

冷却微纳机械振子至其量子基态

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二零一零年五月二日

引言

纳米机械振子 (NMRs) 冷却

基态冷却

电磁感应透明 (EIT) 冷却

集体效应辅助 (CA) 冷却

超导量子比特 (SQ) 纠缠

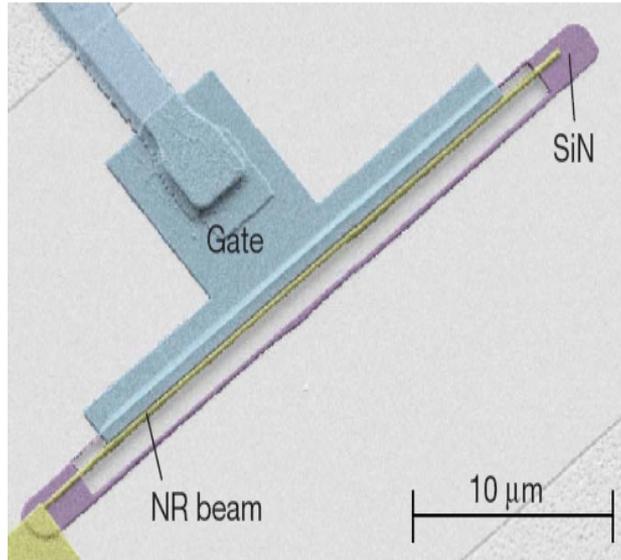
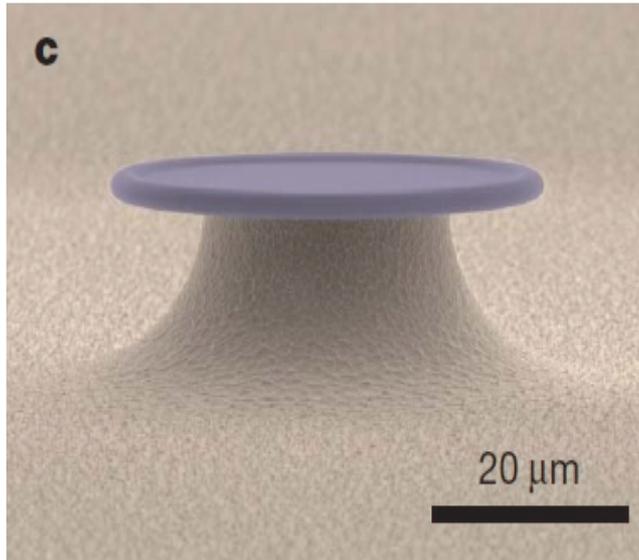
弱耦合

强耦合

总结

引言

纳米机械振子冷却

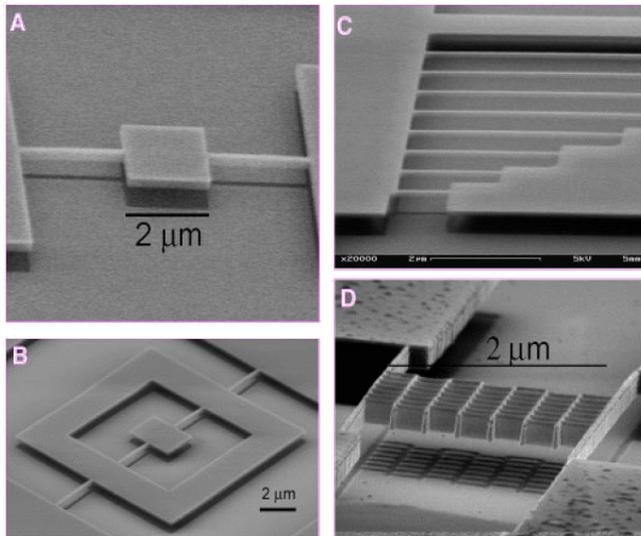


P. Del'Haye, ..., T. J. Kippenberg, *Nature* **450**, 1214 (2007).
H. G. Craighead et al., *Science* **290**, 1532 (2000)
T. Rocheleau et al., *Nature* **463**, 72 (2010);

目标：冷却机械振子到量子基态

动机：

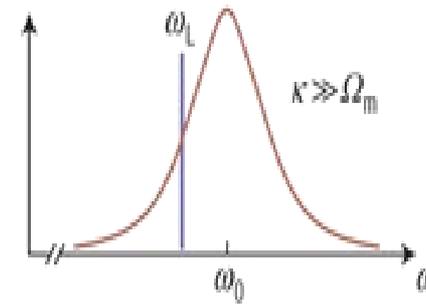
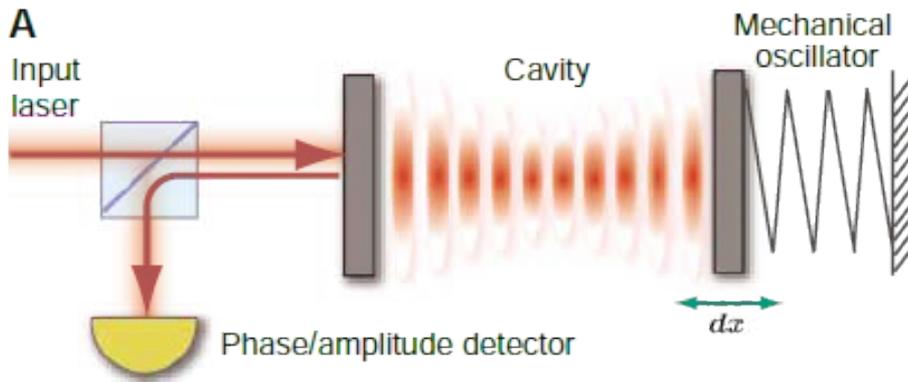
- 宏观领域检验量子力学（纠缠，非经典态）
- 量子信息处理（量子计算，量子存储）
- 量子极限测量（位移，质量，力，...）



引言

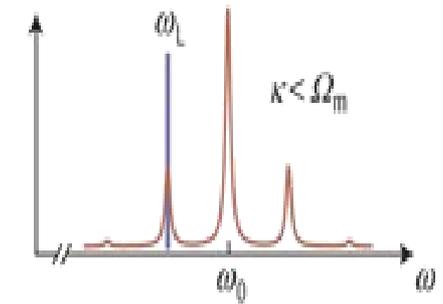
纳米机械振子冷却

边带冷却



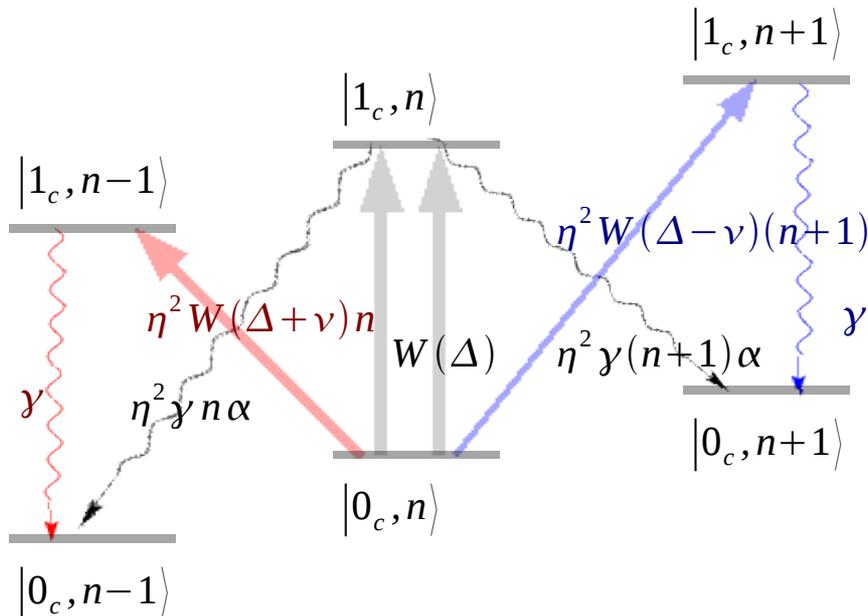
$$n_{\min} \approx \kappa / 4\Omega_m \gg 1$$

边带不可分离



$$n_{\min} = \kappa^2 / 16\Omega_m^2 < 1$$

边带可分离



吸收红失谐光子 → 吸取能量 → 冷却

吸收蓝失谐光子 → 给予能量 → 制热

载波诱导跃迁 → 振动态不变但改变冷却场散射

T. J. Kippenberg et al., Science **321**, 1172 (2008);
Nature Physics **4**, 415 (2008)

其它方法和理论：

- ▶ 反馈冷却
- ▶ 周期性冷却
- ▶ 机械振子冷却量子理论

边带冷却限制：

- ▶ 未知限制 ($n_f \approx 4$)
(T. Rocheleau et al., Nature **463**, 72 (2010))
- ▶ 要求边带可分离
- ▶ 对相位噪声敏感
- ▶ 稳态声子数包含相干成份 (I. Wilson-Rae, ..., T. J. Kippenberg, Phys. Rev. Lett., **99**, 093901 (2007))

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超导量子比特 (SQ) 纠缠

弱耦合

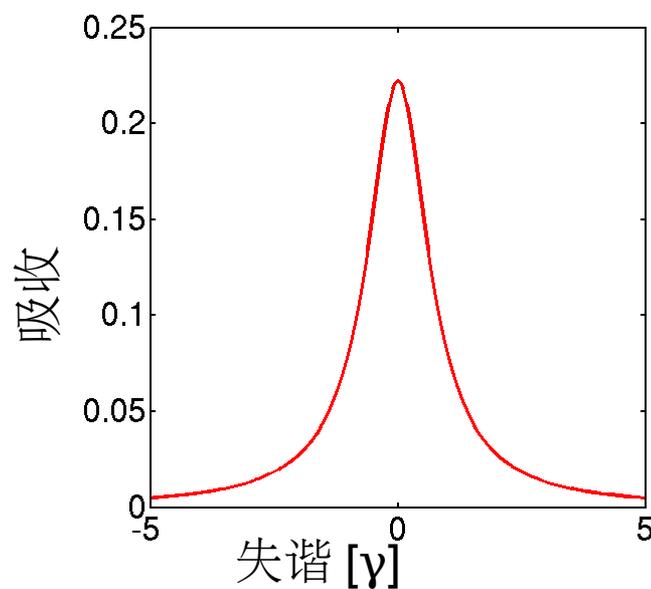
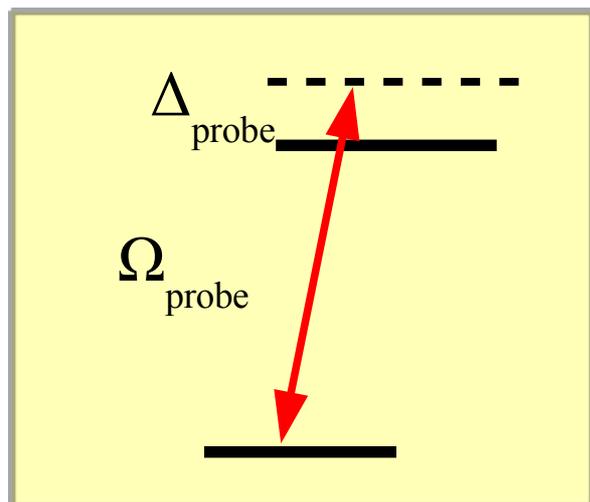
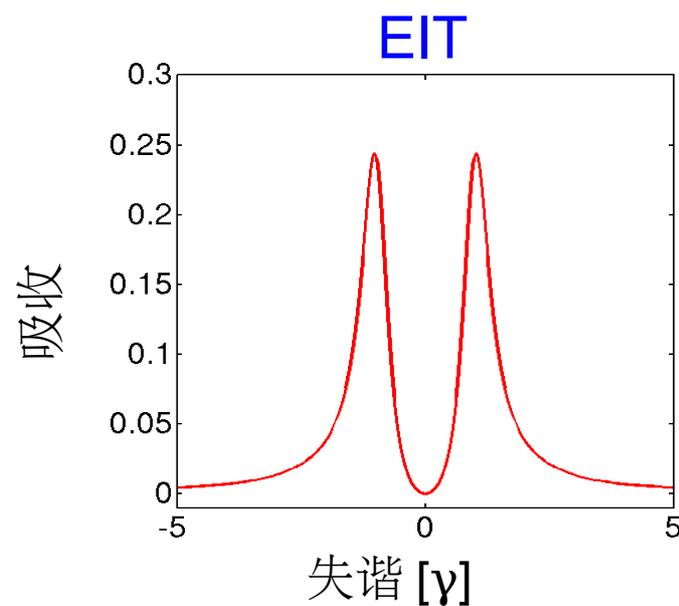
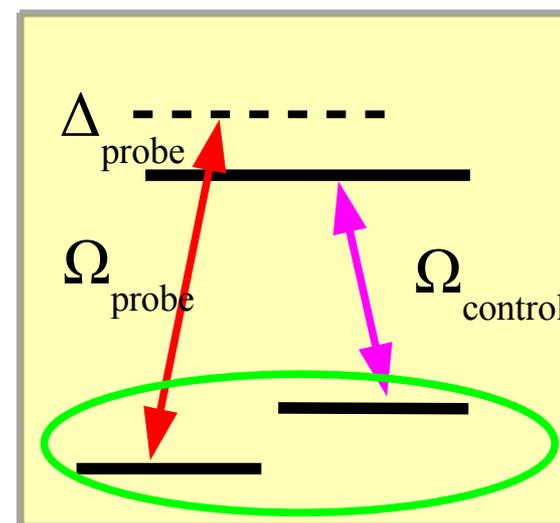
强耦合

总结

基态冷却

EIT 冷却

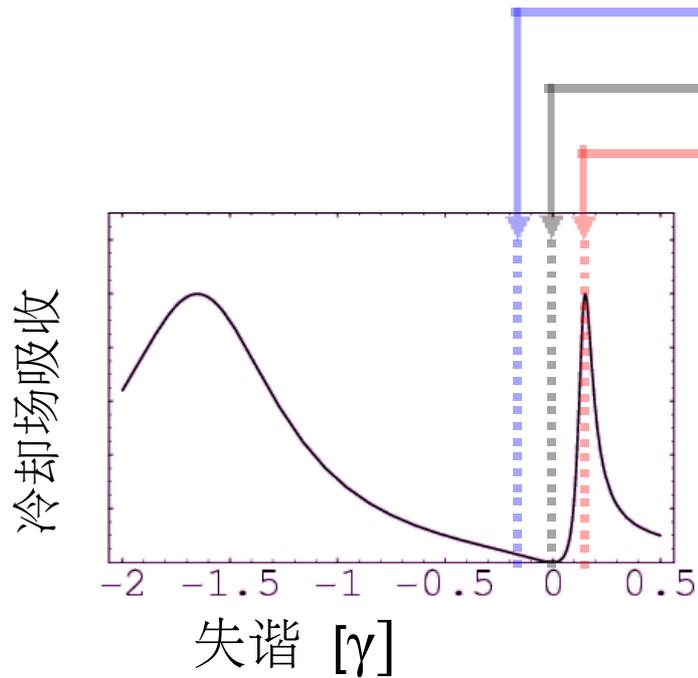
二能级系统

三能级 Λ 型系统

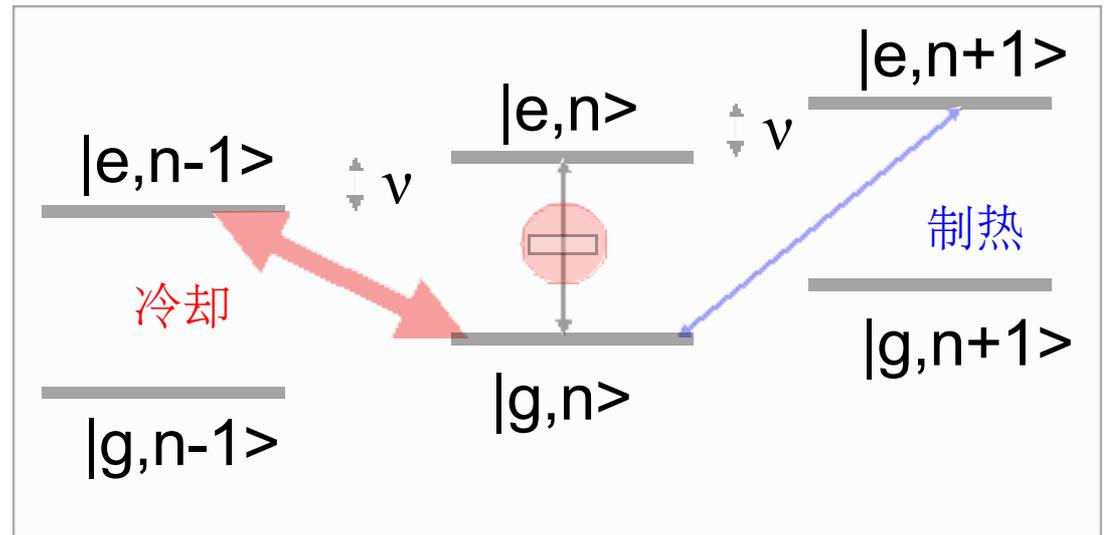
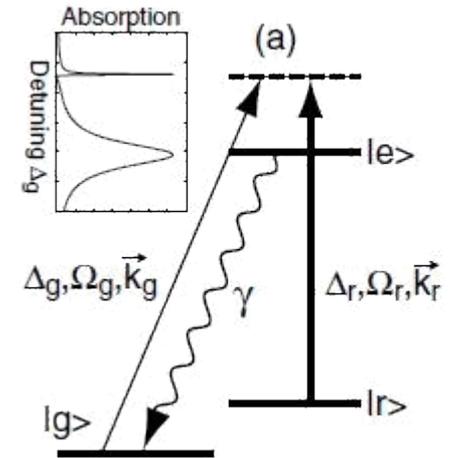
基态冷却

EIT 冷却

原子/离子系统



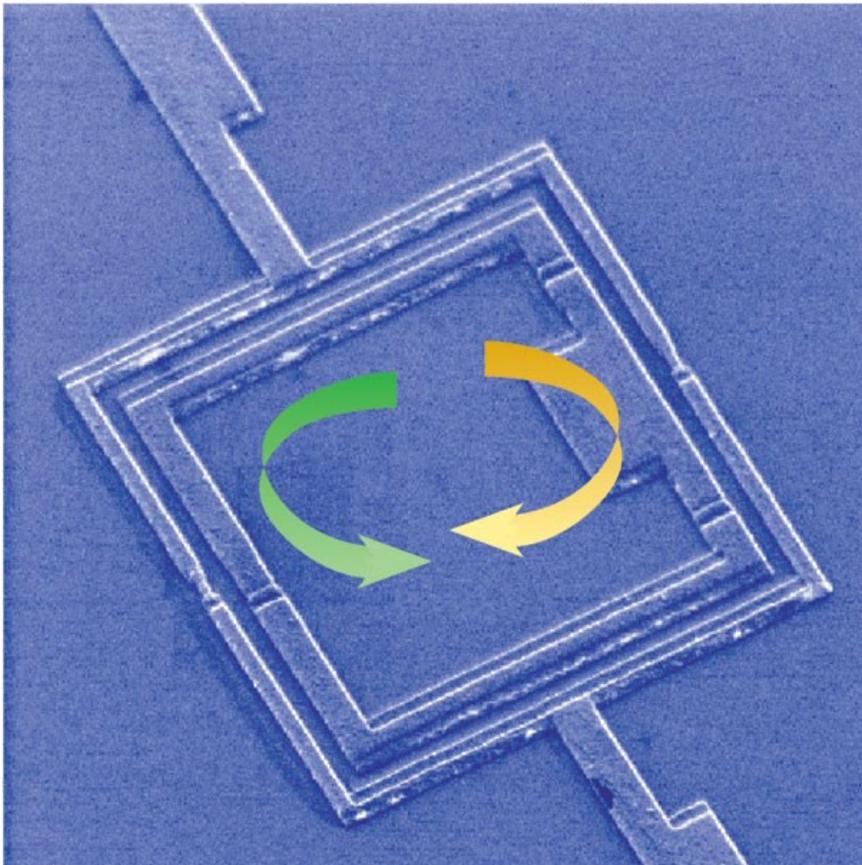
制热抑制
载波诱导跃迁受禁
冷却增强



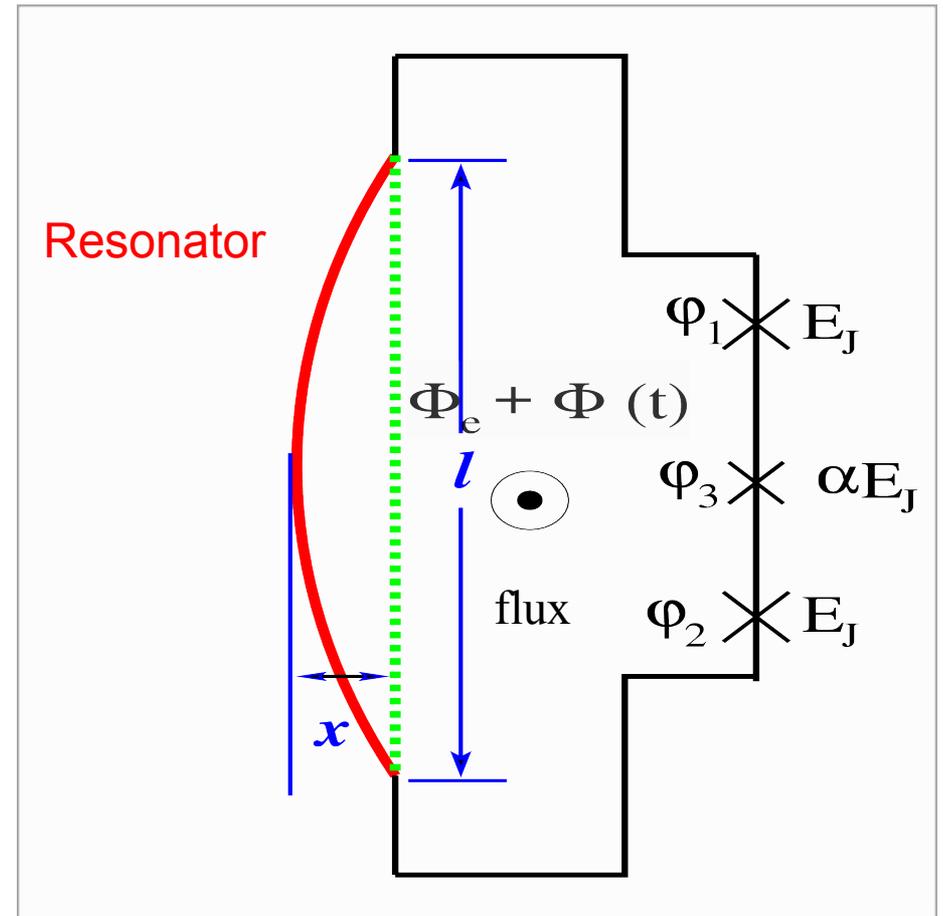
$$N_f^{(SC)} = \frac{\gamma}{4\nu} \Rightarrow N_f^{(EIT)} = \left(\frac{\gamma}{4\Delta} \right)^2$$

Giovanna Morigi, Jürgen Eschner, & Christoph H. Keitel
Phys. Rev. Lett., **85**, 4485 (2000)

系统

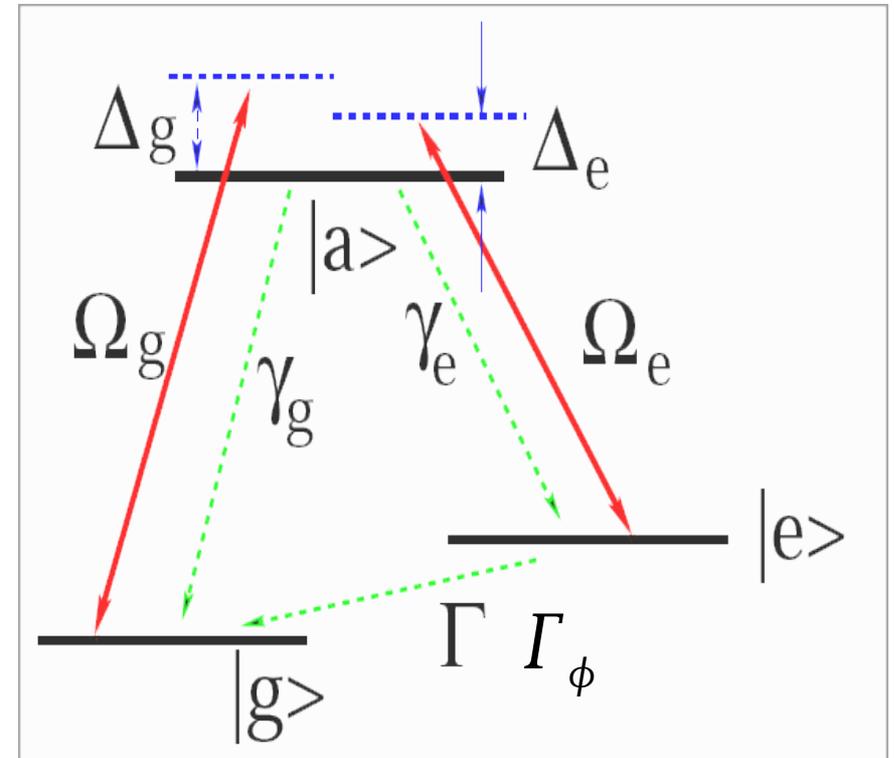
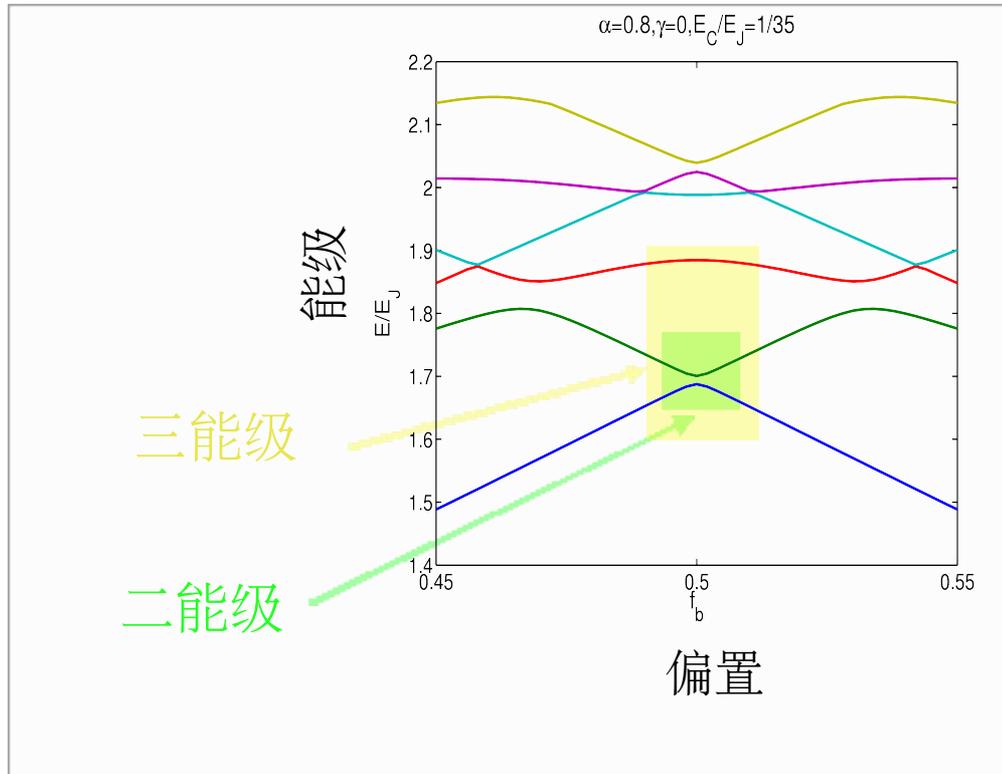


J. Clarke & F. K. Wilhelm, Nature **453**, 1031 (2008).



K. Xia, J. Evers
Phys. Rev. Lett. **103**, 227203 (2009)

量子比特三能级 Λ 型模型



基态冷却

EIT 冷却

冷却极限：

EIT 冷却

弱冷却场情形： $r = \Omega_e / \Omega_g \gg 1$

$$N_f^{EIT} (r \gg 1) \approx \frac{\gamma r^2 N_i}{4\eta^2 Q_m |\Delta|} + \left(\frac{\gamma}{4\Delta}\right)^2$$

强冷却场情形： $r = \Omega_e / \Omega_g \approx 1$

$$N_f^{EIT} (r \approx 1) \approx \frac{\gamma N_i}{\eta^2 Q_m |\Delta|} + \left(\frac{\gamma}{4\Delta}\right)^2$$

- 环境贡献小
- 散射小
- 无相干成份

边带冷却

$$N_f^{BA} \approx \frac{N_i}{\eta_{LD}^2 Q_m \frac{\gamma}{\nu}} + \left(\frac{\gamma}{4\nu}\right)^2 + \eta^2 \left(\frac{\gamma}{4\nu}\right)^2 n_{max}^2$$

$$\eta_{LD} = \eta \sqrt{n_{max}}$$

$$\eta = \frac{x_{zp}}{\nu} \frac{\partial \omega_c}{\partial x}, n_{max} = \frac{P_{in}}{\hbar \omega_c \kappa}$$

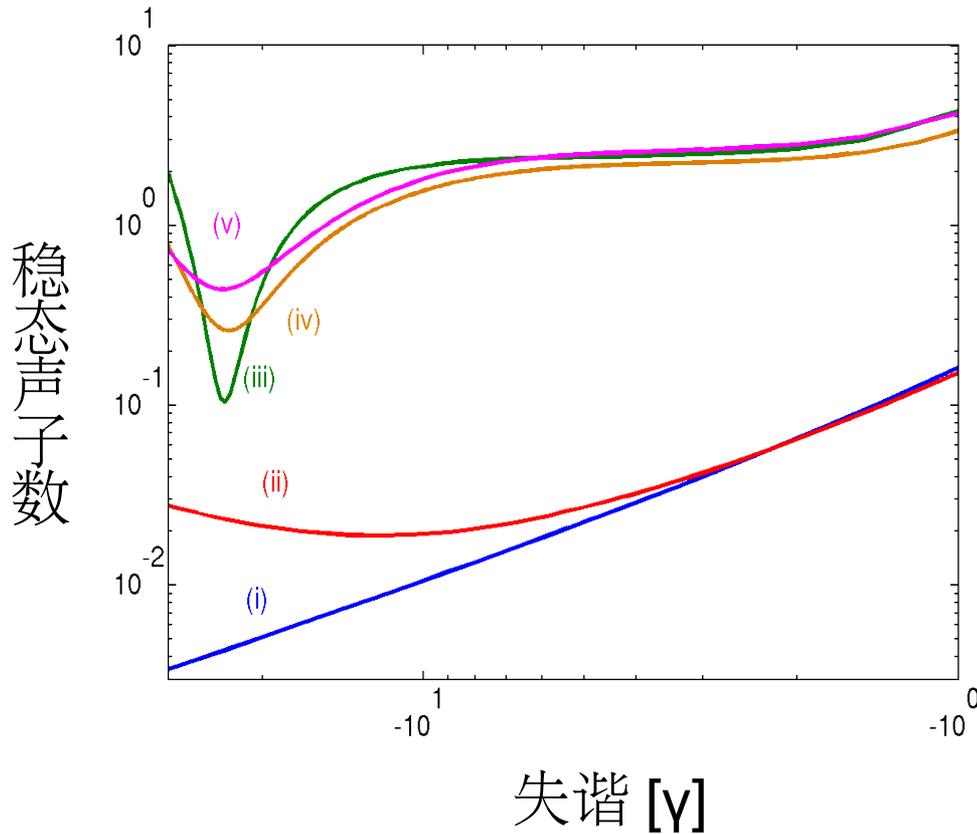
(I. Wilson-Rae, ...,

T. J. Kippenberg, Phys. Rev. Lett., **99**, 093901 (2007))

冷却极限：红色
环境贡献：蓝色
散射：绿色
相干成份：紫色

基态冷却

EIT 冷却



- (I) 理论
- (ii) 无衰减和纯消相干
- (iii) 有衰减但无纯消相干
 $\Gamma = 0.02\gamma$
- (iv) 小纯消相干
 $\Gamma = 0.02\gamma, \Gamma_\phi = \Gamma$
- (v) 大纯消相干
 $\Gamma = 0.02\gamma, \Gamma_\phi = 2\Gamma$

$$N_i = 16, \nu = 0.25\gamma, Q = 5 \times 10^4, \eta_{LD} = 0.0566$$

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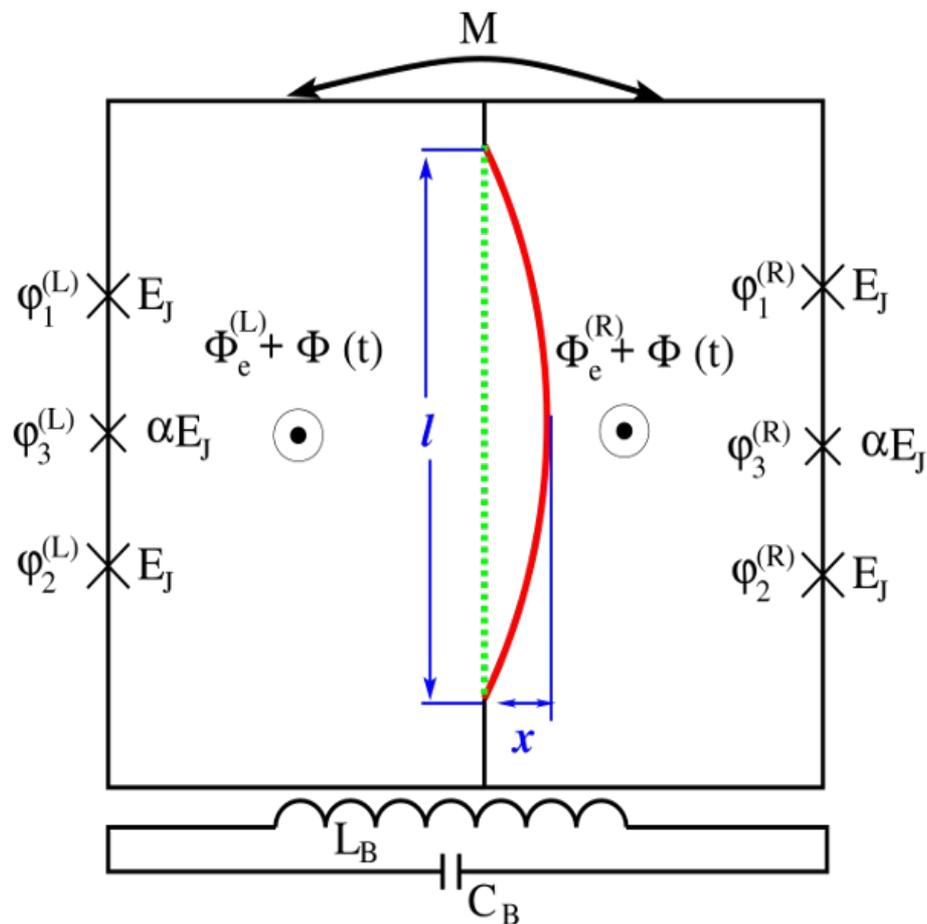
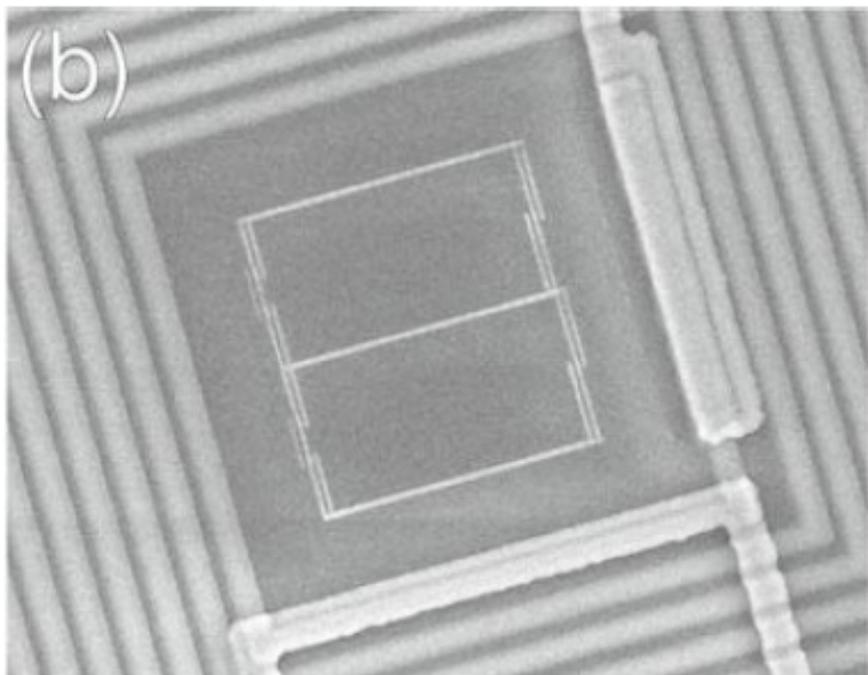
弱耦合

强耦合

总结

基态冷却

CA 冷却



E. Il'ichev, S. H. W. van der Ploeg,
M. Grajcar, H. -G. Meyer, Quantum
Inf Process **8**, 133 (2009).

K. Xia and J. Evers, arXiv:0912.1990

基态冷却

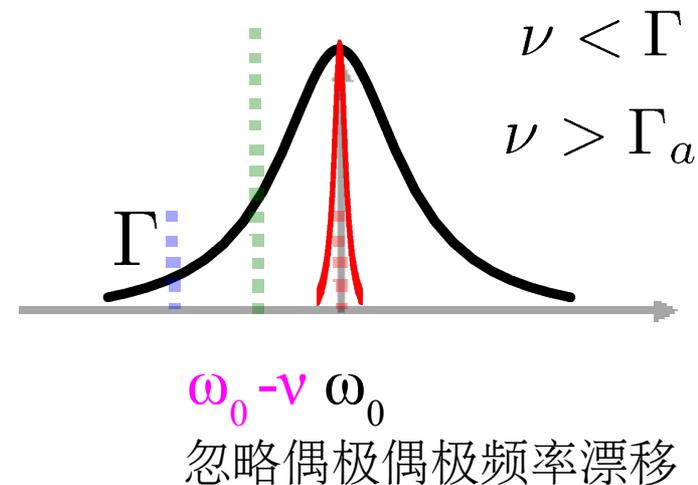
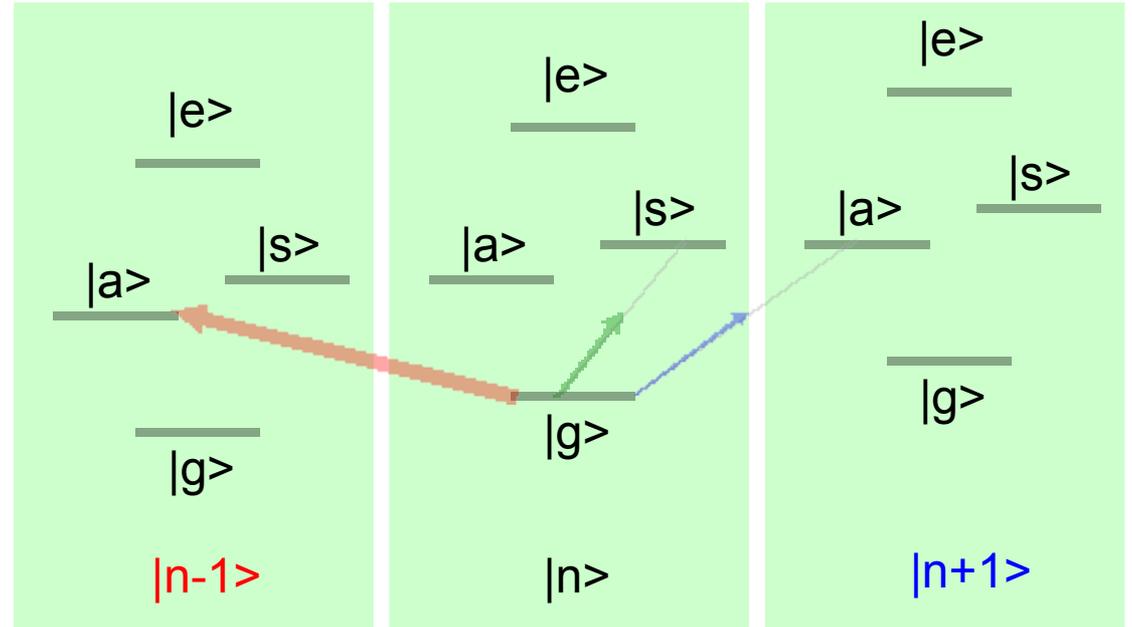
CA 冷却

优点:

- ▶ 无需边带可分离
- ▶ 效率更高
- ▶ 全新的方案

冷却机制:

- ▶ 振子震动改变偏置
- ▶ 载波诱导跃迁耦合到对称态 → 大失谐
- ▶ 边带跃迁耦合到反对称 → 极窄吸收峰



冷却极限：

CA 冷却

$$N_f^{(CA)} \approx C(\eta, \Omega, \Gamma_a) \frac{\Gamma_a \nu}{\gamma^2} \frac{N_i}{(\eta \Omega)^2 Q_m} + G(\eta, \Omega, \Gamma_a) \left(\frac{\Gamma_a}{4\nu} \right)^2$$

- 环境贡献小
- 散射小
- 无相干成份

边带冷却

$$N_f^{BA} \approx \frac{N_i}{\eta_{LD}^2 Q_m \frac{\gamma}{\nu}} + \left(\frac{\gamma}{4\nu} \right)^2 + \eta^2 \left(\frac{\gamma}{4\nu} \right)^2 n_{max}^2$$

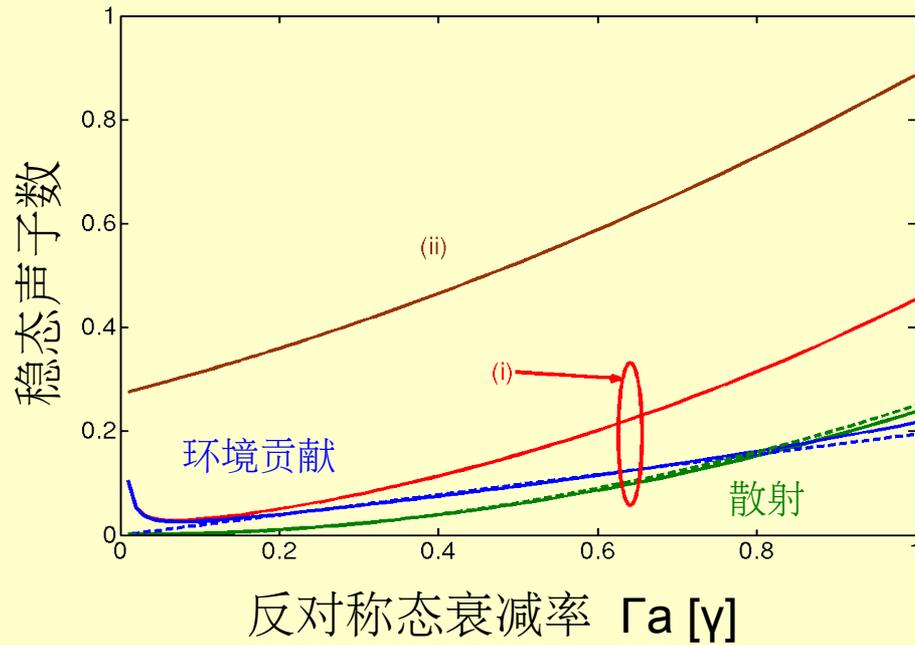
(I. Wilson-Rae, ...,

T. J. Kippenberg, Phys. Rev. Lett., **99**, 093901 (2007))

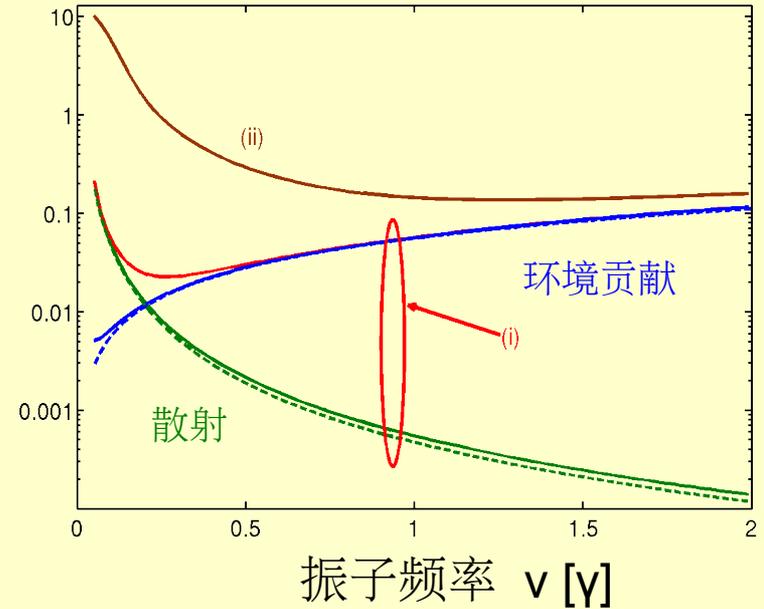
冷却极限：红色
环境贡献：蓝色
散射：绿色
相干成份：紫色

基态冷却

CA 冷却



$$N_i = 400, \nu = 0.5\gamma, Q = 10^6, \eta = 3 \times 10^{-3}$$



$$N_i = 400, Q = 10^6, \eta = 3 \times 10^{-3}, \Gamma_a = 0.05\gamma$$

稳态声子数 = 环境贡献 + 散射

(i) 无纯消相干

(ii) 有消相干

$$\Gamma_\phi = 0, \Omega = 4\gamma, C = 0.14$$

$$\Gamma_\phi = 0.5\gamma, \Omega = 10\gamma, C = 0.3$$

————— 数值结果

----- 理论

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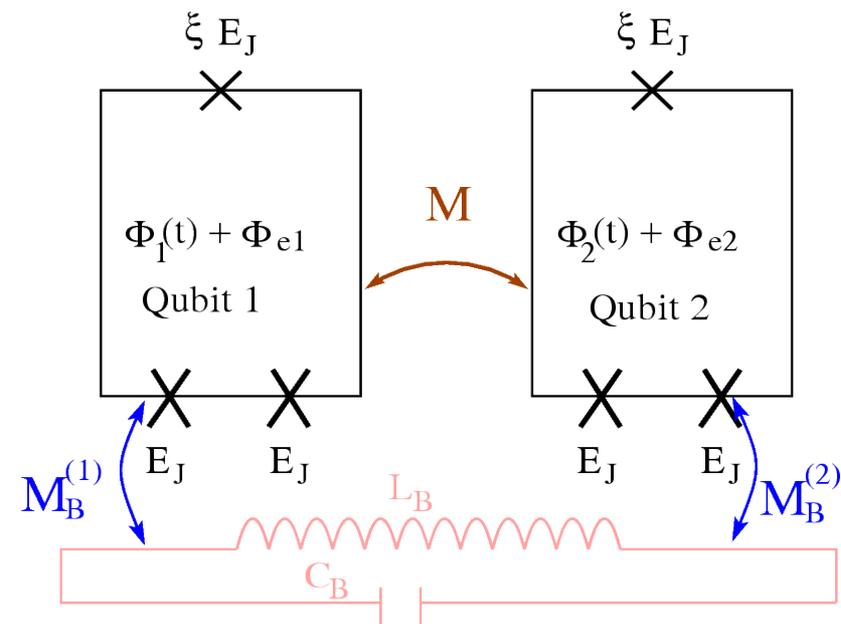
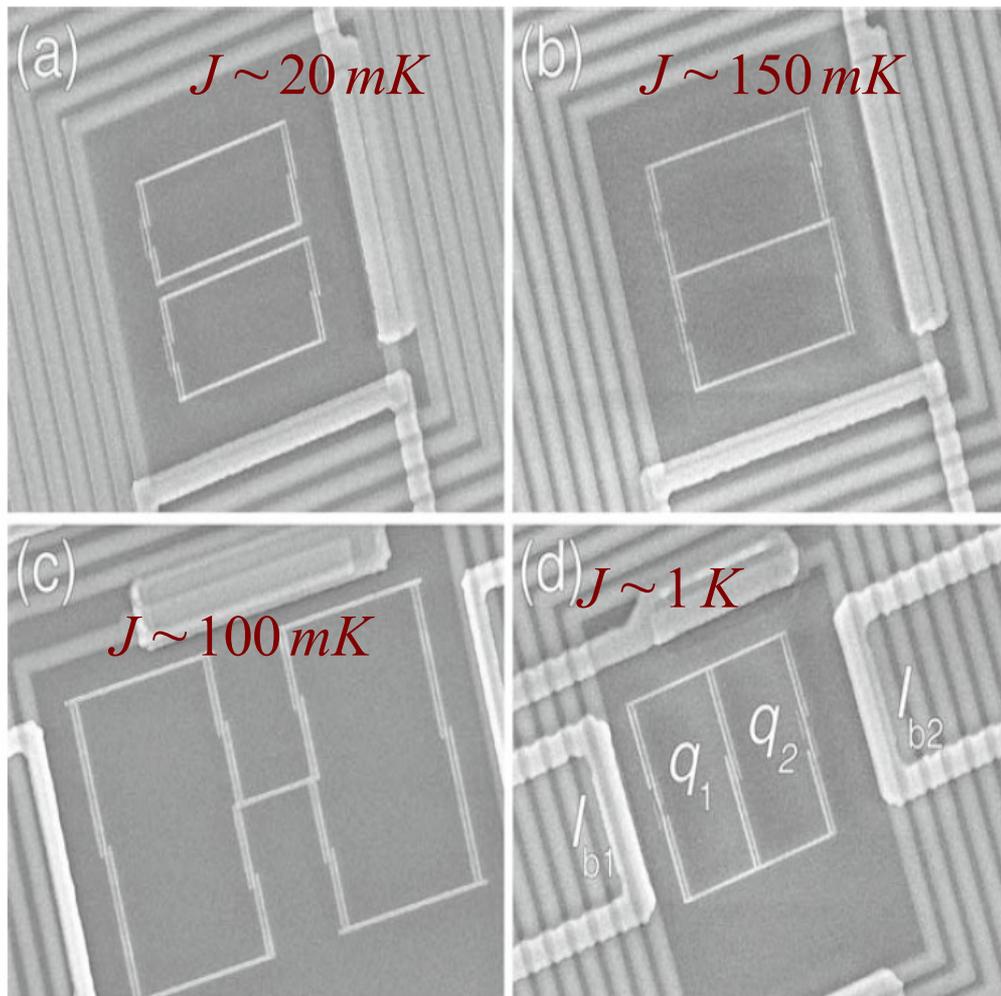
集体效应辅助 (CA) 冷却

超导量子比特 (SQ) 纠缠

弱耦合

强耦合

总结



自由哈密顿量：

$$H_Q = \frac{1}{2} \sum_{l=1}^2 \hbar \omega_0^{(l)} \sigma_z^{(l)} + \hbar J \sigma_x^{(1)} \sigma_x^{(2)}$$

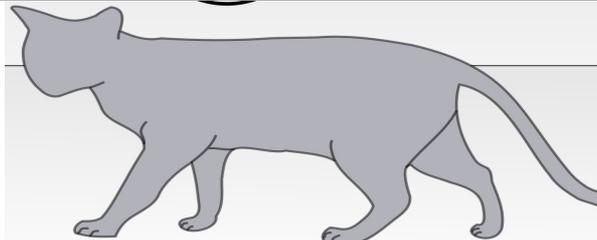
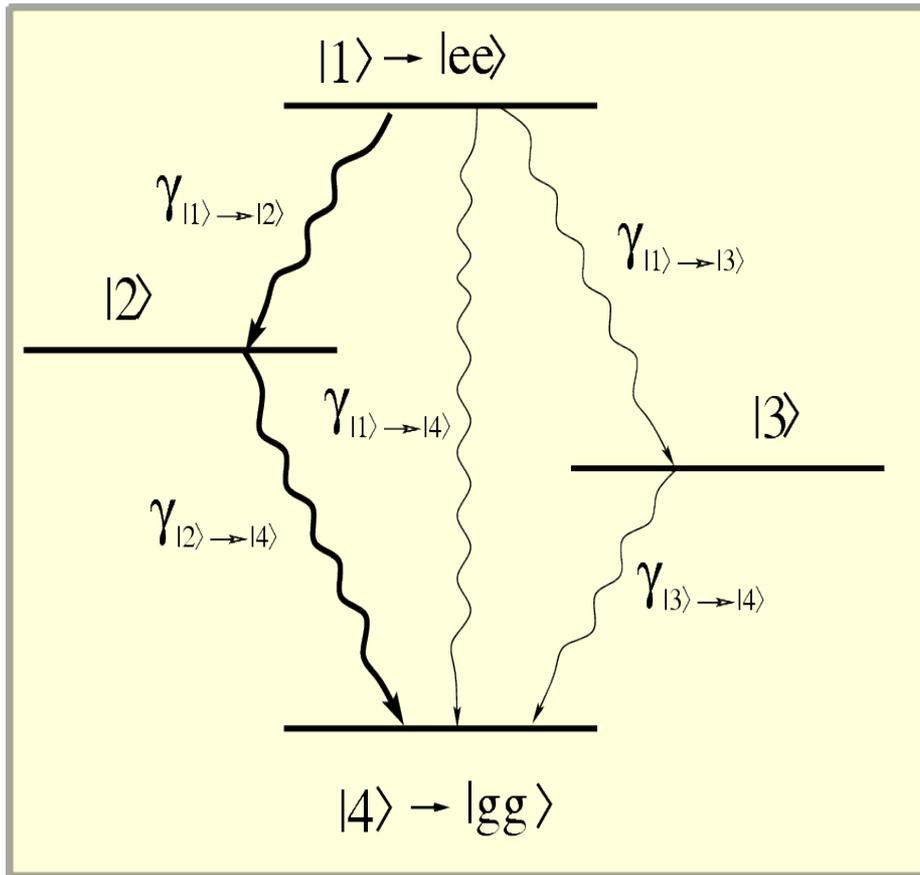
$$J = M I_p^{(1)} I_p^{(2)}$$

E. Il'ichev, S. H. W. van der Ploeg,
M. Grajcar, H. -G. Meyer, Quantum
Inf Process **8**, 133 (2009).

纠缠

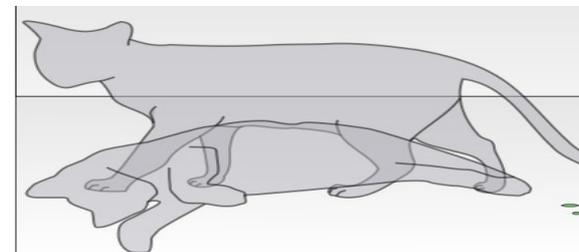
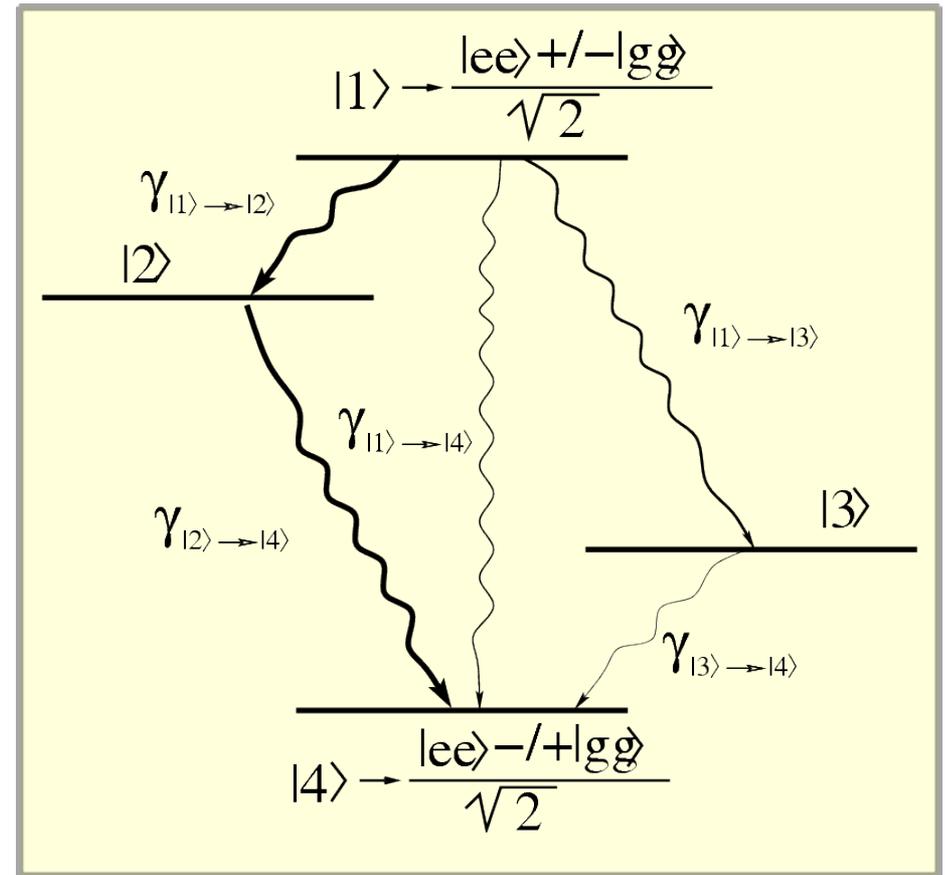
能级结构

弱耦合 $J \ll \omega_0$



图片来自 Wikipedia

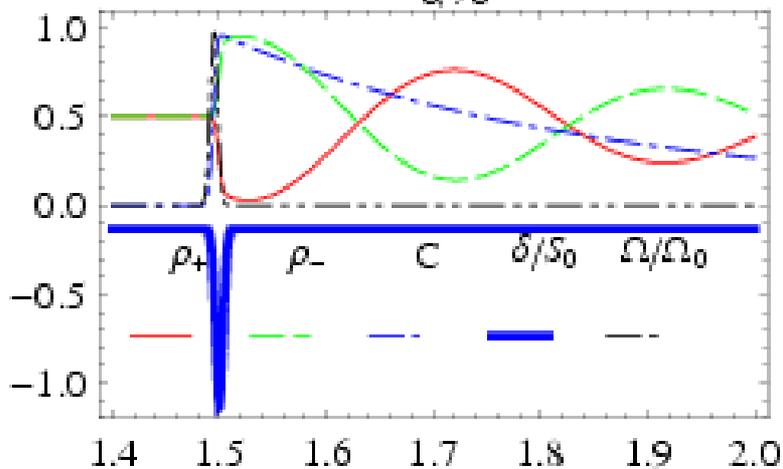
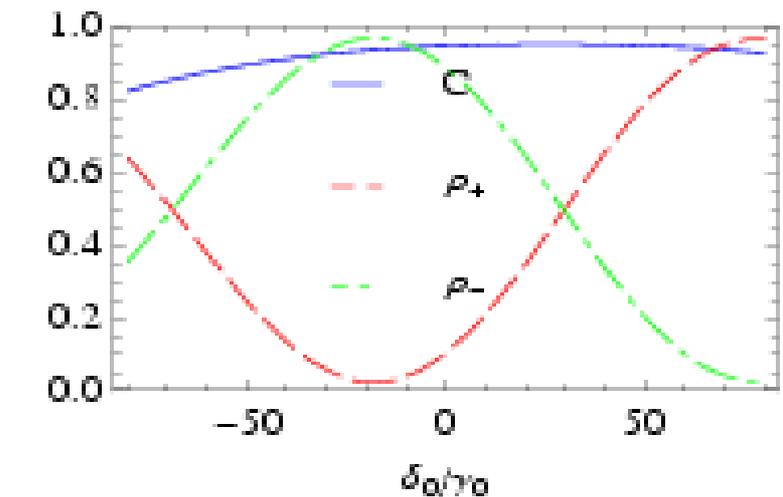
强耦合 $J \gg \omega_0$



纠缠

数值结果

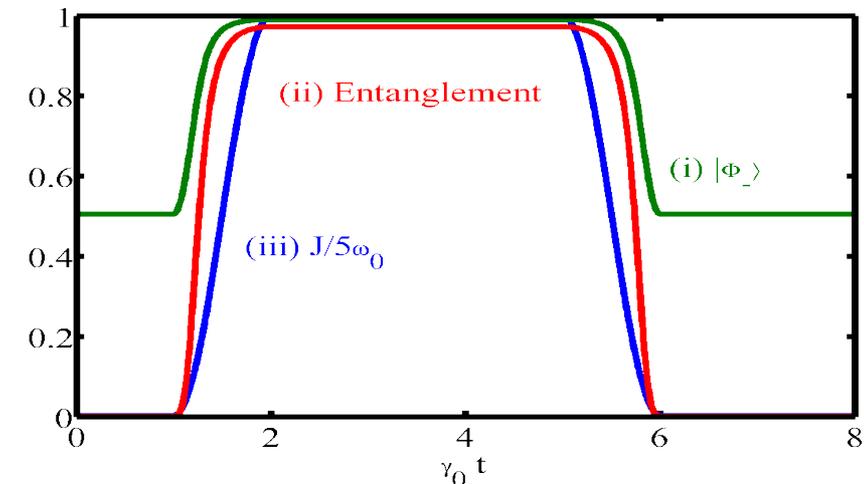
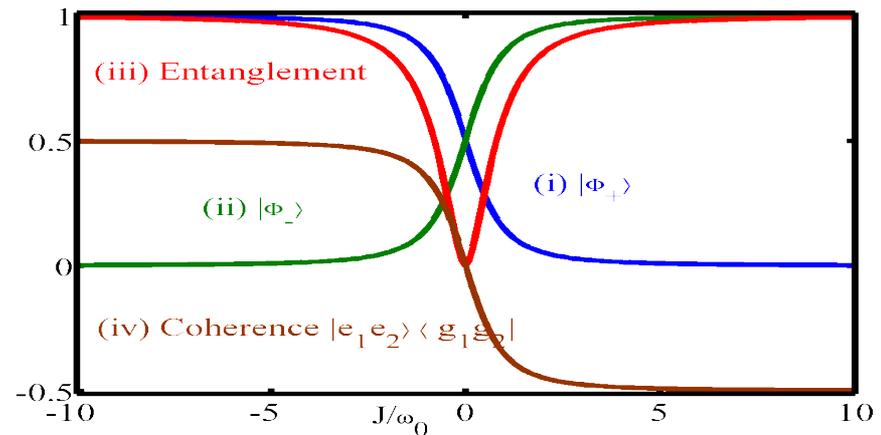
弱耦合
斯塔克啁啾绝热通道技术 (SCRAP)



$$\Omega_0 = 180 \gamma_0, \delta_0 = 16 \gamma_0, S_0 = 30 \gamma_0$$

Keyu Xia, Mihai Macovei, Joerg Evers & Christoph H Keitel, Phys. Rev. B **79**, 024519 (2009)

强耦合
环境驱动



$$\text{distance } r = \lambda_0/20, \omega_0 = 1000 \gamma_0$$

$$\text{two-photon decay rate } \tilde{\gamma}_0 = 0.02 \gamma_0$$

Keyu Xia, Mihai Macovei & Joerg Evers, in preparation

总结

冷却

▶ EIT 冷却

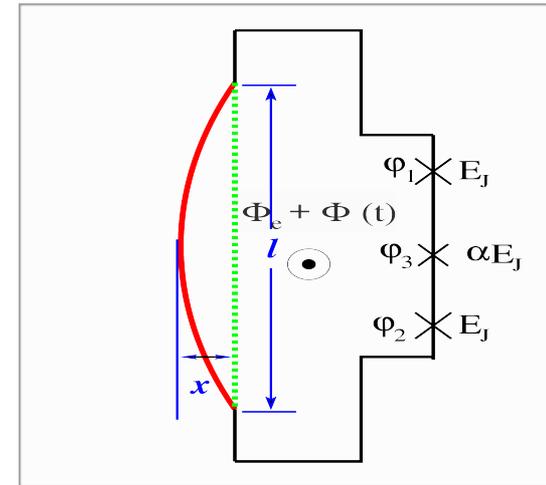
机制：量子干涉

无需边带可分离

冷却率更高，冷却极限减少 $\gamma/|\Delta|$

无相干成份

弱冷却场 $<1 \mu\text{W}$



Keyu Xia, Jörg Evers, Phys. Rev. Lett. 103, 227203 (2009)

▶ CA 冷却

机制：偶极偶极相互作用

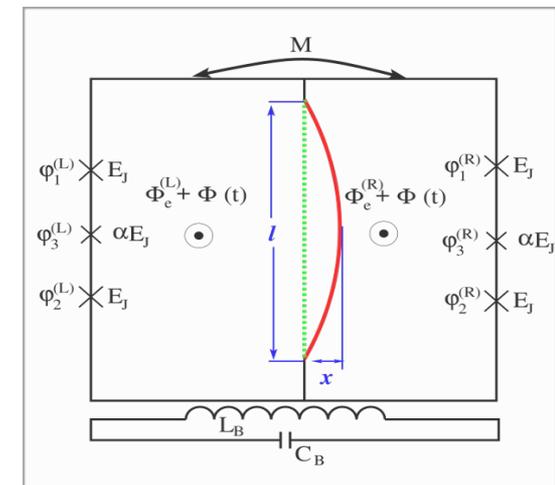
(集体效应)

无需边带可分离

冷却率更高，冷却极限减少 $C\Gamma_{a\nu}/\gamma^2$

无相干成份

弱冷却场 $<1 \text{ nW}$



Keyu Xia, Jörg Evers, arXiv: 0912.1990

总结

纠缠

▶ 弱耦合

耦合强度远小于跃迁频率
用 **SCRAP** 技术稳定制备 **Bell**
态和纠缠

Keyu Xia, Mihai Macovei, Joerg Evers &
Christoph H Keitel, *Phys. Rev. B*, **79**
024519 (2009)

▶ 强耦合

耦合强度远大于跃迁频率
自发辐射产生相干， **Bell** 态和
纠缠 (**纠缠基态**)

Keyu Xia, Mihai Macovei & Joerg Evers,
in preparation

