CENTRE FOR QUANTUM COMPUTER TECHNOLOGY
AUSTRALIAN RESEARCH COUNCIL CENTRE OF EXCELLENCE

Space-time Qubits, Event Operators and Closed Timelike Curves

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THE UNIVERSITY OF QUEENSLAND AUSTRALIA

Overview

* Quantum Information on
Closed Timelike Curves

* Space-time Qubits

* Event operators and a space-time
description of Quantum Information on
Closed Timelike Curves

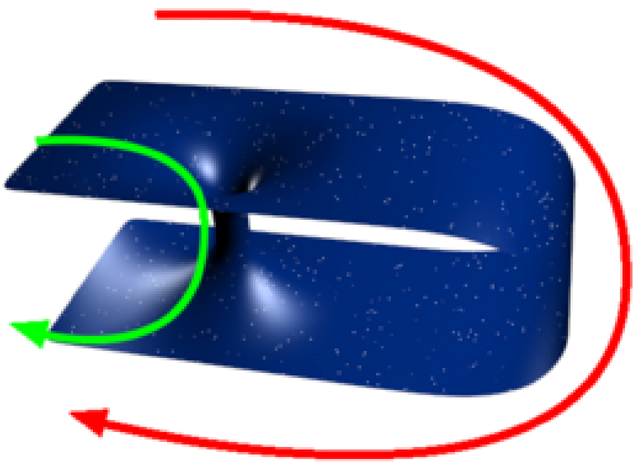
* Conclusions

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
(Received 21 June 1988)



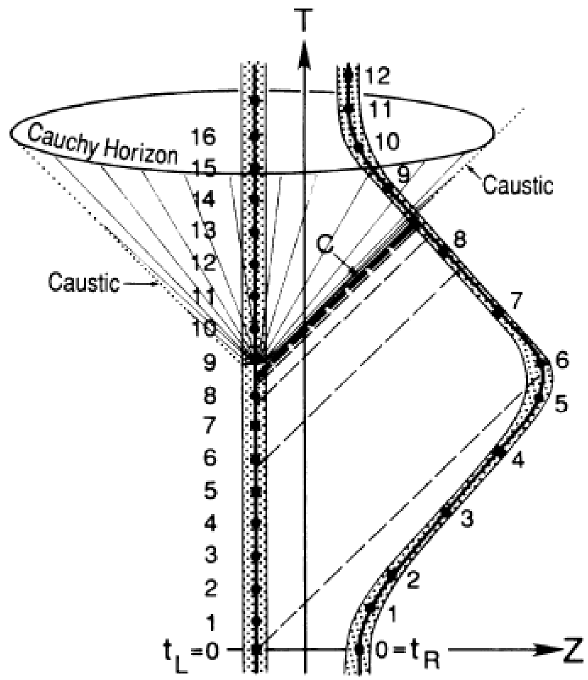
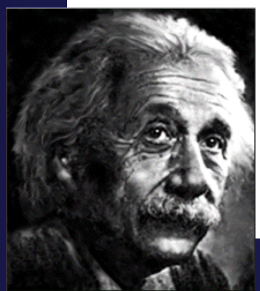
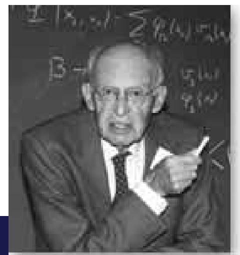


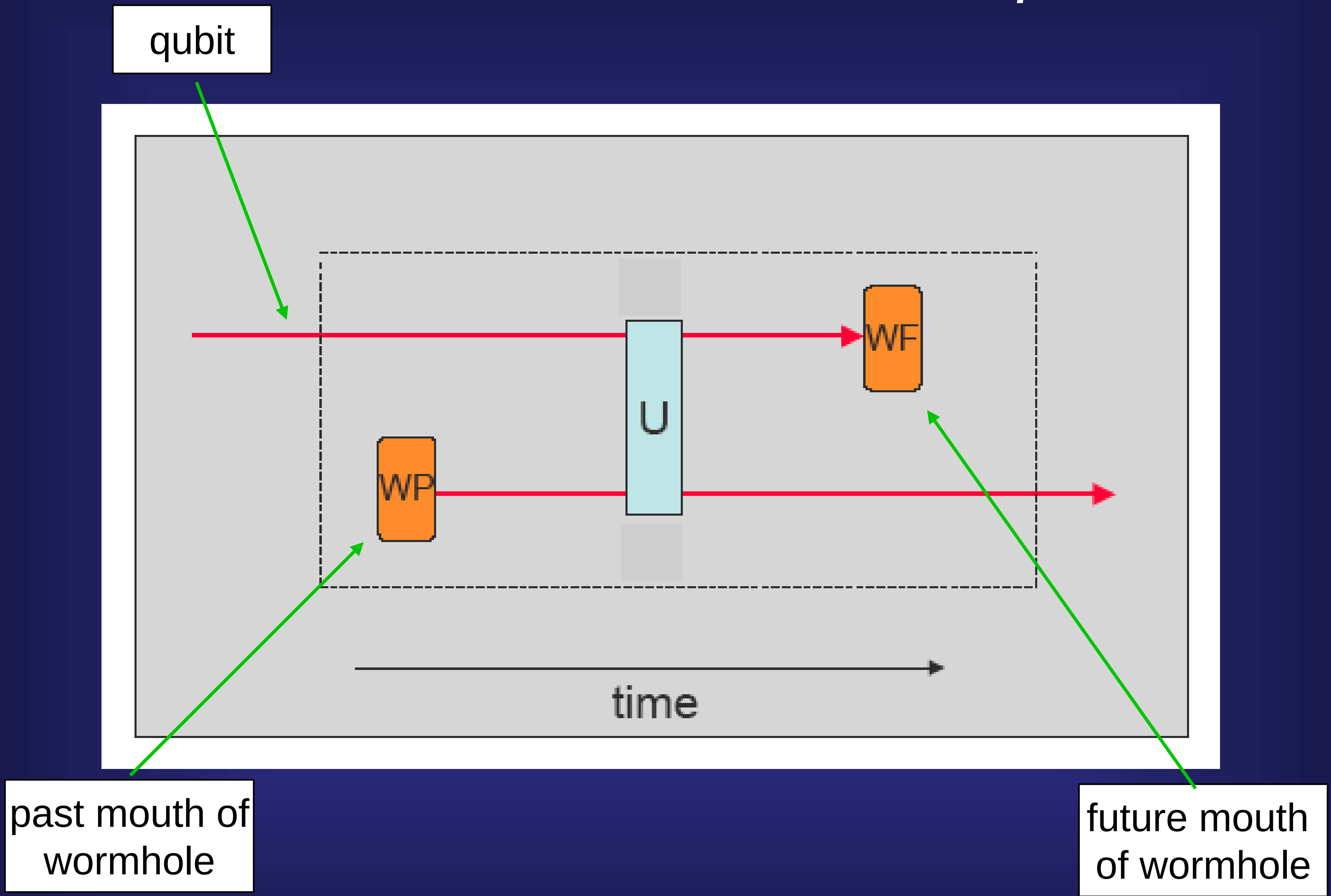
FIG. 2. Spacetime diagram for conversion of a wormhole into a time machine.



also known as Einstein-Rosen bridge



Qubits in the Presence of CTCs



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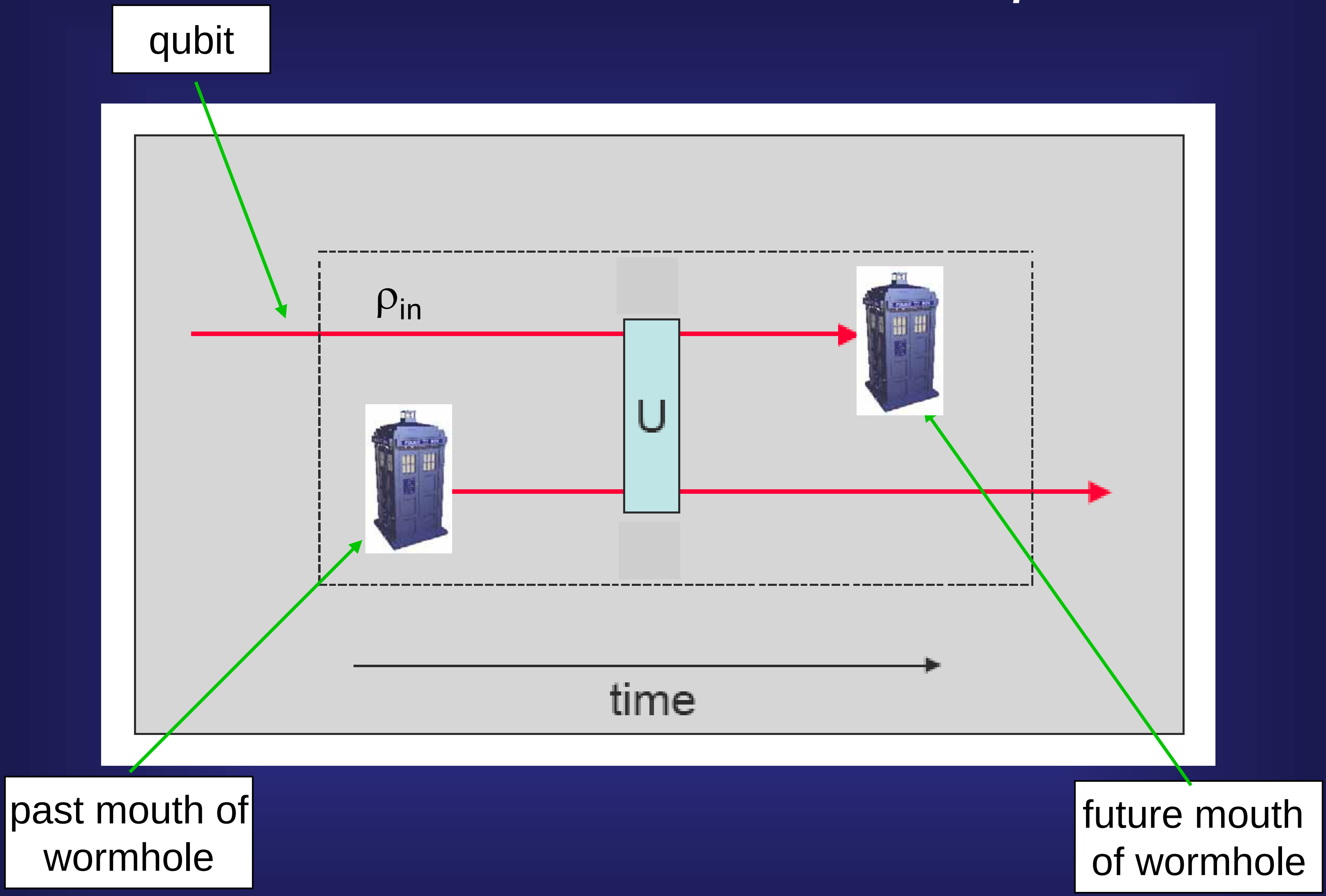

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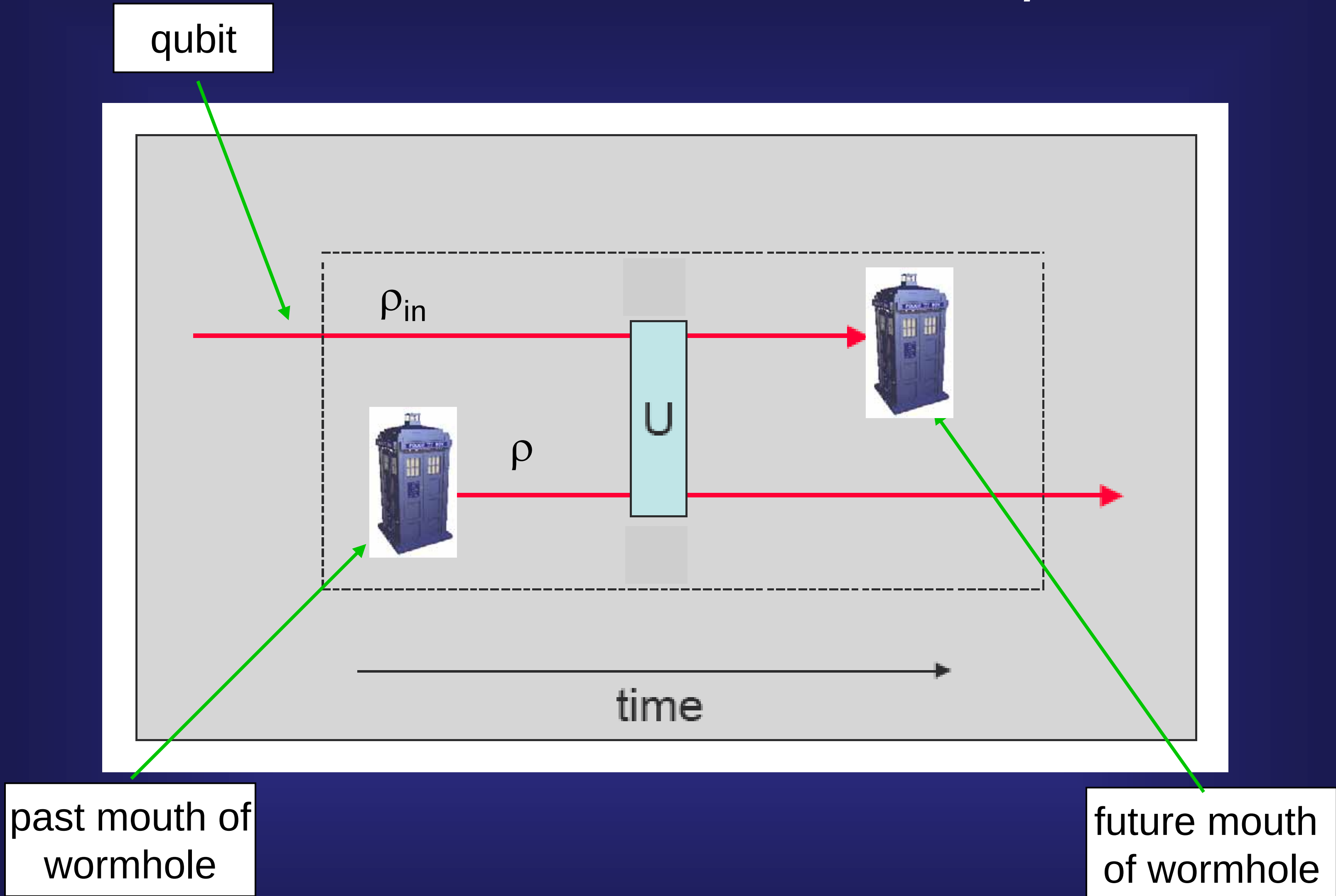

D.Deutsch, Phys.Rev.D, **44**, 3197 (1991),
D.Bacon, Phys.Rev.A, **70** 032309 (2004).

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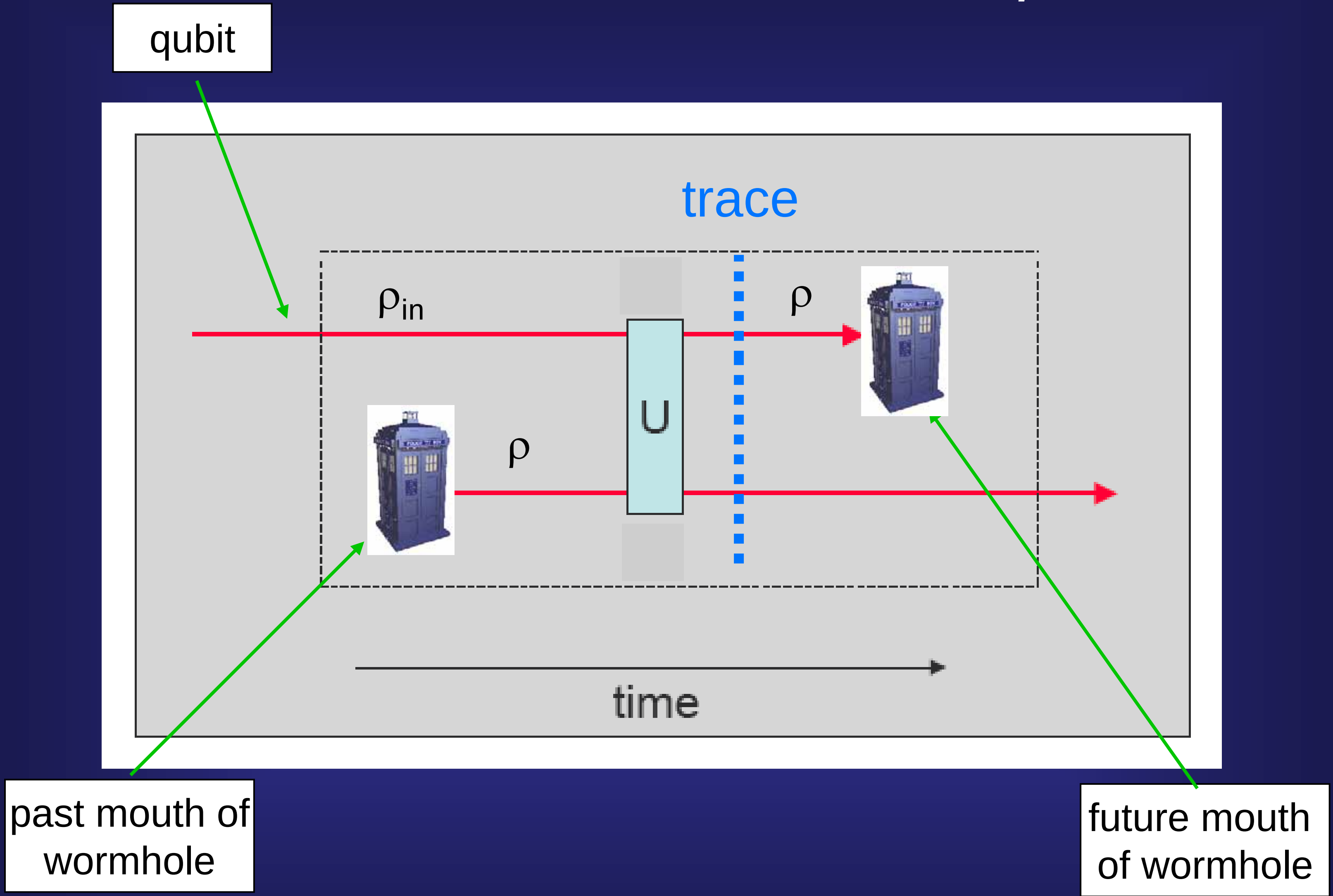

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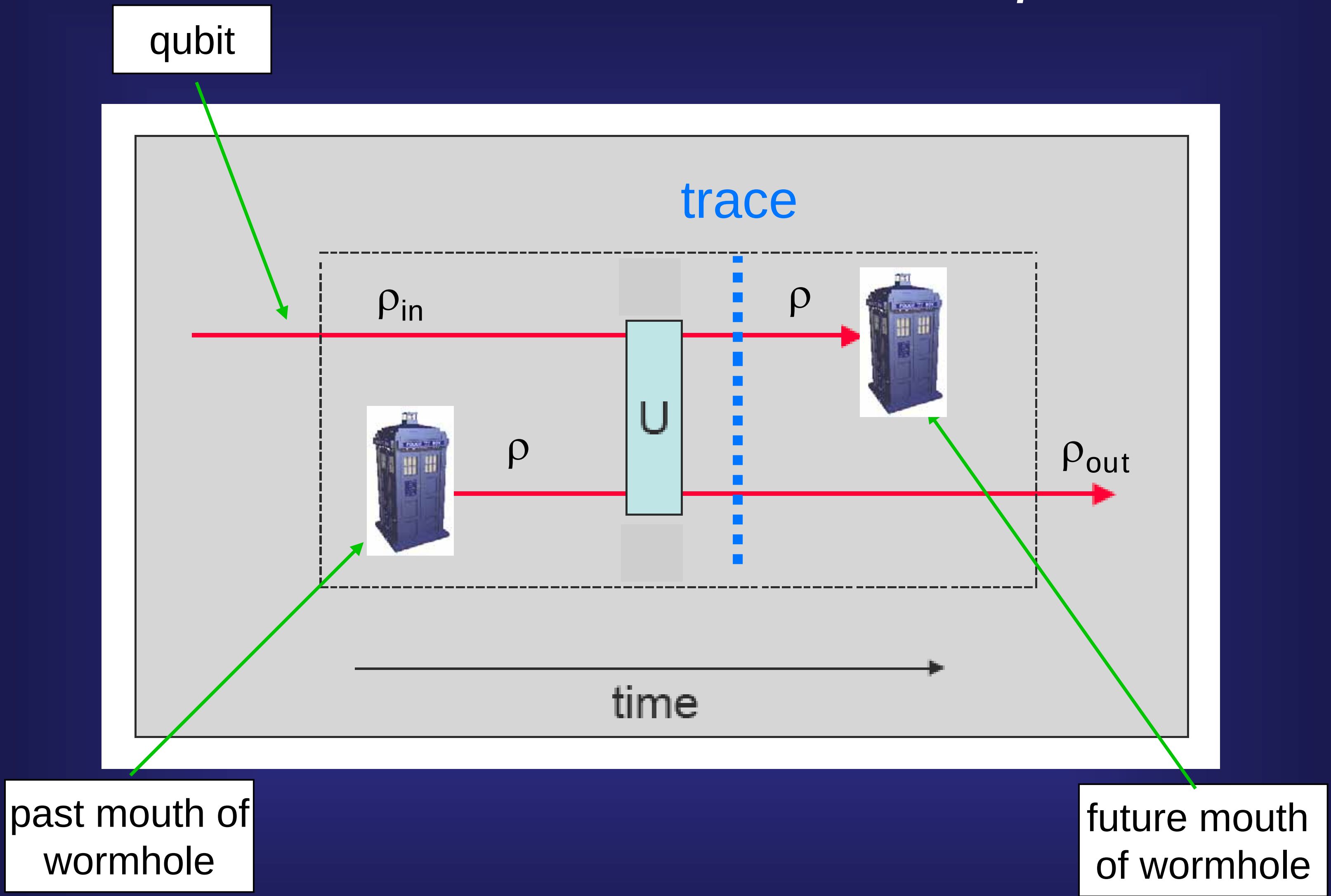

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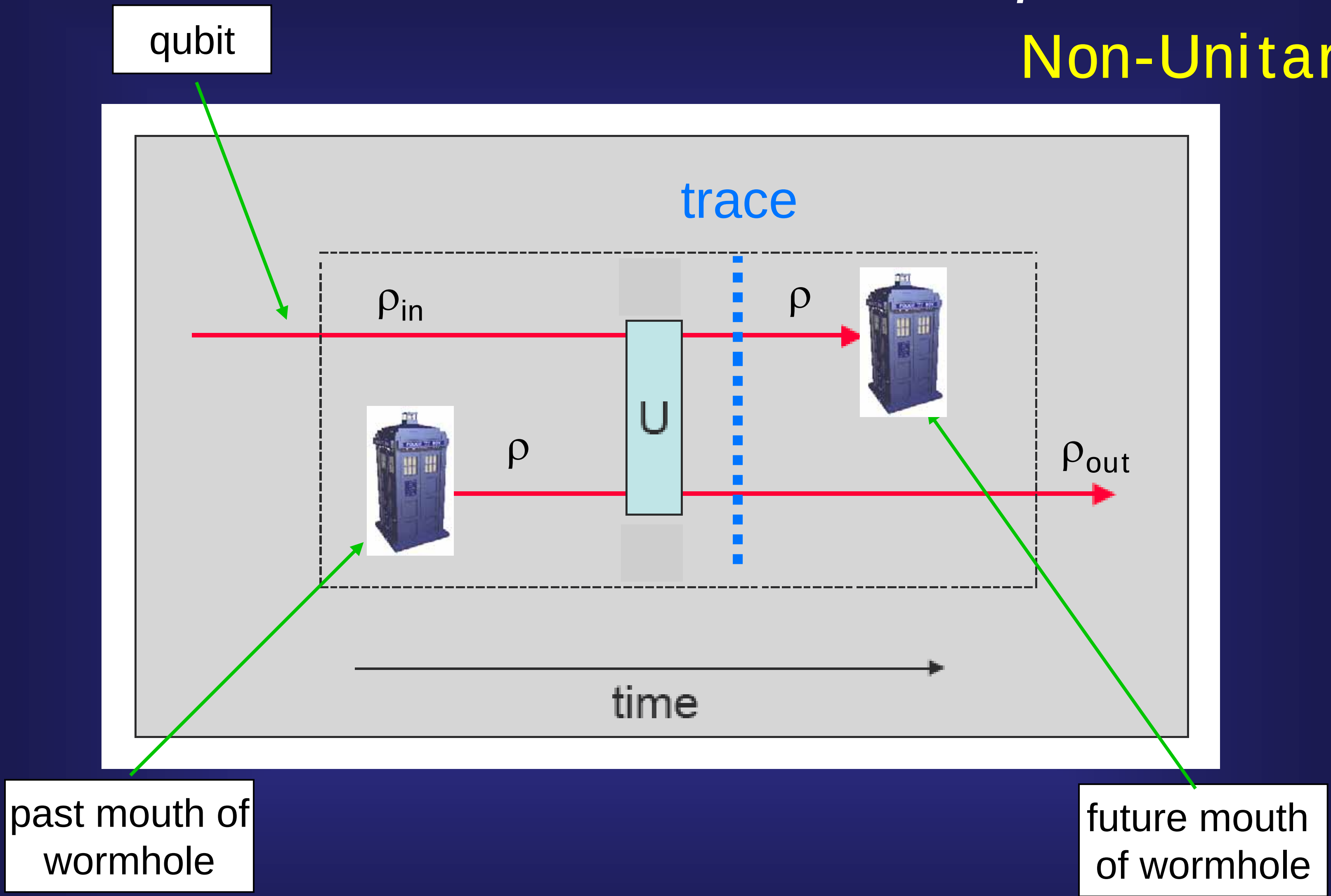
Qubits in the Presence of CTCs

Non-Unitary!



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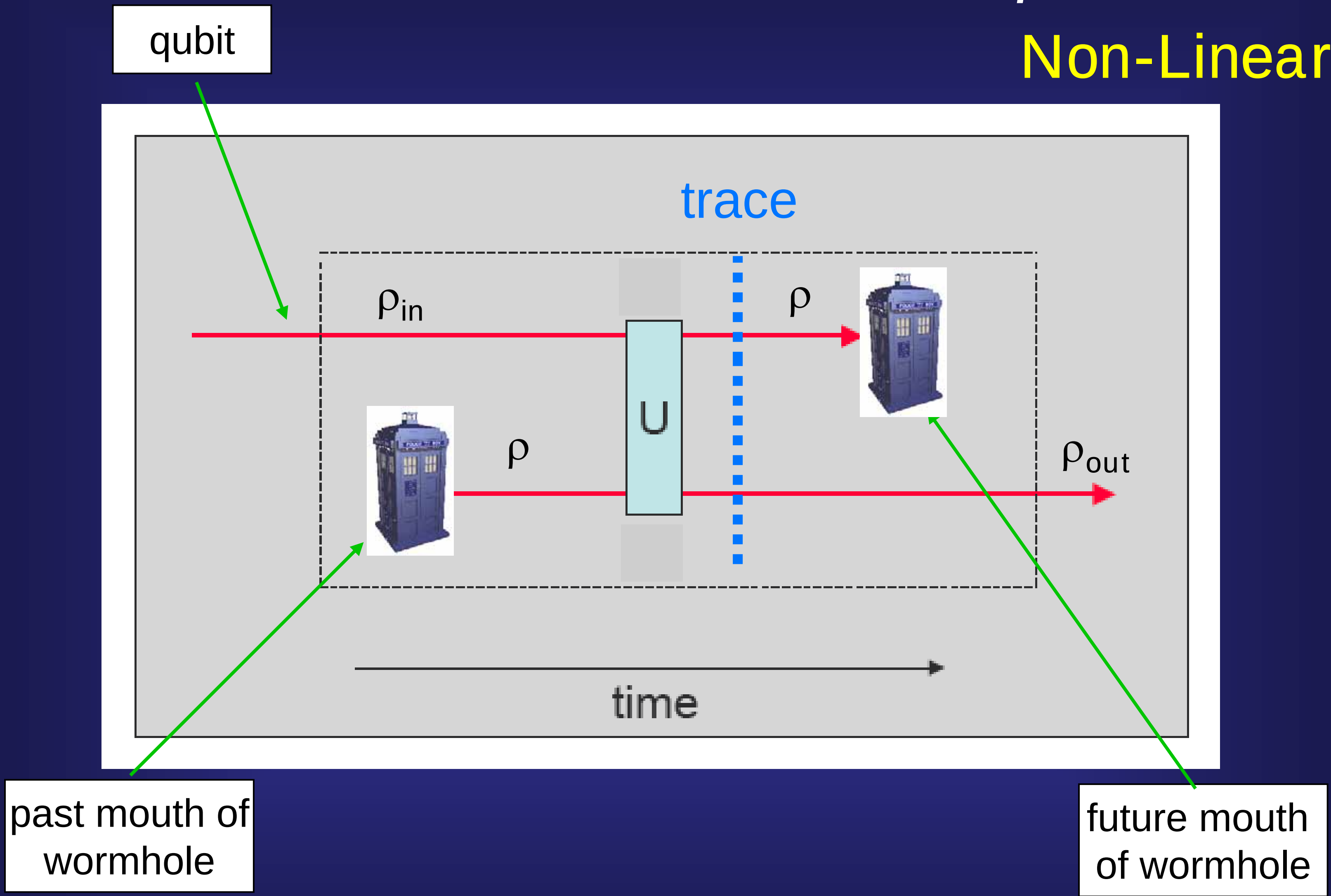
Qubits in the Presence of CTCs

Non-Linear!



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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*
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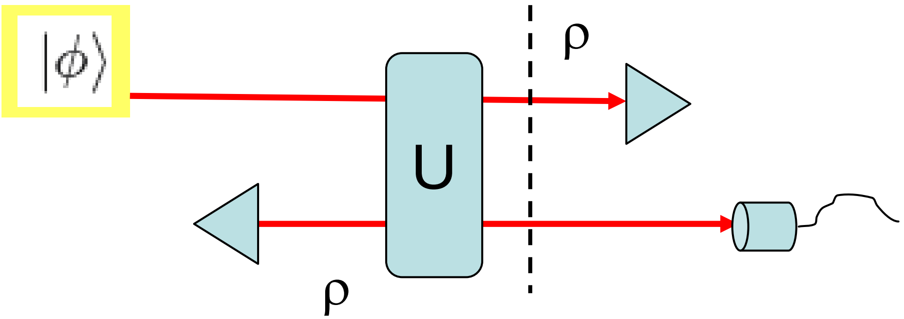
…but all these treatments are non-relativistic (not even dynamic)…

Following the Information Flow



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

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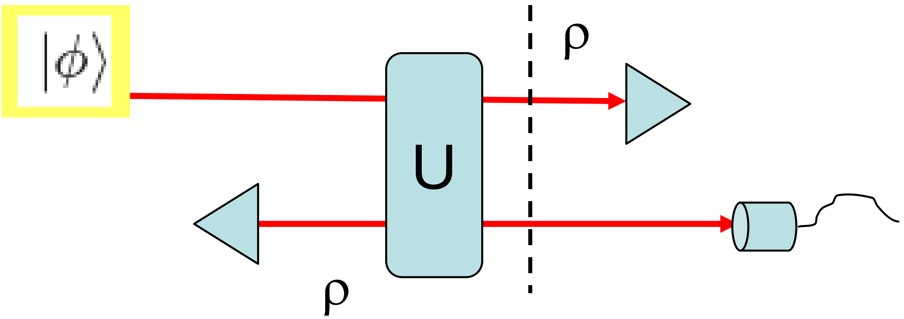

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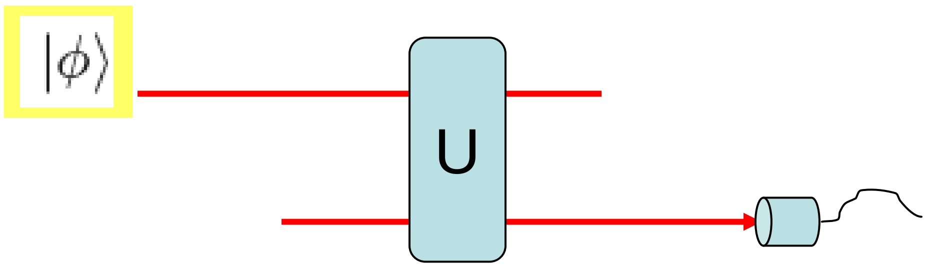

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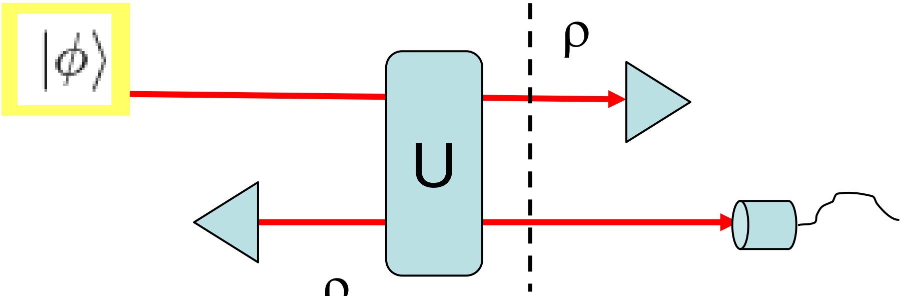

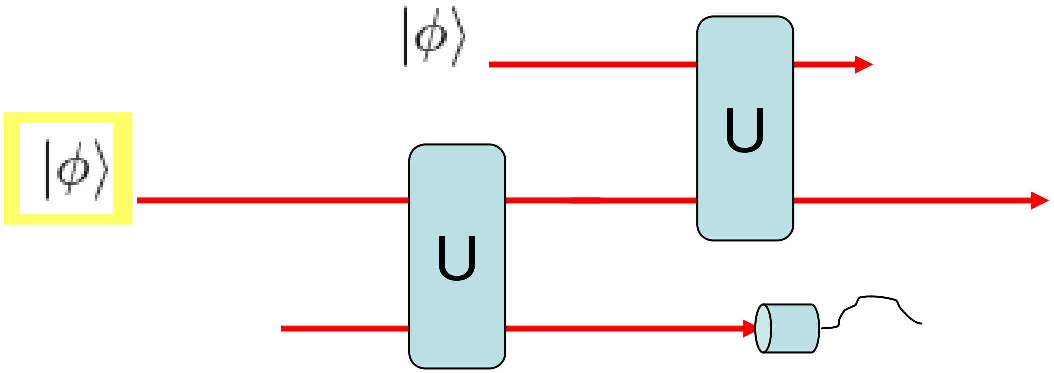

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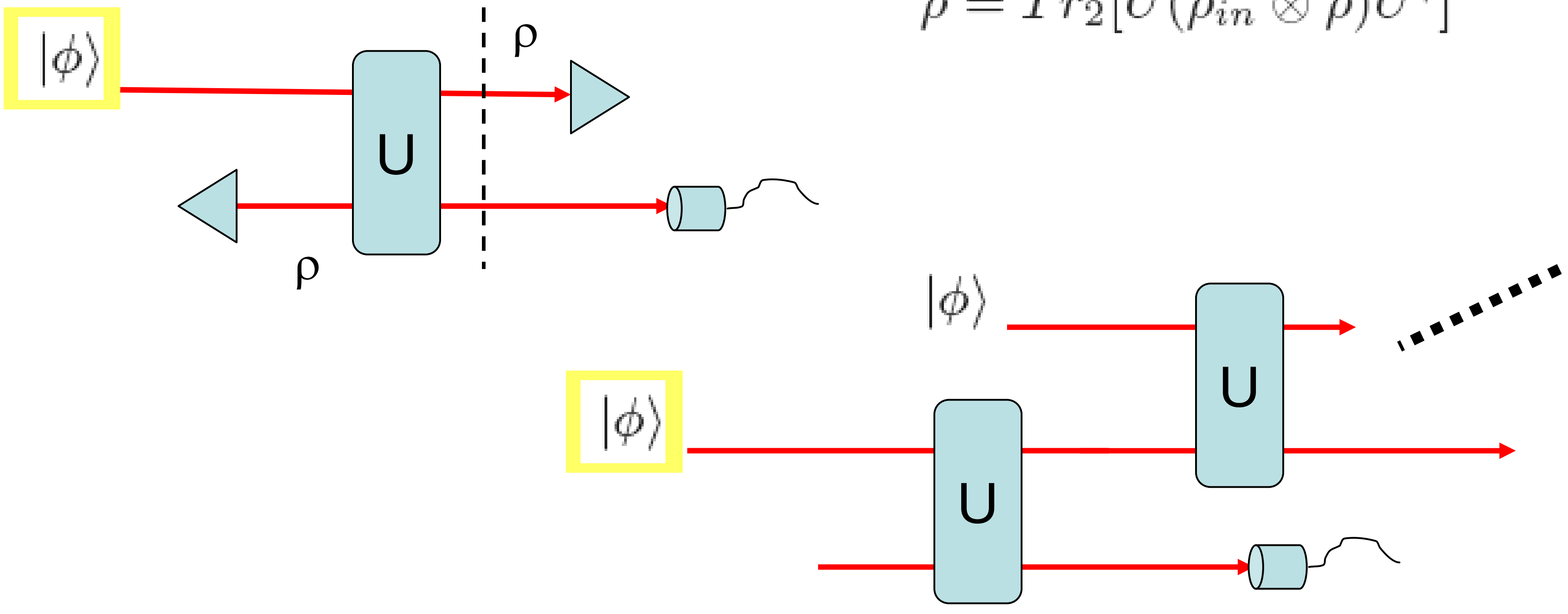

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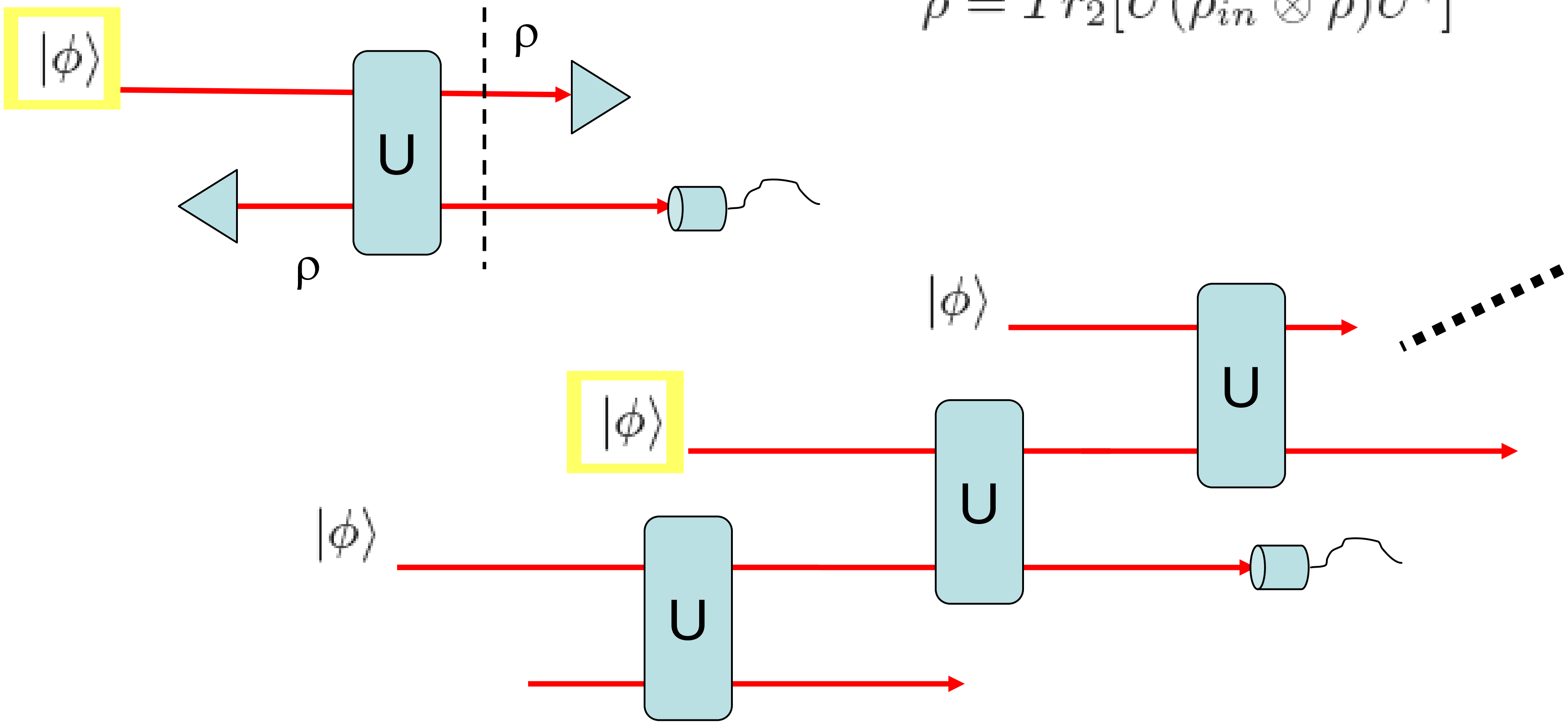
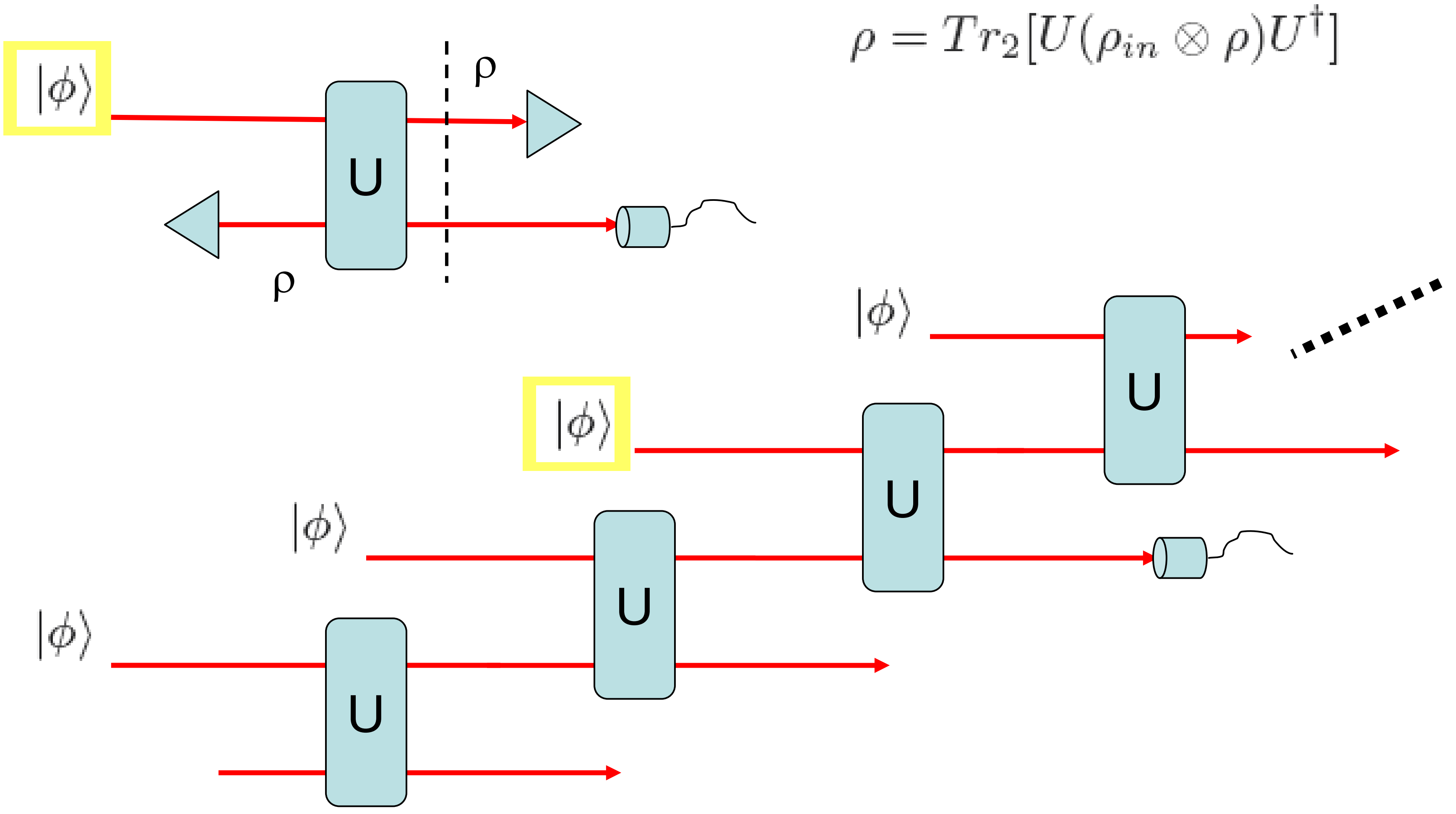


Following the Information Flow



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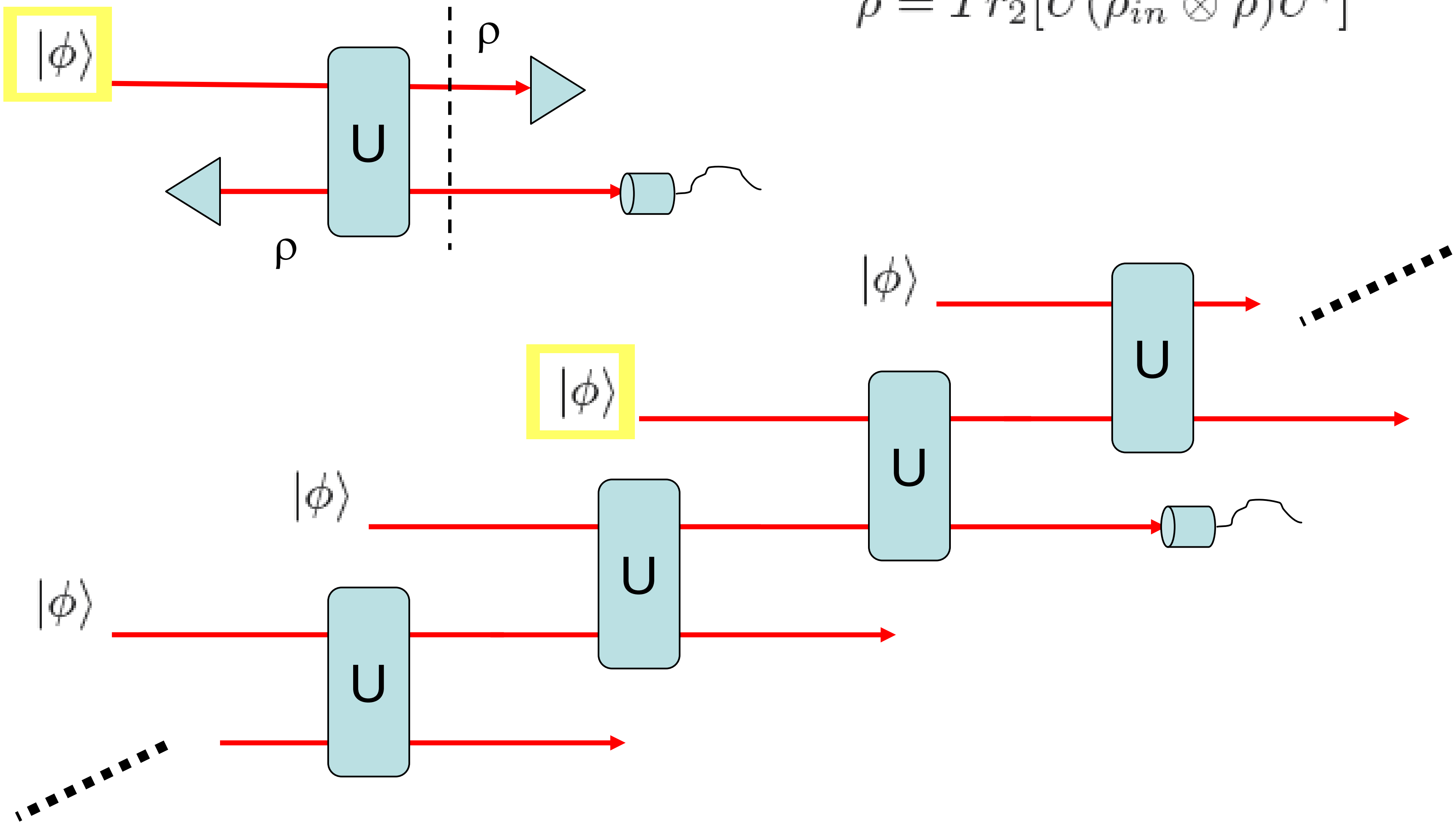

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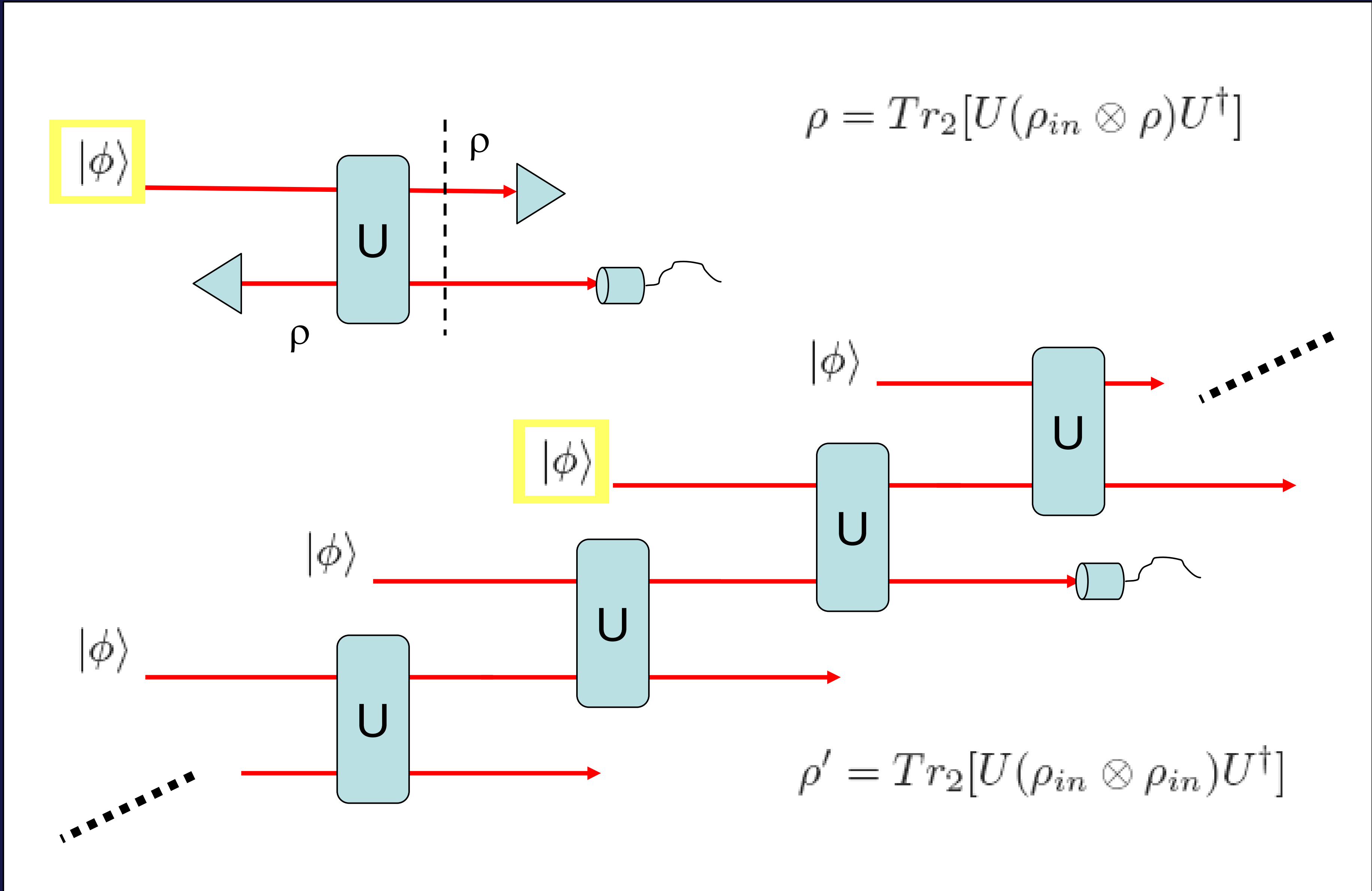

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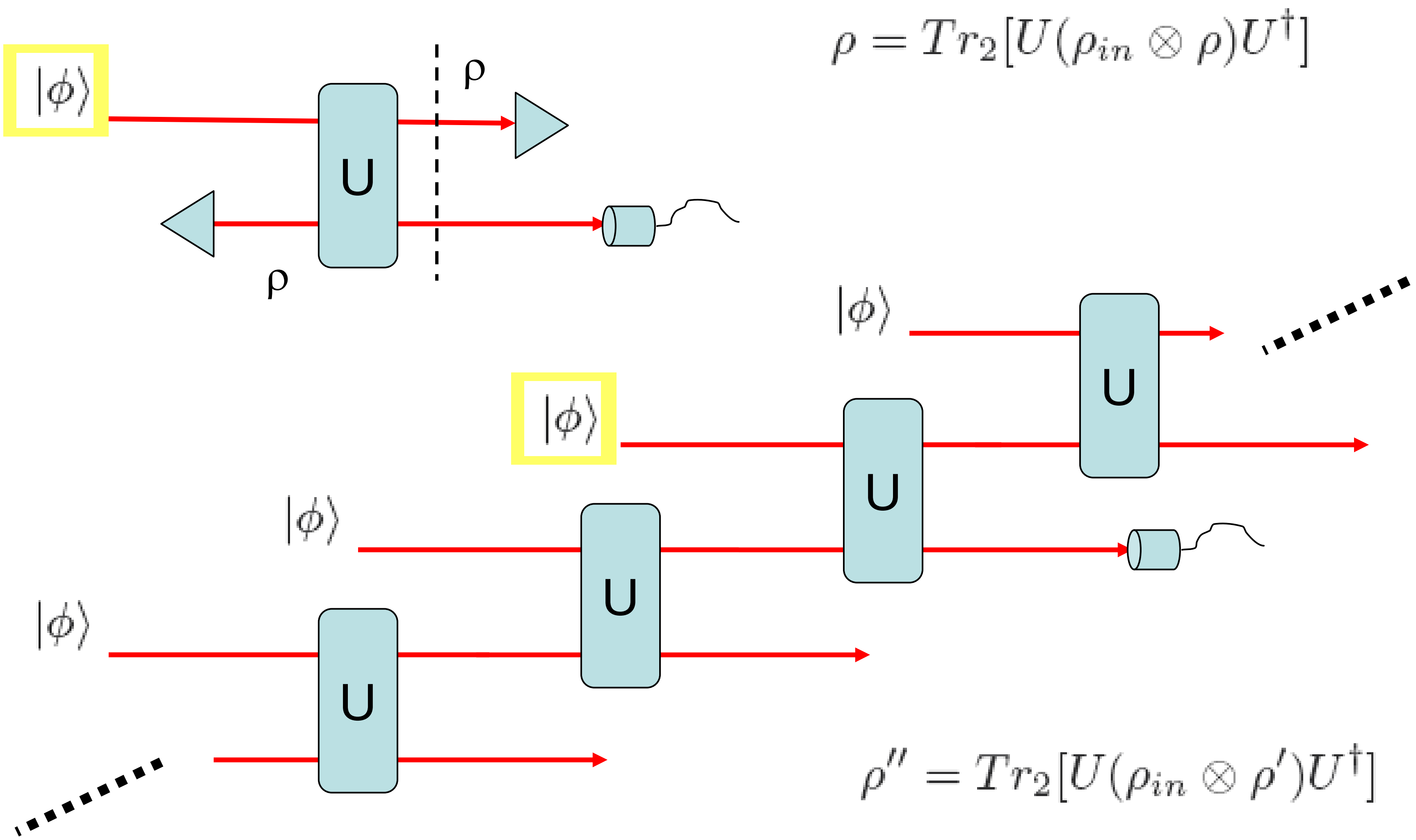

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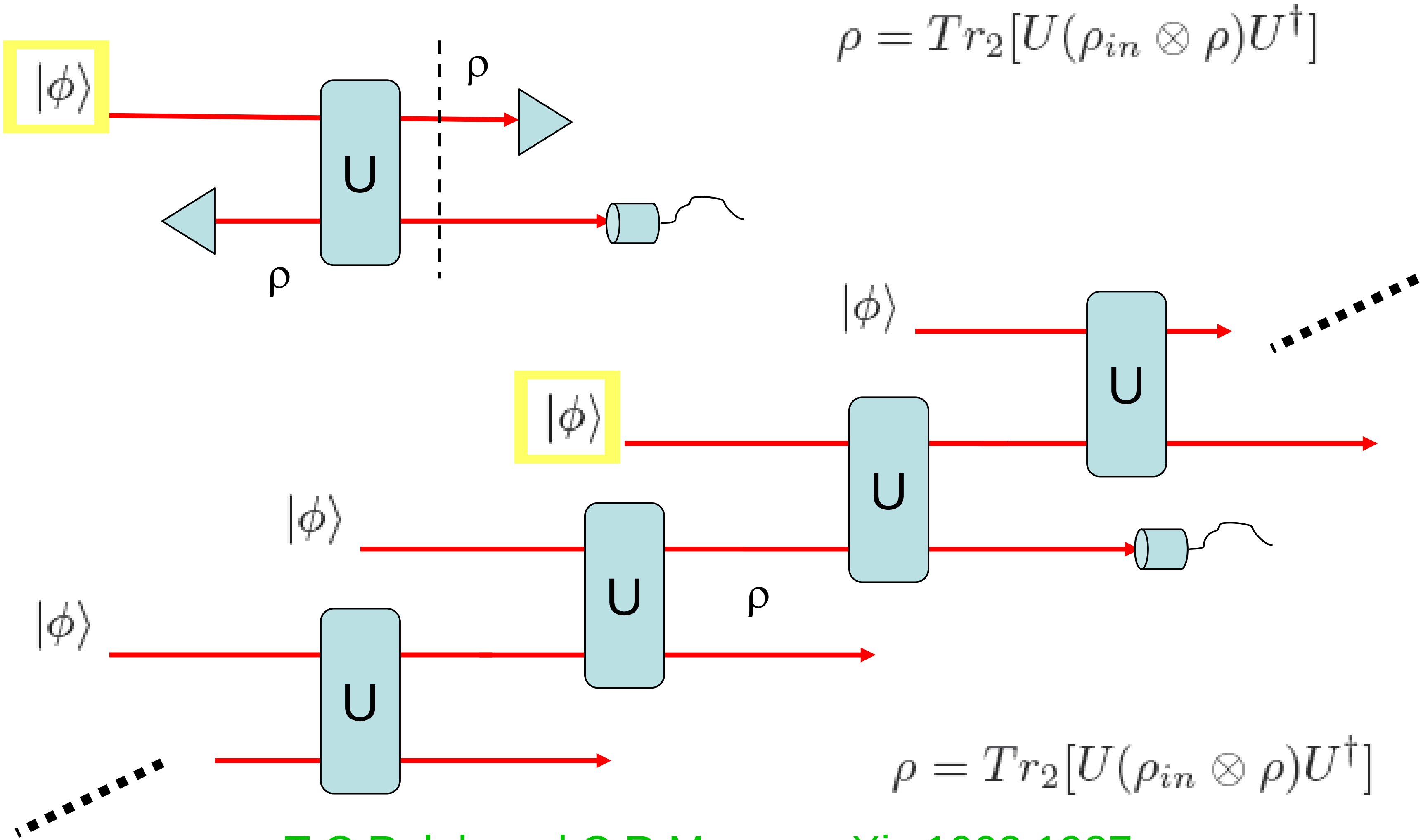
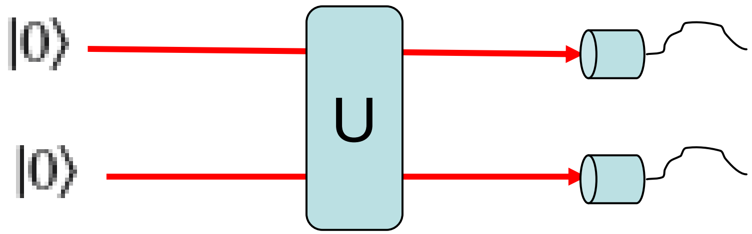


T.C.Ralph and C.R.Myers, arXiv:1003.1987

Space-time Qubits



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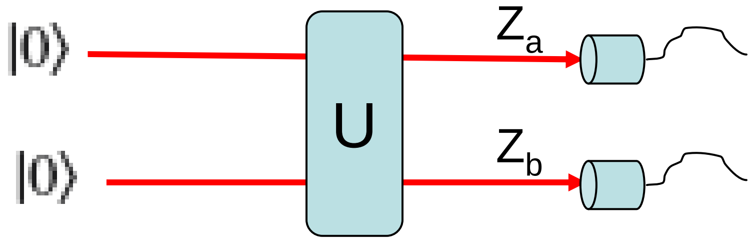

- Heisenberg Picture

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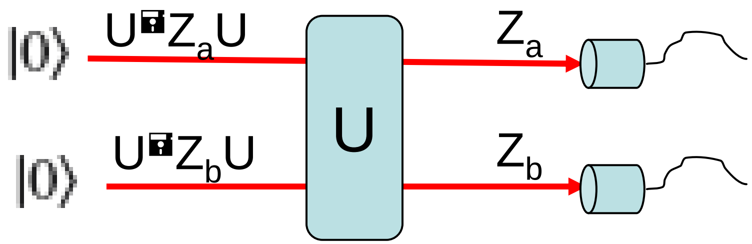

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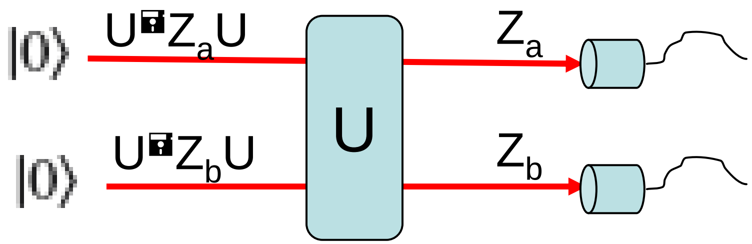

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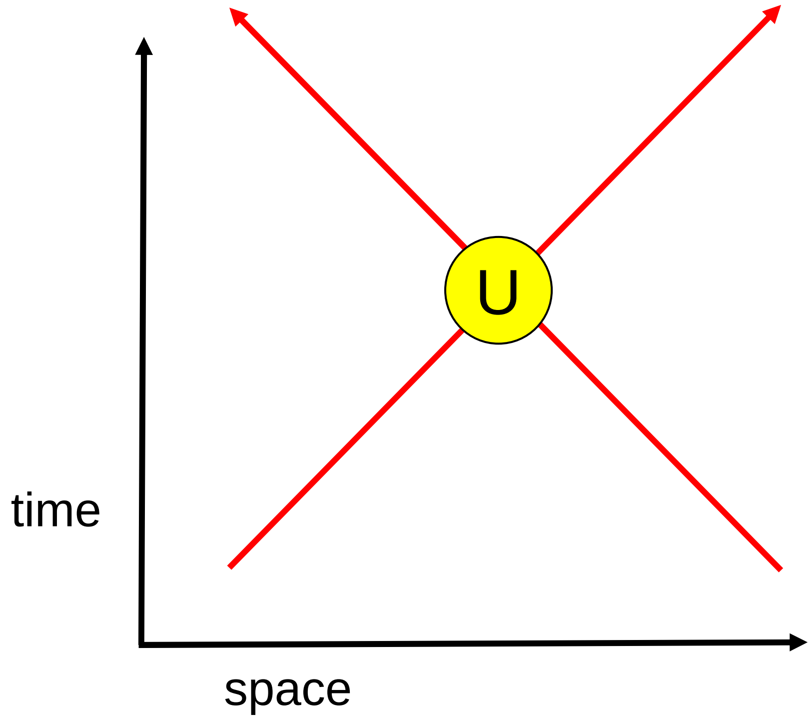

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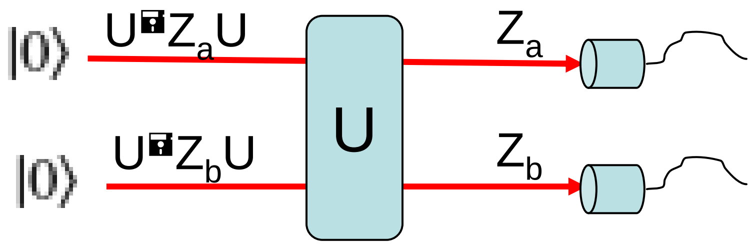

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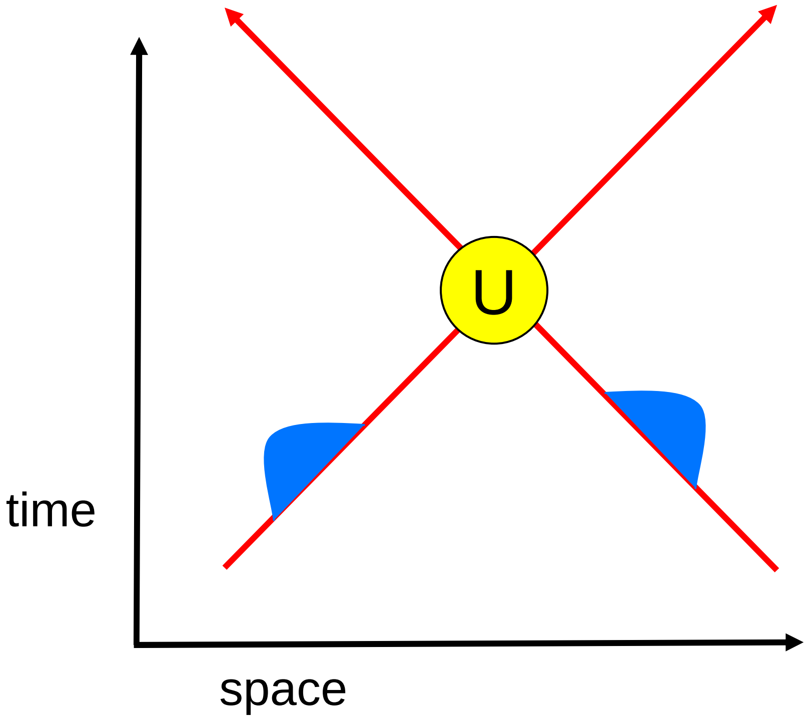

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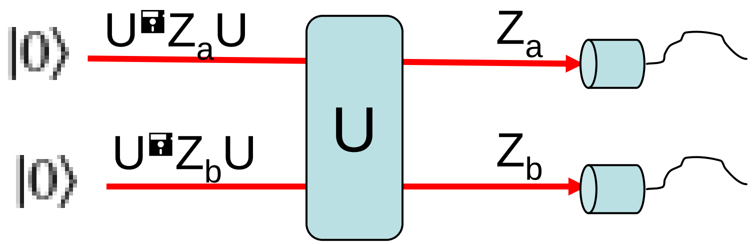
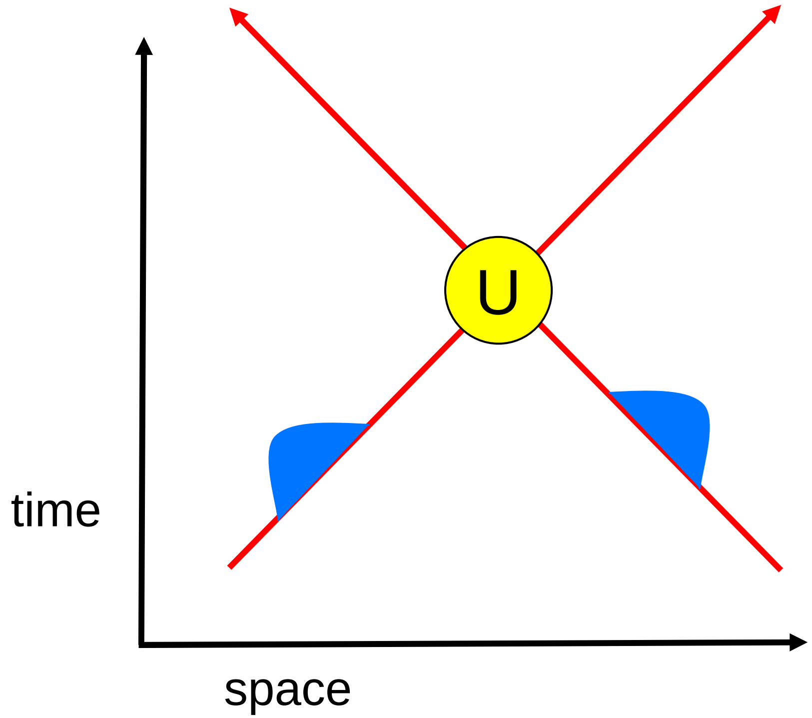
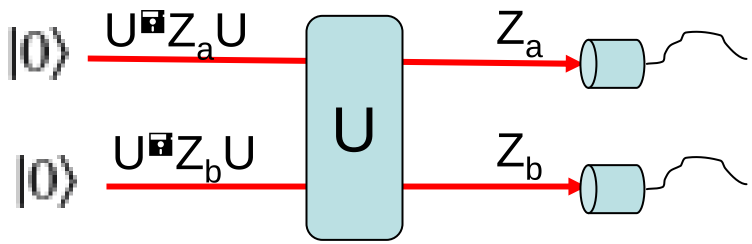


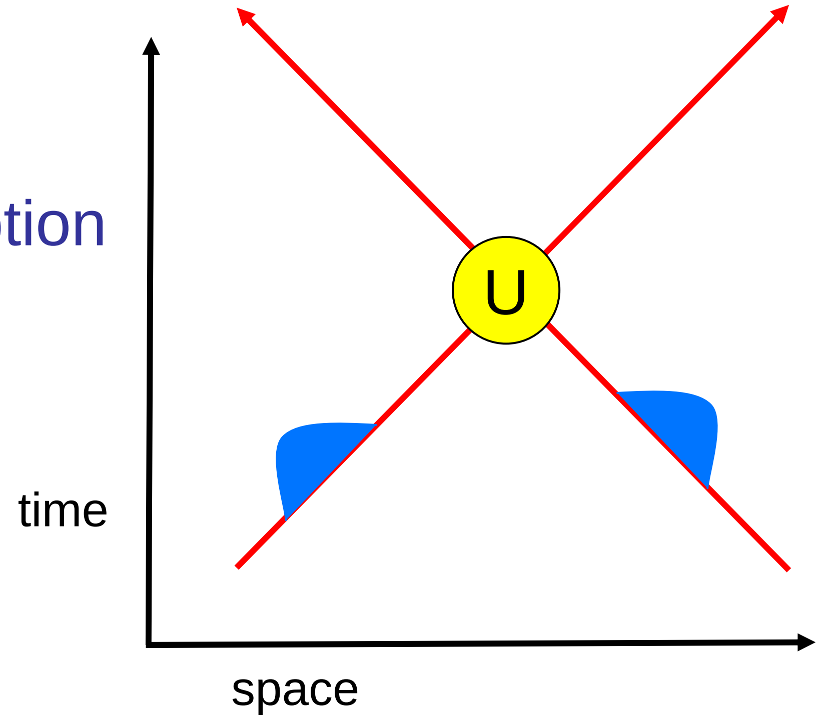
- Heisenberg Picture
- Field ground-state



Space-time Qubits



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



Space-time Qubits

2-tier approach

$$|0\rangle = |vacuum\rangle \qquad |1\rangle = |1st\ excited\rangle$$

Space-time Qubits

2-tier approach

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Field Pauli's: $Z = 1 - 2a^\dagger a \qquad X = a^\dagger(1 - a^\dagger a) + (1 - a^\dagger a)a$

$$Y = i(a^\dagger(1 - a^\dagger a) - (1 - a^\dagger a)a)$$

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$$|0\rangle = |0\rangle_1|1\rangle_2 \qquad |1\rangle = |1\rangle_1|0\rangle_2$$

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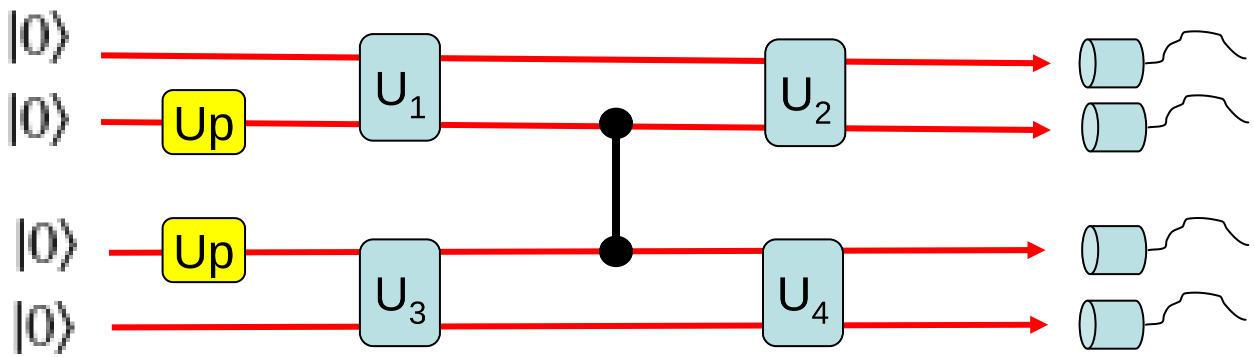
Particle Pauli's: $\mathbf{Z} = Z_1 \qquad \mathbf{X} = X_1 X_2 \qquad \mathbf{Y} = Y_1 X_2$

Heisenberg evolution of single particle production

$$\hat{a}_{out}(k) = \sum_{j=1}^{N} \hat{n}_{b_j} \hat{a}_j(k) \prod_{i=0}^{j-1} (1 - \hat{n}_{b_i}) + \hat{c}\hat{u}$$

Space-time Qubits

2-tier approach:



Space-time Qubits

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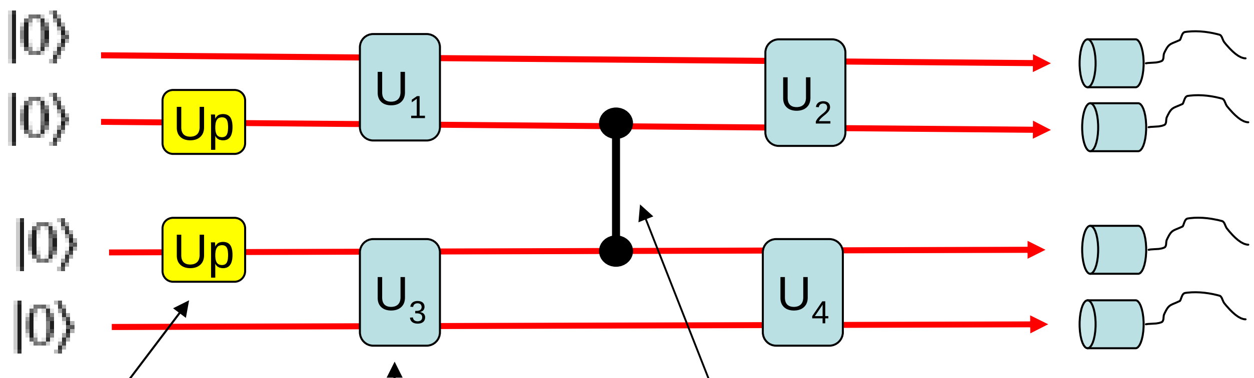


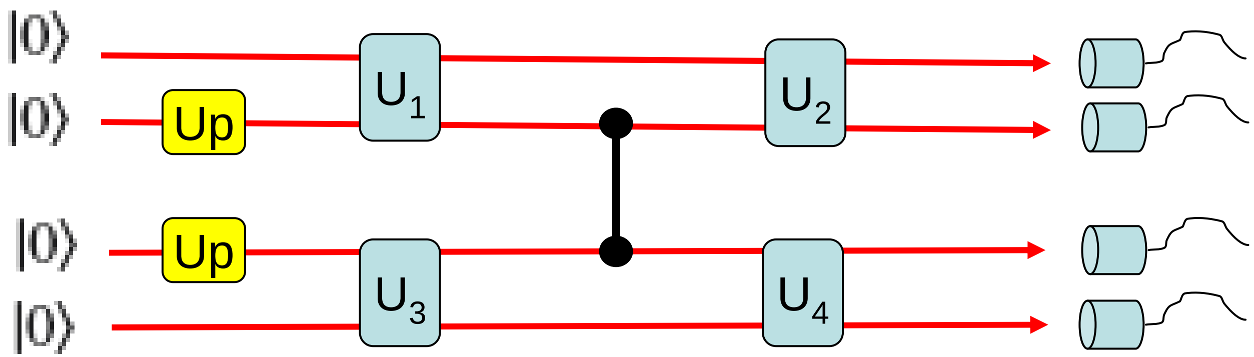
field mode unitary for particle production

particle Pauli unitary for particle state manipulation

field Pauli CS unitary for particle state interaction

Space-time Qubits

2-tier approach:



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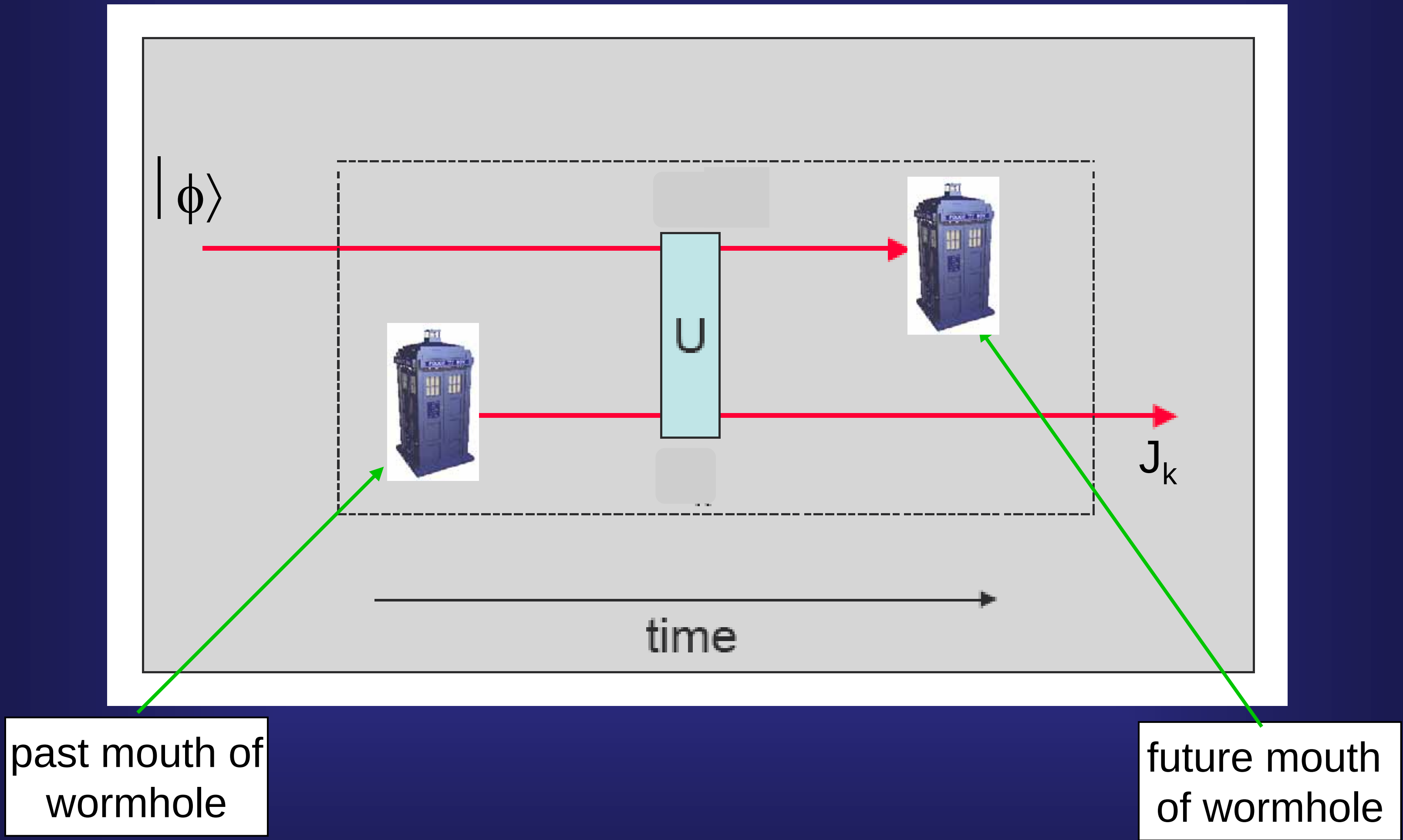
CTCs in the Heisenberg Picture



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

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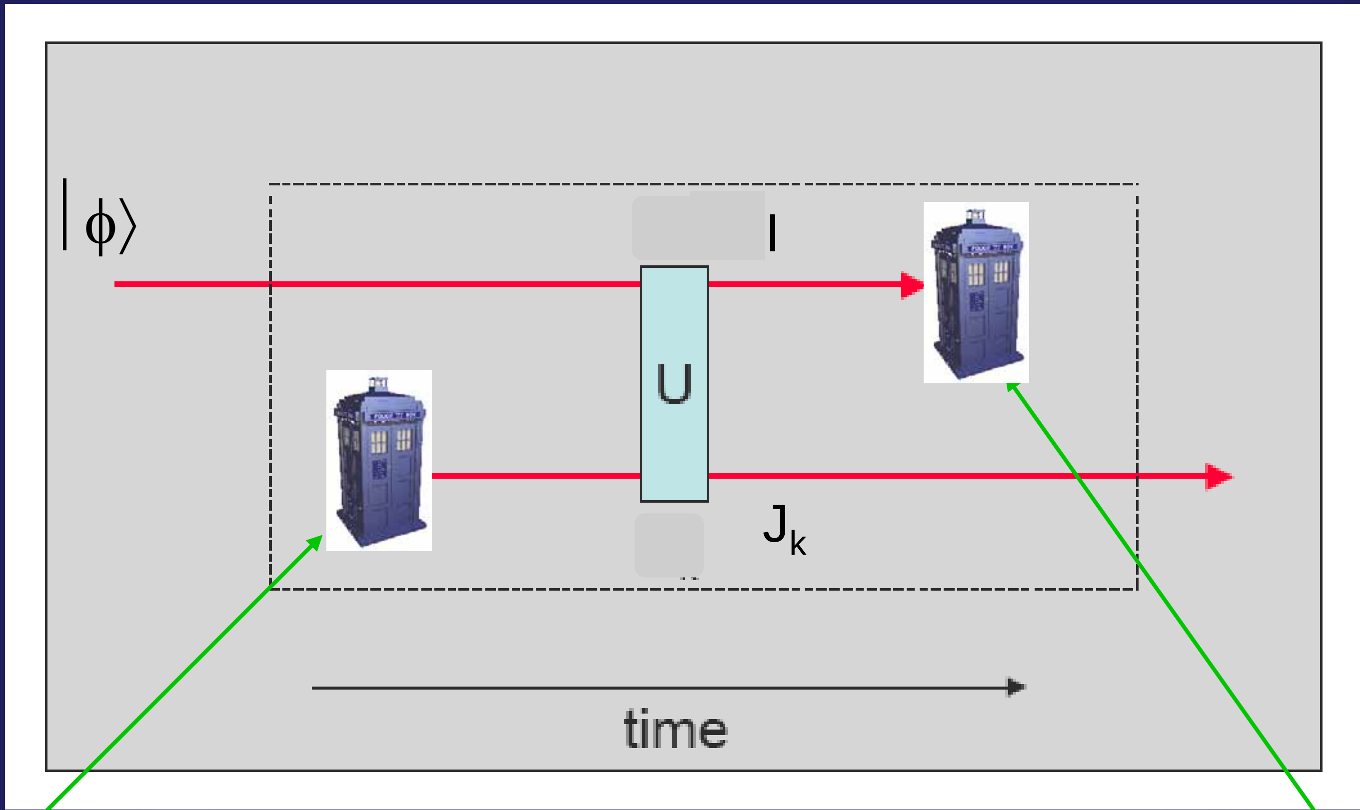

past mouth of wormhole

future mouth of wormhole

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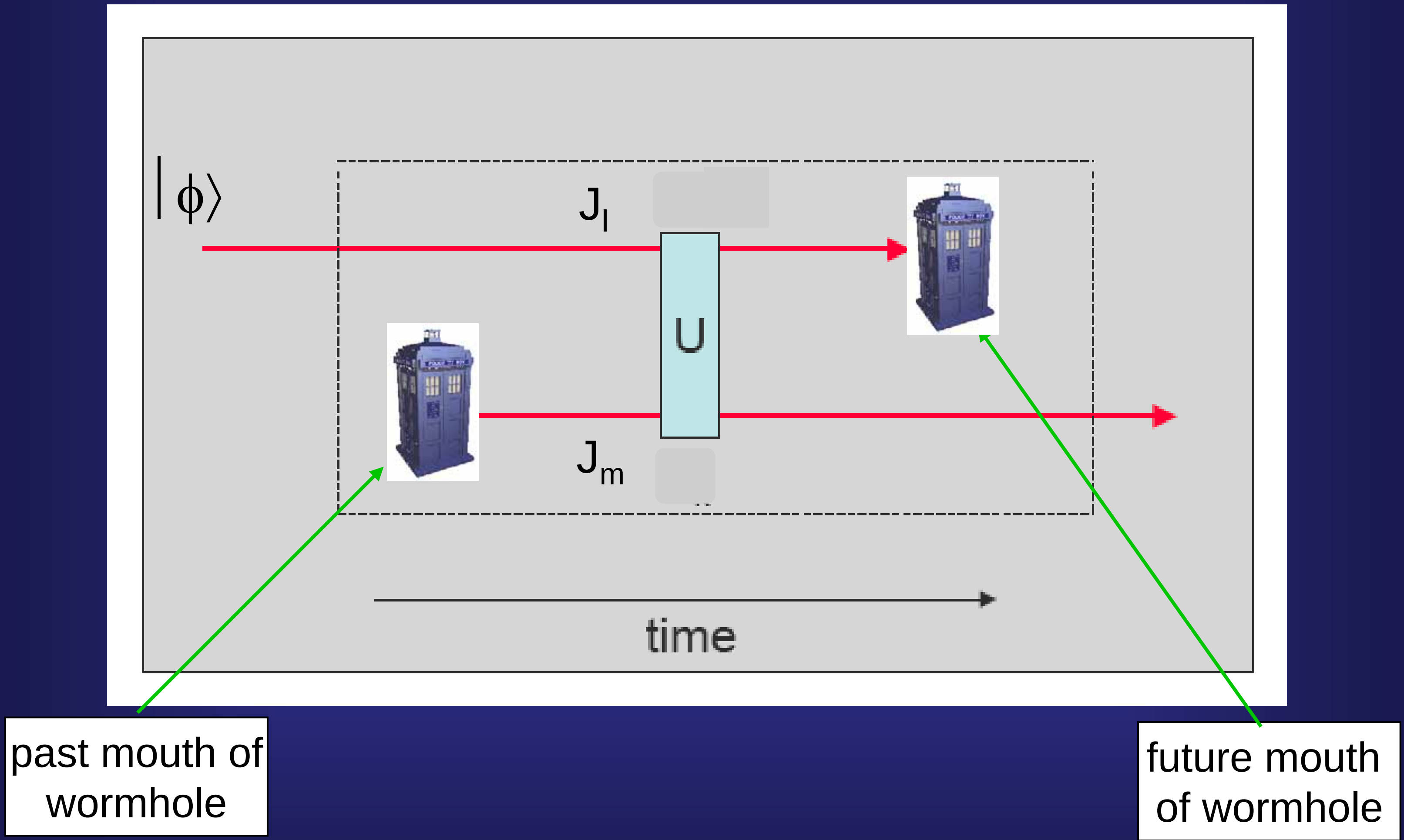
CTCs in the Heisenberg Picture



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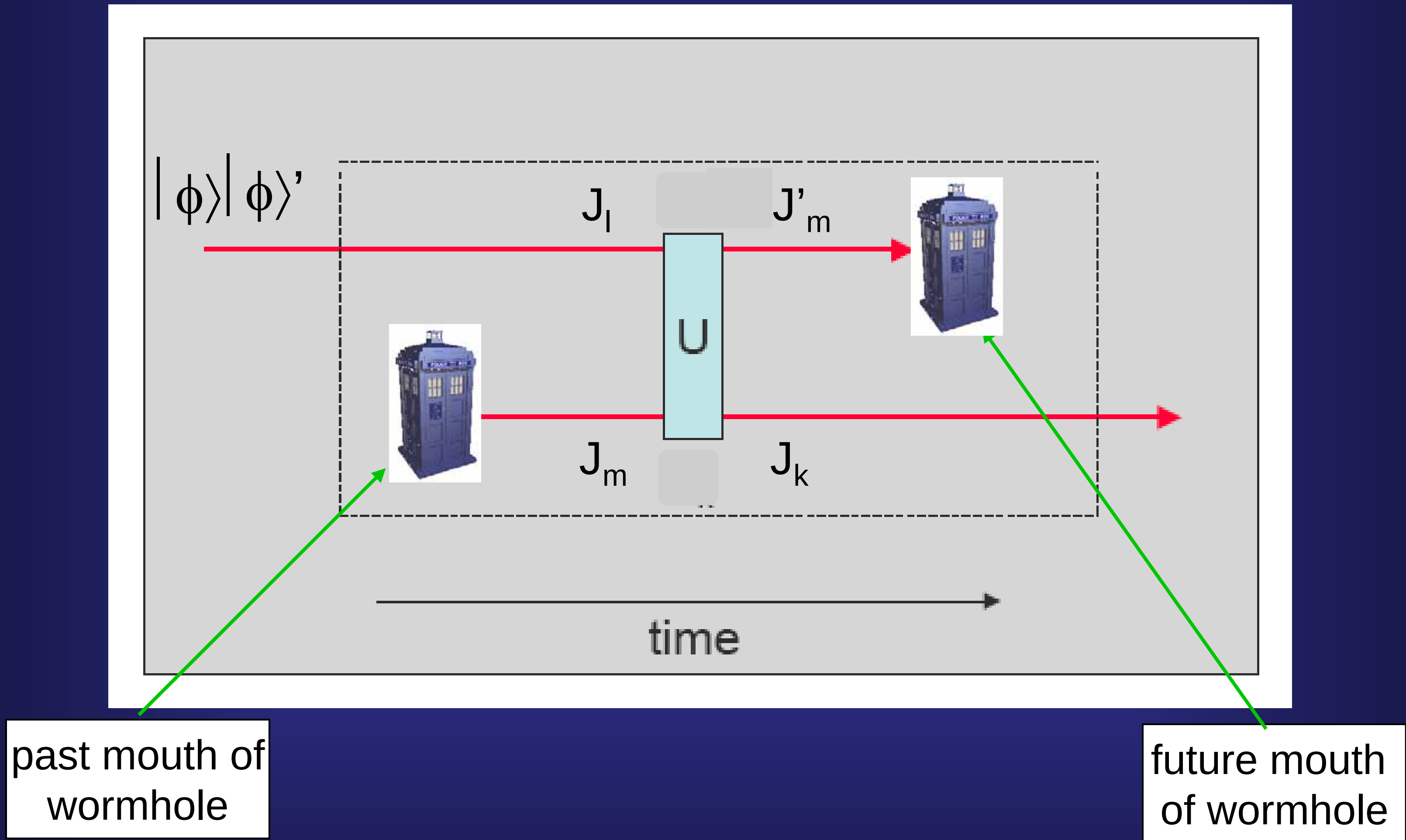

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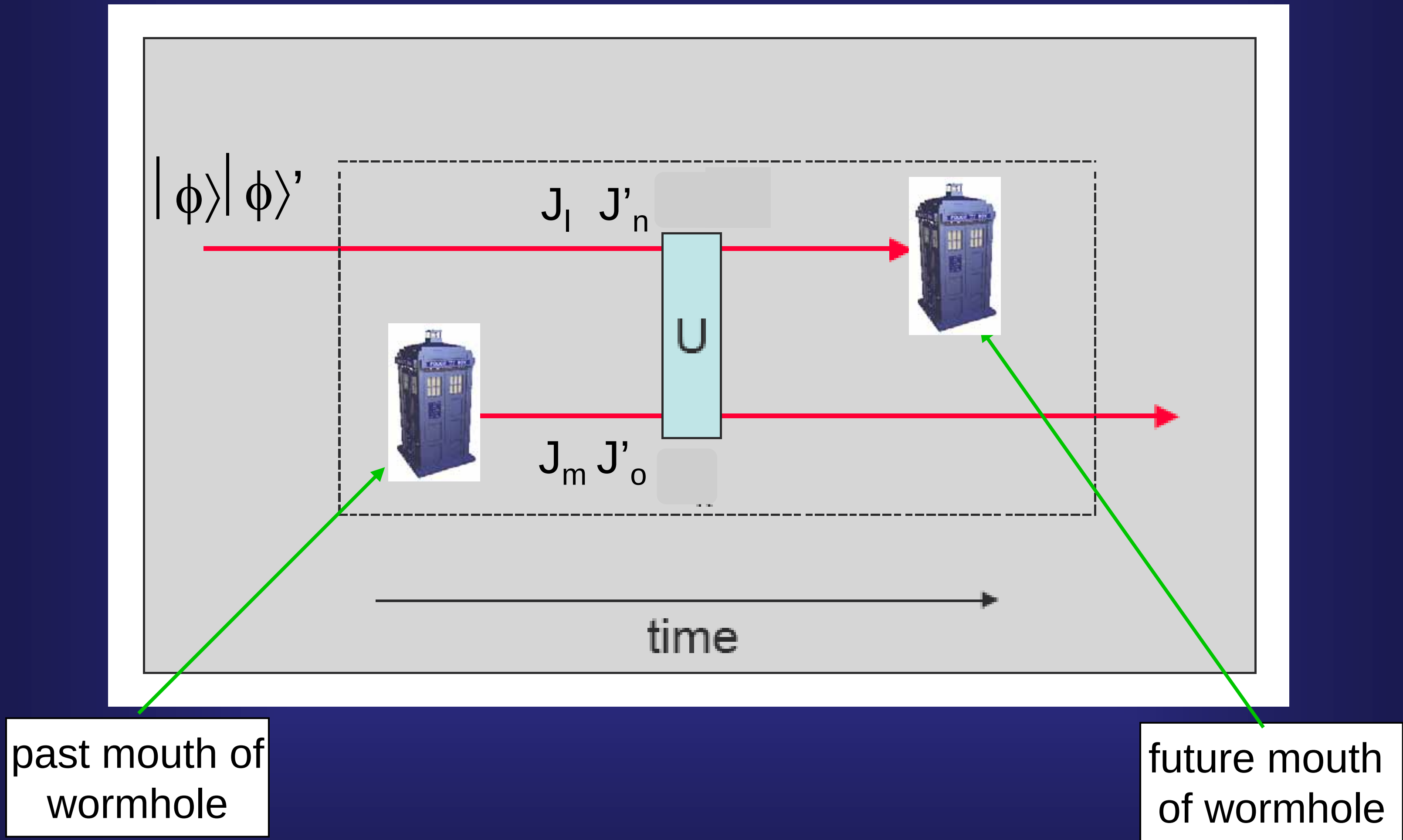

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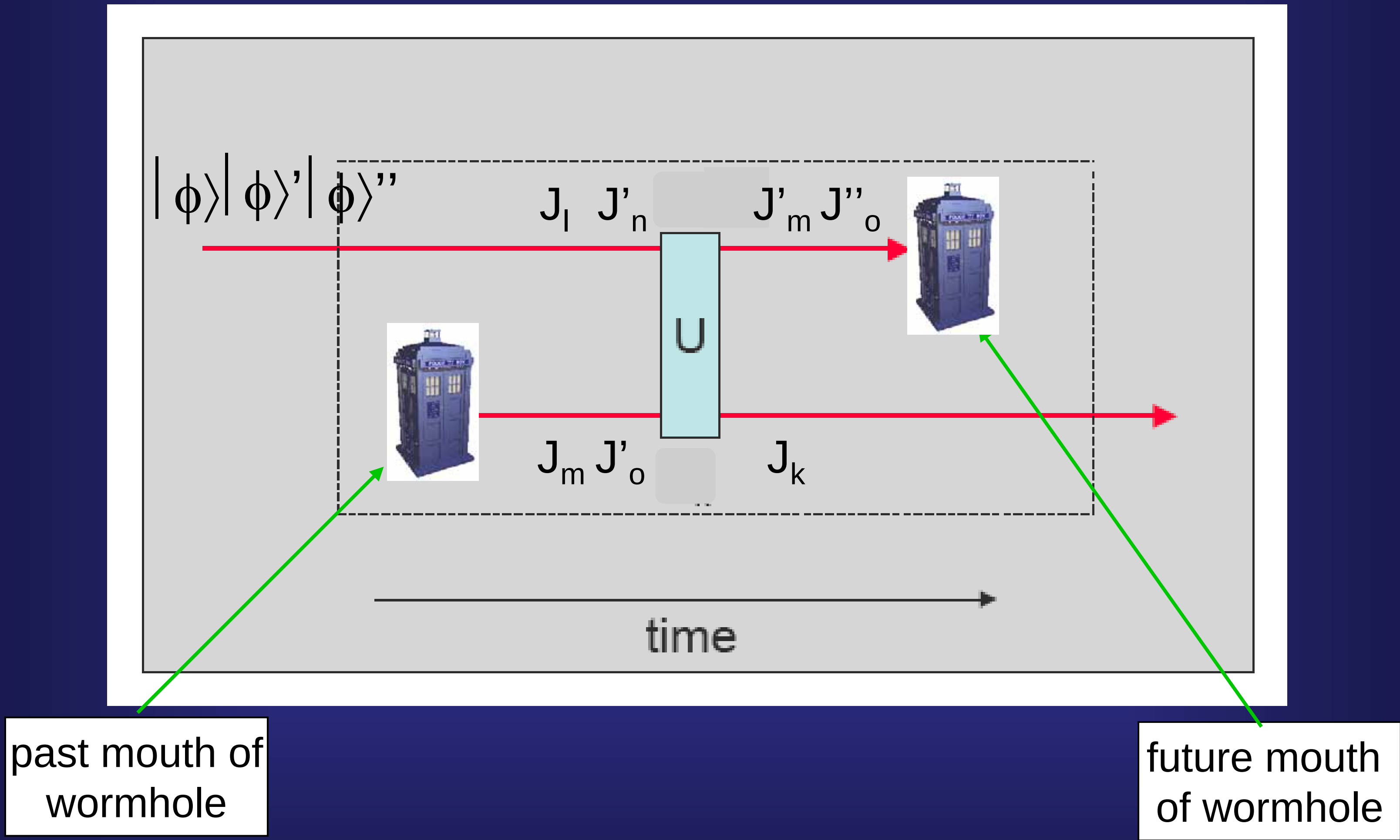

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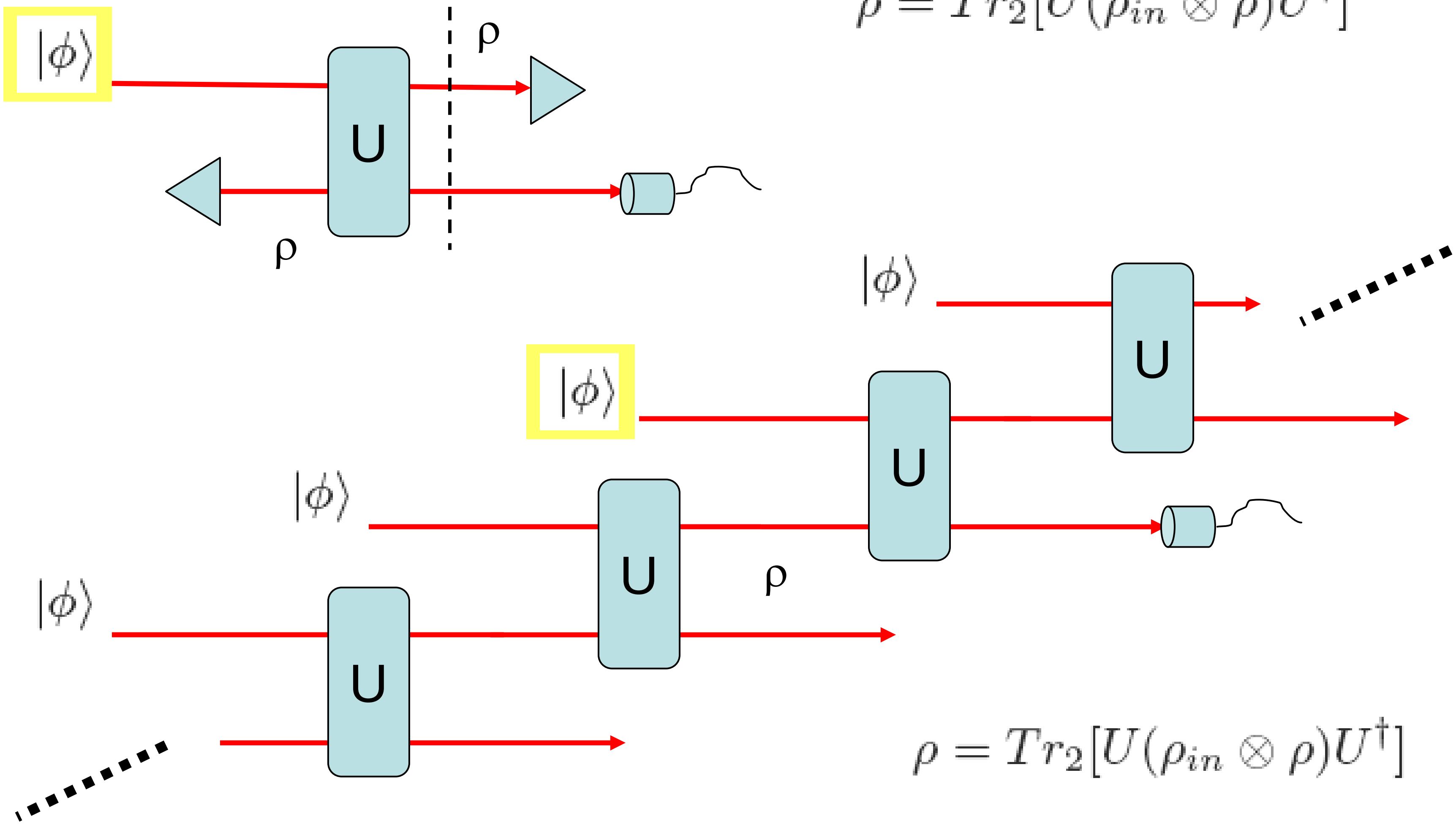
CTCs equivalent circuit



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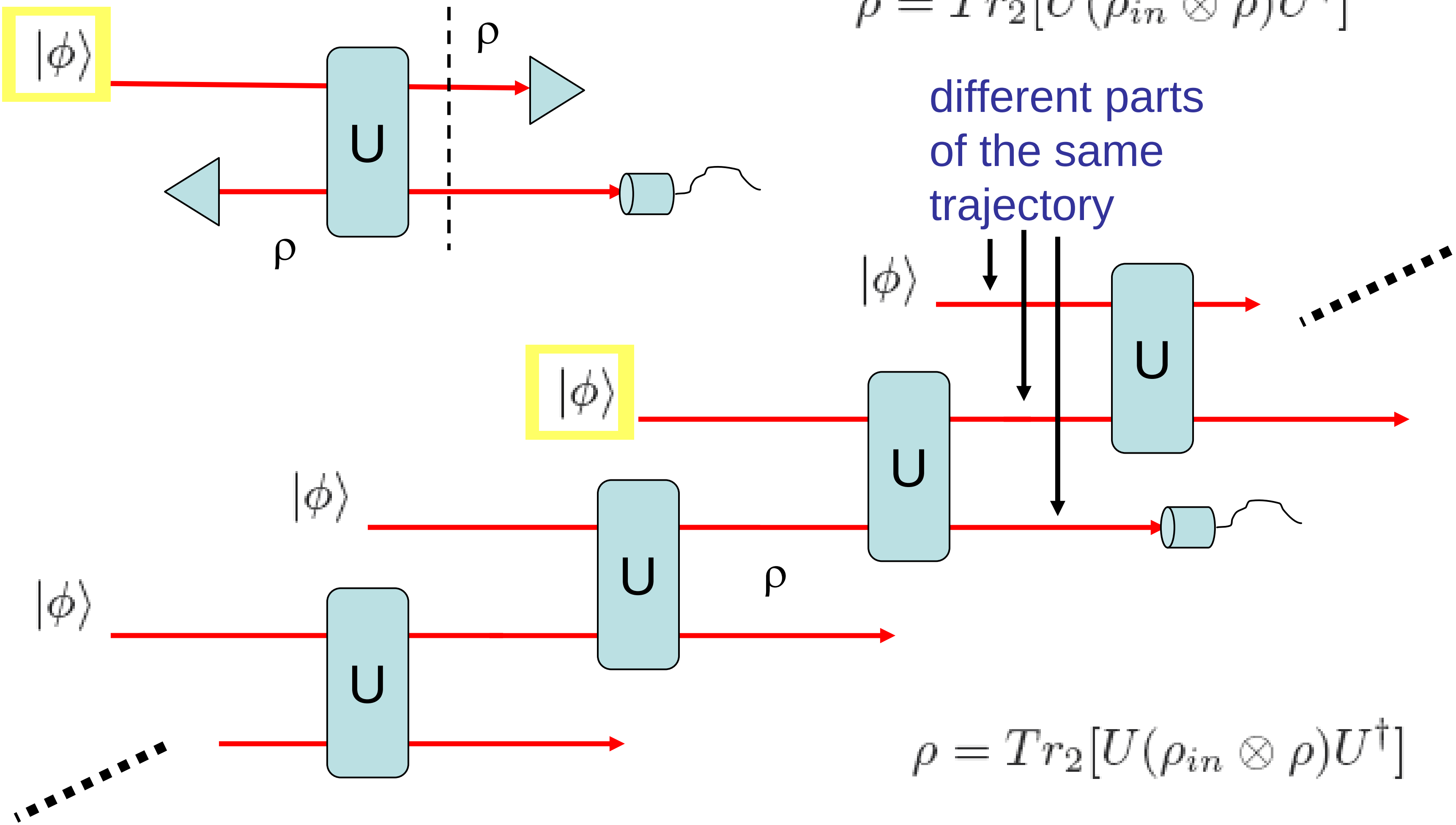

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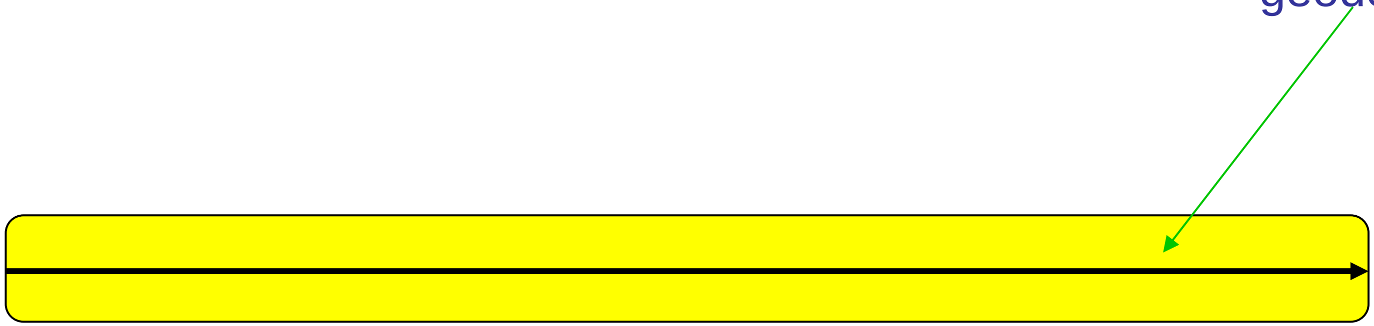
Mode operators

mode operators in quantum optics

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

$$[\hat{a}(t,x_1), \hat{a}(t,x_2)^\dagger] = \int dk |G(k)|^2 e^{ik(x_1-x_2)}$$

geodesic



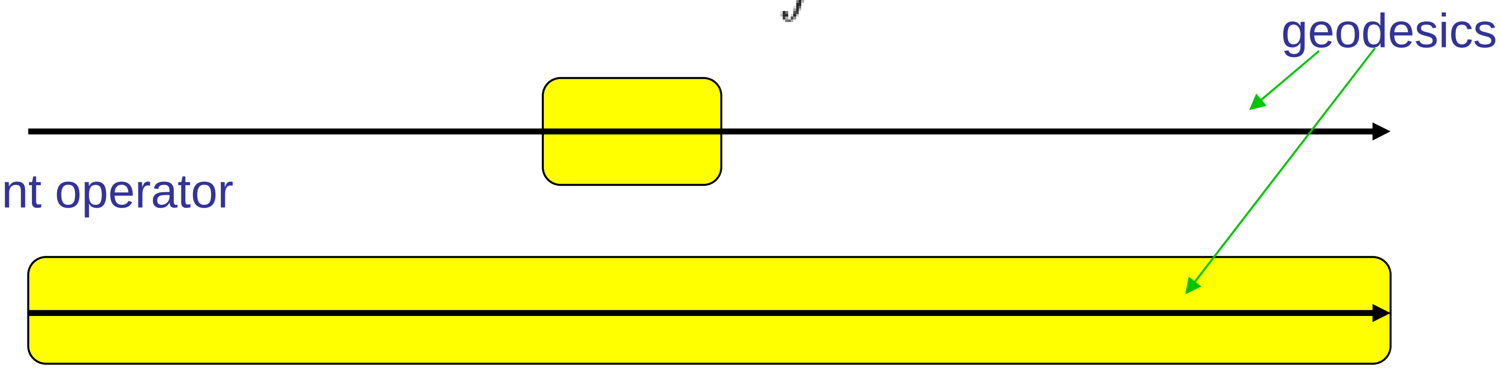
mode operator

Event operators

event operator

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

$$[\hat{a}_{t,x}, \hat{a}^\dagger_{t,x'}] \neq [\bar{a}_{t,x}, \bar{a}^\dagger_{t,x'}] \neq \int dk |G(k)|^2 e^{ik(x-x')}$$



event operator

mode operator

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

Event operators

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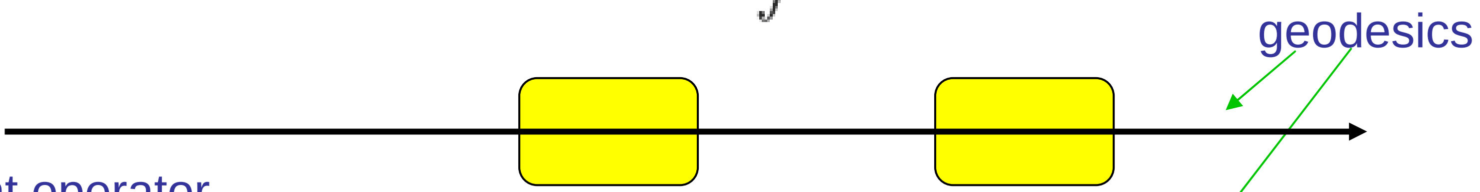

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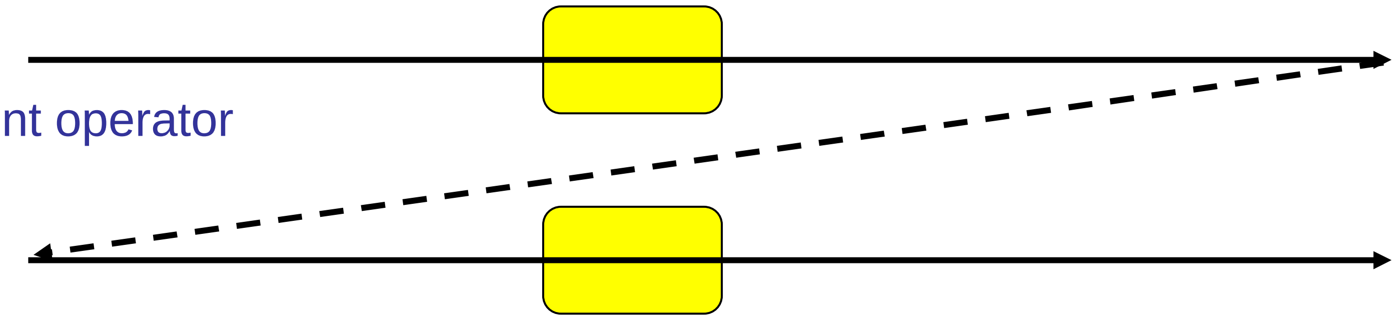

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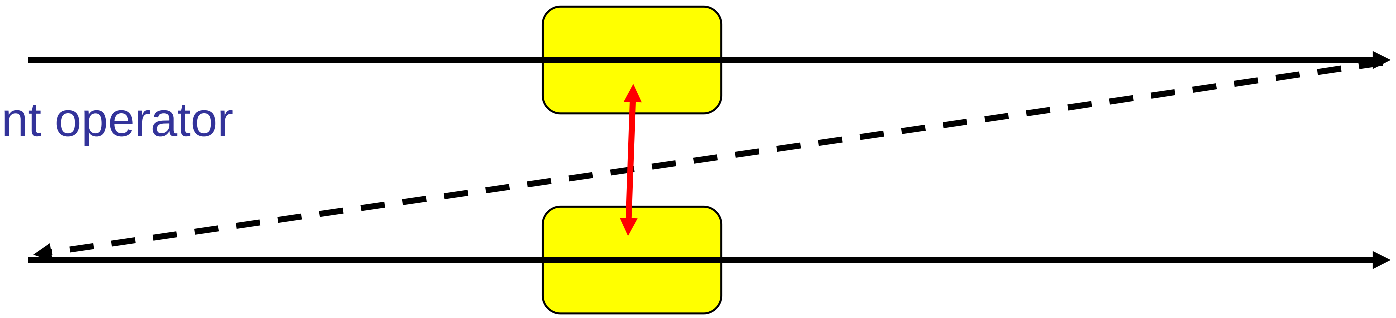

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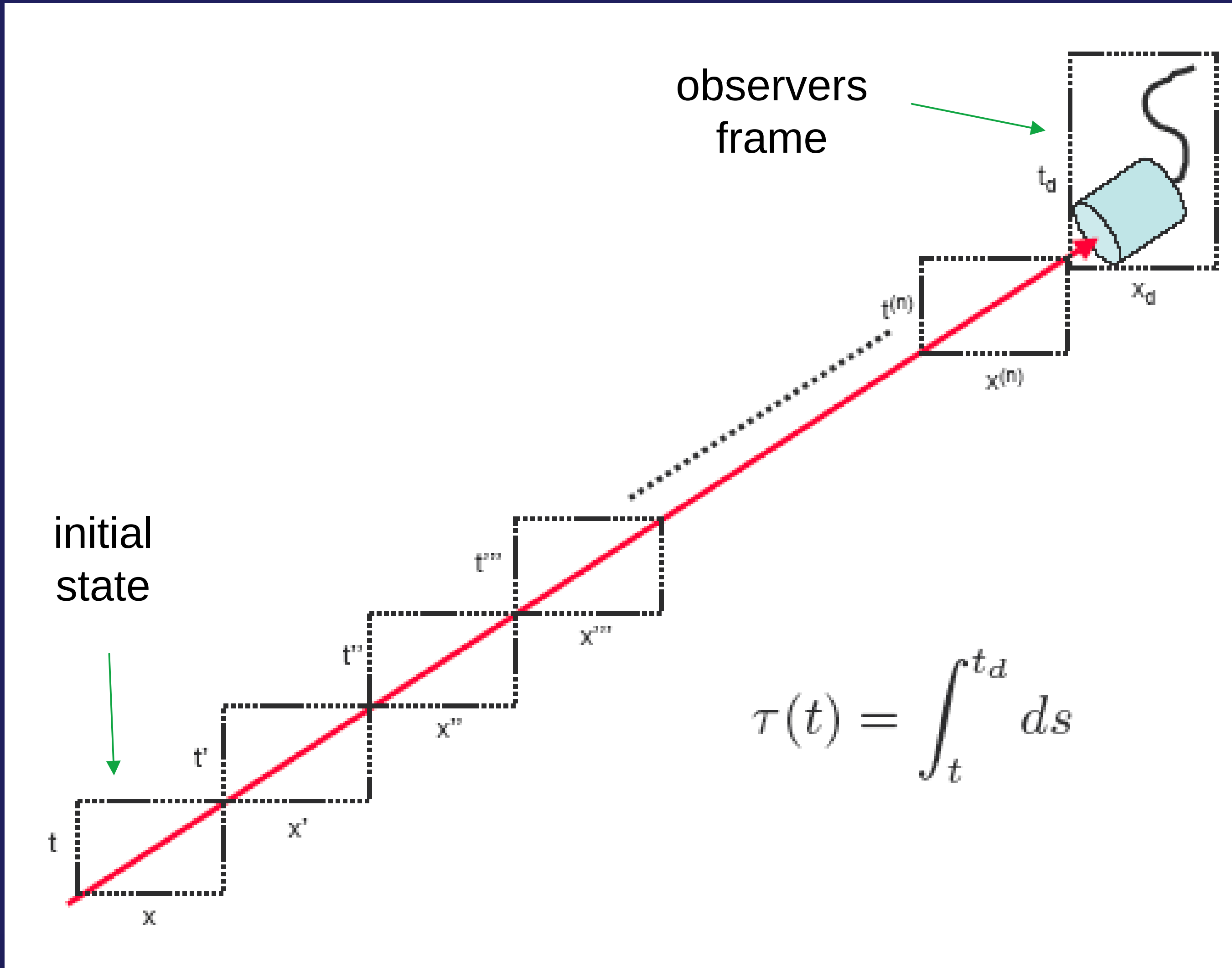
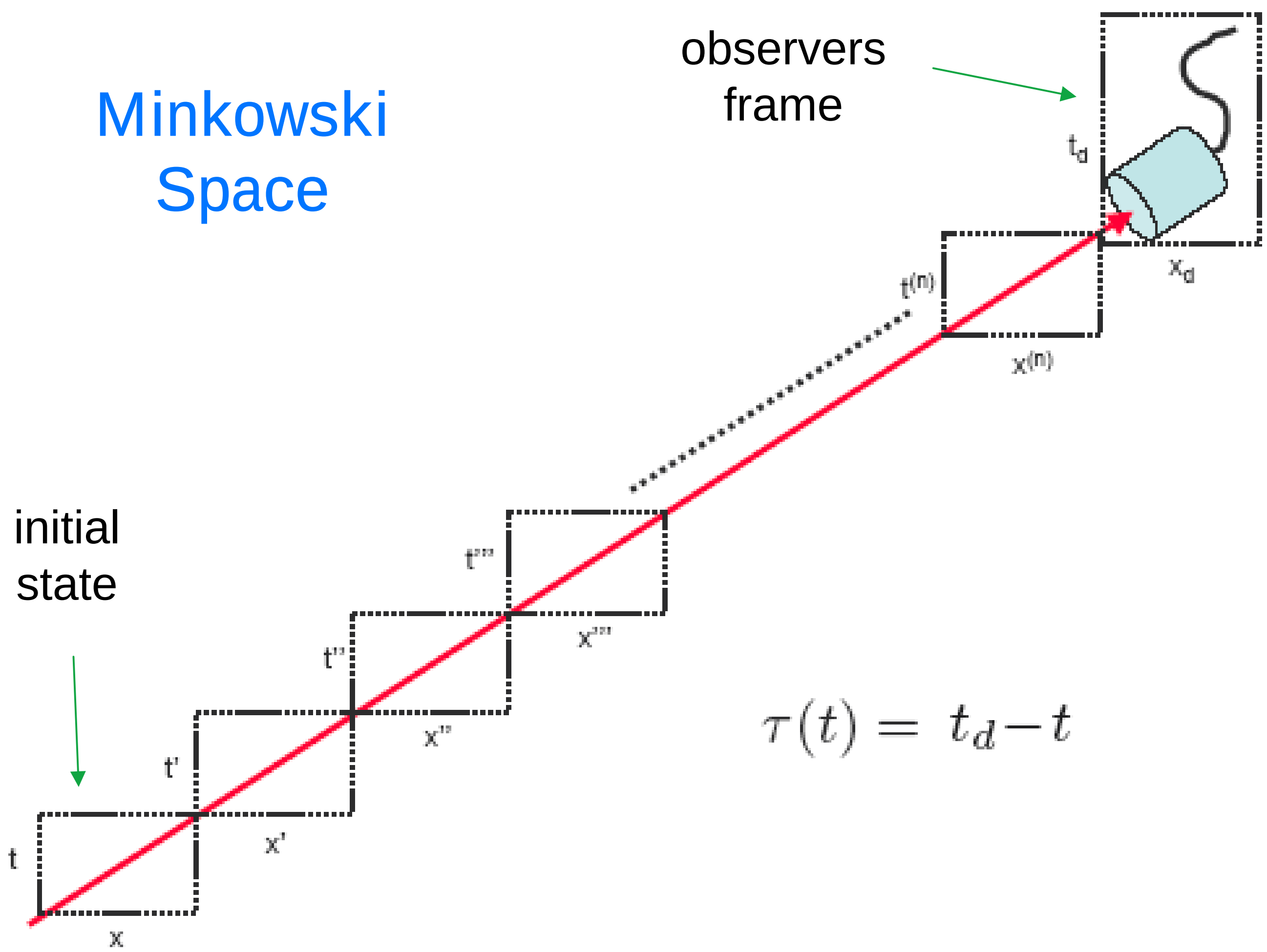


Event operators

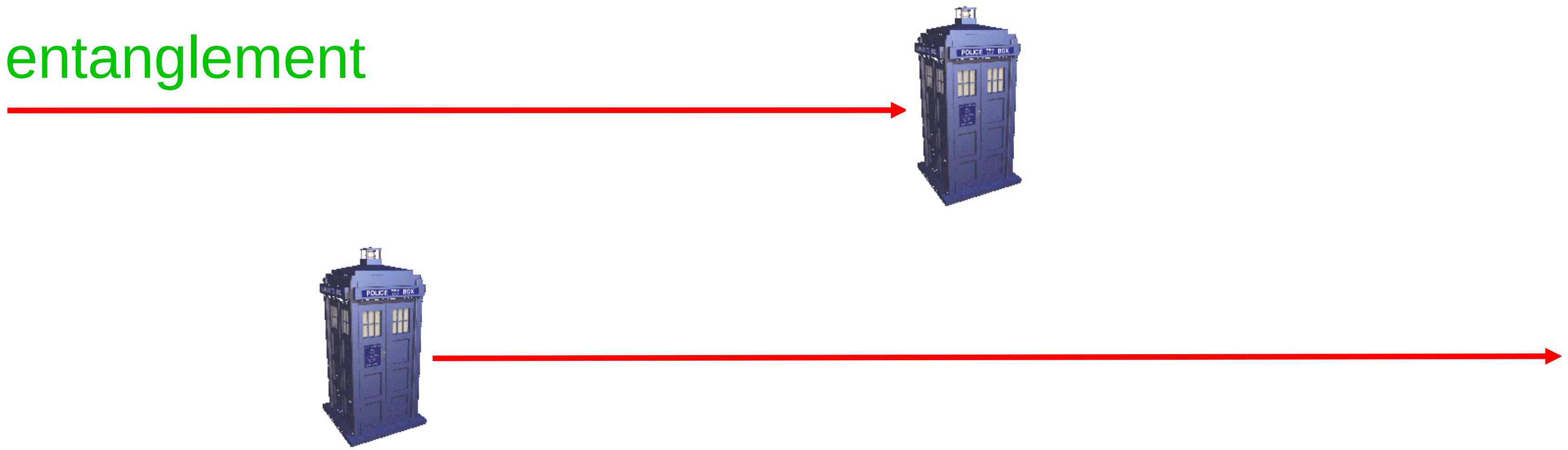


$$\tau(t) = t_d - t$$

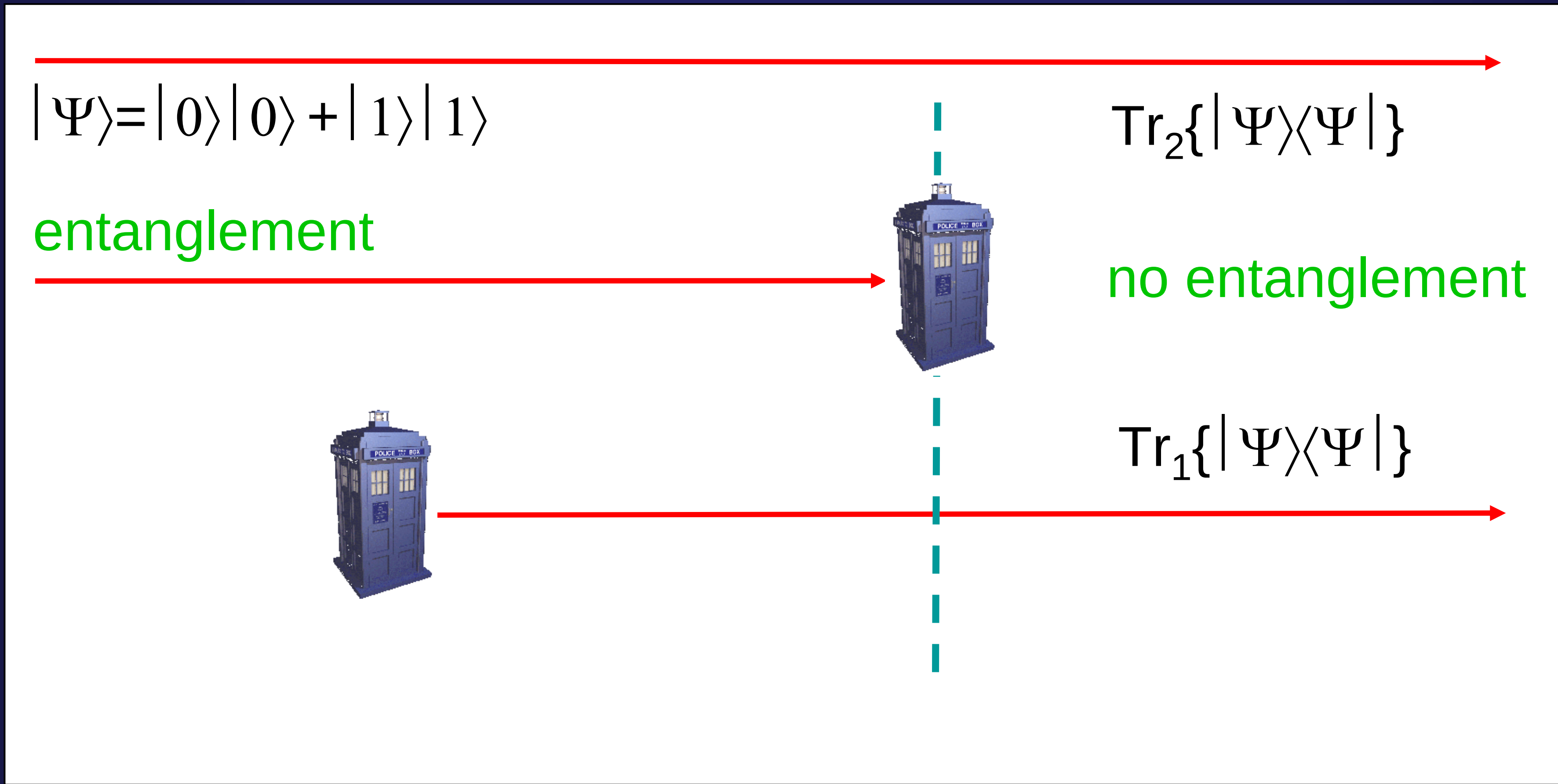
Decorrelation of entanglement

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

entanglement



Decorrelation of entanglement



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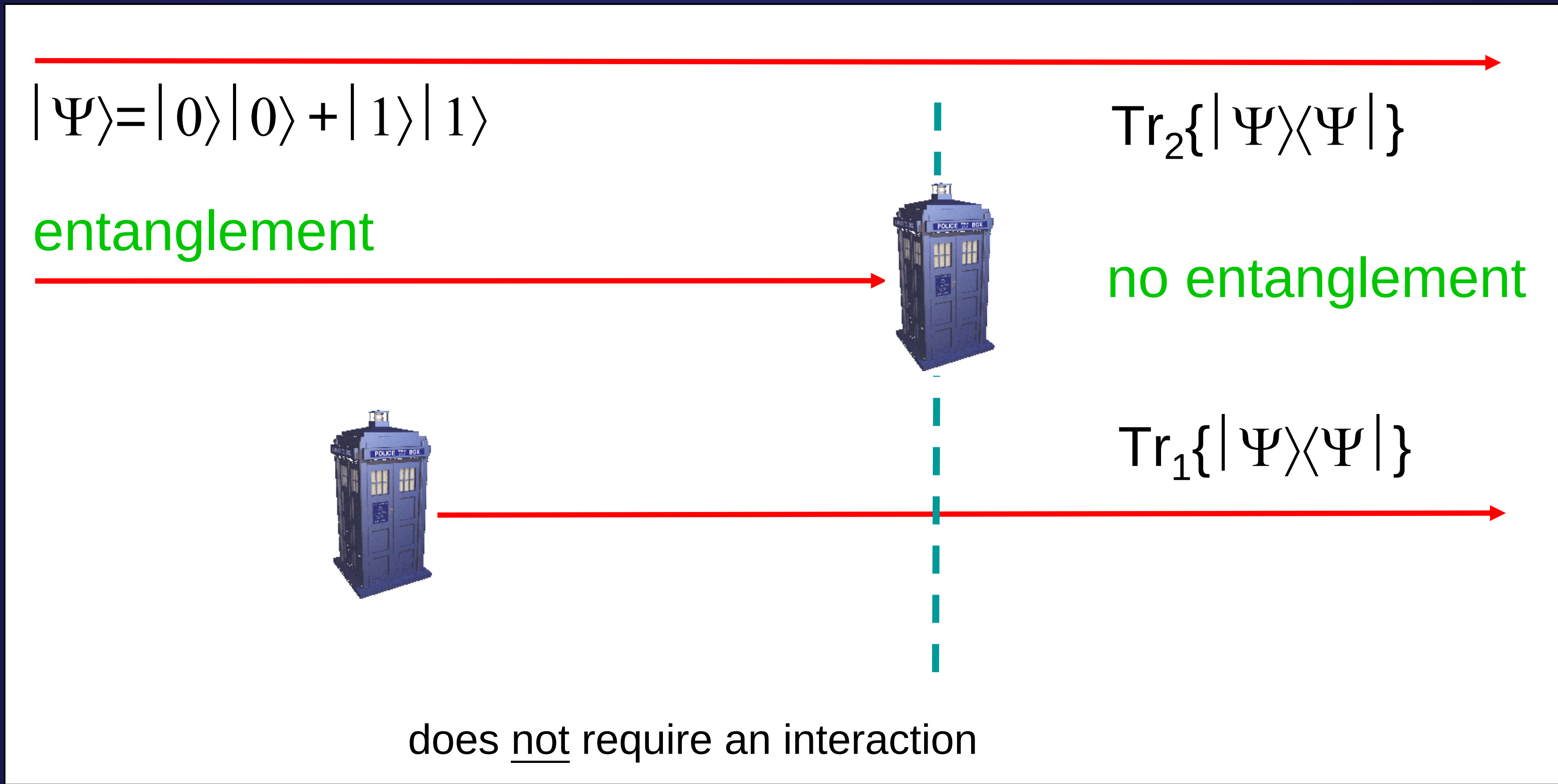
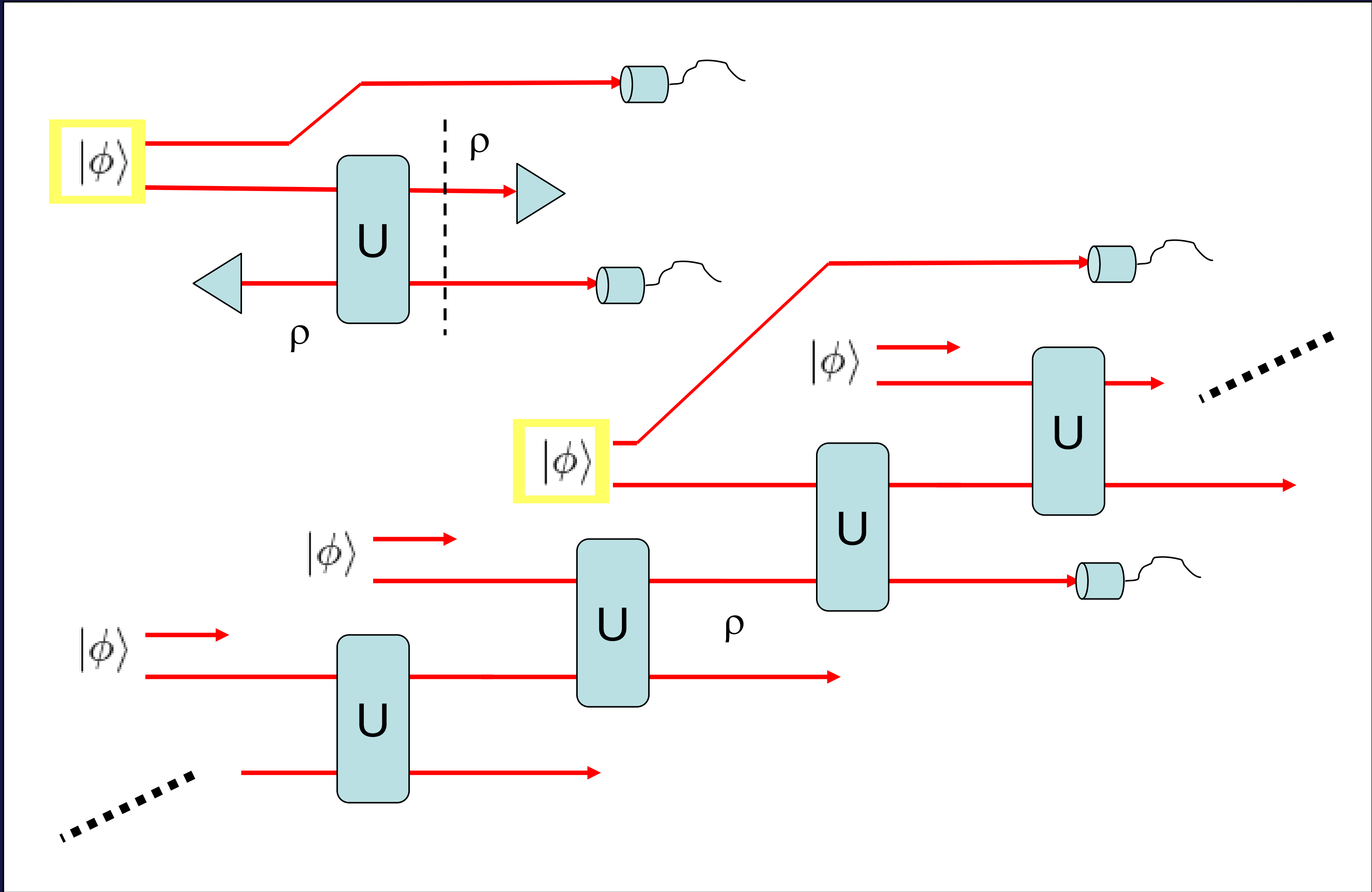


Predicted by all models

Following the Information Flow



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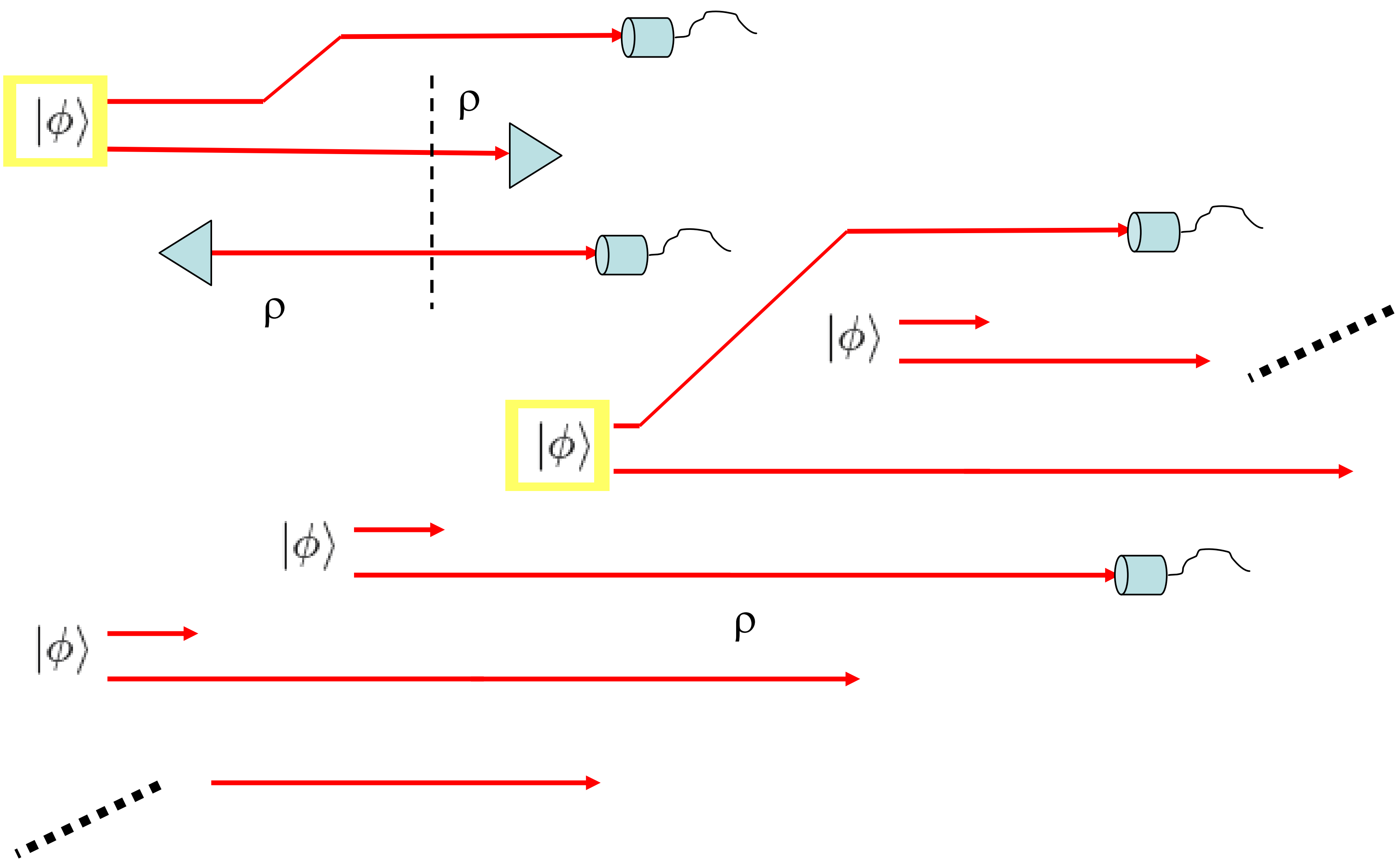

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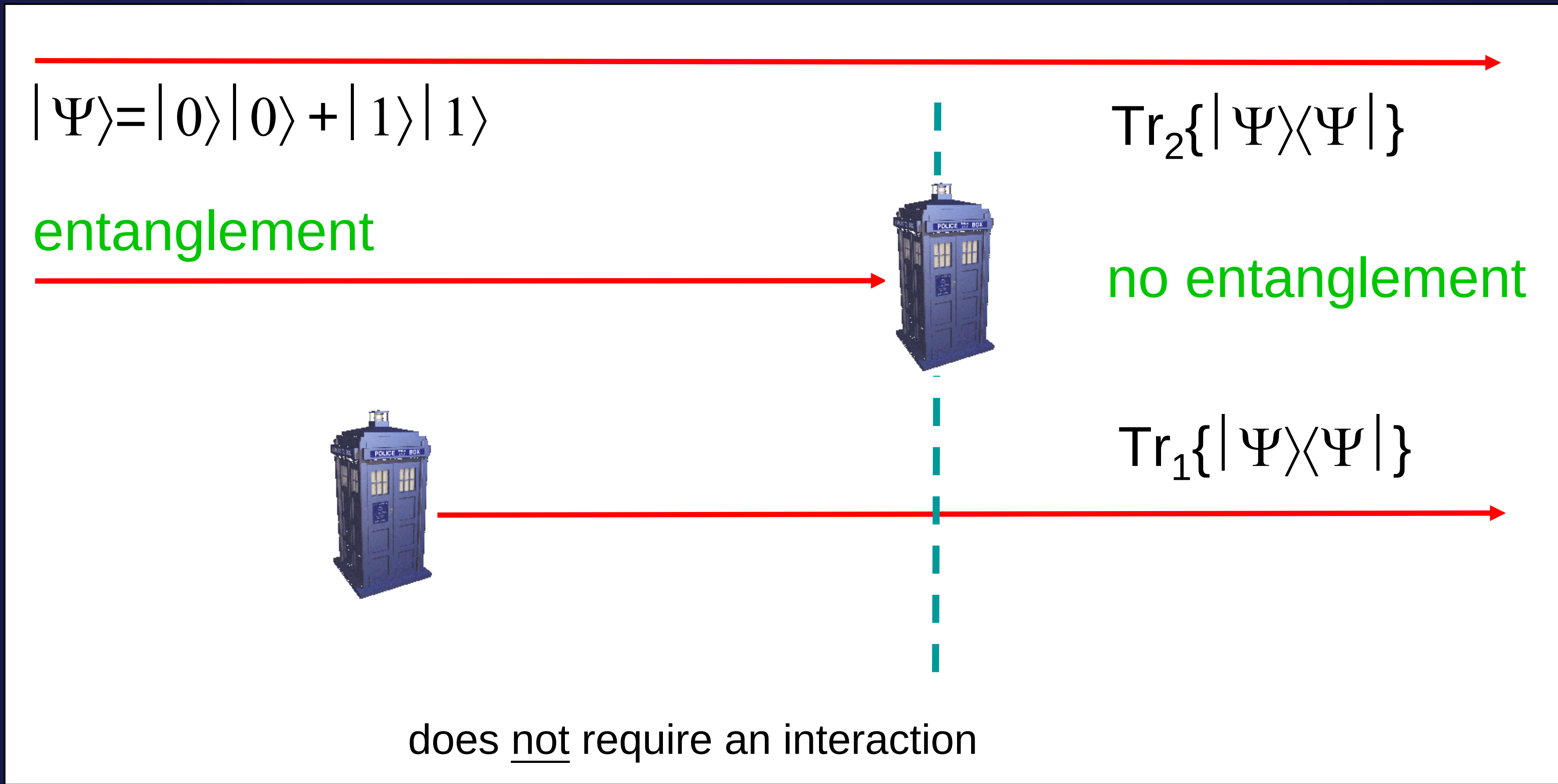

Predicted by all models

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 not require an interaction

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

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Predicted by all models

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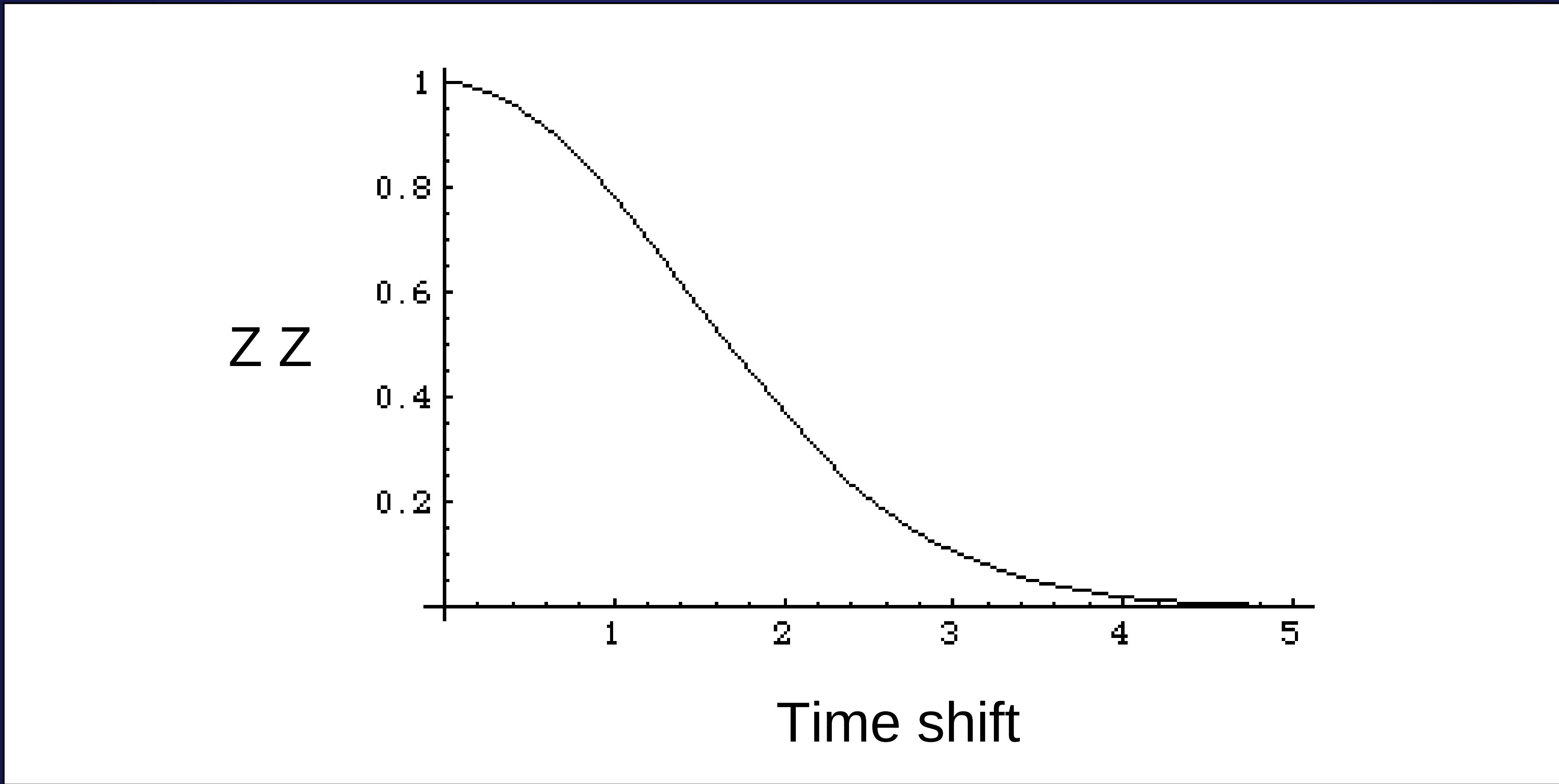
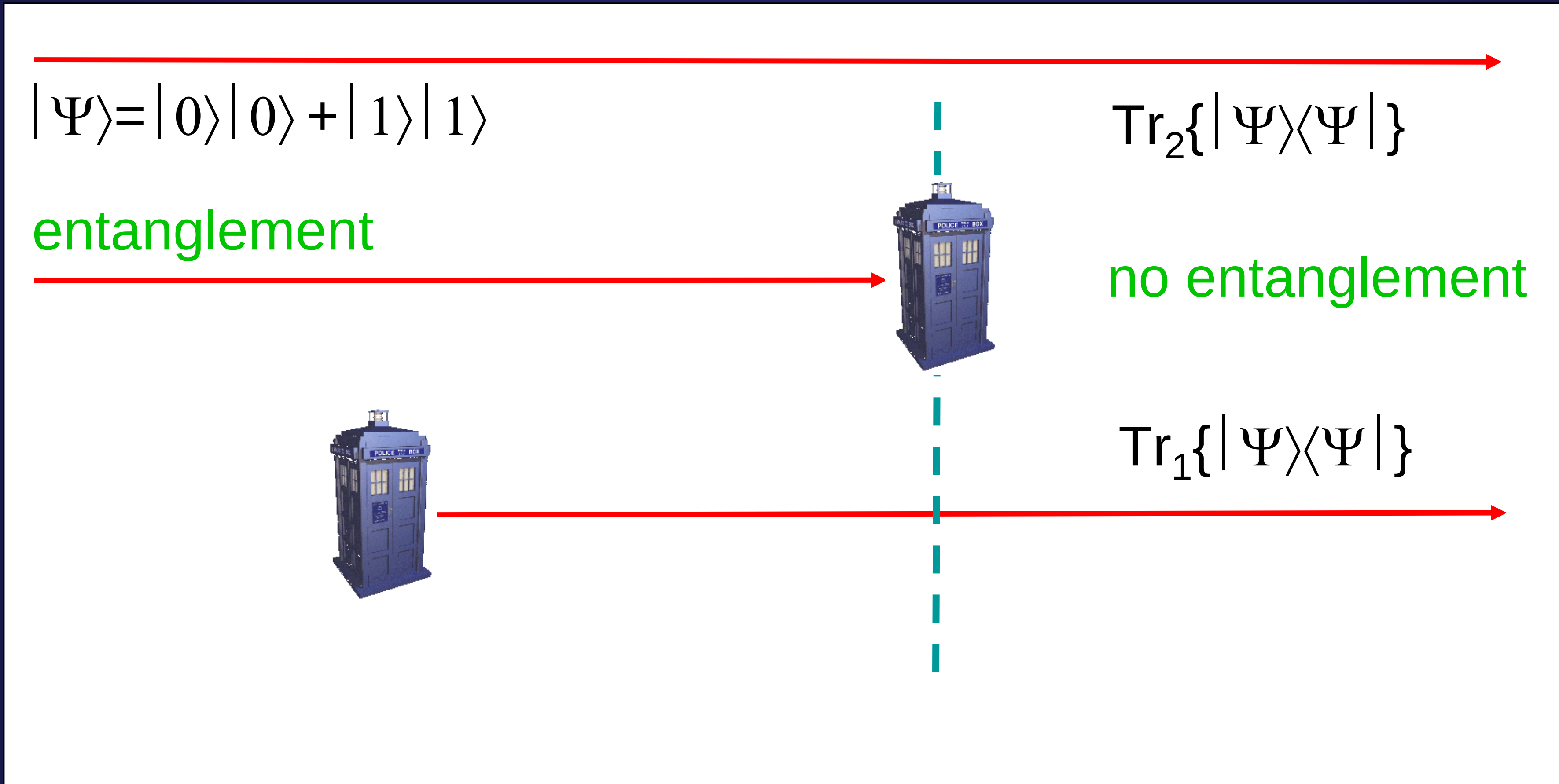
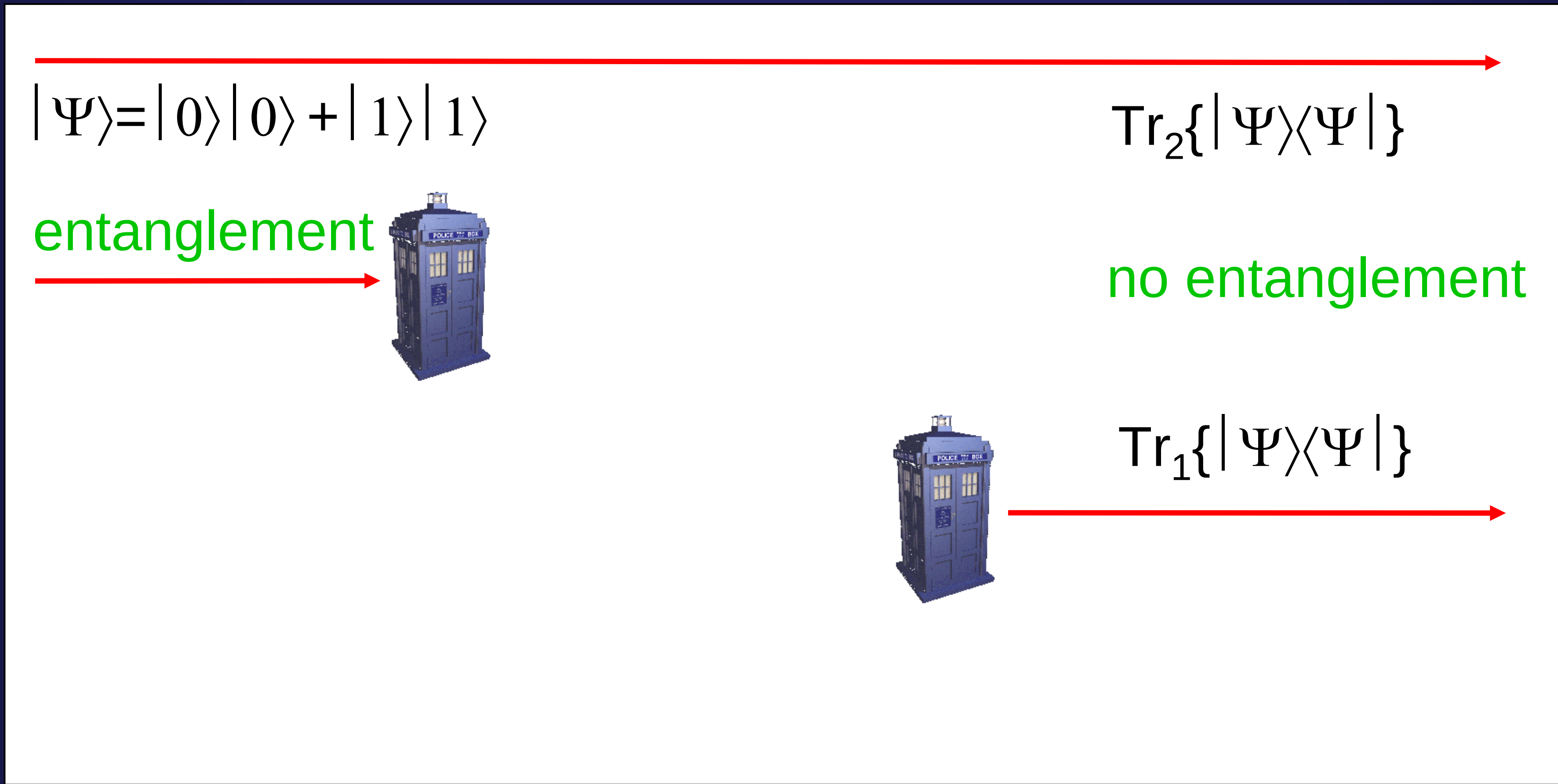


Decorrelation of entanglement



Decorrelation of entanglement



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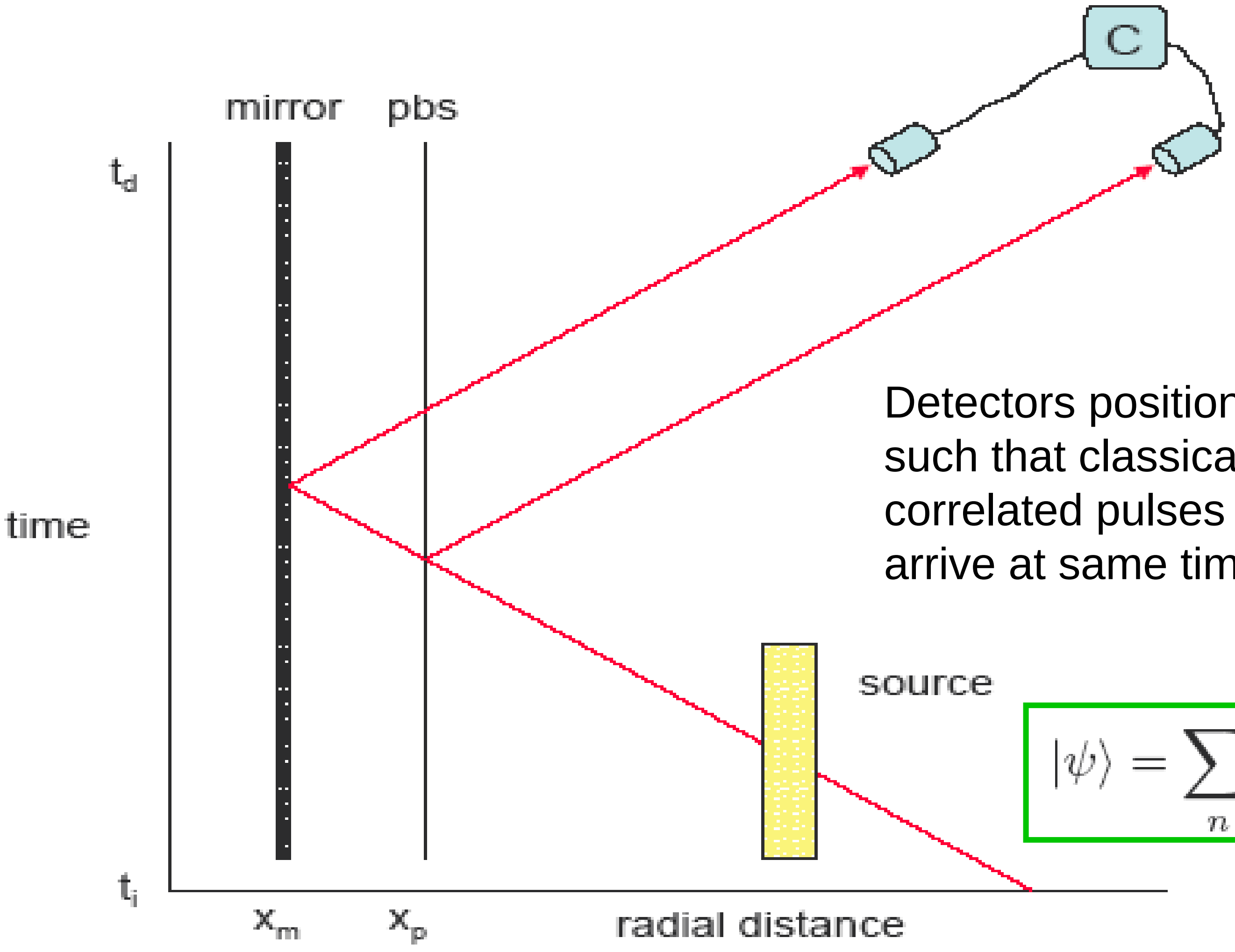
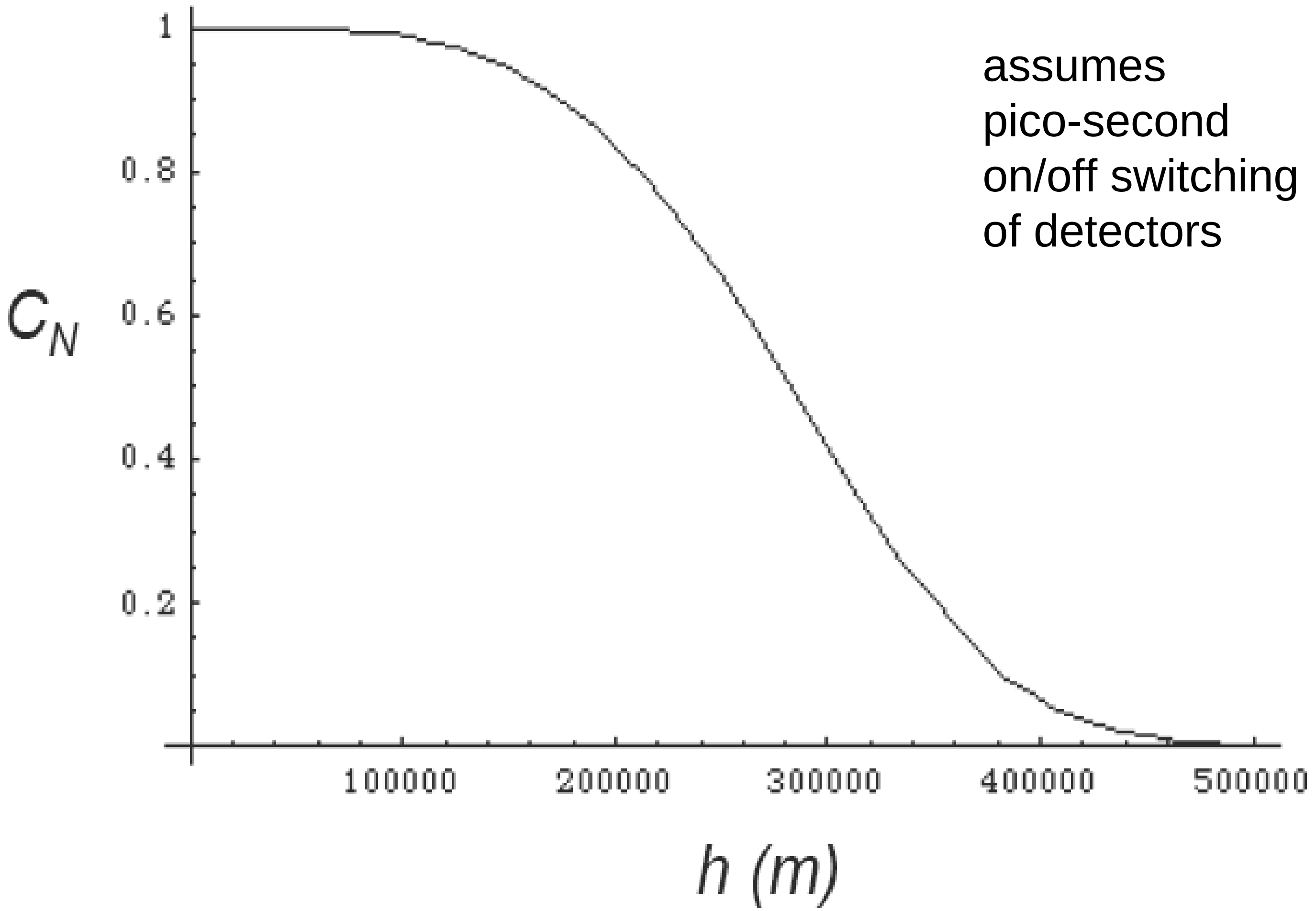
Space time diagram of correlation exp



Detectors positioned such that classically correlated pulses arrive at same time

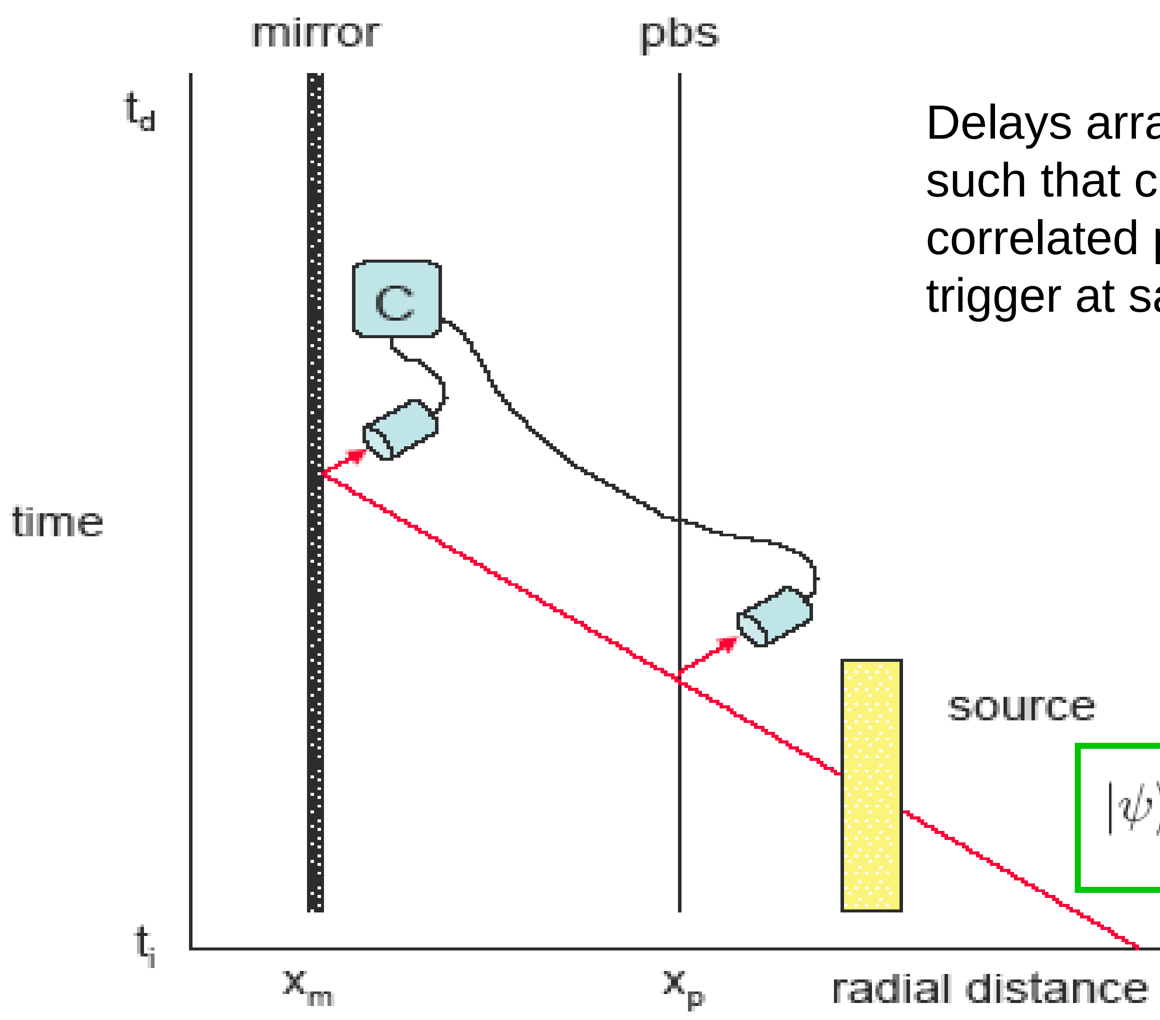
$$|\psi\rangle = \sum_n c_n |n\rangle_a |n\rangle_b$$

Coincidence rate vs height of PBS



assumes
pico-second
on/off switching
of detectors

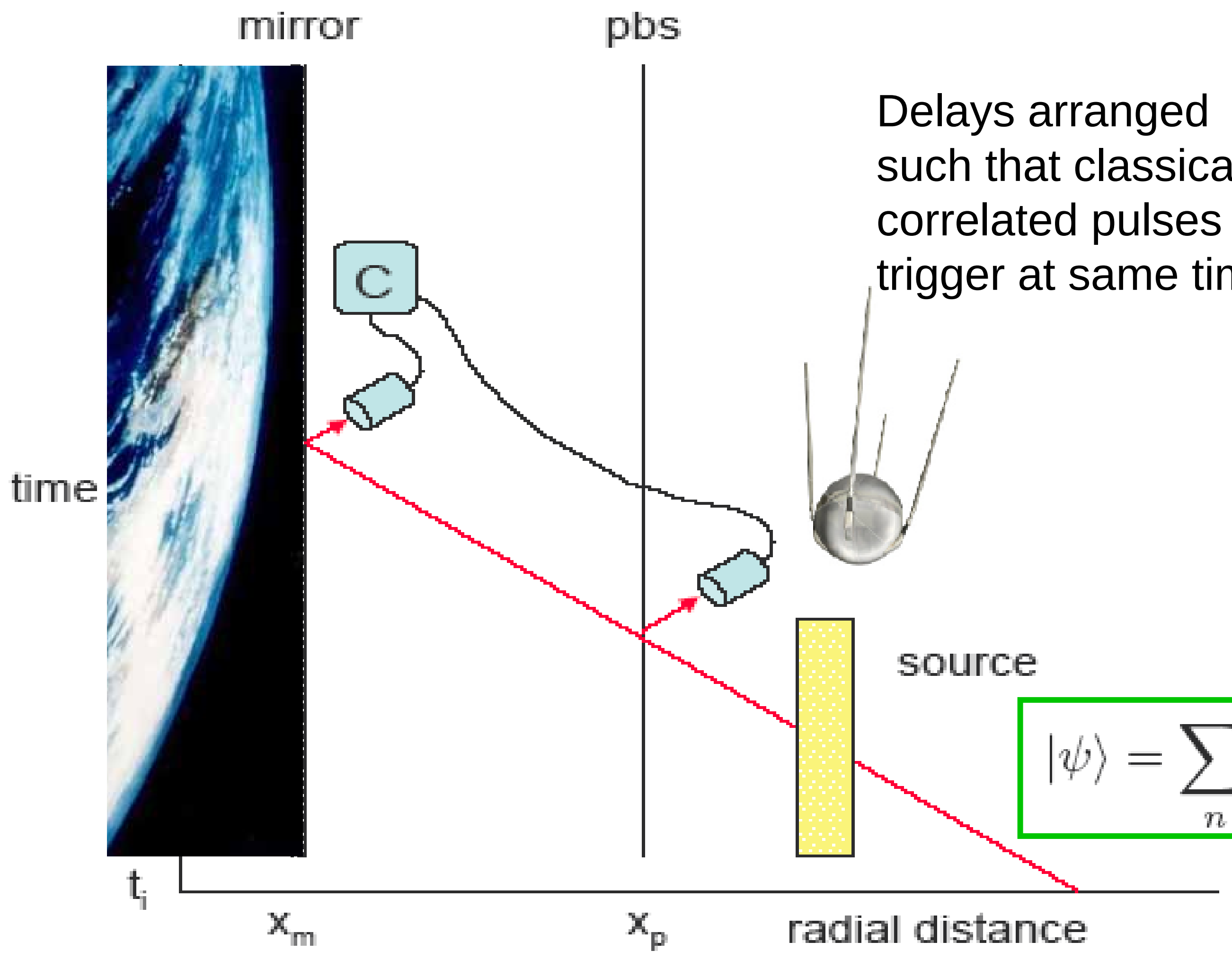
Space time diagram of correlation exp 2



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



Delays arranged such that classically correlated pulses trigger at same time

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Summary

* Described a method for modeling qubits as dynamic space-time objects
* Discussed the physical content of the Deutsch approach to solving CTCs
* Generalized our space-time qubits so as to be compatible with CTCs

International
Relativistic Quantum Information
Workshop

RQI 4

Brisbane, 22 - 26 November 2010

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thanks