QST-2021

Aug. 24 (2021)

Benchmarking Quantum State Transfer in the Cloud

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(FU Berlin, Germany)

Dr. Huan-Yu Ku

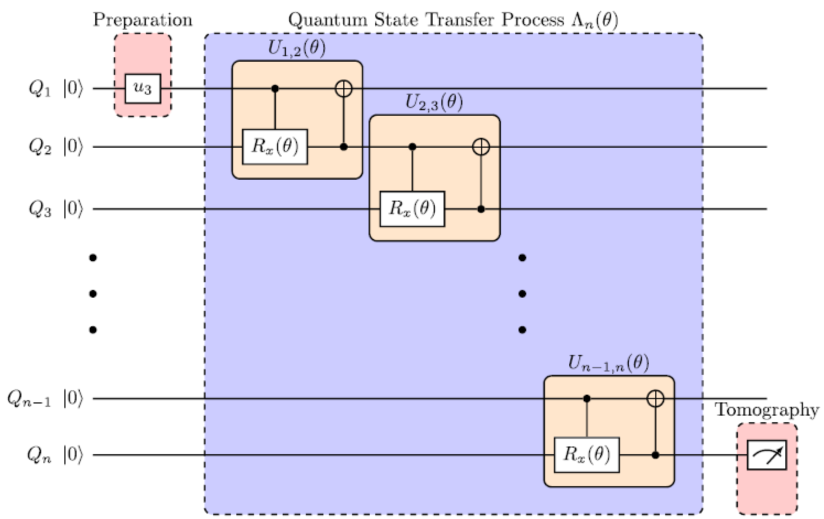
(NCKU, Taiwan)

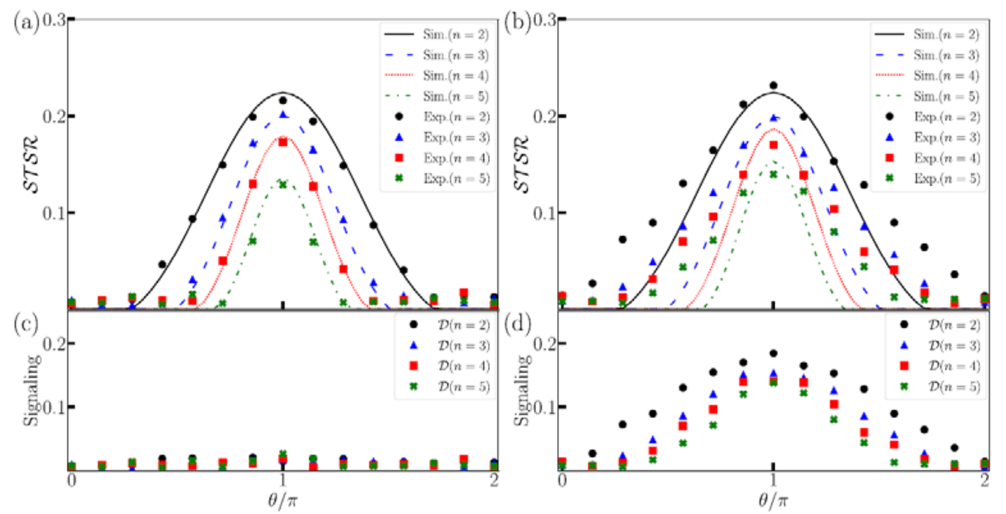
Mr. Yi-De Huang

(NCKU, Taiwan)

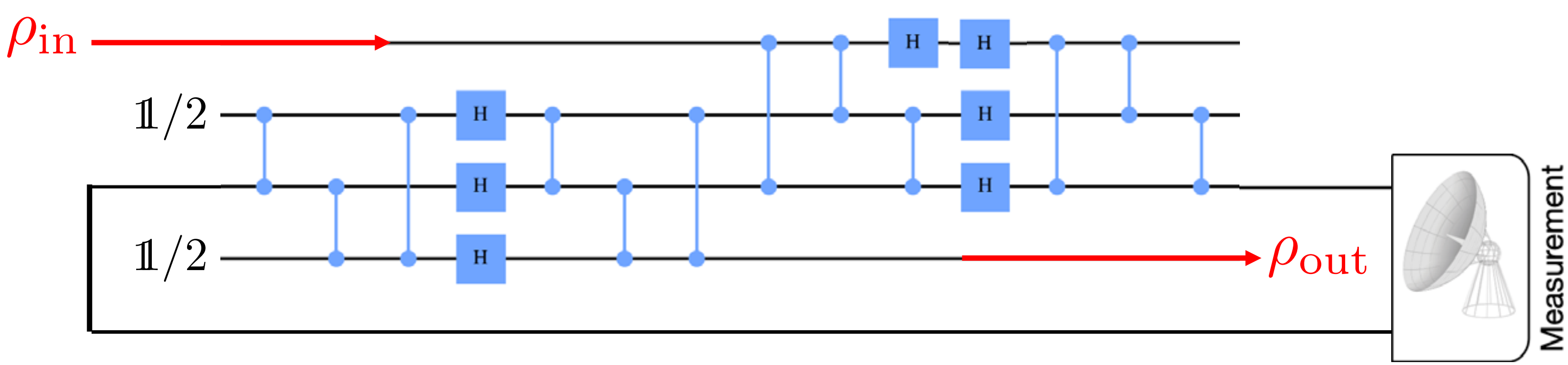
Will show you…

Experimental results on IBMQ and QuTech:

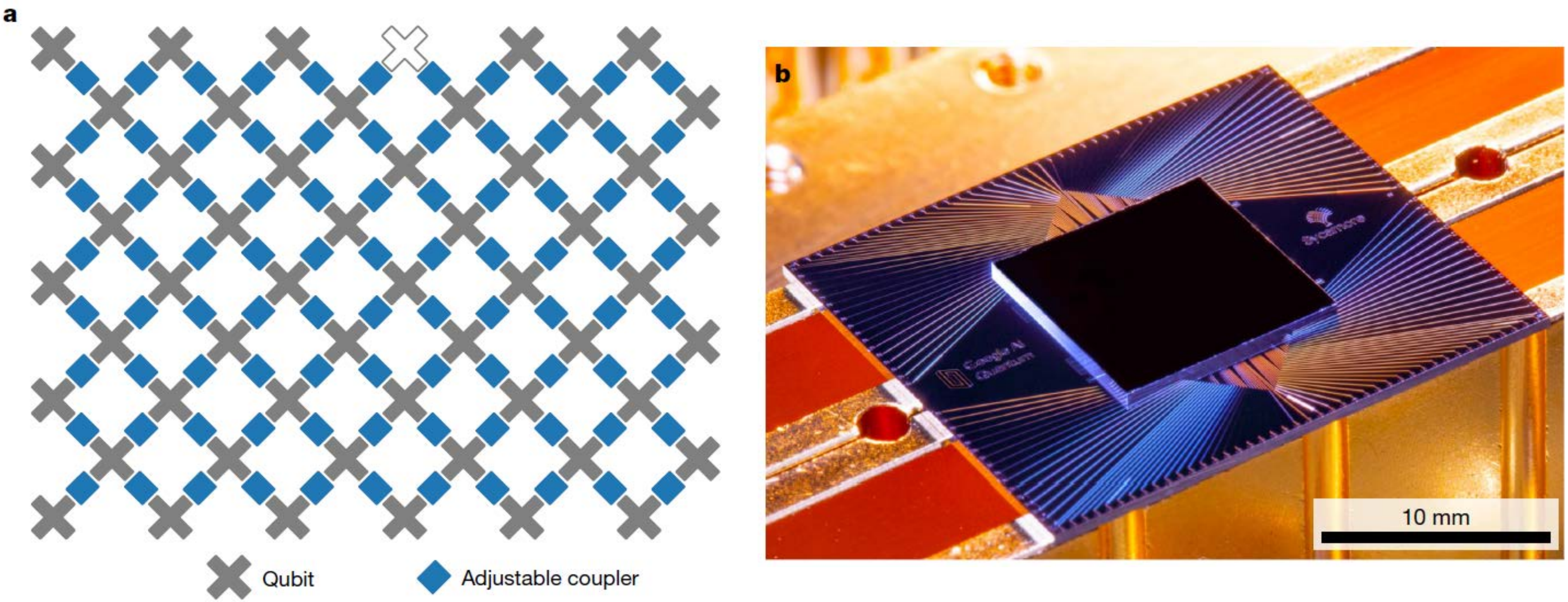




Experimental results of scrambling on Ion-Q:



Quantum supremacy using a programmable superconducting processor



Nature | Vol 574 | 24 OCTOBER 2019 | 505

Quantum computational advantage using photons

Han-Sen Zhong[1,2]*, Hui Wang[1,2]*, Yu-Hao Deng[1,2]*, Ming-Cheng Chen[1,2]*, Li-Chao Peng[1,2], Yi-Han Luo[1,2], Jian Qin[1,2], Dian Wu[1,2], Xing Ding[1,2], Yi Hu[1,2], Peng Hu[3], Xiao-Yan Yang[3], Wei-Jun Zhang[3], Hao Li[3], Yuxuan Li[4], Xiao Jiang[1,2], Lin Gan[4], Guangwen Yang[4], Lixing You[3], Zhen Wang[3], Li Li[1,2], Nai-Le Liu[1,2], Chao-Yang Lu[1,2]†, Jian-Wei Pan[1,2]†

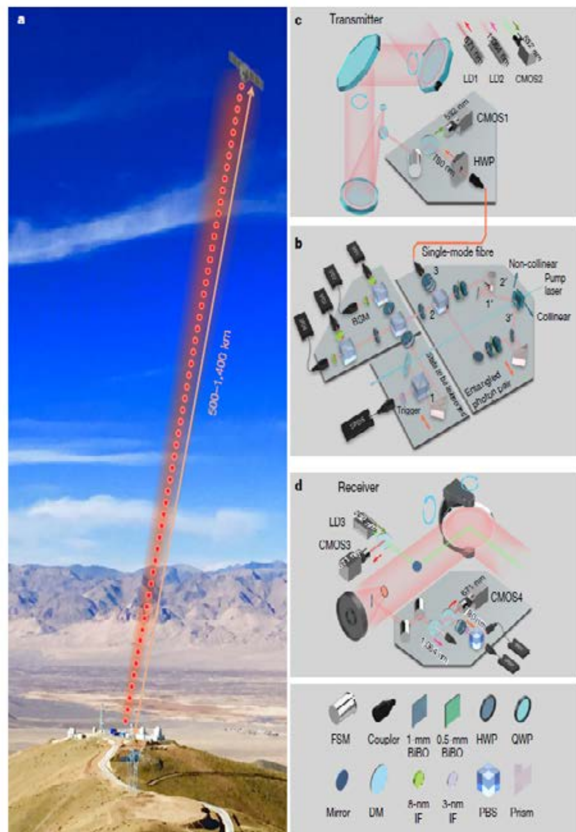
Zhong *et al.*, *Science* **370**, 1460–1463 (2020)

Quantum Satellite-Mozi (2016-8-16)

Ground-to-satellite quantum teleportation

Ji-Gang Ren[1,2], Ping Xu[1,2], Hai-Lin Yong[1,2], Liang Zhang[2,3], Sheng-Kai Liao[1,2], Juan Yin[1,2], Wei-Yue Liu[1,2], Wen-Qi Cai[1,2], Meng Yang[1,2], Li Li[1,2], Kui-Xing Yang[1,2], Xuan Han[1,2], Yong-Qiang Yao[4], Ji Li[5], Hai-Yan Wu[5], Song Wan[6], Lei Liu[6], Ding-Quan Liu[3], Yao-Wu Kuang[3], Zhi-Ping He[3], Peng Shang[1,2], Cheng Guo[1,2], Ru-Hua Zheng[7], Kai Tian[8], Zhen-Cai Zhu[6], Nai-Le Liu[1,2], Chao-Yang Lu[1,2], Rong Shu[2,3], Yu-Ao Chen[1,2], Cheng-Zhi Peng[1,2], Jian-Yu Wang[2,3] & Jian-Wei Pan[1,2]

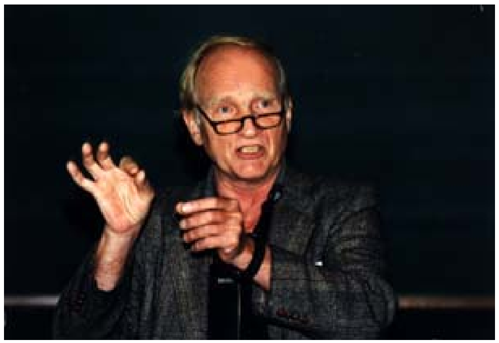
70 | NATURE | VOL 549 | 7 SEPTEMBER 2017

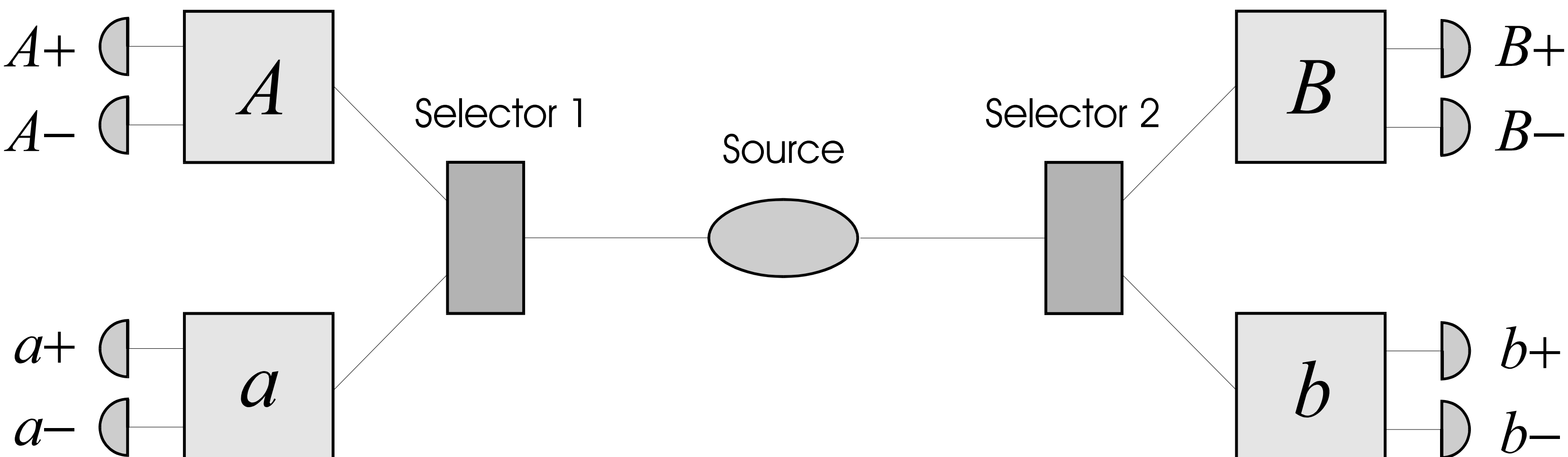


The Bell-CHSH inequality

Quantum vs Classical

Bell’s Inequality: Locality and Realism



$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|01\rangle - |10\rangle\right)$$

The Bell-CHSH inequality

$$A, a, B, b \in \{-1,1\}$$

$$(A-a, A+a) \in \{(0,\pm 2),(\pm 2,0)\}$$

$$(A-a)B-(A+a)b \in \{-2,2\}$$

$$-2 \leq \langle AB - Ab - aB - ab \rangle \leq 2$$

$$\left| \langle AB \rangle - \langle Ab \rangle - \langle aB \rangle - \langle ab \rangle \right| \leq 2$$

Predictions of QM for the *singlet* state

$$\left|\psi^-\right\rangle = \frac{1}{\sqrt{2}}\left(\left|01\right\rangle - \left|10\right\rangle\right)$$

$$\left\langle AB\right\rangle = \left\langle \psi^- \middle| \hat{A}\otimes\hat{B} \middle| \psi^- \right\rangle$$
$$= -\cos\theta_{AB}$$

QM violates the Bell-CHSH inequality

$$F_{\mathrm{QM}} = \left| \langle AB \rangle - \langle Ab \rangle - \langle aB \rangle - \langle ab \rangle \right|$$

$$= \left| -\cos\theta_{AB} + \cos\theta_{Ab} + \cos\theta_{aB} + \cos\theta_{ab} \right|$$

$$\hat{A} = \sigma_x$$

$$\hat{a} = \sigma_y$$

$$\hat{B} = (\sigma_y - \sigma_x)/\sqrt{2}$$

$$\hat{b} = (\sigma_y + \sigma_x)/\sqrt{2}$$

$$F_{\mathrm{QM}} = 2\sqrt{2} > 2!!!$$

VOLUME 47, NUMBER 7 PHYSICAL REVIEW LETTERS 17 AUGUST 1981

Experimental Tests of Realistic Local Theories via Bell's Theorem

Alain Aspect, Philippe Grangier, and Gérard Roger
Institut d'Optique Théorique et Appliquée, Université Paris-Sud, F-91406 Orsay, France
(Received 30 March 1981)

We have measured the linear polarization correlation of the photons emitted in a radiative atomic cascade of calcium. A high-efficiency source provided an improved statistical accuracy and an ability to perform new tests. Our results, in excellent agreement with the quantum mechanical predictions, strongly violate the generalized Bell's inequalities, and rule out the whole class of realistic local theories. No significant change in results was observed with source-polarizer separations of up to 6.5 m.

VOLUME 49, NUMBER 2 PHYSICAL REVIEW LETTERS 12 JULY 1982

Experimental Realization of Einstein-Podolsky-Rosen-Bohm *Gedankenexperiment*: A New Violation of Bell's Inequalities

Alain Aspect, Philippe Grangier, and Gérard Roger
Institut d'Optique Théorique et Appliquée, Laboratoire associé au Centre National de la Recherche Scientifique, Université Paris-Sud, F-91406 Orsay, France
(Received 30 December 1981)

The linear-polarization correlation of pairs of photons emitted in a radiative cascade of calcium has been measured. The new experimental scheme, using two-channel polarizers (i.e., optical analogs of Stern-Gerlach filters), is a straightforward transposition of Einstein-Podolsky-Rosen-Bohm *gedankenexperiment*. The present results, in excellent agreement with the quantum mechanical predictions, lead to the greatest violation of generalized Bell's inequalities ever achieved.

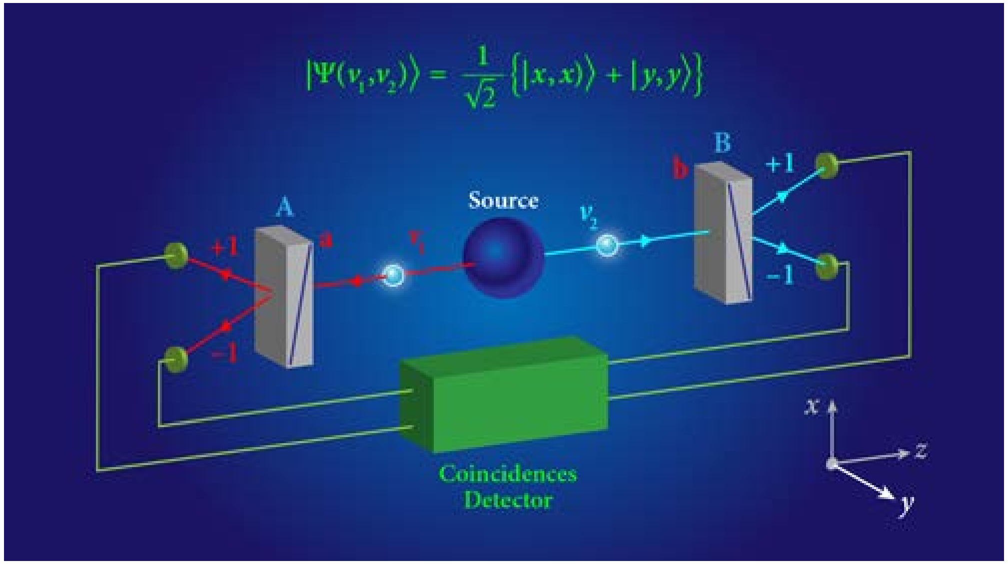
VOLUME 49, NUMBER 25 PHYSICAL REVIEW LETTERS 20 DECEMBER 1982

Experimental Test of Bell's Inequalities Using Time-Varying Analyzers

Alain Aspect, Jean Dalibard,[a] and Gérard Roger
Institut d'Optique Théorique et Appliquée, F-91406 Orsay Cédex, France
(Received 27 September 1982)

Correlations of linear polarizations of pairs of photons have been measured with time-varying analyzers. The analyzer in each leg of the apparatus is an acousto-optical switch followed by two linear polarizers. The switches operate at incommensurate frequencies near 50 MHz. Each analyzer amounts to a polarizer which jumps between two orientations in a time short compared with the photon transit time. The results are in good agreement with quantum mechanical predictions but violate Bell's inequalities by 5 standard deviations.

Closing the Door on Einstein and Bohr's Quantum Debate



B. Hensen *et al.*, "Loophole-free Bell Inequality Violation Using Electron Spins Separated by 1.3 Kilometres," **Nature 526, 682 (2015)**.

M. Giustina *et al.*, "Significant-Loophole-Free Test of Bell's Theorem with Entangled Photons," **Phys. Rev. Lett. 115, 250401 (2015)**.

L. K. Shalm *et al.*, "Strong Loophole-Free Test of Local Realism," **Phys. Rev. Lett. 115, 250402 (2015)**.

Leggett-Garg Inequality (Bell's inequality in time)

Realism and non-invasive measurement

Quantum mechanics versus macroscopic realism:
Is the flux there when nobody looks?

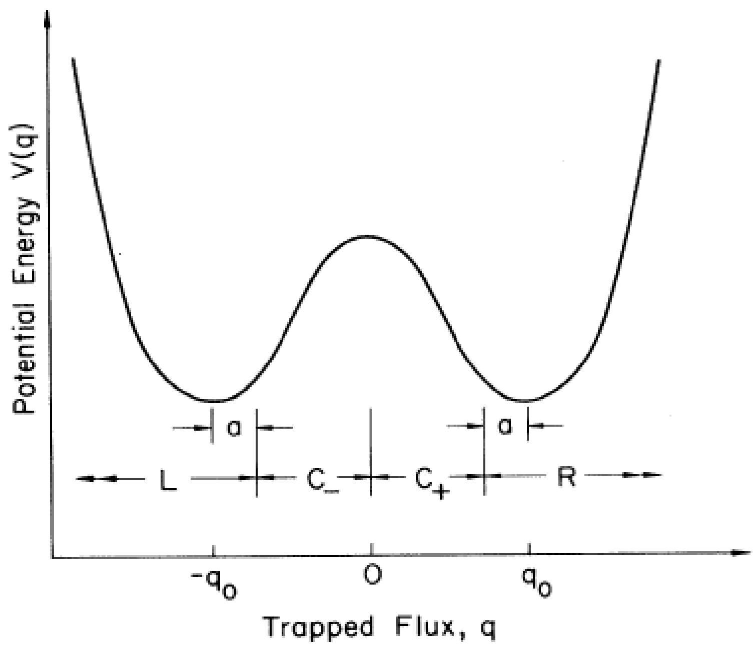


FIG. 1. The potential $V(q)$ for the trapped flux q. The various notations are explained in the text.

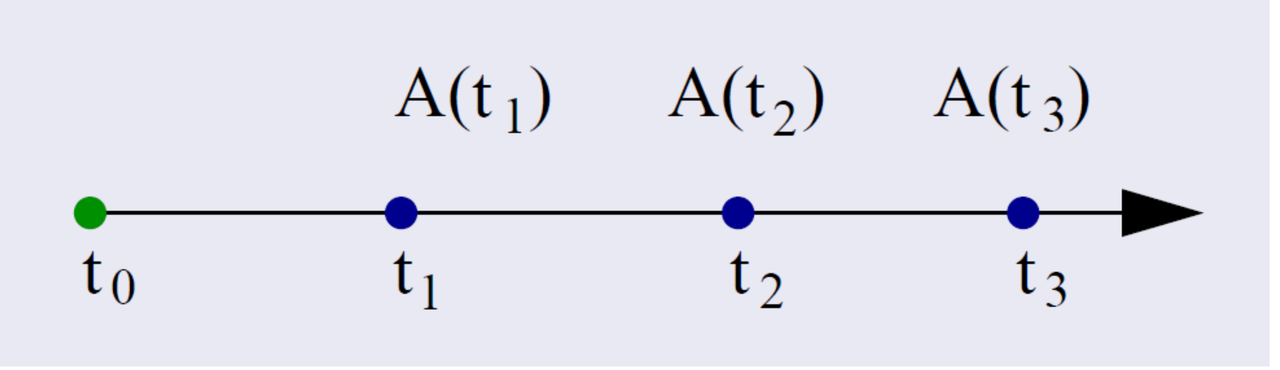
Leggett and Garg, **Phys. Rev. Lett. 54**, 857–860 (1985)
C. Emary, N. Lambert, F. Nori, **Rep. Prog. Phys. 77**, 016001 (2014)

Given an observable $A(t)$, bound above and below by $|A(t)| \leq 1$, the assumption of:

- macroscopic realism, and
- non-invasive measurement,

implies the inequality,

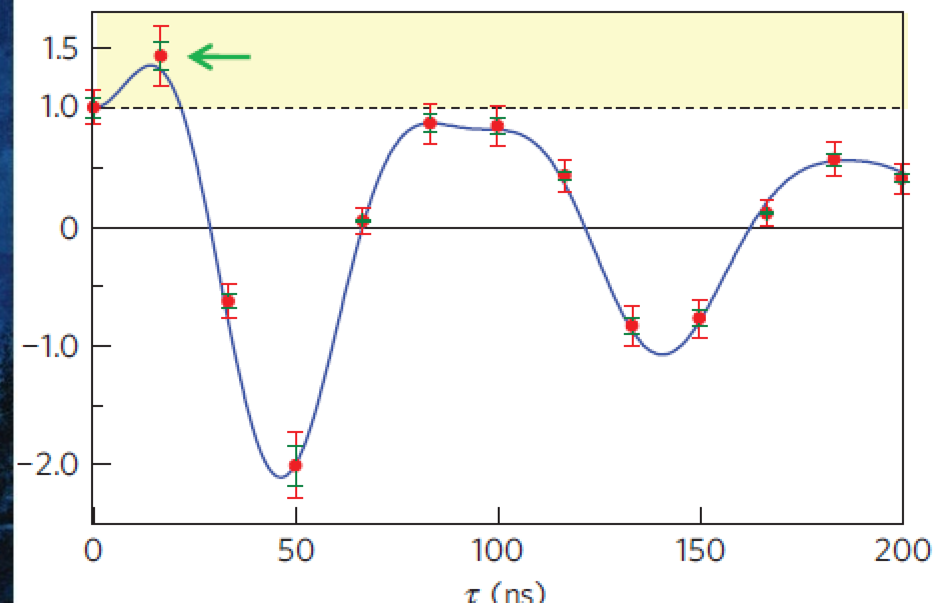
$$\langle A(t_2)A(t_1)\rangle + \langle A(t_3)A(t_2)\rangle - \langle A(t_3)A(t_1)\rangle \leq 1$$



$\Rightarrow$ This can be violated by QM systems!

No moon there

An experiment reveals that micrometre-sized superconducting circuits follow the laws of quantum mechanics, and thus defy common experience of how macroscopic objects should behave.



Palacios-Laloy, A. *et al.*
Nature Phys. ***6, 442–447 (2010).***

ARTICLE

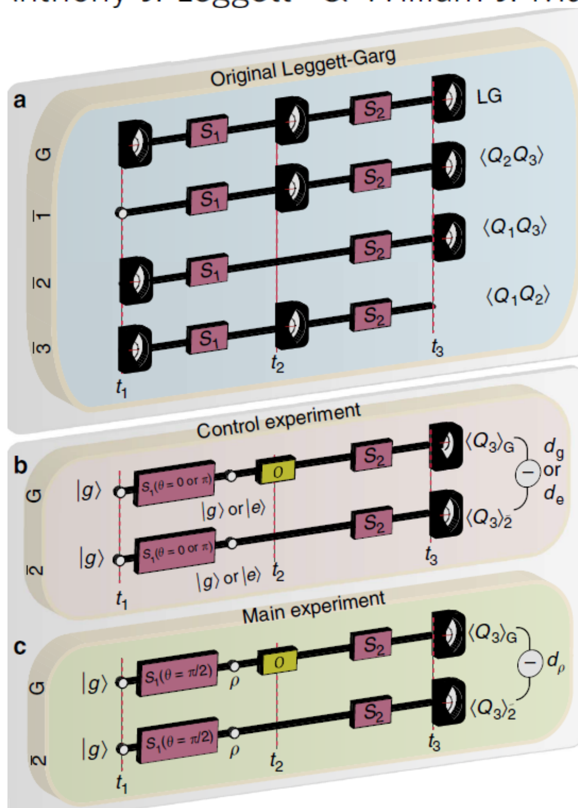
Received 26 Feb 2016 | Accepted 15 Sep 2016 | Published 4 Nov 2016

DOI: 10.1038/ncomms13253

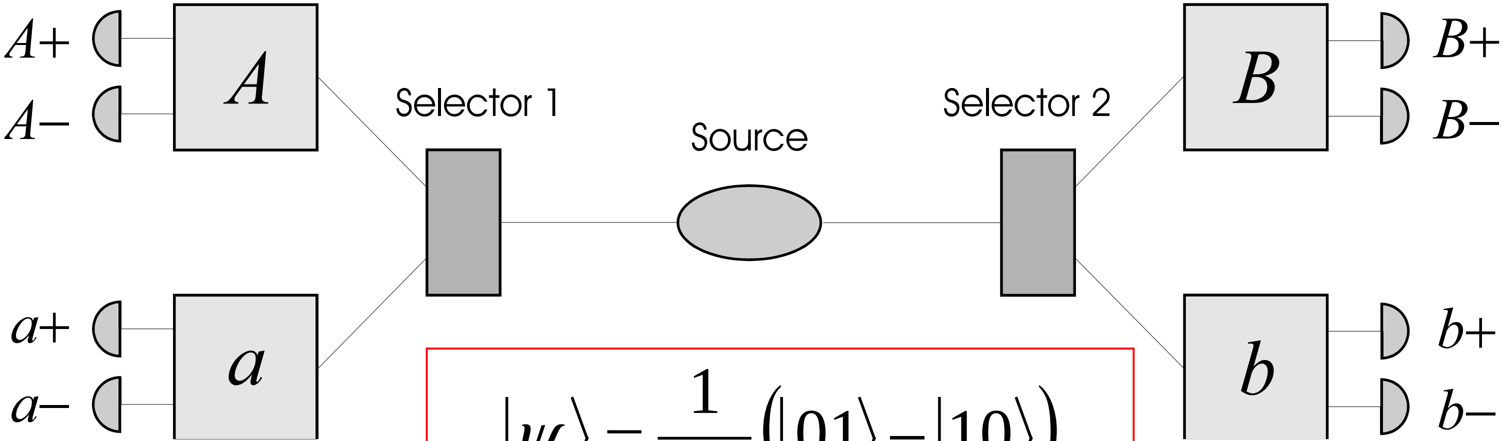
OPEN

A strict experimental test of macroscopic realism in a superconducting flux qubit

George C. Knee[1,*,†], Kosuke Kakuyanagi[1,*], Mao-Chuang Yeh[2,*], Yuichiro Matsuzaki[1], Hiraku Toida[1], Hiroshi Yamaguchi[1], Shiro Saito[1], Anthony J. Leggett[2] & William J. Munro[1]

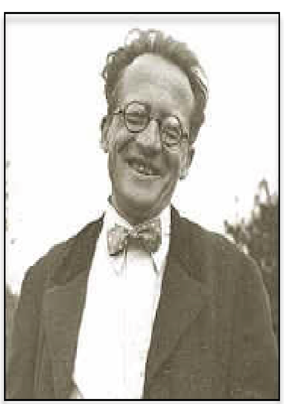


Quantum Steering



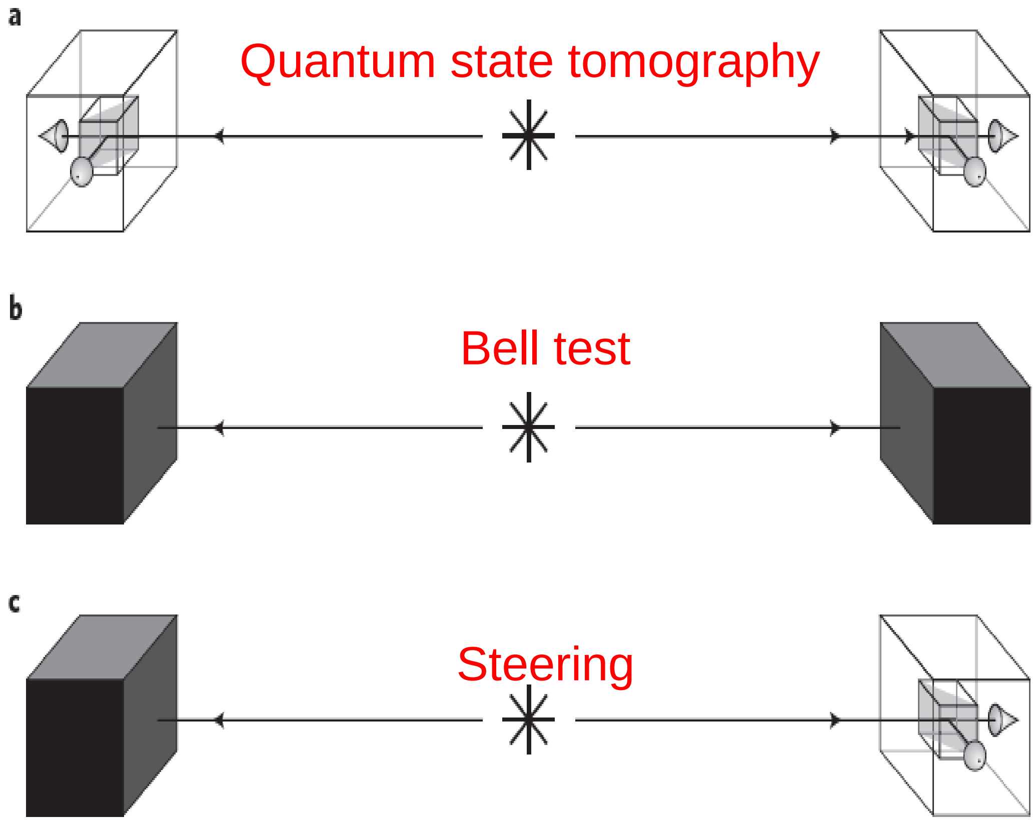
$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|01\rangle - |10\rangle\right)$$

EPR: Alice can measure p_A and find out p_B for Bob's particle or measure q_A and find out q_B. Either QM is incomplete or it violates relativity. Spooky action at a distance!



Schrodinger: Alice could measure any of a number of observables. She can *steer* Bob's state into an eigenstate of one of these. This is not due to the incompleteness of QM but is fundamental to QM. BTW, let's call the resource "entanglement".

Three different forms of quantum non-locality



a, To test for entanglement, trusted devices (white boxes) are used, which are supposed to obey the laws of quantum mechanics. **b**, Non-locality is defined independently of quantum mechanics, however, and can be tested without any prior knowledge about the devices (black boxes). **c**, Steering is intermediate: one party trusts only its own measuring device, but not the other party.

[N. Brunner, Nature Physics 6, 842 (2010)]

The Steering Inequality

$$S_N \equiv \sum_{i=1}^{N} E[\langle \hat{B}_i \rangle_{A_i}^2] \leq 1$$

$$E[\langle \hat{B}_i \rangle_{A_i}^2] \equiv \sum_{a=\pm 1,0} P(A_i = a) \langle \hat{B}_i \rangle_{A_i = a}^2$$

$$\langle \hat{B}_i \rangle_{A_i = a} \equiv P(B_i = +1 \,|\, A_i = a) - P(B_i = -1 \,|\, A_i = a)$$

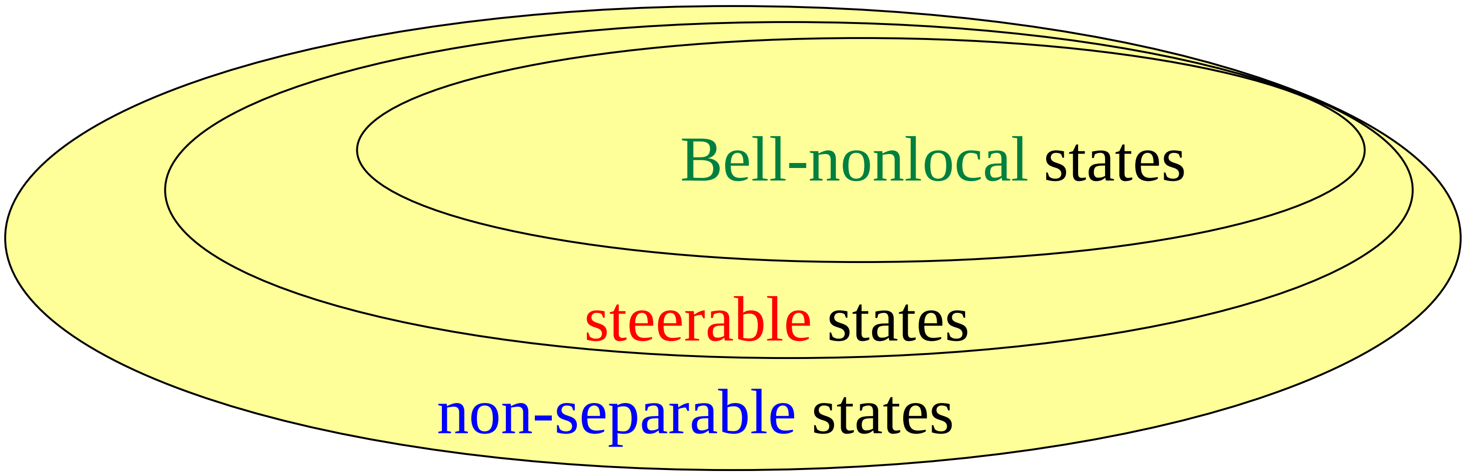
measurements in N = 2 or 3 mutually unbiased bases, for instance of the Pauli X, Y and Z operators

[H. M. Wiseman, S. J. Jones, and A. C. Doherty, Phys.Rev. Lett. **98**, 140402 (2007); E. G. Cavalcanti et al., Phys. Rev. A **80**, 032112 (2009)]

The comparison between different inequalities

The Werner state: $\rho = V|\psi^-\rangle\langle\psi^-| + (1-V)1/4$

$|\psi^-\rangle$ is the Bell singlet state



Bell-nonlocality exists *only if V* > 0.6595…

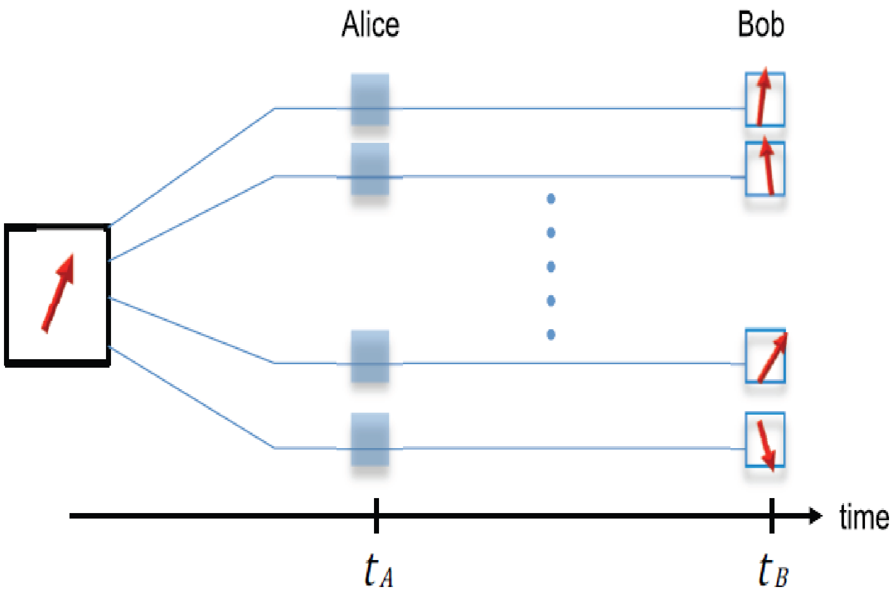
EPR-Steering exists *if and only if V* > 1/2

Non-separability *exists if and only if V* > 1/3

Temporal Steering Inequality

CHSH Inequality $\lvert\langle B_1A_1\rangle + \langle B_1A_2\rangle + \langle B_2A_1\rangle - \langle B_2A_2\rangle\rvert \leq 2$	Leggett-Garg Inequality $\lvert\langle A_{i,t_2}A_{i,t_1}\rangle + \langle A_{i,t_3}A_{i,t_2}\rangle + \langle A_{i,t_4}A_{i,t_3}\rangle - \langle A_{i,t_4}A_{i,t_1}\rangle\rvert \leq 2$
Steering inequality $\sum_{i=1}^{N} E\left[\langle B_i\rangle^2_{A_i}\right] \leq 1$	Temporal steering inequality ?

Temporal Scenario of the steering inequality



An object may be sent into different channels with probability distribution q_λ. Alice claims that the non-invasive measurement is performed at the earlier time t_A, whereas Bob performs the trusted quantum measurement at the later time t_B.

$$S_N \equiv \sum_{i=1}^{N} E\left[\langle B_{i,t_B}\rangle^2_{A_{i,t_A}}\right] \leq 1$$

$$E\left[\langle B_{i,t_B}\rangle^2_{A_{i,t_A}}\right] \equiv \sum_{a=\pm 1} P(A_i = a)\,\langle B_{i,t_B}\rangle^2_{A_{i,t_A}=a}$$

Experimental temporal quantum steering

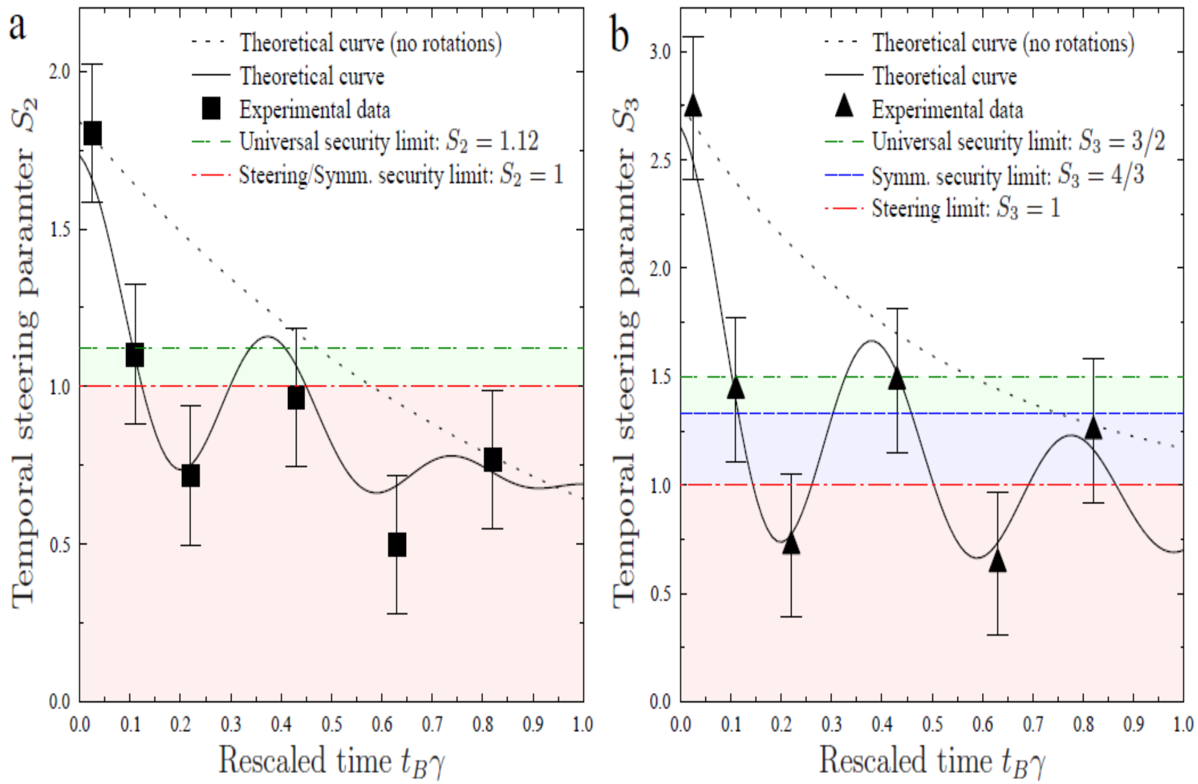


FIG. 2: **Evolution of the temporal steering parameters:** (a) S_2 for BB84 (implemented with the eigenvalues of the Pauli operators σ_1 and σ_2) and (b) S_3 for B98. Here, γ is the damping constant and t_B is the time of the nonunitary evolution between the measurements of Alice and Bob leading to the state defined in Eq. (5). The values of S_3 and S_2 if the rotation $R(4t_B)$ is not implemented (noise for σ_1 and σ_2 measurements is uniform) are given by the dotted curves $S_2 = 2s^2 \exp(-\gamma t_B)$ and $S_3 = s^2[2\exp(-2\gamma t_B) + 1]$, respectively. This also corresponds to our experiment for $4t_B = 2n\pi$, where $n = 0, 1, 2$. The shrinking factor $s = 0.96$ takes into account the initial impurity of the states sent by Alice

[K. Bartkiewicz *et al.*, Sci. Rep. 6, 38076 (2016)]

PRL **116,** 020503 (2016) PHYSICAL REVIEW LETTERS week ending 15 JANUARY 2016

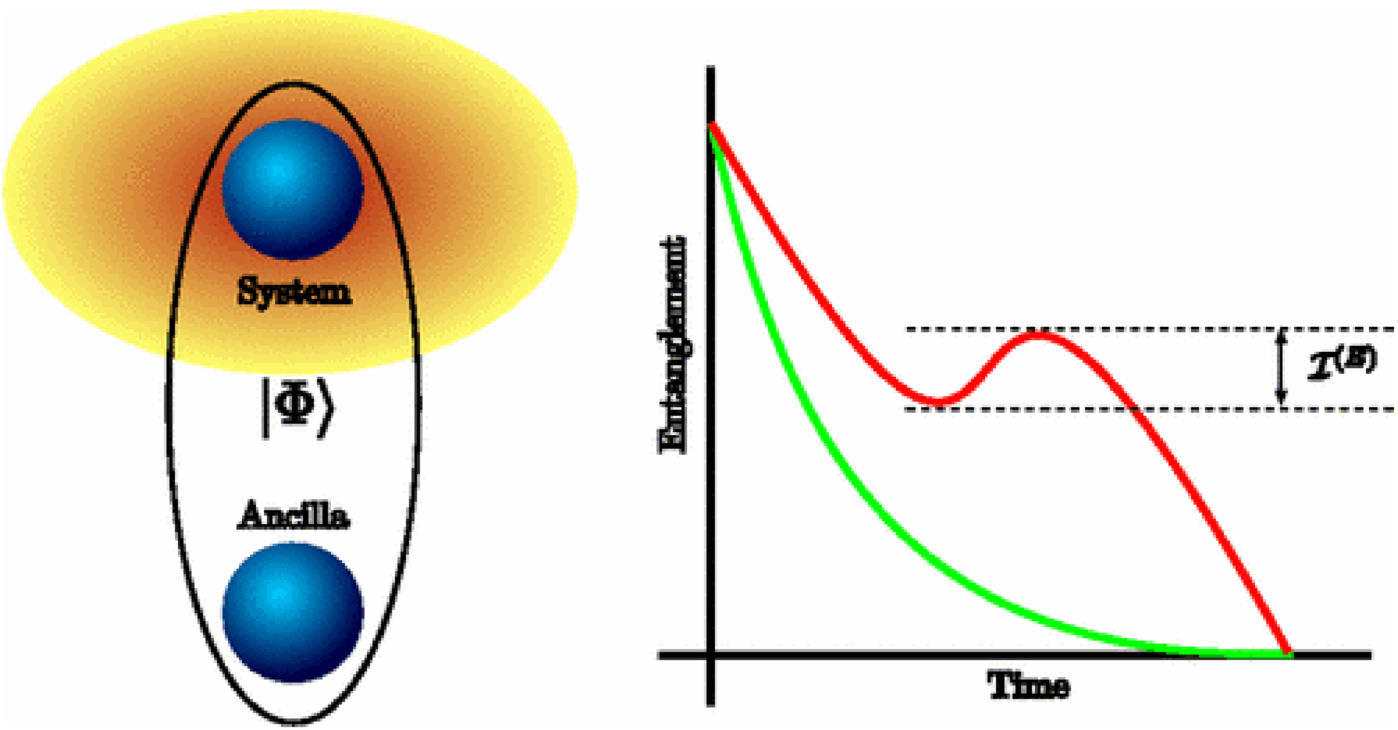
Quantifying Non-Markovianity with Temporal Steering

Shin-Liang Chen,[1] Neill Lambert,[2] Che-Ming Li,[3] Adam Miranowicz,[2,4] Yueh-Nan Chen,[1,2,*] and Franco Nori[2,5]
[1]*Department of Physics and National Center for Theoretical Sciences, National Cheng-Kung University, Tainan 701, Taiwan*
[2]*CEMS, RIKEN, 351-0198 Wako-shi, Japan*
[3]*Department of Engineering Science, National Cheng-Kung University, Tainan City 701, Taiwan*
[4]*Faculty of Physics, Adam Mickiewicz University, 61-614 Poznań, Poland*
[5]*Department of Physics, The University of Michigan, Ann Arbor, Michigan 48109-1040, USA*
(Received 7 August 2015; published 15 January 2016)

Einstein-Podolsky-Rosen (EPR) steering is a type of quantum correlation which allows one to remotely prepare, or steer, the state of a distant quantum system. While EPR steering can be thought of as a purely spatial correlation, there does exist a temporal analogue, in the form of single-system temporal steering. However, a precise quantification of such temporal steering has been lacking. Here, we show that it can be measured, via semidefinite programing, with a *temporal steerable weight*, in direct analogy to the recently proposed EPR steerable weight. We find a useful property of the temporal steerable weight in that it is a nonincreasing function under completely positive trace-preserving maps and can be used to define a sufficient and practical measure of strong non-Markovianity.

DOI: 10.1103/PhysRevLett.116.020503

What is non-Markovian?

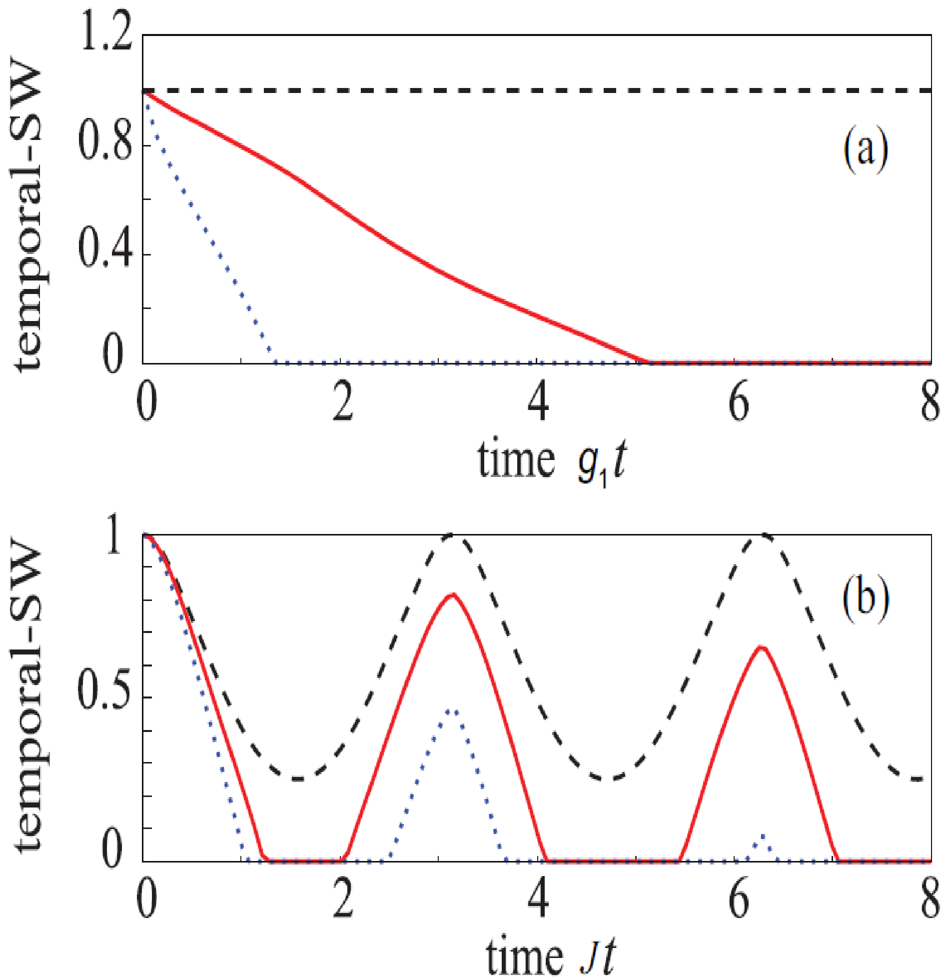


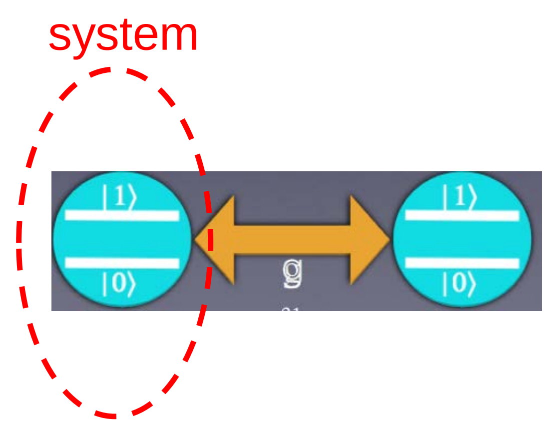
Ángel Rivas, Susana F. Huelga, and Martin B. Plenio, Phys. Rev. Lett. **105**, 050403 (2010)

Quantifying Non-Markovianity with Temporal Steering

EXAMPLE 1: COHERENT RABI OSCILLATIONS OF A MARKOVIAN SYSTEM

EXAMPLE 2: A SIMPLE NON-MARKOVIAN MODEL: A QUBIT COHERENTLY COUPLED TO ANOTHER QUBIT





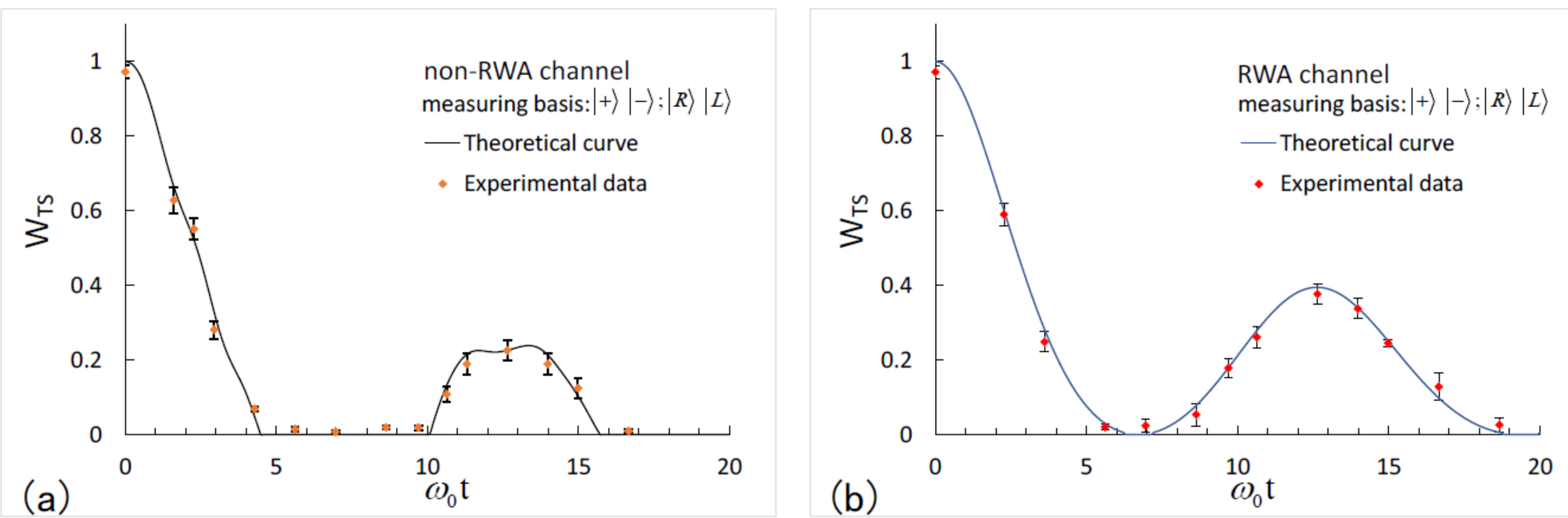
S. L. Chen, N. Lambert, C. M. Li, A. Miranowicz, Y. N. Chen*, and F. Nori,
Phys. Rev. Lett. 116, 020503 (2016).

Experimental simulation of quantum temporal steering beyond rotating-wave approximation

Shao-Jie Xiong,[1] Yu Zhang,[1] Zhe Sun,[1,*] Li Yu,[1] Jinshuang Jin,[1] Xiao-Qiang Xu,[1] Jin-Ming Liu,[2] and Chui-Ping Yang[1,†]

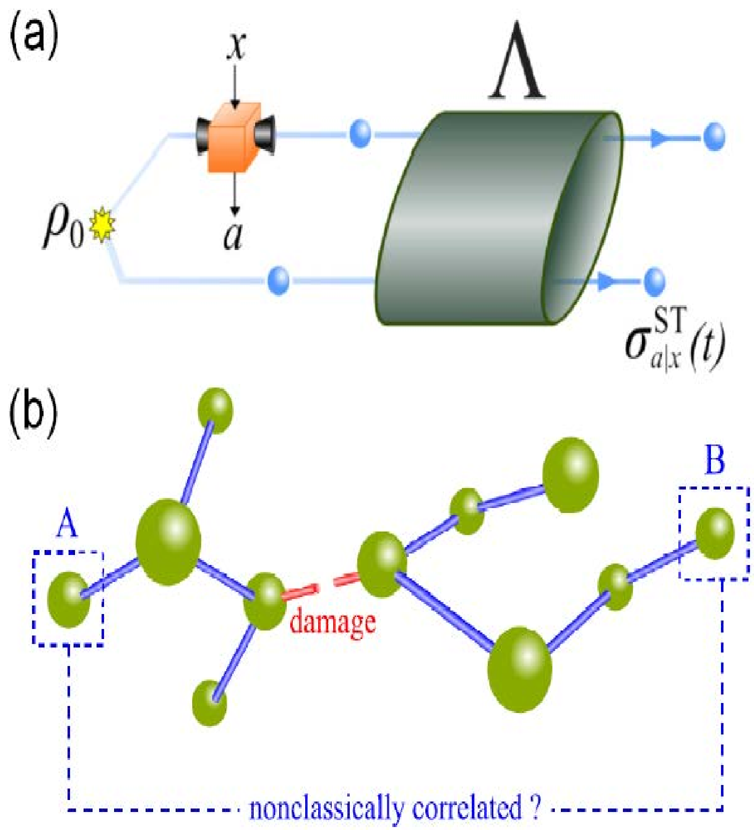
[1] *Department of Physics, Hangzhou Normal University, Hangzhou 310036, China*
[2] *State Key Laboratory of Precision Spectroscopy, East China Normal University, Shanghai 200062, China*

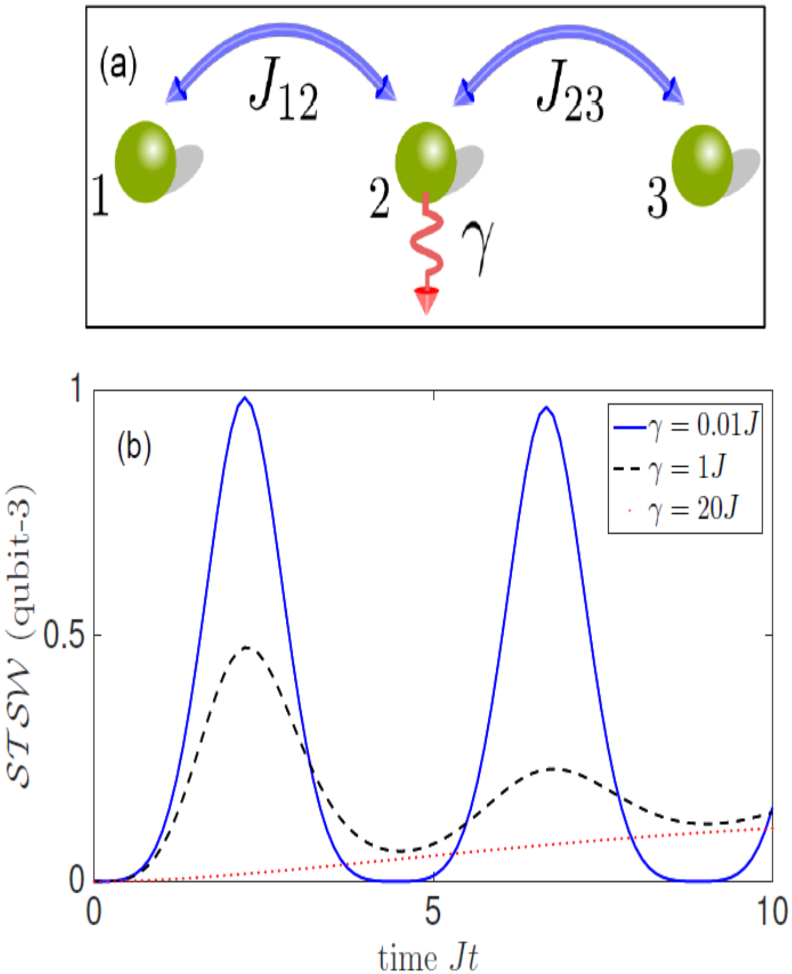
$$H_{\mathrm{Int}} = \sum_k \sigma_x \left(g_k b_k + g_k^* b_k^\dagger \right) \qquad H_{\mathrm{Int}}^{\mathrm{RWA}} = \sum_k \left(g_k \sigma_+ b_k + g_k^* \sigma_+ b_k^\dagger \right) \qquad J(\omega) = \frac{1}{2\pi} \frac{\gamma \lambda^2}{(\omega - \omega_0)^2 + \lambda^2}$$



S. J. Xiong *et al*., **Optica 4**, 1065 (2017)

Spatio-Temporal Quantum Steering for Testing Nonclassical Correlations in Quantum Networks





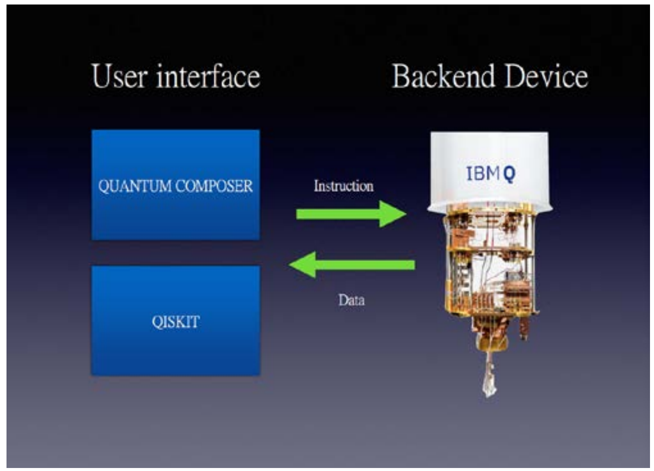
S. L. Chen, N. Lambert, C. M. Li, G. Y. Chen, Y. N. Chen*, A. Miranowicz, and F. Nori, Sci. Rep. 7, 3728 (2017)

Key Message:

Quantum Steering is a Resource!

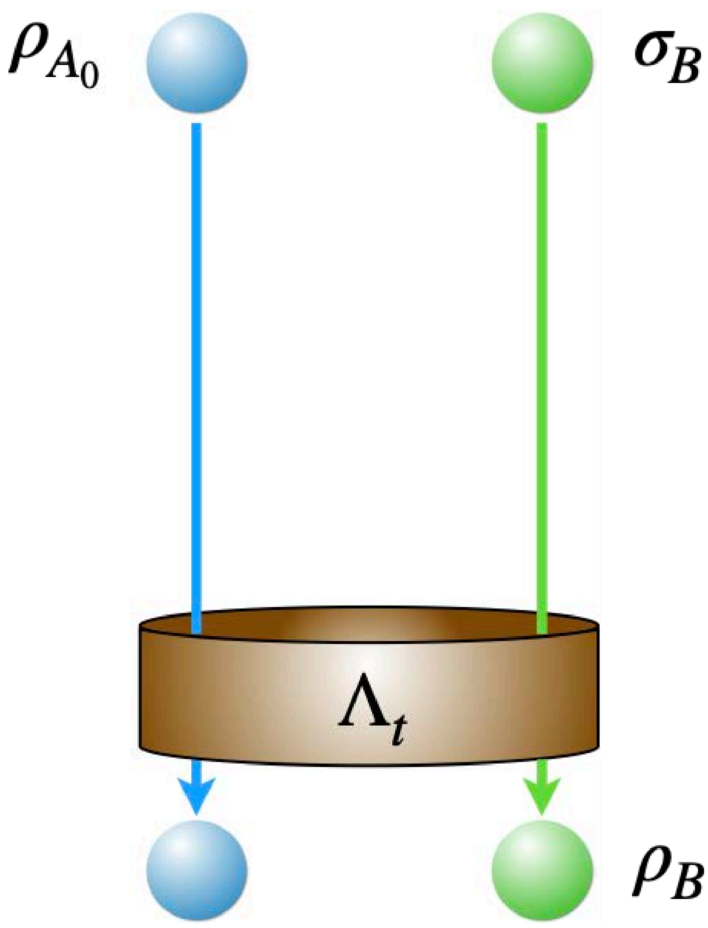
Benchmarking quantum state transfer using spatio-temporal steering

IBM Q



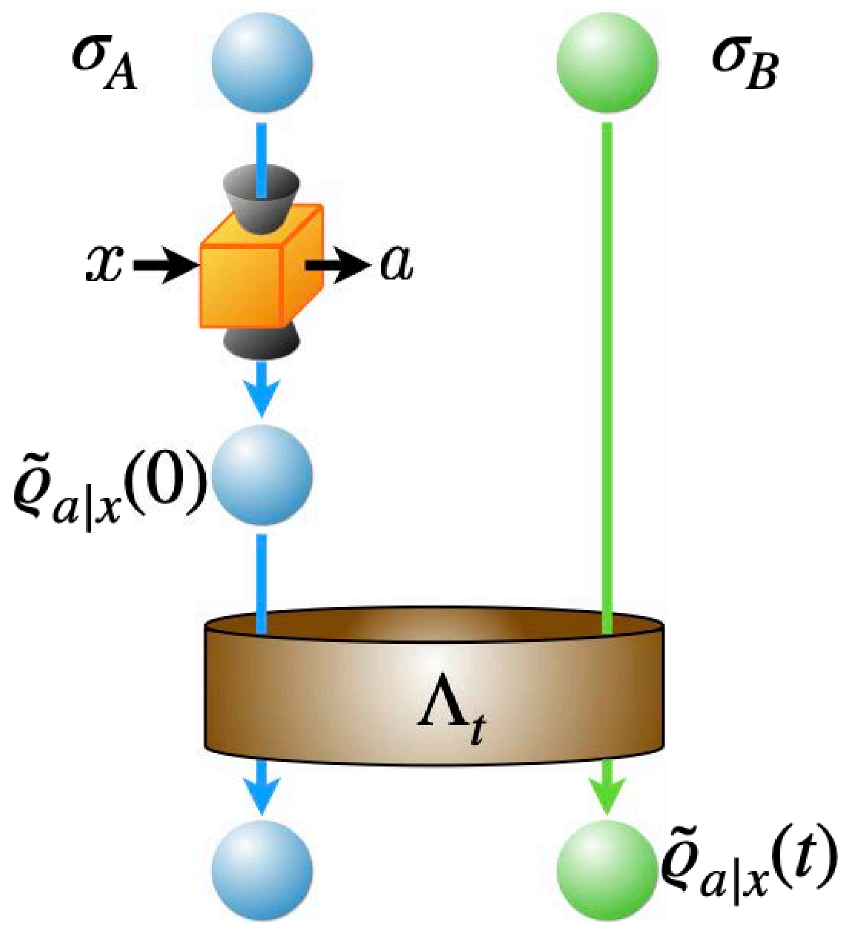
Quantum Devices @ QuTech

Quantum State Transfer



$$\rho_{\mathrm{B}} = \mathrm{Tr}_{\mathrm{A}}[\Lambda_t(\rho_{\mathrm{A}_0} \otimes \sigma_{\mathrm{B}})]$$

Spatio-Temporal Steering



$$\tilde{\varrho}_{a|x}(t) = \mathrm{Tr}_{\mathrm{A}}[\Lambda_t(\tilde{\varrho}_{a|x}(0) \otimes \sigma_{\mathrm{B}})]$$

Spatio-Temporal Steering Robustness (the quantifier)

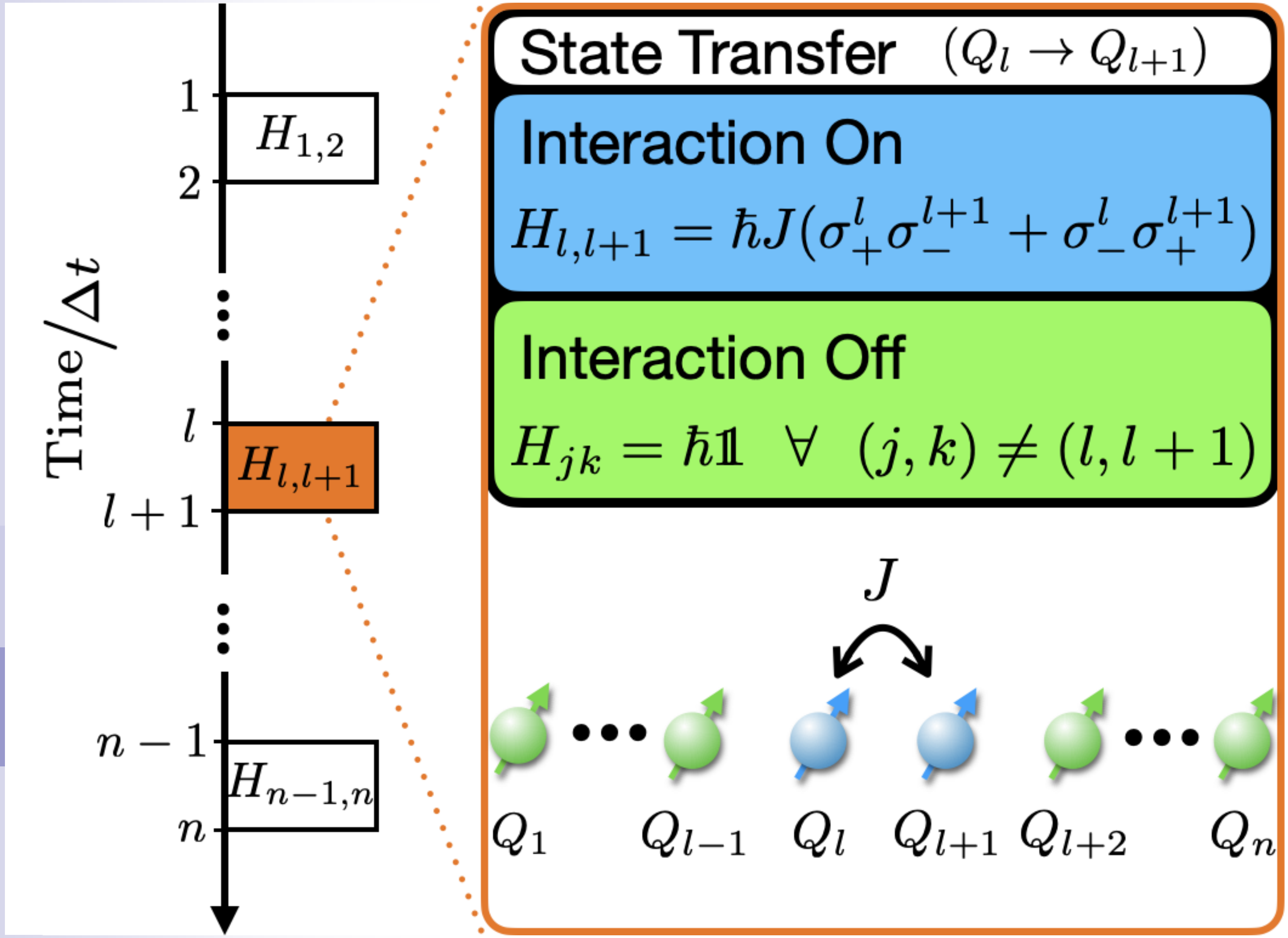
$$\mathcal{STSR}(\{\varrho_{a|x}(t)\}) = \min_{r,\{\tau_{a|x}\},\{\varrho^{\mathrm{LHS}}_{a|x}(t)\}} r \ ,$$

$$\text{s.t.} \quad \frac{1}{1+r}\varrho_{a|x}(t) + \frac{r}{1+r}\tau_{a|x} = \varrho^{\mathrm{LHS}}_{a|x}(t) \quad \forall\ a, x.$$

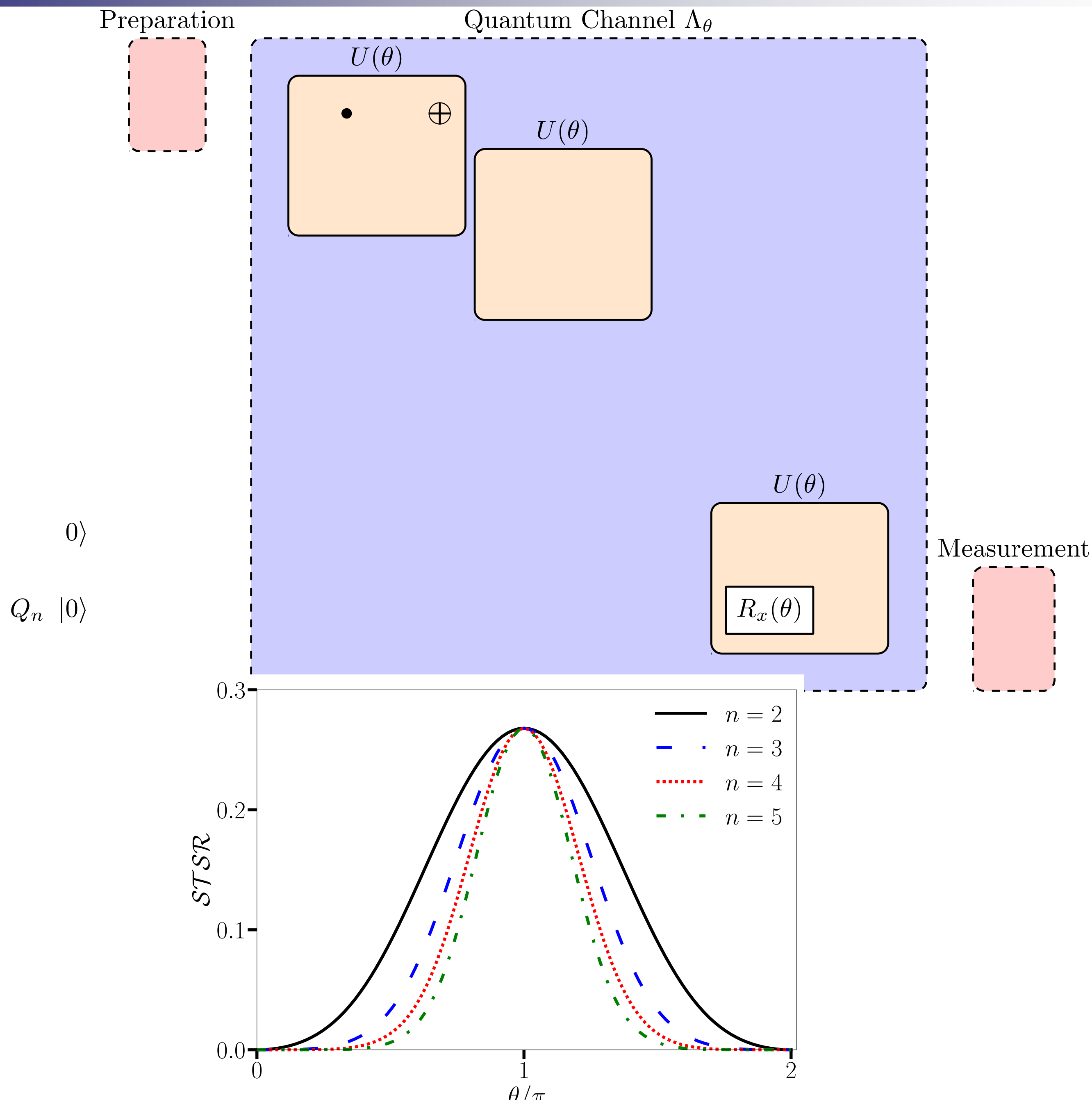
The no-signaling issue may arrise!!

Quantify Signaling effect

$$\mathcal{D} = \max_{x} \ \frac{1}{2}||\sum_{a}\varrho_{a|x}(t) - \sum_{a}\varrho_{a|x'}(t)||_1 \quad \forall \ \ x \neq x'$$

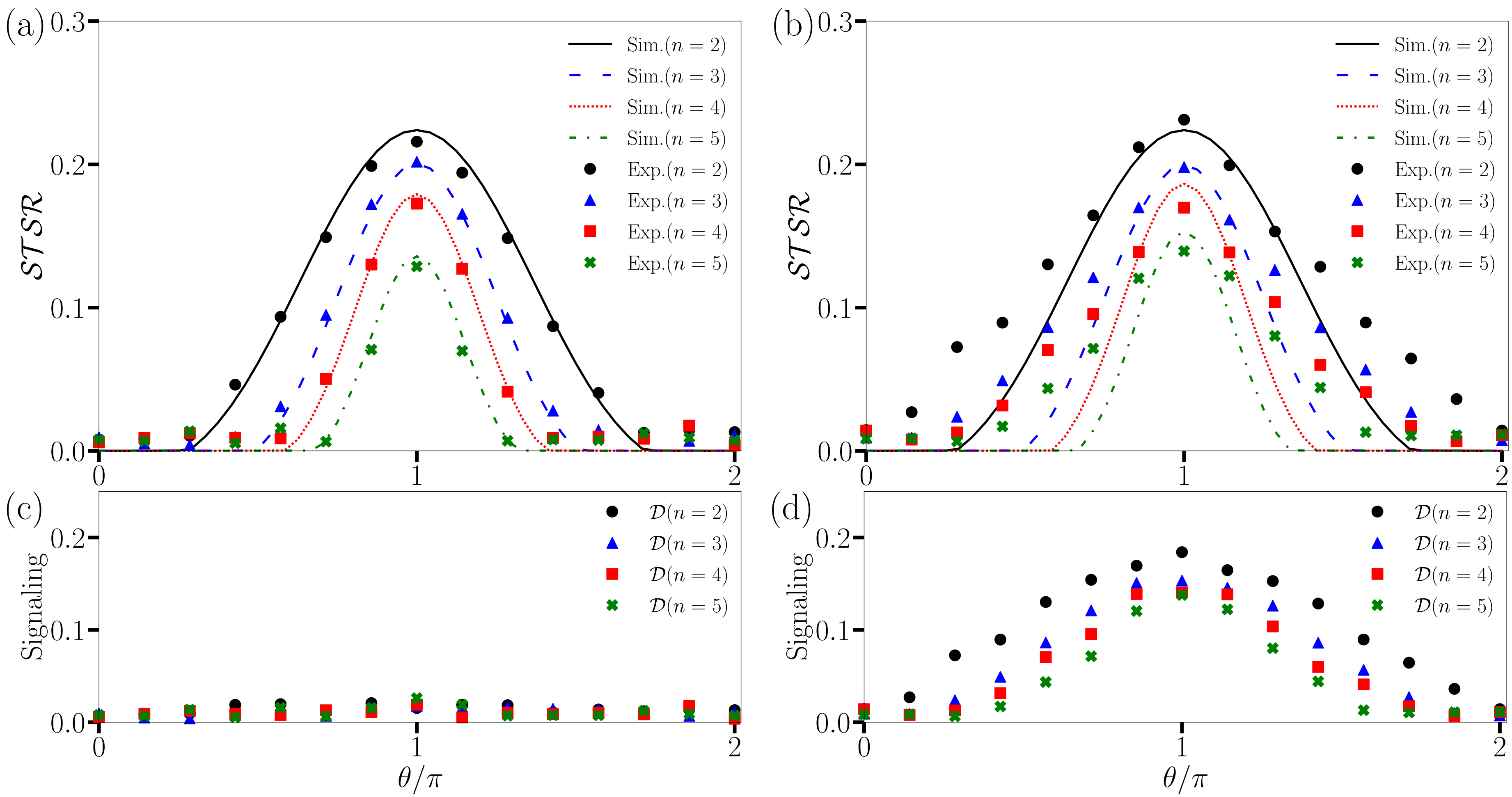


$$\Delta t = \frac{\pi}{2J}$$



Preparation
Quantum Channel Λ_θ
$U(\theta)$
$U(\theta)$
$U(\theta)$
$0\rangle$
Q_n $|0\rangle$
$R_x(\theta)$
Measurement
0.3
0.2
0.1
0.0
$\mathcal{STSR}$
0
1
2
θ/π
$n = 2$
$n = 3$
$n = 4$
$n = 5$

Experimental results on IBM Q



IBMQ boeblingen (Mar, 2020)

IBMQ boeblingen (Jan, 2020)

Experimental results on QuTech & IBM Q

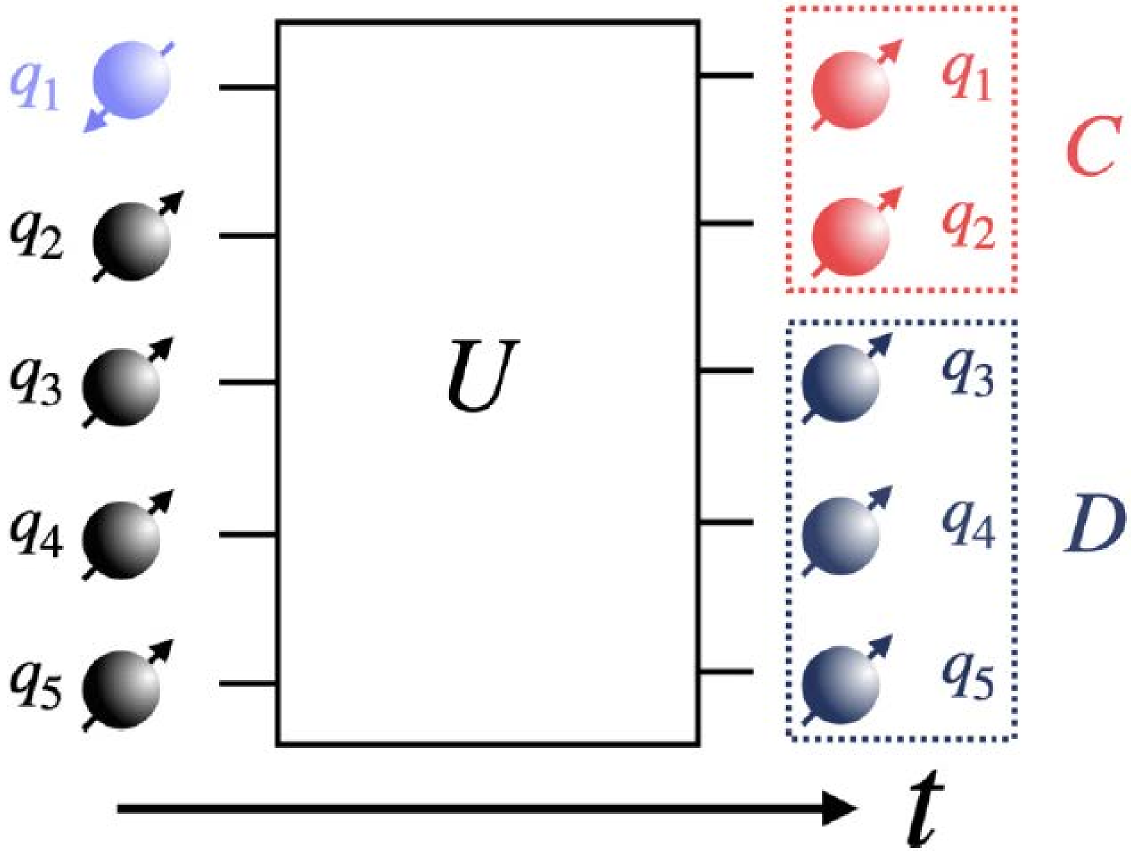
Devices	Transferred routes	n	$STSR$	Signaling
IBMQ boeblingen (Mar, 2020)	$0 \to 1 \to 2 \to 3 \to 4$	2	0.2159	0.0153
		3	0.2019	0.0177
		4	0.1726	0.0190
		5	0.1288	0.0261
QuTech starmon-5 (May, 2020)	$0 \to 2 \to 4$	2	0.1701	0.0515
		3	0.0543	0.0353
QuTech spin-2 (May, 2020)	$0 \to 1$	2	0.1030	0.1002

[Yi-Te Huang, Jhen-Dong Lin, Huan-Yu Ku, and Yueh-Nan Chen*, Phys. Rev. Research 3, 023038 (2021)]

Quantum Scrambling

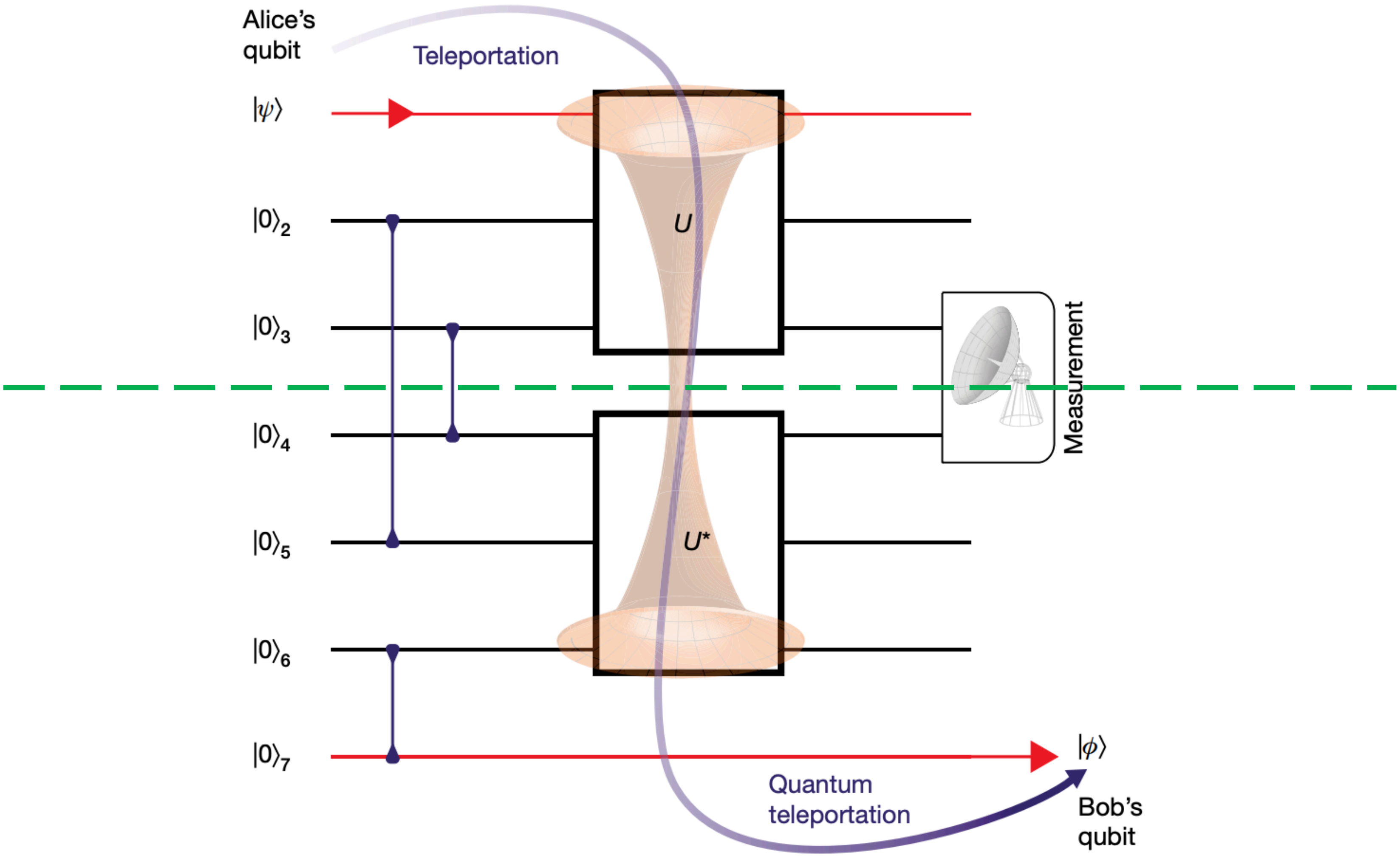
How information spread throughout the whole system

Scrambling Unitary



Information is not lost, just spread throughout the whole system!

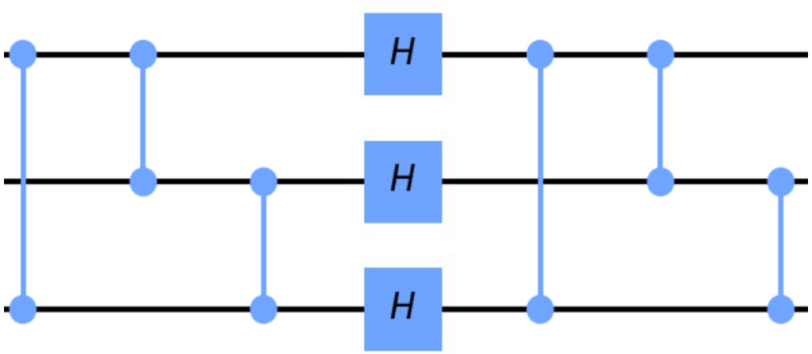
Verified quantum information scrambling



K. A. Landsman, C. Figgatt, T. Schuster, N. M. Linke, B. Yoshida, N. Y. Yao, and C. Monroe, Nature **567**, 61-65 (2019)

Scrambling Unitary

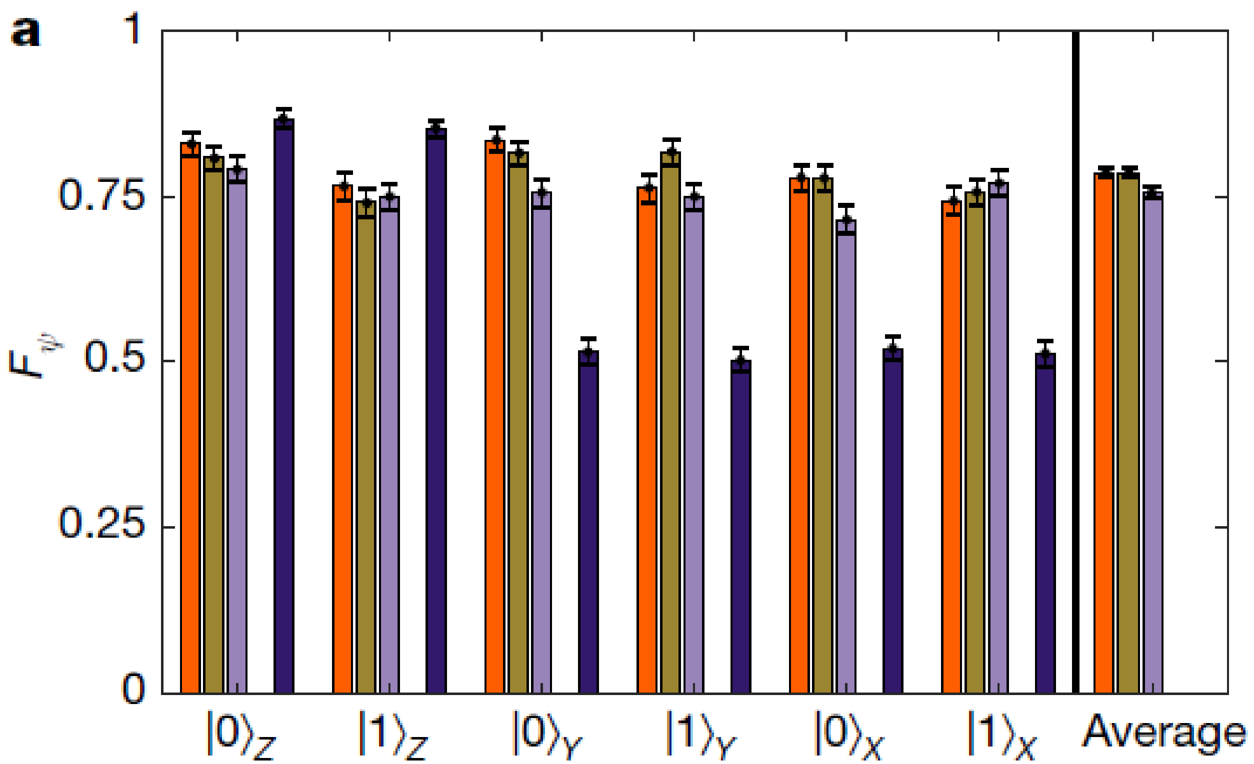
$$U_s = \frac{i}{2}\begin{pmatrix} -1 & 0 & 0 & -1 & 0 & -1 & -1 & 0 \\ 0 & 1 & -1 & 0 & -1 & 0 & 0 & 1 \\ 0 & -1 & 1 & 0 & -1 & 0 & 0 & 1 \\ 1 & 0 & 0 & 1 & 0 & -1 & -1 & 0 \\ 0 & -1 & -1 & 0 & 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & -1 & 0 & 1 & -1 & 0 \\ 1 & 0 & 0 & -1 & 0 & -1 & 1 & 0 \\ 0 & -1 & -1 & 0 & -1 & 0 & 0 & -1 \end{pmatrix}$$



Delocalization

$$U_s(\sigma_x \otimes \mathbb{1} \otimes \mathbb{1})U_s^\dagger = -\sigma_x \otimes \sigma_y \otimes \sigma_y$$
$$U_s(\sigma_y \otimes \mathbb{1} \otimes \mathbb{1})U_s^\dagger = -\sigma_y \otimes \sigma_z \otimes \sigma_z$$
$$U_s(\sigma_z \otimes \mathbb{1} \otimes \mathbb{1})U_s^\dagger = -\sigma_z \otimes \sigma_x \otimes \sigma_x$$
$$U_s(\mathbb{1} \otimes \sigma_x \otimes \mathbb{1})U_s^\dagger = -\sigma_y \otimes \sigma_x \otimes \sigma_y$$
$$U_s(\mathbb{1} \otimes \sigma_y \otimes \mathbb{1})U_s^\dagger = -\sigma_z \otimes \sigma_y \otimes \sigma_z$$
$$U_s(\mathbb{1} \otimes \sigma_z \otimes \mathbb{1})U_s^\dagger = -\sigma_x \otimes \sigma_z \otimes \sigma_x$$
$$U_s(\mathbb{1} \otimes \mathbb{1} \otimes \sigma_x)U_s^\dagger = -\sigma_y \otimes \sigma_y \otimes \sigma_x$$
$$U_s(\mathbb{1} \otimes \mathbb{1} \otimes \sigma_y)U_s^\dagger = -\sigma_z \otimes \sigma_z \otimes \sigma_y$$
$$U_s(\mathbb{1} \otimes \mathbb{1} \otimes \sigma_z)U_s^\dagger = -\sigma_x \otimes \sigma_x \otimes \sigma_z$$

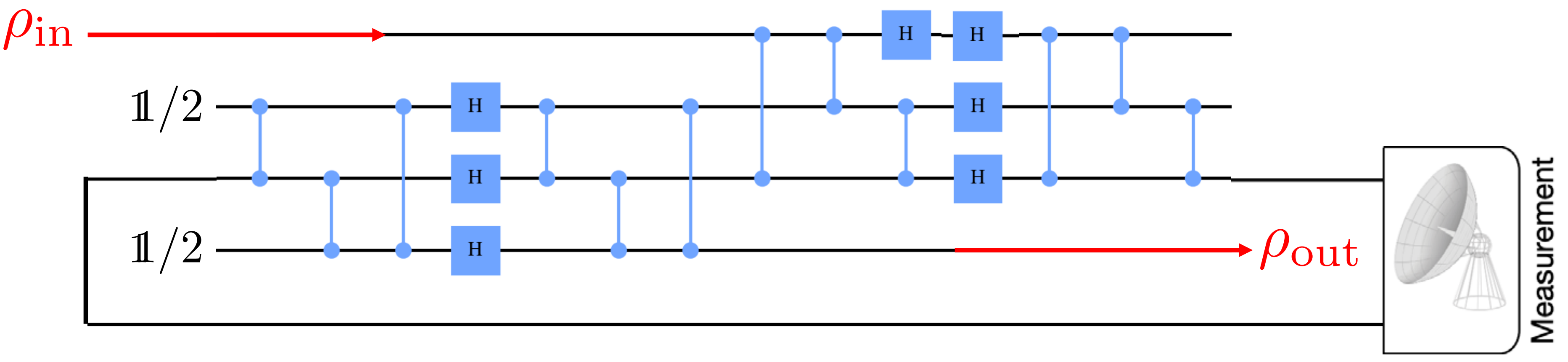
Teleportation fidelity



Measured teleportation fidelities are typically about 80 %.

K. A. Landsman, C. Figgatt, T. Schuster, N. M. Linke, B. Yoshida, N. Y. Yao, and C. Monroe, Nature **567**, 61-65 (2019)

Equivalent Circuit on Ion-Q



Bell State measurement with outcome ’00’

STSR : 0.091

Signaling : 0.085

Fidelity	
$\vert x_+\rangle$	0.862
$\vert x_-\rangle$	0.892
$\vert y_+\rangle$	0.933
$\vert y_-\rangle$	0.916
$\vert z_+\rangle$	0.922
$\vert z_-\rangle$	0.940

Summary

- Quantifying temporal quantum steering
  --measure of non-Markovianity
- Benchmarking quantum state transfer in the cloud (IBM Q & QuTech)
- Quantum scrambling on Ion-Q

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Thank you for your attention!

QFort

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