Cavity QED Construct:

Quantum Information Processing and Quantum Optics for Solid State Artificial Atoms

Chang-Pu Sun **(孙昌璞)**

Institute of Theoretical Physics,

Chinese Academy of Sciences

suncp@itp.ac.cn
http://www.itp.ac.cn/~suncp

Quantum Physics and Quantum Information Processing

QPQIP in ITP CAS

Zi Song (Nankai),

Xue-Feng Liu (PKU),

Y.X. Liu, L.F. Wei (Riken, Japan)

Franco Nori (UM, US)

Paolo Zanardi (ISI, Italy),

J.Q. You (Fudan)

Z.D. Wang, (HKU)

P. Zhang,
Y. Li ,
Y. D. Wang,
H.T. Quan,
F. Xue
L. Zhou

Beijing

T. Shi,
Y . Li
S. Yang
X.F. Qian
N. Zhao
B. Chen

Tianjin

ITP
The Chinese Academy of Science

Outline

Leture1: (Introductions)

Cavity QED Architecture: From Optical to Solid State Systems
---Superconducting Quantum Circuits and Nano-Mechanical Systems
Aprial 4, Tue 16:30-17:15 & 17:30-18:15 2.

Leture2:
Superconducting Quantum Circuit QED for Quantum Computing
Apr 8, Sat 11:30-12:15 (PHY5580)

Lecture 3.
Quantum State Transfer and Storage with Quantum Spin System
Apr 18, Tue 16:30-17:15 & 17:30-18:15

Lecture 4:
Decoherence induced by Quantum Phase Transition In Solid Systems
Apr 25, Tue 16:30-17:15 & 17:30-18:15

ITP
The Chinese Academy of Science

Related Publications and References therein

Leture1 & 2：

1.P. Zhang, Y. D. Wang, and C. P. Sun， Phys. Rev. Lett. 95, 097204 (2005)
2. Y.-x. Liu, J. Q. You, L. F. Wei, C. P. Sun, and F. Nori，Phys. Rev. Lett. 95, 087001 (2005)
3. C. P. Sun, L. F. Wei, Y.-x. Liu, and F. Nori, Phys. Rev. A **73**, 022318 (2006)
4. Y. B. Gao, Y. D. Wang, and C. P. Sun，Phys. Rev. A 71, 032302 (2005)
5. Y. D. Wang, Z. D. Wang, and C. P. Sun，Phys. Rev. B 72, 172507 (2005)
6. Y. D. Wang, P. Zhang, D. L. Zhou, and C. P. Sun, Phys. Rev. B 70, 224515 (2004)
7.Y. D. Wang, Y. B. Gao and C. P. Eur. Phys. Jour. B 40, 321-326 (2004).
8. P. Zhang, Z. D. Wang, J. D. Sun, and C. P. Sun, Phys. Rev. A **71**, 042301 (2005)

Lecture 3：

1. H.T. Quan, Z. Song , X.F. Liu, P. Zanardi , C.P.Sun， Phys. Rev. Lett. (2006) in press
2. X.-F. Qian, T. Shi, Y. Li, Z. Song, and C. P. Sun，Phys. Rev. A 72, 012333 (2005)
4. H. T. Quan, P. Zhang, and C. P. Sun，Phys. Rev. E 72, 056110 (2005)
5. H. T. Quan, P. Zhang, and C. P. Sun,Phys. Rev. E **73**, 036122 (2006)
6. L. Zheng, C. Li, Y. Li, and C. P. Sun，Phys. Rev. A 71, 062101 (2005)
7. F. Xue, S. X. Yu, and C. P. Sun, Phys. Rev. A **73**, 013403 (2006)

ITP
The Chinese Academy of Science

Related Publications and References therein

Lecture 4:

1. C. P. Sun, Y. Li, and X. F. Liu, Phys. Rev. Lett. 91, 147903 (2003)
2. S. Yang, Z. Song, and C. P. Sun, Phys. Rev. A 73, 022317 (2006)
3. X.-F. Qian, Y. Li, Y. Li, Z. Song, and C. P. Sun, Phys. Rev. A 72, 062329 (2005)
4. Z. Song, P. Zhang, T. Shi, and C.-P. Sun, Phys. Rev. B 71, 205314 (2005)
5. T. Shi, Y. Li, Z. Song, and C.-P. Sun, Phys. Rev. A 71, 032309 (2005)
6. Y. Li, T. Shi, B. Chen, Z. Song, and C.-P. Sun, Phys. Rev. A 71, 022301 (2005)
7. R. Xin, Z. Song and C.P. Sun, Physics Letters A, 342,, 30 (2005)

Review Article:

Song Z, Sun CP, LOW TEMPERATURE PHYSICS 31 (8-9): 686 (2005)

Lecture1 - Overviews:

Quantum Information Processing

based on Solid State Systems

---Superconducting Quantum Circuits and Nano-Mechanical Systems

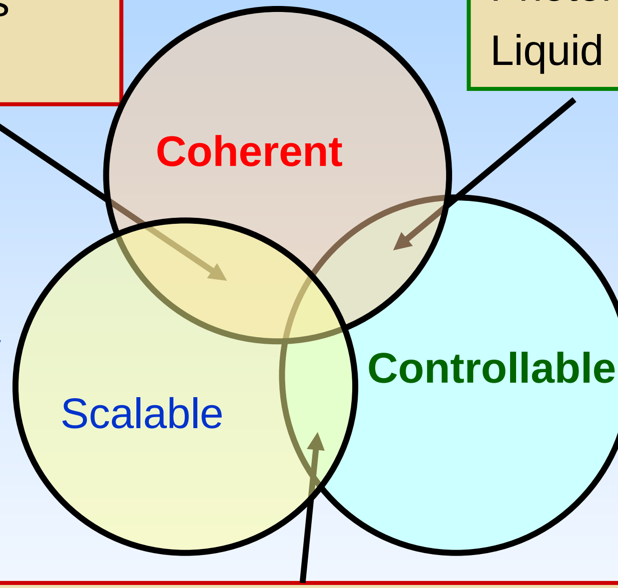
ITP

The Chinese Academy of Science

Physical Realizations of Quantum Bits (Qubits) Require Specially Designed Two-Level Systems:

Spins and Quasi-spins
in Semiconductors
Quantum Dots

Trapped Ion
Photon-Atom
Liquid NMR



Cooper-Pair Box-Charge Qubit
Single Junction – Phase Qubit
Rf-SQUID: Flux Qubit

DiVincenzo Five criteria

1. Well defined addressable qubit array stable memory
2. Initialize in the |000..> state
3. Long decoherence time ($>10^4$ operation time)
4. Universal set of gate operations
5. Single-bit measurement

Main Obstacles and Challenges For QC

quantum decoherence, which can be significantly enhanced in a system of many qubits,

a. In General

One Qubit Dephasing

$$e^{-\gamma t}$$

N Qubit Dephasing

$$e^{-N^2 \gamma t}$$

Sun *et al* , PRA (1993,1998)

b. An Atomic Ensemble

$$H = \sum^{N} g_k \sigma_+^{[K]} + h.c \xrightarrow{?} g\sqrt{N} b^+ + \ldots$$

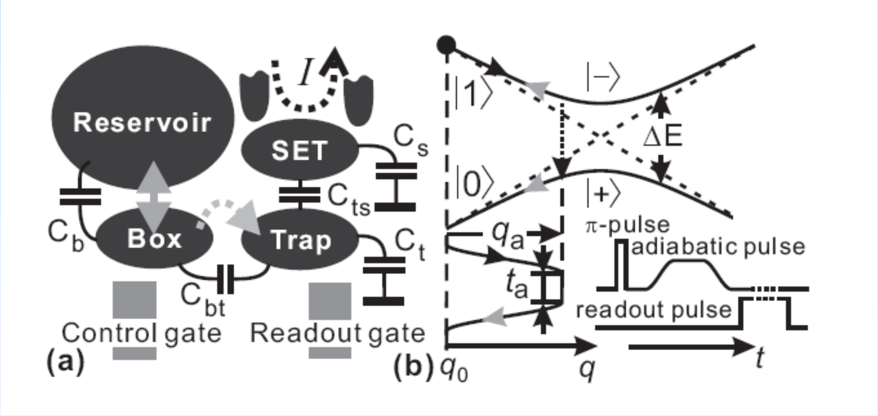
$$\sum^{N} \sigma_+^{[k]} = S_+ \Rightarrow \sqrt{N} b^+$$

Achieve a $\sqrt{N}$ enhanced effective coupling, but

induce a $\sqrt{N}$ enlarged decoherence

Sun, Yi, Li, and You, PRA (2002,2003)

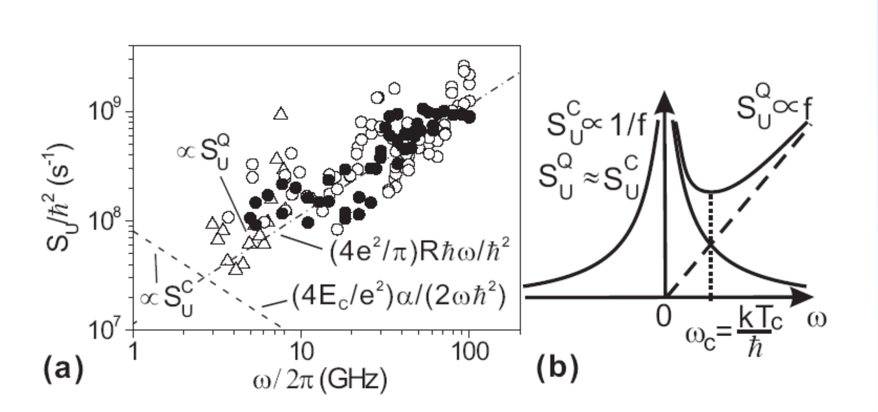
Low Frequency Noise 1/f



NEC experiment 2005

It seems to be a non-principle difficulty , but it challenges all present technologies

Nobody know its origins physically !!!



Quantum Information Meets
Condensed Matter Physics ?

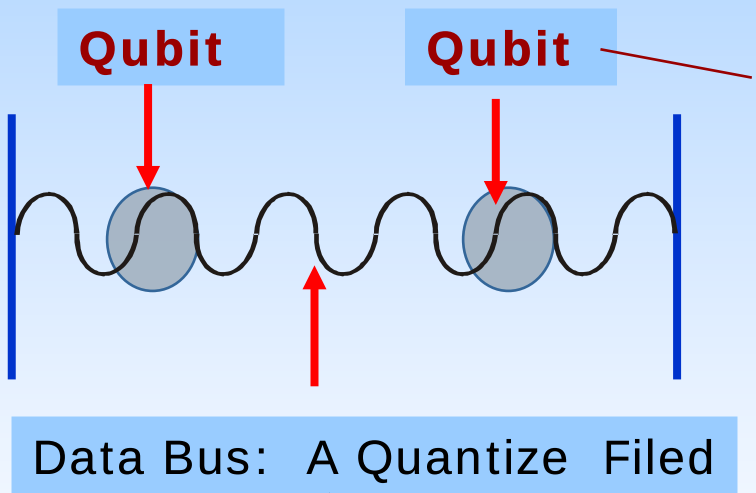
Or

Condensed Matter Physics Beats
Quantum Information ?

ITP
The Chinese Academy of Science

Integrating Various Qubits for QIP

Physics: Creating Distant Entanglement?



Atom, Spin, Ion, or
Artificial Atoms :
Charge, Flux , Quantum Dots

Quantized Electromagnetic Field

Large Josphson Junction (2004, Exp)

Quantum Transmission Line (2004, Exp)

"Phonons": GHz. Nano Mechanical Beam

Examples

(I+N) : Tian, Zoller, PRL **93**, 266403 (04)
(C+N) : Irish , Schwab, PRB,**68**, 155311 (03)
(C+JJ): Wang, Sun, PRB, **70**, 224515 (04)

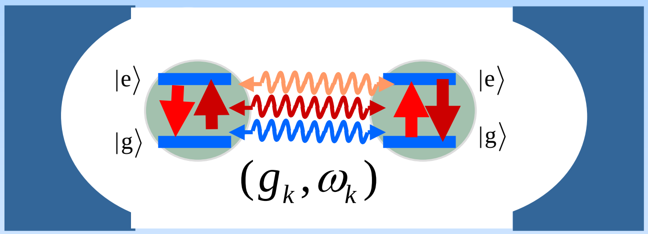
Artificial Cavity QED =

Spin-Boson Model

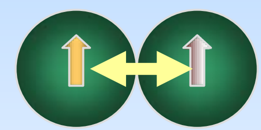
The Chinese Academy of Science

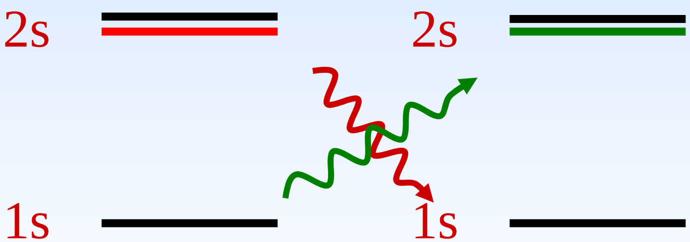
Cavity QED: Virtual Photon Exchange

Induces Qubit-Qubit coupling



Effective Inter-Qubit Coupling

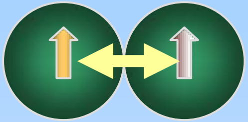




$$J_{eff} = \sum_k \frac{|g_k|^2}{\omega_k - \omega_a}$$

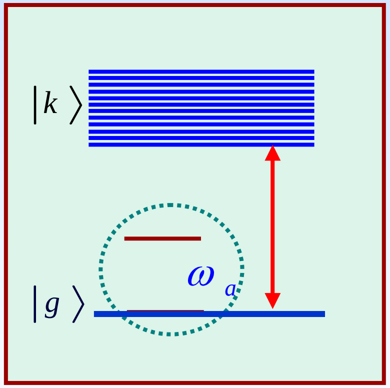
See the details in Lecture 2

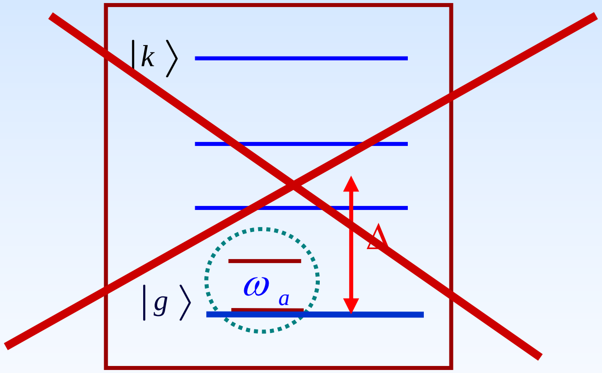
Finite Effective Interaction Requires Gapped Systems



Effective Interaction

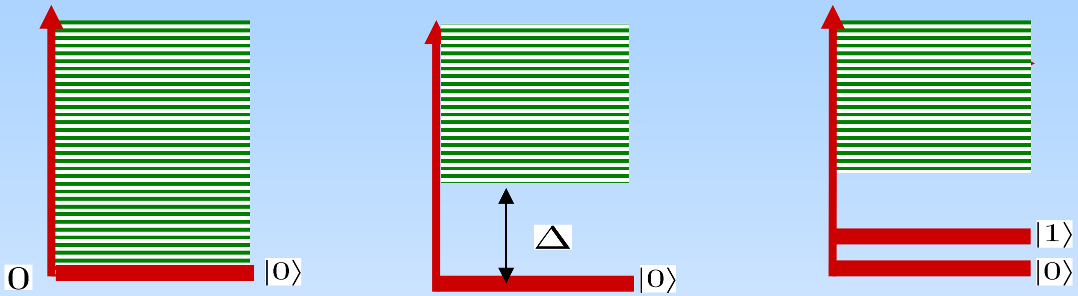
$$J_{eff} = \sum_k \frac{|g_k|^2}{\omega_k - \omega_a}$$



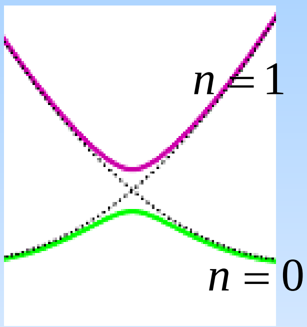


Circuit QED :

Superconducting Transmission Line +Charge Qubit

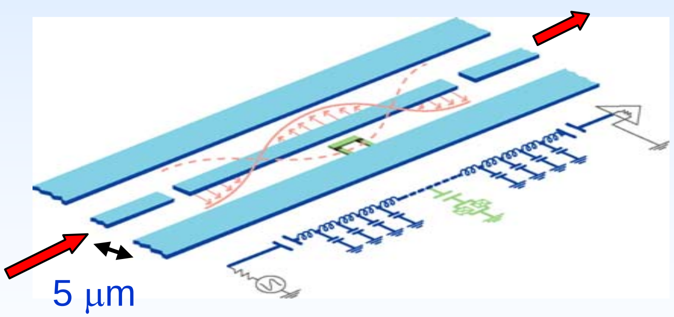


Normal Metal Supercond. with Qubit?



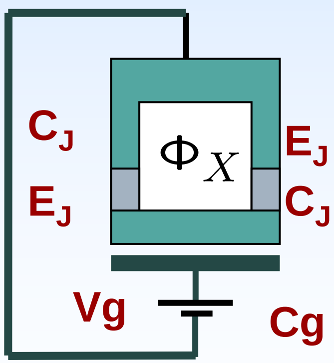
二能级系统

out



DC +6 GHz in

5 μm



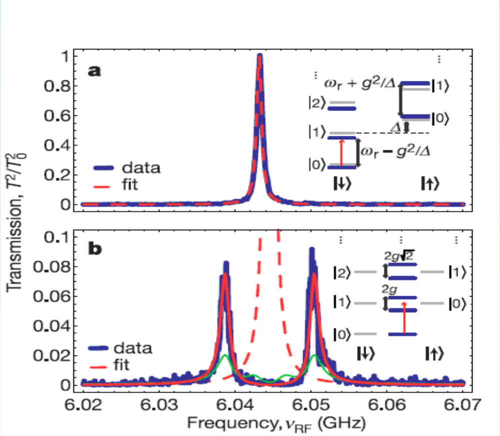
See the details in Next Lecture

Circuit QED Based on Superconductors

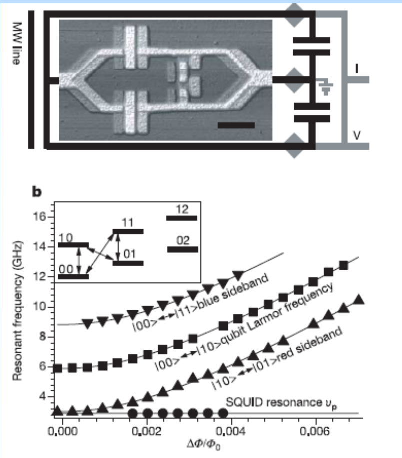
$$H=\hbar\omega a^{+}a+\tfrac{1}{2}\hbar\omega\sigma_z+g(a\sigma_{+}+a^{+}\sigma_{-})$$

Experiments

***Nature* 431, 162 (2004).**



***Nature* 431, 159 (2004).**



Wang, Zhang, Zhou, and Sun, Phys. Rev. B 70, 224515 (2004)

A Earlier Proposal: Circuit QED based on Large junction by us (2002)

Large Junction $V=\cos(\phi)\simeq 1-\frac{1}{2}\phi^2$

Strong Couplings by Circuit QED

Parameter	Symbol	Optical cQED with Cs atoms	Microwave cQED	circuit QED
Dipole moment	d/ea_o	1	1,000	20,000
Vacuum Rabi frequency	g/π	220 MHz	47 kHz	100 MHz
Cavity lifetime	$1/\kappa$; Q	1 ns; 3 x 10^7	1 ms; 3 x 10^8	160 ns; 10^4
Atom lifetime	$1/\gamma$	60 ns	30 ms	> 2 μs
Atom transit time	$t_{transit}$	> 50 μs	100 μs	Infinite
Critical atom #	$N_0=2\gamma\kappa/g^2$	6 x 10^{-3}	3 x 10^{-6}	6 x 10^{-5}
Critical photon #	$m_0=\gamma^2/2g^2$	3 x 10^{-4}	3 x 10^{-8}	1 x 10^{-6}
# of vacuumRabi oscillations	$n_{Rabi}=2g/(\kappa+\gamma)$	10	5	100

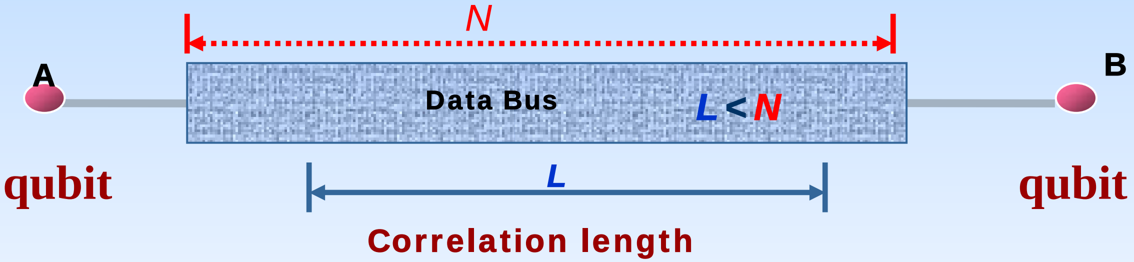
Blais, A., et al., Phys. Rev.A 69, 062320 (2004)

ITP
The Chinese Academy of Science

Other Condensed Matter System seems to Beat Quantum Information ?

Finite Correlated Length vs. Decaying Entanglement
Due to the decreasing effective coupling

QI Transfer from A to B = Dynamic Entangling A and B States



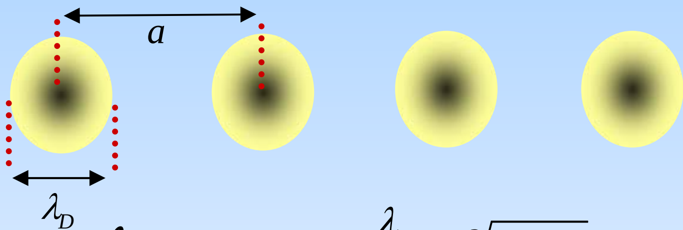
a long range order? $\langle \varphi | \varphi_0 \rangle \sim 1 \text{ or } 1/\mathrm{N}^{\delta}$

$$\langle \Psi(x)\Psi(x')\rangle \propto \exp\left(-\frac{|x-x'|}{L}\right), \quad \mathrm{L} \approx \zeta\Delta$$

BEC : Long distance correlation of Boson System

Off-diagonal long range order (ODLRO)

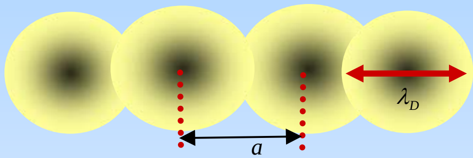
High temperature (T>Tc):



$\lambda_D \ll a$

$\frac{\lambda_D}{a} = \sqrt[3]{2.612},$

Low temperature (T<Tc):



$\lambda_D \sim a$

Coherent Overlap :

Macro-Atoms

$$\rho(x,y) = \frac{n_0}{V} + \int n_k e^{ik(x-y)} dk \to \frac{n_0}{V} + \frac{mkT}{2\hbar^2 r} \exp[-\frac{r}{R}]$$

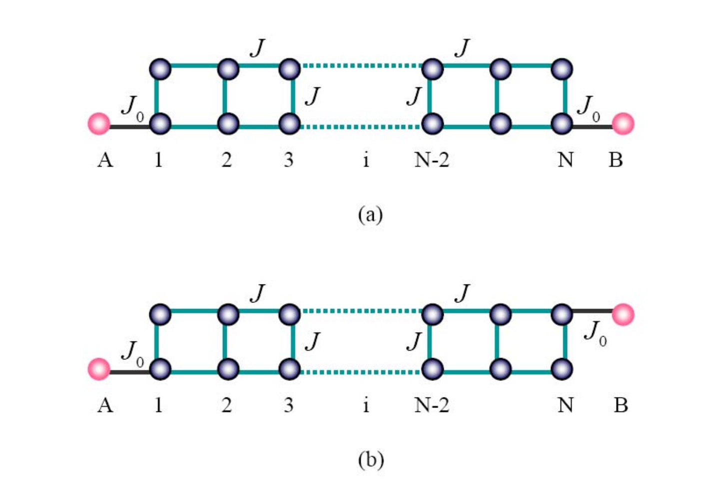
$$\lambda_D = \sqrt{\frac{2\pi\hbar^2}{m k_B T}}$$

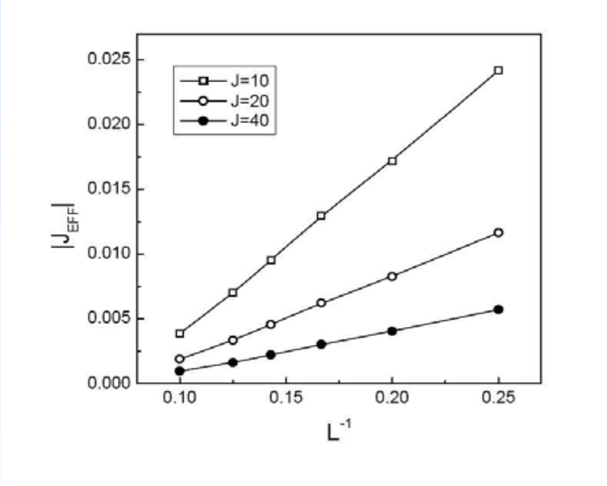
$$r = |x - y| \to \infty \qquad \rho(x,y) \to \frac{n_0}{V}$$

Thermal Wave Length

Quantum state transfer via Spin Ladder

A typical gapped system





$$H_I = J_0 \vec{S}_A \cdot \vec{S}_1 + J_0 \vec{S}_B \cdot \vec{S}_N$$

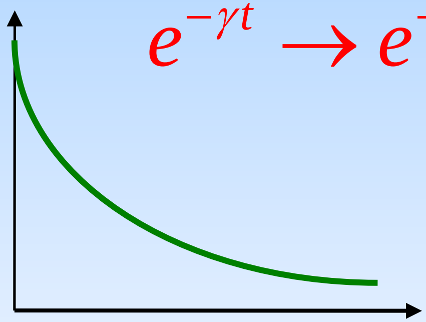
$$H_{\text{int}} = J_0^2 G^{zz} (\omega = 0, x) \vec{S}_A \cdot \vec{S}_B$$

Li, Shi, Chen, Song, Sun, Phys. Rev. A 71, 022301 (2005)

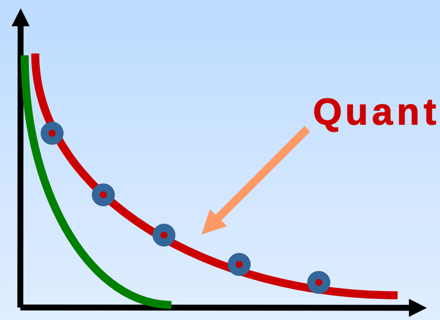
De-entanglement vs. Decoherence

Yu, Eberly, Phys. Rev. Lett. **93**, 140404 (2004)

$$e^{-\gamma t} \rightarrow e^{-N^2 \gamma t}$$



Decoherence of single qubit



Quantum correlations?

Concurrence=entalement

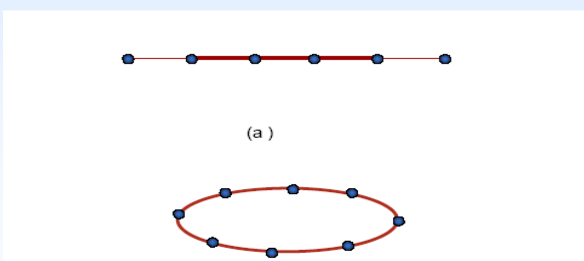
- What characterize the quantum coherence of many body system?
- Entanglement or Corrrelation? Are there differences?

Overcome the difficulty by Engineered Spin Chain With Always-On Interactions

S. Bose, 2003;
M. Christandl, PRL, **92**, (2004)

$$H=\theta\sum_{i=1}^{i=N-1} J_i(S_i^+S_{i+1}^- + S_i^-S_{i+1}^+)$$

$$J_i=\sqrt{i(N-i)}$$



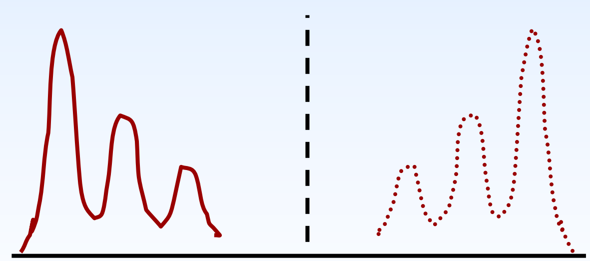
Our discovery :

Commensurate Spectrum

$$U(t_0)=P$$

Shi, Li, Song, and Sun, Phys. Rev. A 71, 032309 (2005)

Time evolution=Parity Reflection

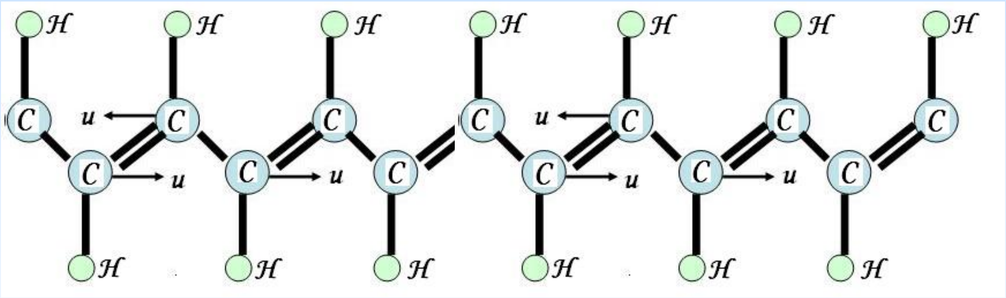


For the details see Lecture 3:

Peierls Distorted Chain for QST

M.X. Huo, Ying Li, Z. Song , C.P. Sun, 2006 in preparation

More Realistic System with spatially-varying Hamiltonian

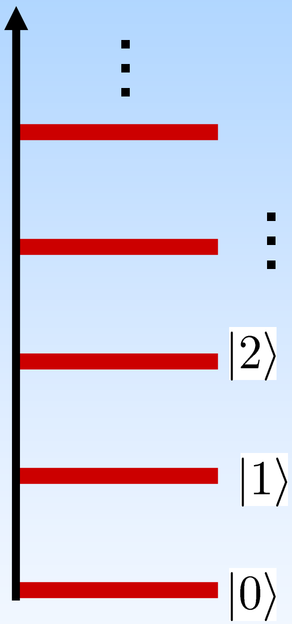


Dimmerization : SSH model

Nano-Mechanical Resonator (NAMR)

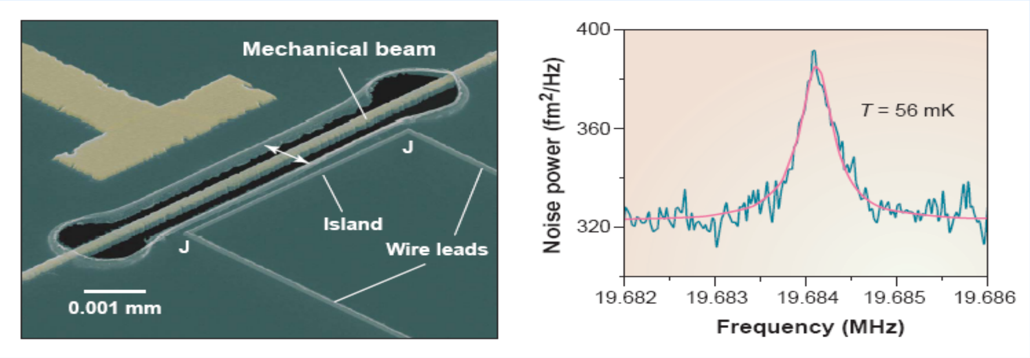
Quantization of Single Model Phonon

$$k_B T = 48mK \cdot k_B \approx \hbar\sqrt{E/\rho}(hL) \approx \hbar \cdot 1GHz$$



Knobel and Cleland, Nature, 2003
La Haye et al., *Science*, 304, 74 (2004)

$$H = \hbar\omega a^{+} a$$



Standard Quantum Limit (SQL):

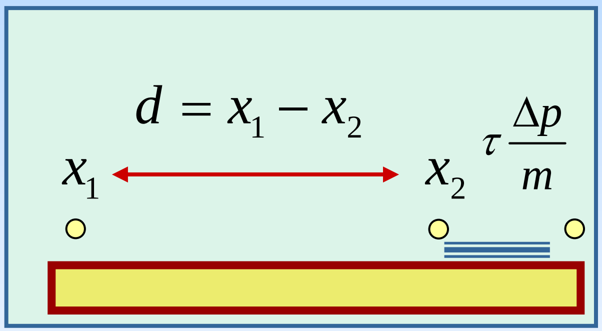
ITP
The Chinese Academy of Science

Standard Quantum Limit (SQL):

Measurement of length Limited by Uncertain Relation

Free Particle

$$\Delta p \Delta x_1 \geq \frac{\hbar}{2}$$



$$\Delta d = \sqrt{(\Delta x_1)^2 + (\Delta x_2)^2 + (\tau \frac{\Delta p}{m})^2}$$

$$\geq \sqrt{2(\Delta x_1)(\tau \frac{\Delta p}{m}) + (\Delta x_2)^2}$$

$$= \sqrt{\frac{\hbar \tau}{m} + (\Delta x_2)^2} \sim \sqrt{\frac{\hbar \tau}{m}}$$

Harmonic Oscillator

$$x(t) = x(0)\cos(\omega t) + \frac{p(0)}{m\omega}\sin(\omega t)$$

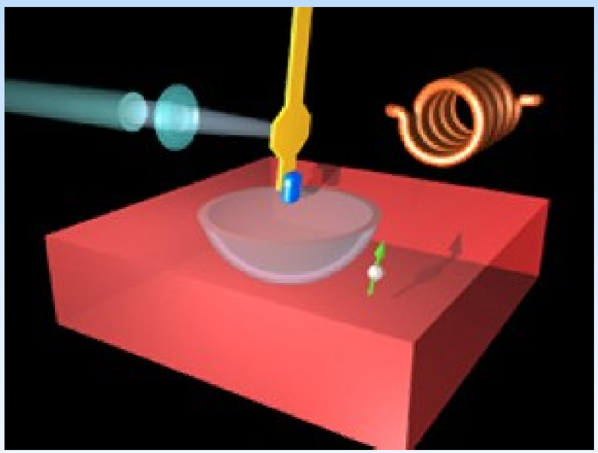
$$\Delta x(t) = \sqrt{(\Delta x)^2 \cos^2(\omega t) + \frac{(\Delta p)^2}{m^2 \omega^2}\sin^2(\omega t)} \geq \sqrt{\frac{\hbar}{m\omega}}$$

ITP

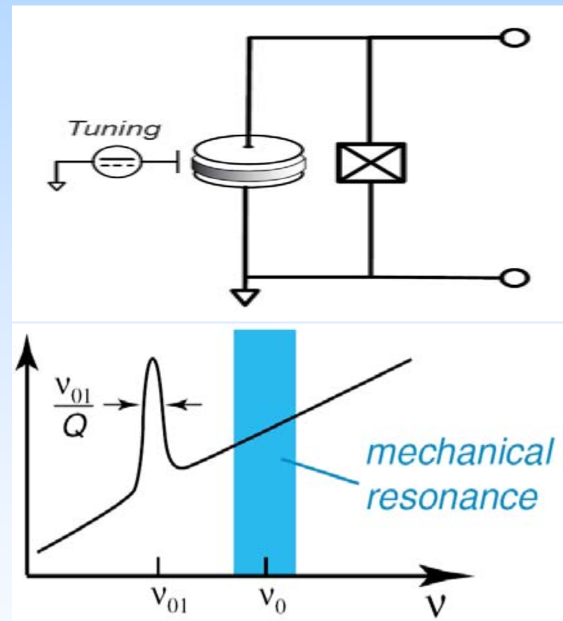
The Chinese Academy of Science

Nano-Mechanical QED (NM-QED)Constructs

1.NAMR + Spins 2. NAMR + Josephson Qubit



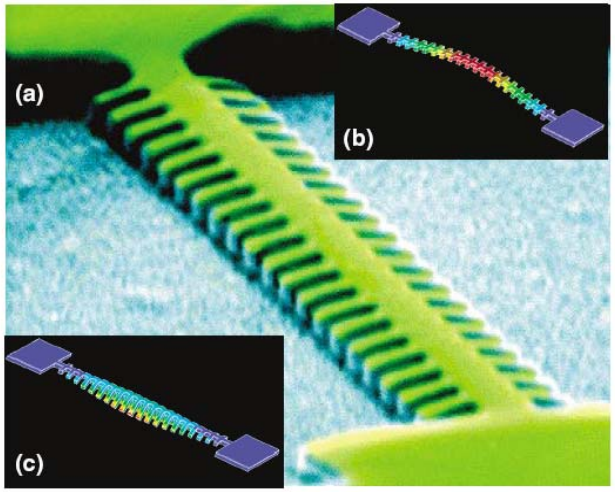
Nature **430, 329 (2004)**



Armour, et al *Phys. Rev. Lett.* **88**, 148301 (2002).

Wang, Gao and Sun. Eur. Phys. Jour. B 40, 321-326 (2004).

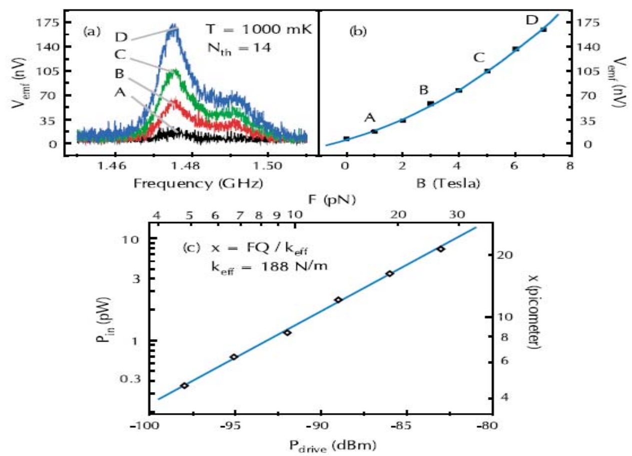
Direct Observation of Quantization of NAMR

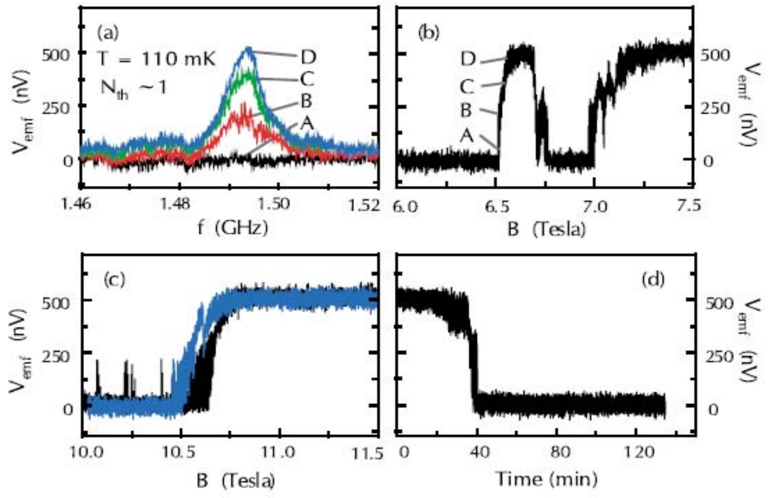


Gaidarzhy et al, PRL. 94, 030402 (2005)

金电极上的电压

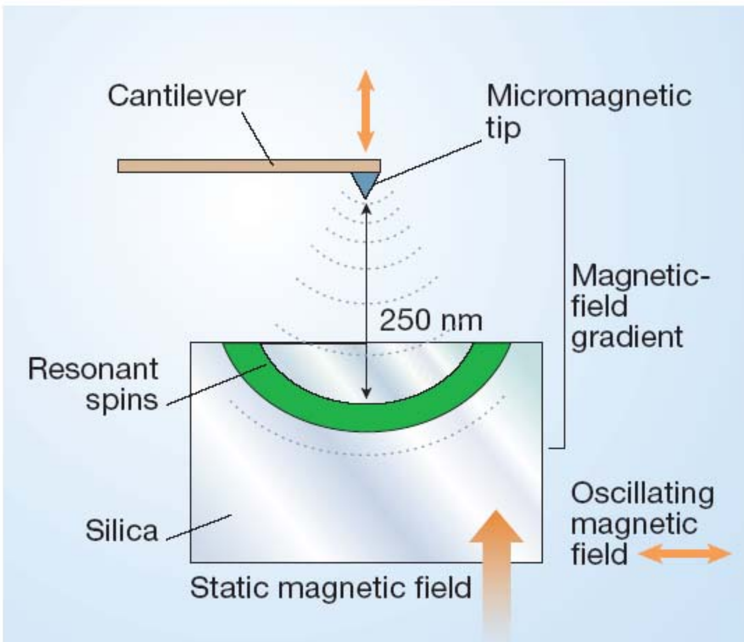
$$V = \frac{i\omega\xi L^2 B^2 / m}{\varpi^2 - \omega^2 + i\varpi\omega / Q} I(\omega)$$



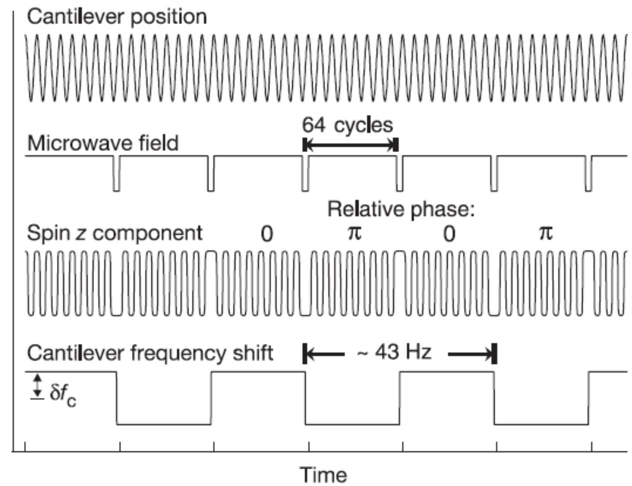


Detection Of Single Spin

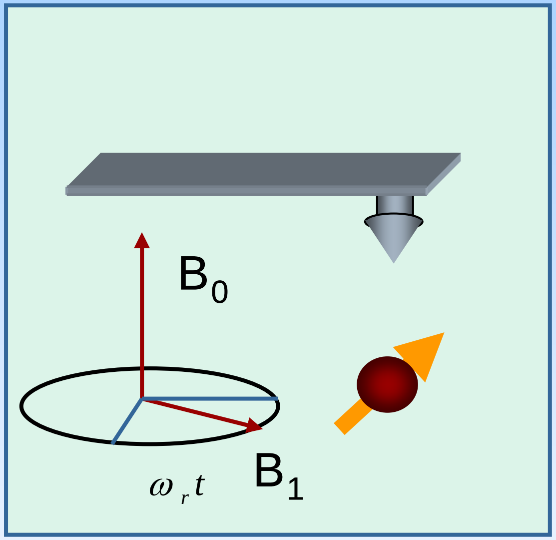
Nature **430, 329 - 332 (15 Jul 2004)**



$$\delta f_c = \pm \frac{2 f_c G \mu_B}{\pi k x_{peak}}, \quad (1)$$



Nano-Mechanical QED: Single Mode Phonon



$$H = \frac{P_z^2}{2M} + \frac{1}{2} M \omega_c^2 z^2 + \gamma \hbar \overleftrightarrow{B} \cdot \vec{S}$$

$$\overleftrightarrow{B} = B_1 \cos(\omega_r t)\hat{e}_x + B_1 \sin(\omega_r t)\hat{e}_y + B_0 \hat{e}_z + \overleftrightarrow{B}_{tip}(z)$$

$$B_{tip} = \frac{\mu_0}{4\pi} \frac{3(\vec{n} \cdot \vec{m})\vec{n} - \vec{m}}{d^3}$$

$$\overleftrightarrow{B}_{tip}(z) \approx (\xi_0 - \xi_1 z)\hat{e}_x + (\eta_0 - \eta_1 z)\hat{e}_z$$

$$\mathbf{H} = (p_x^2 + x^2)/2 + \varepsilon S_x + 2\eta x S_z,$$

Adiabatic Quantum Measurement

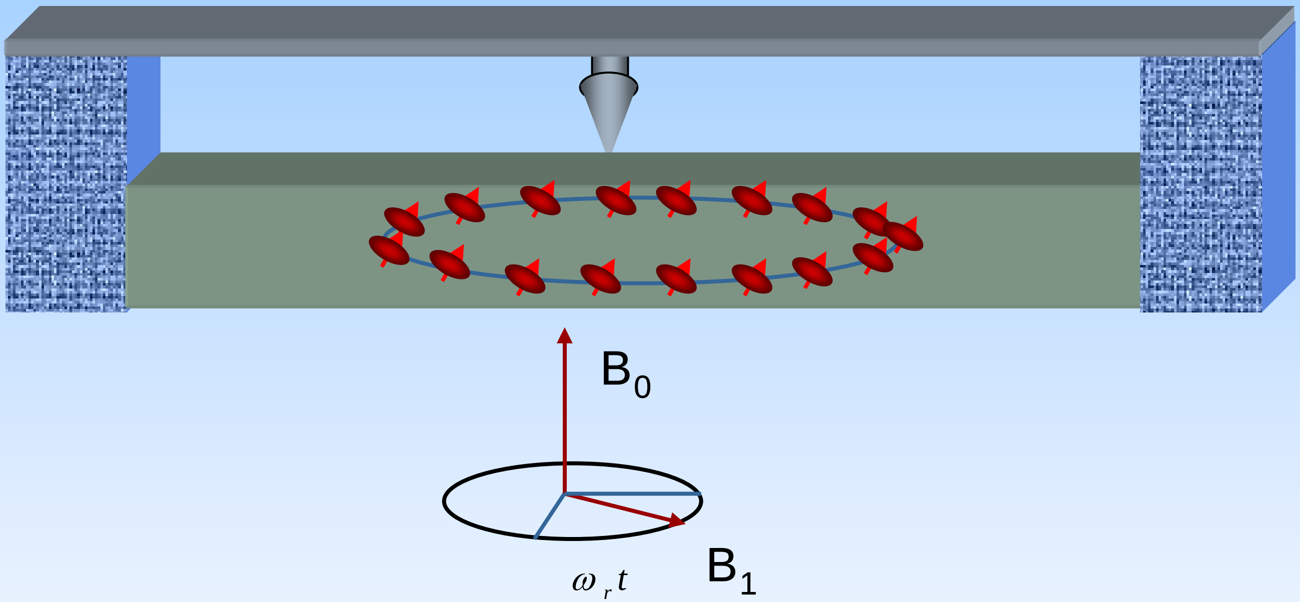
Sun, et al, PHYS REV A 6301 : 2111(2001); EUR PHYS J D 17 :85(2001)

$$(\varepsilon S_x + 2\eta x S_z)|n(x)\rangle = V_n(x)|n(x)\rangle, \quad n = \pm$$

$$V_\pm(x) = \pm\sqrt{\varepsilon^2 + 4\eta^2 x^2} \approx \pm\varepsilon \pm 2\eta^2 x^2/\varepsilon,$$

$$\mathbf{H_{eff}} = (p_x^2 + x^2)/2 + V_\pm$$
$$= (\omega \pm \delta)a^+ a$$

Probe for Spin Wave : Dressed Boson



F. Xue, L. Zhong, C.P. Sun, 2006, PRB

ITP

The Chinese Academy of Science

Artificial Cavity QED Construct

2-Level Artificial Atoms

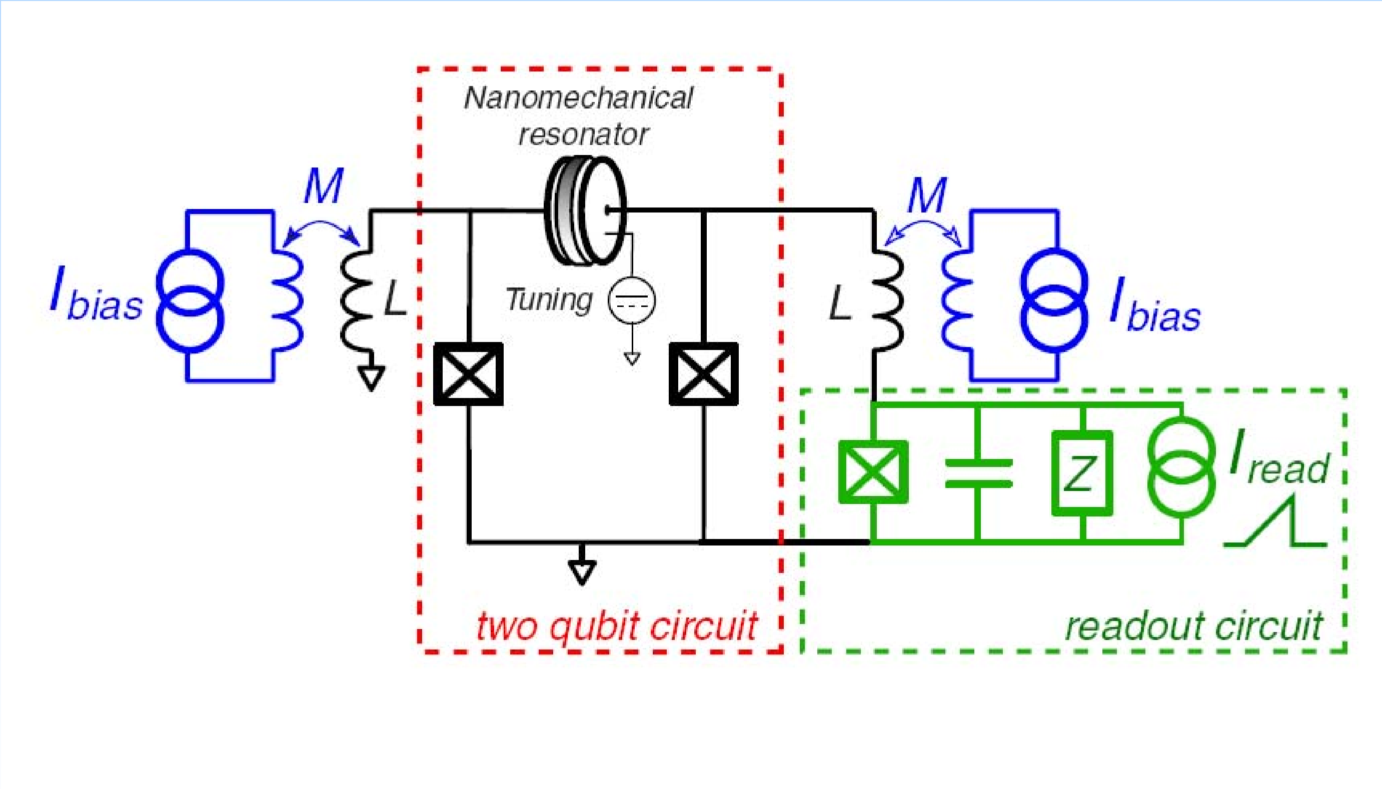
Quantum data bus

	Natural Atom,Ions	Superconducting Qbits	Nuclear Spin,Excitation	Quantum Dots
Q-EM field	CavityQED	Semi-Clas.	Quant.	Quant.
S-TLR	T	Circuit QED	×	×
NAMR	T	NM-QED	Semi-Clas	T
Large JJ	T	Circuit QED	×	×
Collective Spin	×	×	SW.QED	SW.QED

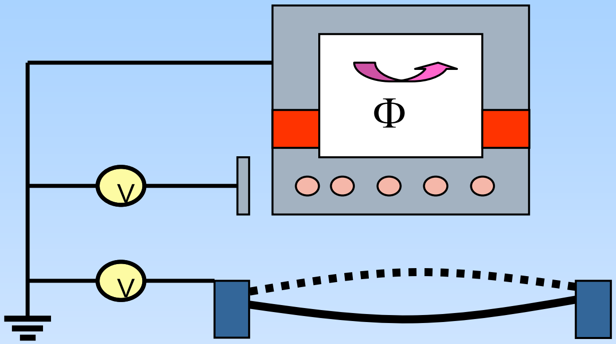
T=Theoretical Protocols

ITP
The Chinese Academy of Science

Cleland, Geller, Cond-mat/0311007



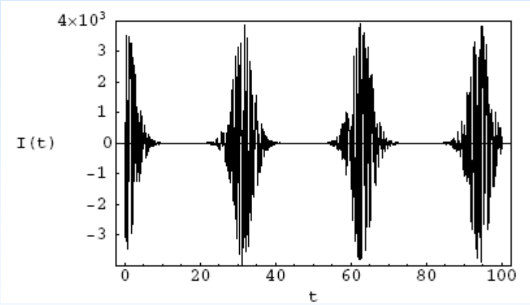
Decoherence showed by Nano MQED

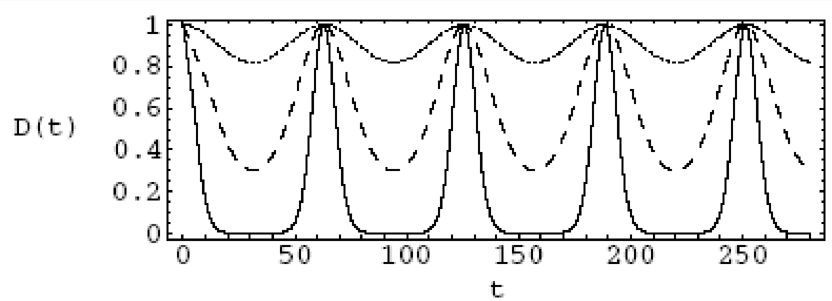


$$H_c = \frac{2e^2\left(\hat{n} - n(\hat{x})\right)^2}{C_\Sigma}$$

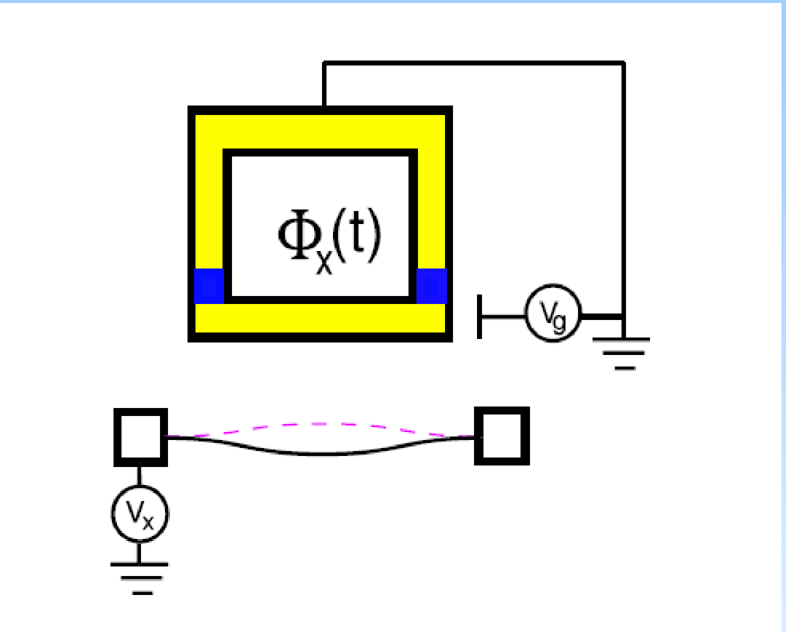
$$n_g(\hat{x}) = \frac{1}{2e}\left(C_g V_g + C_x(\hat{x}) V_x\right)$$
$$= n_g + \delta n(\hat{x})$$

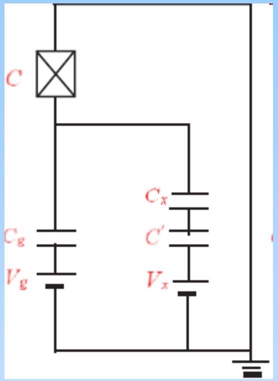
$$H = 4E_c \delta n \sigma_z - \frac{E_J}{2}\sigma_x - \lambda\left(a + a^\dagger\right)\sigma_z + \hbar\omega_0 a^\dagger a$$





Y. D. Wang, Y. B. Gao and C. P. Sun,
Eur. Phys. Jour. B 40, 321-326 (2004).





$$H_c = \frac{2e^2\left(\hat{n} - n(\hat{x})\right)^2}{C_\Sigma}$$

$$n_g\left(\hat{x}\right) = \tfrac{1}{2e}\left(C_g V_g + C_x\left(\hat{x}\right)V_x\right)$$

$$= n_g + \delta n(\hat{x})$$

$$C_x\left(\hat{x}\right) \cong C_x(1 - \frac{x}{d})$$

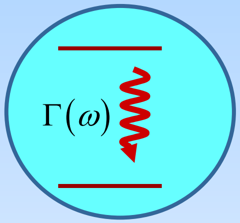
$$\delta n\left(x\right) = -n_x \frac{\Delta_x}{d}\left(\hat{a} + \hat{a}^\dagger\right)$$

$$H = 4E_c \delta n \sigma_z - \frac{E_J}{2}\sigma_x - \lambda(a + a^\dagger)\sigma_z + \hbar\omega_0 a^\dagger a$$

Cooling Nano-Mechanical Resonator

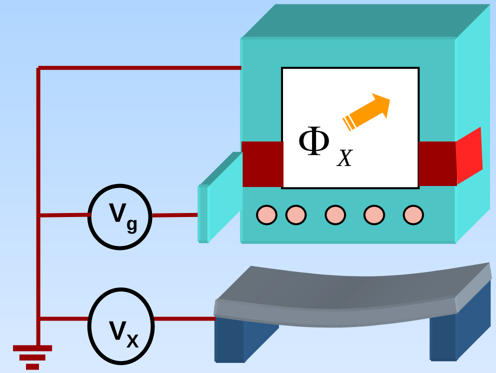
By "Bang-bang " couplings to Charge Qubit

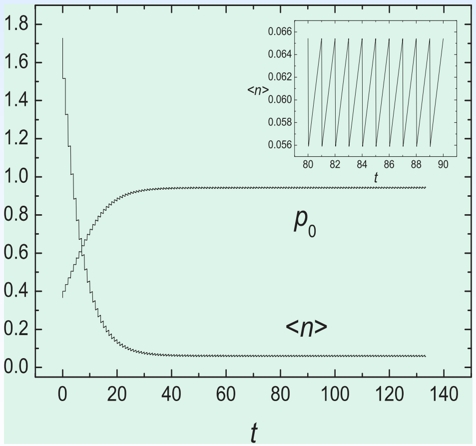
Zhang, Wang, Sun, PRL, 097204 (2005) ,

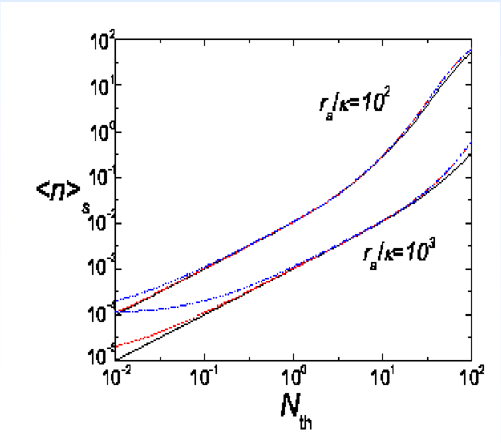


$$\Gamma(\omega)=\tfrac{\pi}{2}\alpha_g\omega\left[\coth\left(\frac{\omega}{2k_BT}\right)+1\right]$$

$$\omega=E_J\cos\left(\pi\frac{\Phi_x}{\Phi_0}\right)$$







$N_{\text{th}}\approx 1.7;$

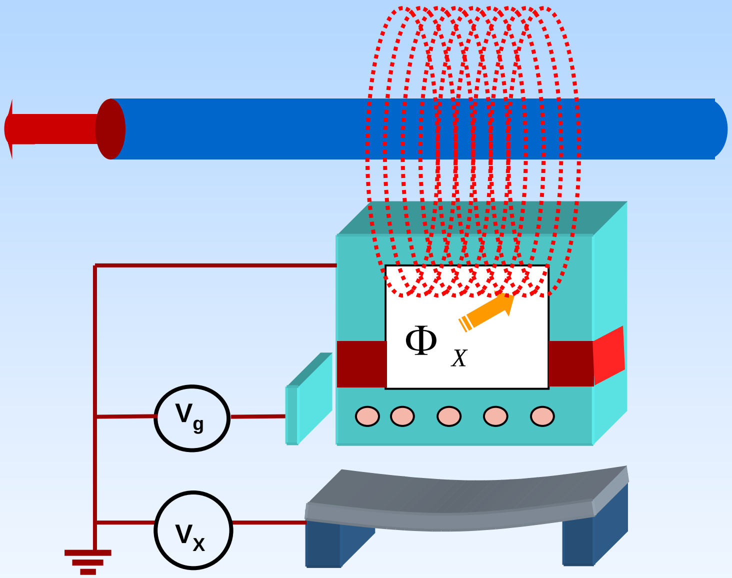
$g\tau=\pi/8;$

$r_a/\kappa=133$

Our result : Cooling efficiency vs. initial state

Quantum transducers:

Sun, Wei, Liu, Nori, PRA, 2006

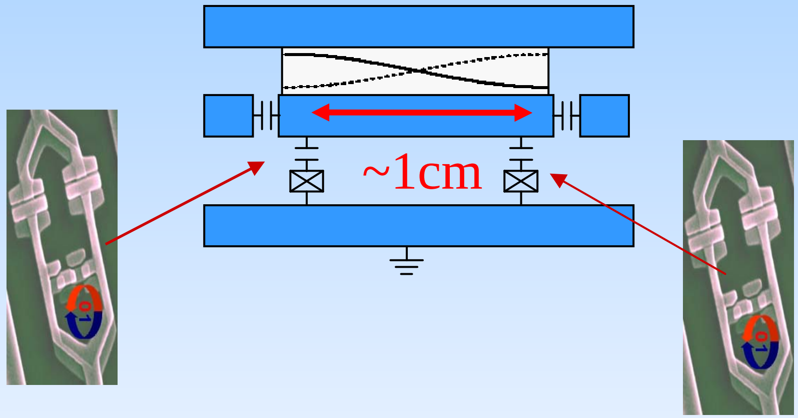


$$\Phi_q = i\sum_k \phi_k (a_k - a_k^\dagger),$$

$$H = \frac{\omega}{2}\sigma_z' + \omega_b b^\dagger b + \lambda(b^\dagger + b)\sigma_z'$$
$$-\frac{E_J}{2}\cos(\frac{\pi\Phi_x}{\Phi_0})\sigma_x'$$

Mechnical QED and Circuit QED

—link Qubits with quantum Data Bus



Jaynes-Cummings (JC) Model

What is New Physics ?

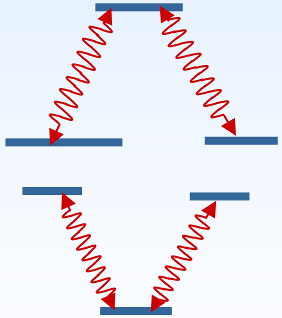
Exotic features
of Superconducting Artificial Atoms

Liu, You, Wei , Sun, and Nori, PRL, (2005)

No Δ-Type Natural Atoms in Electric Dipole Transitions

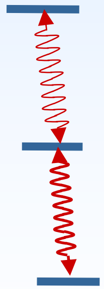
Winger –Ekert Theorem with SO(3) or SO(4) Symmetry

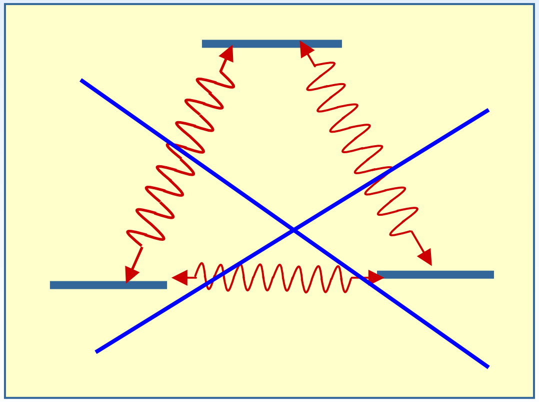
$\Lambda - Type$



$V - Type$

$\Xi - Type$

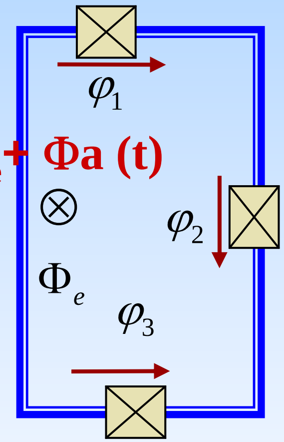


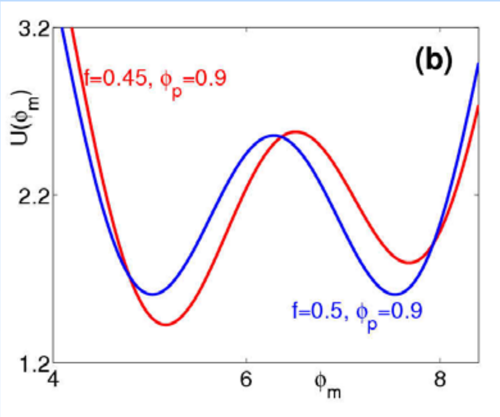


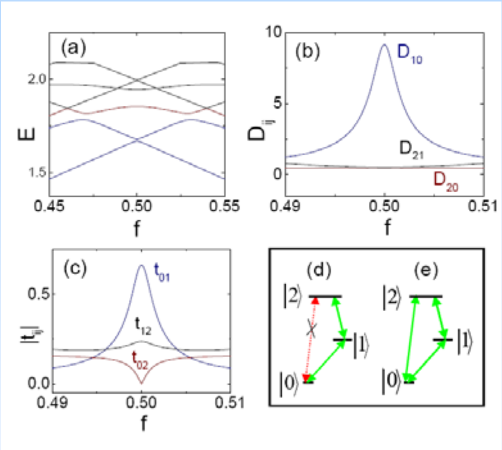
Things change dramatically for the Artificial Atoms

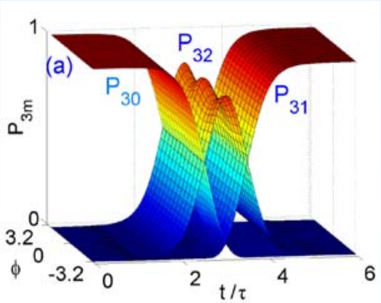
in Symmetry Breaking

Liu, You, Wei , Sun, and Nori, PRL, (2005,)









Total Phase Sensitiveness

for Adiabatic Manipulations

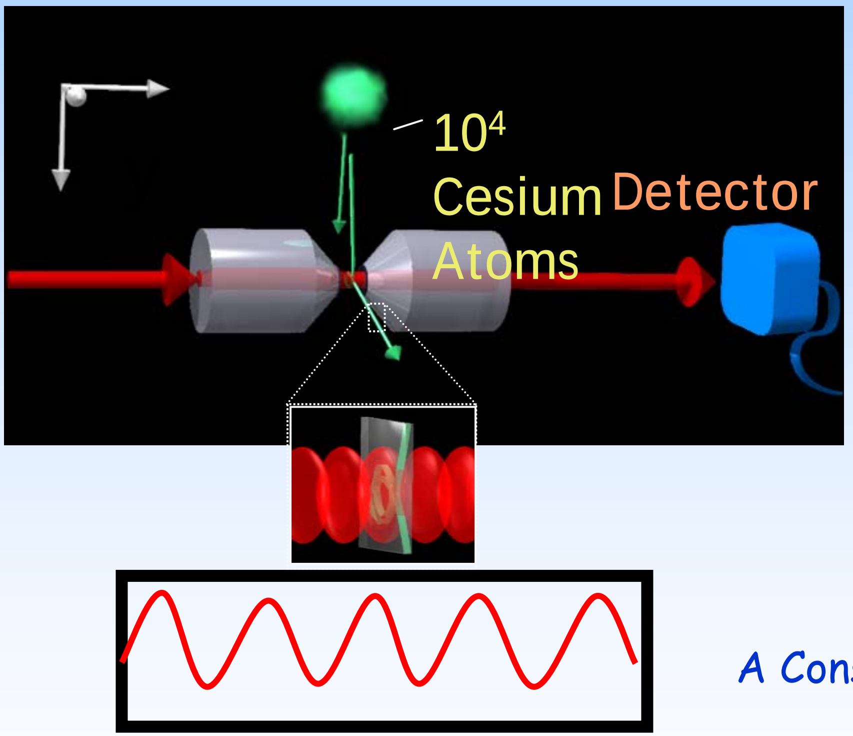
ITP
The Chinese Academy of Science

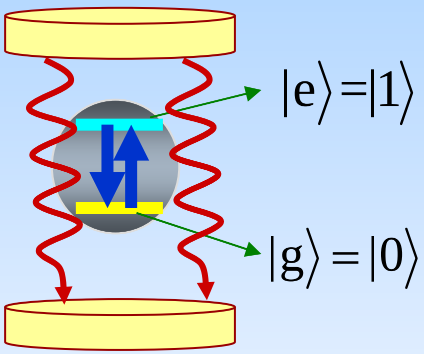
Thank you!

ITP
The Chinese Academy of Science

Appendix 1:

Cavity QED for Atom-Photon system





A Constrained Photon System

Model and Effects of Cavity QED :

Jaynes-Cummings (JC) Model = Spin-Boson Model

$$H=\hbar\omega a^{+}a+\tfrac{1}{2}\hbar\omega_a\sigma_z+g(a\sigma_{+}+a^{+}\sigma_{-})$$

$$[a, a^{+}]=1$$

1. Enhancement and suppression spontaneous emission
2. Vacuum Rabi Splits in Spectrum
3. Collapse and revivals of Atomic Population
4. Coherent Forces for Atoms entering the cavity

ITP
The Chinese Academy of Science

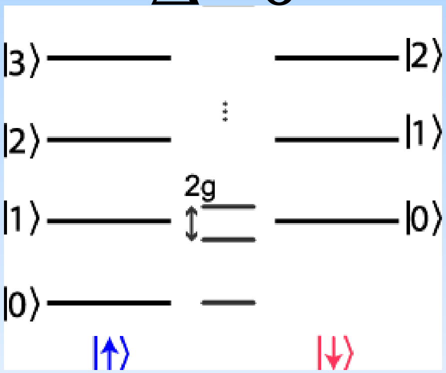
Energies of Dressed States

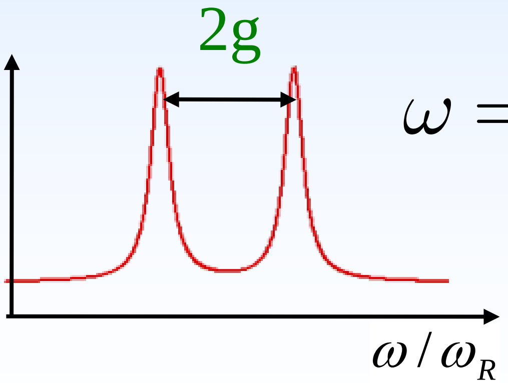
$$|+,n)\rangle = \sin\theta_n\,|g,n+1\rangle + \cos\theta_n\,|e,n\rangle$$
$$|-,n)\rangle = \cos\theta_n\,|g,n+1\rangle - \sin\theta_n\,|e,n\rangle$$

$$\Delta=\omega_a-\omega \qquad \cos 2\theta_n = \frac{\Delta}{\sqrt{4g^2(n+1)+\Delta^2}}$$

$$E_\pm = \hbar\omega\left(n+\frac{1}{2}\right) \pm \frac{\hbar}{2}\sqrt{\Delta^2+4g^2(n+1)}$$

$\Delta=0$





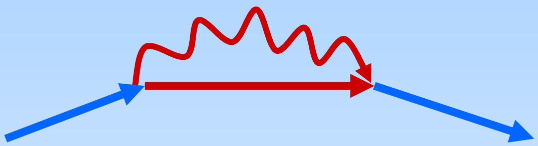
$\omega = \omega_a$

Single Qubit - Single Model Virtual Photon Process

$$H = H_0 + V \ :$$

$$H_0 = \frac{1}{2}\omega_a \sigma_Z + \omega a^+ a,$$

$$V = g a \sigma_+ + h.c$$



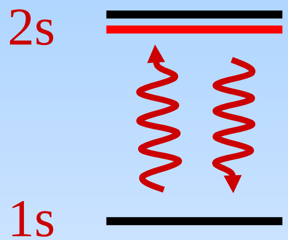
2'nd Order Process

$$H_e \sim H_0 + V_{eff} = H_0 + \frac{1}{2}[V, S],$$

$$0 = V + [H_0, S] \Rightarrow S = \frac{g}{\omega - \omega_a} a \sigma_+ - h.c$$

The Lamb Shifts :

$$V_f = \xi a a^{+} \sigma_3 \equiv \frac{1}{2} \frac{g^2}{\omega - \omega_a} a a^{+} \sigma_3$$



$$H_{\text{eff}} \approx \left(\omega_r - \frac{g^2}{\Delta} \sigma_z \right) a^{\dagger} a - \frac{1}{2} \left(\omega_{01} + \frac{g^2}{\Delta} \right) \sigma_z$$

Atom AC Stark shift

Optical AC Stark Effect

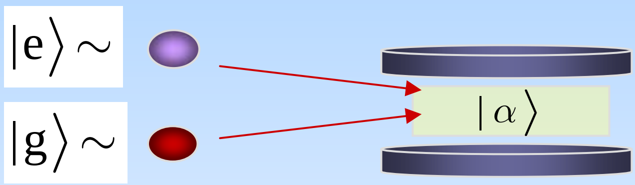
$$E_{\pm} \approx \hbar \left(\omega \pm \frac{g^2}{\Delta}\right)\left(n + \frac{1}{2}\right) \pm \frac{\hbar}{2}\left(\Delta \mp \frac{g^2}{\Delta}\right)$$

ITP

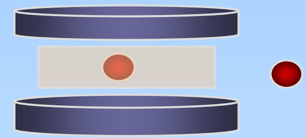
The Chinese Academy of Science

Decoherence due to Lamb Shifts :

Large detuning

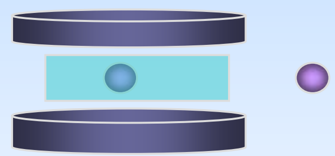


$$\frac{g^2}{|\omega-\omega_a|^2} \ll 1$$



$|e^{-it\kappa_-}\alpha\rangle \otimes |g\rangle$

$$\kappa_\pm = \omega \pm \xi$$



$|e^{-it\kappa_+}\alpha\rangle \otimes |e\rangle$

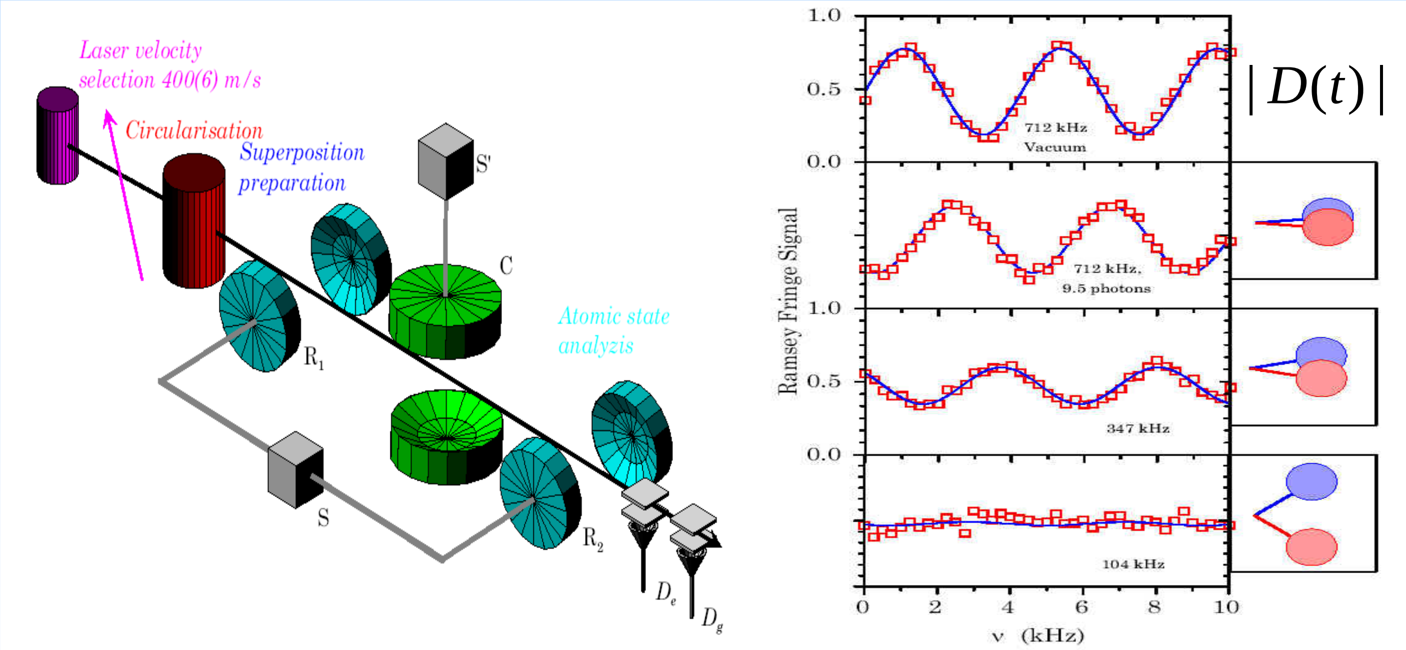
$$|\alpha\rangle \otimes (b|e\rangle + c|g\rangle) \Rightarrow b|e^{-it\kappa_+}\alpha\rangle\otimes|e\rangle + c|e^{-it\kappa_-}\alpha\rangle\otimes|g\rangle$$

$$\rho_f(t) = |a|^2|g\rangle\langle g| + |b|^2|e\rangle\langle e| + ab^* D(t)|e\rangle\langle g| + h.c$$

ITP
The Chinese Academy of Science

Progressive Decoherence Experiment

$$D(t) = \left\langle e^{-it\kappa_+}\alpha \,|\, e^{-it\kappa_-}\alpha \right\rangle$$



Haroch's Group

Phys. Rev. Lett. 77,4887,(1996)

Entanglement due to Virtual Photon Exchange

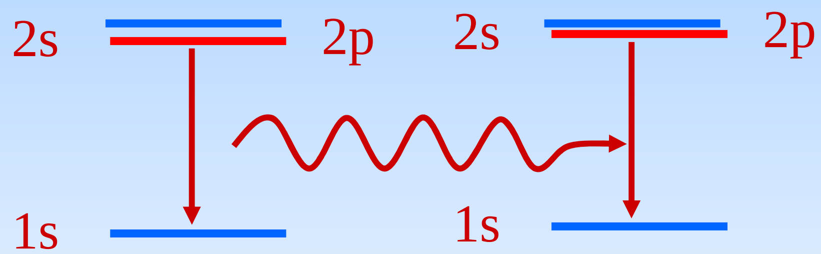
$$H = H_0 + V \ :$$

$$H_0 = \frac{1}{2}\omega_a(\sigma_Z^{(1)} + \sigma_Z^{(2)}) + \omega a^+ a$$

$$V = ga(\sigma_+^{(1)} + \sigma_+^{(2)}) + ga^+(\sigma_-^{(1)} + \sigma_-^{(2)})$$

Virtual Photon Process

With Two Atoms



$$H_f \simeq -\frac{g^2}{\omega - \omega_a}(\sigma_+^{(2)}\sigma_-^{(1)} + \sigma_+^{(1)}\sigma_-^{(2)})$$

$$+\frac{g^2}{\omega - \omega_a}(a^+ a + 1/2)](\sigma_Z^{(1)} + \sigma_Z^{(2)})$$

Large detuning

$$\frac{g^2}{|\omega - \omega_a|^2} \ll 1$$

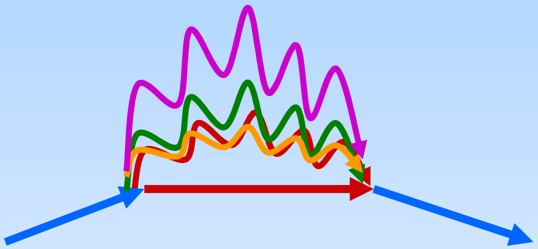
Small $g_{eff} = g^2 / |\omega - \omega_a|$ means a slow process

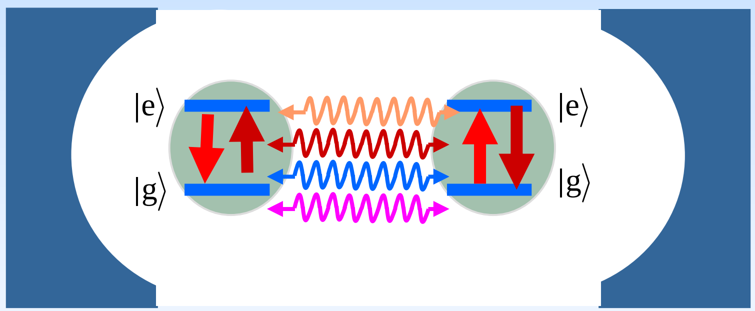
Multi-model virtual photon Process

$$H = H_0 + V \ :$$

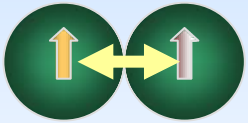
$$H_0 = \frac{1}{2}\omega_a(\sigma_Z^{(1)} + \sigma_Z^{(2)}) + \sum_k \omega_k a_k^+ a_k$$

$$V = \sum_k g_k a_k^+ (\sigma_-^{(1)} + \sigma_-^{(2)}) + hc$$





??



Second order perturbation

$$H_e \sim H_0 + V_{eff} = H_0 + \frac{1}{2}[V, S],$$

$$S = \sum_k \frac{g_k}{\omega_k - \omega_a} a_k^+ (\sigma_-^{(1)} + \sigma_-^{(2)}) - hc$$

$$V_{eff} = ... + J_{eff}(\sigma_-^{(1)}\sigma_+^{(2)} + hc) + \frac{1}{2}[\omega_a + \delta(a_k{}^+ a_{k'})](\sigma_Z^{(1)} + \sigma_Z^{(2)})$$

$$J_{eff} = \sum_k \frac{|g_k|^2}{\omega_k - \omega_a}$$

$$\delta(a_k{}^+ a_{k'}) = \sum_k \frac{a_{k'}^+ a_k g_k g_{k'}}{(\omega_k - \omega_a)}$$

Off-diagonal Lamb shift

ITP

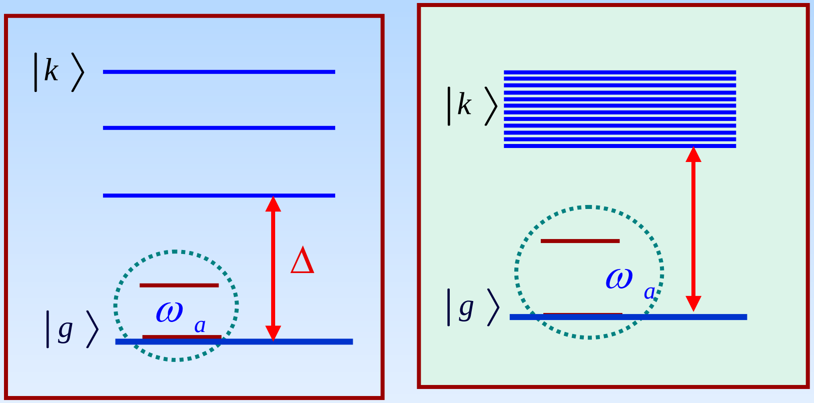
The Chinese Academy of Science

Condition for Finite Effective Coupling

$$J_{eff} = \sum_k \frac{|g_k|^2}{\omega_k - \omega_a}$$

二阶微扰成立条件

$$\frac{|g_k|^2}{|\omega_k - \omega_a|^2} \ll 1$$



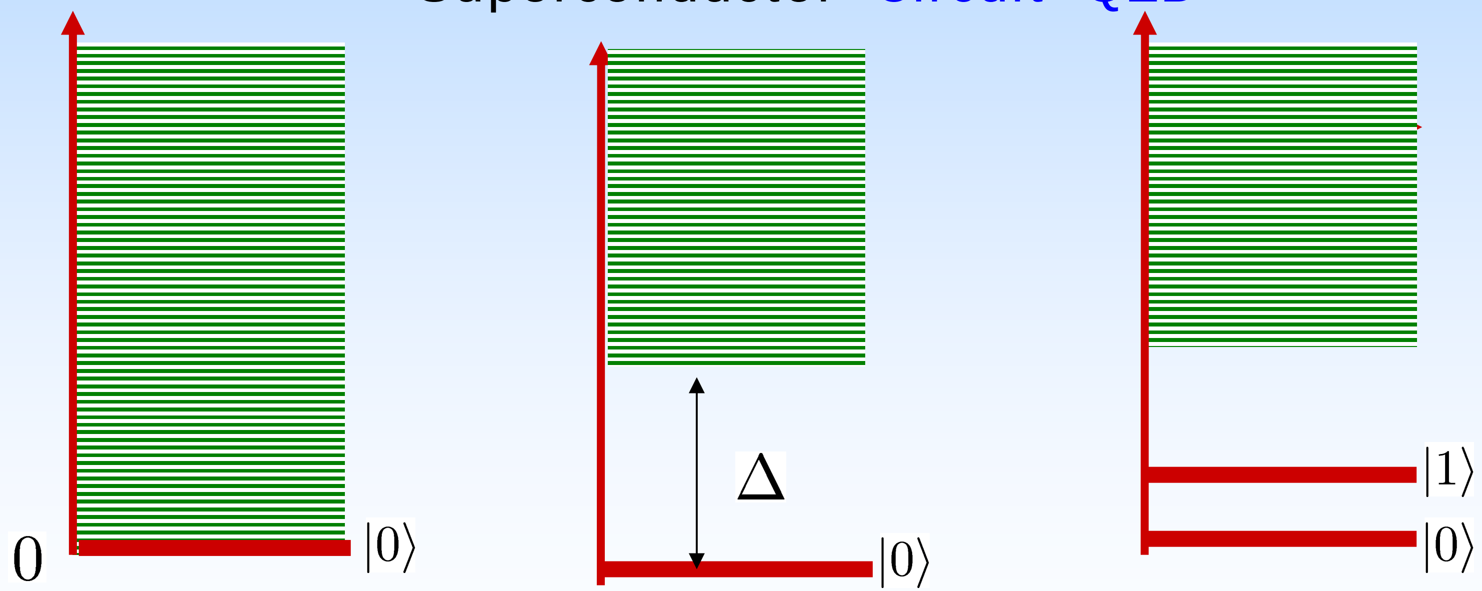
Gapped System is needed !!!

In Quantum Computing, fast operation requires *that* the sum $\sum_k \frac{|g_k|^2}{\omega_k - \omega_a}$ is not too small

Towards to Fully Solid State Cavity QED

SS Qubits + SS Data Bus

Superconductor Circuit QED



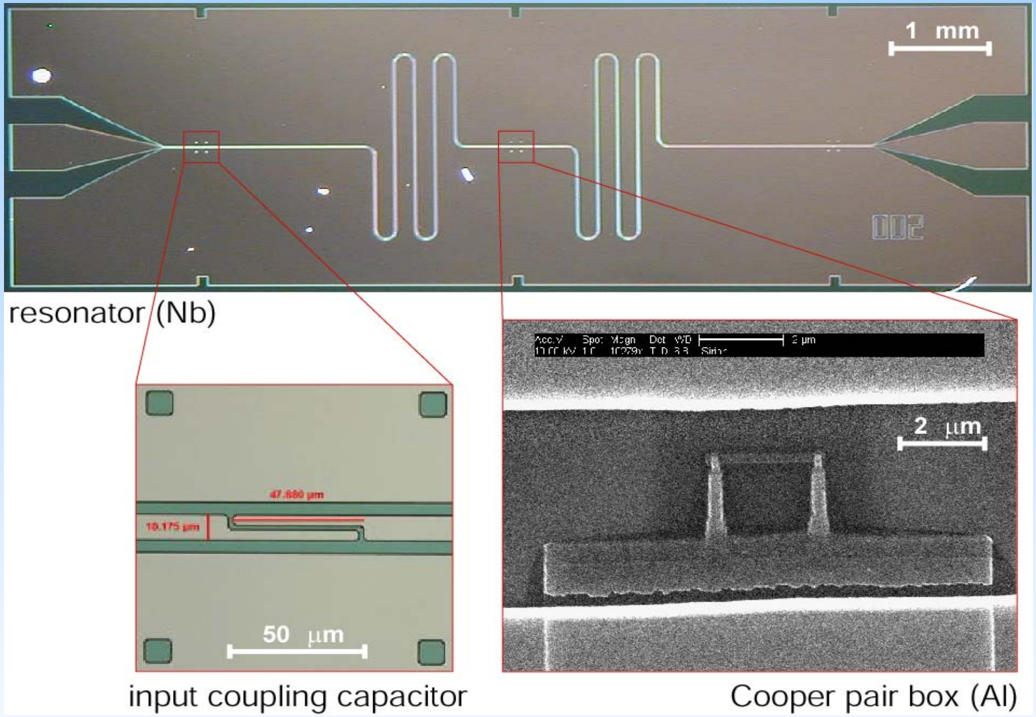
Normal Metal

Superconductor

JJ Qubits

ITP
The Chinese Academy of Science

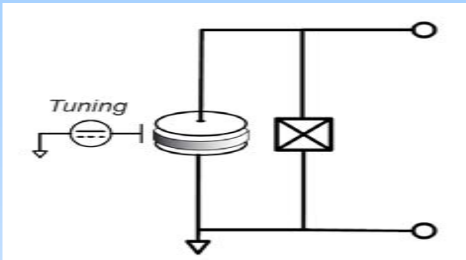
Circuit QED based Josephson Junction

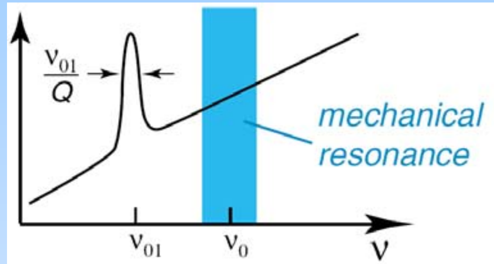


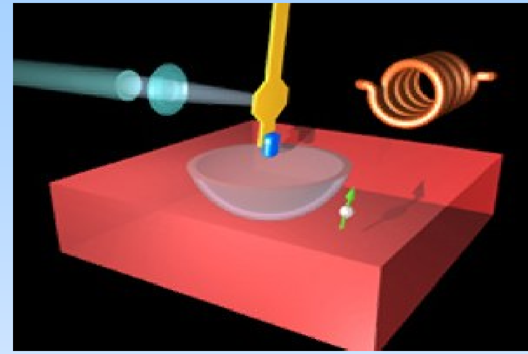
Nature **431 162 (2004)**

Nano-Mechanic (NM)- QED

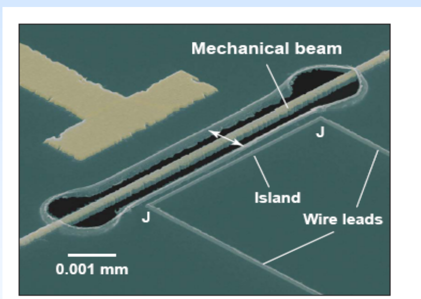
Integrating Josephson Qubit or Spin wit A nano -beam

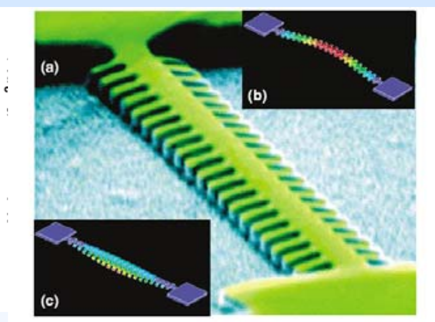


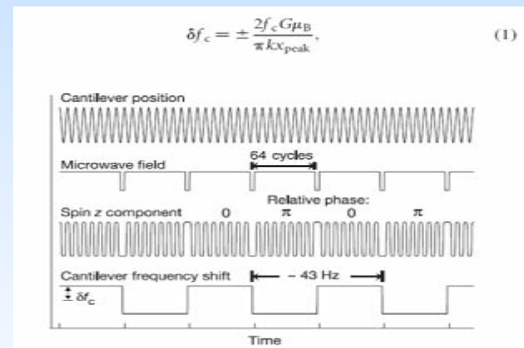




Fast Progresses In experiments





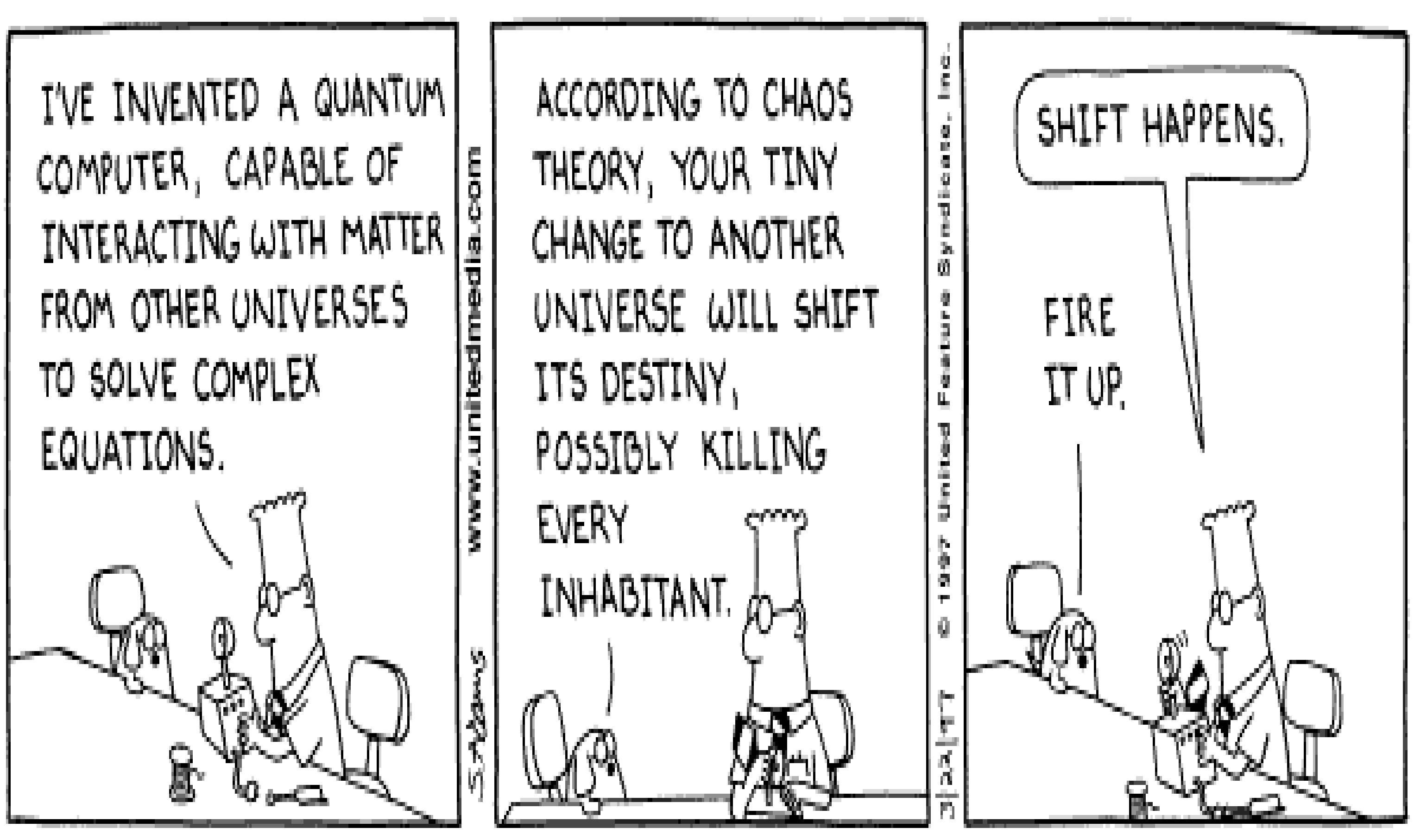


Knobel etal , Nature, 2003
LaHaye et al., *Science* (2004),

Gaidarzhy et al, PRL. 94, 030402 (2005)

Nature 430, 329 (2004)

Quantum Information is Fragile



Physics of Quantum Information: