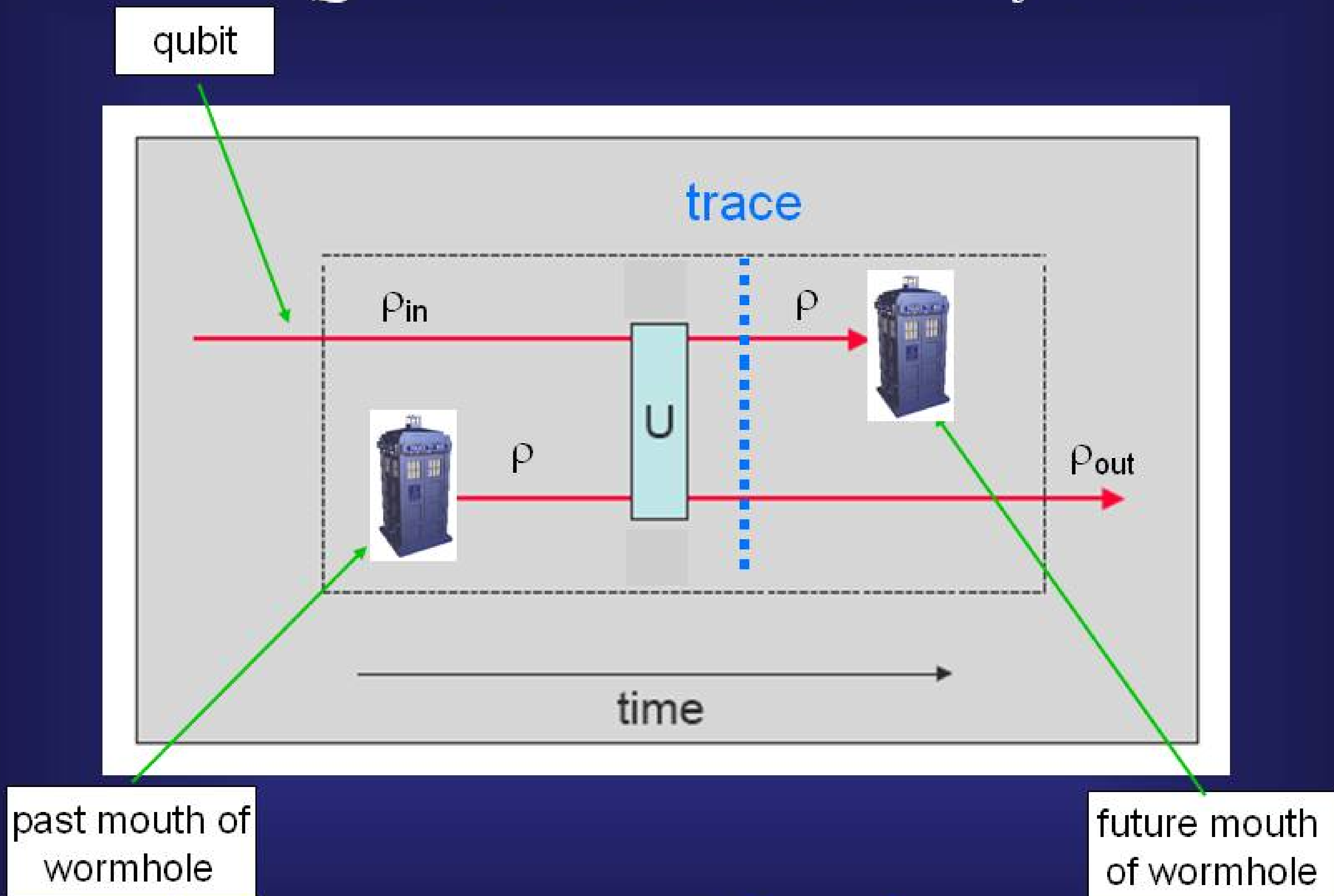
(i) Multiple solution ambiguity?

(ii) Initial state ambiguity?

(iii) non-unitarity?

(iv) Extension to field description?

Qubits in the Presence of CTCs



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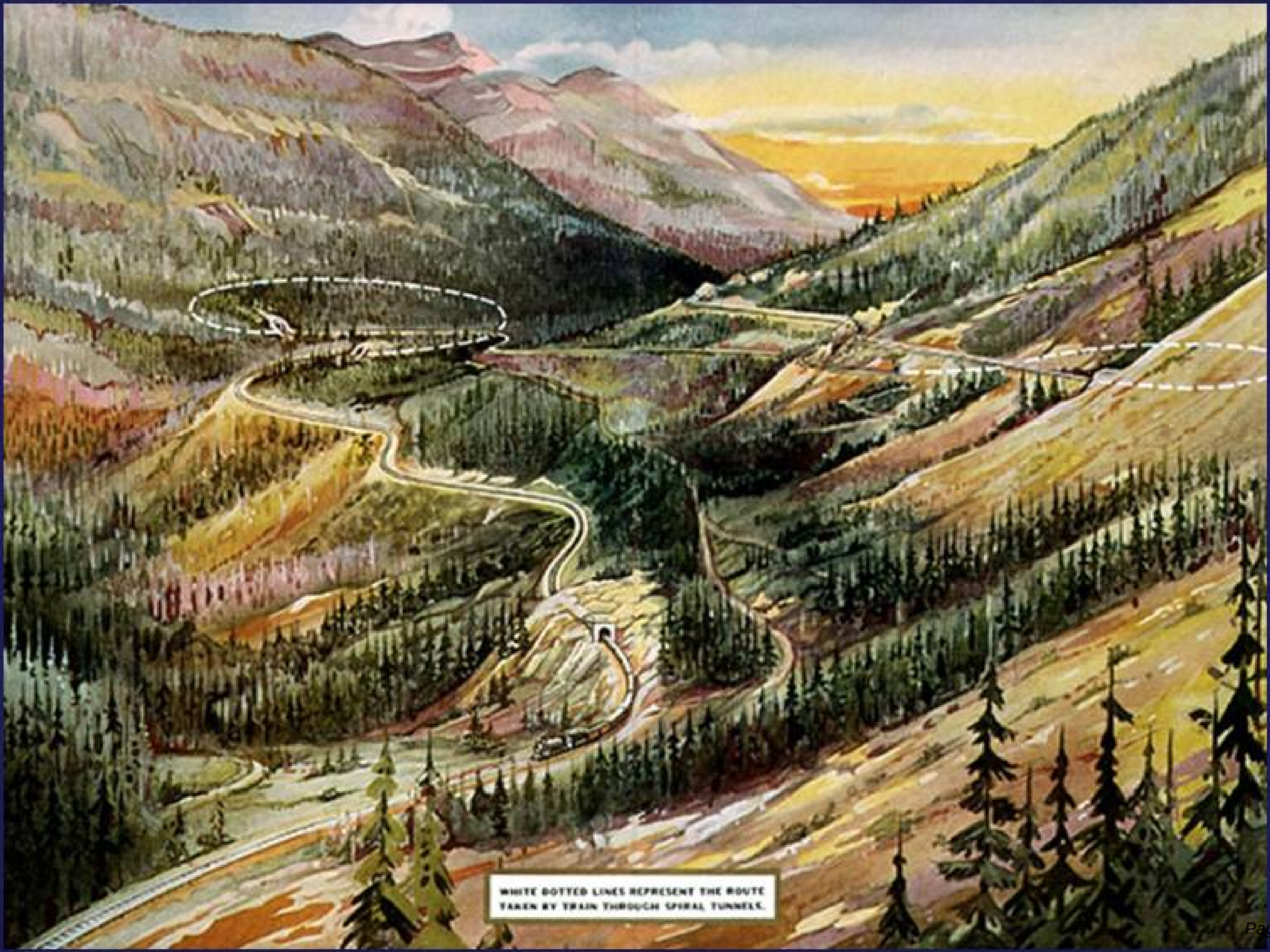
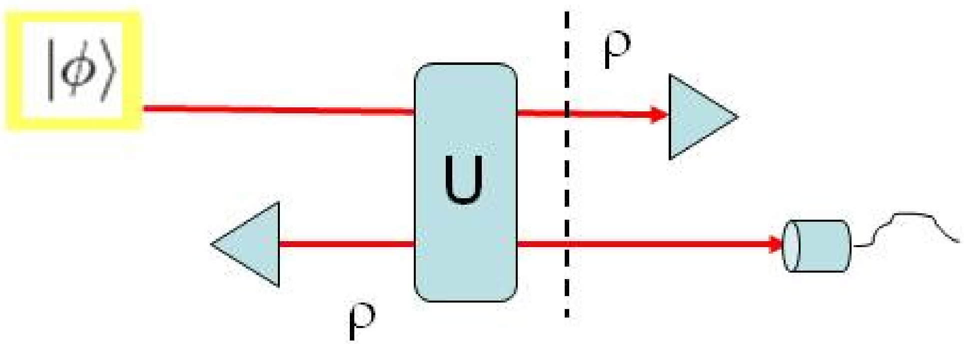
Bird's eye view



Traveler's eye view

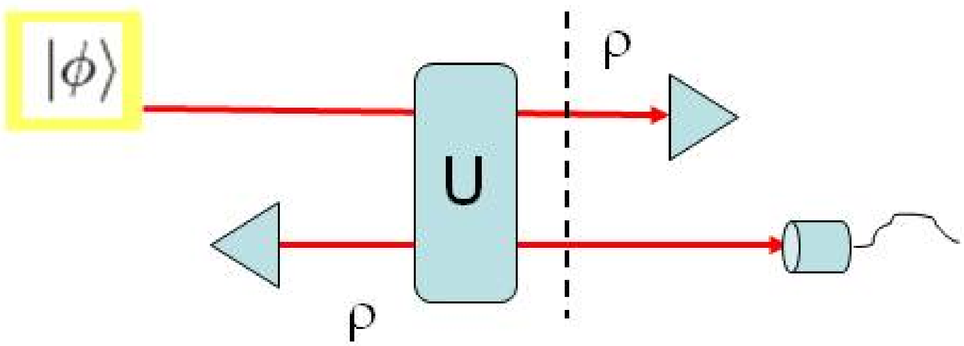
Following the Information Flow



$$\rho = Tr_2[U(\rho_{in} \otimes \rho)U^\dagger]$$

$$\rho_{out} = Tr_1[U(\rho_{in} \otimes \rho)U^\dagger]$$

Following the Information Flow



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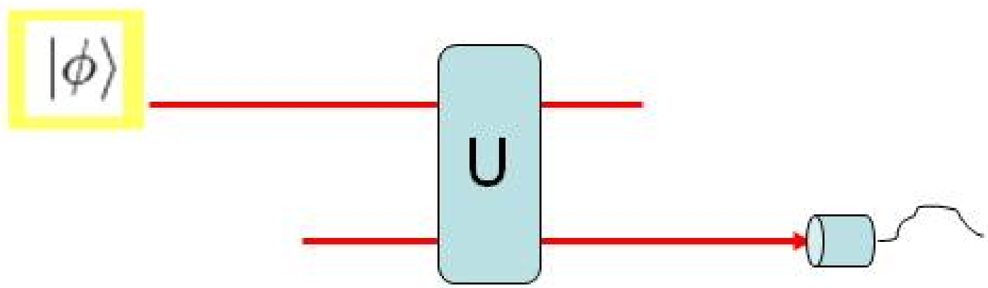

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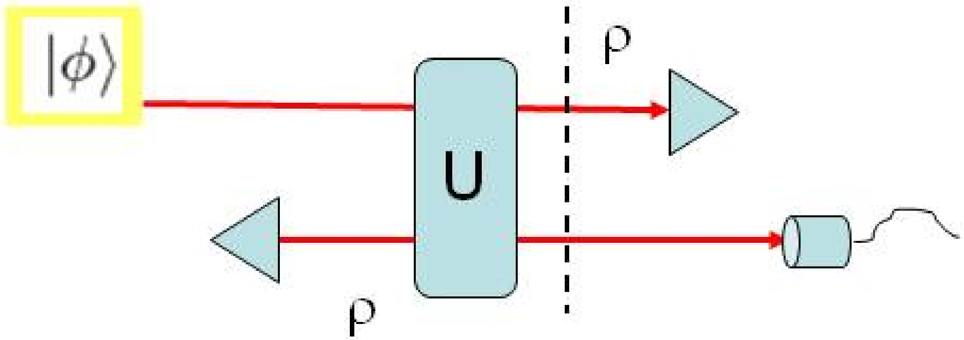

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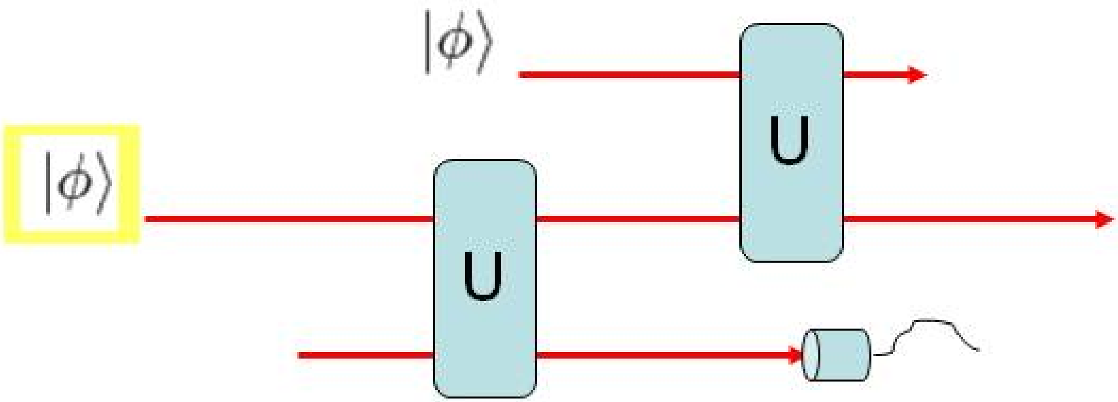

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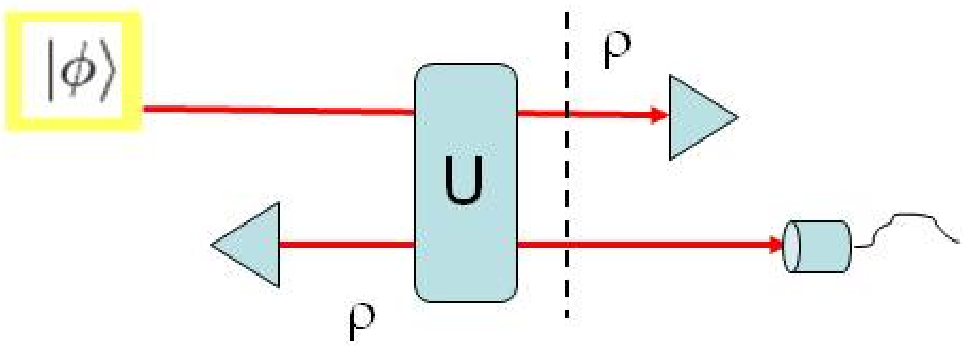

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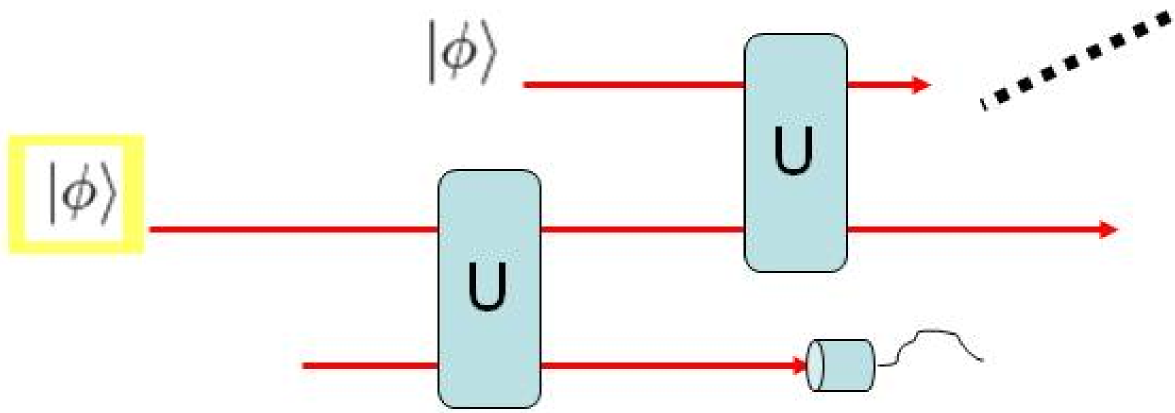

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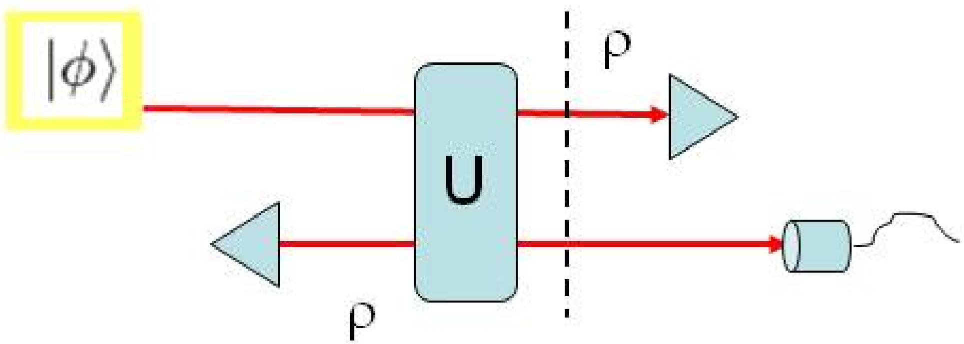

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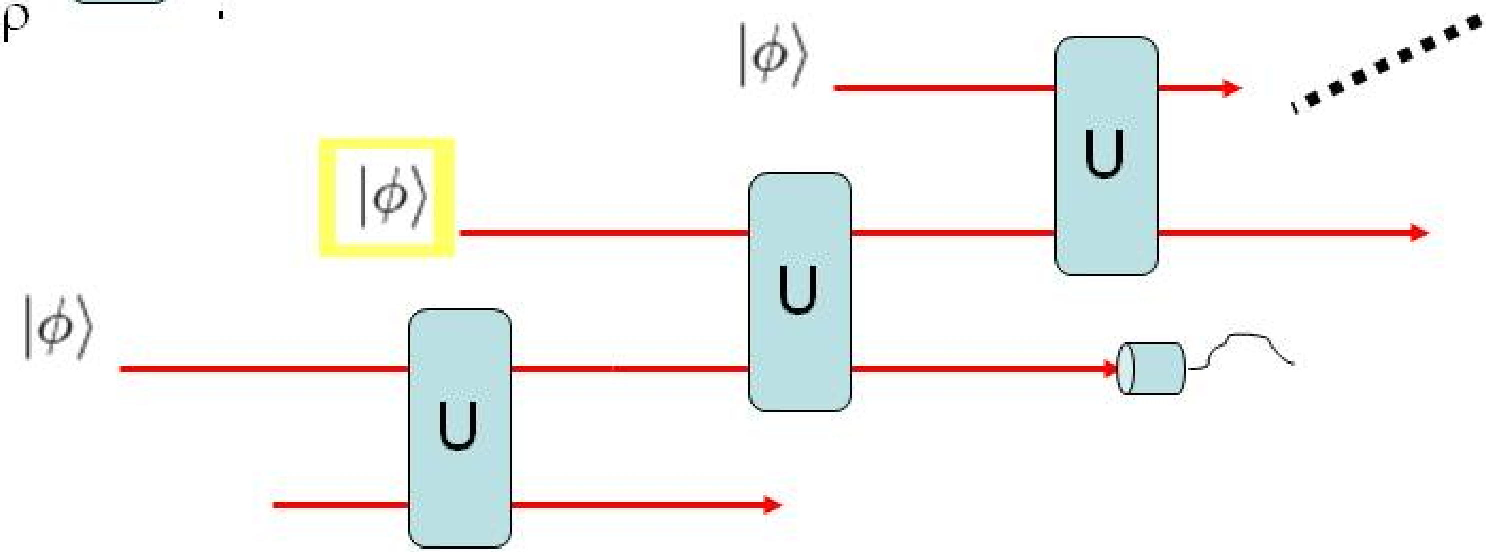

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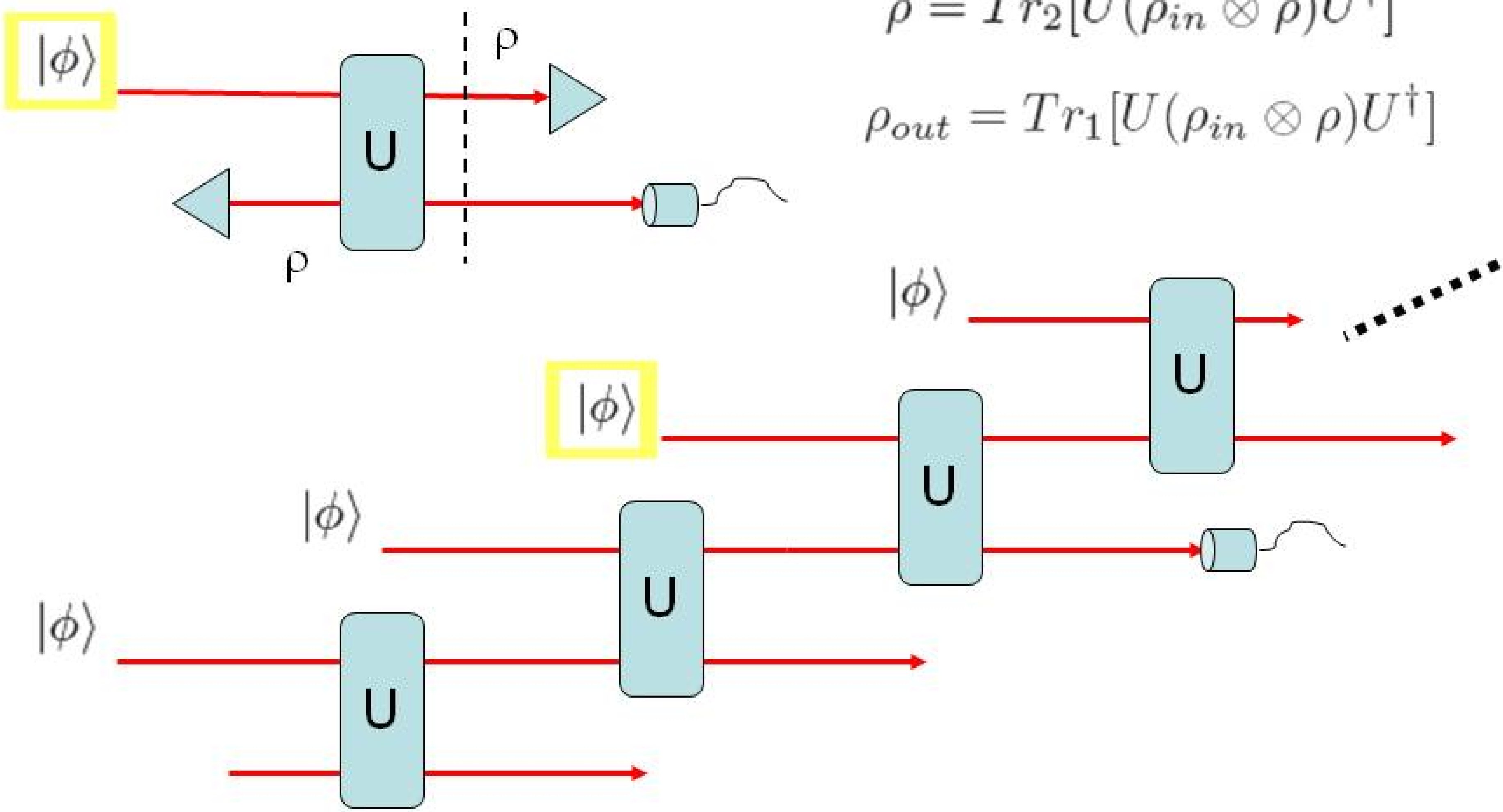

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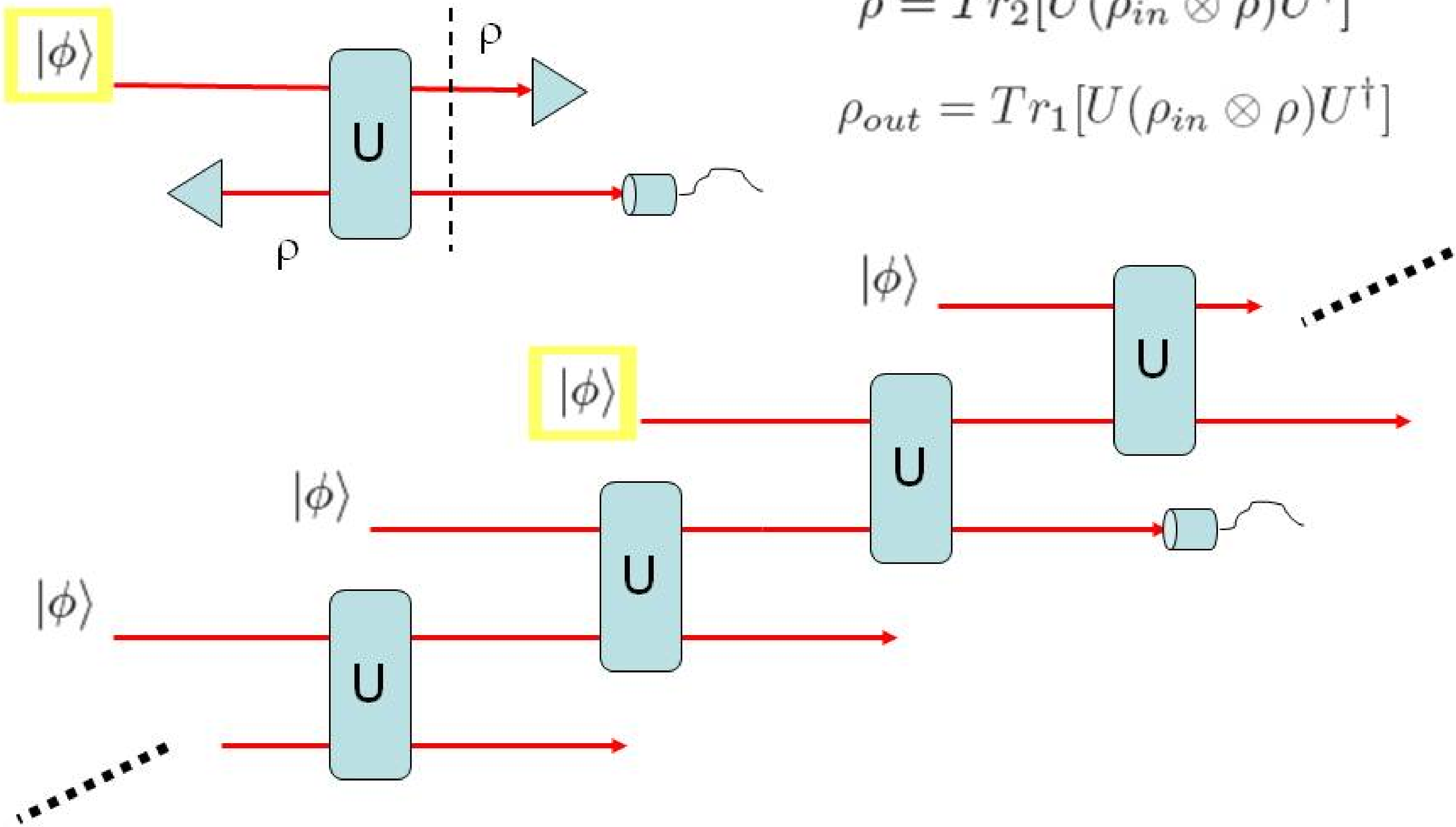

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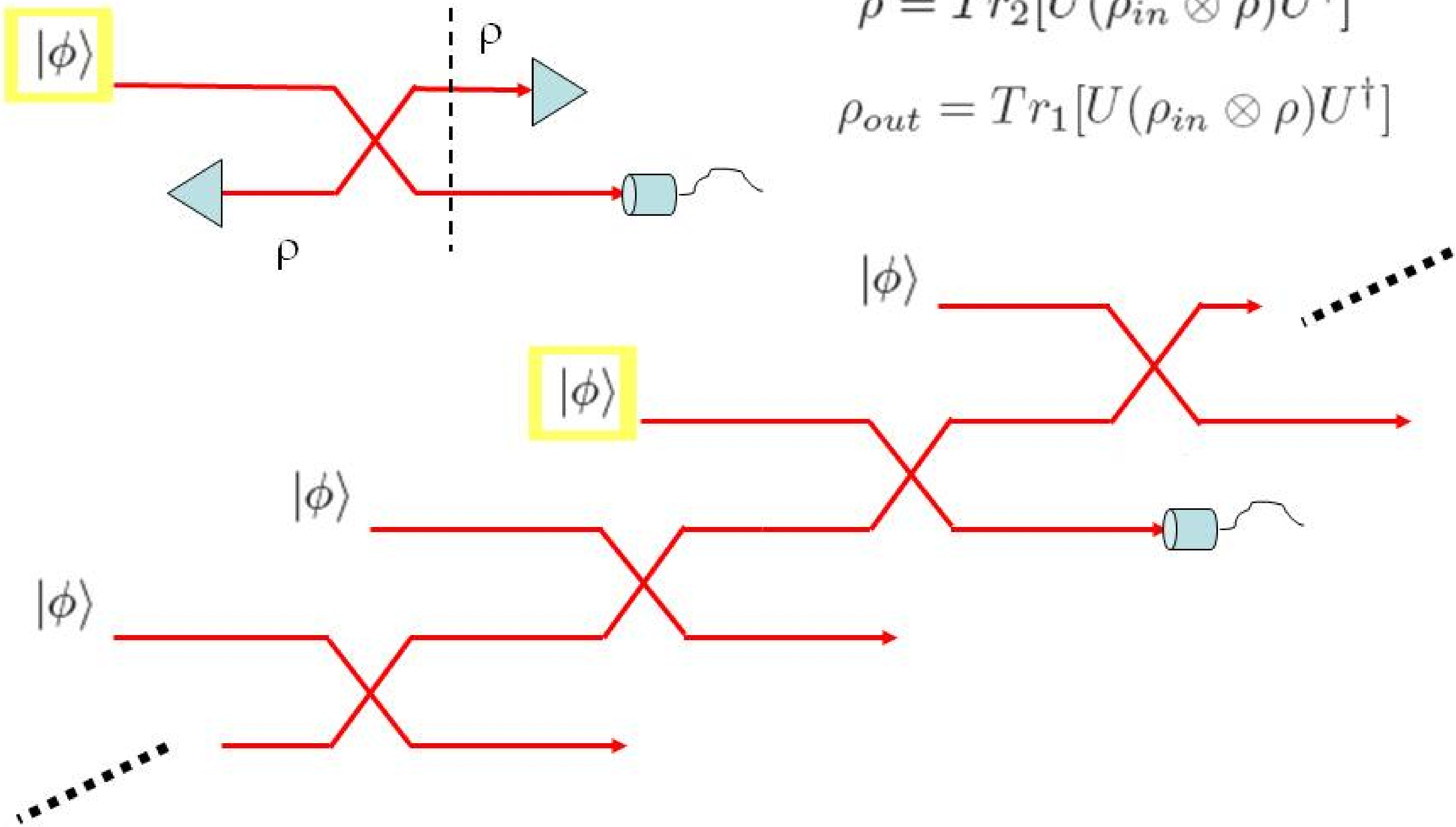

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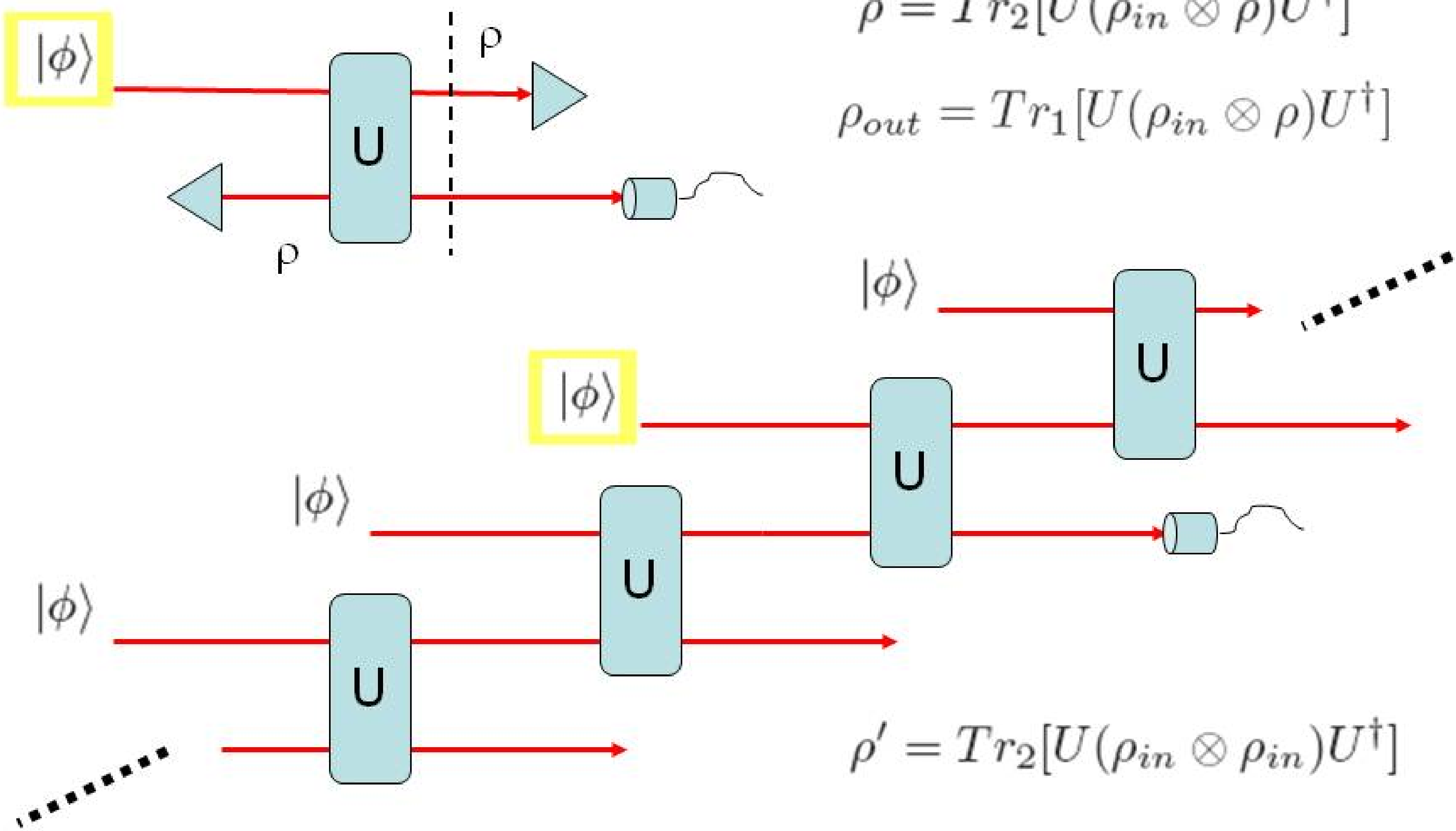
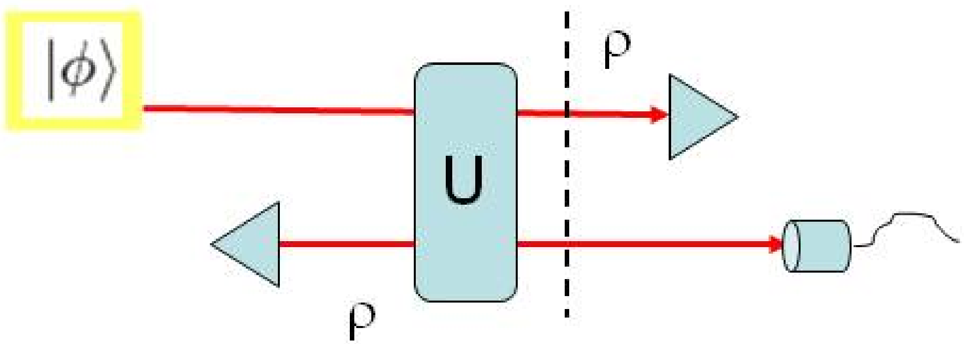


$$\rho = Tr_2[U(\rho_{in} \otimes \rho)U^\dagger]$$

$$\rho_{out} = Tr_1[U(\rho_{in} \otimes \rho)U^\dagger]$$

$$\rho' = Tr_2[U(\rho_{in} \otimes \rho_{in})U^\dagger]$$

Following the Information Flow



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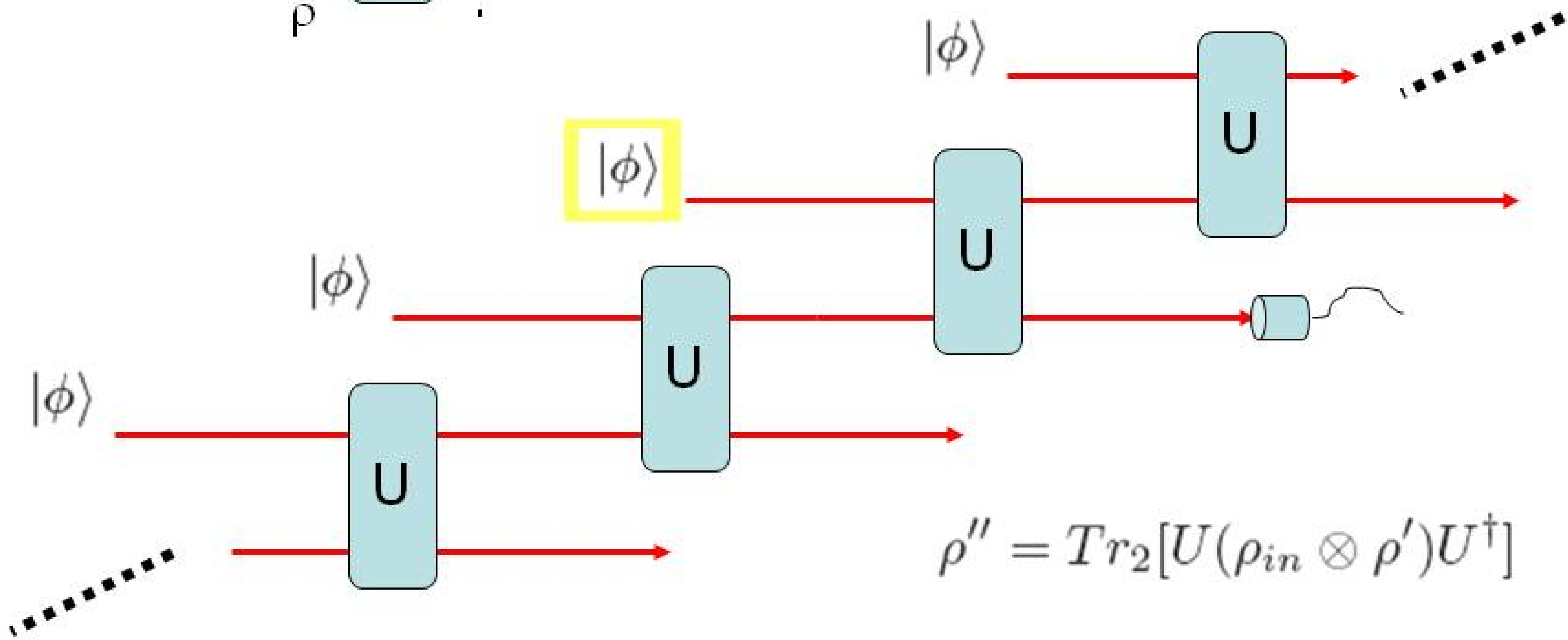
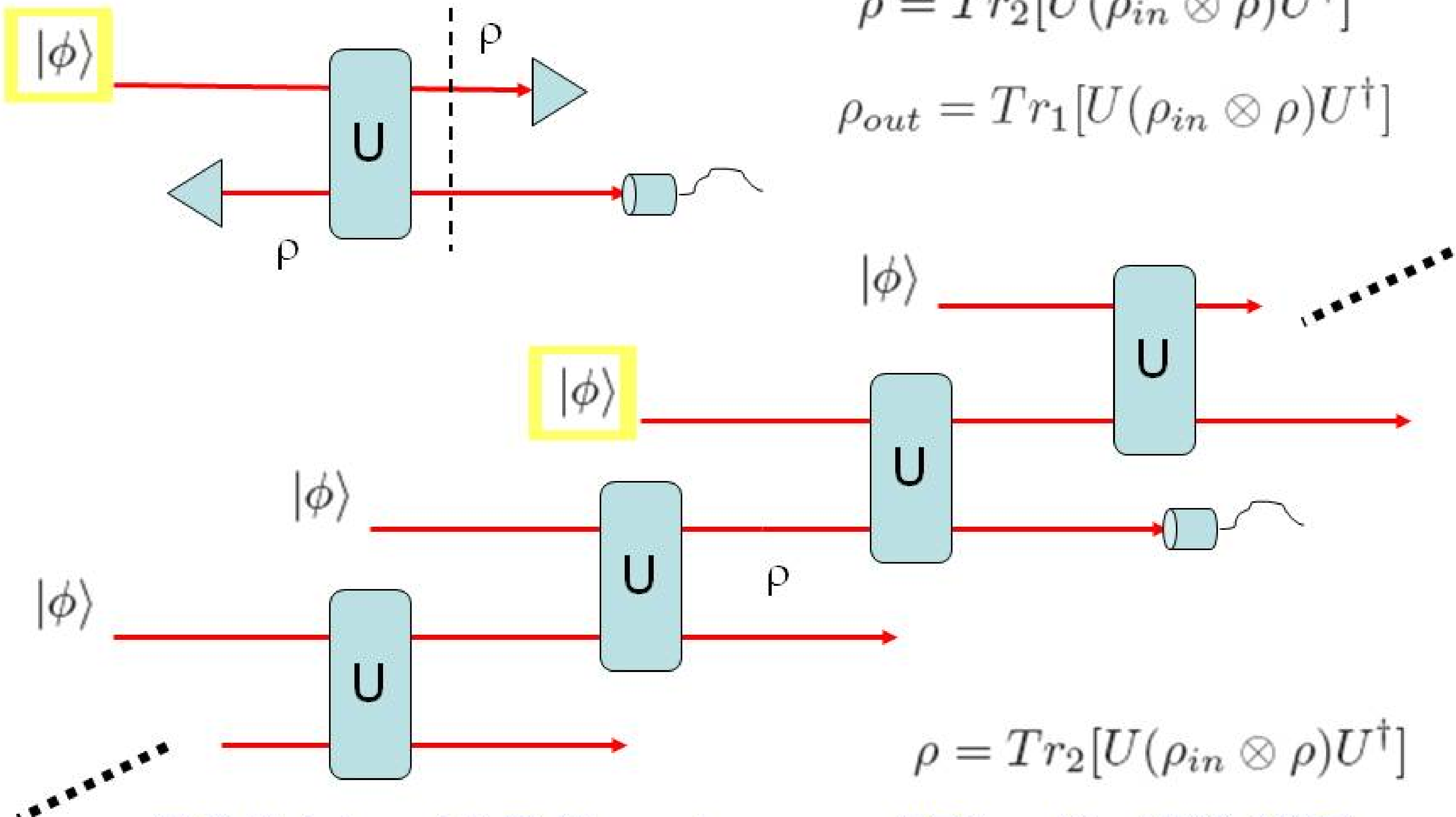


$$\rho'' = Tr_2[U(\rho_{in} \otimes \rho')U^\dagger]$$

Following the Information Flow



$$\rho = Tr_2[U(\rho_{in} \otimes \rho)U^{\dagger}]$$

$$\rho_{out} = Tr_1[U(\rho_{in} \otimes \rho)U^{\dagger}]$$

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T.C.Ralph and C.R.Myers, to appear PRA, arXiv:1003.1987

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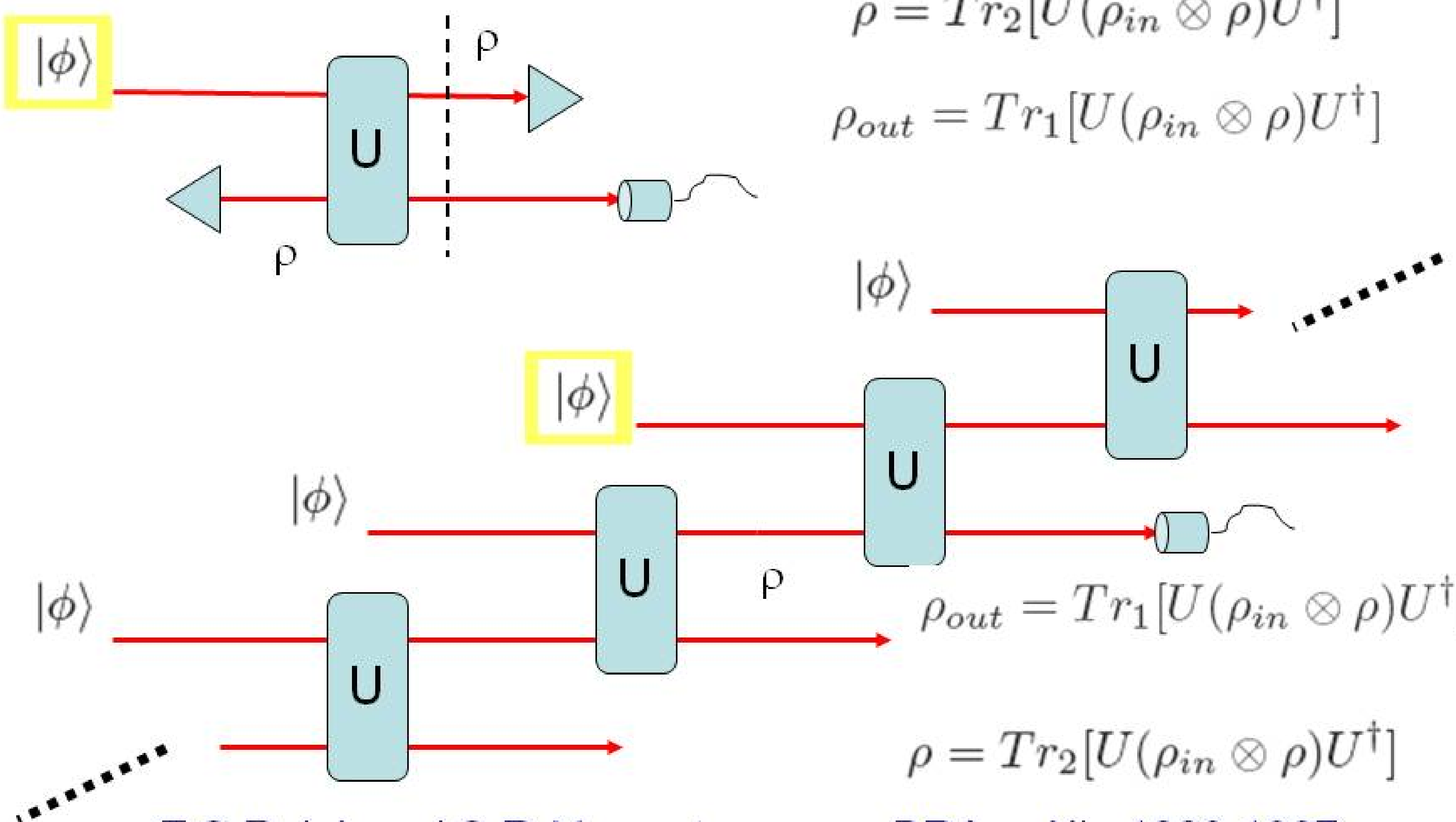

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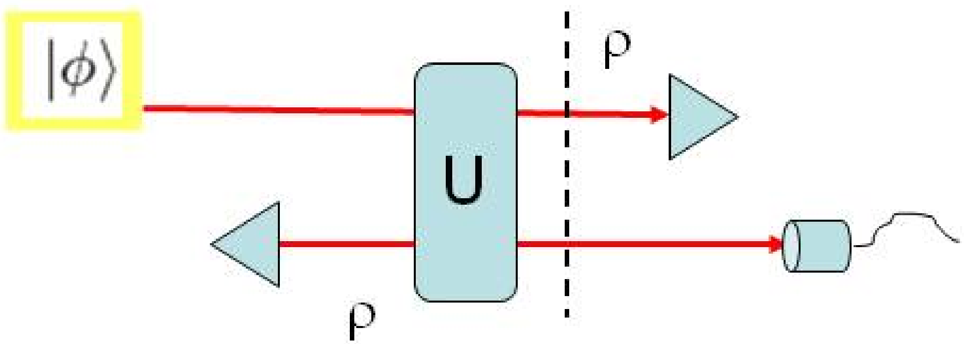
(i) Multiple Solutions



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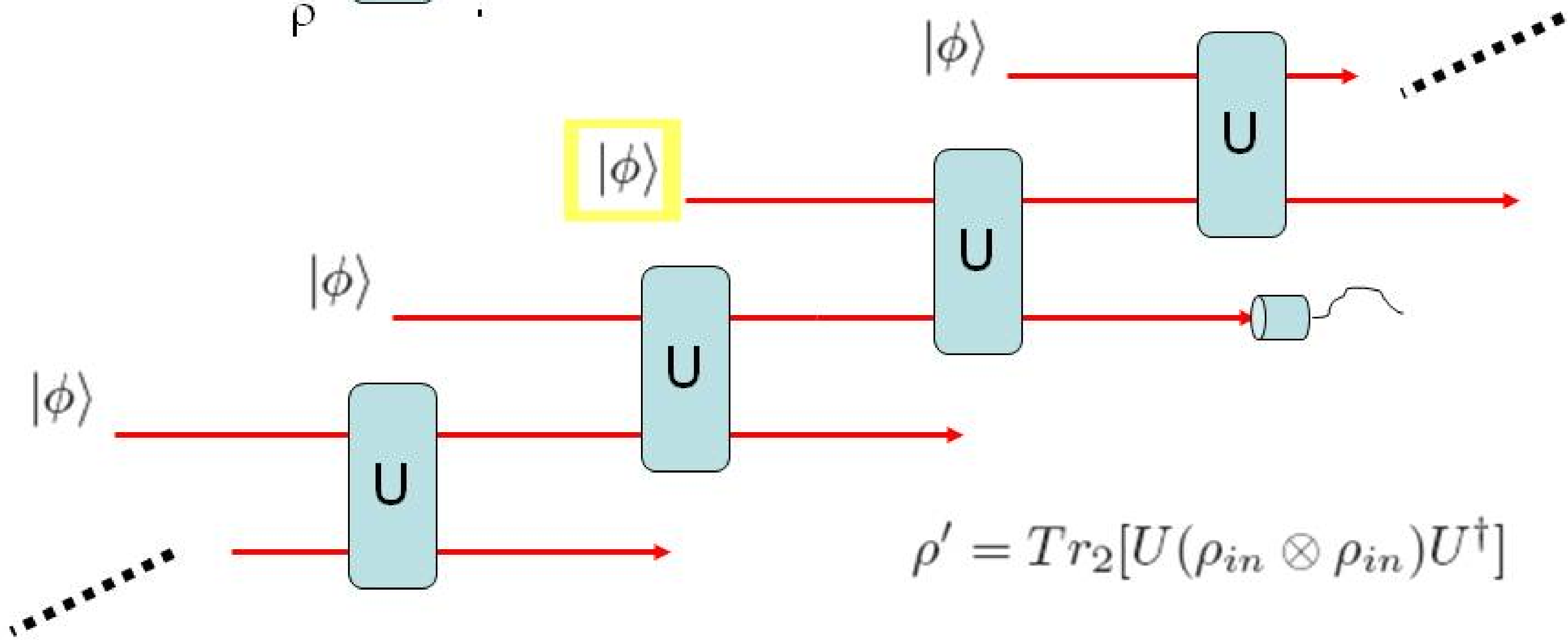

$$\rho' = Tr_2[U(\rho_{in} \otimes \rho_{in})U^\dagger]$$

(i) Multiple Solutions

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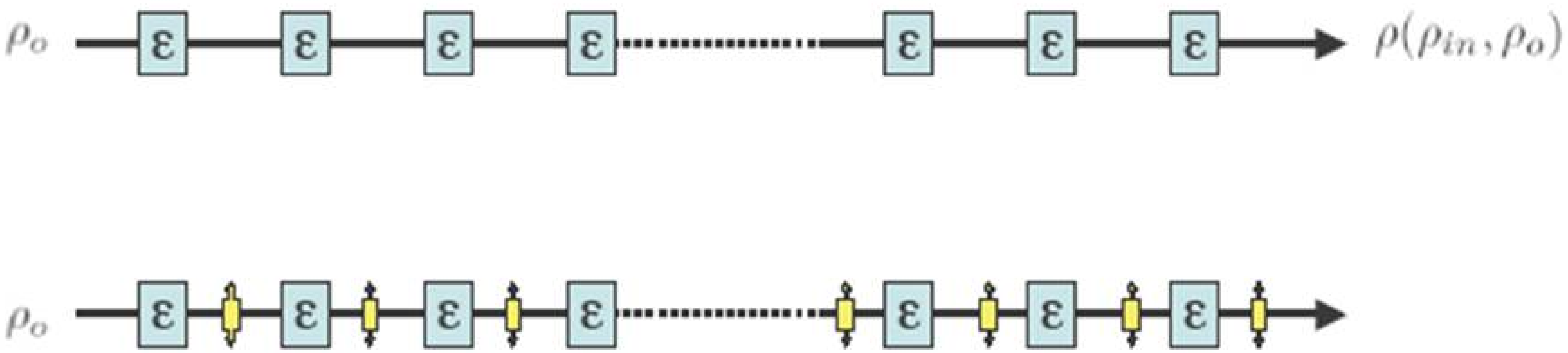

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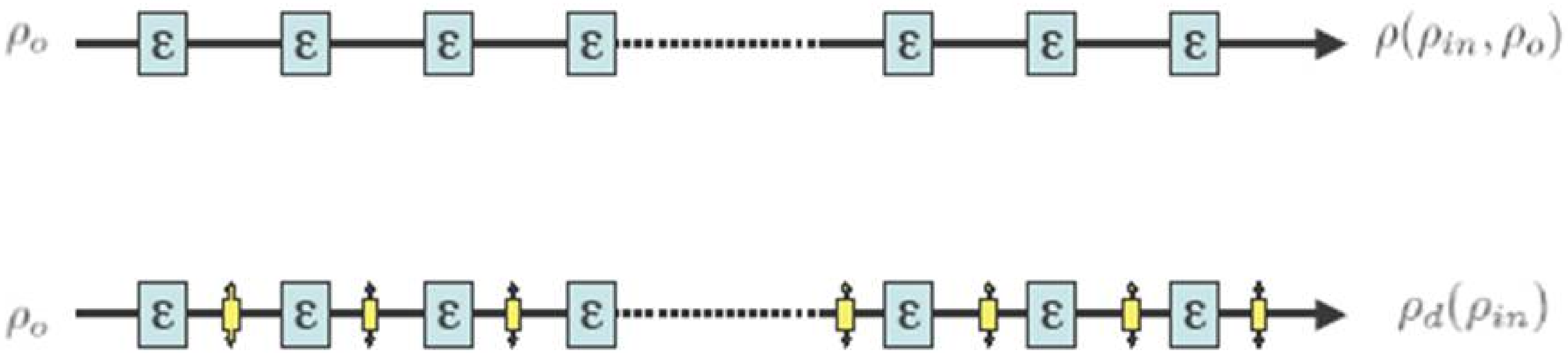

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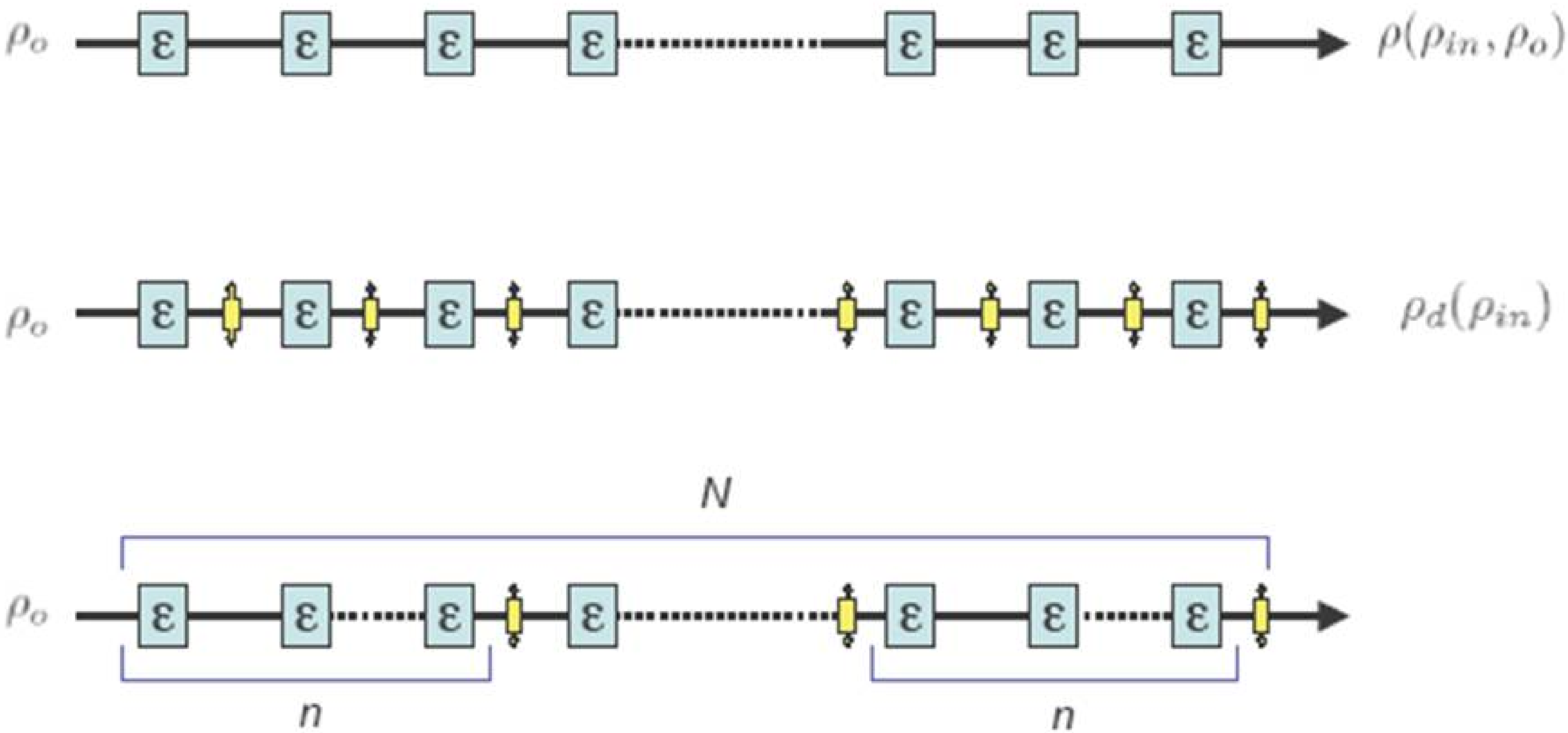

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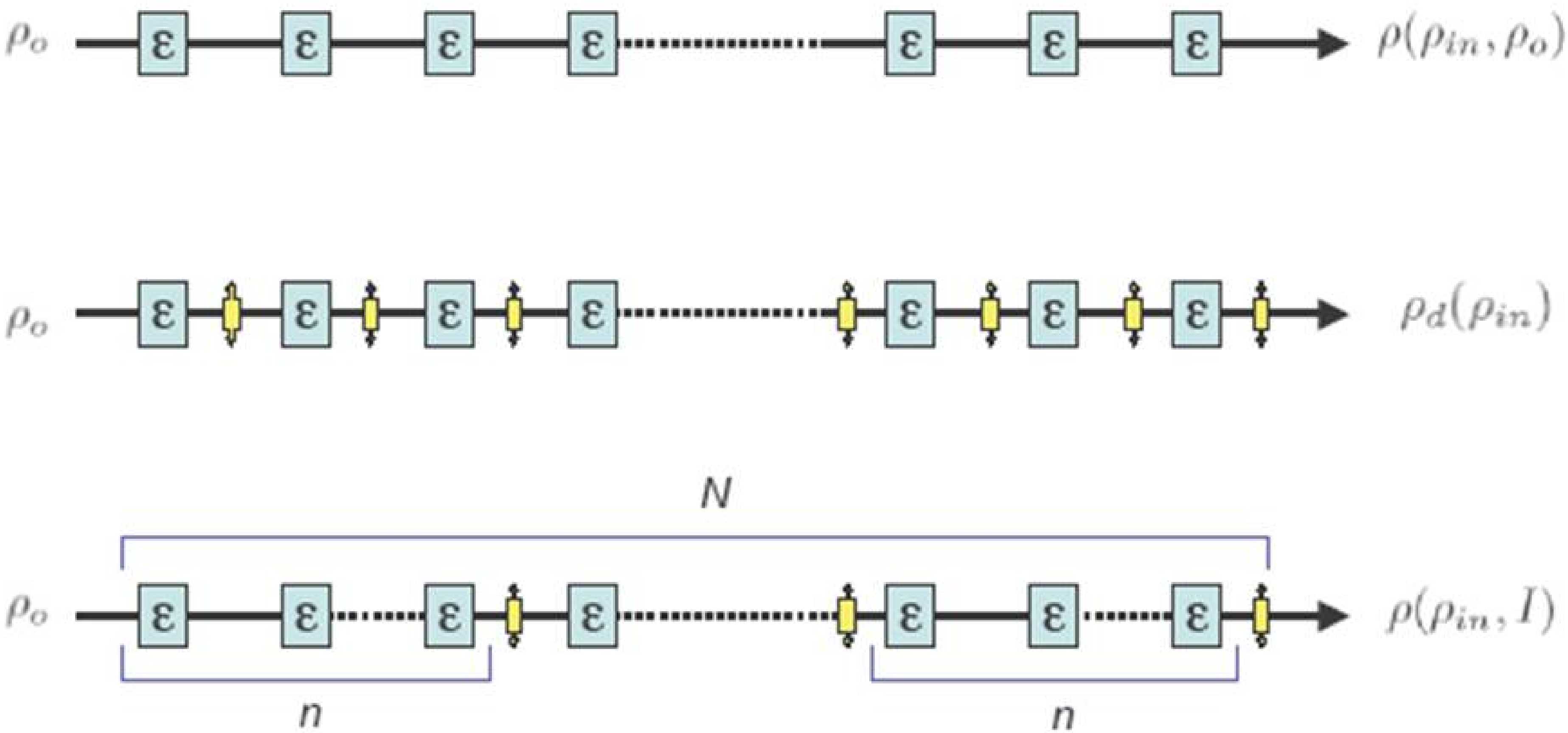

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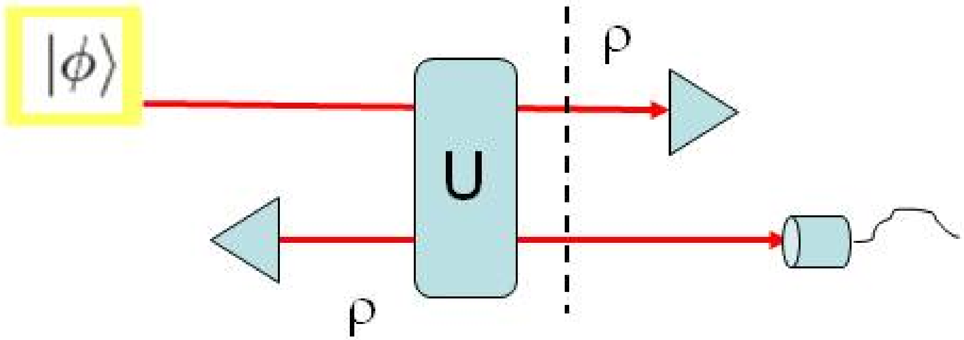

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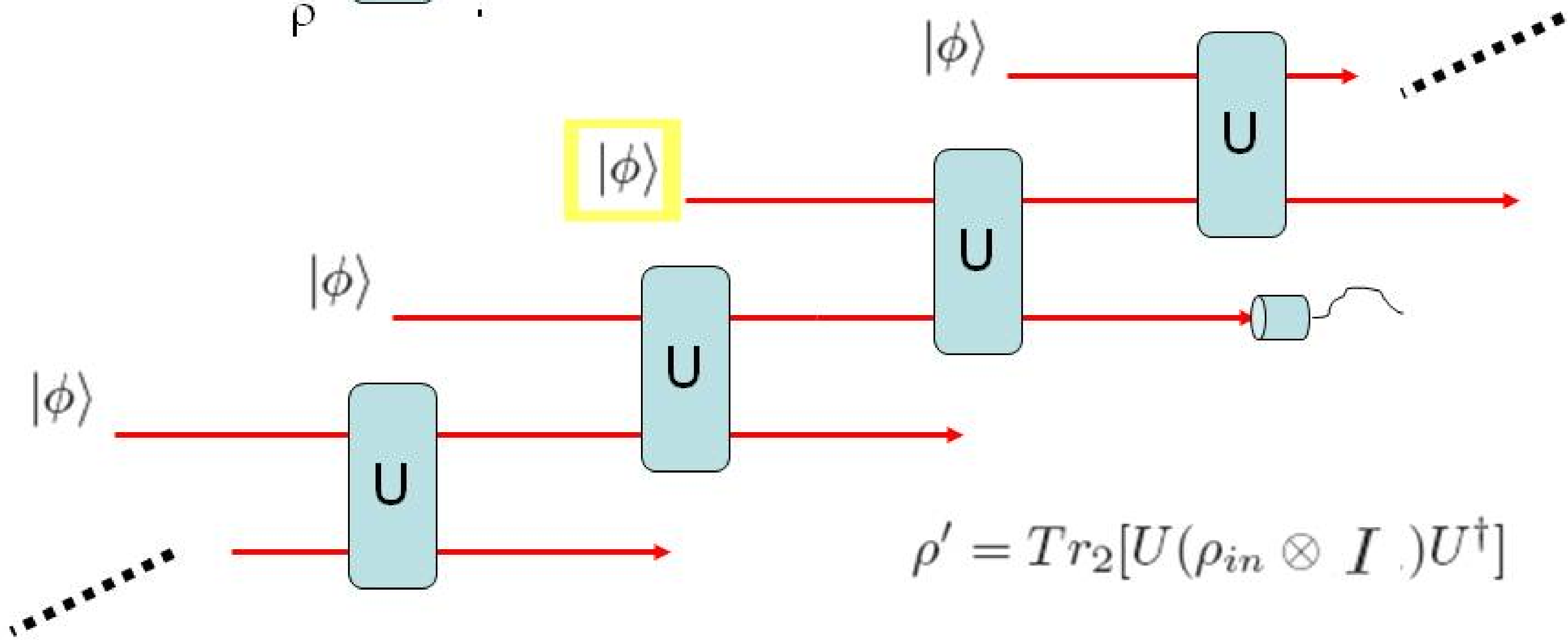
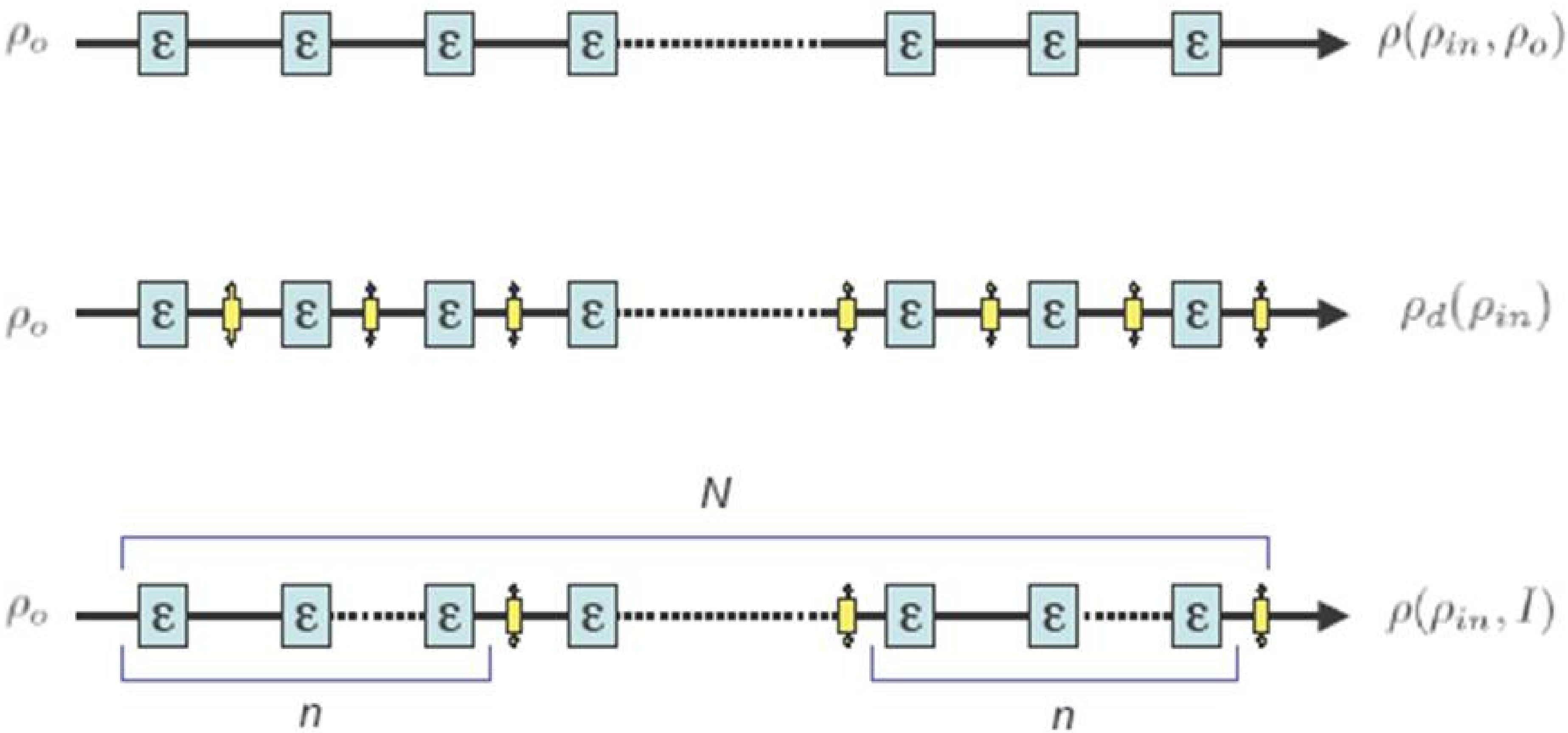


$$\rho' = Tr_2[U(\rho_{in} \otimes \; I \;)U^\dagger]$$

(i) Multiple Solutions



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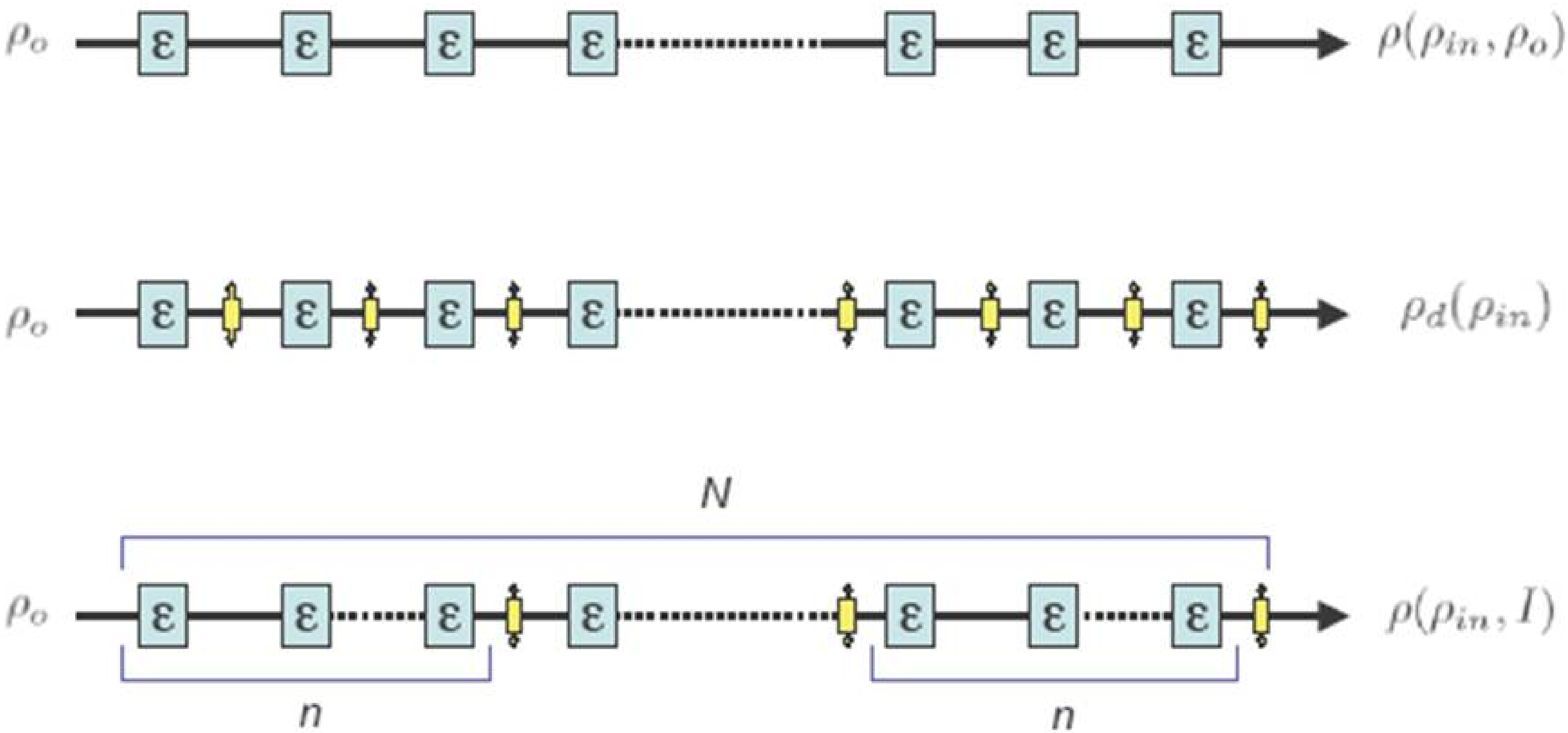
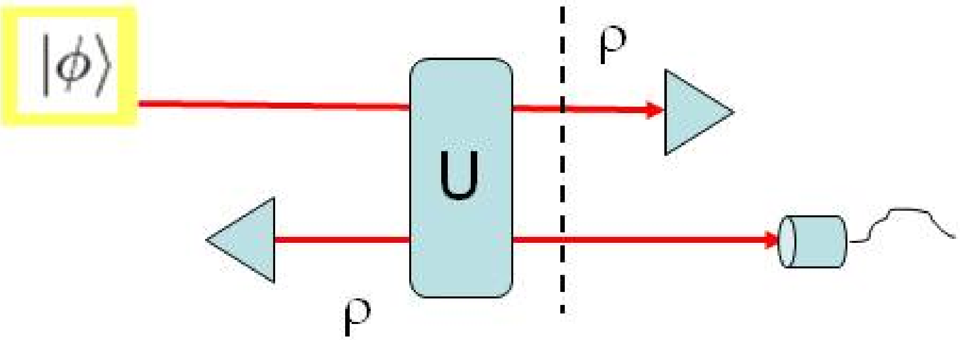


$$\rho(\rho_{in}, I) = I$$

T.C.Ralph and C.R.Myers, to appear PRA, arXiv:1003.1987

(ii) Initial state ambiguity



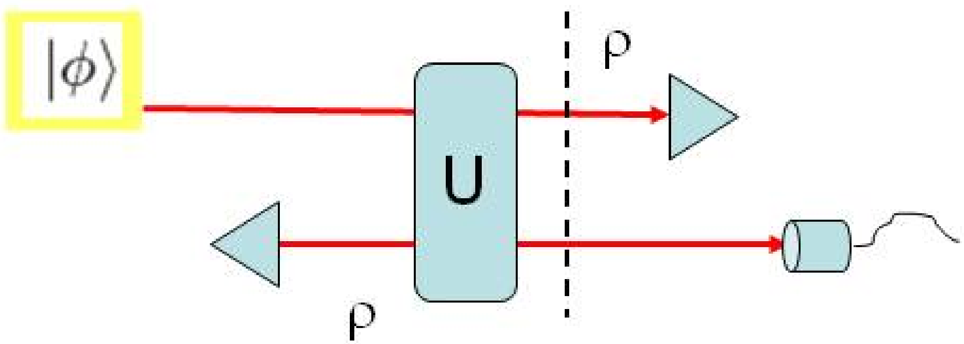
$$\rho = Tr_2[U(\rho_{in} \otimes \rho)U^\dagger]$$

$$\rho_{out} = Tr_1[U(\rho_{in} \otimes \rho)U^\dagger]$$

Suppose

$$\rho_{inE} = \Sigma_{k=1}^{K} P_k |\phi_k\rangle\langle\phi_k|$$

(ii) Initial state ambiguity



$$\rho = Tr_2[U(\rho_{in} \otimes \rho)U^\dagger]$$

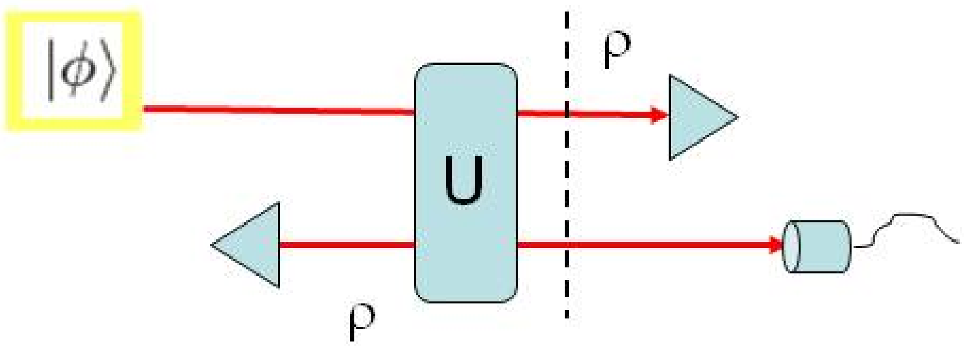
$$\rho_{out} = Tr_1[U(\rho_{in} \otimes \rho)U^\dagger]$$

Suppose

$$\rho_{inE} = \Sigma_{k=1}^{K} P_k |\phi_k\rangle\langle\phi_k|$$

Because the system is **nonlinear**, in general the answer obtained by **mixing over the inputs** will be **different** to the answer obtained by **mixing over the outputs**!

(ii) Initial state ambiguity



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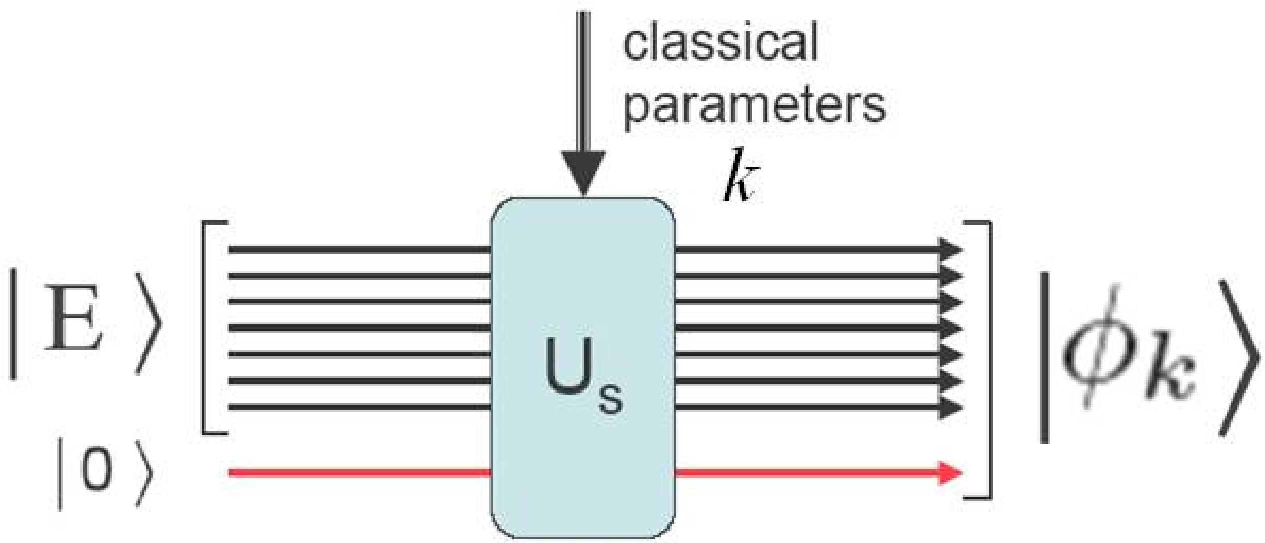
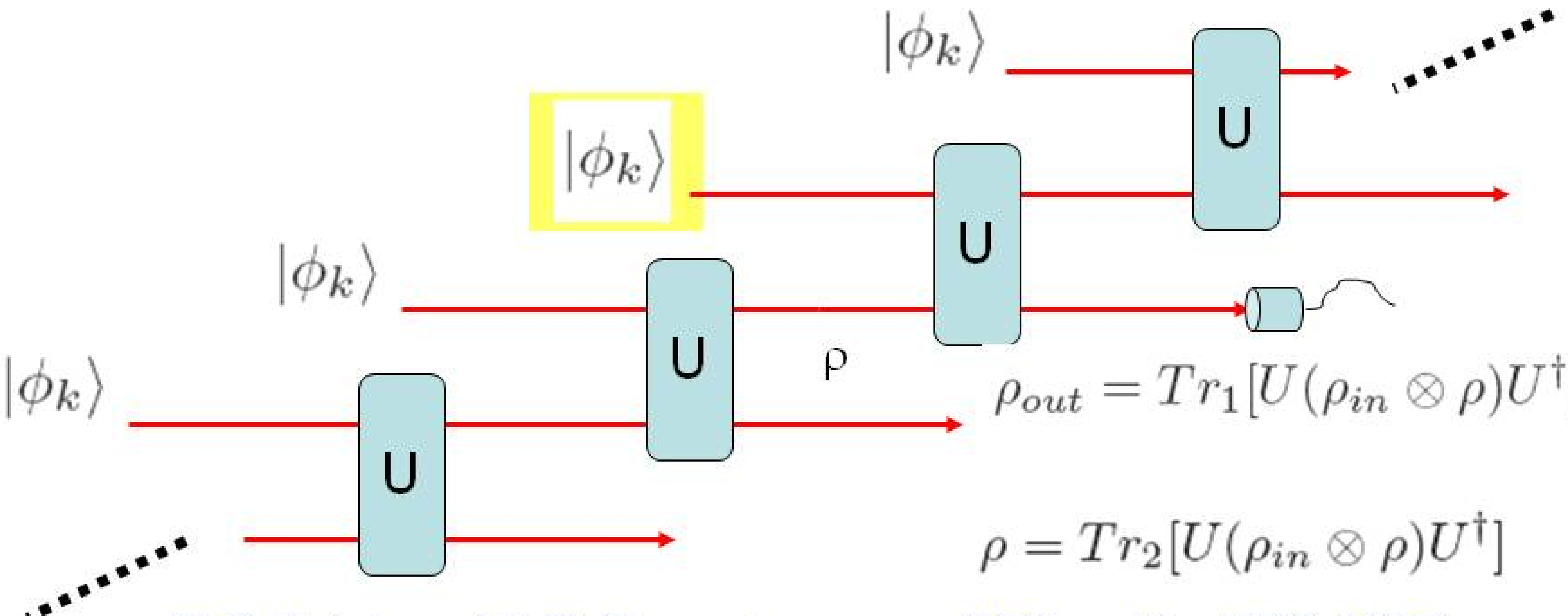


(ii) Initial state ambiguity

$$\rho_{in} = |\phi_k\rangle^{\otimes n}\langle\phi_k|^{\otimes n}$$



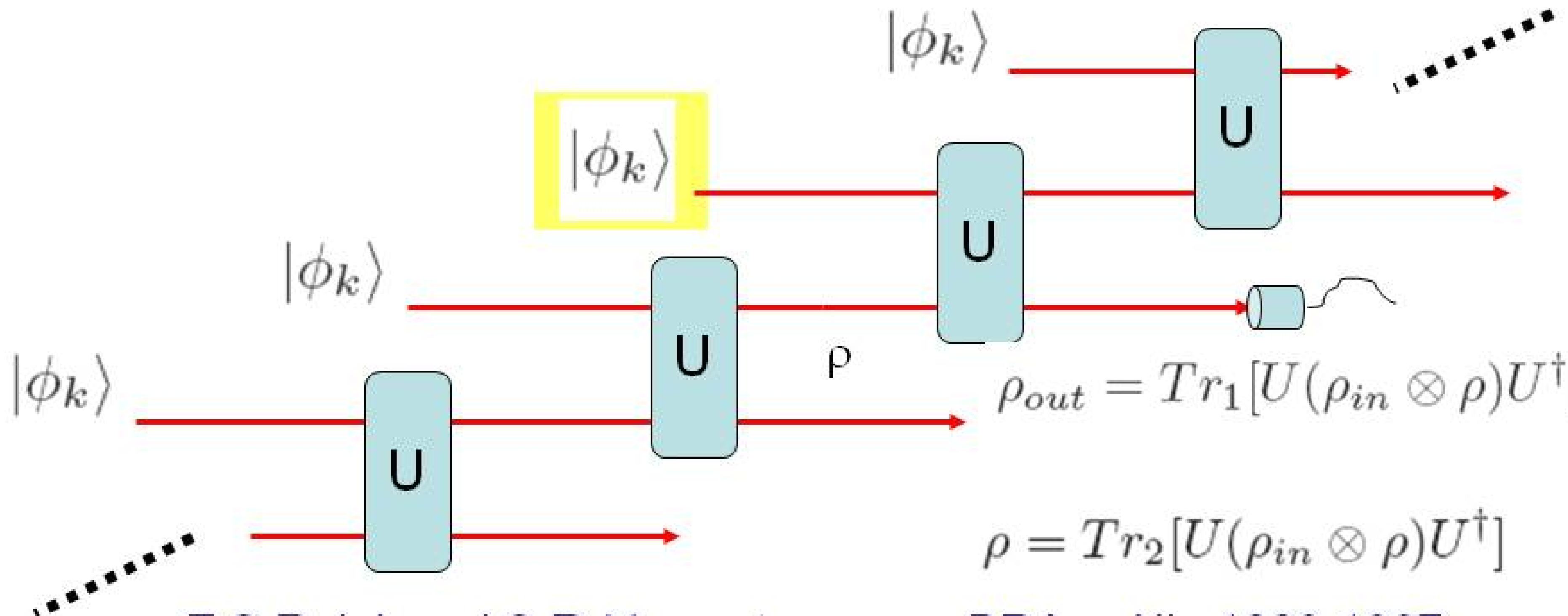
$$\rho_{out} = Tr_1[U(\rho_{in} \otimes \rho)U^\dagger]$$

$$\rho = Tr_2[U(\rho_{in} \otimes \rho)U^\dagger]$$

T.C.Ralph and C.R.Myers, to appear PRA, arXiv:1003.1987

(ii) Initial state ambiguity

$$\rho_{inE} = \Sigma_{k=1}^{K} P_k |\phi_k\rangle^{\otimes n} \langle\phi_k|^{\otimes n}$$



$$\rho_{out} = Tr_1[U(\rho_{in} \otimes \rho)U^\dagger]$$

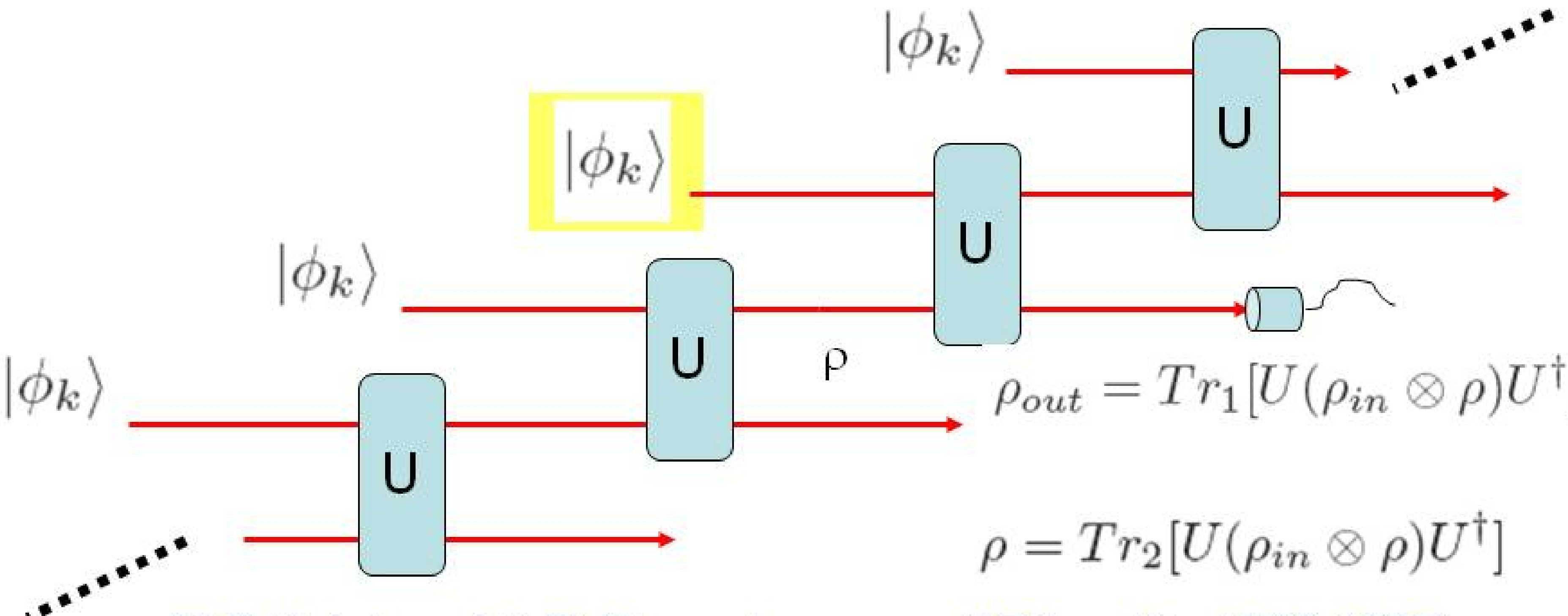
$$\rho = Tr_2[U(\rho_{in} \otimes \rho)U^\dagger]$$

T.C.Ralph and C.R.Myers, to appear PRA, arXiv:1003.1987

(ii) Initial state ambiguity

Corresponds to
mixing over the outputs!

$$\rho_{inE} = \Sigma_{k=1}^{K} P_k |\phi_k\rangle^{\otimes n} \langle\phi_k|^{\otimes n}$$



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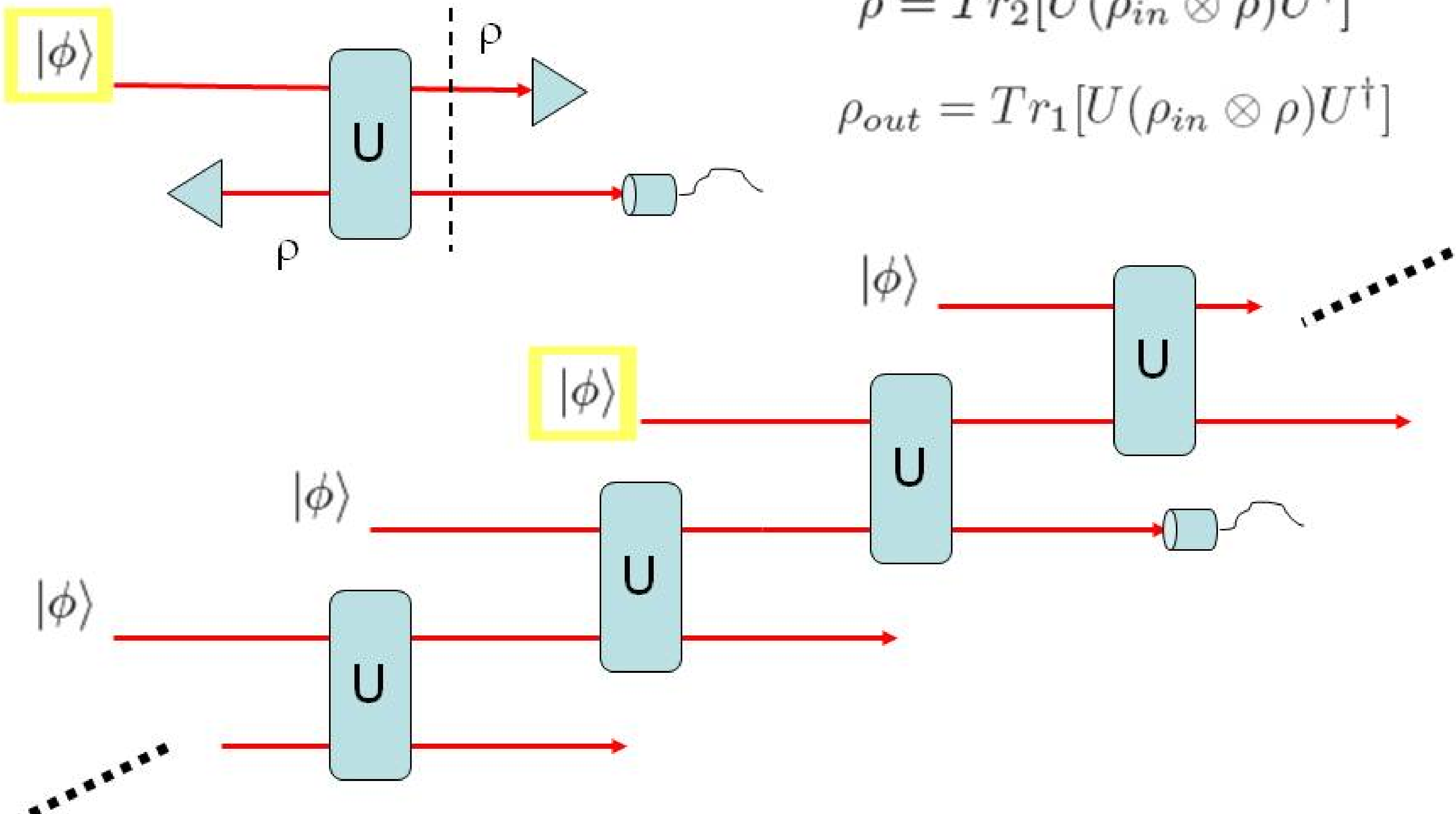
T.C.Ralph and C.R.Myers, to appear PRA, arXiv:1003.1987

(iii) Non-unitarity



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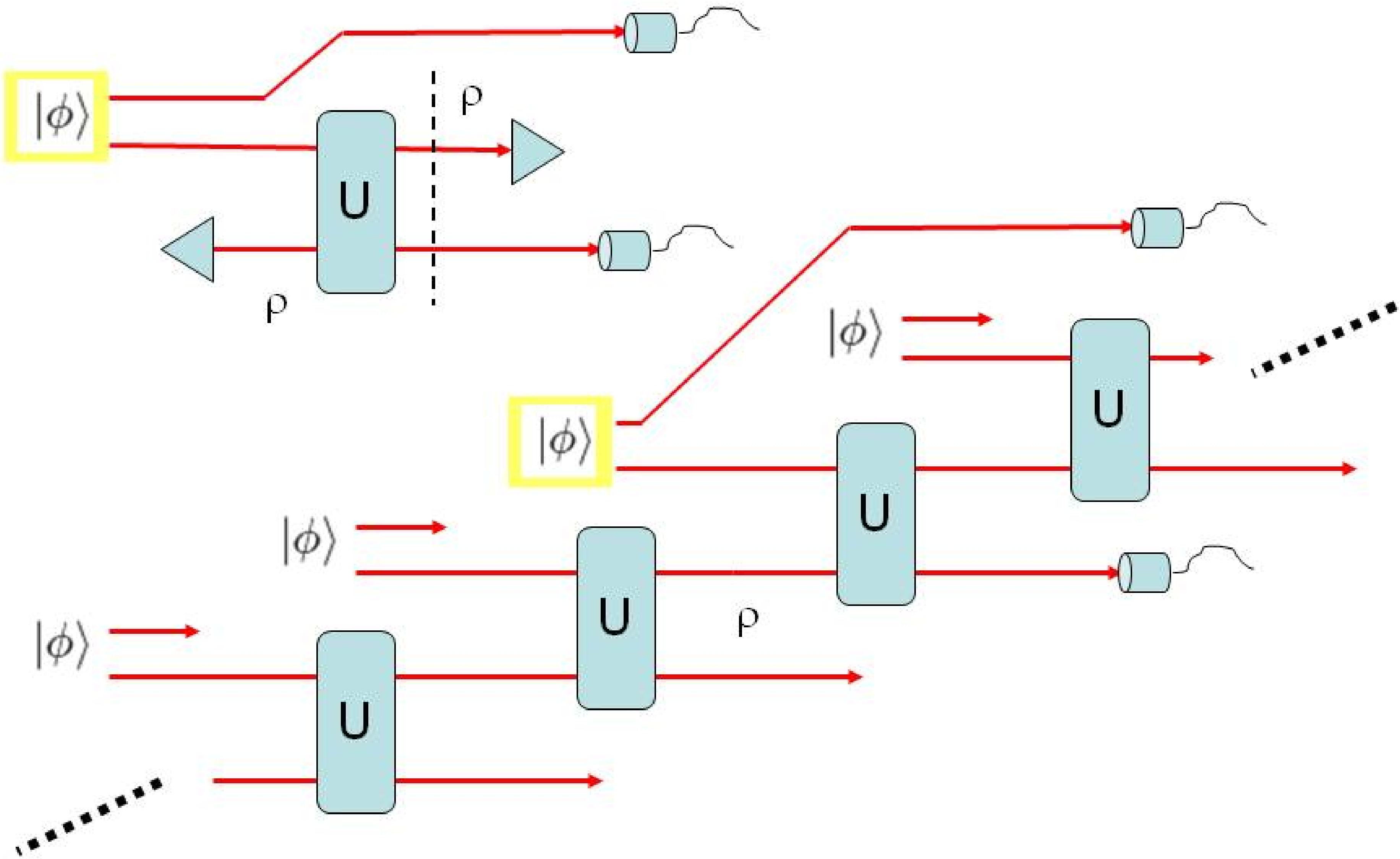

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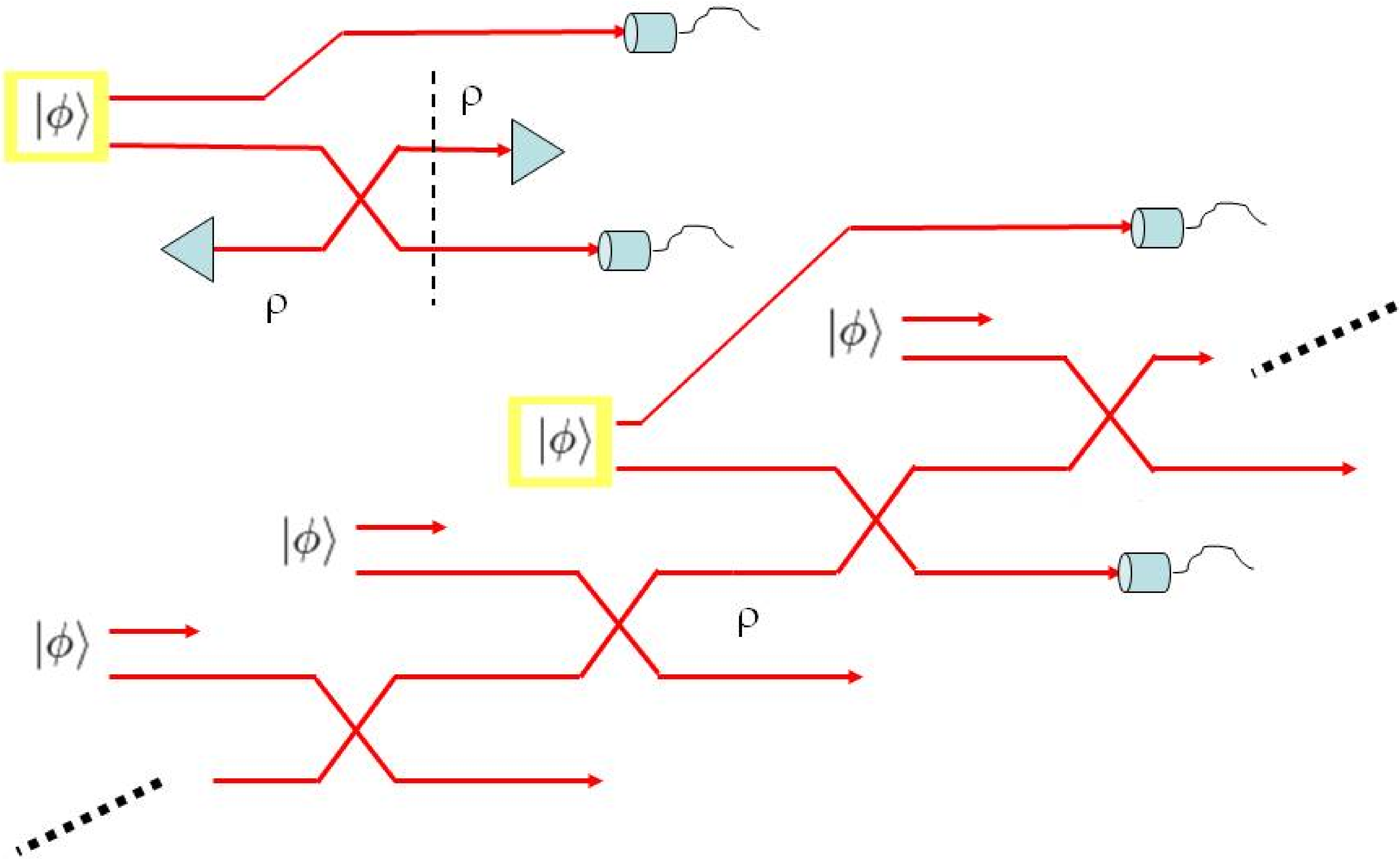

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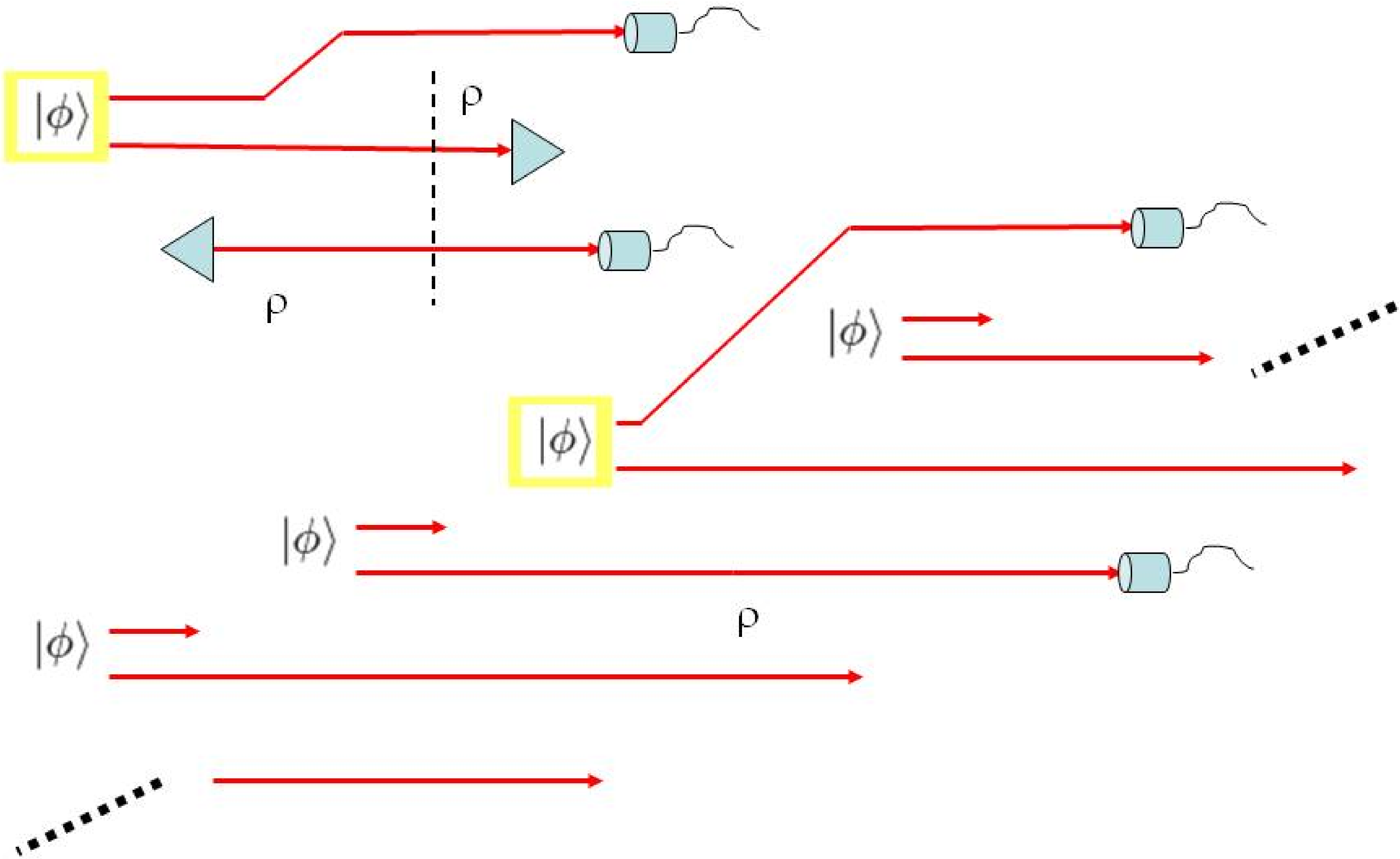

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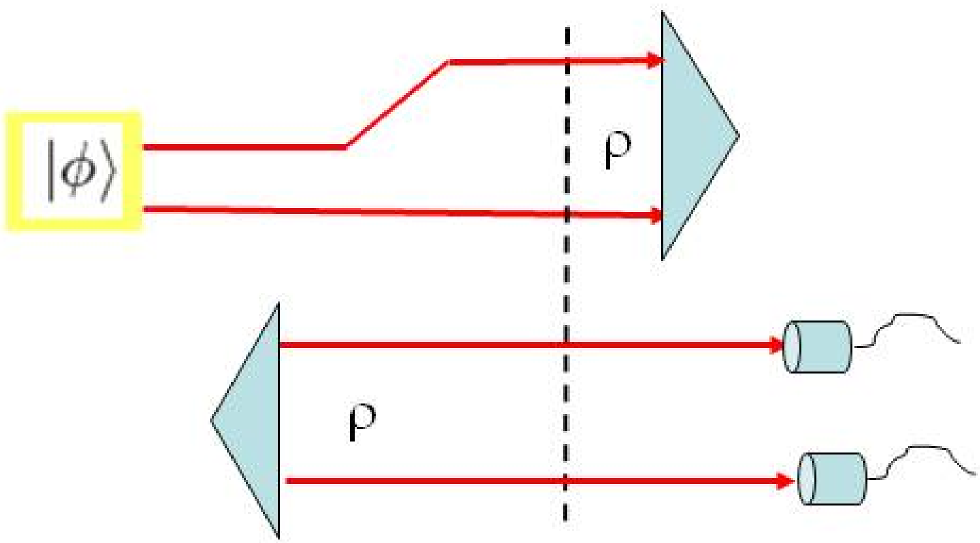

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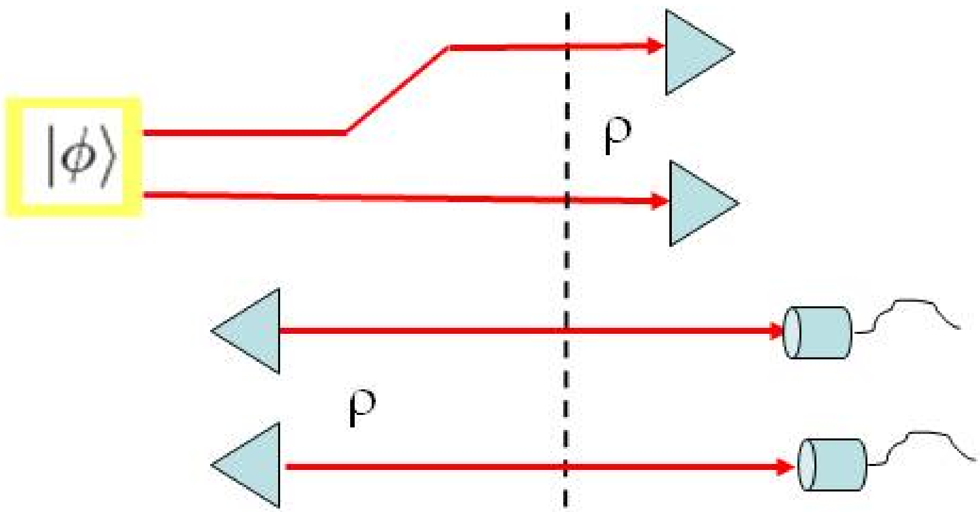

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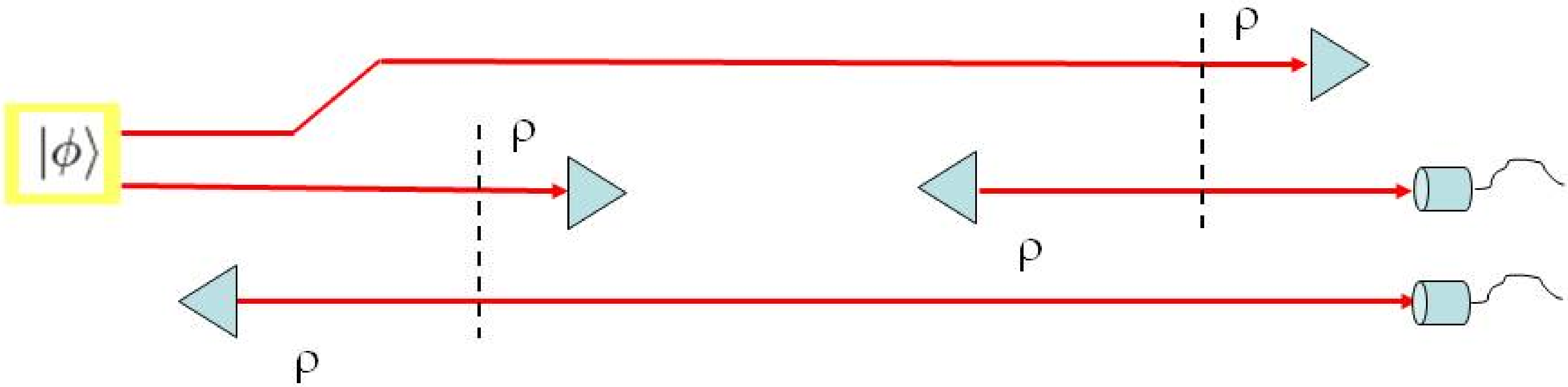

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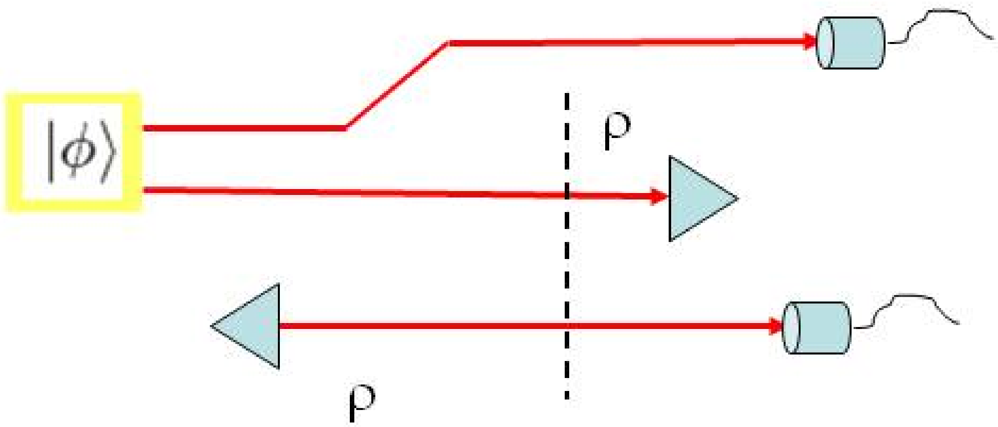

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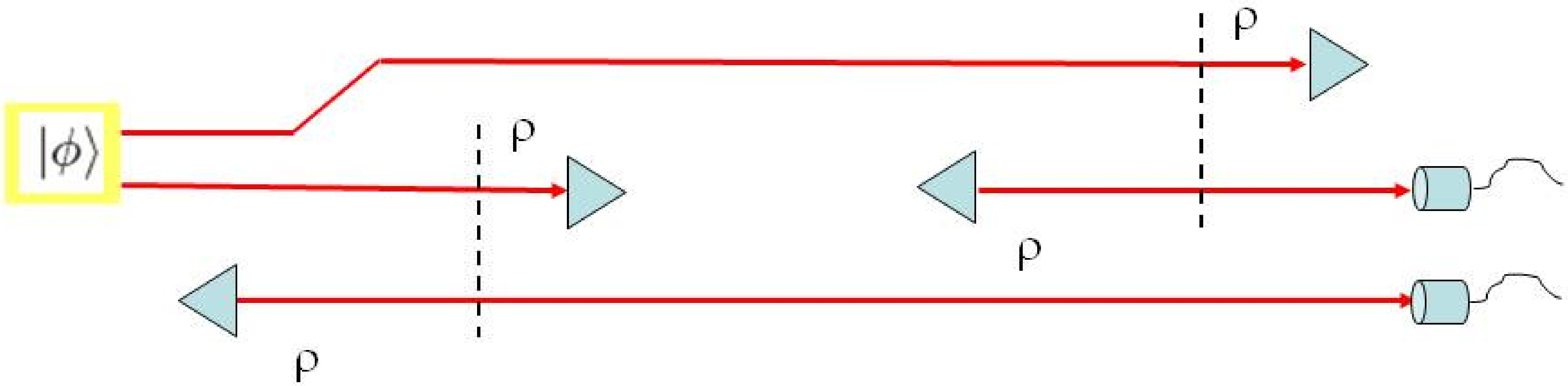

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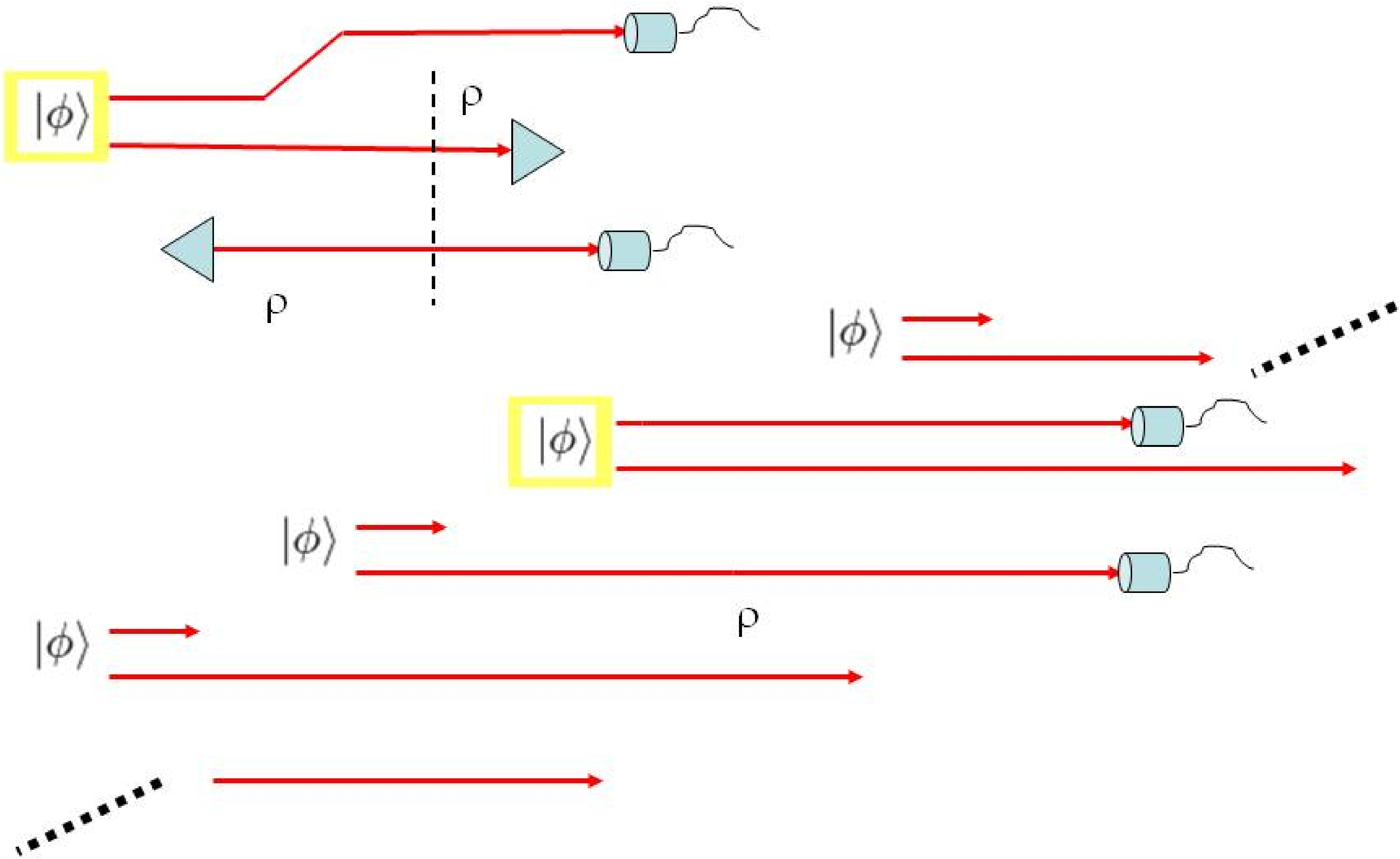

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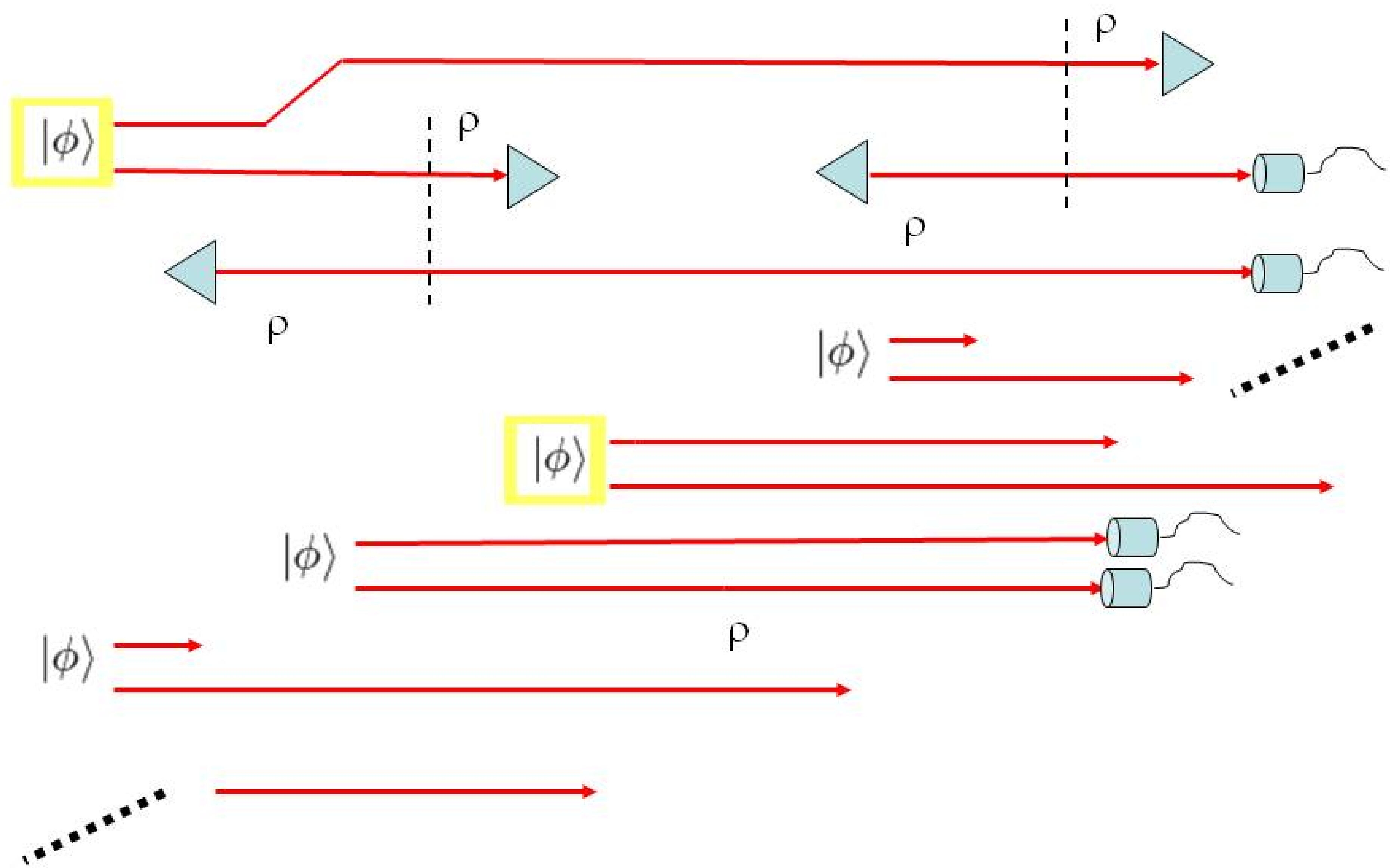

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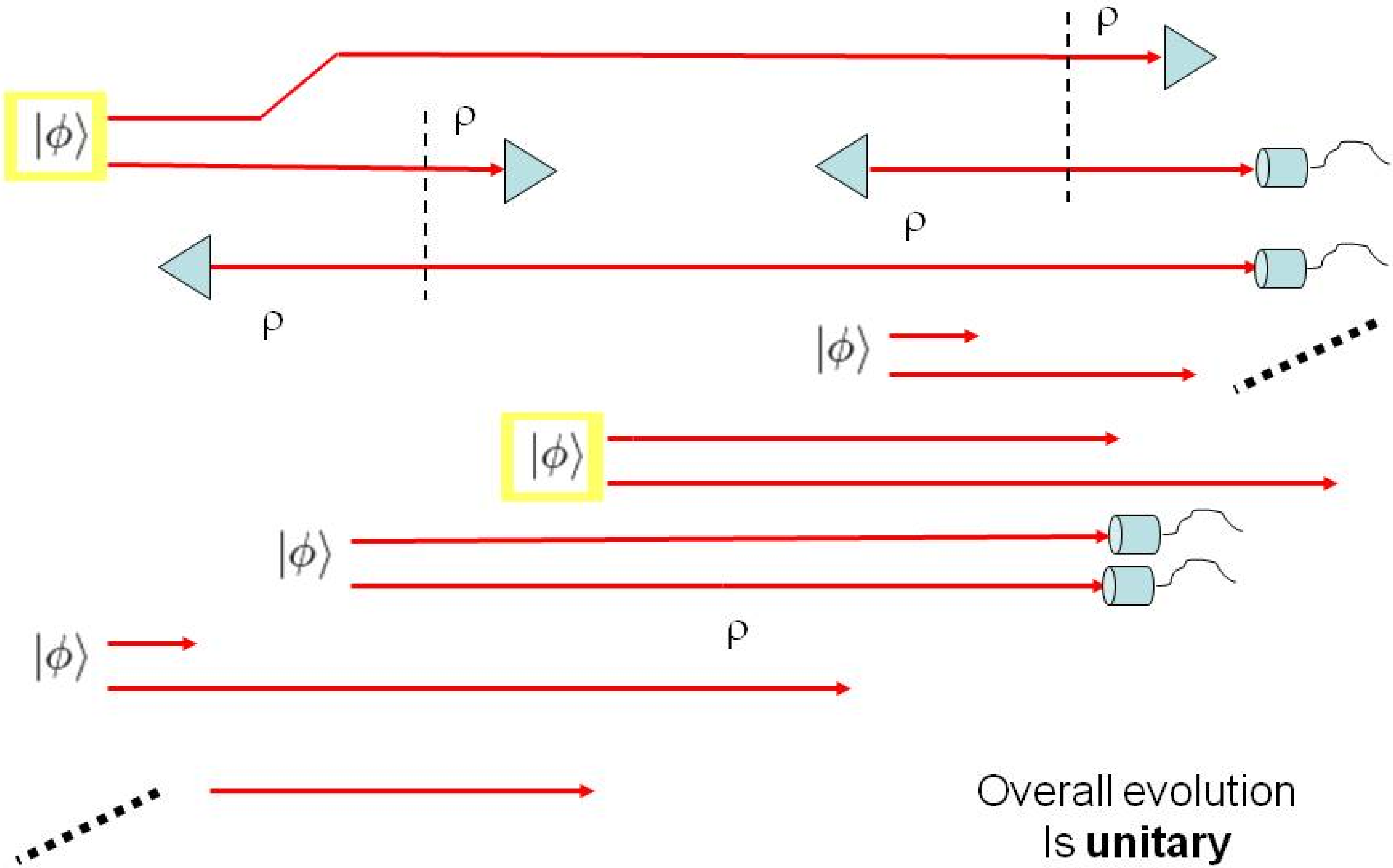
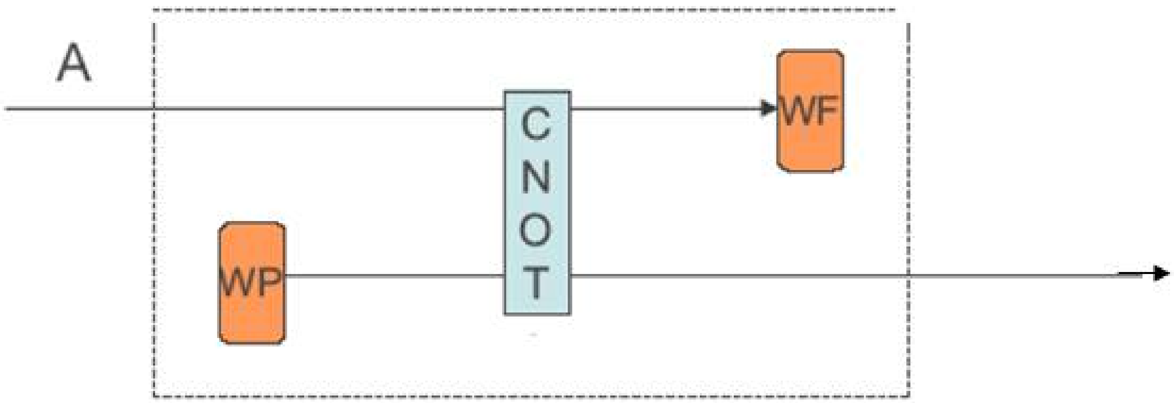


Overall evolution
Is **unitary**

(iii) Non-unitarity



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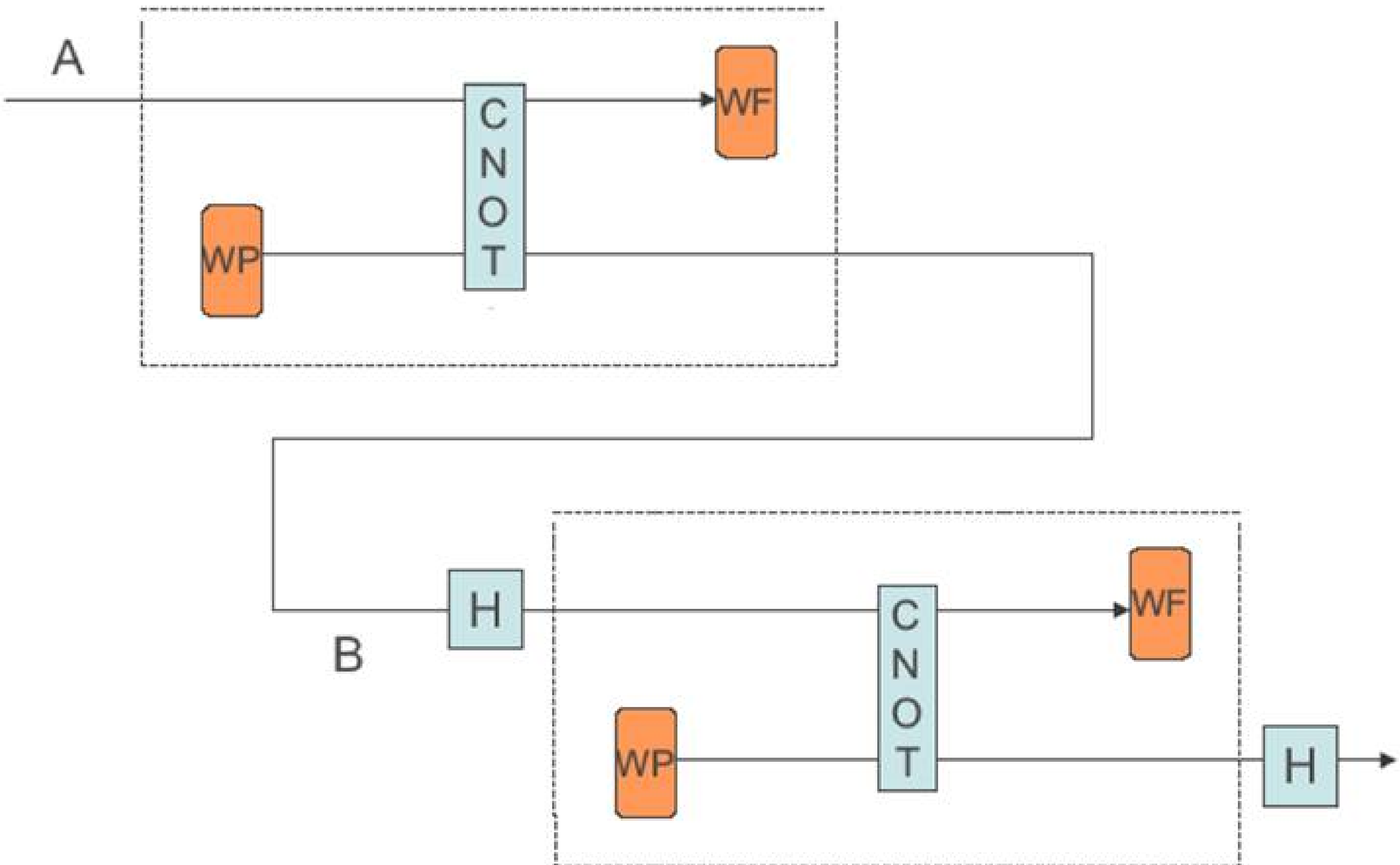
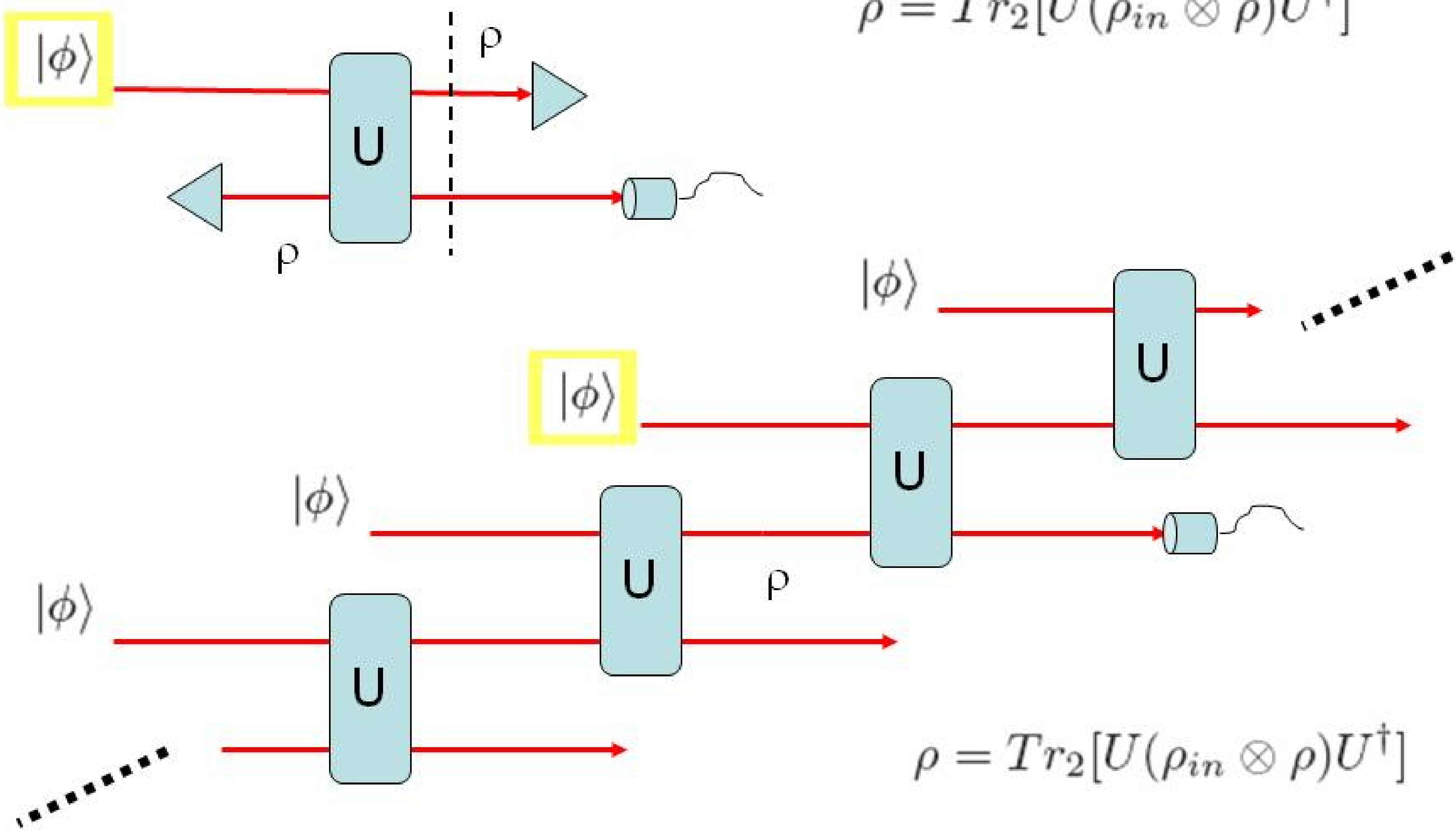


Overall evolution
Is **unitary**

T.C.Ralph, Phys.Rev.A **76**, 012336 (2007)

(iv) Extension to field modes



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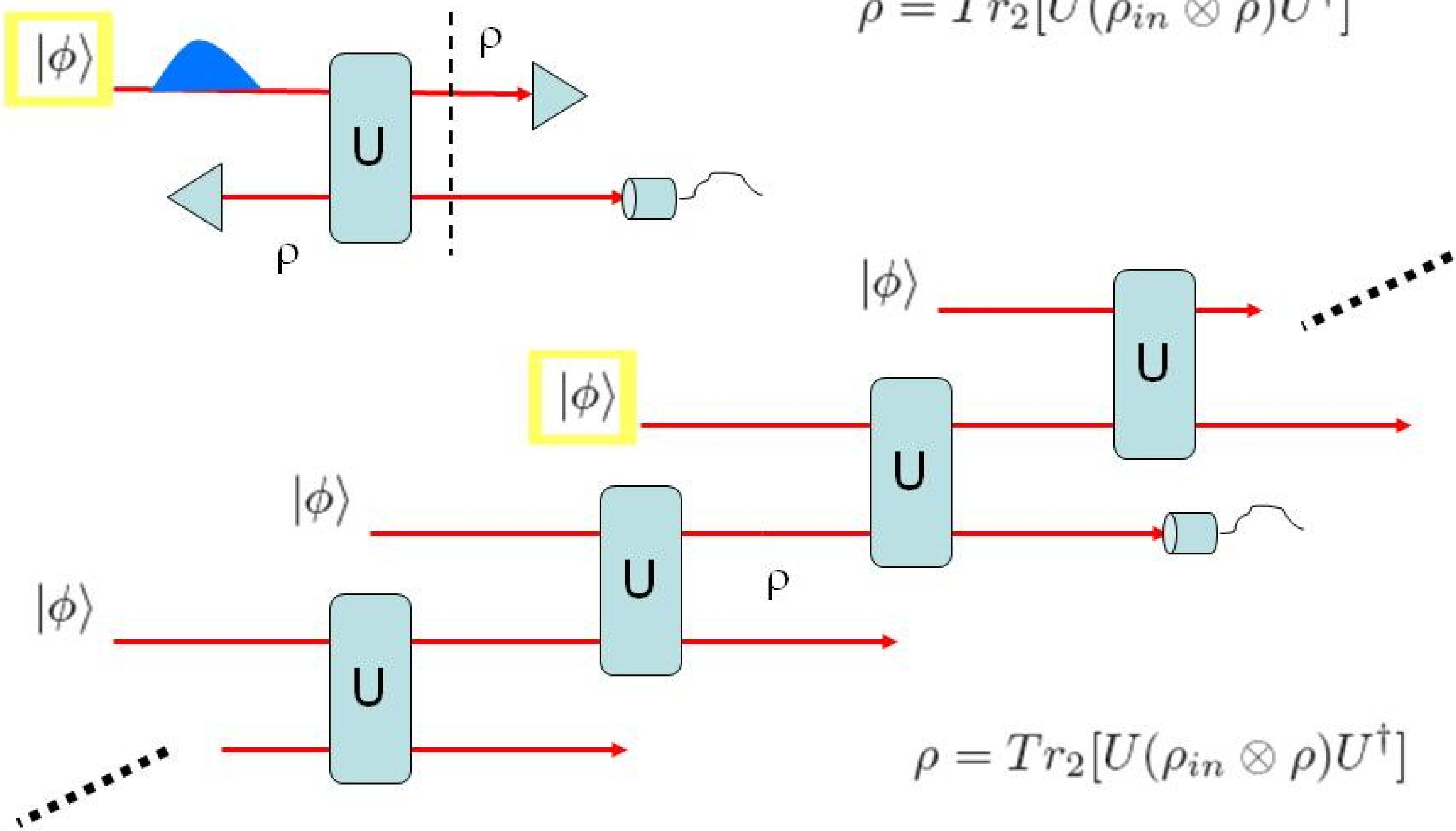

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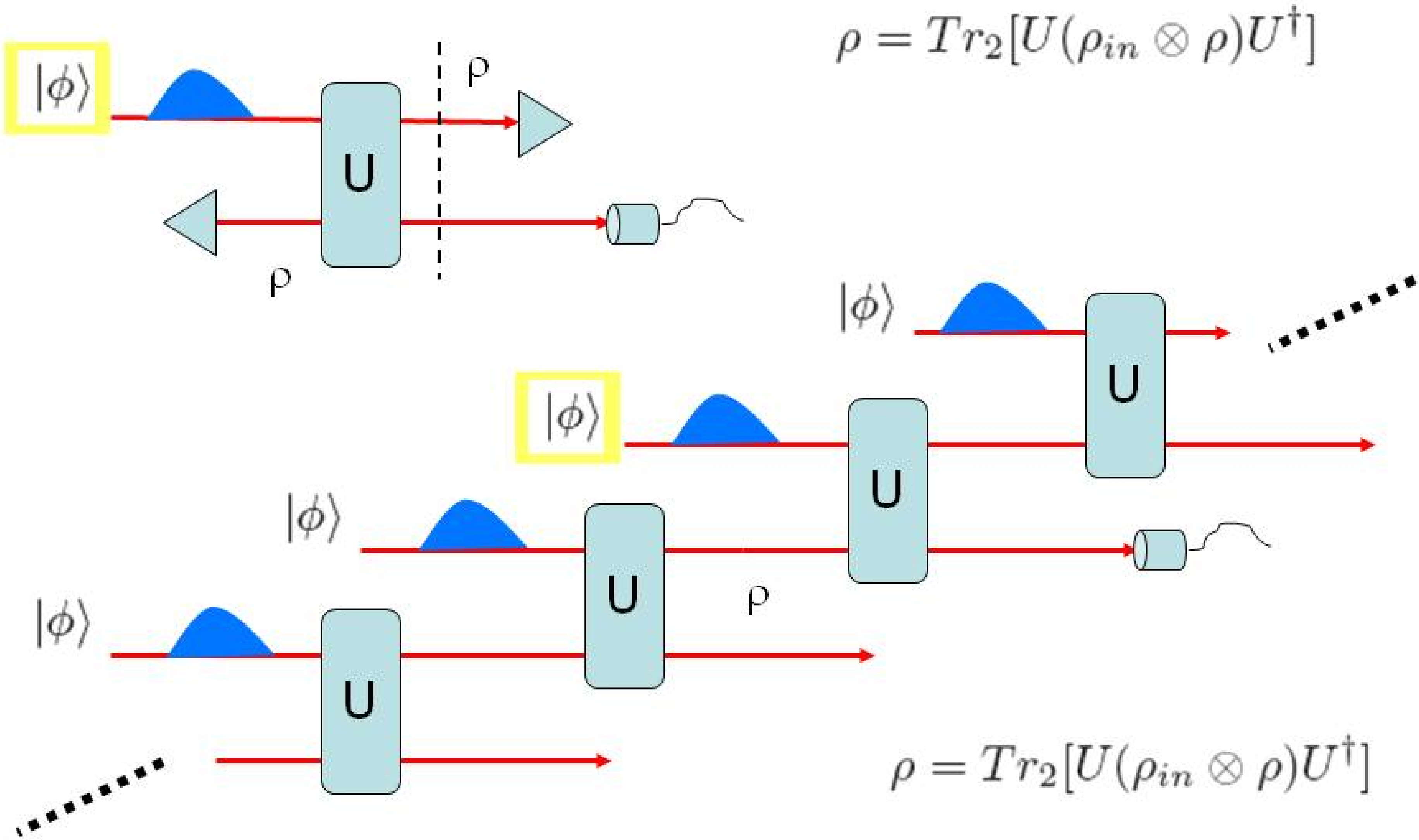
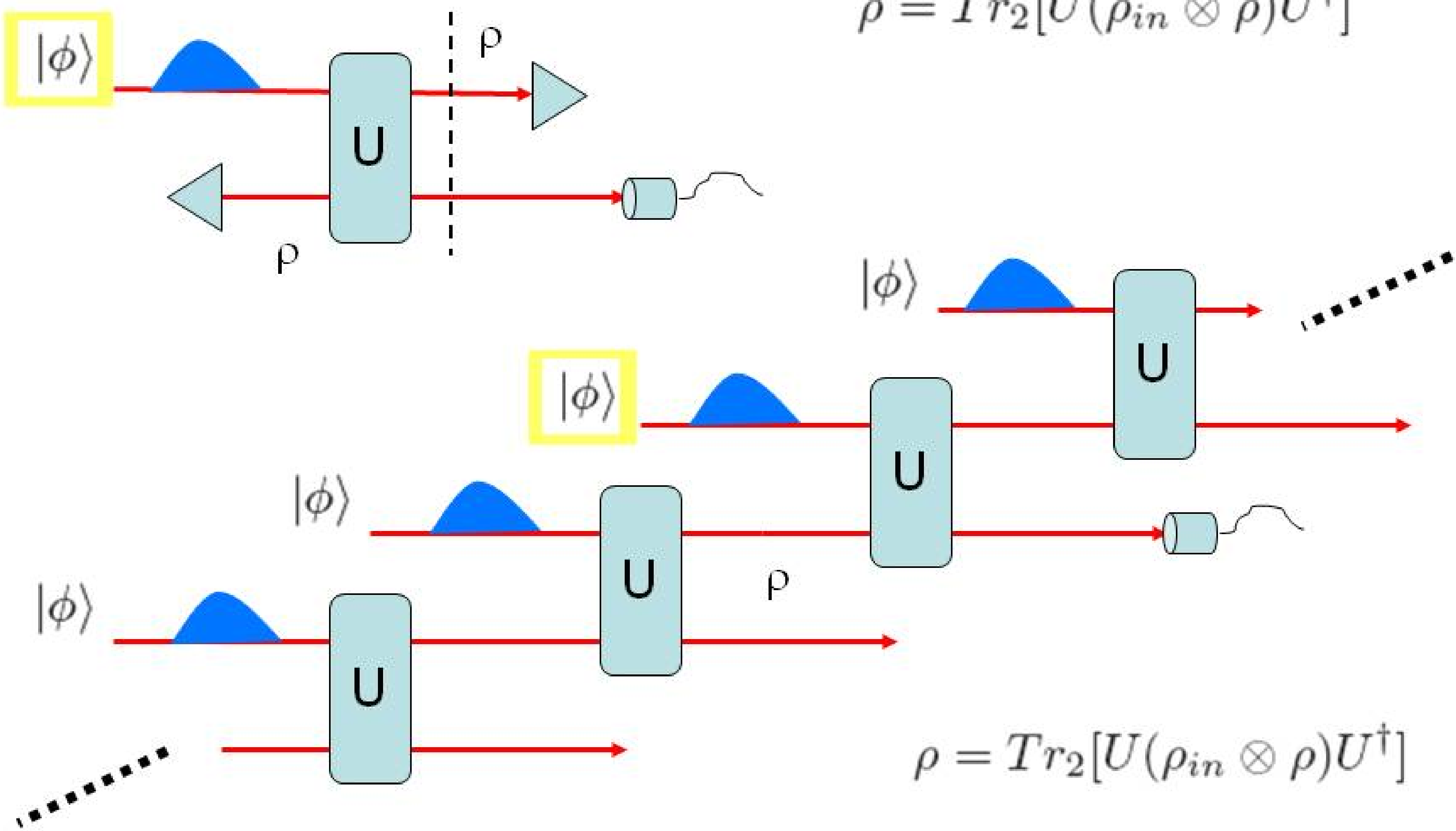


Mode operators

mode operators in quantum optics

$$\hat{a}(t,x) = \int dk\, G(k)\, e^{ik(x-t+\phi^{+})}\hat{a}_k$$

(iv) Extension to field modes



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Mode operators

mode operators in quantum optics

$$\hat{a}(t,x) = \int dk\, G(k)\, e^{ik(x-t+\phi^+)} \hat{a}_k$$

event operator

$$\bar{a}_i(x,t) \;=\; \int dk\, G(k)\, e^{ik(x-t+\phi^+)} \int d\Omega\, J(\Omega)\, e^{i\Omega(t_d-\tau(t))} \bar{a}_{i,k,\Omega}$$

T.C.Ralph, G.J.Milburn and T.Downes, Phys.Rev.A. **79**, 022121 (2009).

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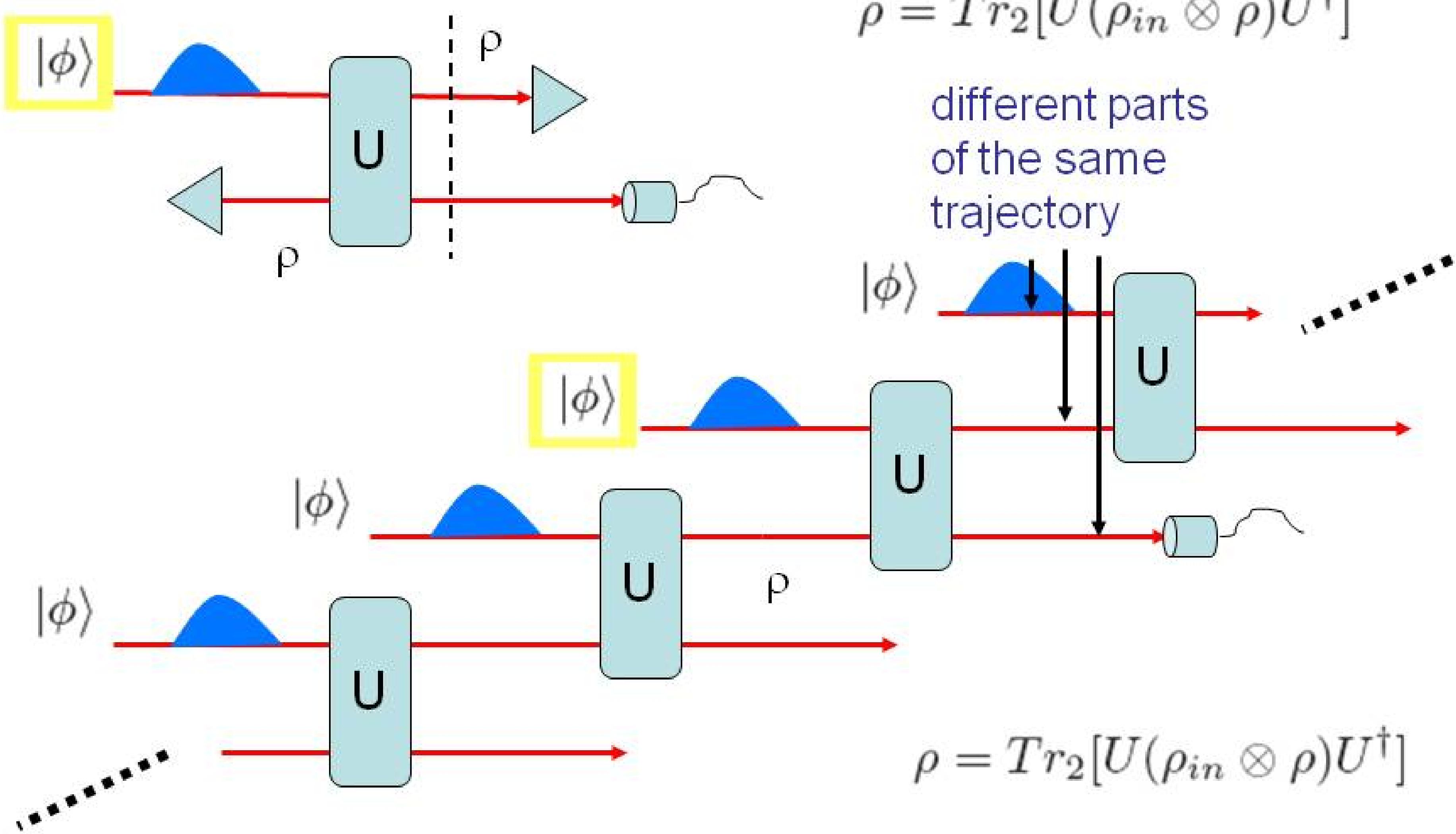

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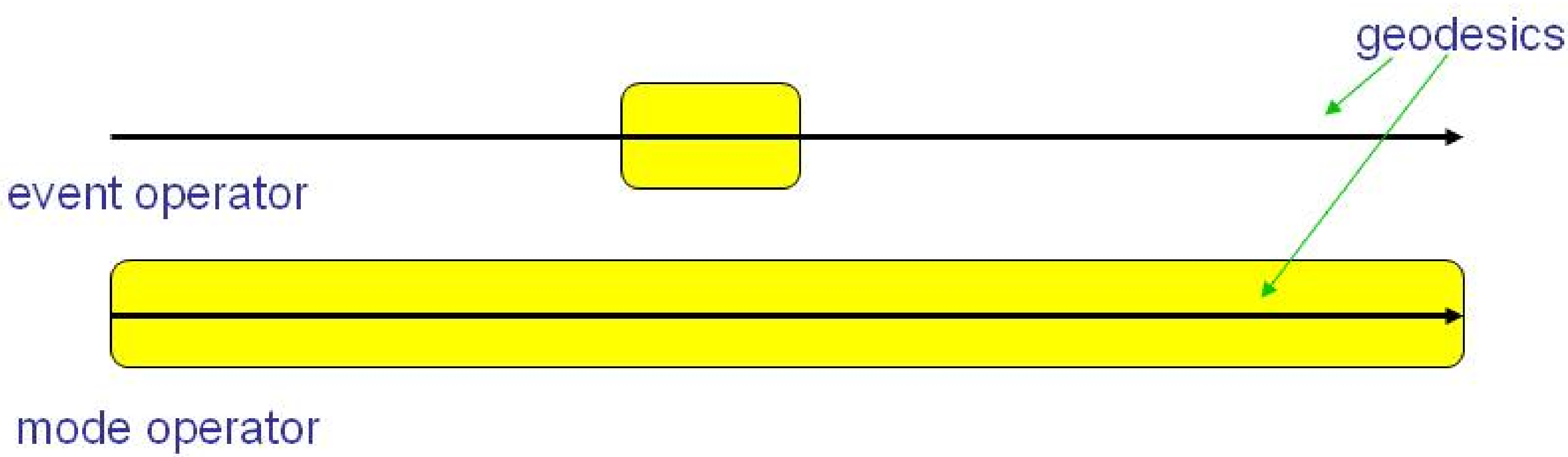

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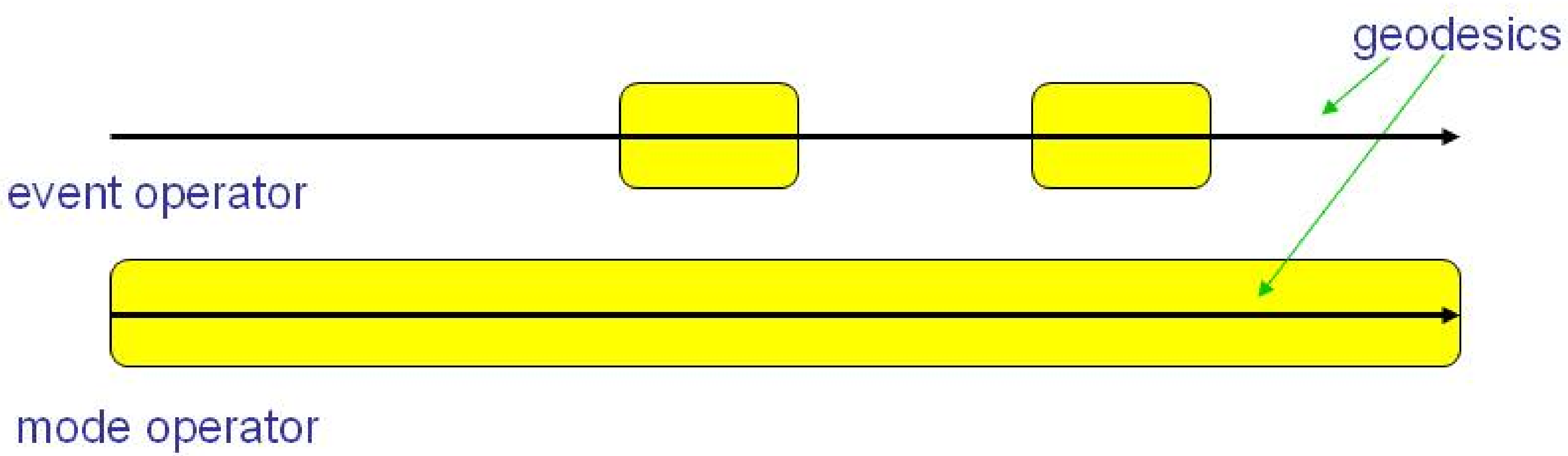

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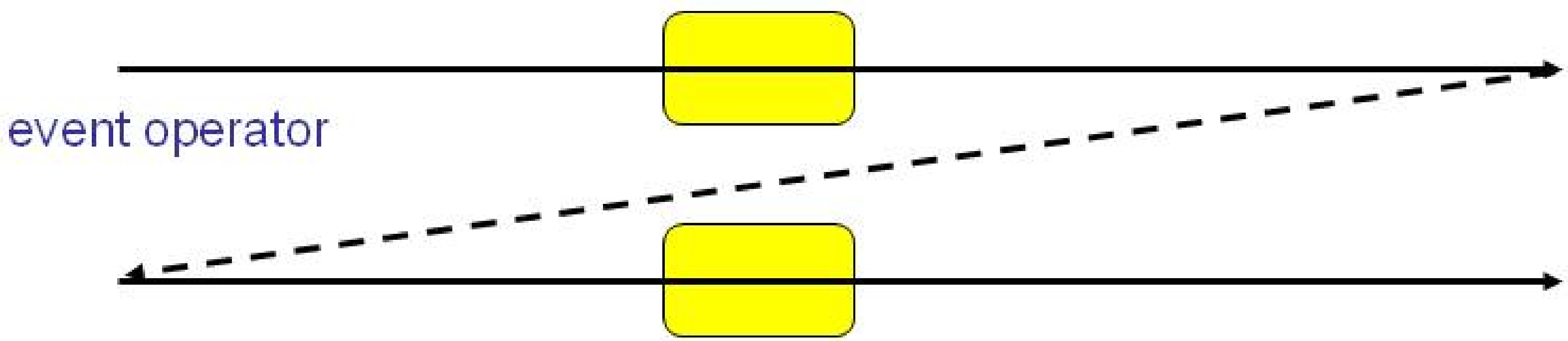

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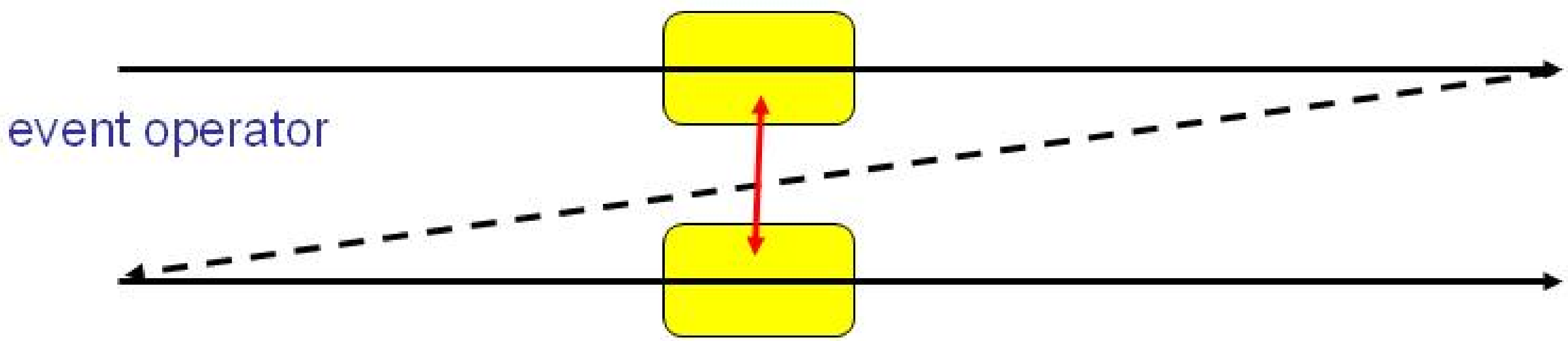


T.C.Ralph, G.J.Milburn and T.Downes, Phys.Rev.A. **79**, 022121 (2009).

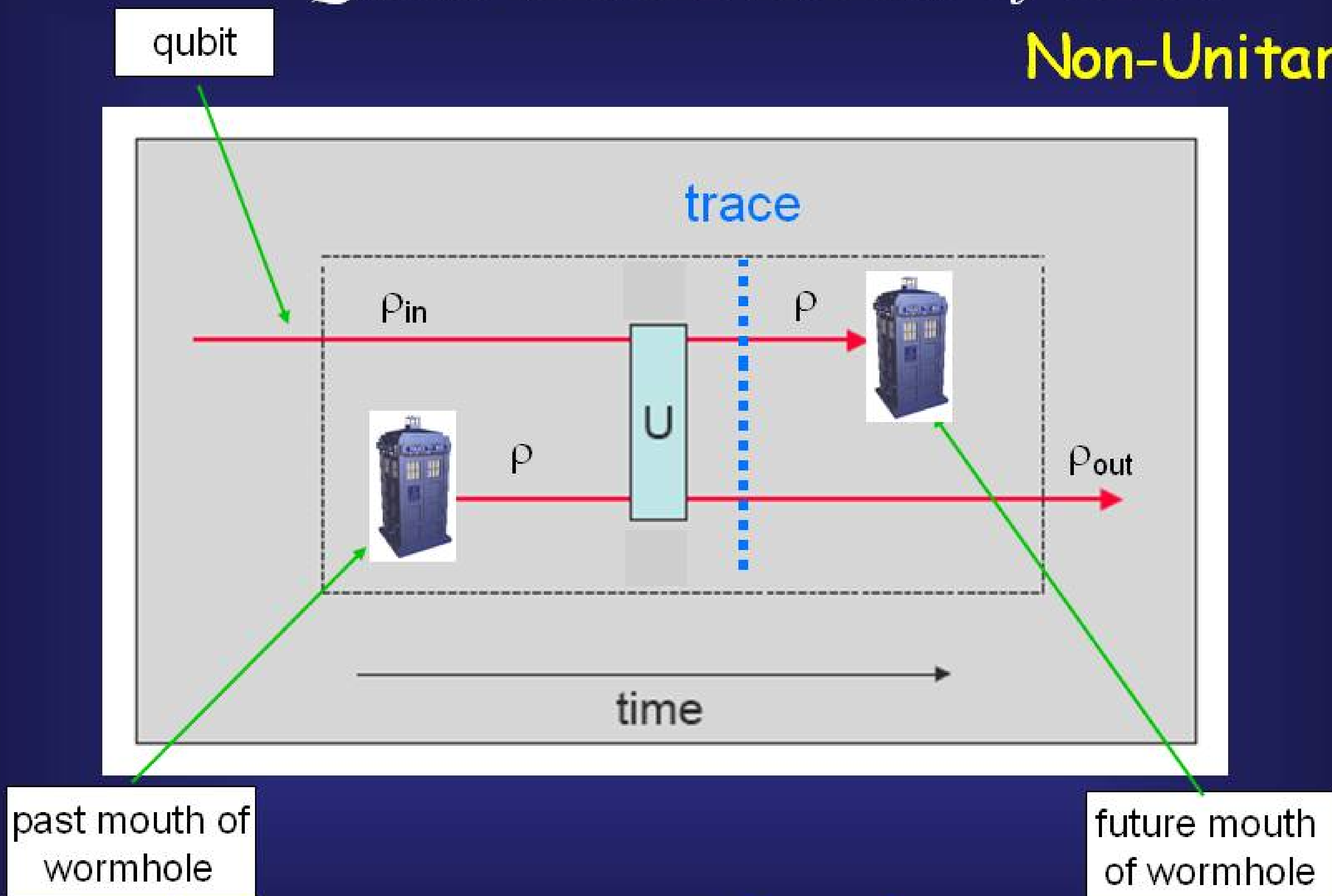
Summary

* Described a method for modeling qubits interacting with geometric CTCs.
* Showed that the model agrees with the Deutsch model of qubit/CTC interactions - but resolves several problems.
* Discussed how the model can be extended to more general quantum field states.

thanks

Qubits in the Presence of CTCs

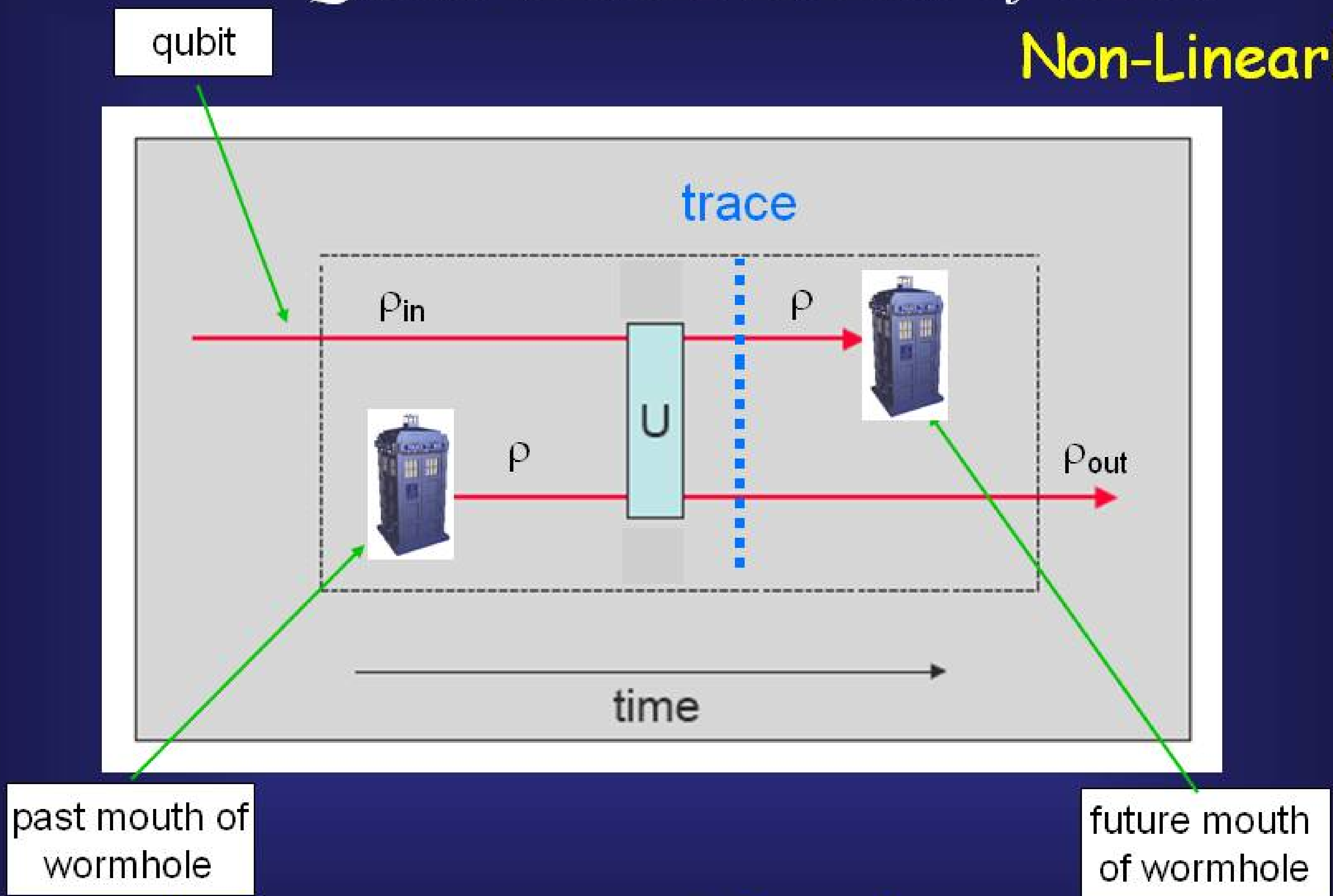
Non-Unitary!



D.Deutsch, Phys.Rev.D, **44**, 3197 (1991),
D.Bacon, Phys.Rev.A, **70** 032309 (2004).

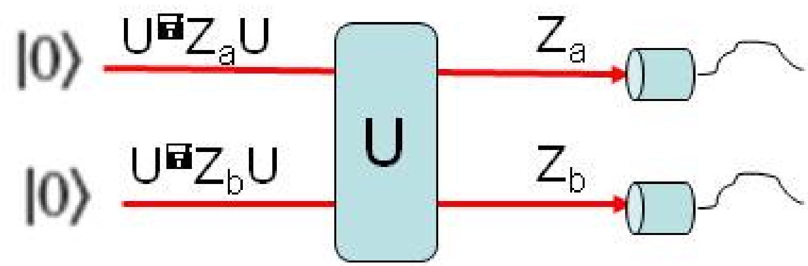
Qubits in the Presence of CTCs

Non-Linear!

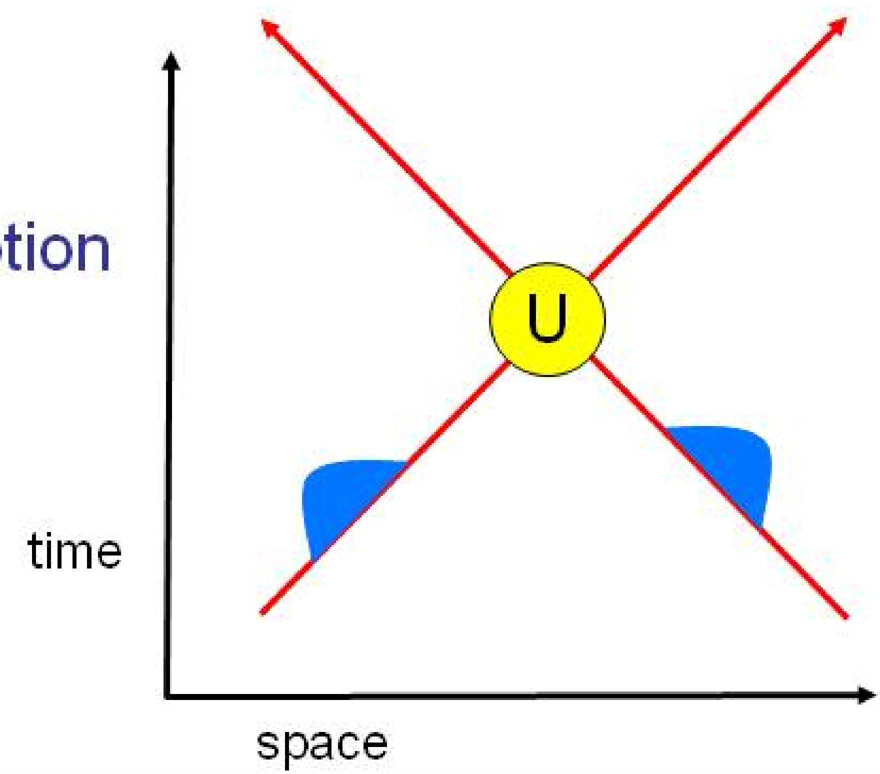


D.Deutsch, Phys.Rev.D, **44**, 3197 (1991),
D.Bacon, Phys.Rev.A, **70** 032309 (2004).

Space-time Qubits



- Heisenberg Picture
- Field ground-state
- Retain Pauli description of qubits



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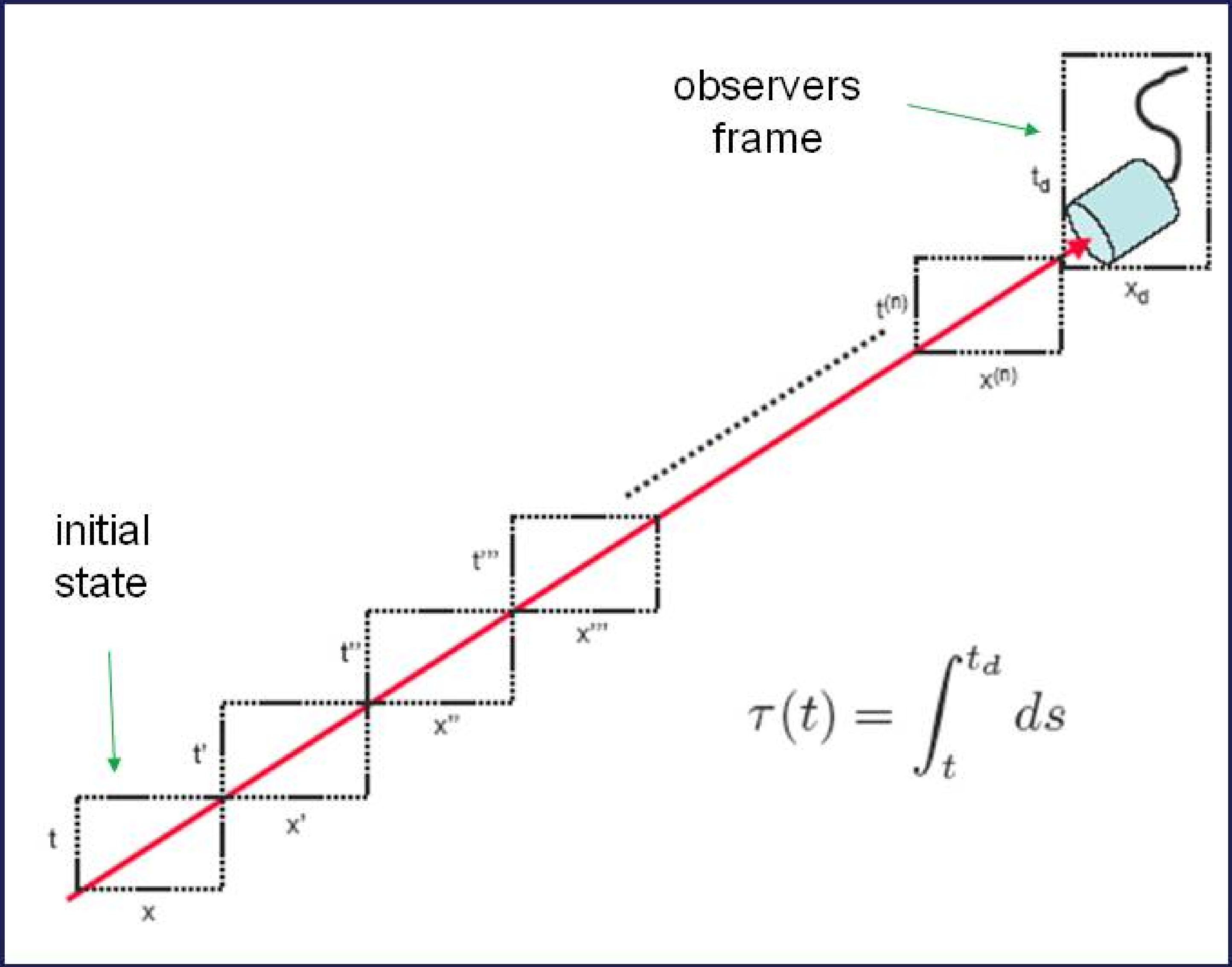

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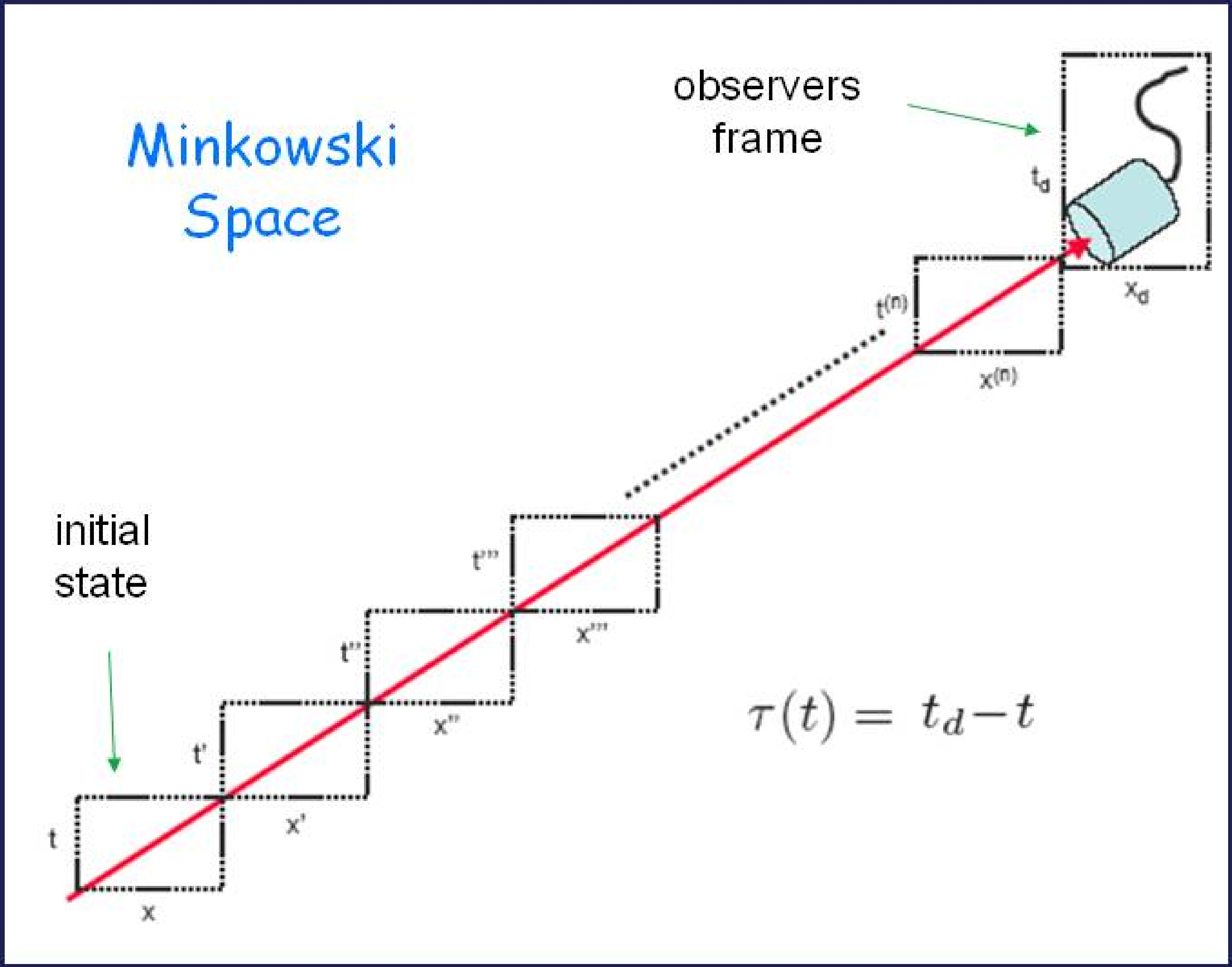
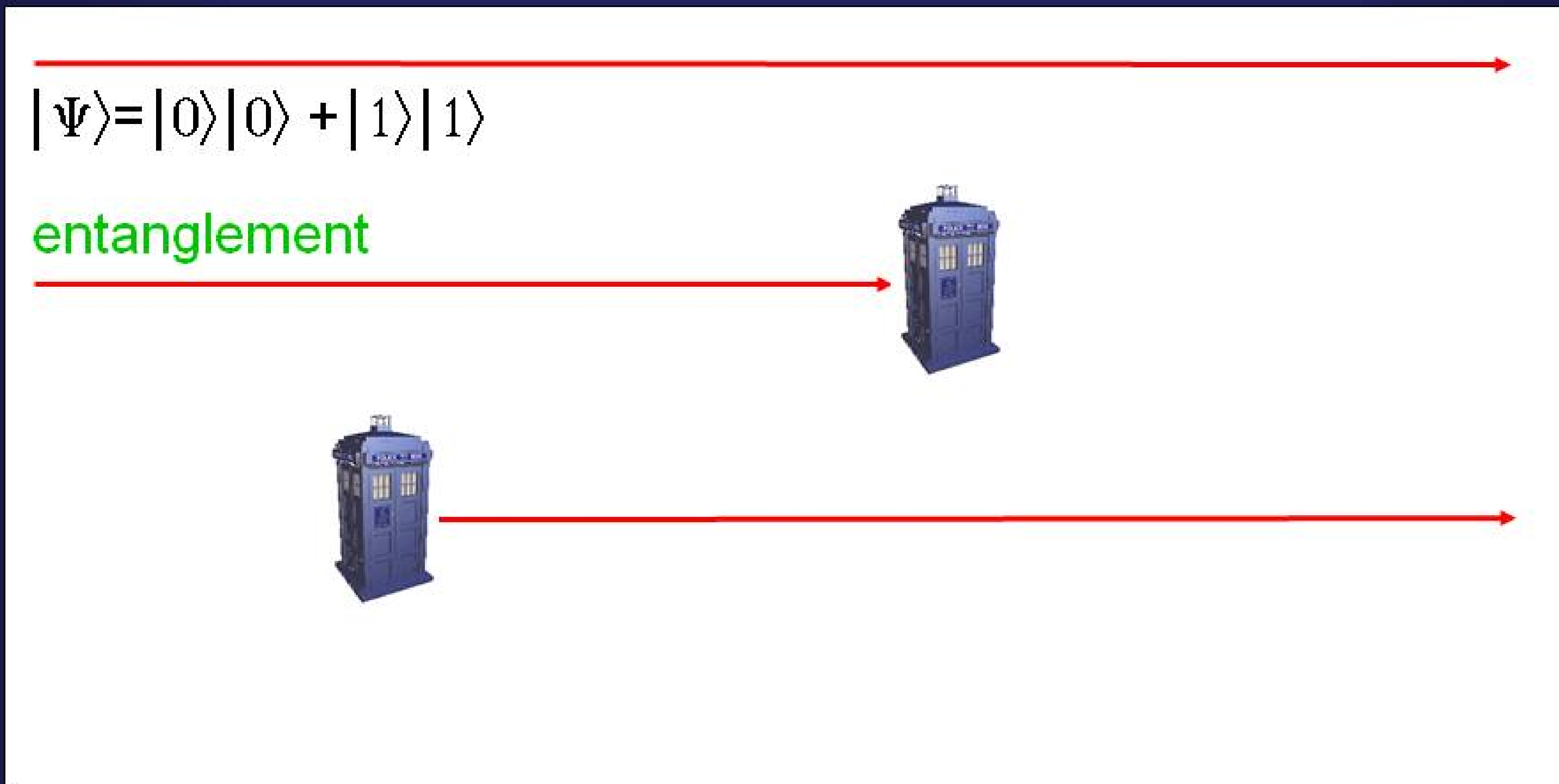


Decorrelation of entanglement



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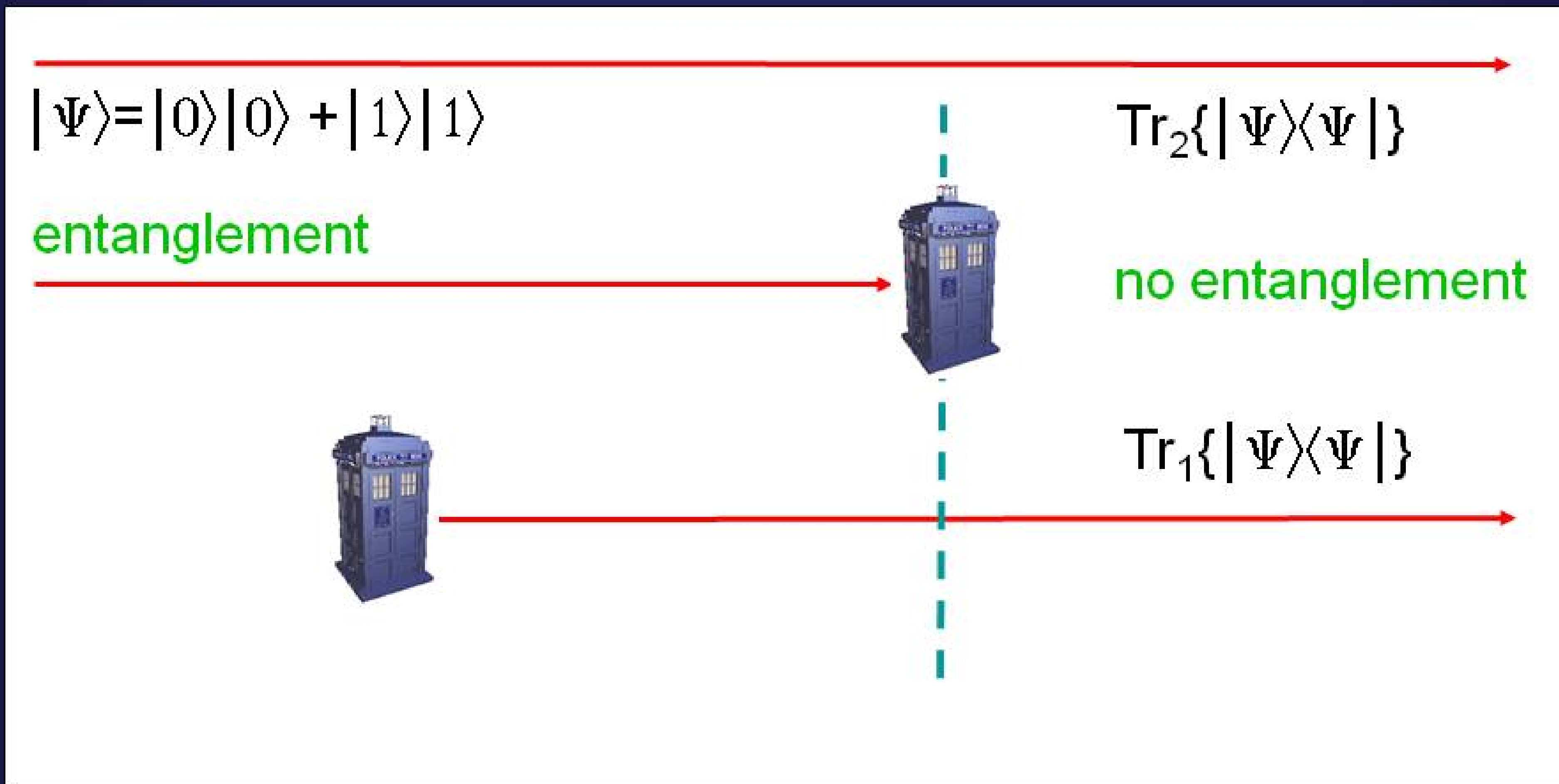

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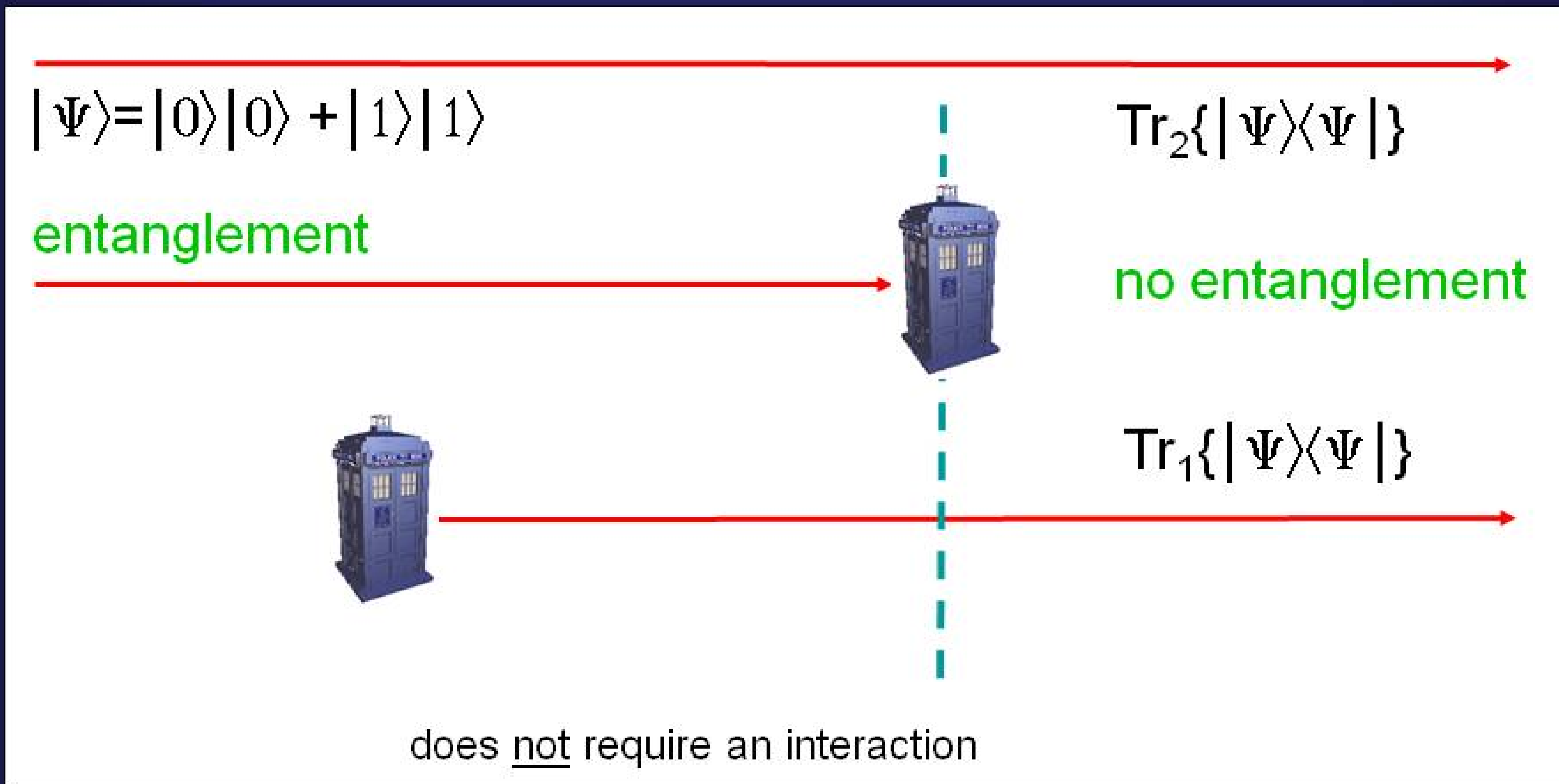
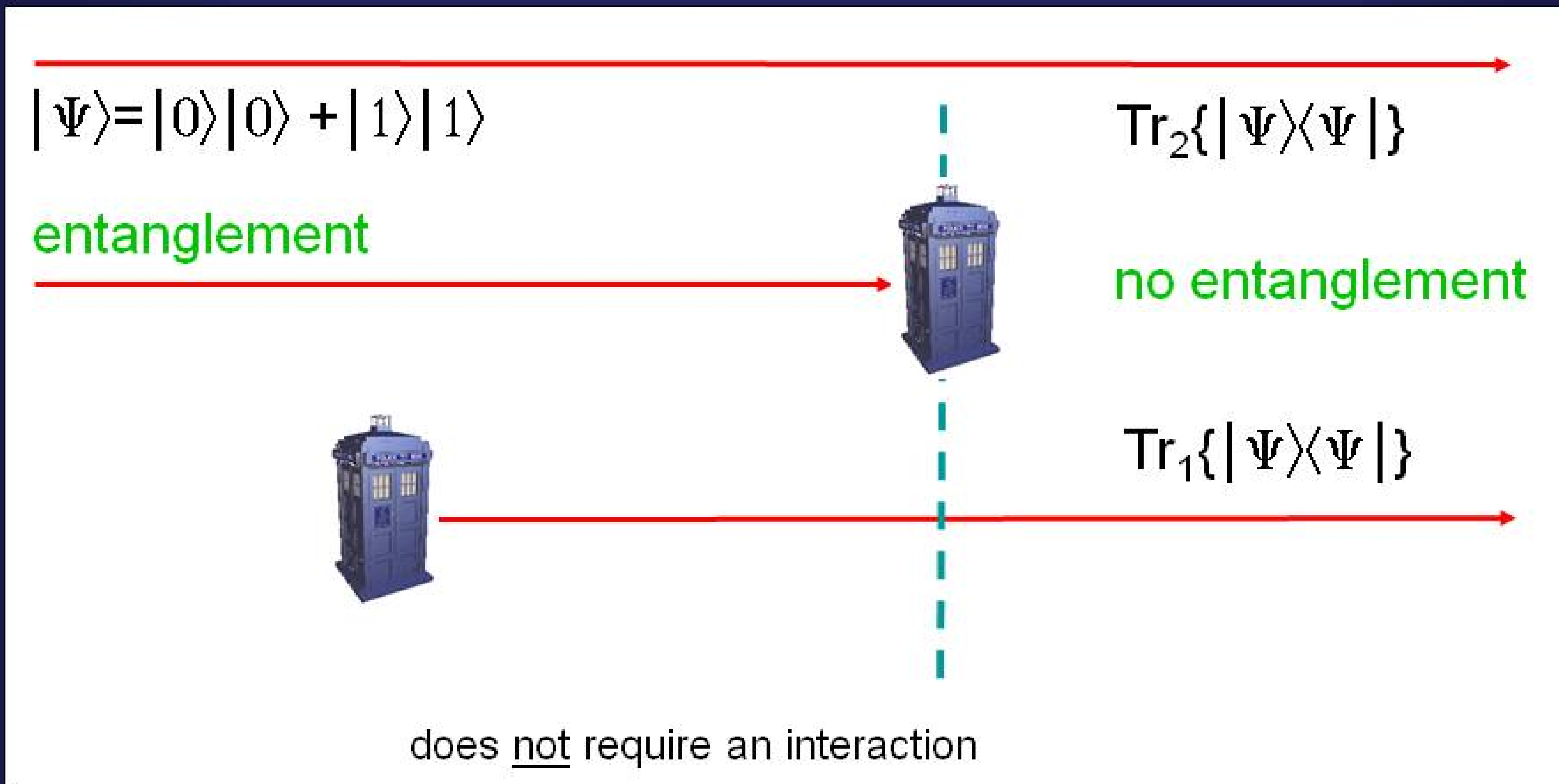


Predicted by all models

Decorrelation of entanglement



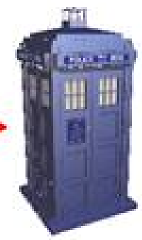
Predicted by all models

Decorrelation of entanglement

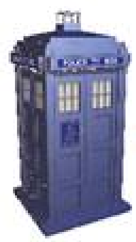
$|\Psi\rangle = |0\rangle|0\rangle + |1\rangle|1\rangle$

$\mathrm{Tr}_2\{|\Psi\rangle\langle\Psi|\}$

entanglement



no entanglement



$\mathrm{Tr}_1\{|\Psi\rangle\langle\Psi|\}$

does <u>not</u> require an interaction

Predicted by all models

Decorrelation of entanglement

$|\Psi\rangle = |0\rangle|0\rangle + |1\rangle|1\rangle$

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entanglement

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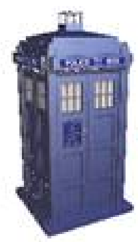

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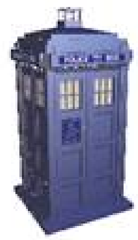

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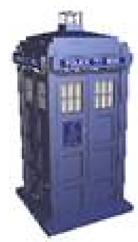

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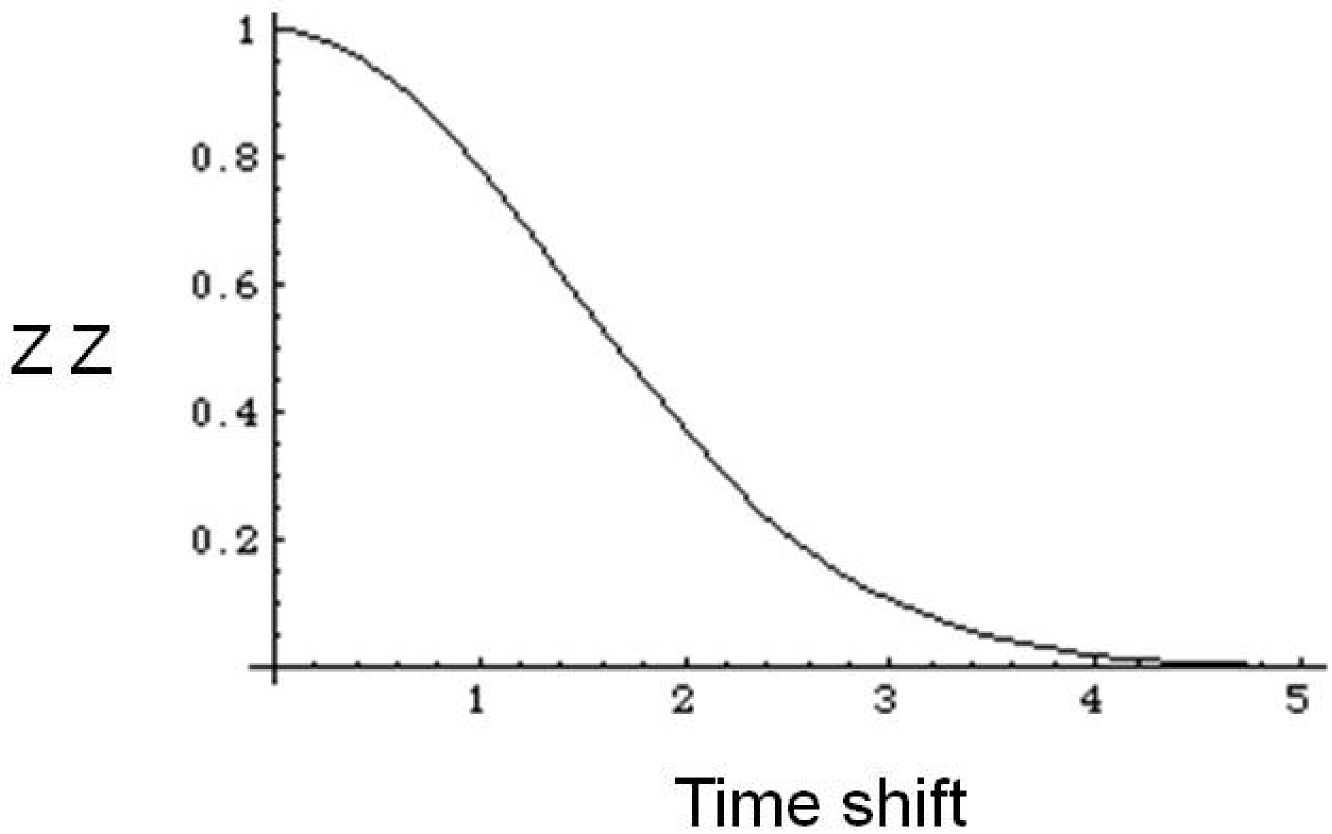

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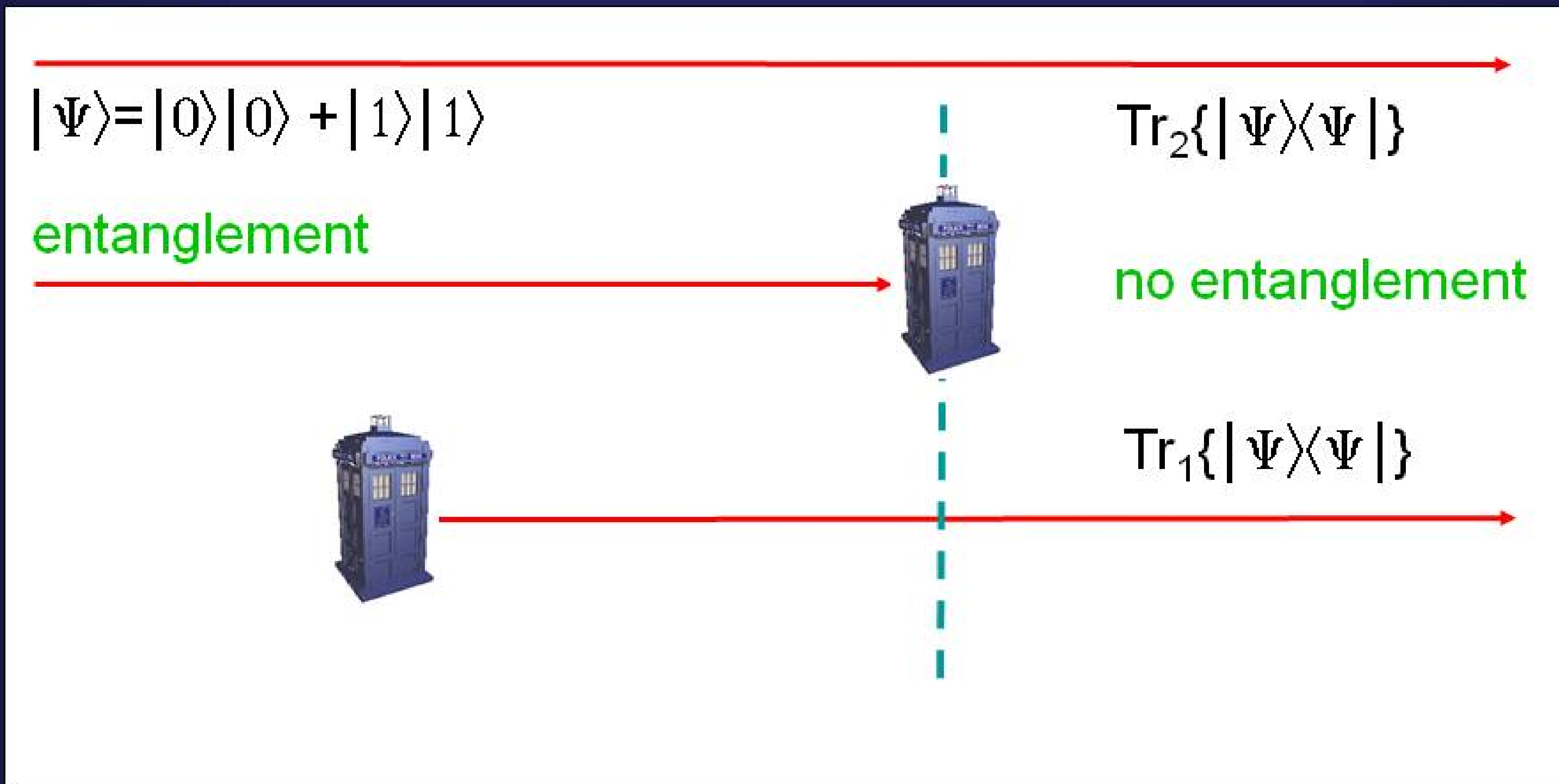

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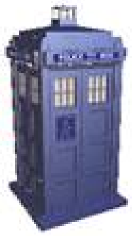

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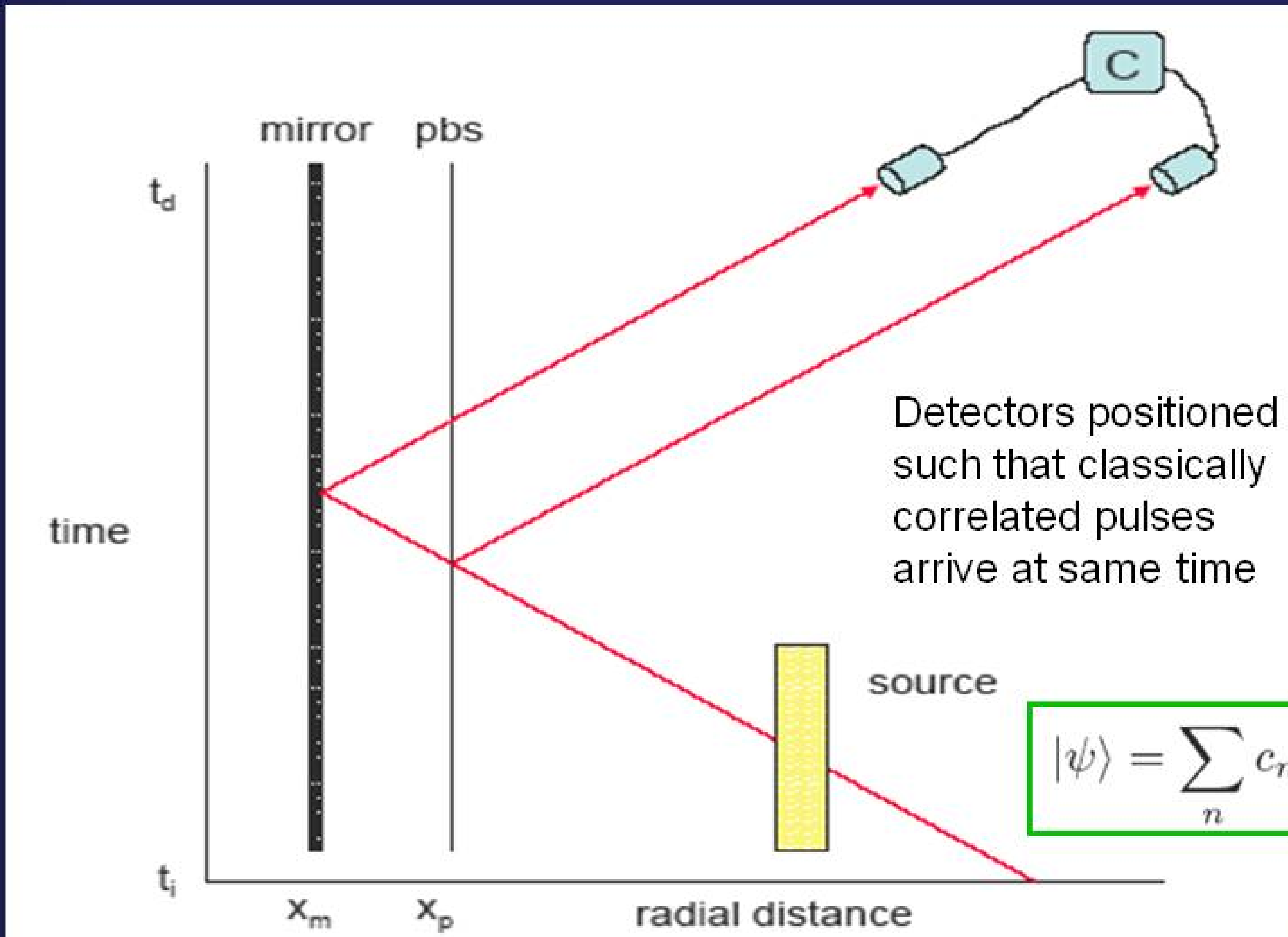
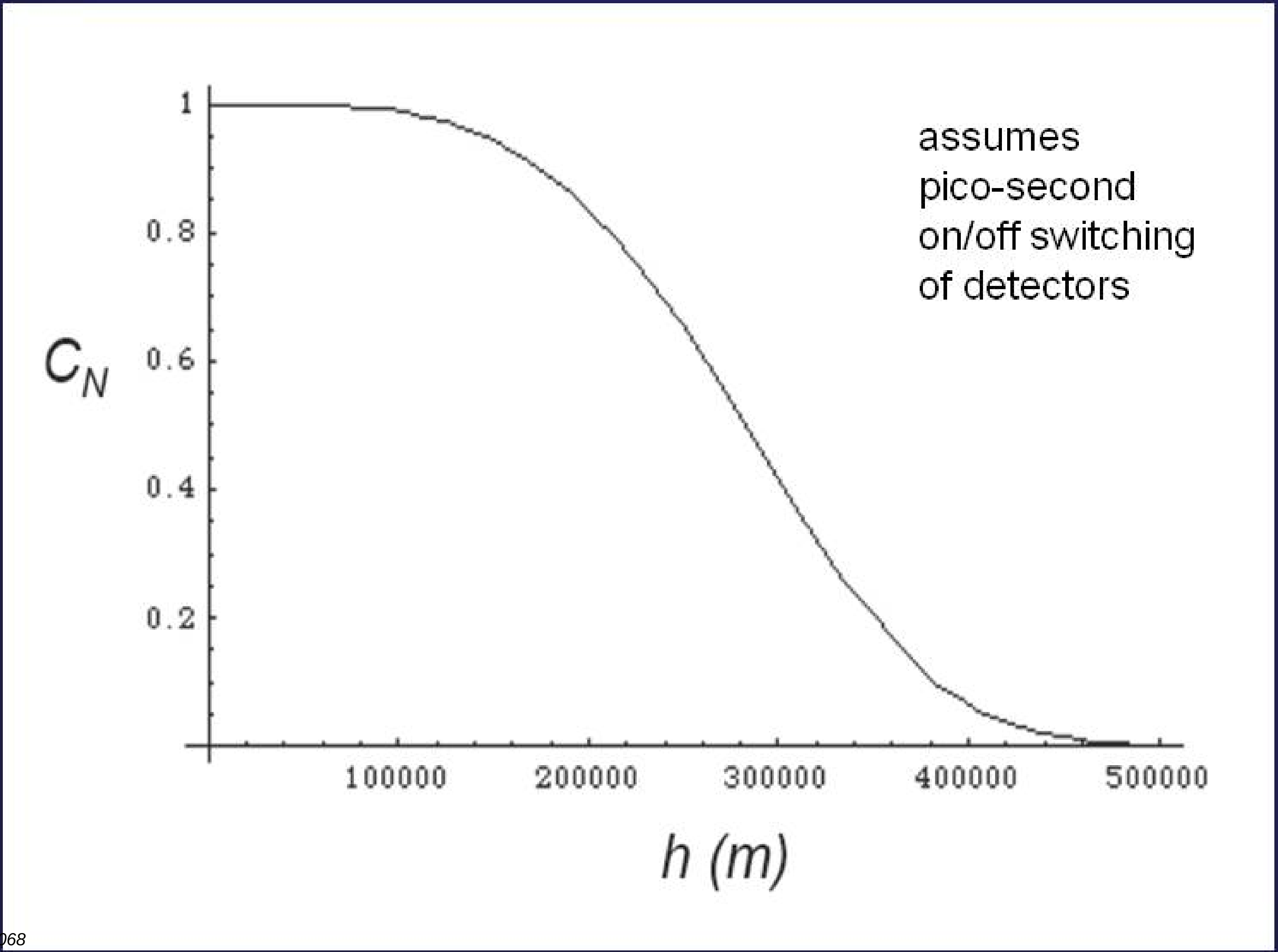
T.C.Ralph, G.J.Milburn and T.Downes, Phys.Rev.A. **79**, 022121 (2009).

Space time diagram of correlation exp

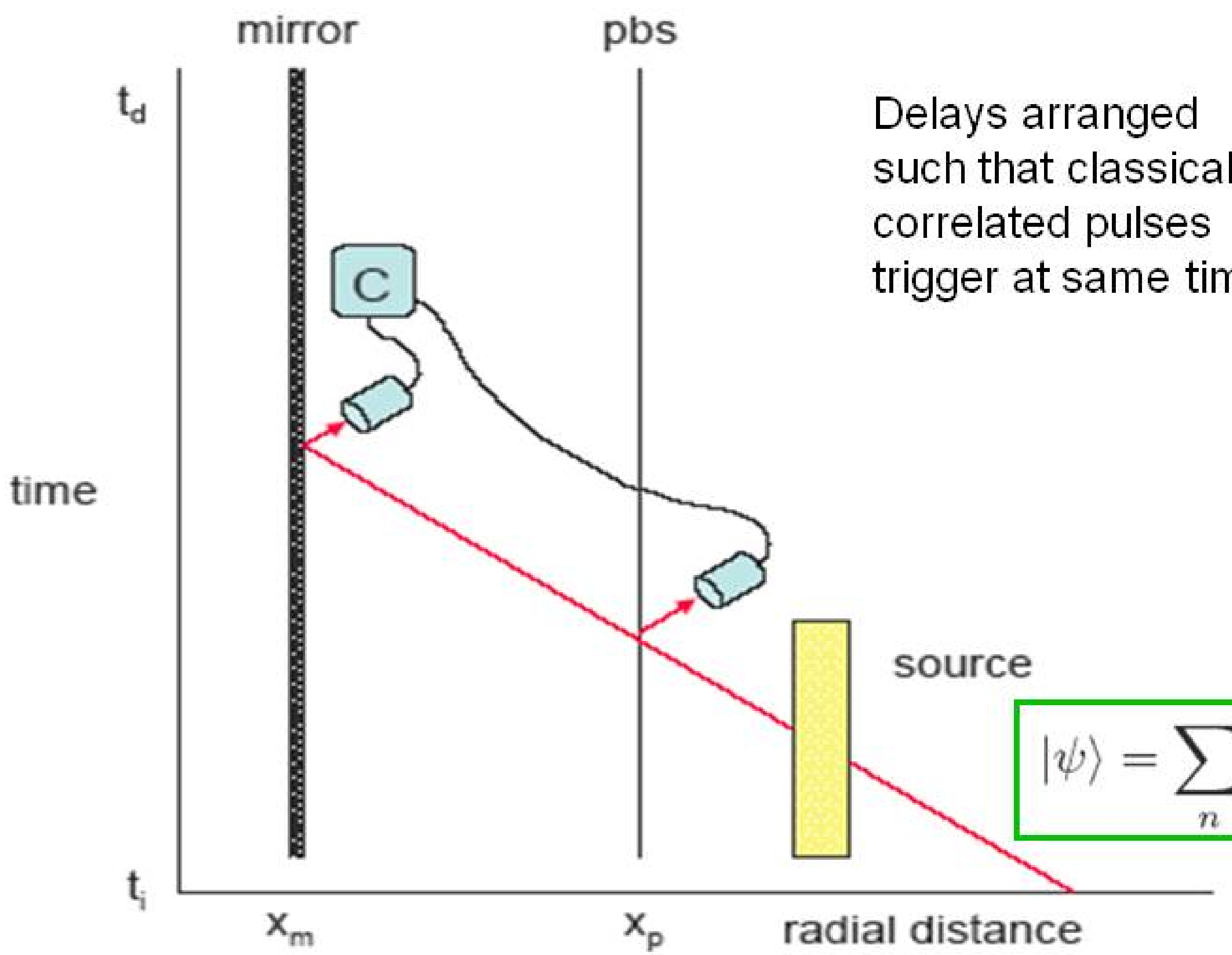


$$|\psi\rangle = \sum_n c_n |n\rangle_a |n\rangle_b$$

Coincidence rate vs height of PBS



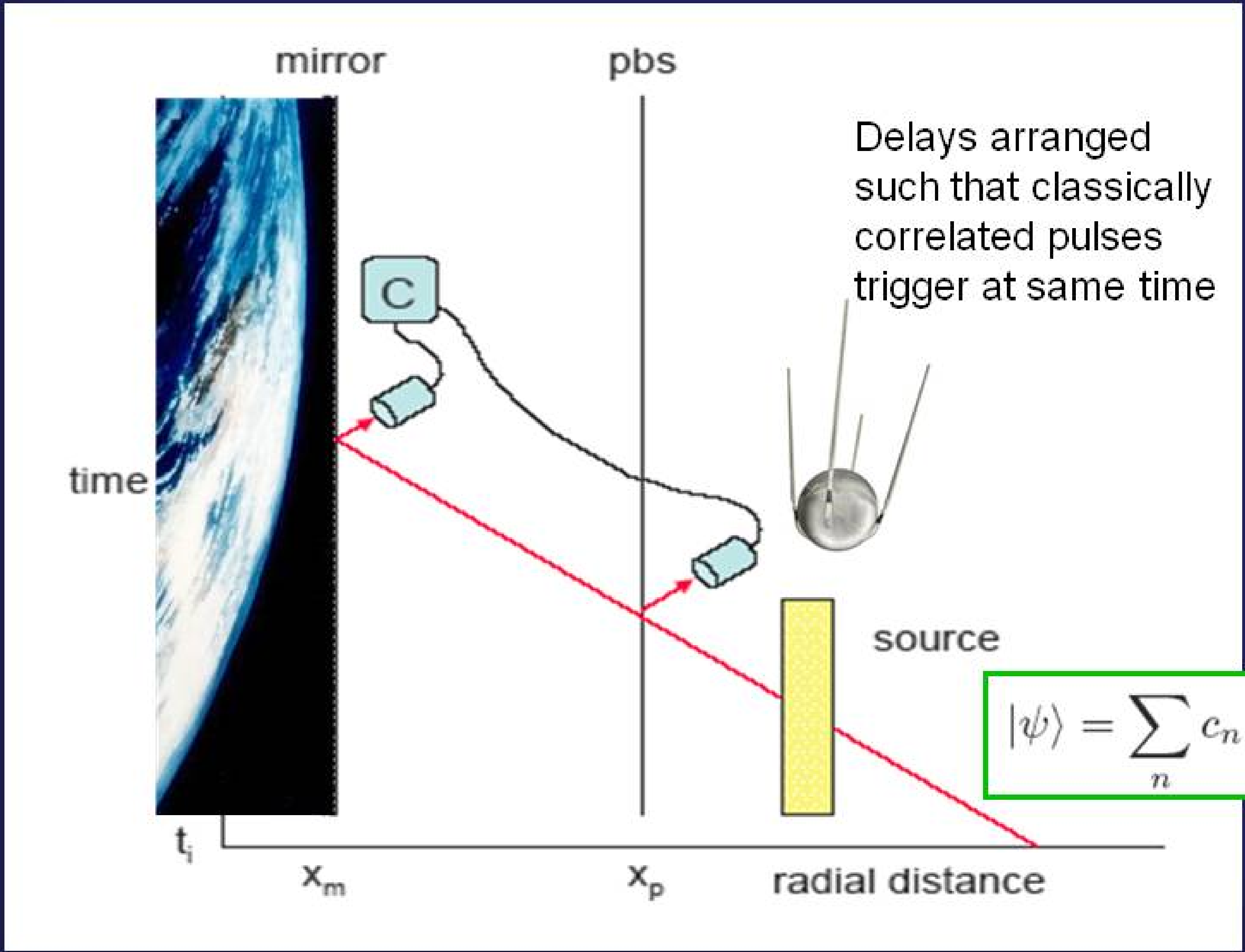
Space time diagram of correlation exp 2



Delays arranged such that classically correlated pulses trigger at same time

$$|\psi\rangle = \sum_n c_n |n\rangle_a |n\rangle_b$$

Space time diagram of correlation exp 2



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