The Abdus Salam International Centre for Theoretical Physics

2445-06

Advanced Workshop on Nanomechanics

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Probing macroscopic realism via Ramsey correlation measurements

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Collaborations:

- A. Asadian, C. Brukner (Vienna)
- S. Bennett, M. Lukin (Harvard)

ATOMINSTITUT

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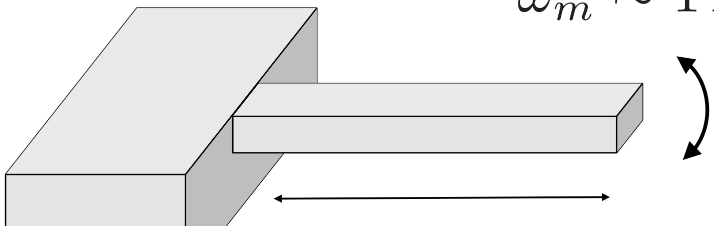
Vienna University of Technology

FWF
Der Wissenschaftsfonds.

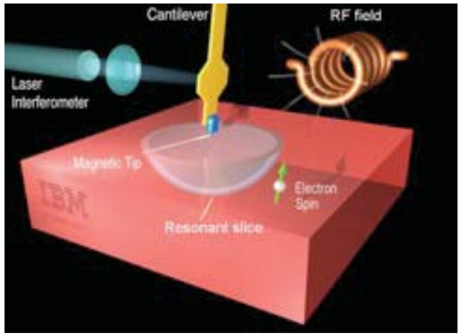
“Quantum” mechanical resonators ...

$\omega_m \sim 1\,\mathrm{MHz}$



$\sim 10\mu\mathrm{m}$

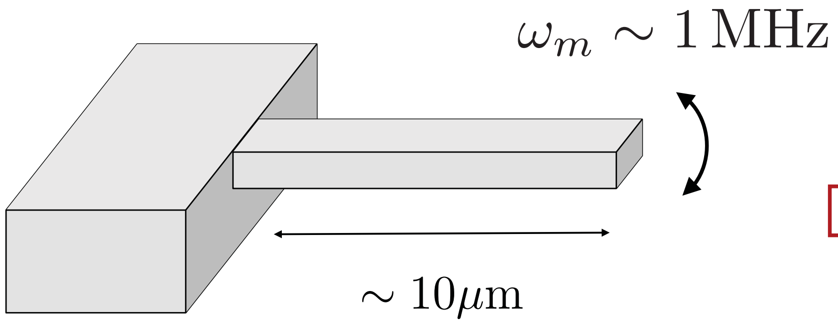
macroscopic mechanical systems in the quantum regime !



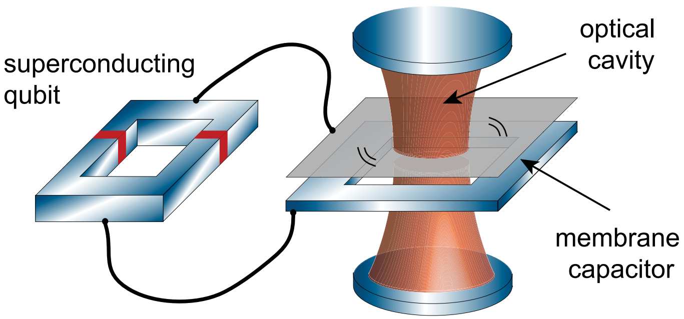
⇒ *Quantum limits to force measurements !*

⇒ *Quantum enhanced sensing applications !*

“Quantum” mechanical resonators ...

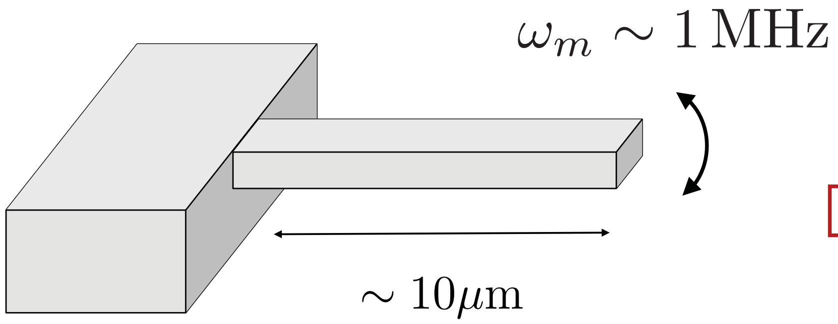


macroscopic mechanical systems in the quantum regime !

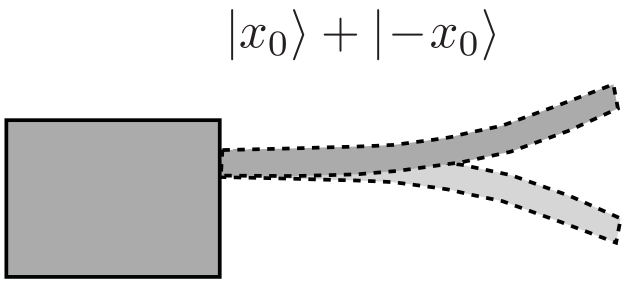


Mechanical transducers for quantum information processing applications!

“Quantum” mechanical resonators ...



macroscopic mechanical systems in the quantum regime !

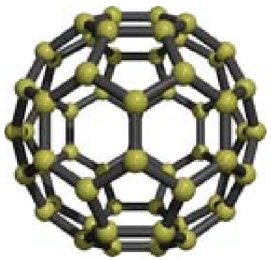


Macroscopic superpositions & fundamental tests of Quantum Mechanics !

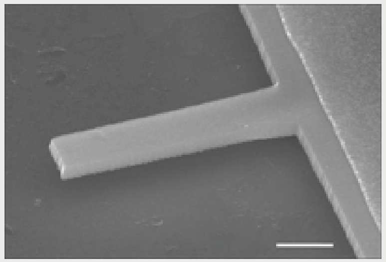
“Macroscopic” quantum superpositions ...

“microscopic” “macroscopic”

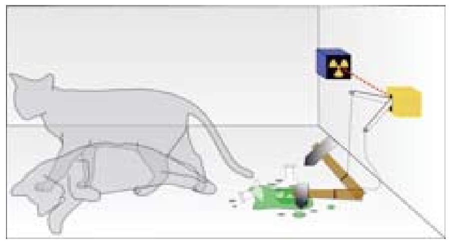
atoms,
ions, ...



~1000 atoms [1]



~10^12 atoms
“macroscopic”

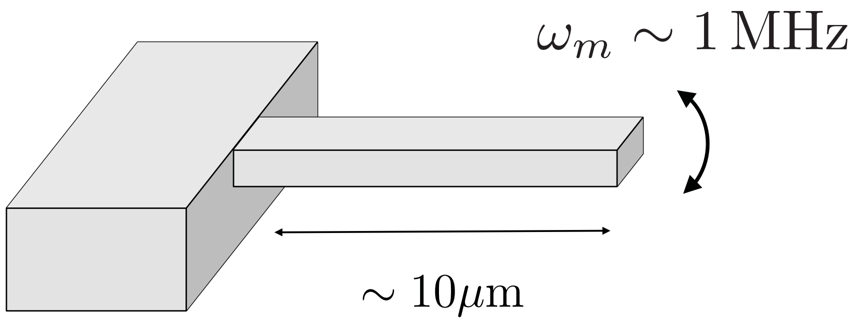


[1] M. Arndt (Vienna)

“Macroscopic” quantum superpositions ...

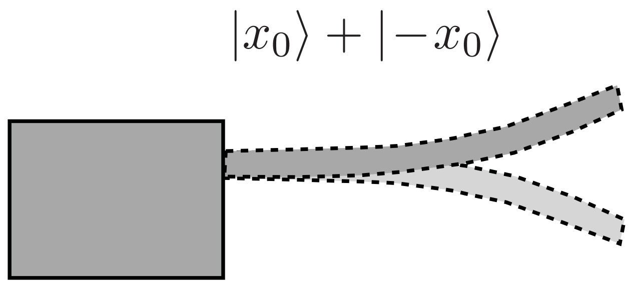
- *QM is essentially unexplored for massive objects !*
- *Alternative theories and (gravity induced) collapse models predict corrections to QM !*

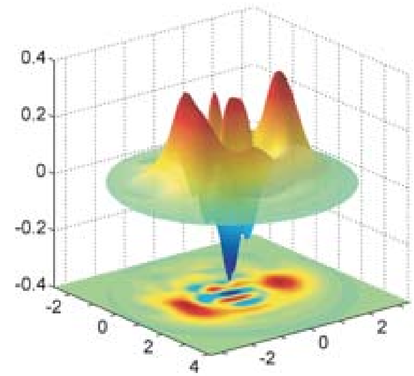
Quantum physics with macroscopic objects ?



Goal:

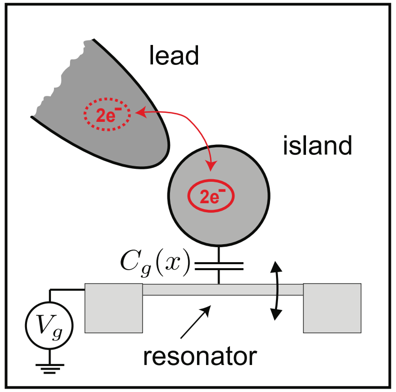
- *macroscopic superpositions*
- *macroscopic quantum interference phenomena*



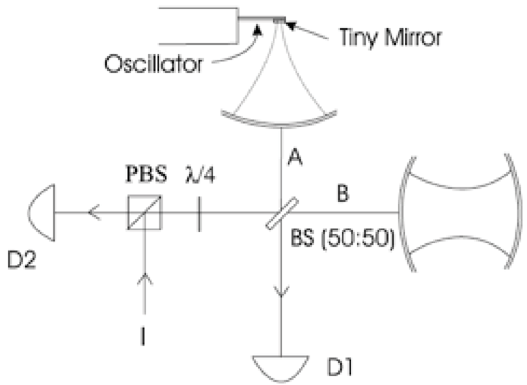


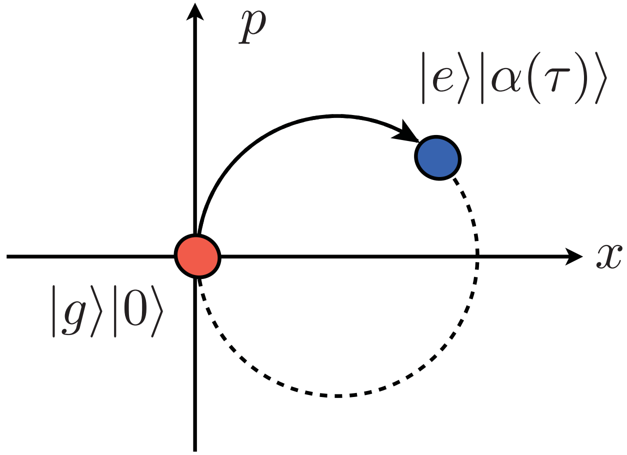
Macroscopic quantum interference ...

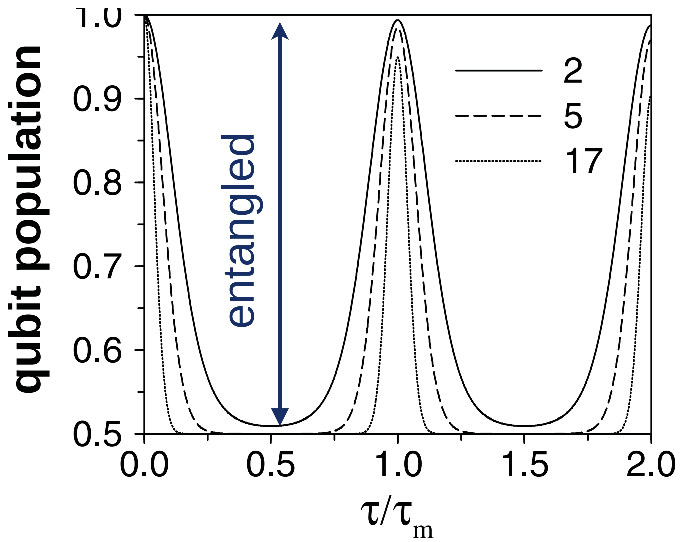
- **charge qubit + resonator [1]:**



- **photonic qubit + resonator [2]:**

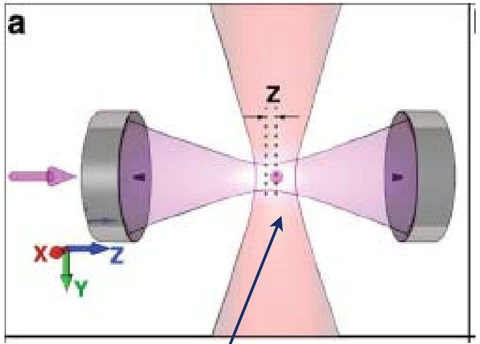




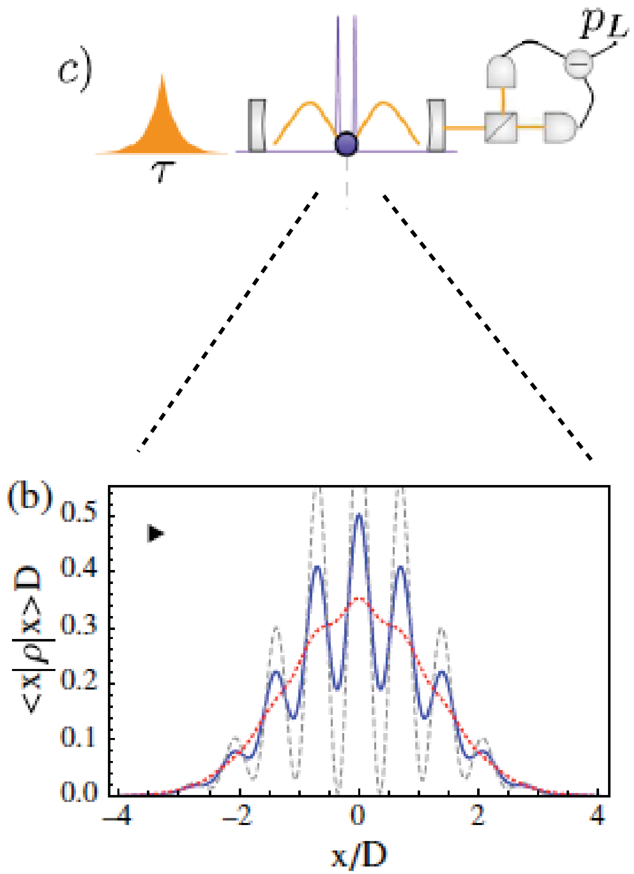


[1] A. Armour, M. Blencowe, K. Schwab, PRL (2002)
[2] W. Marshall, C. Simon, R. Penrose, D. Bouwmeester, PRL (2003)

Macroscopic quantum interference ...



levitated
nano-particle



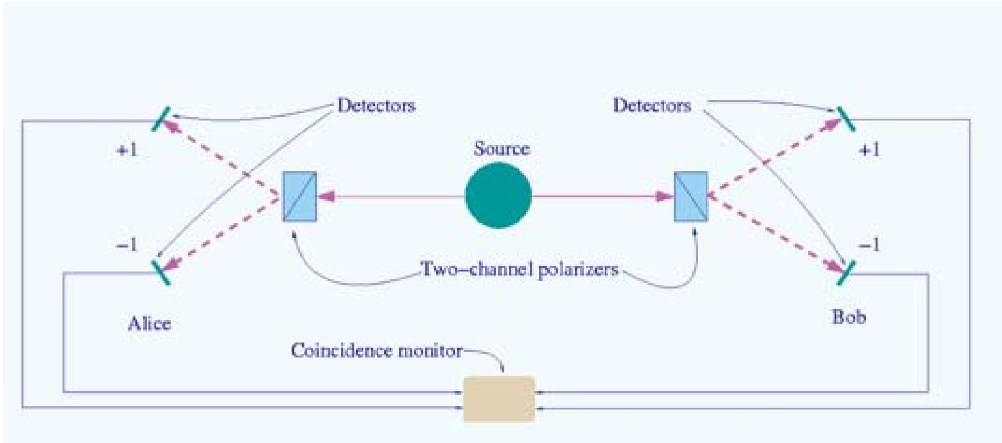
⇒ double split experiment

with massive particles !

*O. Romero-Isart et al. PRL **107**, 020405 (2011);* *Talk by N. Kiesel on Friday !*

Quantum mechanics vs. "realism" ...

J. Bell



Correlation between spatially separate measurements:

$$|E(a,b) - E(a,b') + E(a',b) + E(a'b')| \leq 2 \qquad \leq \; 2\sqrt{2}$$

local realism (hidden variable theories)

quantum mechanics

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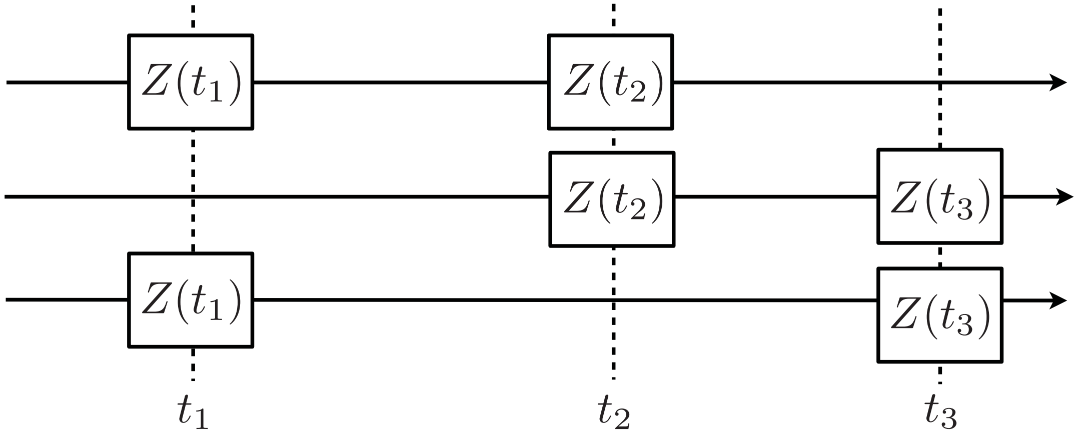
*J. S. Bell, Physics **1**, 195 (1964);*
*J. F. Clauser, M. A. Horne, A. Shimony, R. A. Holt, PRL **23**, 880 (1969)*

Quantum mechanics vs. “realism” ...

temporal correlations:

A. Leggett



$$Z(t_i) = \pm 1, \quad C(t_i, t_j) = \langle Z(t_j) Z(t_i) \rangle$$

⇒ *Leggett-Garg inequality:*

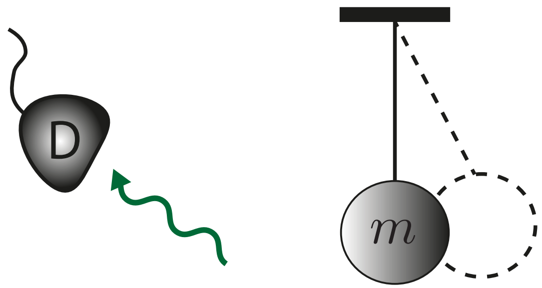
$$C(t_1, t_2) + C(t_2, t_3) - C(t_1, t_3) \leq 1 \quad \leq \; 1.5$$

“macro-realistic” theories

quantum mechanics

*A. J. Leggett and A. Garg, PRL **54**, 857 (1985).*

Probing "realism" with massive objects ...



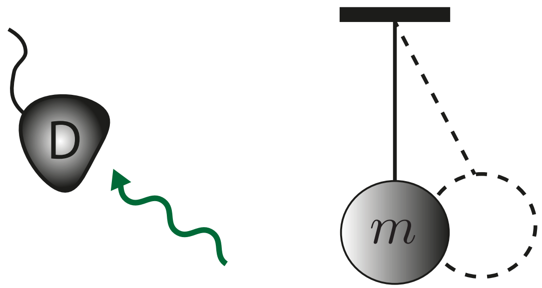
Goal:

$$C(t_1, t_2) + C(t_2, t_3) - C(t_1, t_3) \leq 1$$

- *Direct test of the most fundamental aspects of quantum physics in the macroscopic domain.*

- *Unambiguous experimental signatures to distinguish the predictions of quantum mechanics from those of classical physics or more general (hidden variable) theories.*

Probing “realism” with massive objects ...



Goal:

$$C(t_1, t_2) + C(t_2, t_3) - C(t_1, t_3) \leq 1$$

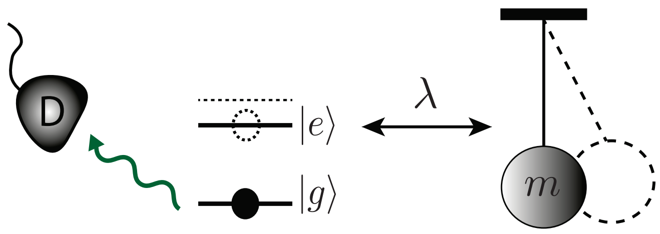
Problems:

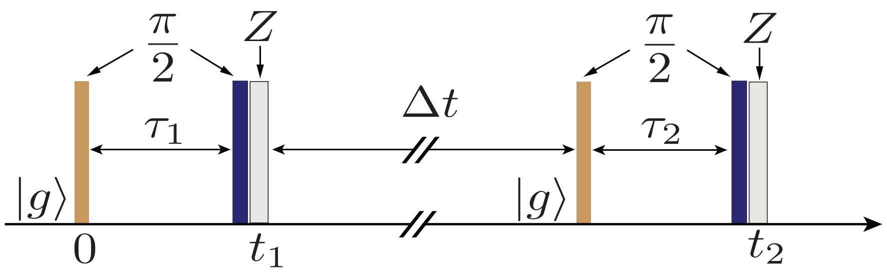
- *Experimental difficulty of preparing quantum superpositions of large objects.*

- *Fundamental test of quantum mechanics are often formulated for discrete systems. Extensions to continuous variable systems not straightforward.*

This talk ...

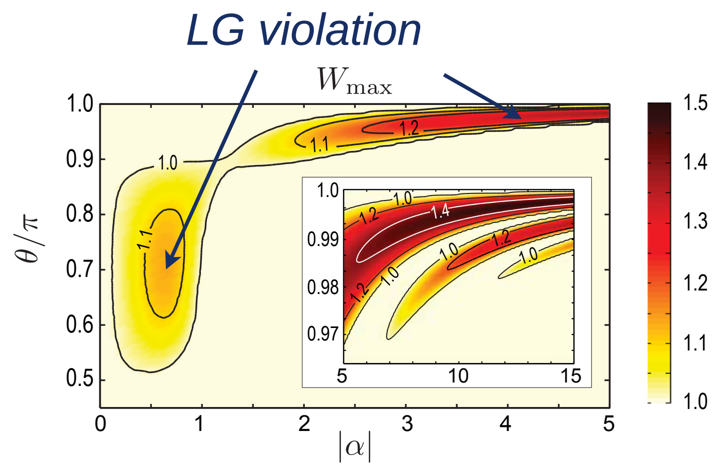
Ramsey correlation measurements:





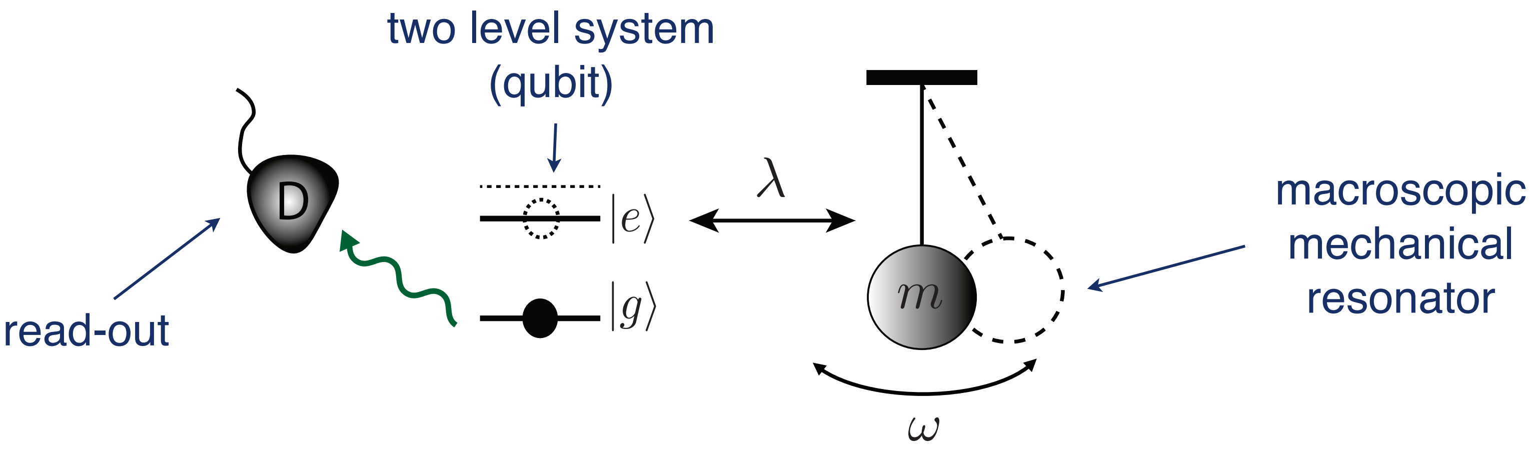
- *Leggett-Garg Inequality:*

$$C(t_1,t_2)+C(t_2,t_3)-C(t_1,t_3)\leq 1$$



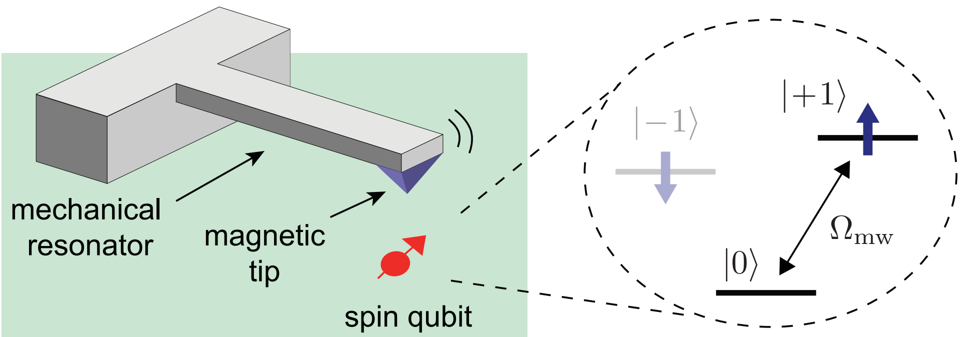
- *Conceptually simple & experimentally realistic scheme !*
- *Versatile measurement tool for various fundamental test of quantum mechanics with massive objects !*

Setup ...



Qubit-resonator coupling:

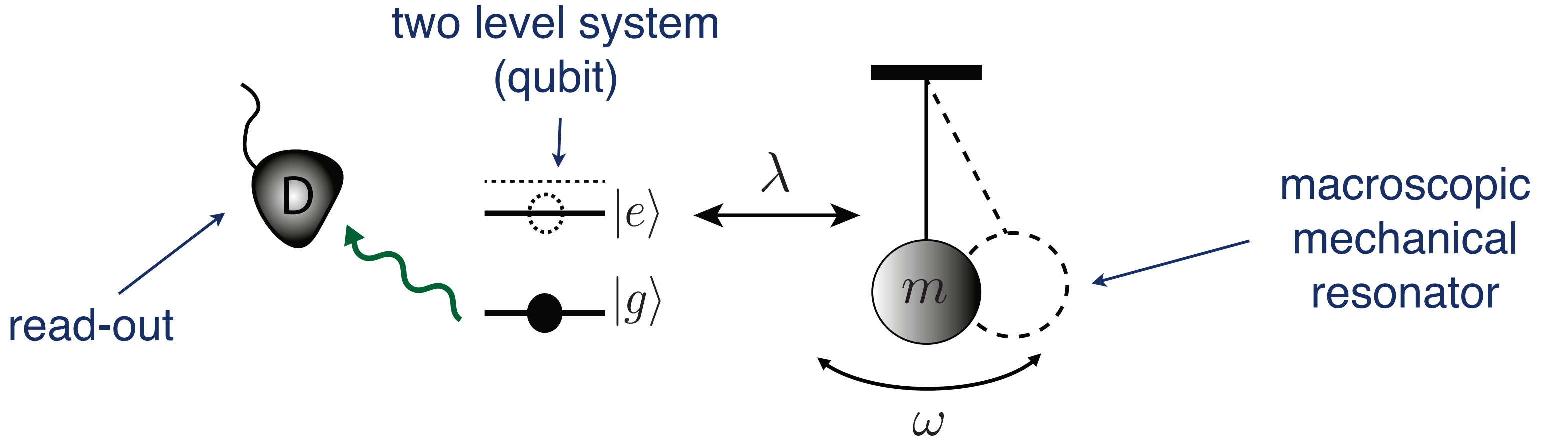
$$H = \omega a^\dagger a + \lambda(a + a^\dagger)|e\rangle\langle e|$$



Magnetic coupling
to spin qubit.

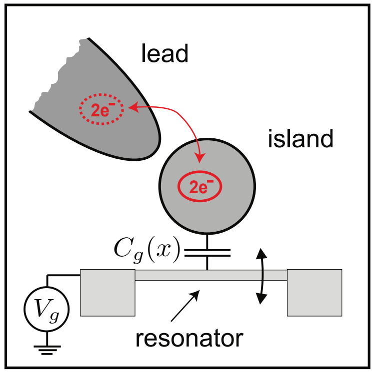
PR et al. PRB (2009)

Setup ...



Qubit-resonator coupling:

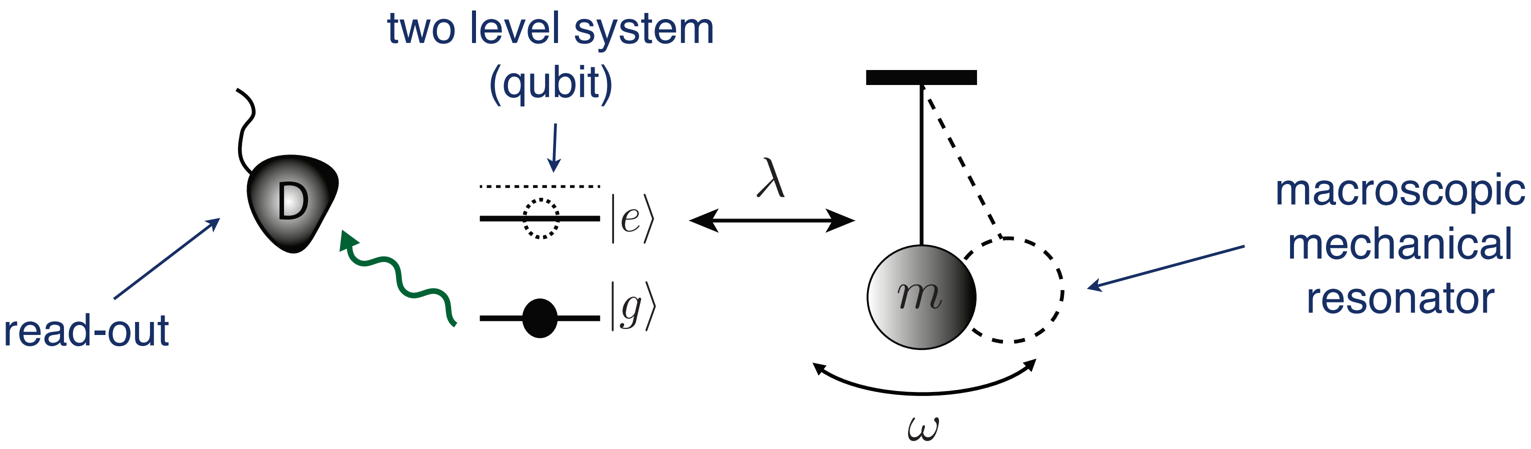
$$H = \omega a^\dagger a + \lambda(a + a^\dagger)|e\rangle\langle e|$$



Electrostatic coupling to superconducting qubits.

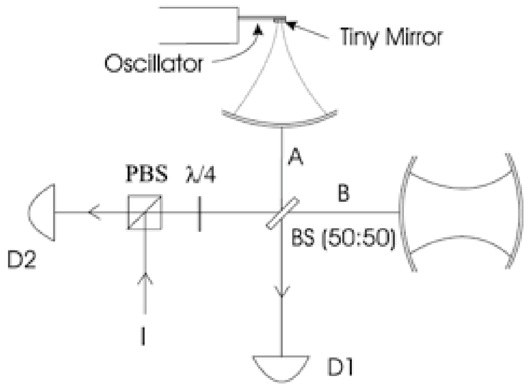
A. Armour et al., PRL (2002)
L. Tian, PRB (2005)

Setup ...



Qubit-resonator coupling:

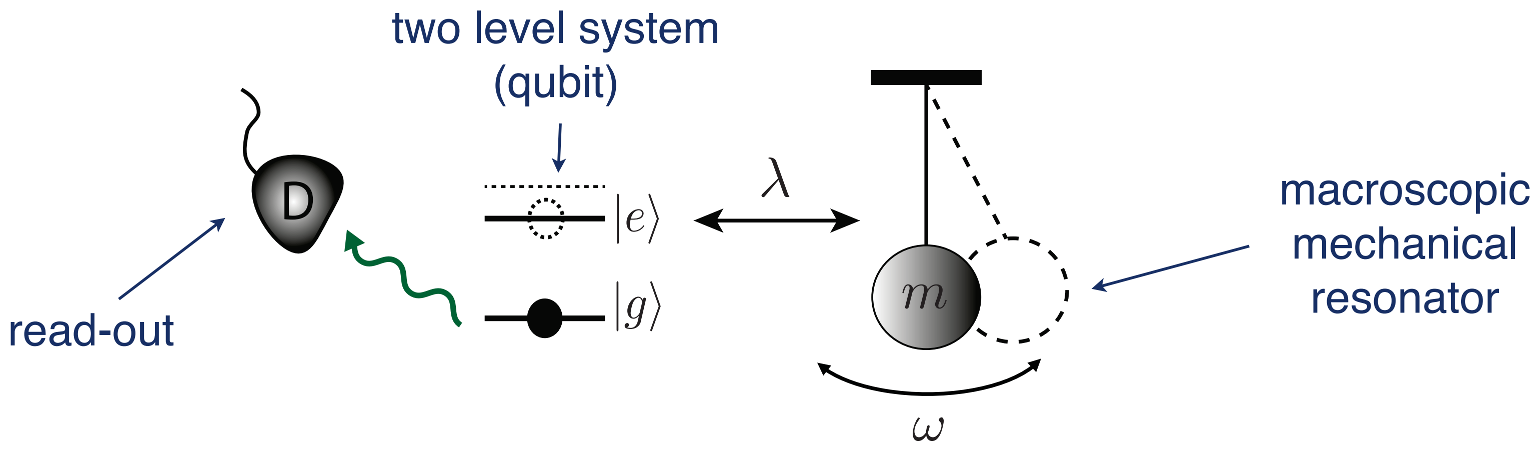
$$H = \omega a^\dagger a + \lambda(a + a^\dagger)|e\rangle\langle e|$$



Radiation pressure force between mirror and a single photon.

W. Marshall et al. PRL (2003)

Setup ...



Qubit-resonator coupling:

$$H = \omega a^\dagger a + \lambda(a + a^\dagger)|e\rangle\langle e|$$

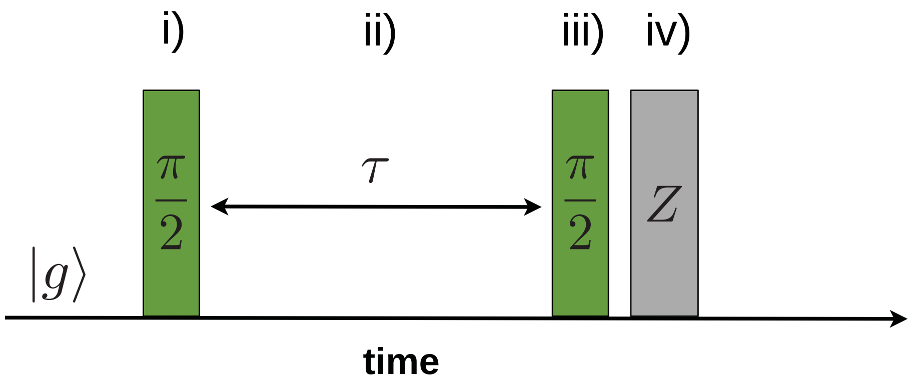
- *A frequency shift of the excited state $\propto$ to the resonator displacement*

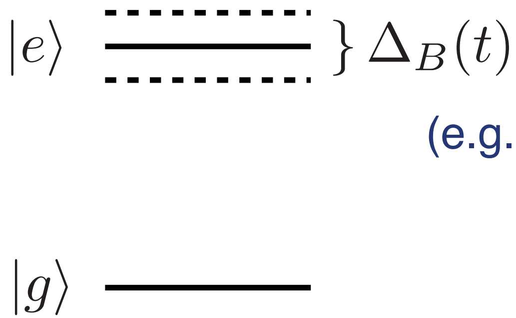
  $\Longrightarrow$ *Ramsey measurement !*

- *A state dependent force acting on the resonator mode*

  $\Longrightarrow$ *quantum backaction !*

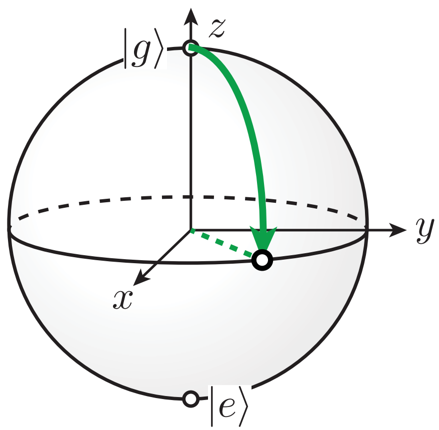
Magnetometry / Ramsey measurements ...





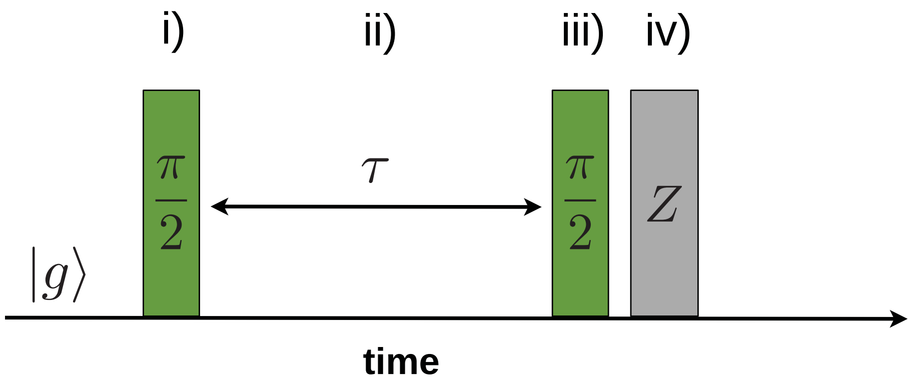
(e.g. magnetic field)

i) $|g\rangle \rightarrow \frac{1}{\sqrt{2}}\left(|g\rangle + e^{i\varphi}|e\rangle\right)$



$R_{\pi/2}(\varphi)$

Magnetometry / Ramsey measurements ...

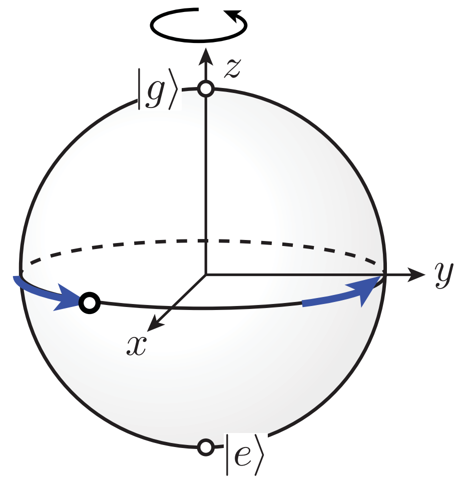


$$H(t) = \Delta_B(t)|e\rangle\langle e|$$

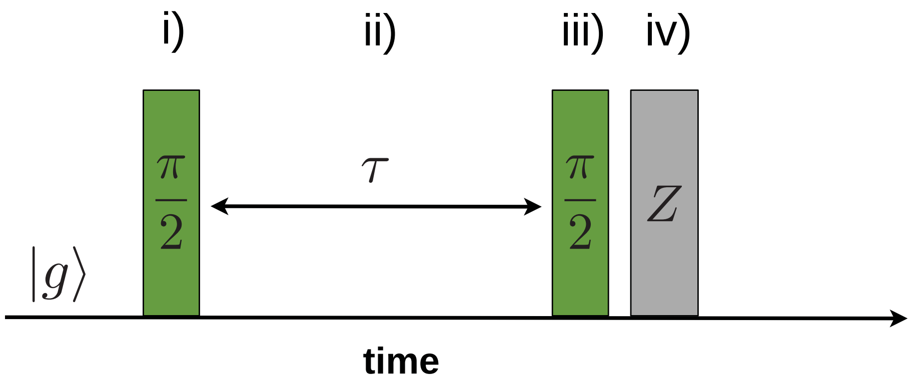
$$\Phi(\tau) = \int_0^\tau dt' \, \Delta_B(t')$$

i) $|g\rangle \rightarrow \frac{1}{\sqrt{2}}\left(|g\rangle + e^{i\varphi}|e\rangle\right)$

ii) $\rightarrow \frac{1}{\sqrt{2}}\left(|g\rangle + e^{i\varphi}e^{-i\Phi(\tau)}|e\rangle\right)$



Magnetometry / Ramsey measurements ...



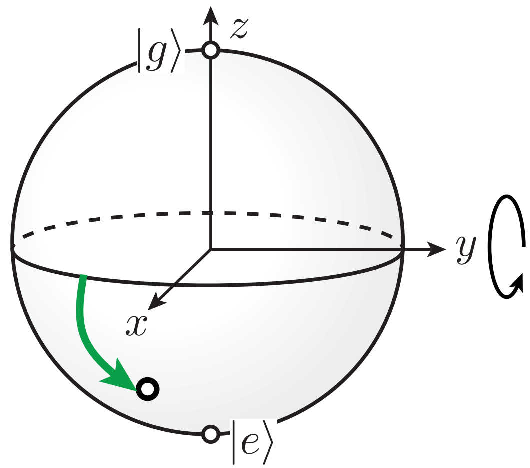
$$H(t) = \Delta_B(t)|e\rangle\langle e|$$

$$\Phi(\tau) = \int_0^\tau dt' \, \Delta_B(t')$$

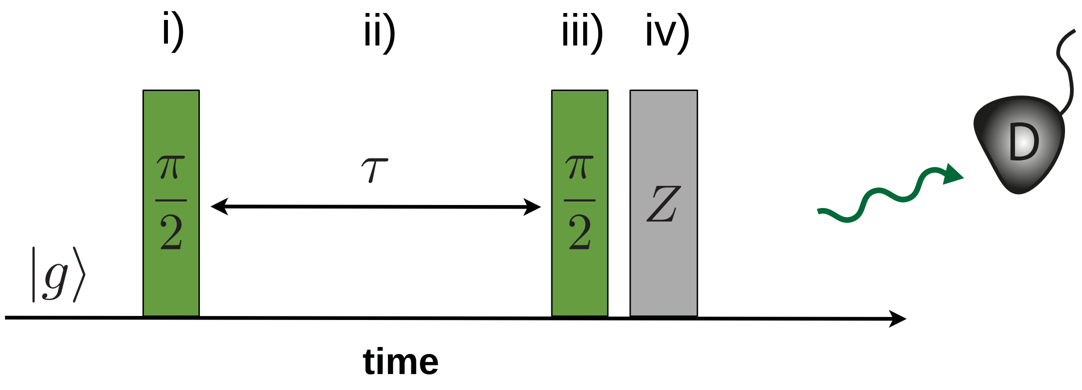
i) $|g\rangle \rightarrow \frac{1}{\sqrt{2}}\left(|g\rangle + e^{i\varphi}|e\rangle\right)$

ii) $\rightarrow \frac{1}{\sqrt{2}}\left(|g\rangle + e^{i\varphi}e^{-i\Phi(\tau)}|e\rangle\right)$

iii) $\rightarrow \frac{1}{2}\left(1 + e^{i(\varphi-\Phi(\tau))}\right)|g\rangle + \frac{1}{2}\left(1 + e^{i(\varphi-\Phi(\tau))}\right)|e\rangle$



Magnetometry / Ramsey measurements ...



$|e\rangle : \ Z = +1$

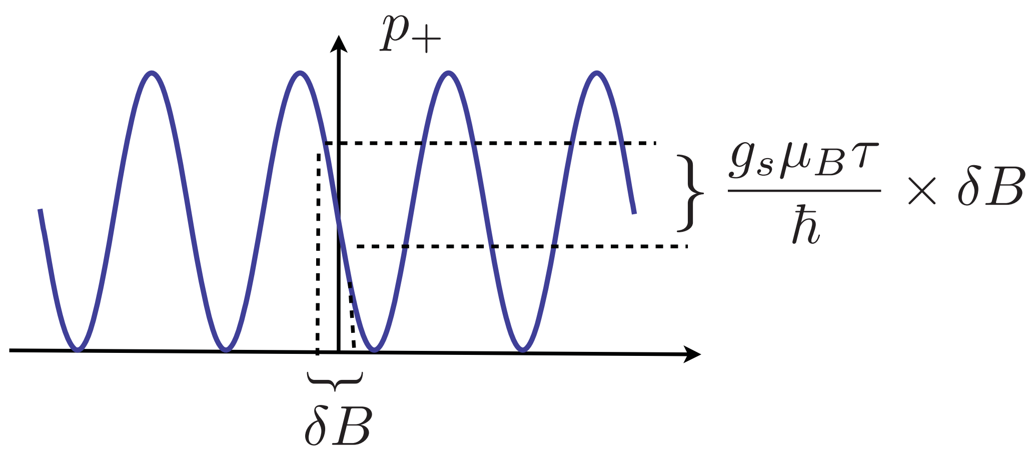
$|g\rangle : \ Z = -1$

iv) Measurement: $$p_{\pm} = \frac{1}{2}\left(1 \pm \cos(\varphi - \Phi(\tau))\right)$$

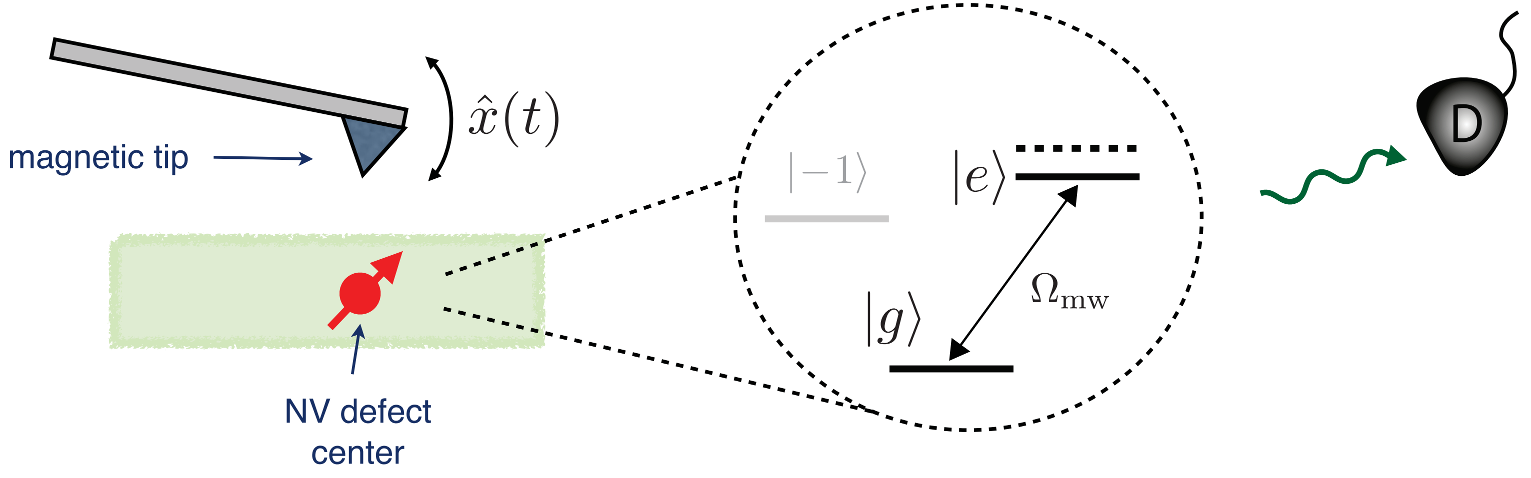
Example:

$$\Phi(\tau) = \frac{g_s \mu_B \tau}{\hbar} \times \delta B$$

(constant magnetic field)



“Quantum Magnetometry” ...

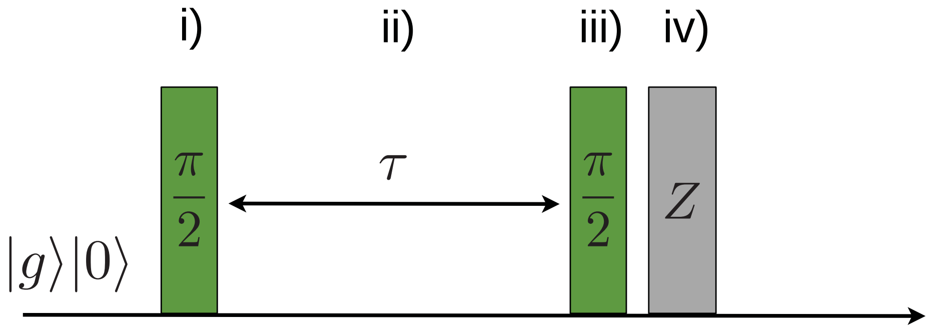


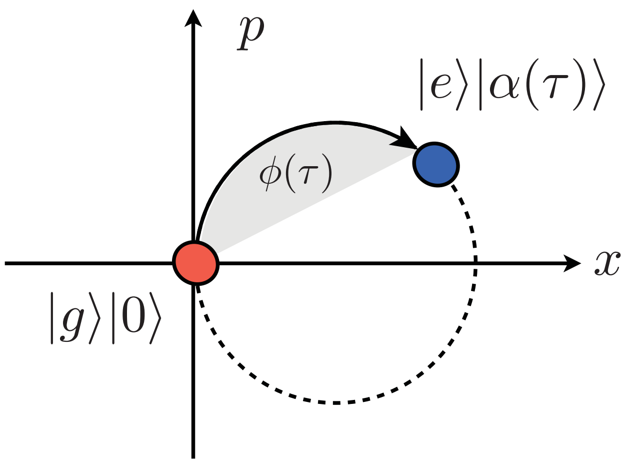
Qubit-resonator coupling:

$$H = \omega a^\dagger a + \lambda(a + a^\dagger)|e\rangle\langle e|$$

⇒ *Use Ramsey method to detect “quantum field”* $\hat{x}(t)$ *!?*

“Quantum Magnetometry” ...





i) $$|g\rangle|0\rangle \rightarrow \frac{1}{\sqrt{2}}\left(|g\rangle + e^{i\varphi}|e\rangle\right)|0\rangle$$

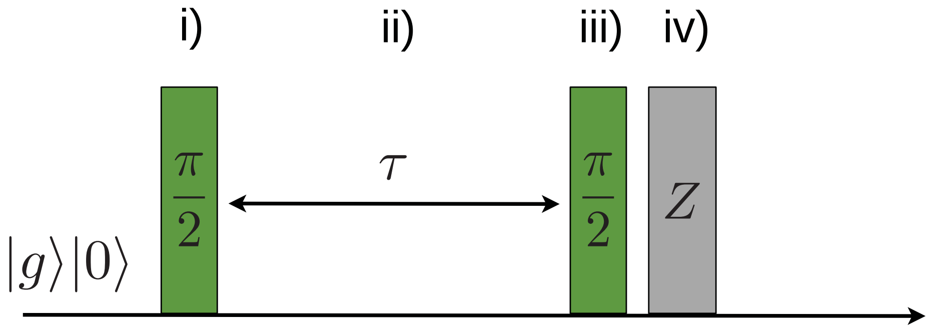
ii) $$\rightarrow \frac{1}{\sqrt{2}}(|g\rangle|0\rangle + e^{i\bar{\varphi}(\tau)}|e\rangle|\alpha(\tau)\rangle)$$

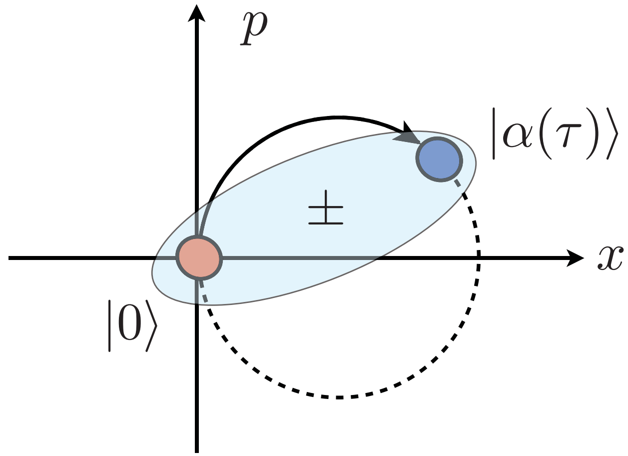
$$\bar{\varphi}(\tau) = \varphi + \phi(\tau)$$

“geometric phase”

$$\alpha(\tau) = \frac{\lambda}{\omega_m}(e^{-i\omega_m\tau} - 1)$$

“Quantum Magnetometry” ...



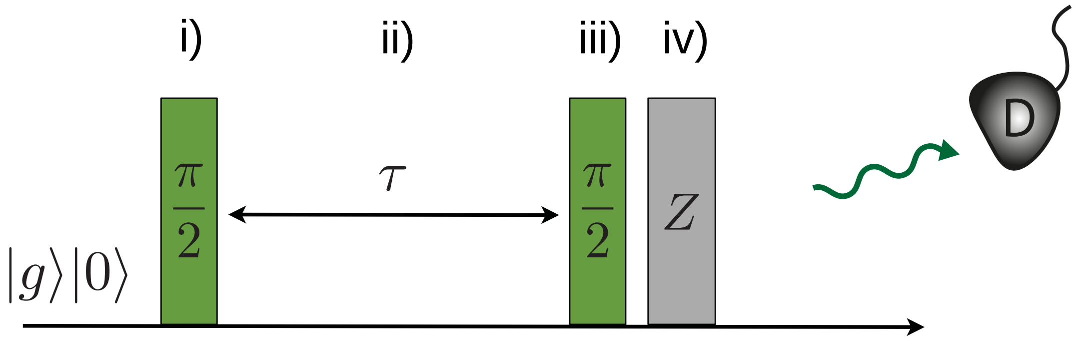


i) $$|g\rangle|0\rangle \rightarrow \frac{1}{\sqrt{2}}\left(|g\rangle + e^{i\varphi}|e\rangle\right)|0\rangle$$

ii) $$\rightarrow \frac{1}{\sqrt{2}}(|g\rangle|0\rangle + e^{i\bar{\varphi}(\tau)}|e\rangle|\alpha(\tau)\rangle)$$

iii) $$\rightarrow \frac{|0\rangle - e^{i\bar{\varphi}}|\alpha(\tau)\rangle}{2}|g\rangle + \frac{|0\rangle + e^{i\bar{\varphi}}|\alpha(\tau)\rangle}{2}|e\rangle$$

“Quantum Magnetometry” ...



$$|e\rangle : \quad Z = +1$$

$$|g\rangle : \quad Z = -1$$

iii) $$|\psi\rangle = \frac{|0\rangle - e^{i\bar{\varphi}}|\alpha(\tau)\rangle}{2}|g\rangle + \frac{|0\rangle + e^{i\bar{\varphi}}|\alpha(\tau)\rangle}{2}|e\rangle$$

iv)

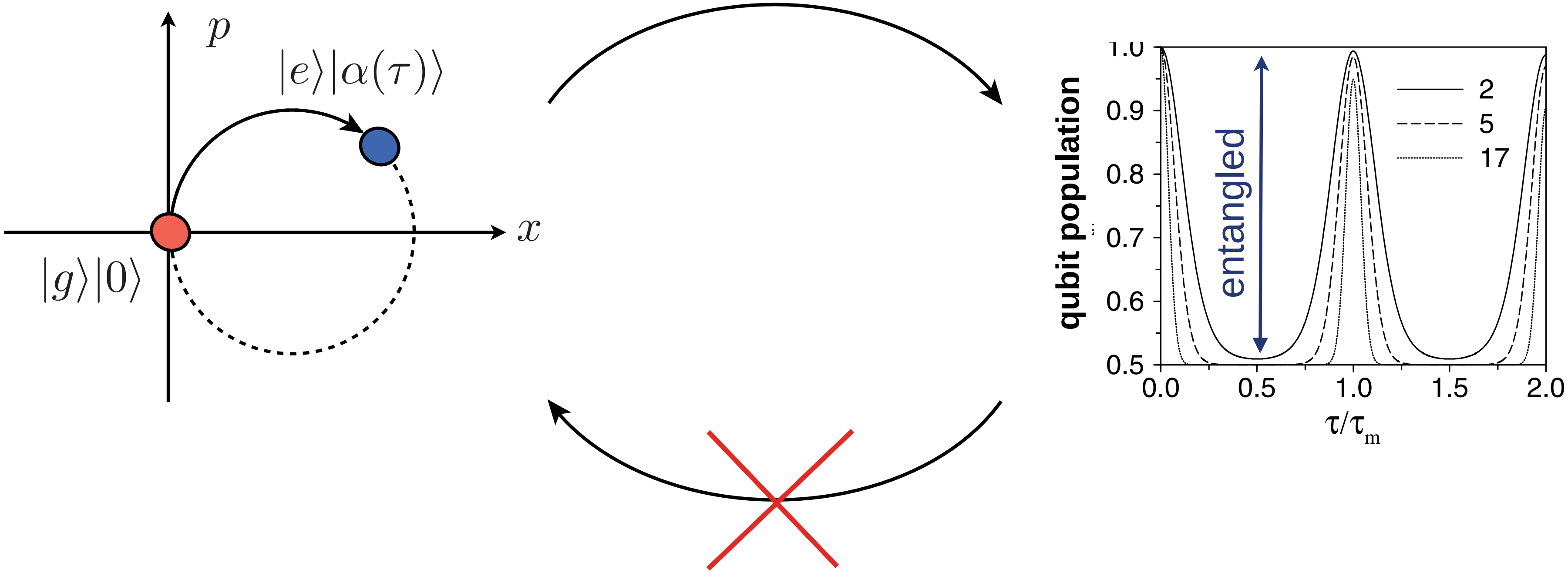
- *Probabilities:* $$p_\pm = \frac{1}{2}\left(1 \pm \cos(\bar{\varphi})e^{-|\alpha(\tau)|^2/2}\right)$$

- *Conditioned resonator state after the measurement:*

$$|\psi\rangle_\pm = \frac{|0\rangle \pm e^{i\bar{\varphi}}|\alpha(\tau)\rangle}{2\sqrt{p_\pm}}$$

Collapse & revivals ...

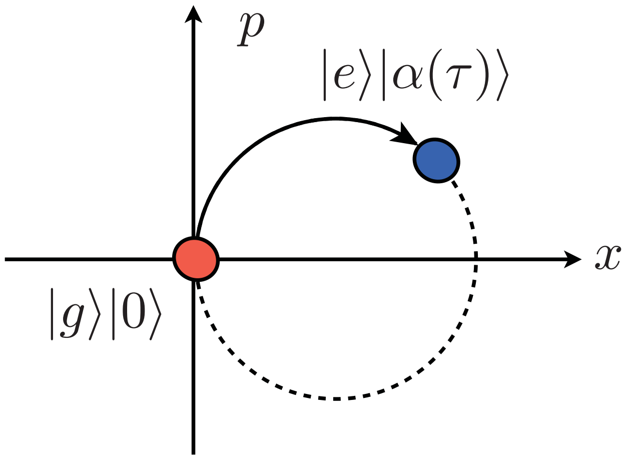
$$p_{\pm} = \frac{1}{2}\left(1 \pm \cos(\bar{\varphi})e^{-|\alpha(\tau)|^2/2}\right)$$

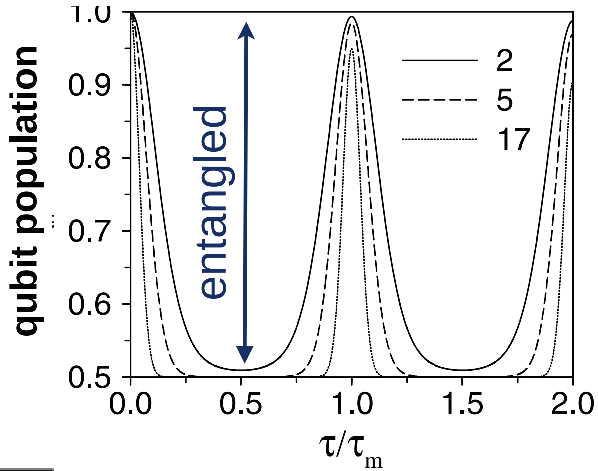


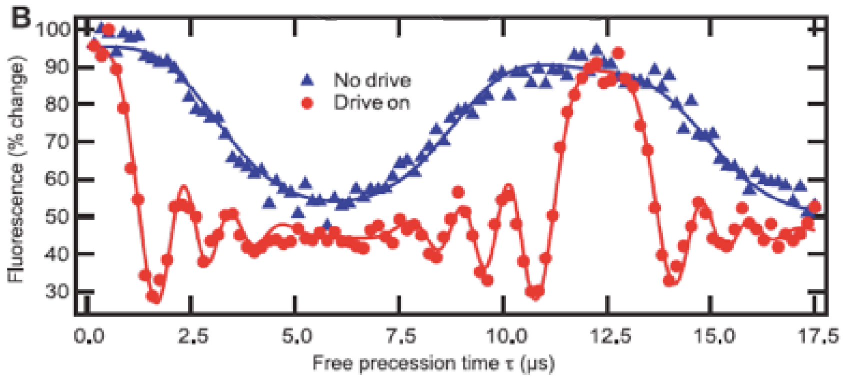
A. Armour, M. Blencowe, K. Schwab, PRL (2002);
W. Marshall, C. Simon, R. Penrose, D. Bouwmeester, PRL (2003); ....

Collapse & revivals ...

$$p_{\pm} = \frac{1}{2}\left(1 \pm \cos(\bar{\varphi}) e^{-|\alpha(\tau)|^2/2}\right)$$



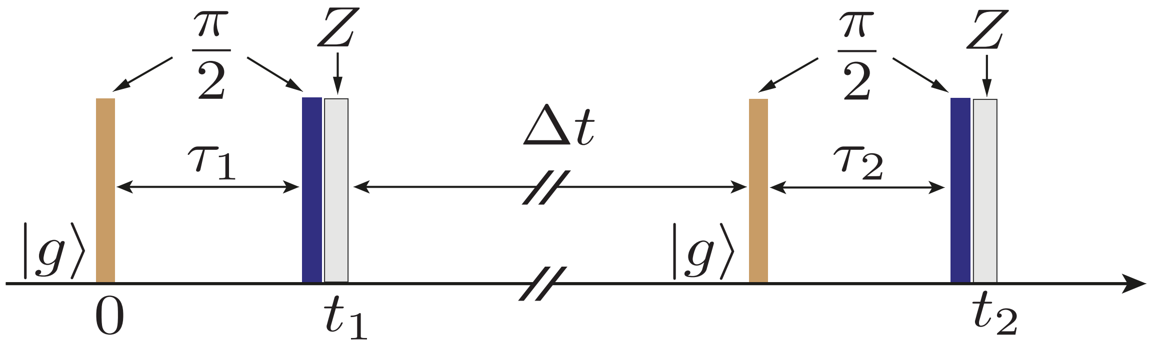




driven, thermal
(T=300 K) resonator !

[1] S. Kolkowitz et al, Science (2012); S. Bennett et al. NJP (2012)

Ramsey correlation measurements ...



$$Z(t_1) = \pm 1$$

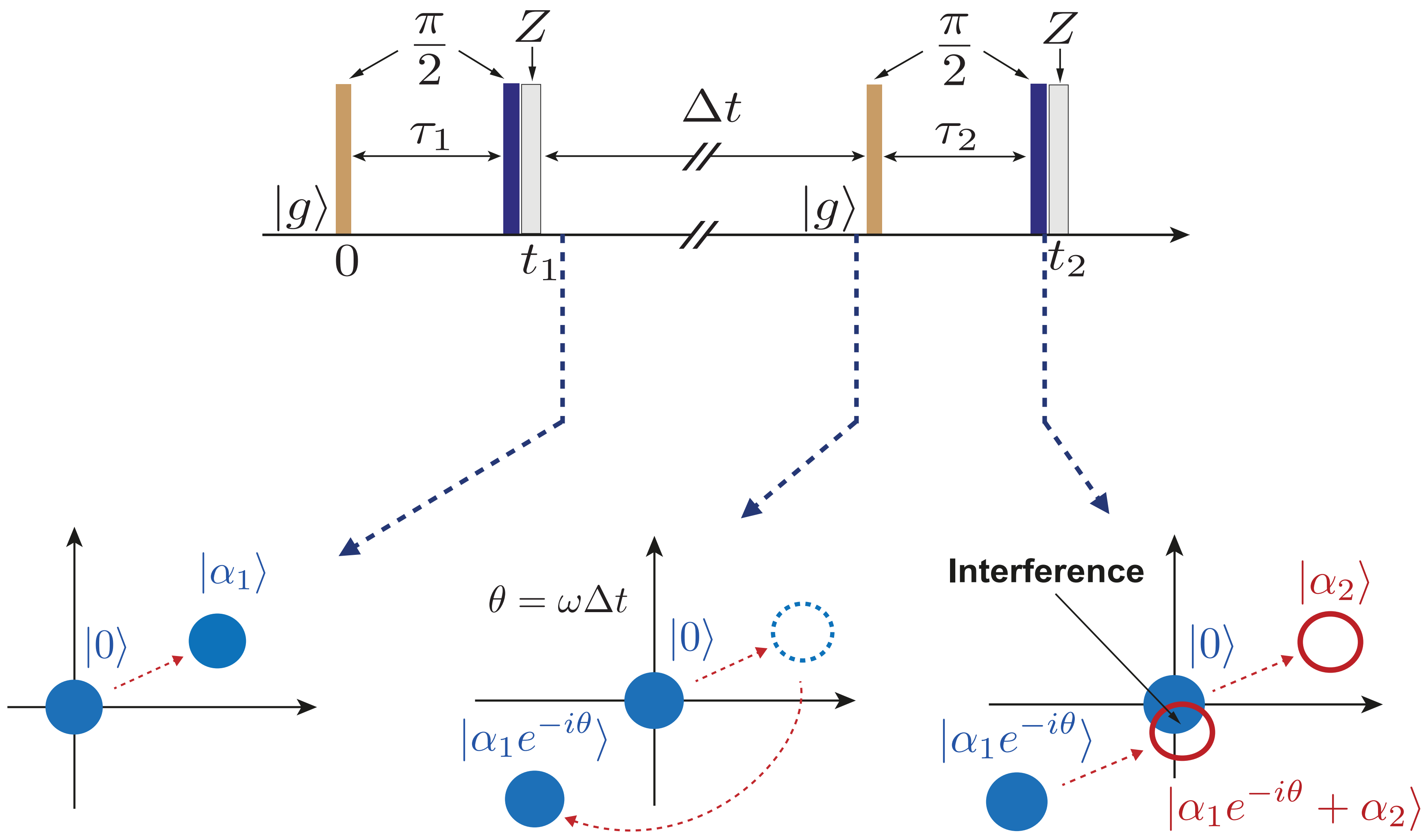
Idea:

Conditioned on the outcome of the first measurement the resonator is projected into one of the superposition states

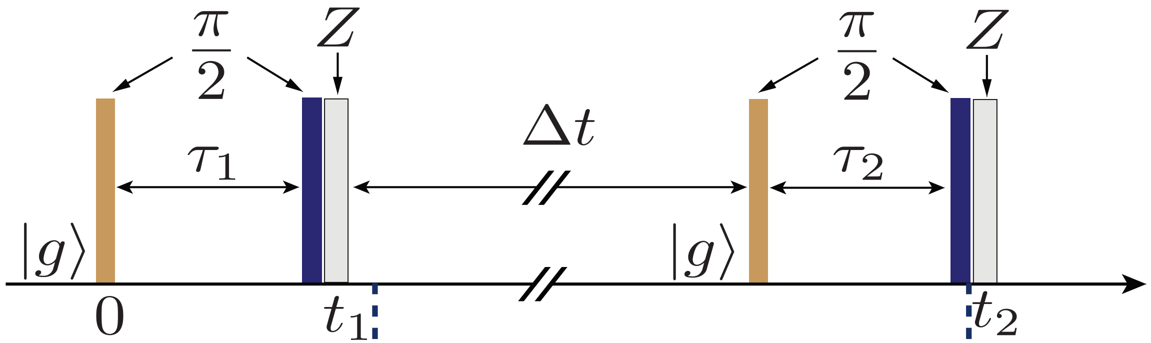
$$|\psi^{\pm}\rangle = \frac{|0\rangle \pm e^{i\bar{\varphi}}|\alpha(\tau)\rangle}{2\sqrt{p_{\pm}}}$$

Use correlation between the first and second measurement to probe quantum superpositions over a time Δt .

Ramsey correlation measurements ...



Ramsey correlation measurements ...



$$|\psi^+\rangle = \frac{|0\rangle + e^{i\bar{\varphi}}|\alpha_1\rangle}{2\sqrt{p_+}}$$

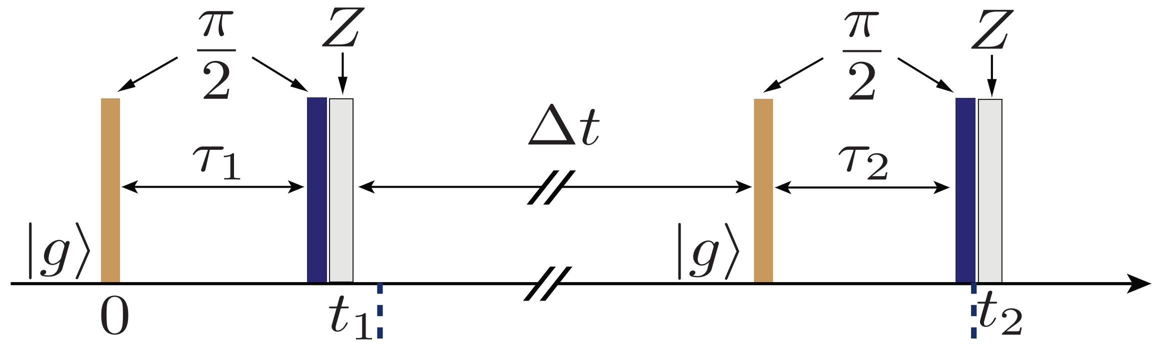
$$|\psi^{-|+}\rangle|g\rangle + |\psi^{+|+}\rangle|e\rangle$$

Four-partite cat state:

$$|\psi^{\pm|+}\rangle = \frac{|0\rangle + e^{i\bar{\varphi}_1}|\alpha_1 e^{-i\theta}\rangle \pm e^{i\bar{\varphi}_2}|\alpha_2\rangle \pm e^{i(\bar{\varphi}_1+\bar{\varphi}_1+\gamma)}|\alpha_1 e^{-i\theta}+\alpha_2\rangle}{4\sqrt{p_+}}$$

$$\gamma = \mathrm{Im}\{\alpha_2\alpha_1^* e^{i\theta}\}$$

Ramsey correlation measurements ...



$$|\psi^{+}\rangle = \frac{|0\rangle + e^{i\bar{\varphi}}|\alpha_1\rangle}{2\sqrt{p_+}}$$

$$|\psi^{-|+}\rangle|g\rangle + |\psi^{+|+}\rangle|e\rangle$$

Four-partite cat state:

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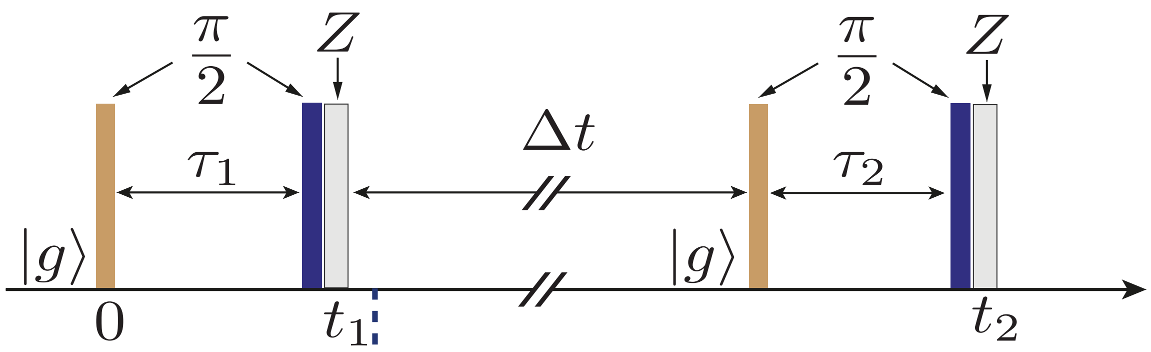
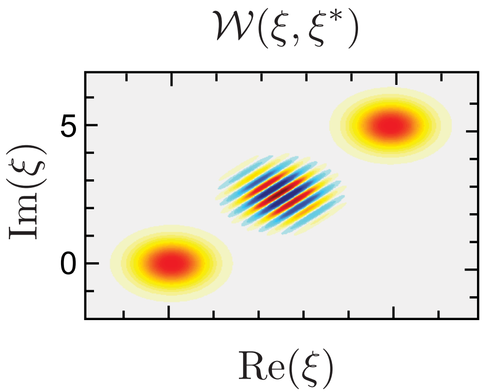
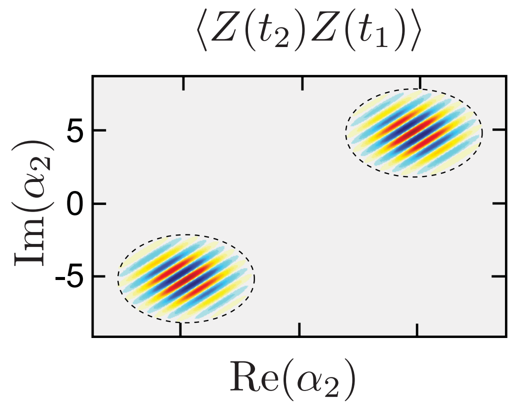
⇒ *Conditioned probabilities:* $p_{\pm|+},\, p_{\pm|-}$ $\Rightarrow \langle Z(t_2)Z(t_1)\rangle$

Ramsey correlation measurements ...



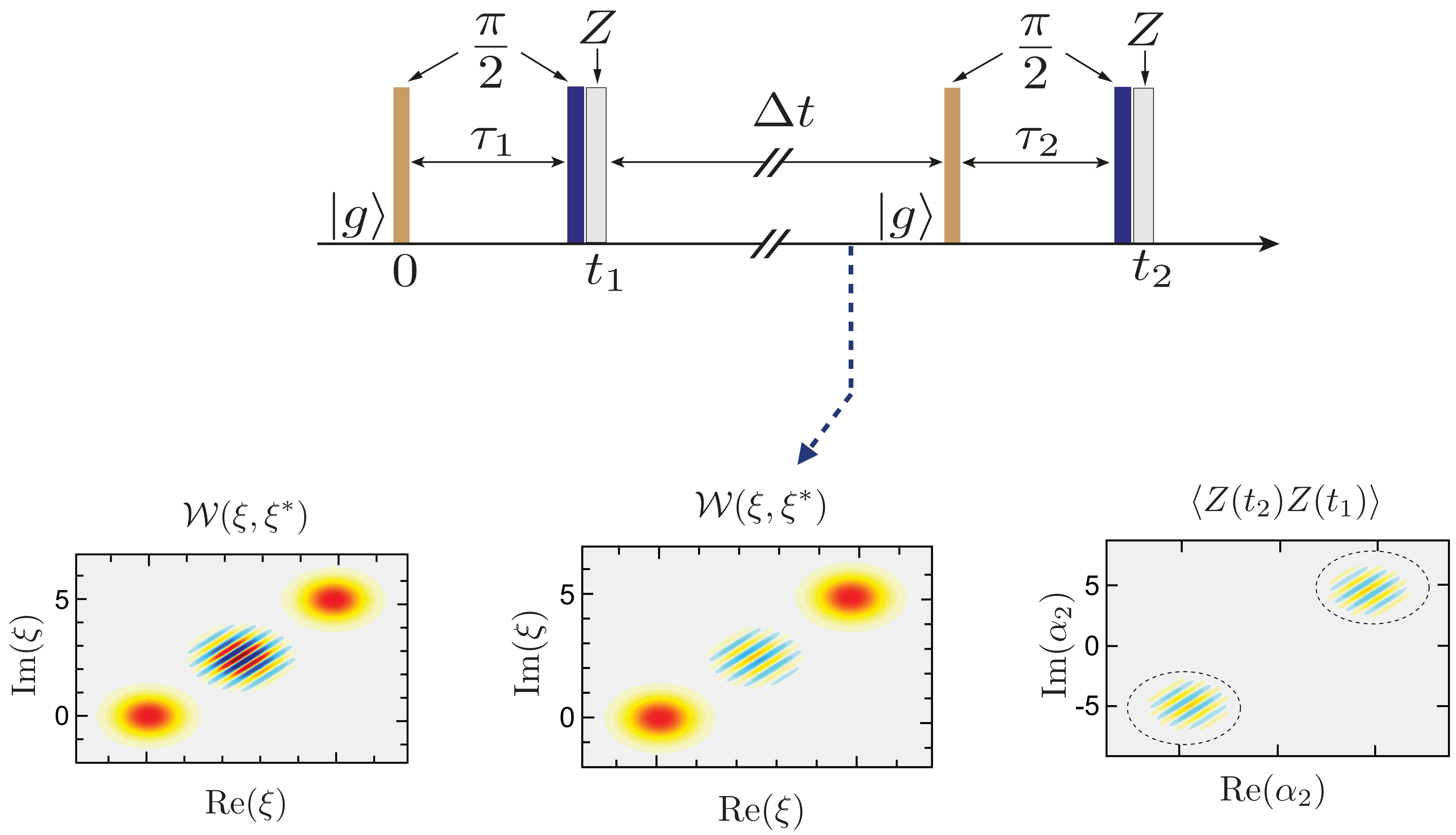


Wigner function of the conditioned state



correlations between the two measurements

Ramsey correlation measurements ...

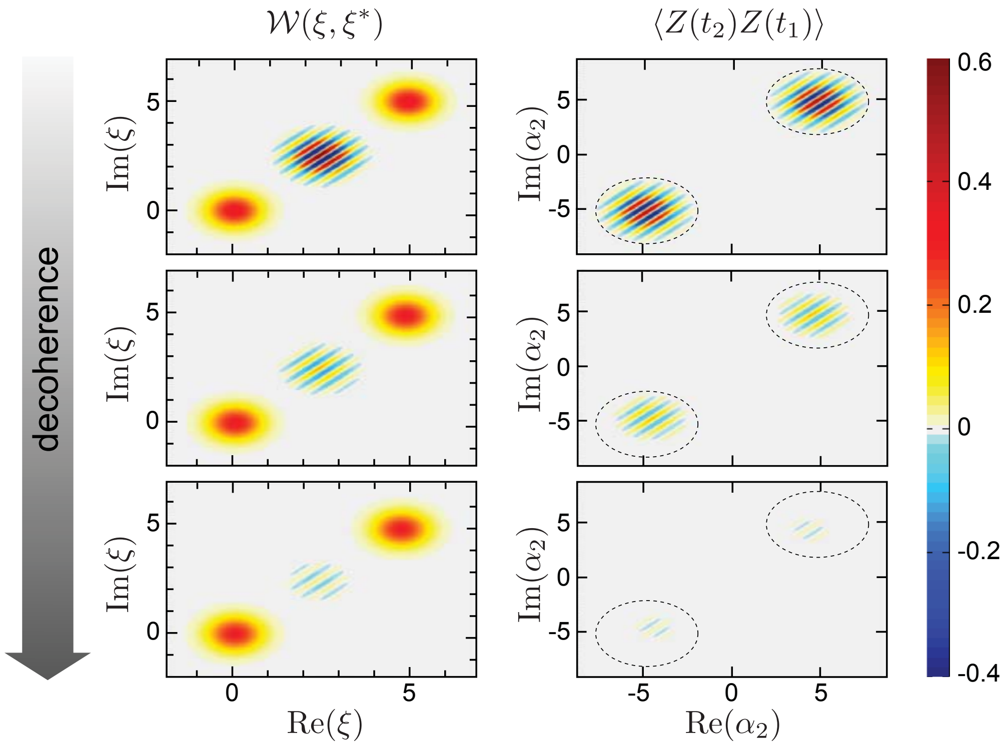


Wigner function of the conditioned state

decoherence

correlations between the two measurements

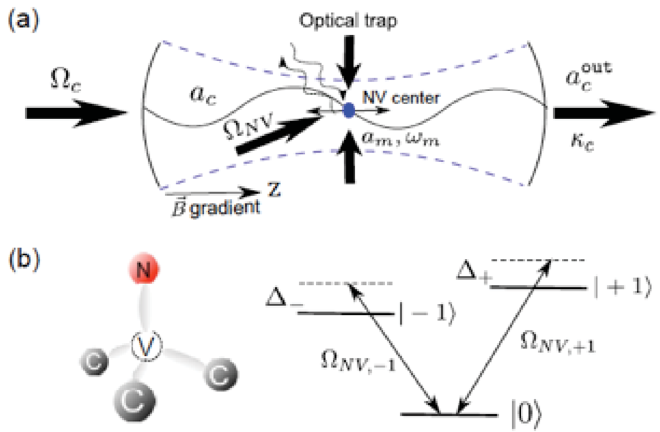
Ramsey correlation measurements ...



⇒ *The correlation function* $C(t_1, t_2) = \langle Z(t_2)Z(t_1)\rangle$ *provides direct measure for the survival/decay of macroscopic superposition states !*

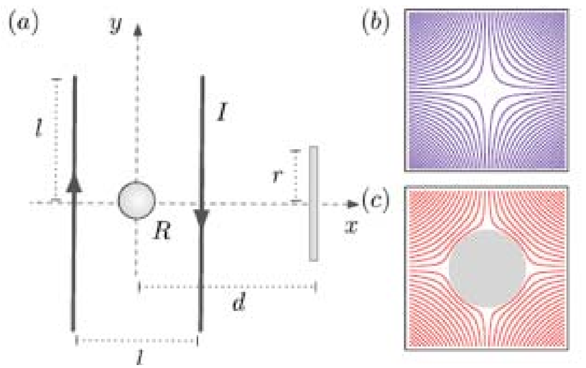
⇒ *During the waiting time the resonator is **decoupled** from the qubit !*

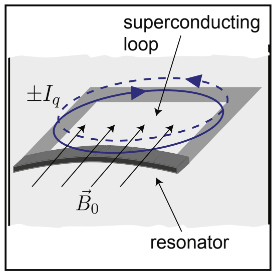
Levitated objects ...



optically levitated nanodiamonds
+ NV centers !

(Z. Yin et al, arXiv:1305.1701)

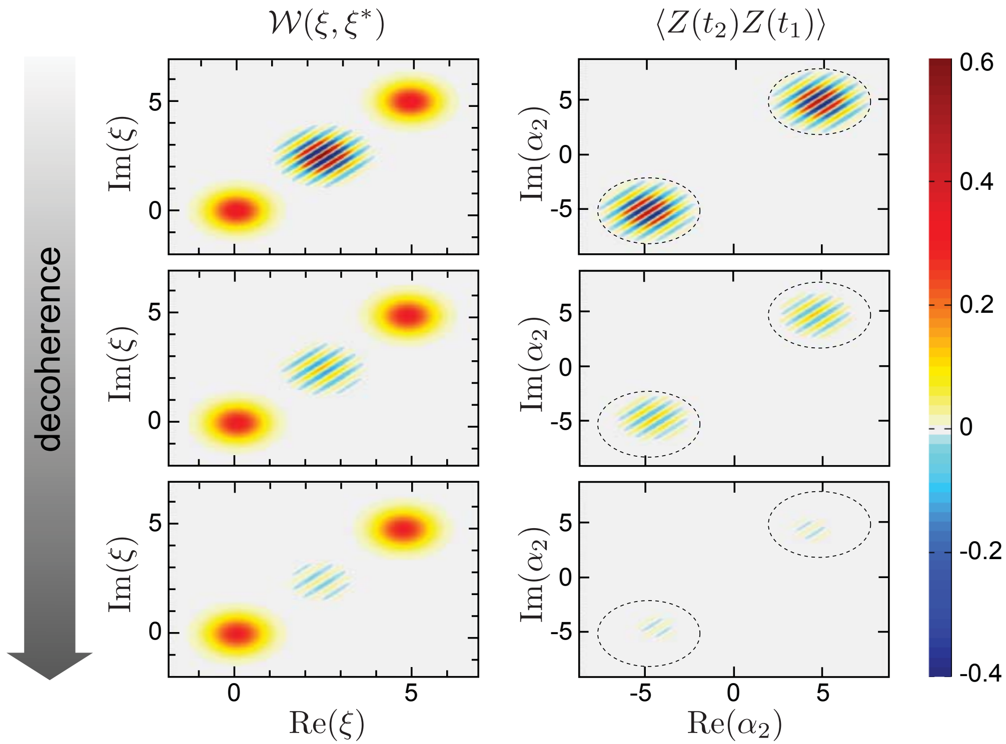




magnetic levitation +
superconducting flux qubits

(O. Romero-Isart et al. PRL 2012;
M. Cirio et al. PRL 2012)

Ramsey correlation measurements ...

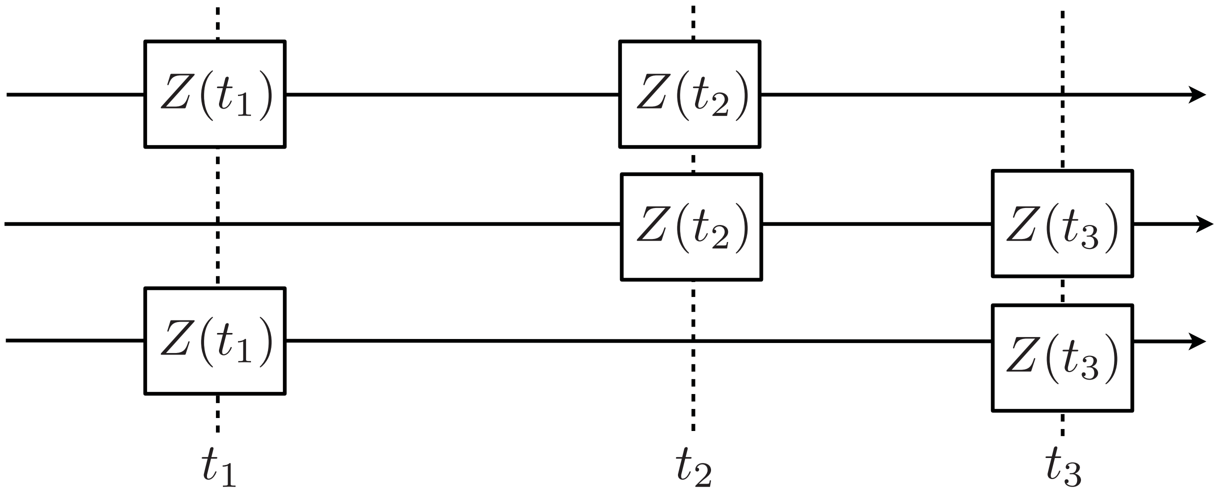


Not a PROOF yet!

⇒ *The correlation function* $C(t_1,t_2)=\langle Z(t_2)Z(t_1)\rangle$ *provides direct measure for the survival/decay of macroscopic superposition states !*

⇒ *During the waiting time the resonator is* ***decoupled*** *from the qubit !*

Leggett-Garg inequalities ...



$|Z(t_i)| \leq 1$

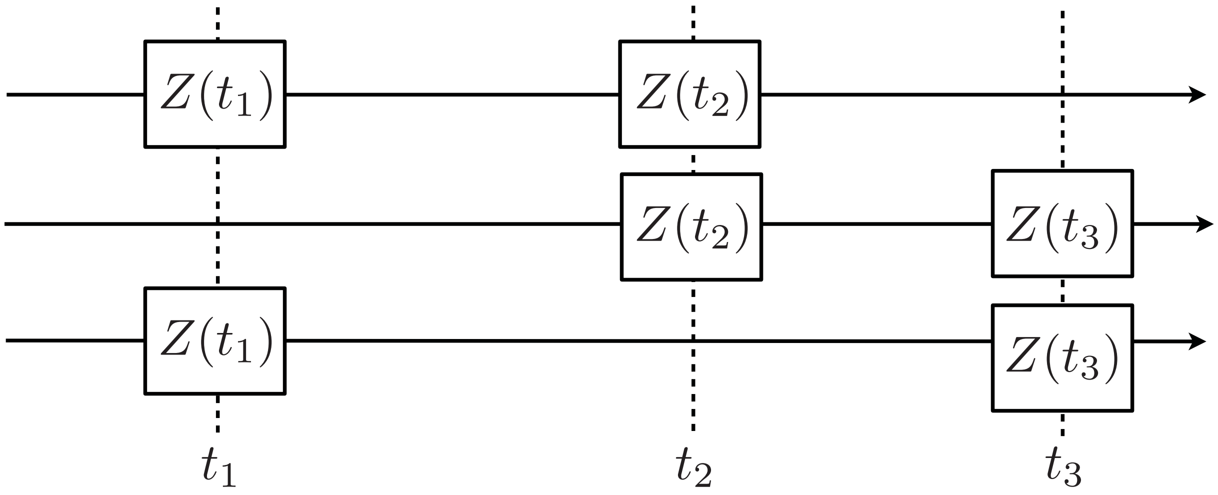
$C(t_i, t_j) = \langle Z(t_j) Z(t_i) \rangle$

$t_i < t_j$

⇒ *For any "macro-realistic" system these correlations are bound by the (Wigner type) Leggett-Garg inequality:*

$$C(t_1, t_2) + C(t_2, t_3) - C(t_1, t_3) \leq 1$$

Leggett-Garg inequalities ...



$$|Z(t_i)| \leq 1$$

$$C(t_i, t_j) = \langle Z(t_j) Z(t_i) \rangle$$

$$t_i < t_j$$

"Macrorealism" [1]:

(1) Macrorealism per se: *A measurement on a macroscopic system reveals a well-defined pre-existing value.*

(2) Non-invasive measurability: *At least in principle, we can measure this value without disturbing the system.*

[1] Leggett, J. Phys. Condens. Matter ***14****, R415 (2002);*
Emary, Lambert, Nori, arXiv:1304.5133

Leggett-Garg inequalities ...

$t_i < t_j$

$C(t_i, t_j) = \langle Z(t_j) Z(t_i) \rangle$

Example:
Thermal resonator state, identical measurements $(\alpha = \alpha_1 = \alpha_2)$

$$C(t_i, t_j) = \frac{1}{2}\Big[\cos(\bar{\varphi}_i + \bar{\varphi}_j + \gamma_{ij})e^{-|\alpha|^2(2\bar{n}+1)(1+\cos\theta_{ij})} + \cos(\bar{\varphi}_i - \bar{\varphi}_j - \gamma_{ij})e^{-|\alpha|^2(2\bar{n}+1)(1-\cos\theta_{ij})}\Big]$$

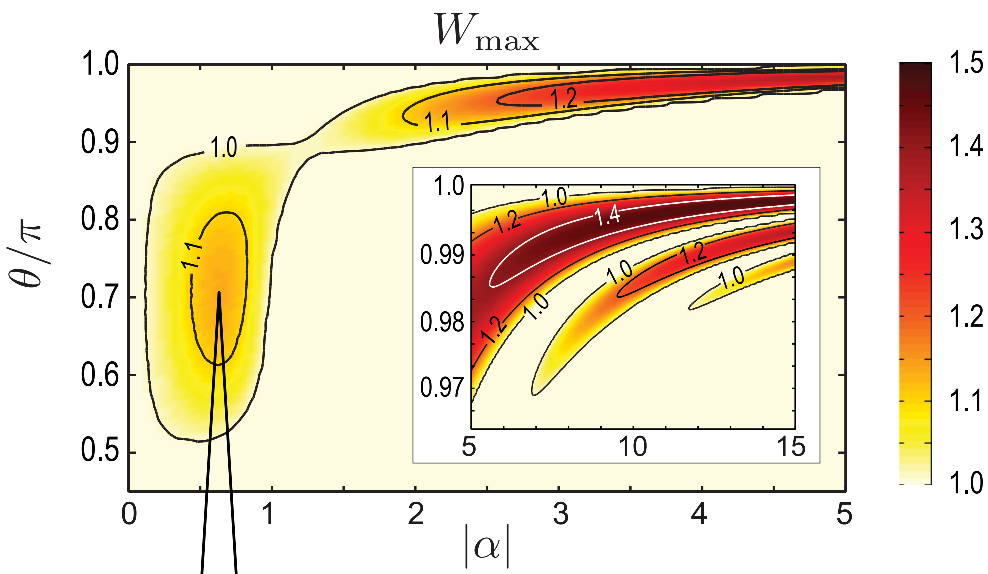
$$\gamma_{ij} = |\alpha|^2 \sin(\theta_{ij}) \qquad \theta_{ij} = \omega(t_j - t_i)$$

Leggett-Garg inequalities ...

Leggett-Garg inequality (LGI):

$$W = C(t_1, t_2) + C(t_2, t_3) - C(t_1, t_3) \leq 1$$

Result:



$$(\bar{n} = 0)$$

$$\theta = \theta_{12} = \theta_{23}$$

Arbitrarily small displacements can lead to a violation of the LGI:

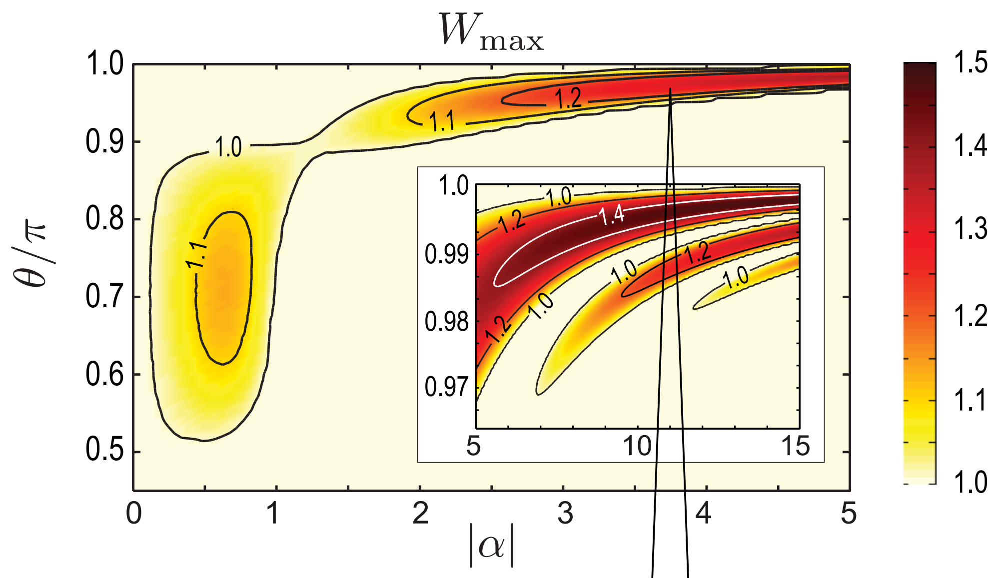
$$W \simeq 1 + |\alpha|^2(\sqrt{2}/2 - 2\bar{n})$$

Leggett-Garg inequalities ...

Leggett-Garg inequality (LGI):

$$W = C(t_1, t_2) + C(t_2, t_3) - C(t_1, t_3) \leq 1$$

Result:



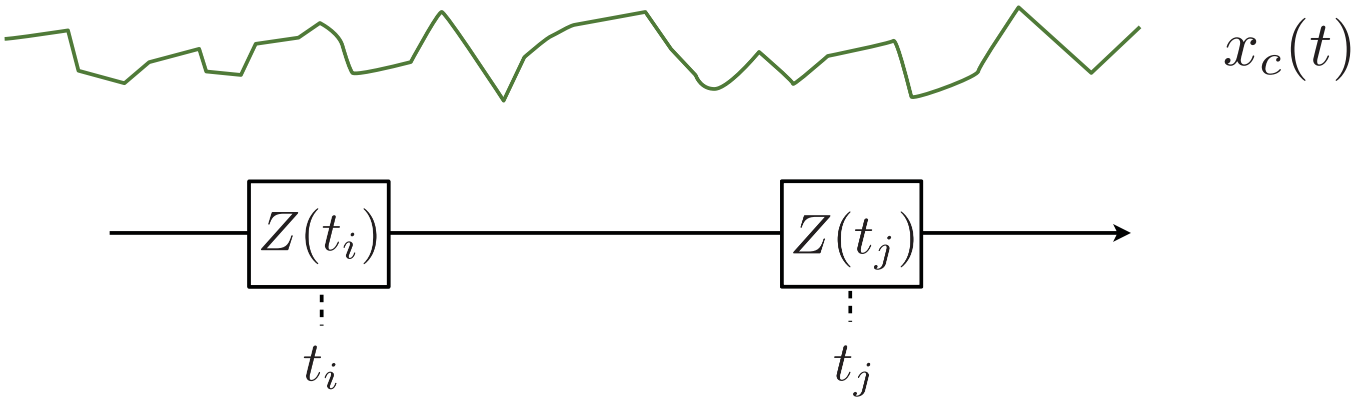
$(\bar{n} = 0)$

$\theta = \theta_{12} = \theta_{23}$

Maximal & robust violation of the LGI for large displacements:

$$W \simeq \frac{3}{2}\left(1 - \frac{\pi^2}{4|\alpha|^2}(2\bar{n}+1)\right)$$

Quantum vs. classical correlations ...

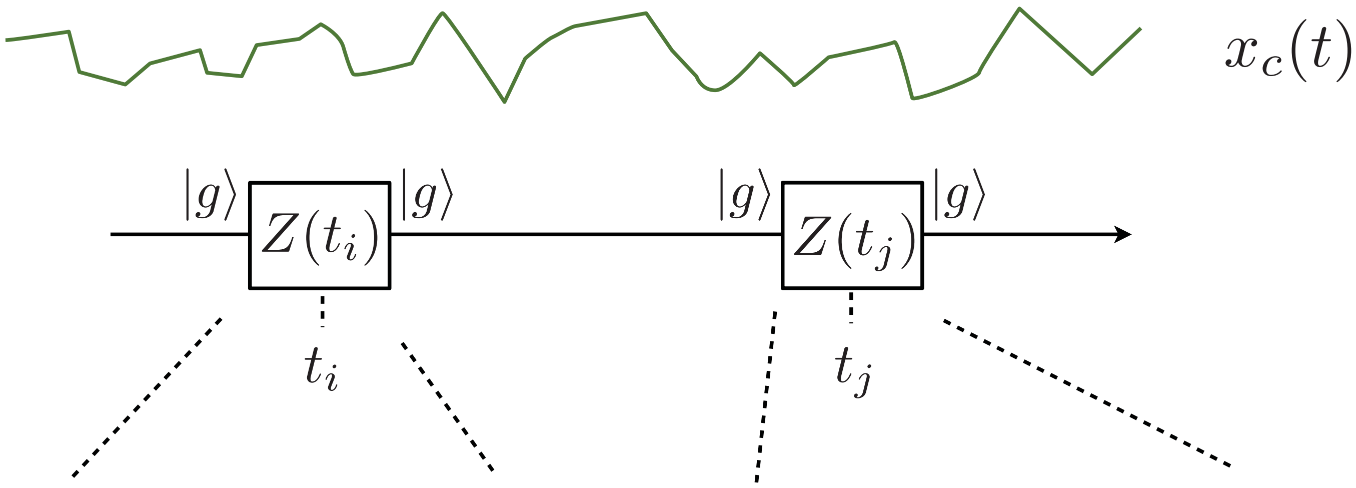


Qubit probing a classical field:

$$H_{\text{int}} = \sqrt{2}\lambda x_c(t)|e\rangle\langle e|$$

(random) trajectory, but with a specific value at each time

Quantum vs. classical correlations ...



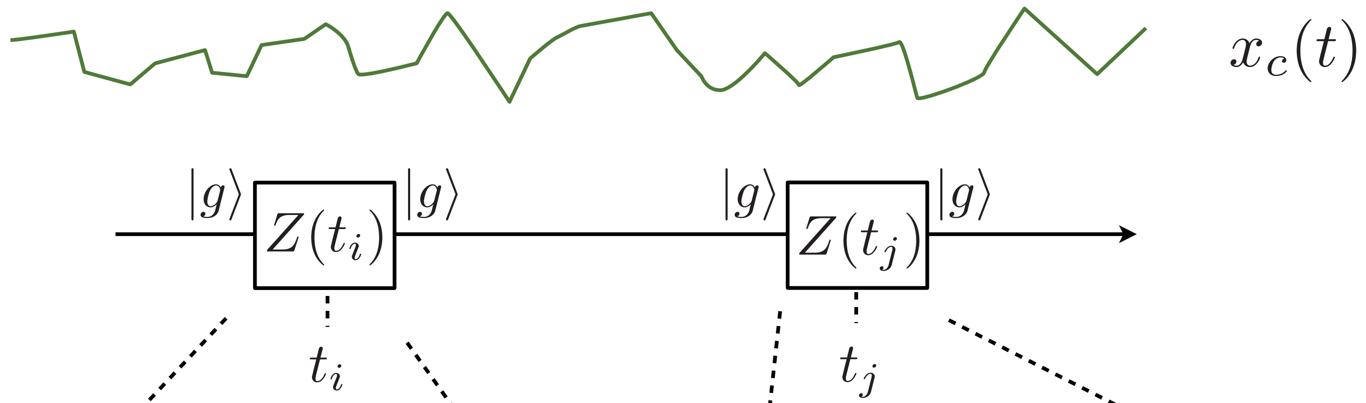
$$\Phi_i = \sqrt{2}\lambda \int_{t_i - \tau_i}^{t_i} x_c(s) ds \qquad \Phi_j = \sqrt{2}\lambda \int_{t_j - \tau_j}^{t_j} x_c(s) ds$$

For a given trajectory:

$$\langle Z(t_i) \rangle = \cos(\varphi_i - \Phi_i) \qquad \langle Z(t_j) \rangle = \cos(\varphi_j - \Phi_j)$$

$$\langle Z(t_j) Z(t_i) \rangle = \cos(\varphi_i - \Phi_i) \cos(\varphi_j - \Phi_j)$$

Quantum vs. classical correlations ...



$$\Phi_i = \sqrt{2}\lambda \int_{t_i-\tau_i}^{t_i} x_c(s)ds \qquad \Phi_j = \sqrt{2}\lambda \int_{t_j-\tau_j}^{t_j} x_c(s)ds$$

General correlations:

$$\langle Z(t_i)Z(t_j)\rangle = \int d\Phi_i d\Phi_j P(\Phi_i,\Phi_j)\cos(\varphi_i+\Phi_i)\cos(\varphi_j+\Phi_j)$$

proper probability distribution (derived from the classical process $x_c(t)$)

bound variables

LG inequality applies !

Quantum vs. classical correlations ...

Example: *thermal classical field*

$$x_c(t) = \underbrace{A}_{\text{Gaussian amplitude}} \cos(\omega t + \underbrace{\delta_0}_{\text{random initial phase}})$$

Classical:

$$C(t_1, t_2) = \frac{1}{2}\Big[\cos(\varphi_1 + \varphi_2) e^{-2|\alpha(\tau)|^2 \langle x_c^2\rangle (1+\cos\theta)} + \cos(\varphi_1 - \varphi_2) e^{-2|\alpha(\tau)|^2 \langle x_c^2\rangle (1-\cos\theta)}\Big]$$

Quantum:

$$C(t_1, t_2) = \frac{1}{2}\Big[\cos(\bar{\varphi}_1 + \bar{\varphi}_2 + \gamma) e^{-|\alpha(\tau)|^2 (2\bar{n}+1)(1+\cos\theta)} + \cos(\bar{\varphi}_1 - \bar{\varphi}_2 - \gamma) e^{-|\alpha(\tau)|^2 (2\bar{n}+1)(1-\cos\theta)}\Big]$$

Violation of LG inequality: requirements

1) Dispersive qubit-resonator coupling:

$$H = \omega a^\dagger a + \lambda(a + a^\dagger)|e\rangle\langle e|$$

✓

2) Qubit control & readout:

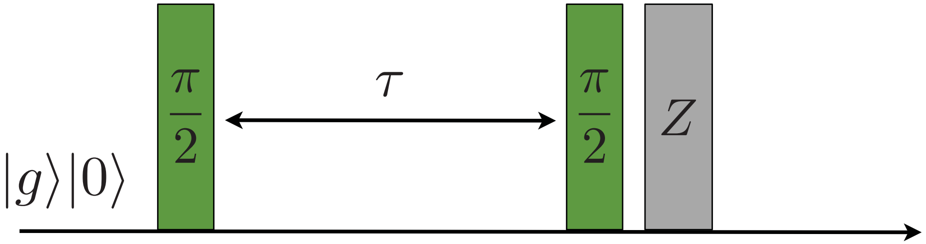
$\Rightarrow$ *see literature on NV centers, superconducting qubits, ...* ✓

3) Low mechanical occupation numbers $\bar{n} \sim \mathcal{O}(1)$***:***

$\Rightarrow$ *T~50 mK, active (optomechanical) cooling methods* ✓

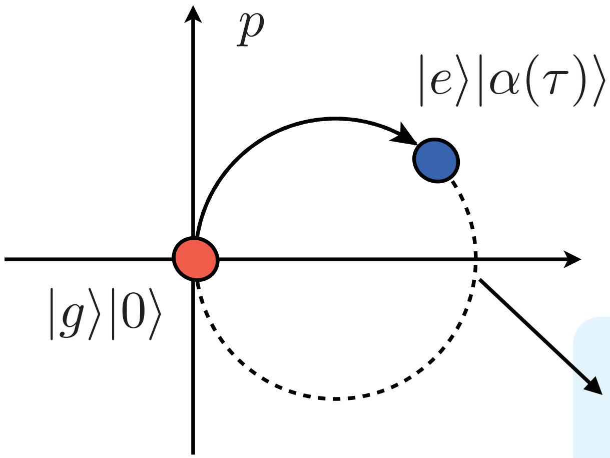
4) State dependent displacement $|\alpha(\tau)| \sim \mathcal{O}(1)$***:*** **?**

Displacement amplitude ...



$$H_{\rm int} = \lambda(a + a^\dagger)|e\rangle\langle e|$$

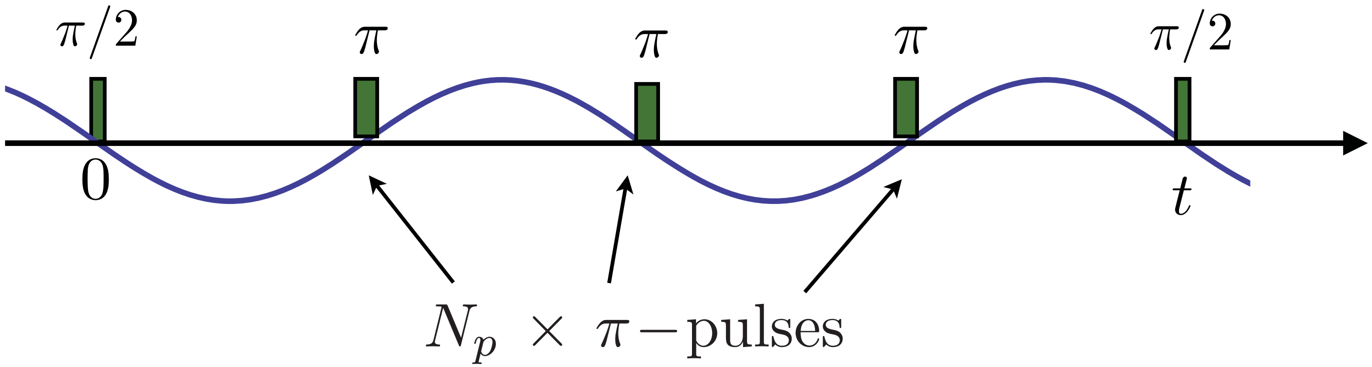
static coupling

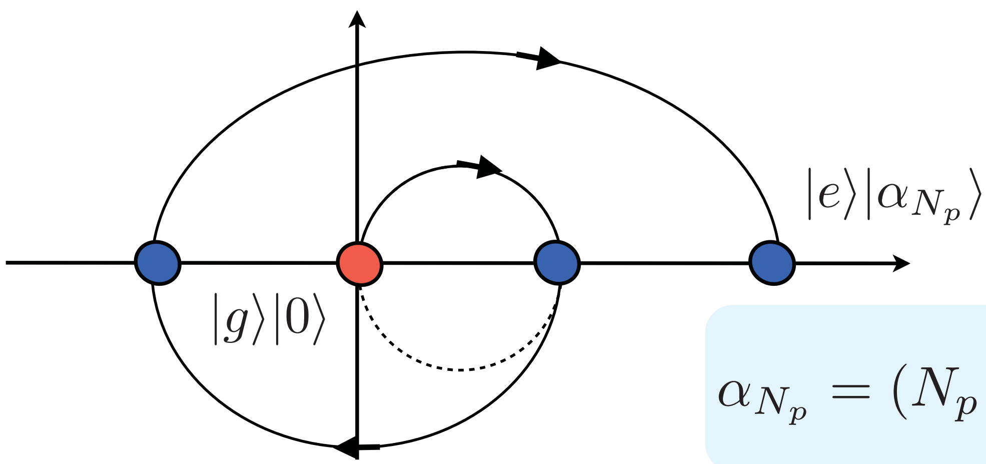


most experimental settings

$$|\alpha(\tau)| \leq \frac{2\lambda}{\omega} \quad < 1$$

Parametrically enhanced displacements ...

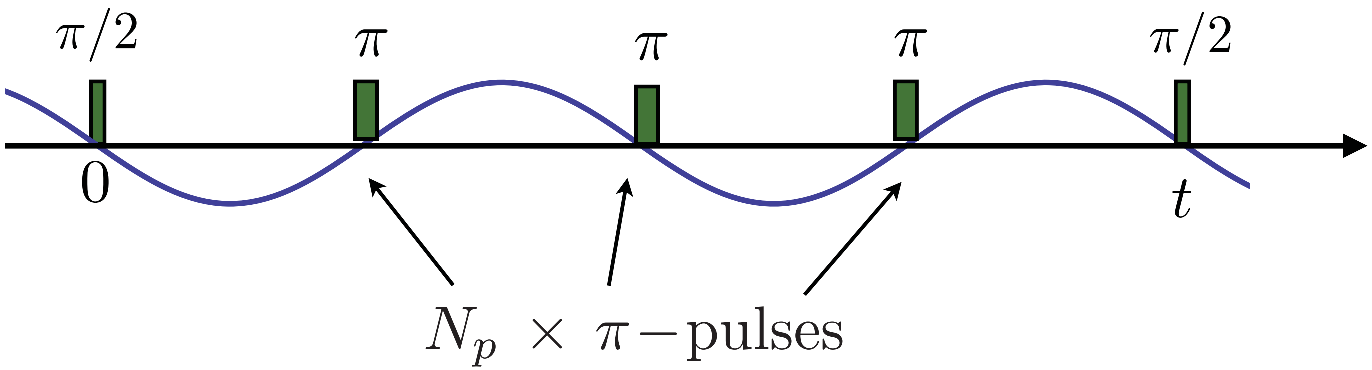




$$\alpha_{N_p} = (N_p + 1)\frac{2\lambda}{\omega}$$

L. Tian, PRB (2005); S. Bennett et al. NJP (2012)

Parametrically enhanced displacements ...



How many pulses can I do? $\Rightarrow$ *decoherence !*

$$|\alpha_{\mathrm{max}}| \lesssim \frac{\lambda}{\pi} \times \min\{T_2, T_{\mathrm{th}}\} \qquad T_{\mathrm{th}}^{-1} = \frac{k_B T}{\hbar Q}$$

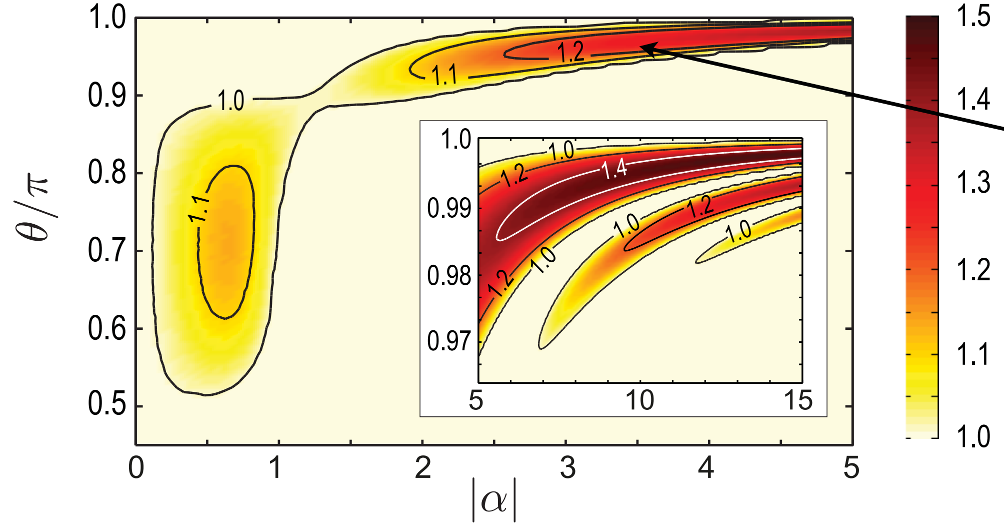
4) State dependent displacement $|\alpha(\tau)| \sim \mathcal{O}(1)$***:***

$\Rightarrow$ ***Strong coupling regime !***

-) theory: Armour et al, PRL (2002), Tian, PRB (2005); P.R. et al PRB (2009), ...
-) see recent experiments with superconducting qubits & NV center

work in progress

Leggett-Garg inequality: Summary

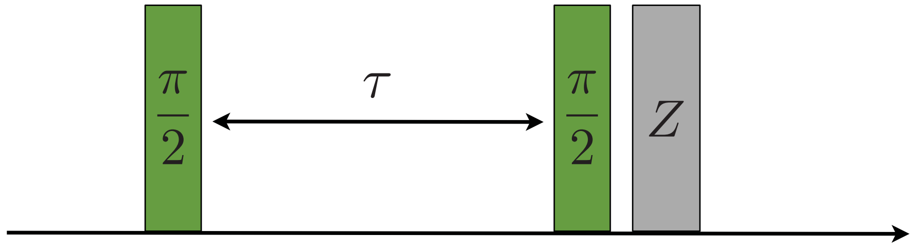


non-classical correlations LG>1 !

$$LG = C(t_1, t_2) + C(t_2, t_3) - C(t_1, t_3) \leq 1$$

Clear experimental signature to distinguish between quantum and classical signals!

Modular variables ...



$$\langle Z(t_1)\rangle = \mathrm{Tr}\{Q(\bar{\varphi}_1, \alpha_1)\rho_0\}$$

*Ramsey measurement allows us to measure **“modular variables”** [1] of a macroscopic continuous variable system:*

$$Q(\varphi,\alpha) = \cos\left(\varphi + \sqrt{2}\mathrm{Im}(\alpha)x - \sqrt{2}\mathrm{Re}(\alpha)p\right)$$

bound observables

infinite dimensional Hilbertspace

[1] Aharonov, Rohrlich, “Quantum Paradoxes”; S. Popescu, Nature Phys (2010)

Modular variables ...

$$\Psi_\alpha(x) = \frac{1}{\sqrt{2}}\left(\Psi_1(x) + e^{i\alpha}\Psi_2(x)\right)$$

macroscopic superposition

non-local phase

$$\langle x^n \rangle = \frac{1}{2}\int dx\, x^n |\Psi_1(x)|^2 + \frac{1}{2}\int dx\, x^n |\Psi_2(x)|^2$$

$$\langle \cos(p) \rangle = \quad \ldots \quad + e^{i\alpha} \cdots + e^{-i\alpha} \ldots$$

[1] Aharonov, Rohrlich, "Quantum Paradoxes"; S. Popescu, Nature Phys (2010)

Quantum contextuality ...

X_{jk}	$k=1$	$k=2$	$k=3$
$j=1$	x_1	p_2	$-x_1-p_2$
$j=2$	$-x_2$	p_1	x_2-p_1
$j=3$	x_2-x_1	$-p_1-p_2$	$x_1-x_2+p_1+p_2$

two
resonator modes

$$A_{jk} = e^{i\sqrt{\pi}X_{jk}} = \cos\left(\sqrt{\pi}X_{jk}\right) + i\sin\left(\sqrt{\pi}X_{jk}\right)$$

Non-contextual theories: *The pre-existing value of an observable does not depend in which combination of other compatible observables it is measured.* $\Rightarrow$

$$|\langle R_1\rangle + \langle R_2\rangle + \langle R_3\rangle + \langle C_1\rangle + \langle C_2\rangle - \langle C_3\rangle| \leq 3\sqrt{3}$$

$$R_j = A_{j1}A_{j2}A_{j3} \qquad\qquad C_k = A_{1k}A_{2k}A_{3k}$$

A. Plastino and A. Cabello, PRA ***82****, 022114 (2010)*

Quantum contextuality ...

X_{jk}	$k=1$	$k=2$	$k=3$
$j=1$	x_1	p_2	$-x_1-p_2$
$j=2$	$-x_2$	p_1	x_2-p_1
$j=3$	x_2-x_1	$-p_1-p_2$	$x_1-x_2+p_1+p_2$

two
resonator modes

$$A_{jk} = e^{i\sqrt{\pi}X_{jk}} = \cos\left(\sqrt{\pi}X_{jk}\right) + i\sin\left(\sqrt{\pi}X_{jk}\right)$$

Non-contextual theories: *The pre-existing value of an observable does not depend in which combination of other compatible observables it is measured.* $\Rightarrow$

$$|\langle R_1\rangle + \langle R_2\rangle + \langle R_3\rangle + \langle C_1\rangle + \langle C_2\rangle - \langle C_3\rangle| \leq 3\sqrt{3}$$

- *We can test such inequalities by looking at three-point correlations*

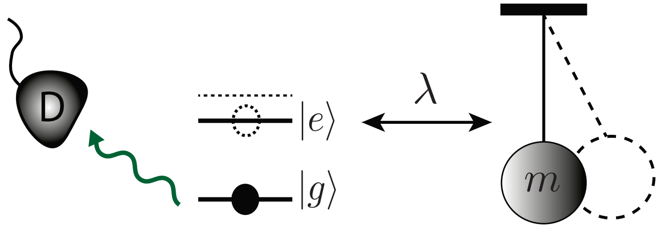
$$\langle Z(t_1)Z(t_2)Z(t_3)\rangle = \mathrm{Tr}\{Q_{t_3}Q_{t_2}Q_{t_1}\rho_0\}$$

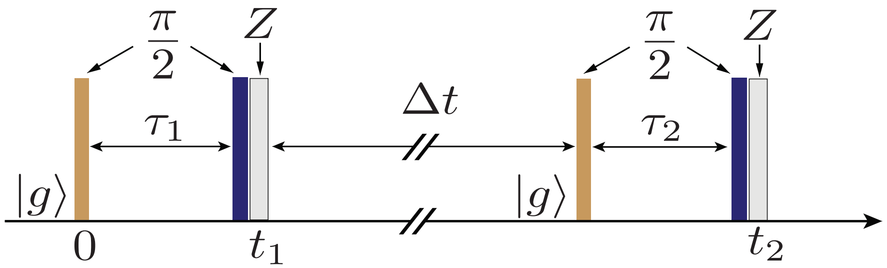
A. Plastino and A. Cabello, PRA ***82****, 022114 (2010)*

Conclusions & Outlook

Summary ...

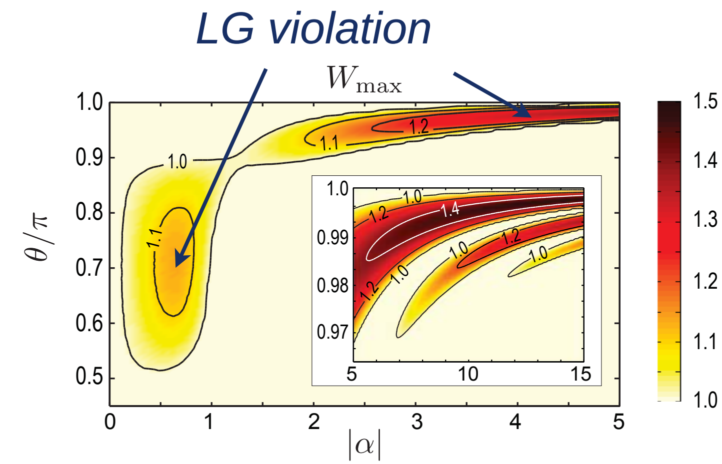
Ramsey correlation measurements:





- *Leggett-Garg Inequality:*

$$C(t_1, t_2) + C(t_2, t_3) - C(t_1, t_3) \leq 1$$

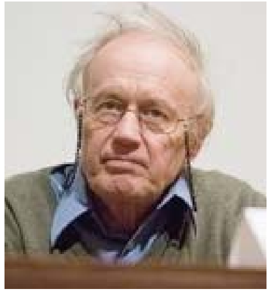


- *Versatile & experimentally feasible measurement tool for fundamental test of quantum mechanics with massive objects !*

- *Implementation with various spin, charge & photonic qubits, levitated objects, ...*

A. Asadian, C. Brukner, PR, arXiv:1309.2229

Outlook: beyond Leggett-Garg ...

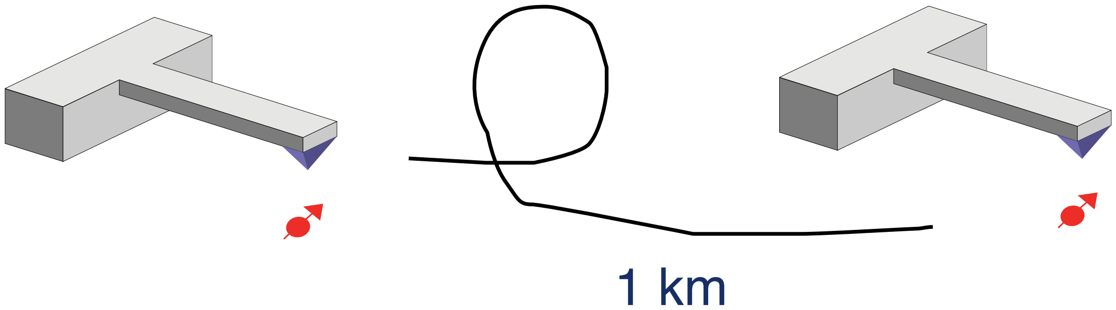


Leggett: "Macro-realism"
= Macrorealism per se & non-invasive measurability

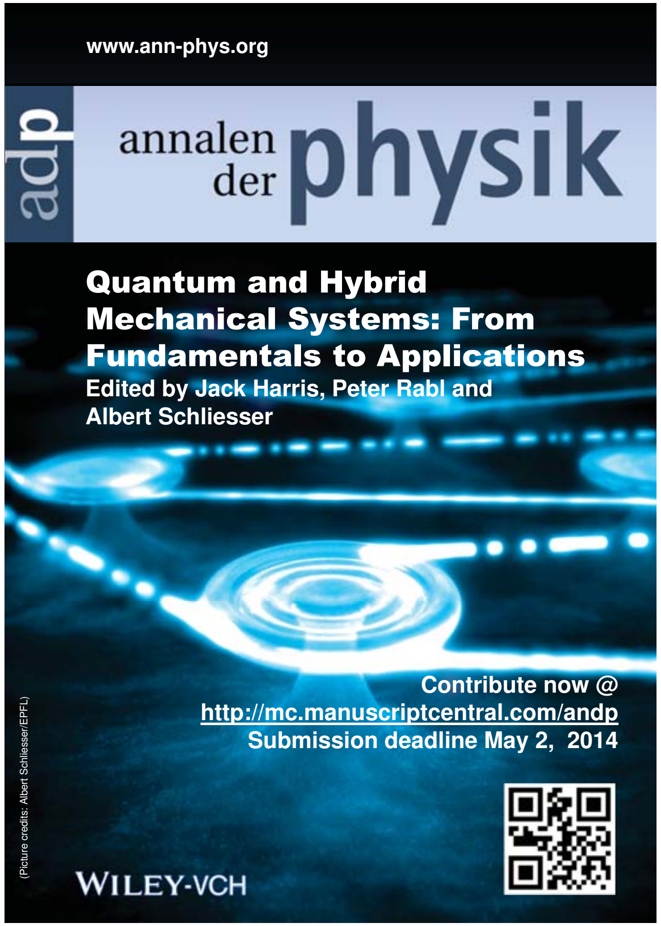
---

1) Evaluation of potential classical "invasive" effects.
Exclude such effects by complementary measurements !

2) Generalization to Bell-type measurements
between space-like separated resonators !



Announcement ...



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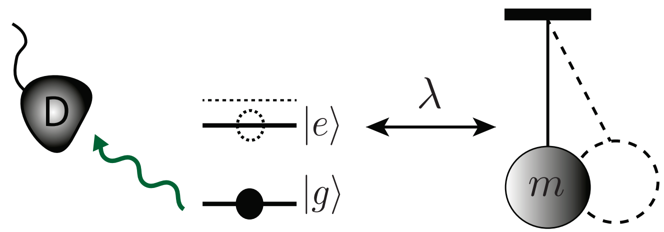
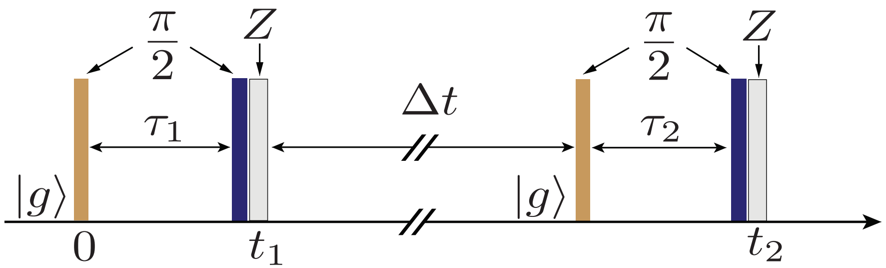
Probing macroscopic realism via Ramsey correlation measurements

- *A two level system is used to probe quantum superpositions of macroscopic resonators via multiple Ramsey measurements:*



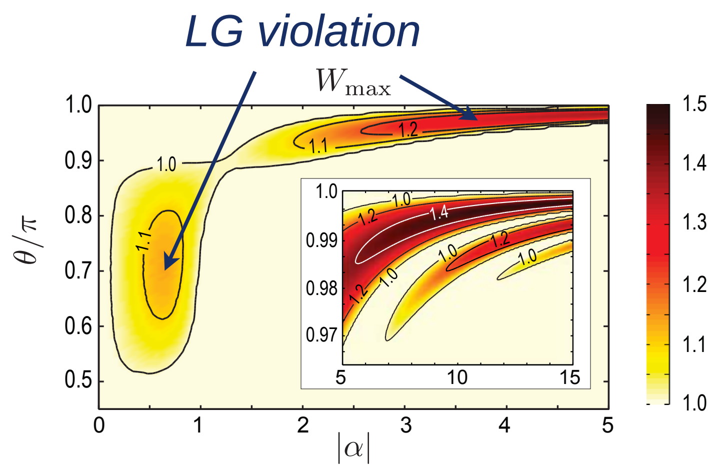


$$\Rightarrow \; C(t_1, t_2) = \langle Z(t_2) Z(t_1) \rangle$$

- *Theory predicts that correlations between subsequent measurement outcomes violate the Leggett-Garg inequality:*

$$C(t_1, t_2) + C(t_2, t_3) - C(t_1, t_3) \leq 1$$

and can be used for other fundamental tests of quantum mechanics !



A. Asadian, C. Brukner, P. Rabl (poster & talk)