The 8th IWSSQC

Dec. 14 (2016)

Spatio-Temporal Quantum Steering

Y. N. Chen*, C. M. Li, N. Lambert, Y. Ota, S. L. Chen, G. Y. Chen, and F. Nori,
Phys. Rev. A 89, 032112 (2014)
S. L. Chen, N. Lambert, C. M. Li, A. Miranowicz, Y. N. Chen*, and F. Nori,
Phys. Rev. Lett. 116, 020503 (2016)
S. L. Chen, N. Lambert, C. M. Li, G. Y. Chen, Y. N. Chen*, A. Miranowicz, and F. Nori,
arXiv:1608.03150 (2016)

Yueh-Nan Chen

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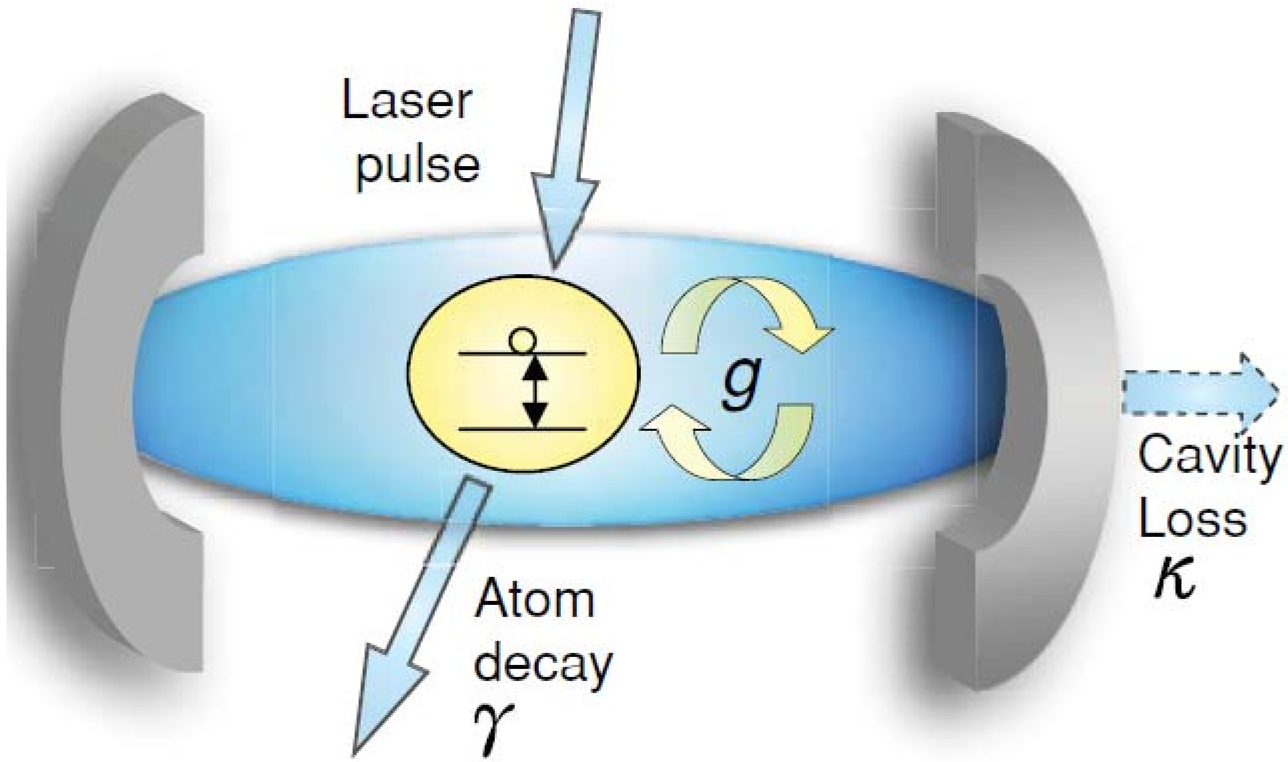
National Center for Theoretical Sciences

Cavity QED

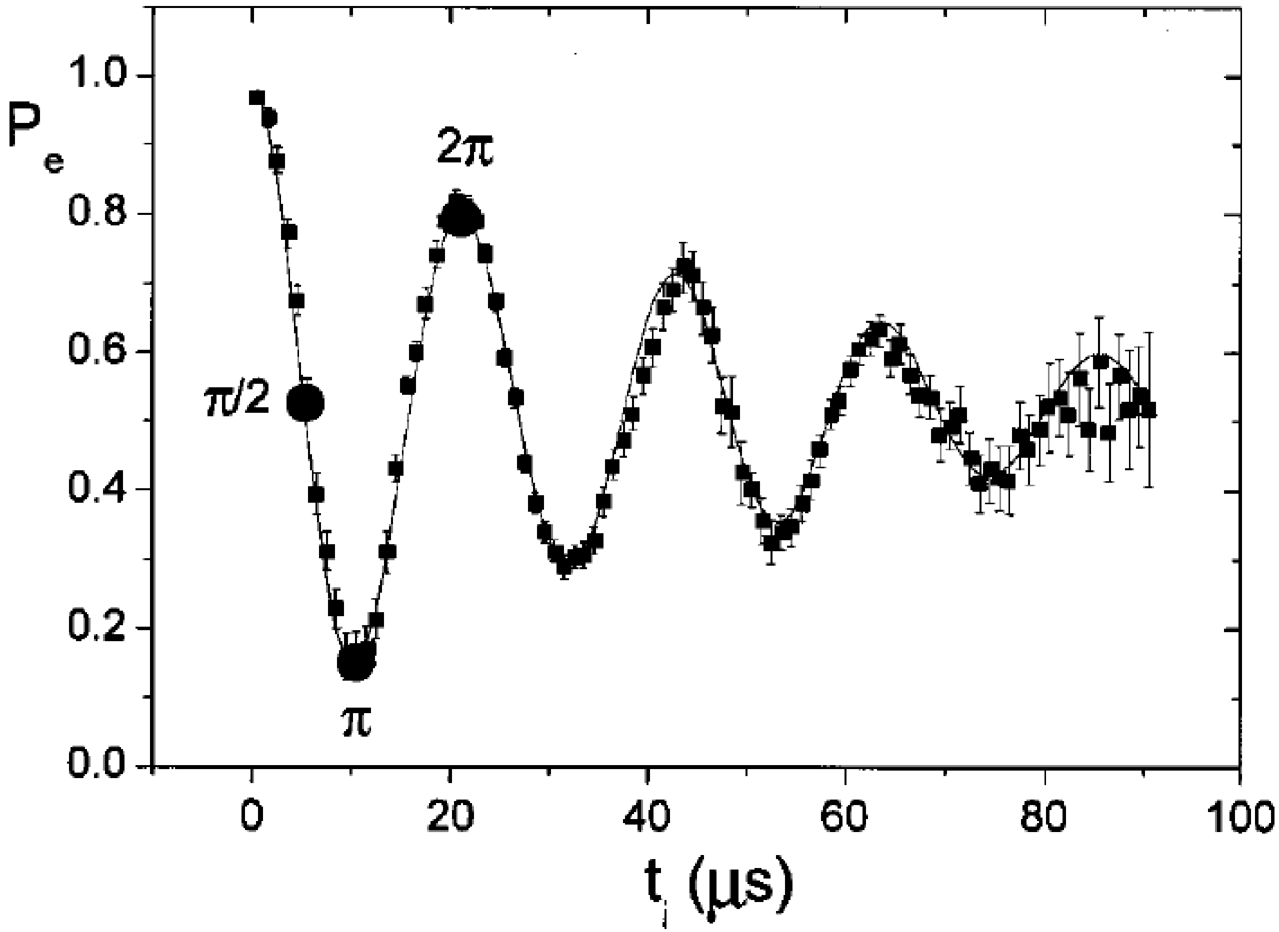
Two-level atom inside a cavity

The interaction between the atom and single-mode cavity:

$$H' = \hbar g(\sigma_+ b^- + \sigma_- b^+) \qquad \left|\Psi(t)\right\rangle = f_+(t)\left|+;0\right\rangle + f_-(t)\left|-;1\right\rangle$$

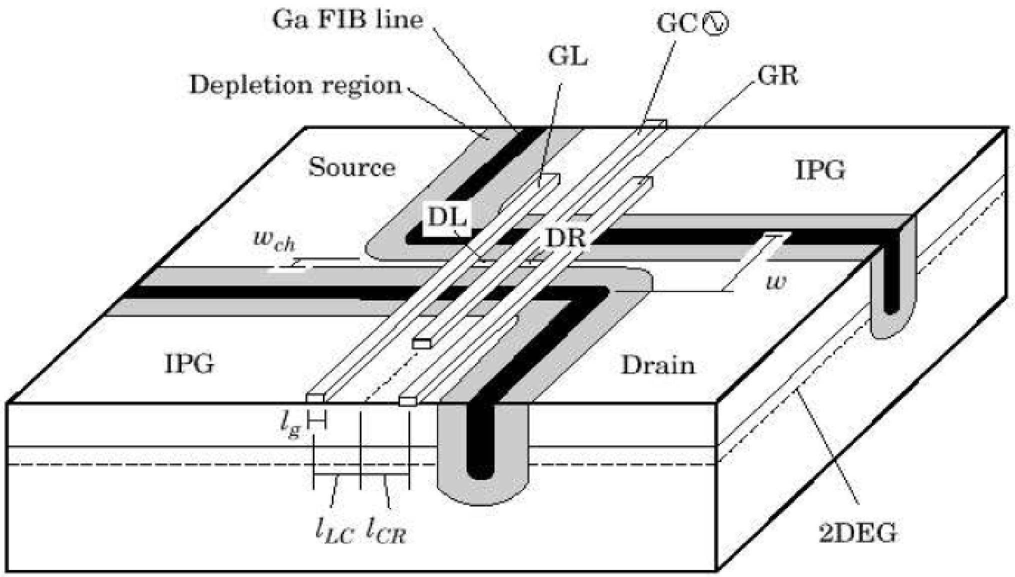


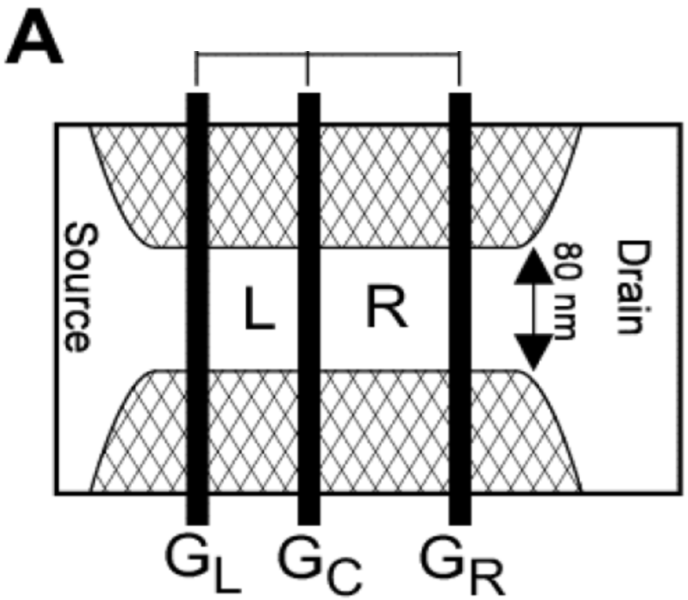
Vacuum Rabi oscillations

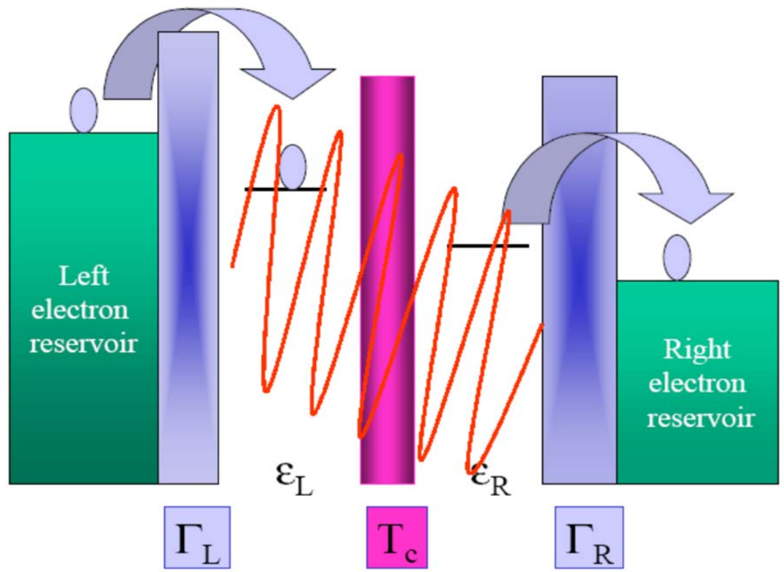


J. M. Raimond, M. Brune, and S. Haroche, Rev. Mod. Phys. **73,** 565 (2001).

Gate-confined Double Quantum Dots



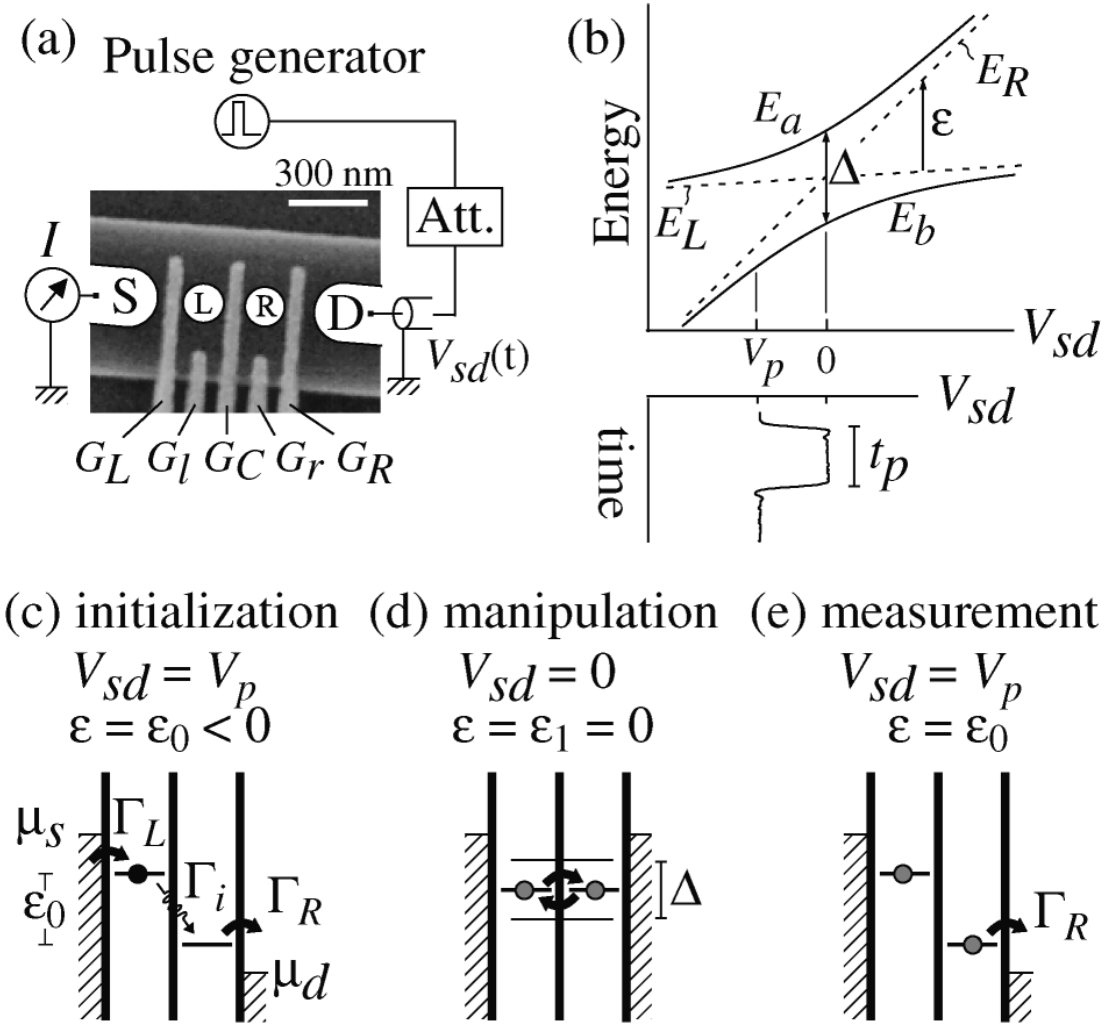


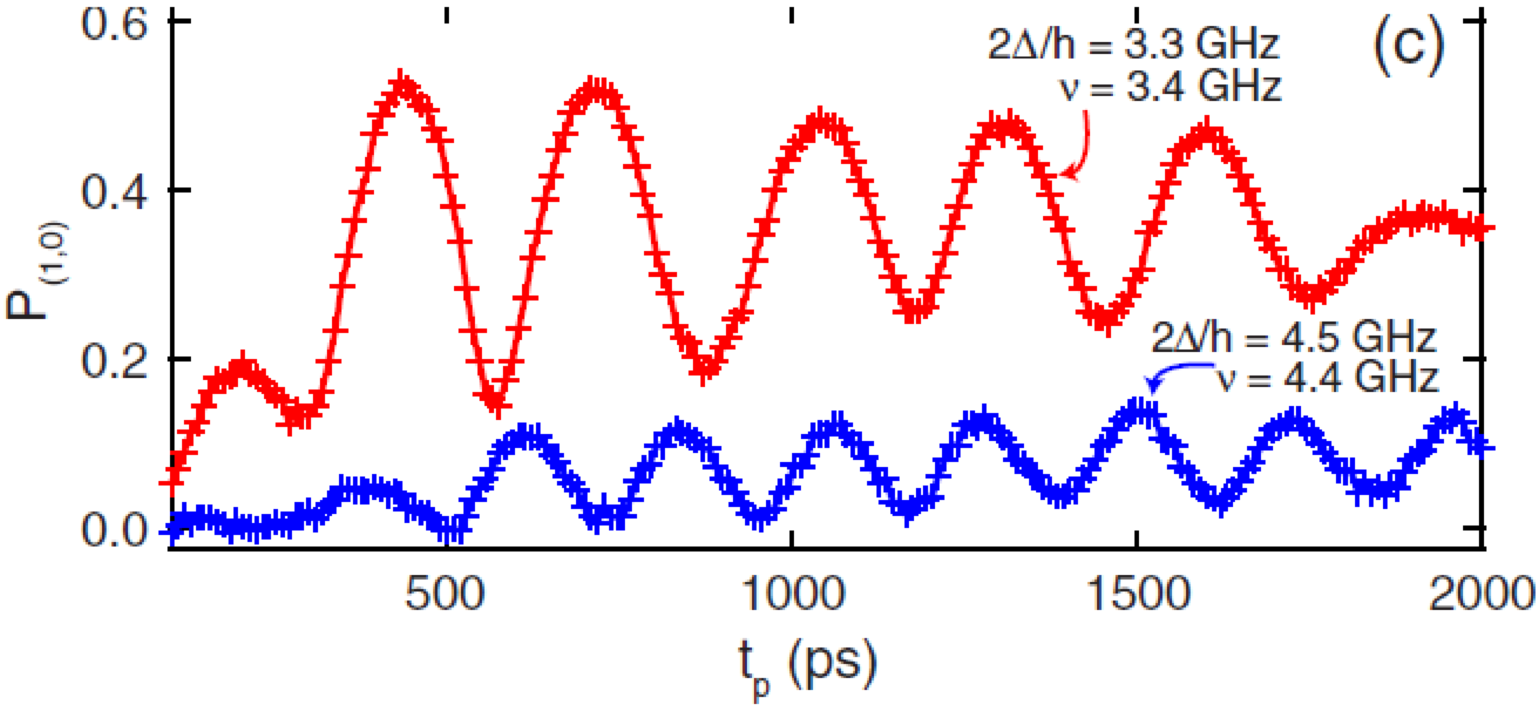


T. Brandes, **Phys. Rep. 408**, 315 (2005)

Quantum Coherence in Double Quantum Dots

$$H = \frac{1}{2}\epsilon\sigma_z + \Delta\sigma_x$$

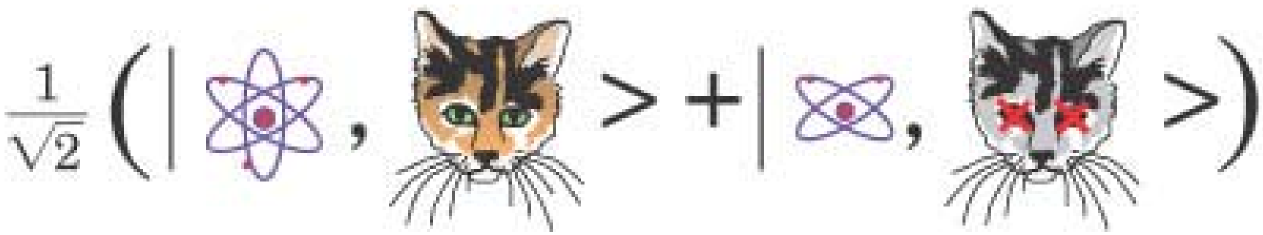




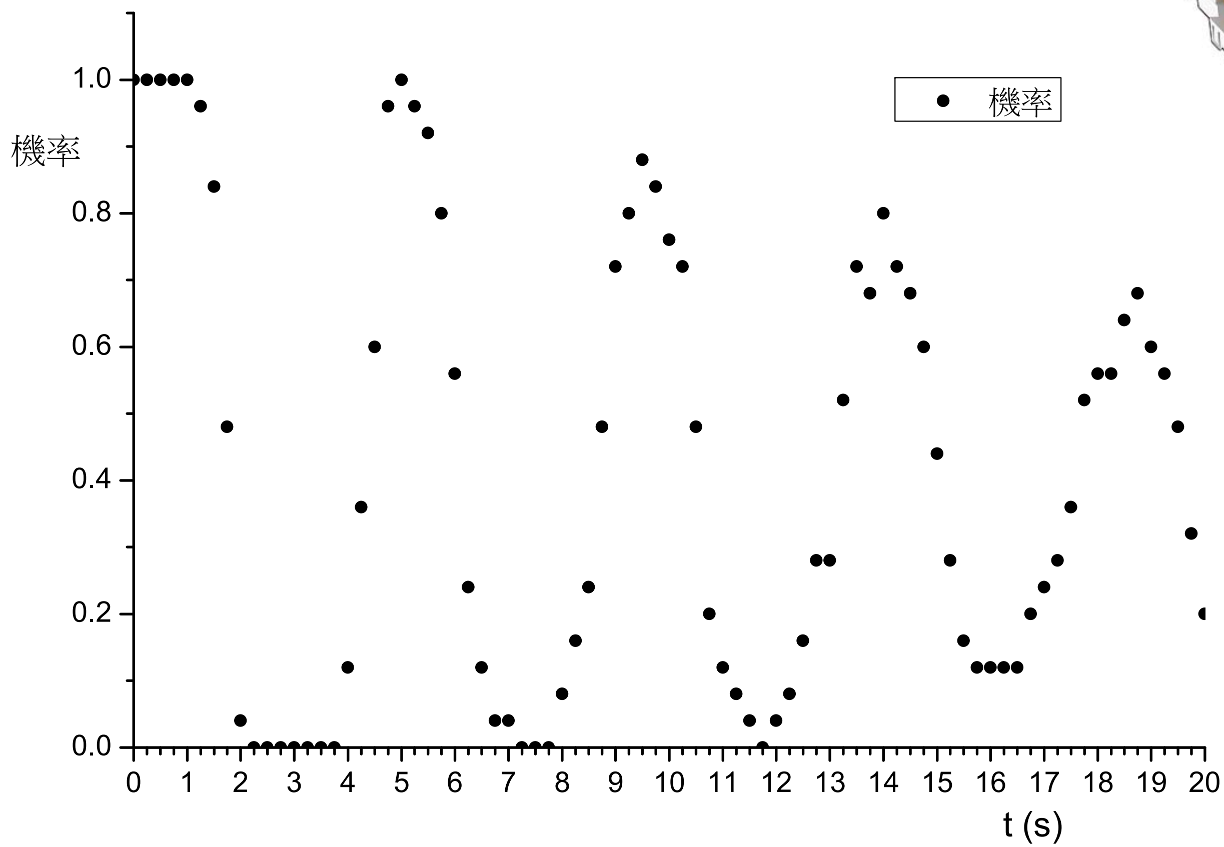
K. D. Petersson, J. R. Petta, H. Lu, and A. C. Gossard, PRL 105, 246804 (2010)

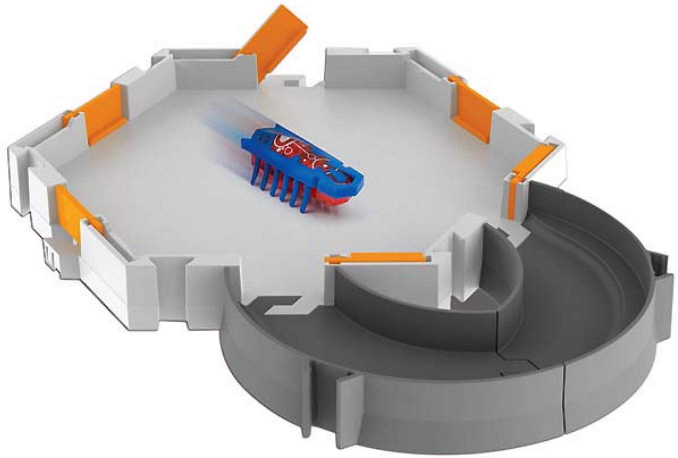
Question:

Are they truly quantum?



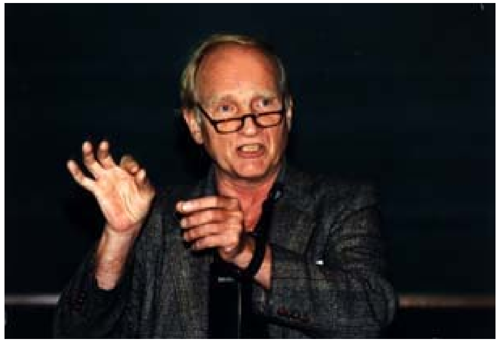
The Robotic Bugs

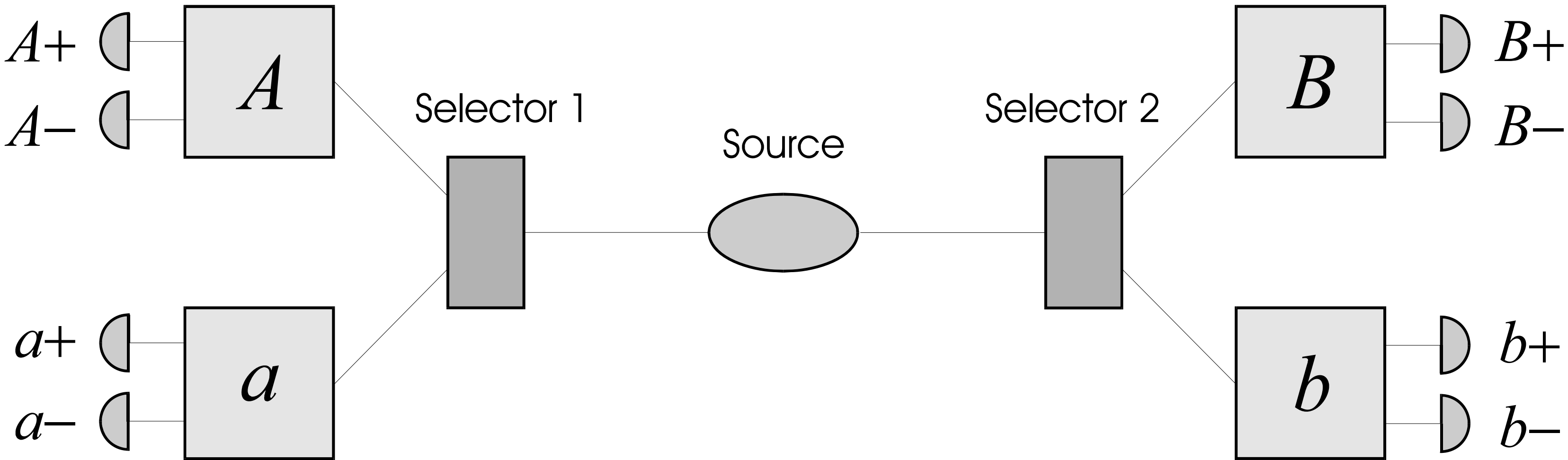




Quantum vs Classical

Bell’s Inequality: Locality and Realism



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

The Bell-CHSH inequality

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

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

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

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

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

Predictions of QM for the *singlet* state

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

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

QM violates the Bell-CHSH inequality

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

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

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

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

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

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

$$\boxed{F_{\text{QM}} = 2\sqrt{2} > 2!!!}$$

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.

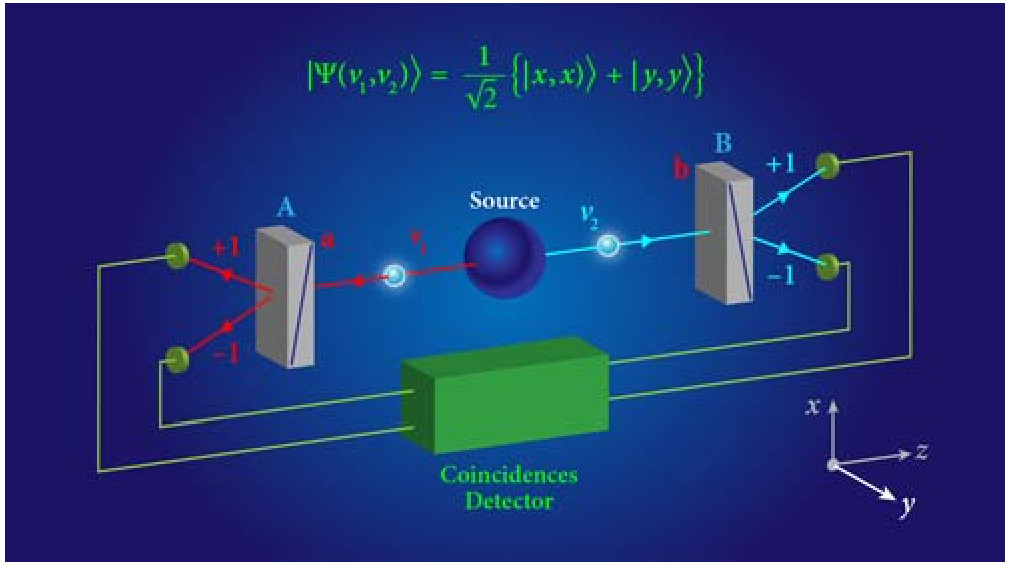
VOLUME 49, NUMBER 25 PHYSICAL REVIEW LETTERS 20 DECEMBER 1982

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?

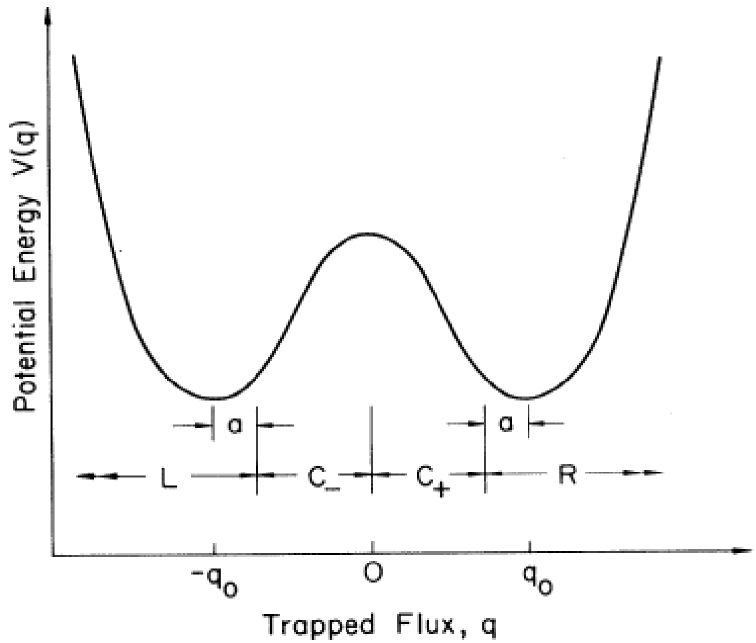


FIG. 1. The potential $V(q)$ for the trapped flux q. The various notations are explained in the text.

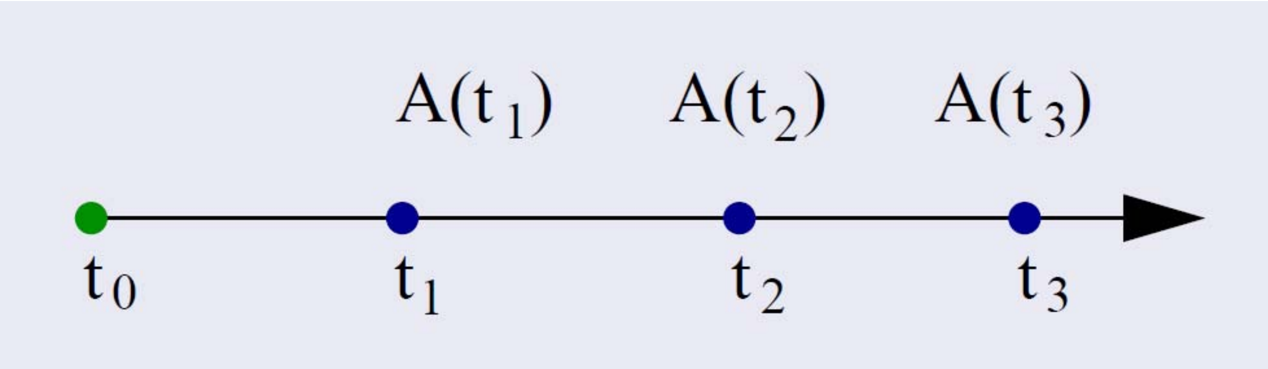
Leggett and Garg, **Phys. Rev. Lett. 54**, 857–860 (1985)
C. Emary, N. Lambert, F. Nori, **Rep. Prog. Phys. 77**, 016001 (2014)

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,

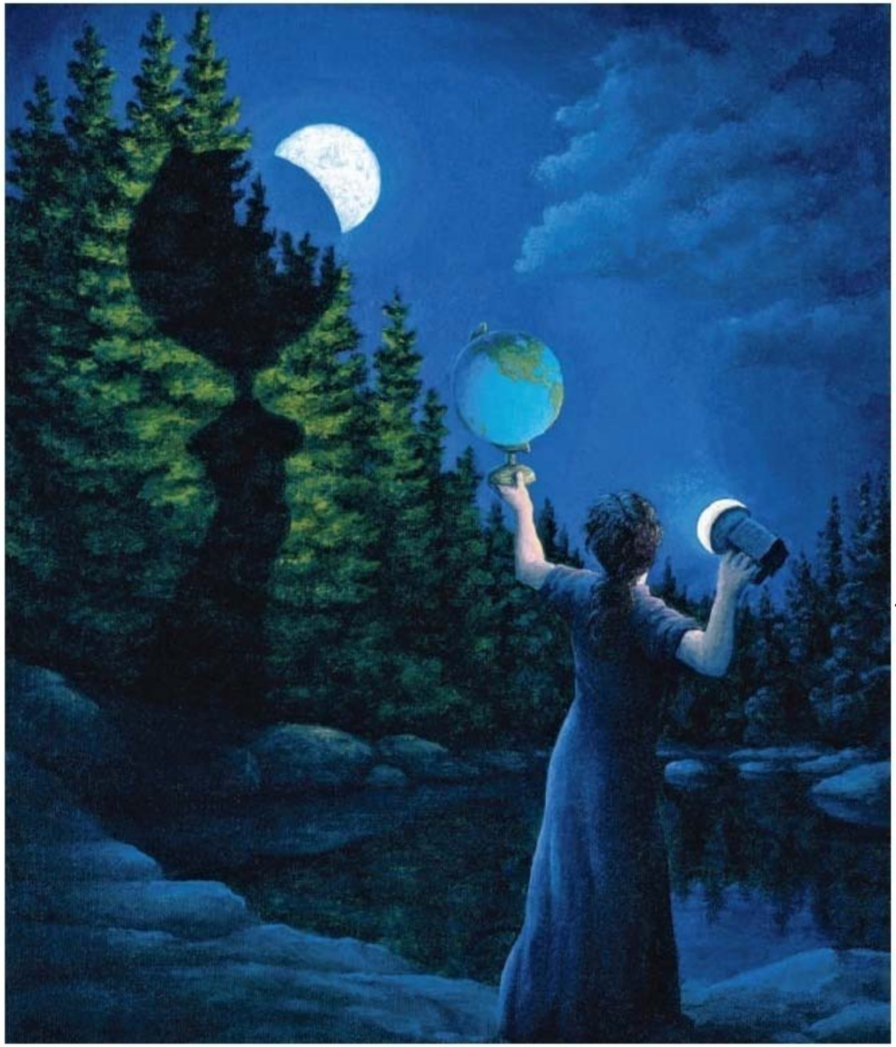
$$\boxed{\langle A(t_2)A(t_1)\rangle + \langle A(t_3)A(t_2)\rangle - \langle A(t_3)A(t_1)\rangle \leq 1}$$

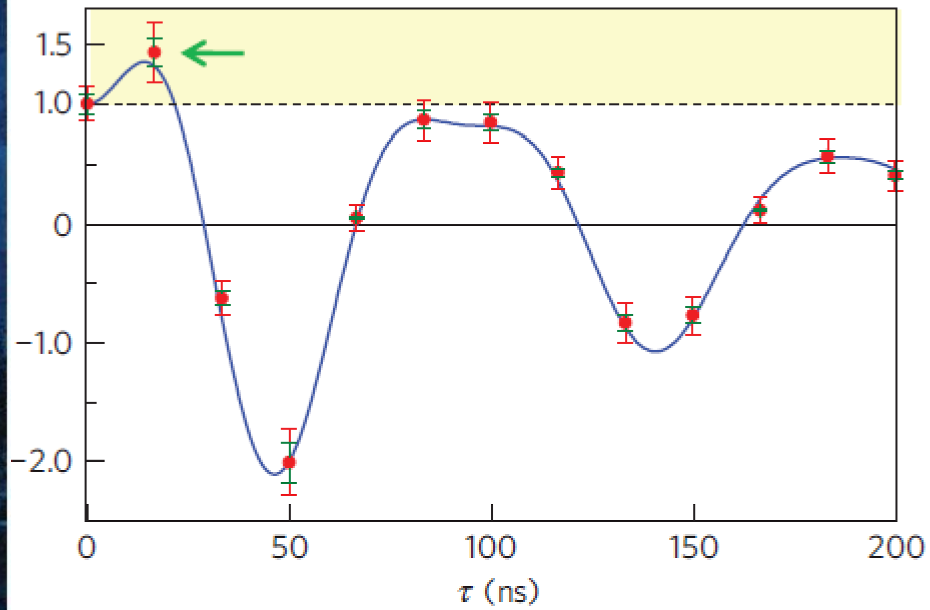


$\Rightarrow$ This can be violated by QM systems!

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

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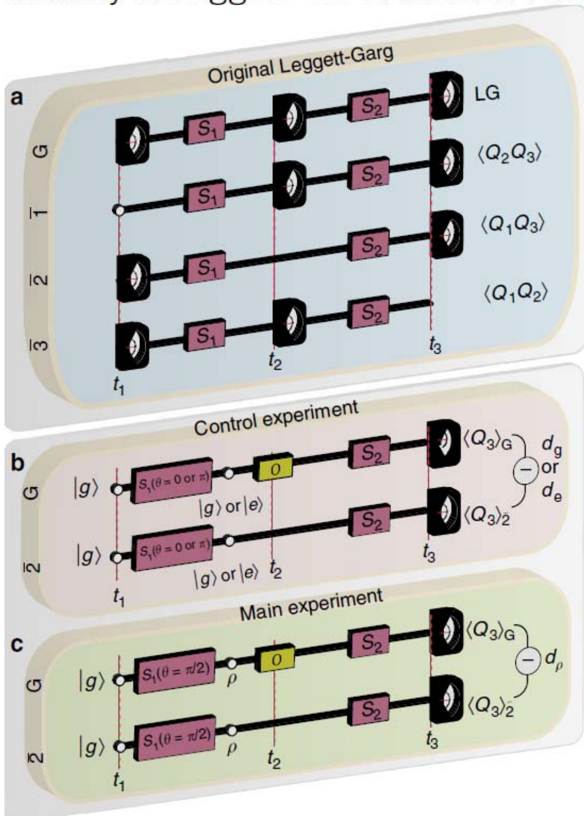
DOI: 10.1038/ncomms13253 OPEN

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

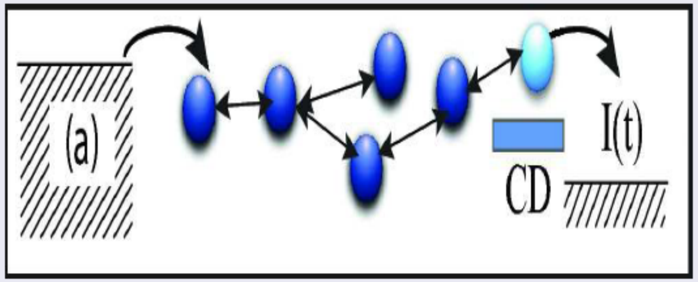
George C. Knee[1,⋆,†], Kosuke Kakuyanagi[1,⋆], Mao-Chuang Yeh[2,⋆], Yuichiro Matsuzaki[1], Hiraku Toida[1], Hiroshi Yamaguchi[1], Shiro Saito[1], Anthony J. Leggett[2] & William J. Munro[1]



Distinguishing Quantum and Classical Transport through Nanostructures

Transport Charge Inequality:

Open, nonequillibrium system



cf. Ruskov '06, weak measurement of closed system

Charge detection

measure charge, Q

- non-invasive
- system in state n: $Q_n \geq 0$
- max value: $Q_N = Q_{\max}$

e.g. QPC

Charge inequality

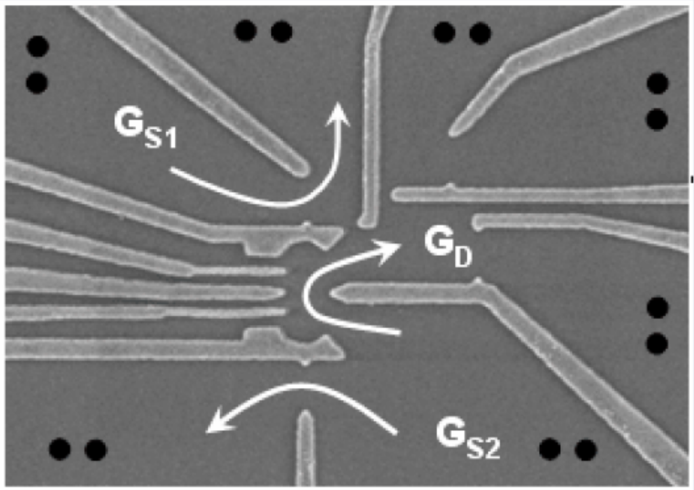
Stationary LG with $A = 2Q/Q_{\max} - 1$; $t_2 - t_1 = t_3 - t_2 = t$:

$$\boxed{|2\langle Q(t)Q\rangle - \langle Q(2t)Q\rangle| \leq Q_{\max}\langle Q\rangle}$$

N. Lambert, C. Emary, Y. N. Chen, and F. Nori, **Phys. Rev. Lett. 105**, 176801 (2010)

Double Quantum Dot

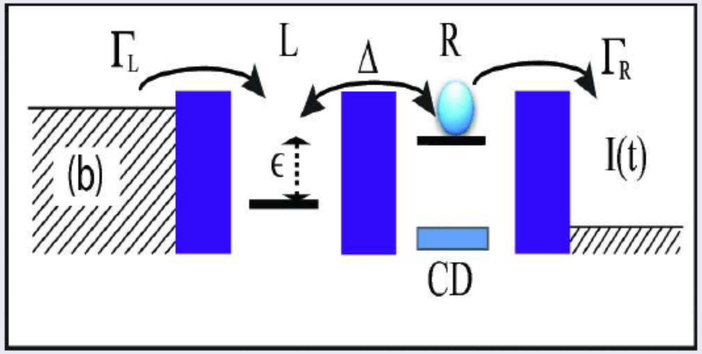
Experiment



Manipulation of a single charge in a double quantum dot

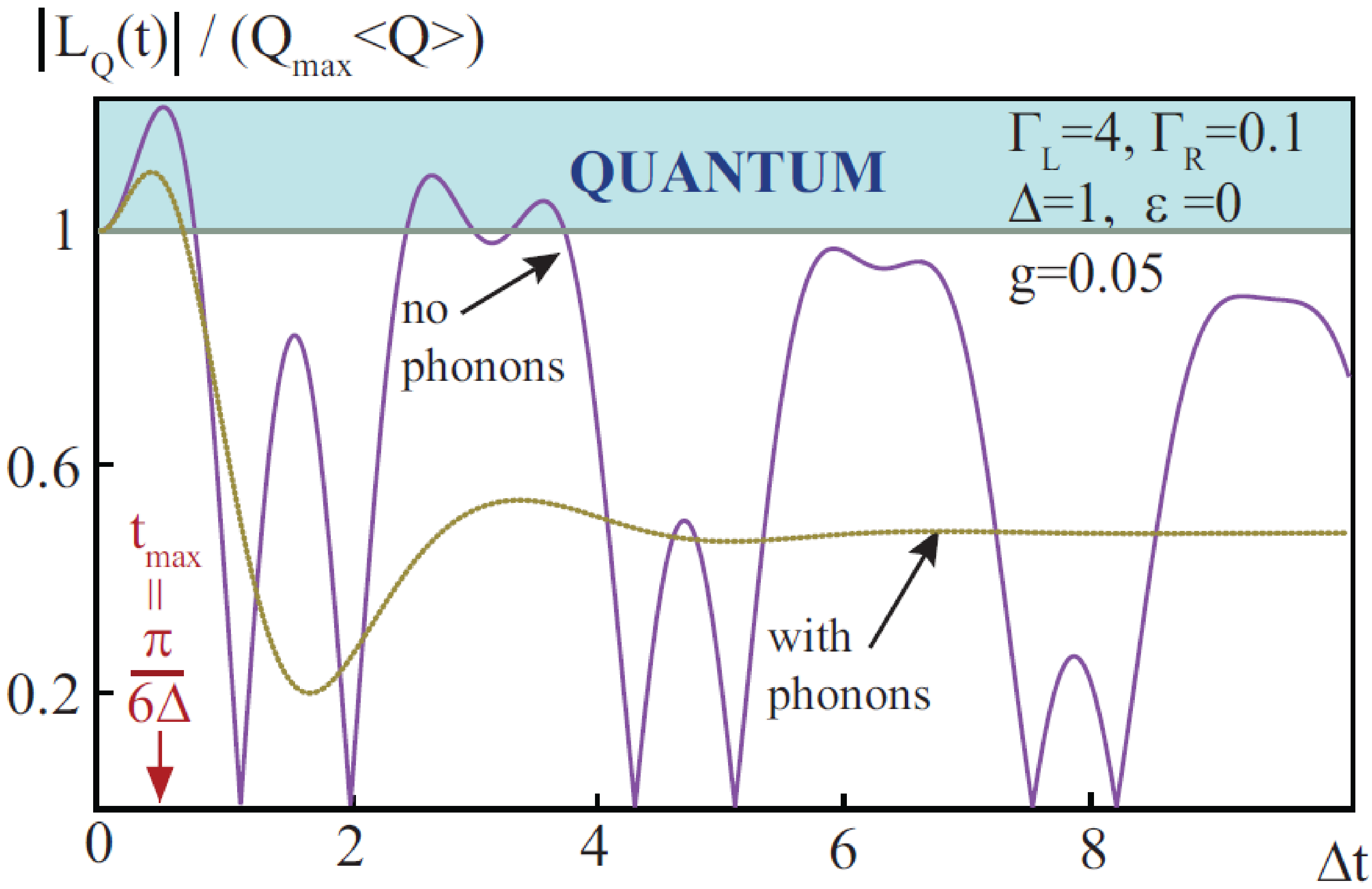
Petta et al. PRL '04

Model



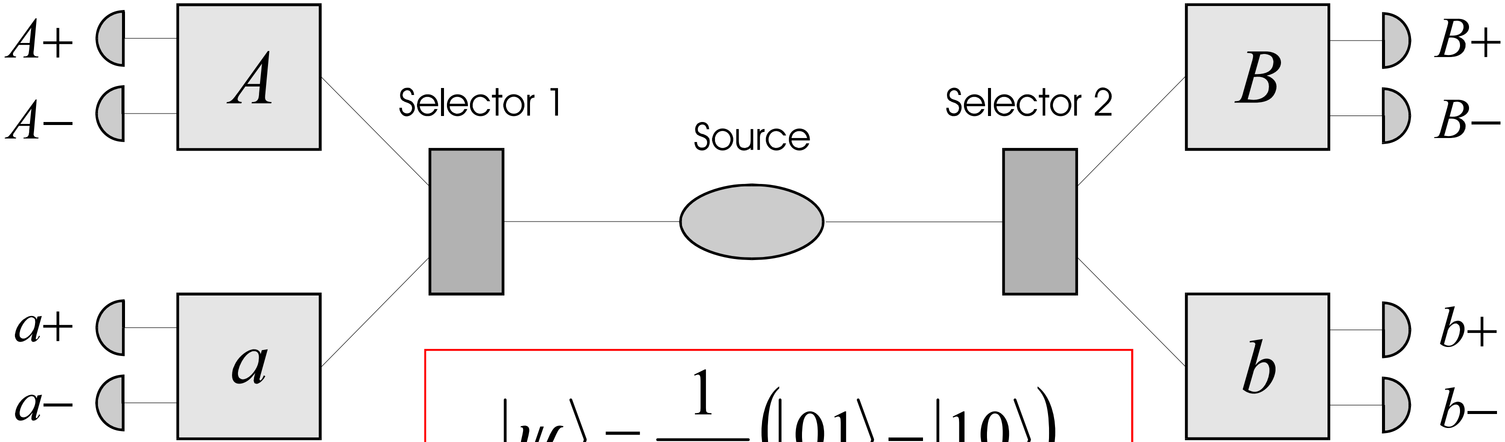
- strong Coulomb blockade
- 0-1 excess electrons
- large bias limit

Violation of charge inequality for DQD



$$|L_Q(t)| \equiv |2\langle Q(t)Q\rangle - \langle Q(2t)Q\rangle| \leq Q_{\max}\langle Q\rangle$$

Quantum Steering

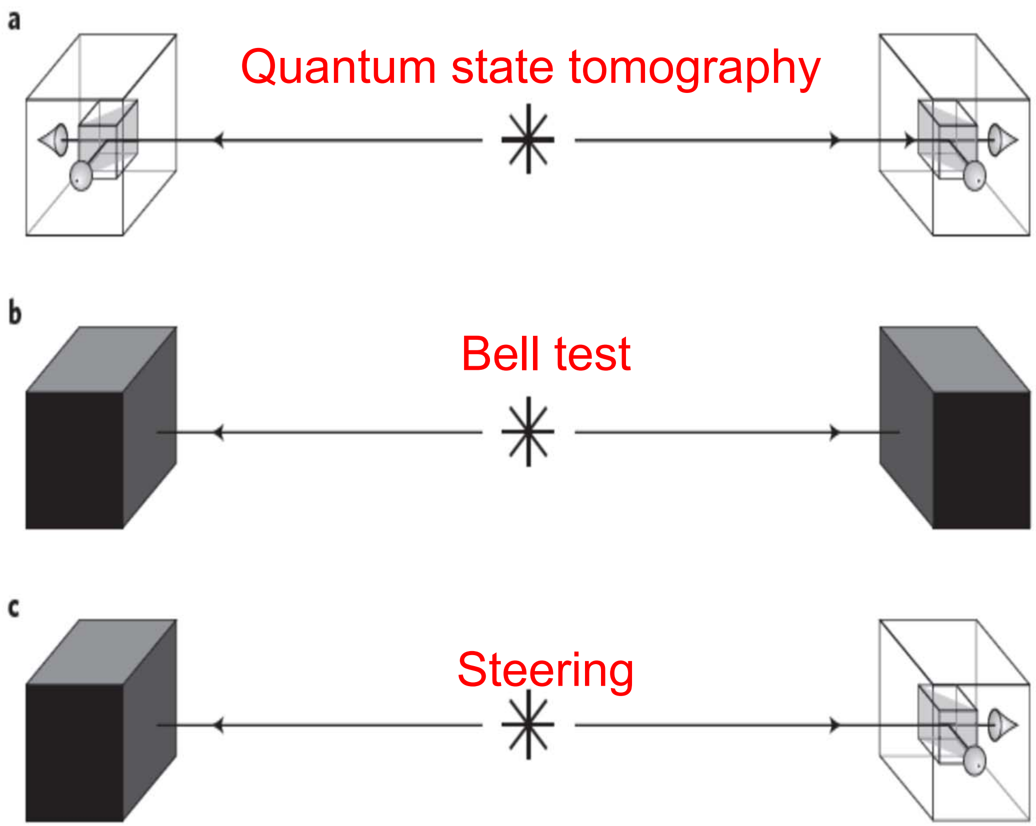


$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|01\rangle - |10\rangle\right)$$

<u>EPR</u>: 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!

<u>Schrodinger</u>: 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

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

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

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

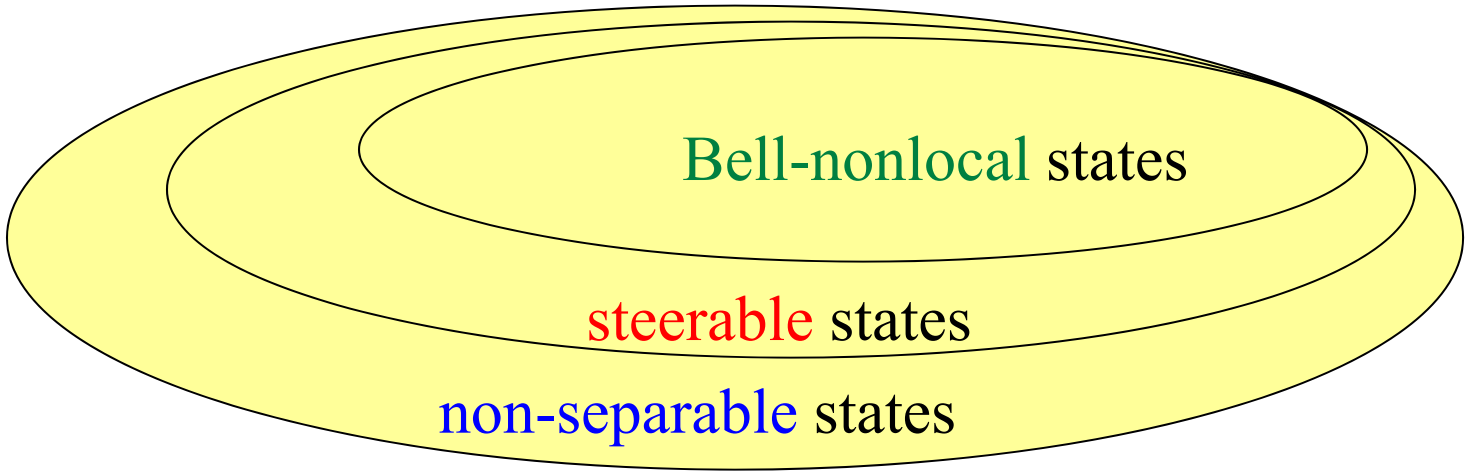
measurements in N = 2 or 3 mutually unbiased bases,
for instance of the Pauli X, Y and Z operators

[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

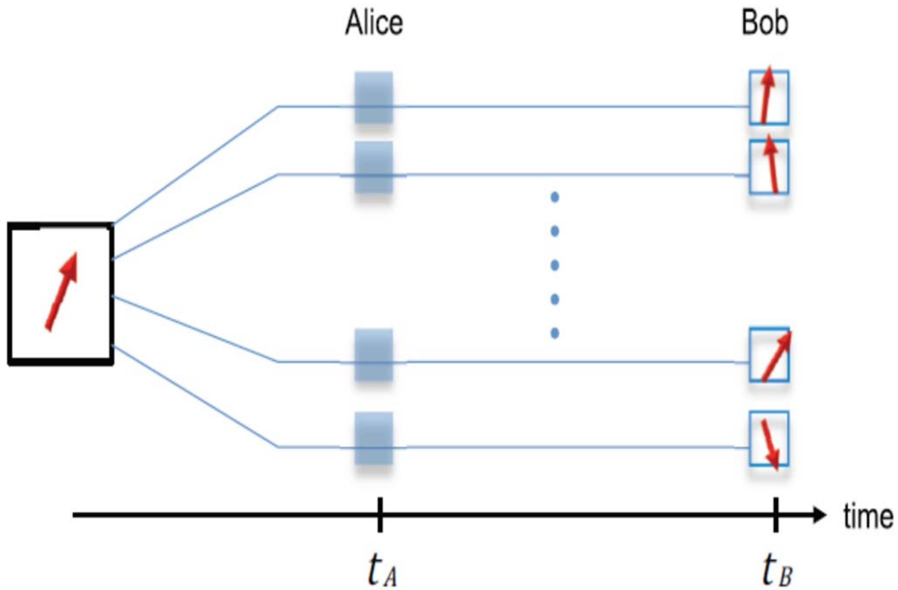
Non-separability *exists if and only if V* > 1/3

Temporal Steering Inequality

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

?

Temporal Scenario of the steering inequality



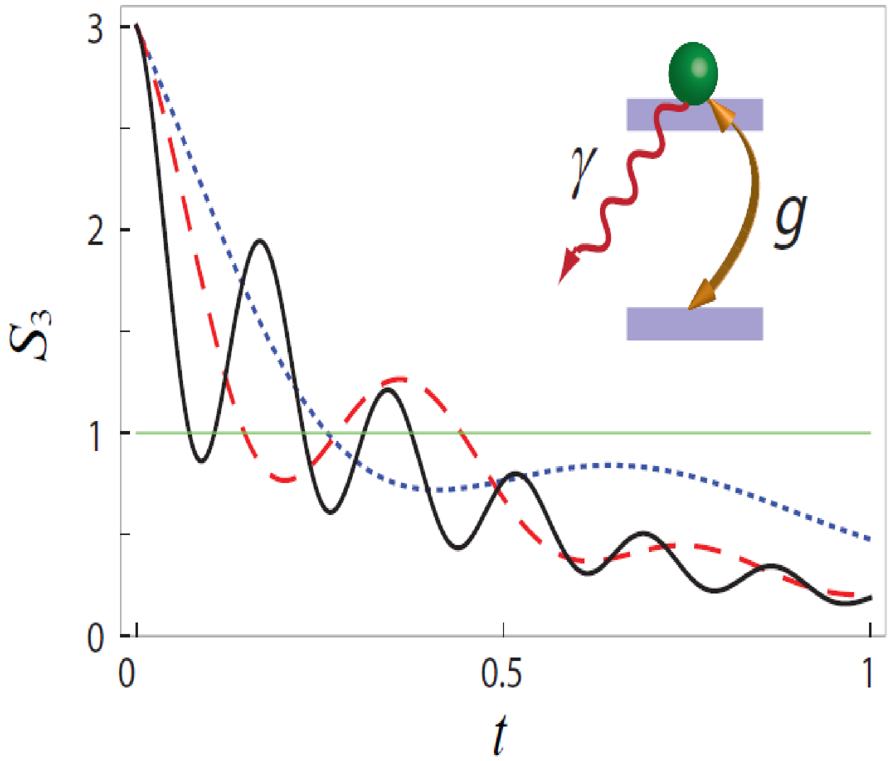
An object may be sent into different channels with probability distribution q_λ. Alice claims that the non-invasive measurement is performed at the earlier time t_A, whereas Bob performs the trusted quantum measurement at the later time t_B.

$$\boxed{S_N \equiv \sum_{i=1}^{N} E\left[\langle B_{i,t_\mathrm{B}}\rangle^2_{A_{i,t_\mathrm{A}}}\right] \leq 1}$$

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

A single qubit undergoes Rabi oscillations

Initial condition: $\rho_{t=0} = \begin{pmatrix} \frac{1}{2} & 0 \\ 0 & \frac{1}{2} \end{pmatrix}$



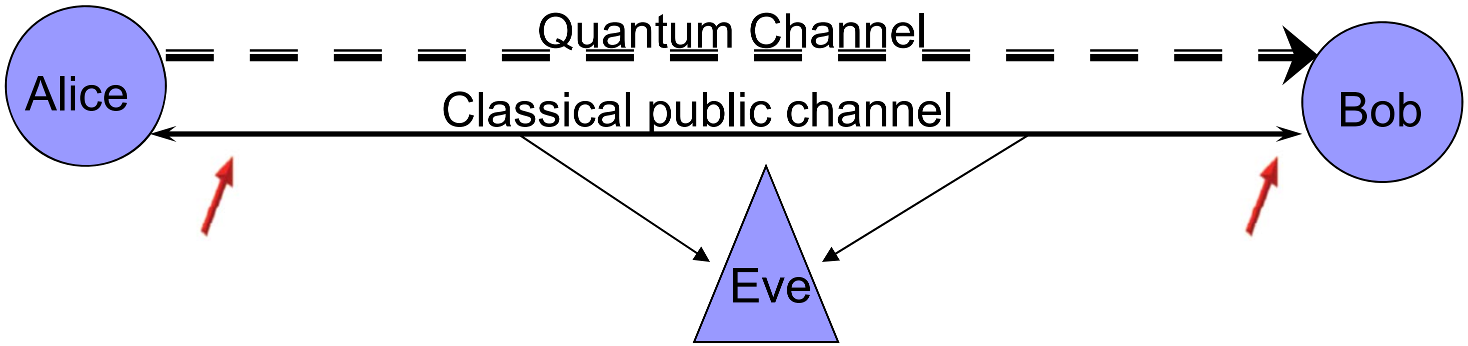
The black-solid, red-dashed, and blue-dotted curves represent the results of g = 9γ, 4γ, and 2γ, respectively

[Y. N. Chen, C. M. Li, N. Lambert, Y. Ota, S. L. Chen, G. Y. Chen, and F. Nori, PRA 89, 032112 (2014)]

Relation to Quantum Cryptography

- In 1984 Bennett and Brassard propose that the qubit with its basis {0,1} vs. {+,-} can be used in quantum key distribution protocol

- Measuring a quantum system in general disturbs it and yields incomplete information about its state before the measurement



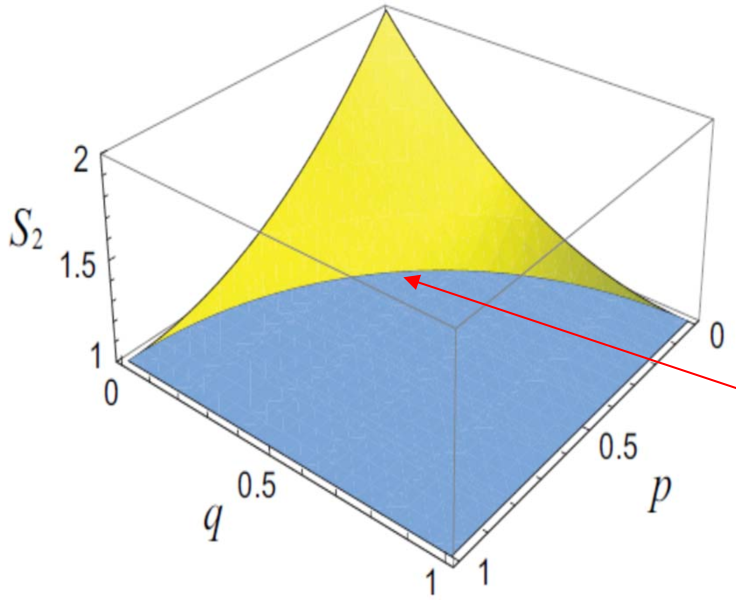
- Without knowing the proper basis, Eve is not possible to
  - Copy the qubits
  - Measure the qubits without disturbing
- Any serious attempt by Eve will be detected when Alice and Bob by performing "equality check"

Relation to Quantum Cryptography

- The tolerance in BB84 protocol under incoherent attack:

the error rate ~ 14.6447%

- The steering inequality under the incoherent attack:



$$S_2 = (1-p)^2 + (1-q)^2$$

When p=q, the threshold error rate for S_2=1:

$$\boxed{R_{\mathrm{err}}(p=q) = 0.146447}$$

$$R_{\mathrm{err}} = \frac{1}{4}(p+q)$$

The steering parameter S_2 under the disturbance by the third party, Eve, with the probabilities of measurements q (along the z direction) and p (along the x direction).

Experimental temporal quantum steering

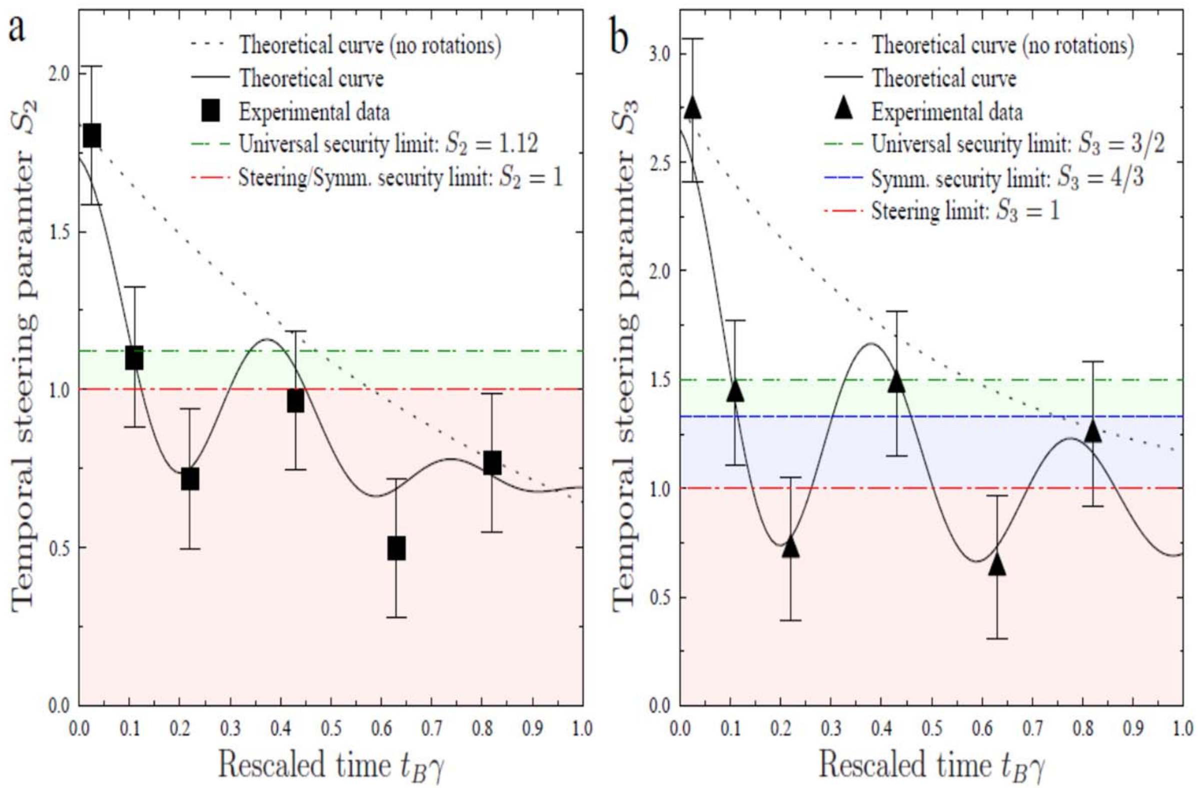


FIG. 2: **Evolution of the temporal steering parameters:** (a) S_2 for BB84 (implemented with the eigenvalues of the Pauli operators σ_1 and σ_2) and (b) S_3 for B98. Here, γ is the damping constant and t_B is the time of the nonunitary evolution between the measurements of Alice and Bob leading to the 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

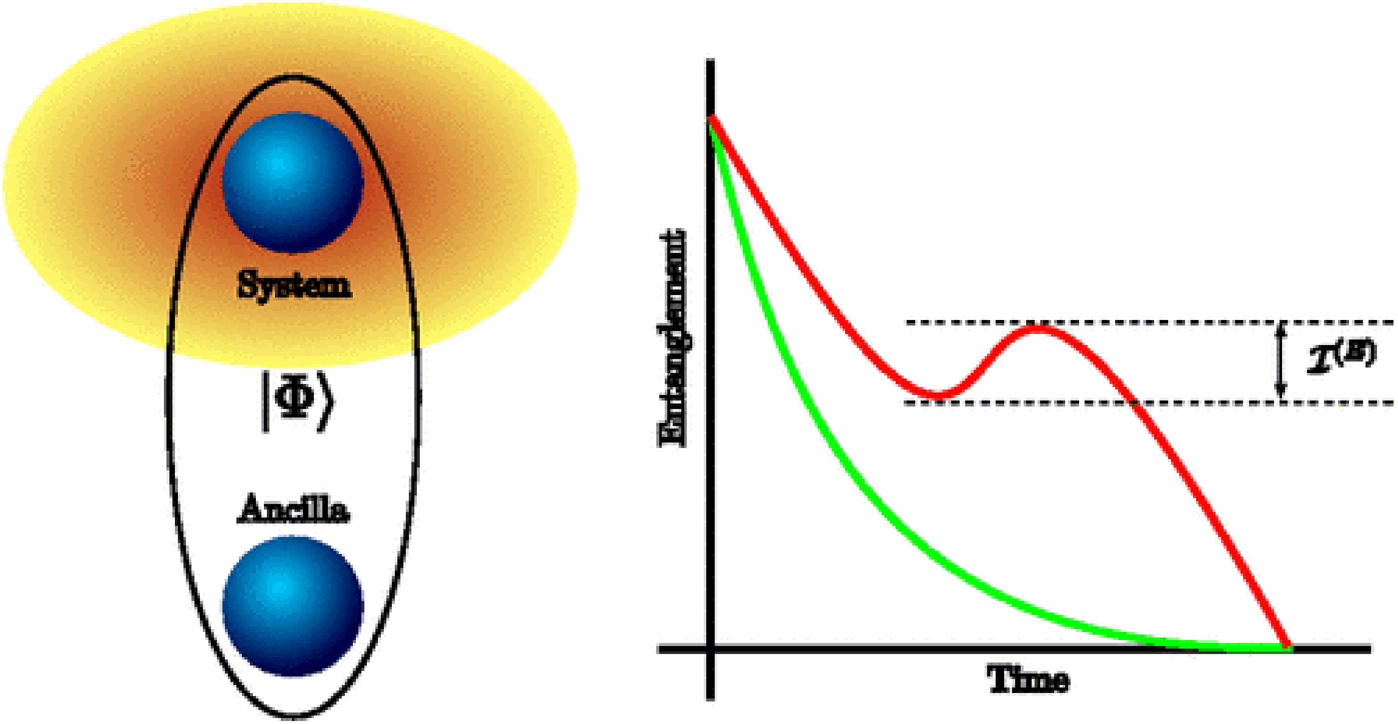
[K. Bartkiewicz *et al.*, Sci. Rep. 6, 38076 (2016)]

Quantifying Non-Markovianity

with

Temporal Steering

What is non-Markovian?



[Ángel Rivas, Susana F. Huelga, and Martin B. Plenio, Phys. Rev. Lett. **105**, 050403 (2010)]
[W. M. Zhang, P. Y. Lo, H. N. Xiong, M. W.-Y Tu, and F. Nori, Phys. Rev. Lett. **109**, 170402 (2012)]
[F. A. Pollock, C. Rodríguez-Rosario, T. Frauenheim, M. Paternostro, K. Modi, **arXiv:1512.00589**]

Temporal Steerable Weight

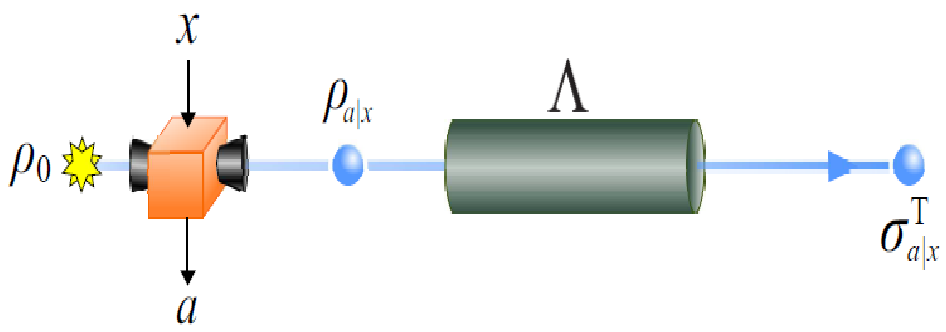


FIG. 1. (Color online) Schematic diagram of temporal steering. In the beginning, Alice performs the measurement $F_{a|x} = M^{\dagger}_{a|x} M_{a|x}$ on an initial state ρ_0. Then, ρ_0 is mapped to $\rho_{a|x}$ and sent into a quantum channel Λ. Finally, Bob receives the assemblage $\{\sigma^{\mathrm{T}}_{a|x}\}$ at time t.

$$\rho_0 \mapsto \rho_{a|x} = \frac{M_{a|x}\, \rho_0\, M^{\dagger}_{a|x}}{p(a|x)} \qquad \sigma^{\mathrm{T}}_{a|x} \equiv p(a|x)\, \sigma_{a|x}$$

$$\sigma^{\mathrm{T,US}}_{a|x} = \sum_{\lambda} P(\lambda)\, P(a_{|x}|\lambda)\, \sigma_{\lambda} \qquad \boxed{\sigma^{\mathrm{T}}_{a|x} = \mu\, \sigma^{\mathrm{T,US}}_{a|x} + (1-\mu)\sigma^{\mathrm{T,S}}_{a|x}} \qquad \boxed{\mathrm{TSW} = 1 - \mu^{*}}$$

Measure of Non-Markovianity via Temporal Steering

The temporal steerable weight (TSW) is a non-increasing function under CPTP map

$$\mathrm{TSW}_{\rho} \geq \mathrm{TSW}_{\Phi(\tau)\rho}$$

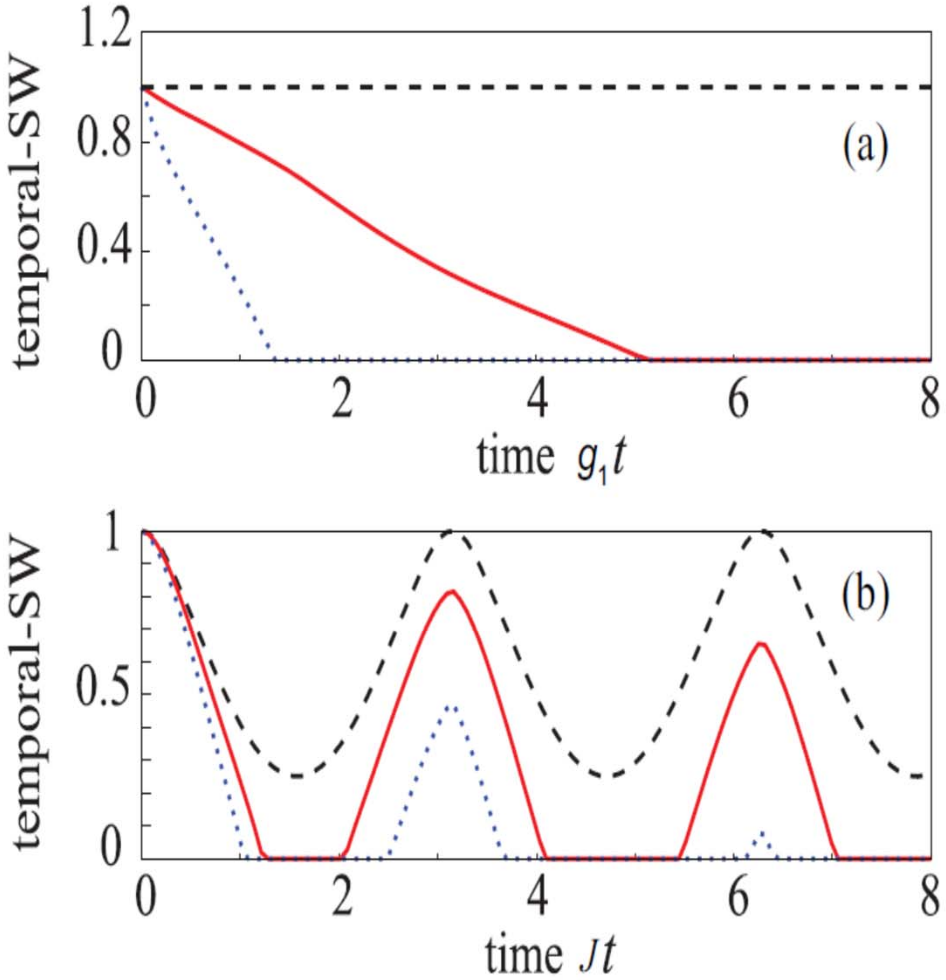
$$\Phi(\tau + t, 0) = \Phi(\tau + t, t)\Phi(t, 0)$$

Measure of non-Markovianity is defined by integrating the positive slope of the TSW

$$\mathcal{N}_{\mathrm{TSW}} \equiv \int_{\sigma_{\mathrm{TSW}}>0} dt\, \sigma_{\mathrm{TSW}}(t, \rho_0, \Phi), \qquad \sigma_{\mathrm{TSW}}(t, \rho_0, \Phi) = \frac{d}{dt}\mathrm{TSW}_{\Phi(t)\rho_0}$$

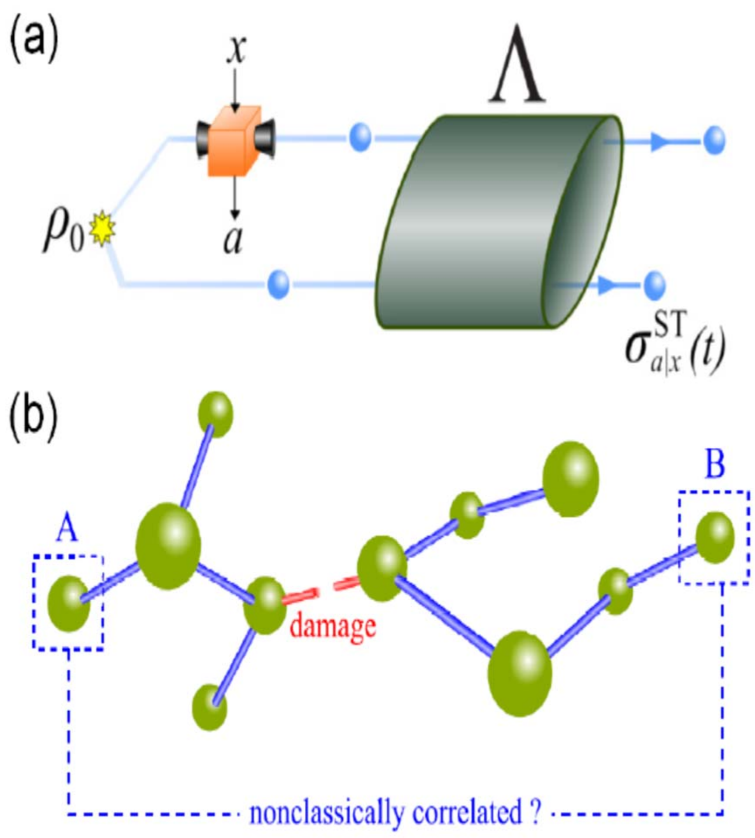
EXAMPLE 1: COHERENT RABI OSCILLATIONS OF A MARKOVIAN SYSTEM

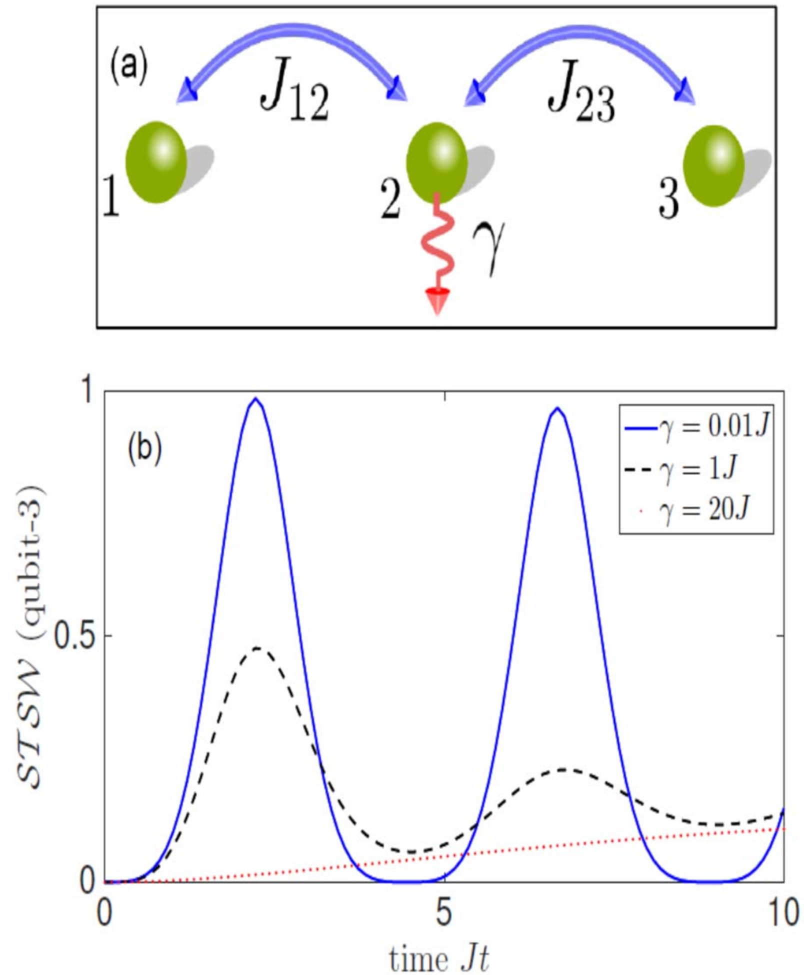
EXAMPLE 2: A SIMPLE NON-MARKOVIAN MODEL: A QUBIT COHERENTLY COUPLED TO ANOTHER QUBIT



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

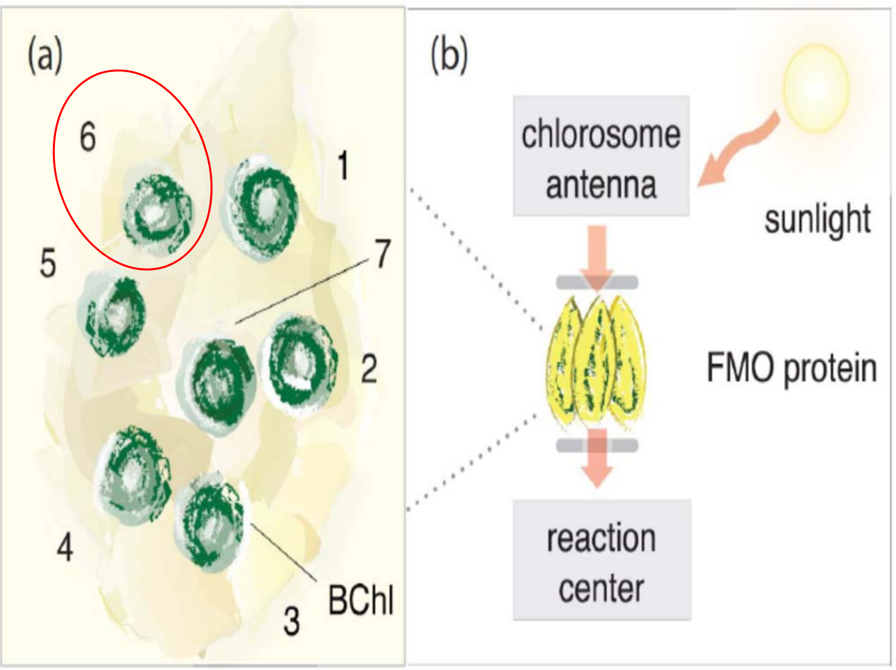
Spatio-Temporal Quantum Steering for Testing Nonclassical Correlations in Quantum Networks

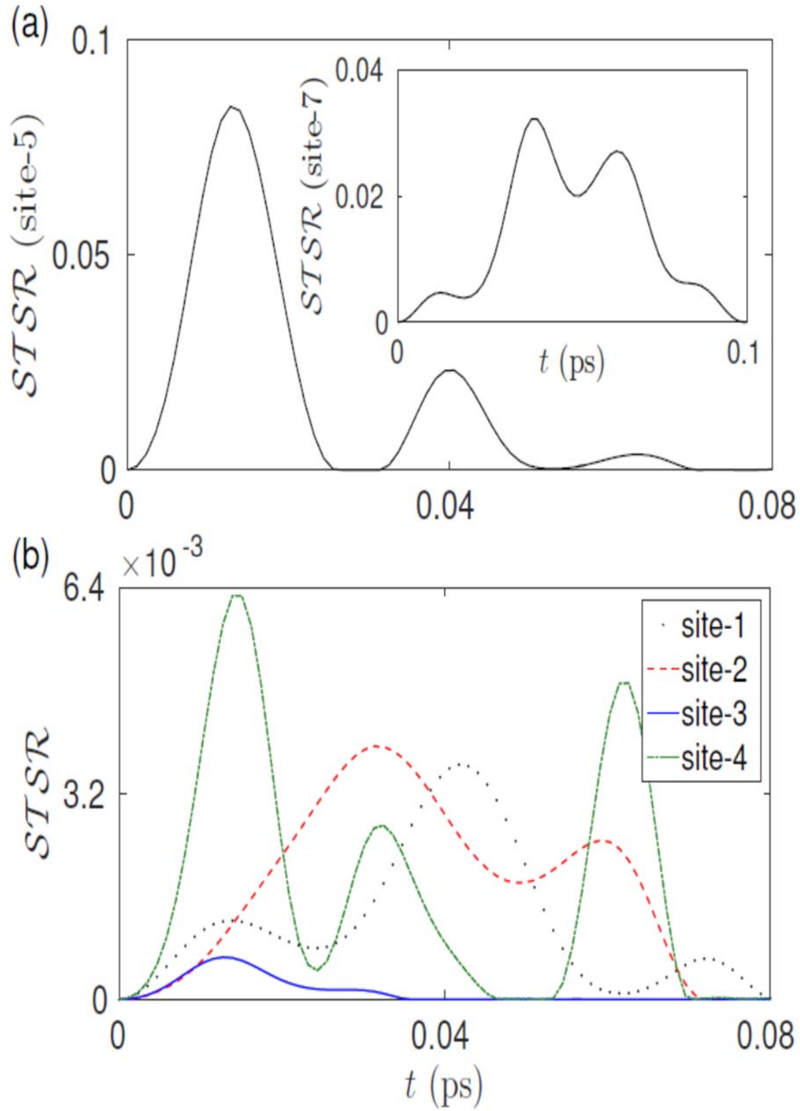




S. L. Chen, N. Lambert, C. M. Li, G. Y. Chen, Y. N. Chen*, A. Miranowicz, and F. Nori, **arXiv:1608.03150** (2016)

Spatio-Temporal Steering in the Fenna-Matthews-Olson complex





N. Lambert, Y. N. Chen, Y. C. Cheng, C. M. Li, G. Y. Chen, and F. Nori, **Nature Physics 9**, 10 (2013).

Summary

(a)

CHSH Inequality	Leggett-Garg Inequality
$\lvert\langle B_1 A_1\rangle + \langle B_1 A_2\rangle + \langle B_2 A_1\rangle - \langle B_2 A_2\rangle\rvert \leq 2$	$\lvert\langle A_{i,t_2} A_{i,t_1}\rangle + \langle A_{i,t_3} A_{i,t_2}\rangle + \langle A_{i,t_4} A_{i,t_3}\rangle - \langle A_{i,t_4} A_{i,t_1}\rangle\rvert \leq 2$
Steering inequality	**Temporal steering inequality**
$\sum_{i=1}^{N} E\left[\langle B_i\rangle_{A_i}^2\right] \leq 1$	$\sum_{i=1}^{N} E\left[\langle B_{i,t_{\mathrm{B}}}\rangle_{A_{i,t_{\mathrm{A}}}}^2\right] \leq 1$

(b)

The Temporal Steerable Weight can be used to define a sufficient and practical measure of strong non-Markovianity.

(c)

The Spatio-Temporal steering can be used to test the non-classical correlations in quantum networks.

Y. N. Chen, C. M. Li, N. Lambert, Y. Ota, S. L. Chen, G. Y. Chen, and F. Nori, **PRA 89**, 032112 (2014)

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

S. L. Chen, N. Lambert, C. M. Li, G. Y. Chen, Y. N. Chen*, A. Miranowicz, and F. Nori, **arXiv:1608.03150** (2016)

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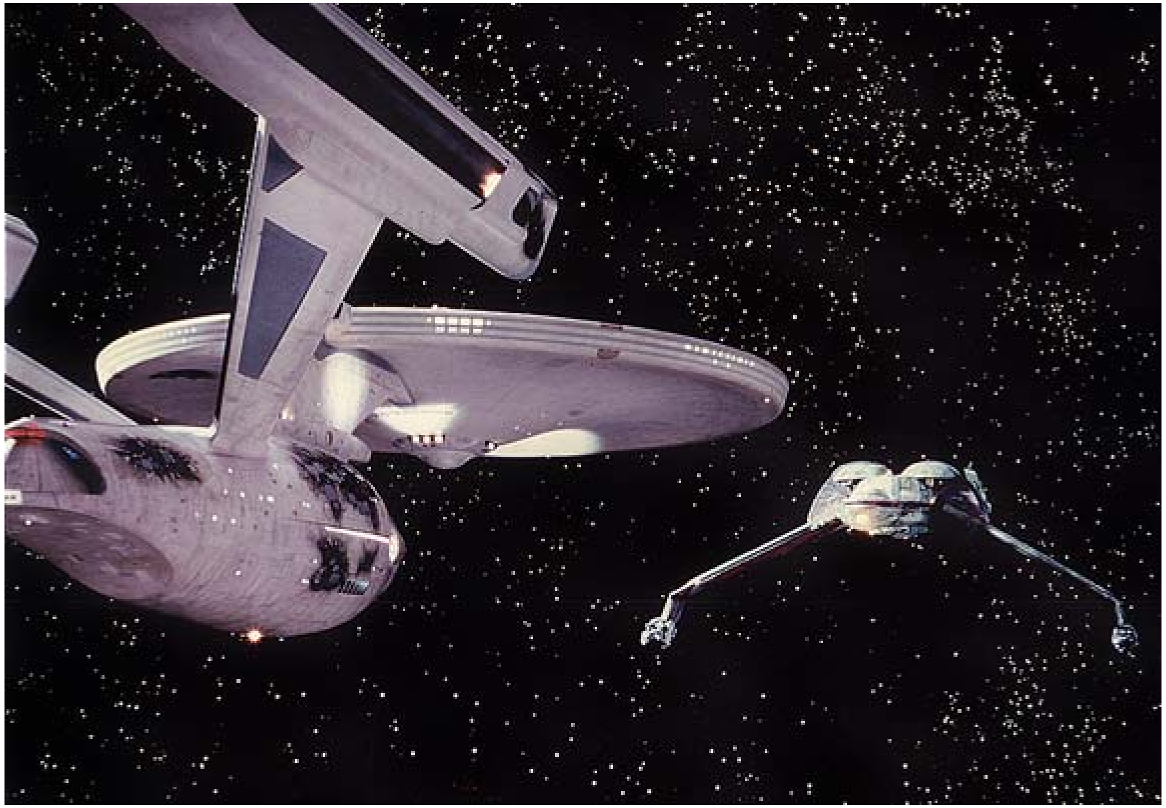
Thank you for your attention!



Ideal negative result measurements

(a) Imagine a measuring device that is physically incapable of interacting with a system in state ↑, but that will (possibly invasively) detect a system in state ↓.

(b) Suppose we apply this detector to our system and it does not 'click'; the macrorealist infers the system is in state ↑, and was in this state immediately before measurement—but this information is obtained without any interaction.

(c) Switching to a complementary measuring device that perceives only the ↑ state allows one to obtain the full set of data non-invasively, as long as one always abandons all experiments where the detector clicks.

[G. C. Knee *et al*., Nature Commun. 3, 606 (2012)]