Adiabatic manipulation of architectures of multilevel artificial atoms

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QUINN – **QU**antum **IN**formation & **N**anostructures

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Istituto Nazionale di Fisica Nucleare

Boris Altshuler's 60th birthday

Frontiers of Nanoscience, Trieste Aug-Sept 2015

quantum coherence in the solid state

a 35 years (very short & personal) roadmap

Fluctuations in the extrinsic conductivity of disordered conductors

B. L. Al'tshuler

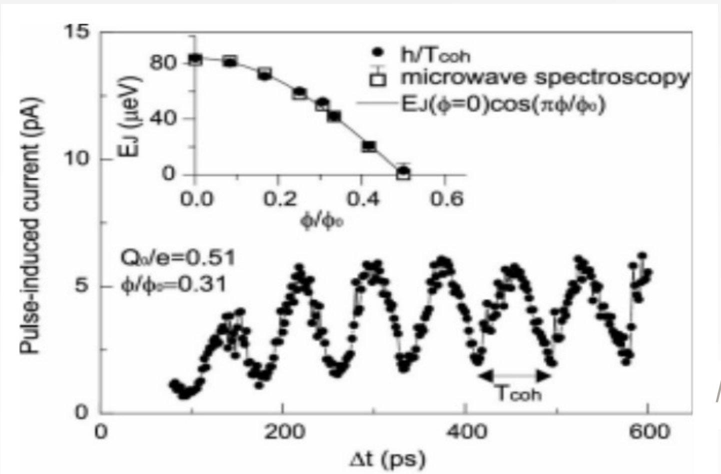
B. P. Konstantinov Institute of Nuclear Physics, Academy of Sciences of the USSR

(Submitted 16 May 1985)

Pis'ma Zh. Eksp. Teor. Fiz. **41**, No. 12, 530–533 (25 June 1985)

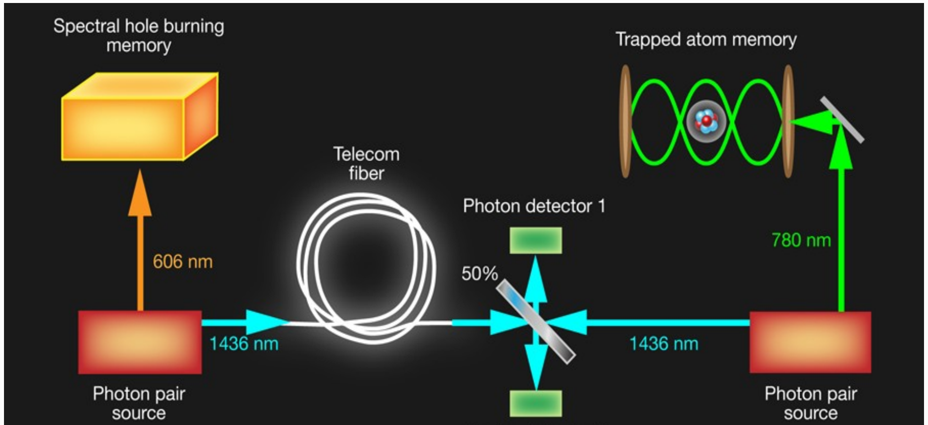
- **mesoscopic phenomena in solids**

  "*Quantum mechanical coherence of electron wavefunctions in materials with imperfections has led to major revisions in the theory of electrical conductivity and to novel phenomena in submicron devices.*" *Altshuler & Lee, Phys Today (1988)*



- **quantum bits in a solid state devices**

  Nakamura et al. Nature 398,786 (1999)



J. Fekete, et al. , PRL (2013)

- Frontier of Nanoscience

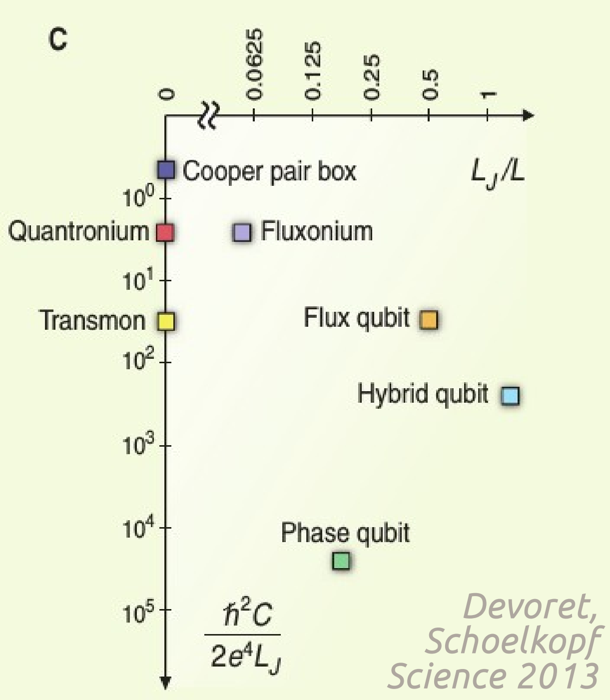
  quantum coherent hybrid netwoks

superconducting-based artificial atoms

mesoscopic devices with the functionality of atoms

why ? With respect to natural atoms they present

- much more **flexible design** → several design solutions
- large degree of **integration**
- on-chip **tunability**
- stronger **couplings** → faster processing
- easy signal production and detection
- photons easily confined in 1D



Devoret, Schoelkopf Science 2013

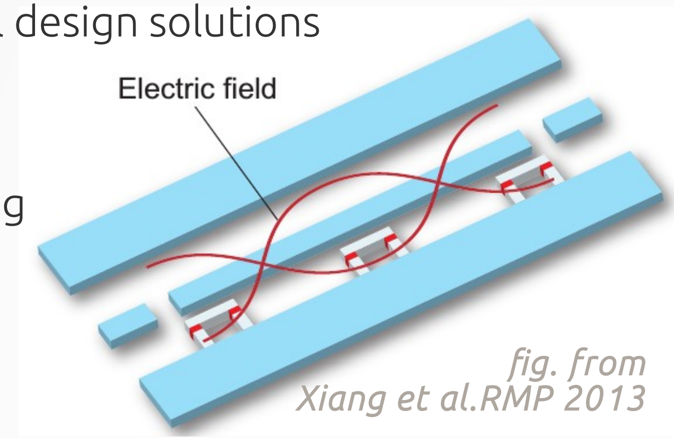
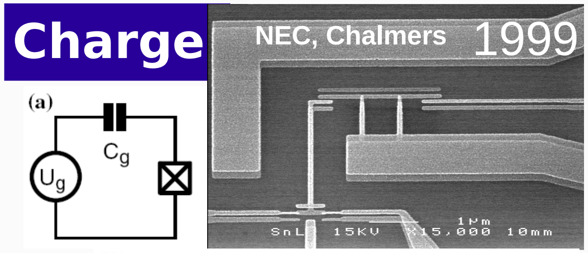
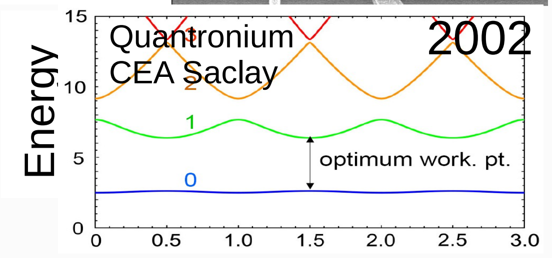
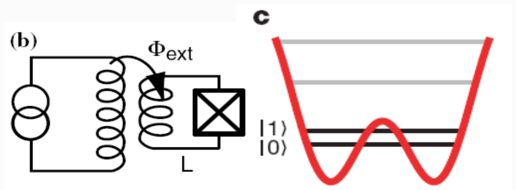


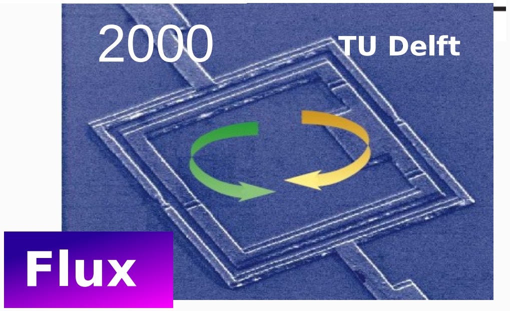
fig. from Xiang et al.RMP 2013

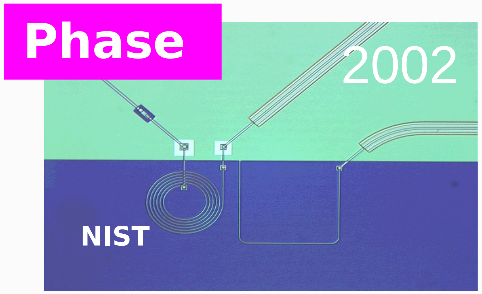
main design solutions

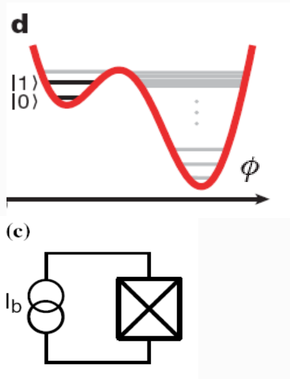






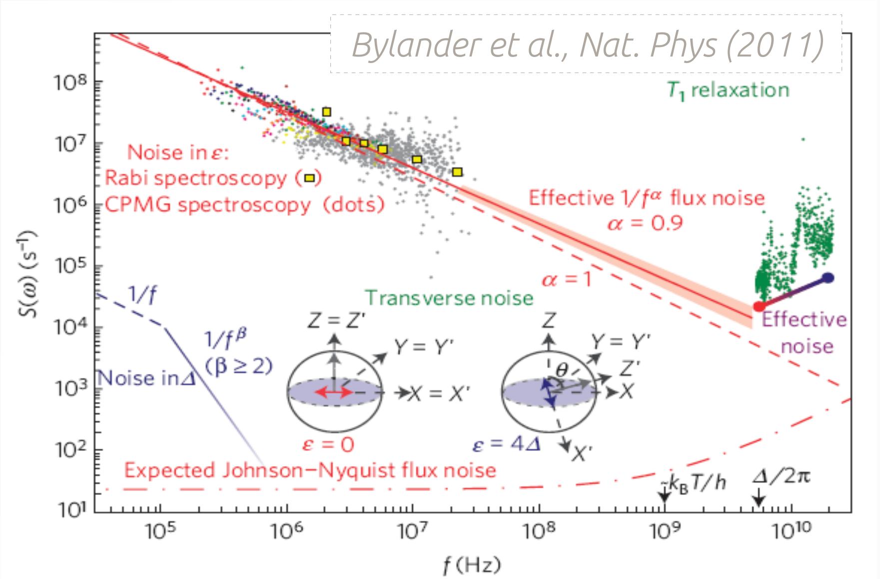






- Noise is broad band colored **low (1/f)** and **high-frequency (quantum)**

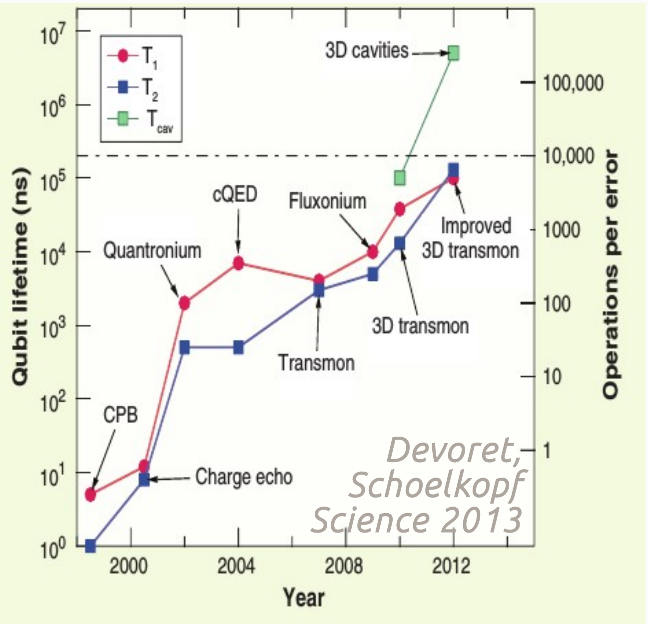
Paladino, Galperin, Falci, Altshuler, RMP (2014)



- Noise sources

design	dominant source	subdominant
Cooper pair box	charge	flux/phase/circuit
flux	flux	crit. current/charge
phase	crit. curr/impurities	dielectric losses

- major drawback **decoherence** but figures **tremendously improved** in the last few years



- Highly **noise protected** qubits
  - Design of **symmetric *H*** suppresses low-frequency dominant noise → increase dephasing
  - Subdominant sources → spontaneuos decay further limited in 3D cavity design

mesoscopic devices with the functionality of atoms

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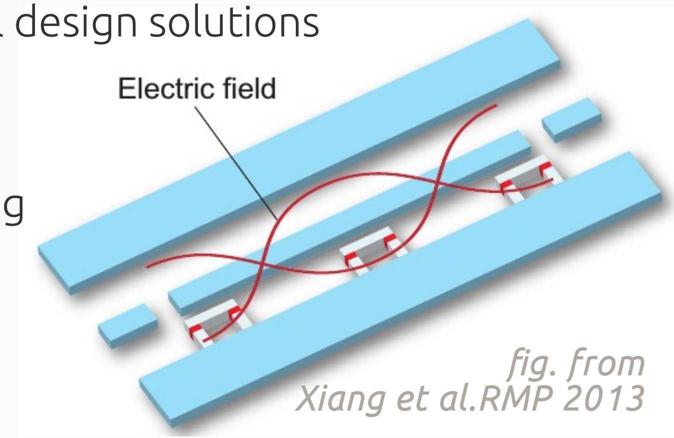

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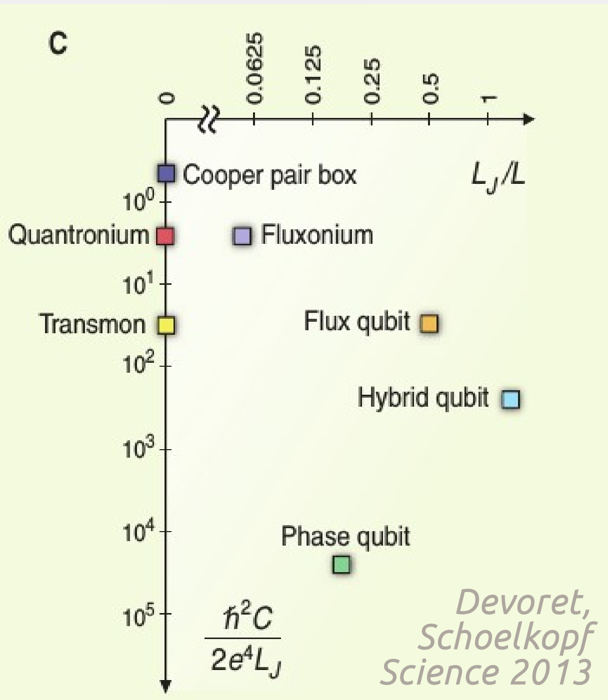

Devoret, Schoelkopf Science 2013

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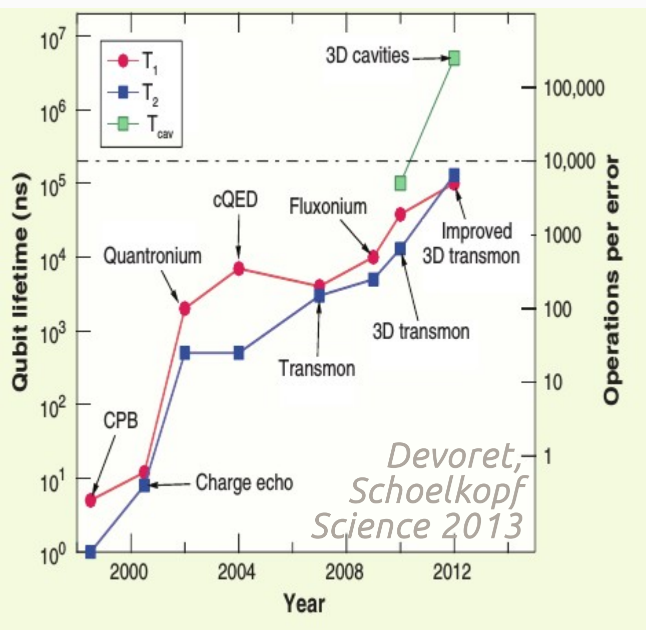


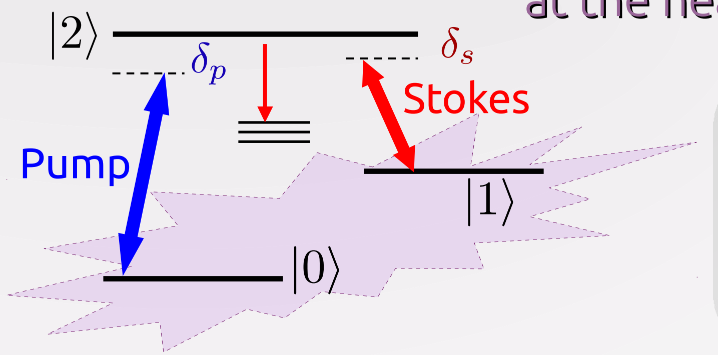
Devoret, Schoelkopf Science 2013

However

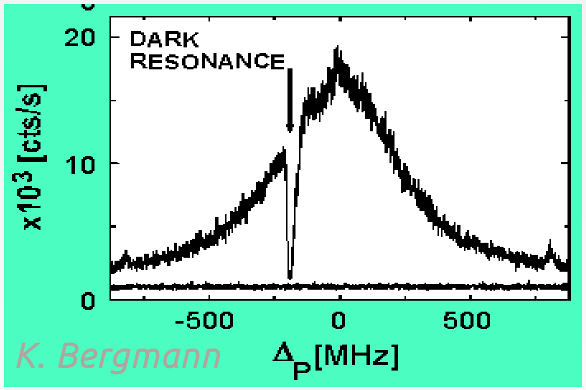
- combining advantages is **not trivial**
  tradeoff protection ↔ available control
- paradigmatic example: the **Lambda network**

why multilevel coherence in artifical atoms ?

at the heart of QM: interference and control of individual systems



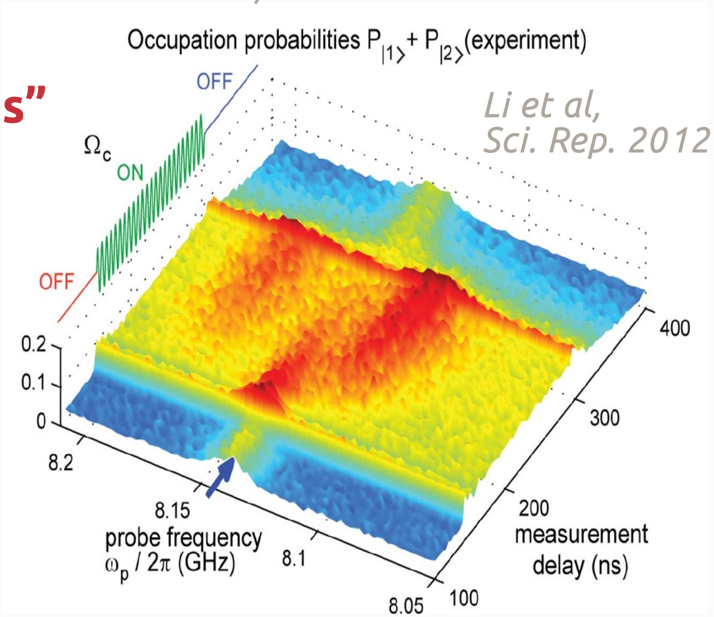
- in atomic physics ↔ **interference effects** in Λ network
  - Coherent Population Trapping
  - EIT, Autler Townes etc. *C. Cohen-Tannjoudi, Kosmos Revue 2009* *Scully and Zubairy, Quantum Optics 1997*



- **individual** atoms (EIT, STIRAP) *Bergmann Theuer Shore, RMP 1998* *Mücke et al., Nature 2010*
  - controlling light with light

- in solid-state **"artificial atoms"**
  - AT, EIT , quantum switch, Lasing & Cooling

  Review You-Nori,Nature 2011



- **motivation** – advanced control tools for q-networks & fault tolerant architectures
- **perspective** – highly integrated q-networks available → new applications/effects

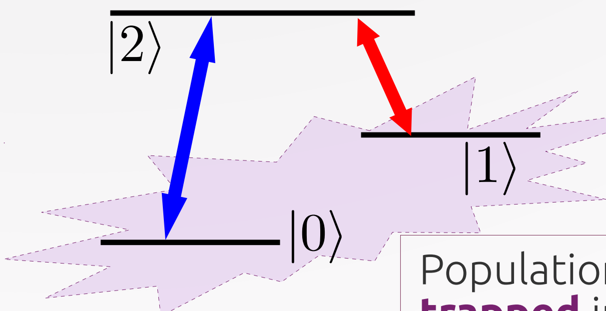
- Q-control & Q-optics in the solid state
  - not a mere translation of q-optics: **new elements** come into play → **2+1 STIRAP**
  - **new physical regimes/phenomena** in sold-state → **ultrastrong coupling**

Λ scheme, CPT and STIRAP

coherent population trapping → stimulated Raman adiabatic passage

$$H_{RWA} \equiv \begin{bmatrix} 0 & 0 & \frac{\Omega_p^*(t)}{2} \\ 0 & \delta & \frac{\Omega_s^*(t)}{2} \\ \frac{\Omega_p(t)}{2} & \frac{\Omega_s(t)}{2} & \delta_p \end{bmatrix}$$

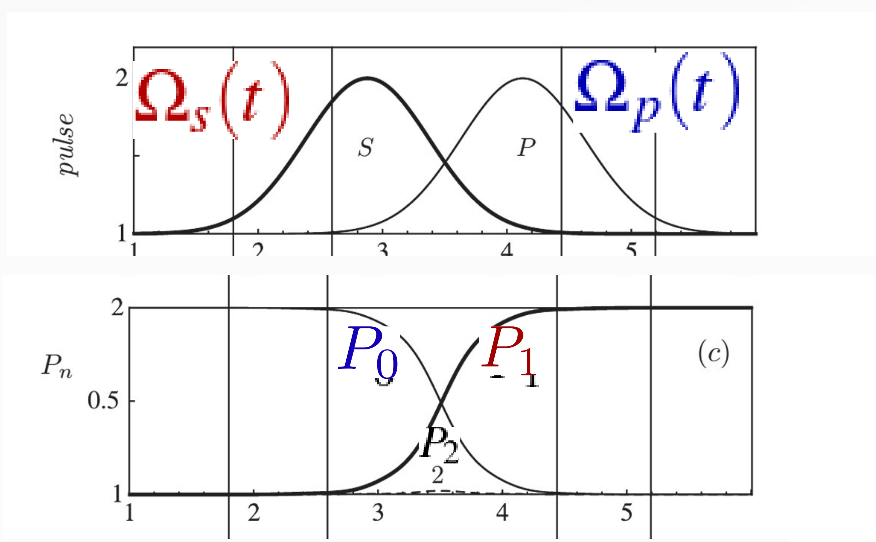
- technical tool: **3-LS RWA Hamiltonian**
  Vitanov et al., Adv. in At. Mol. and Opt. Phys. 2001
  - **Stokes** and **Pump** external AC driving fields
  - parameters: **Rabi frequencies** Ω_k and **detunings** δ_k
  - **two-photon detuning** $\delta = \delta_p - \delta_s$



- **@ two-photon** resonance

$\delta = 0$ → **Dark state** $|D\rangle = \dfrac{\Omega_s(t)|0\rangle - \Omega_p(t)|1\rangle}{\sqrt{|\Omega_s|^2 + |\Omega_p|^2}}$

Population **coherently trapped** in lowest doublet

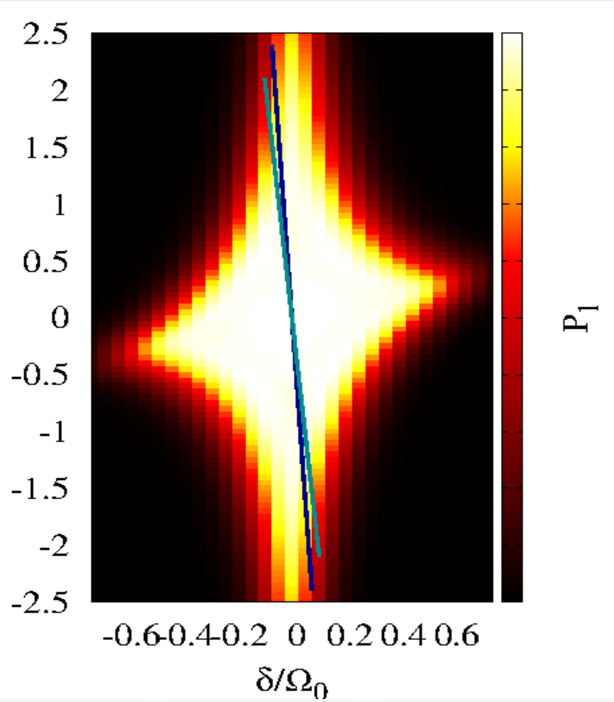


Counterintuitive sequence (first Stokes then pump)

STIRAP

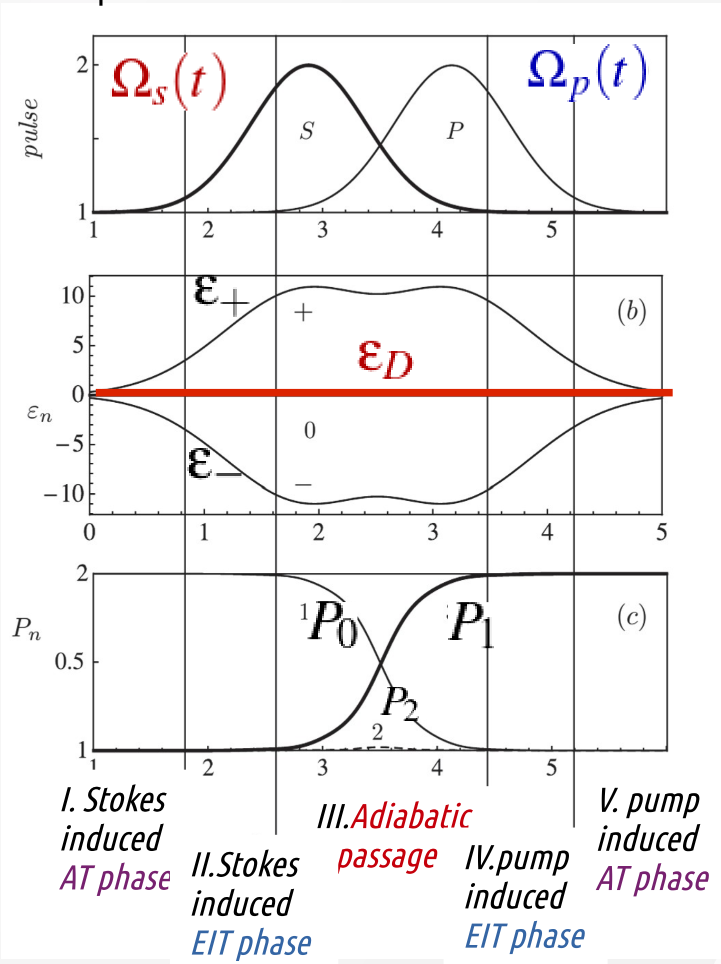
adiabatic following of the **dark state**
yields **complete population transfer** $|0\rangle \rightarrow |1\rangle$
while $|2\rangle$ remains always unoccupied

Bergmann Theuer Shore, RMP 1998
Vitanov et al., Adv. in At. Mol. and Opt. Phys. 2001



- **Coherence** guarantees **robustness** against imperfections in the control
- **Sensitivity** to **two-photon detunig** δ

- **several** 3-level interference phenomena involved

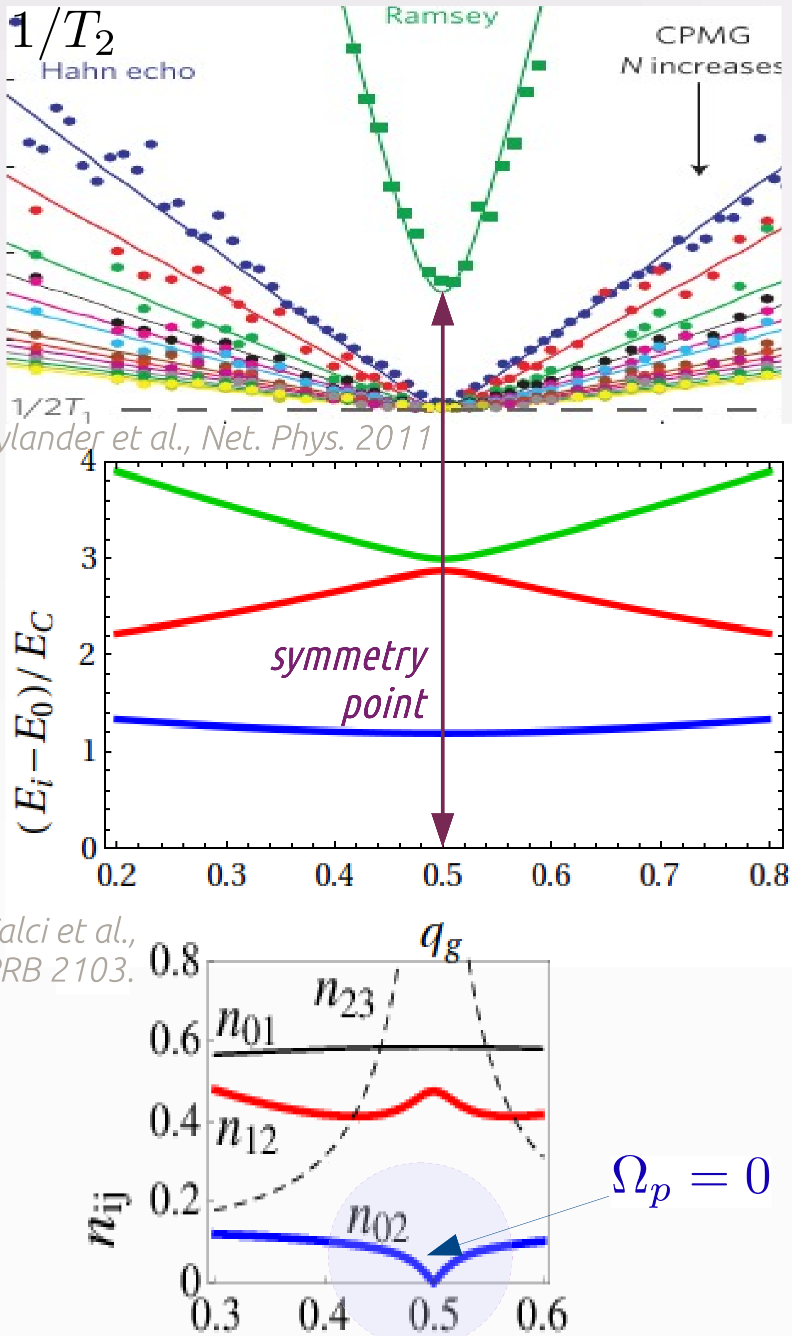


Vitanov et al., Adv. in At. Mol. Opt. Phys. 2001

Involves absorption-emission cycles → **building block** for processing in complex solid-state architectures

STIRAP **benchmark** for multilevel control In **artifical atoms**

Λ-STIRAP in artificial atoms ?



Bylander et al., Nat. Phys. 2011

Falci et al., PRB 2103.

- Λ-STIRAP **not yet observed** in artificial atoms

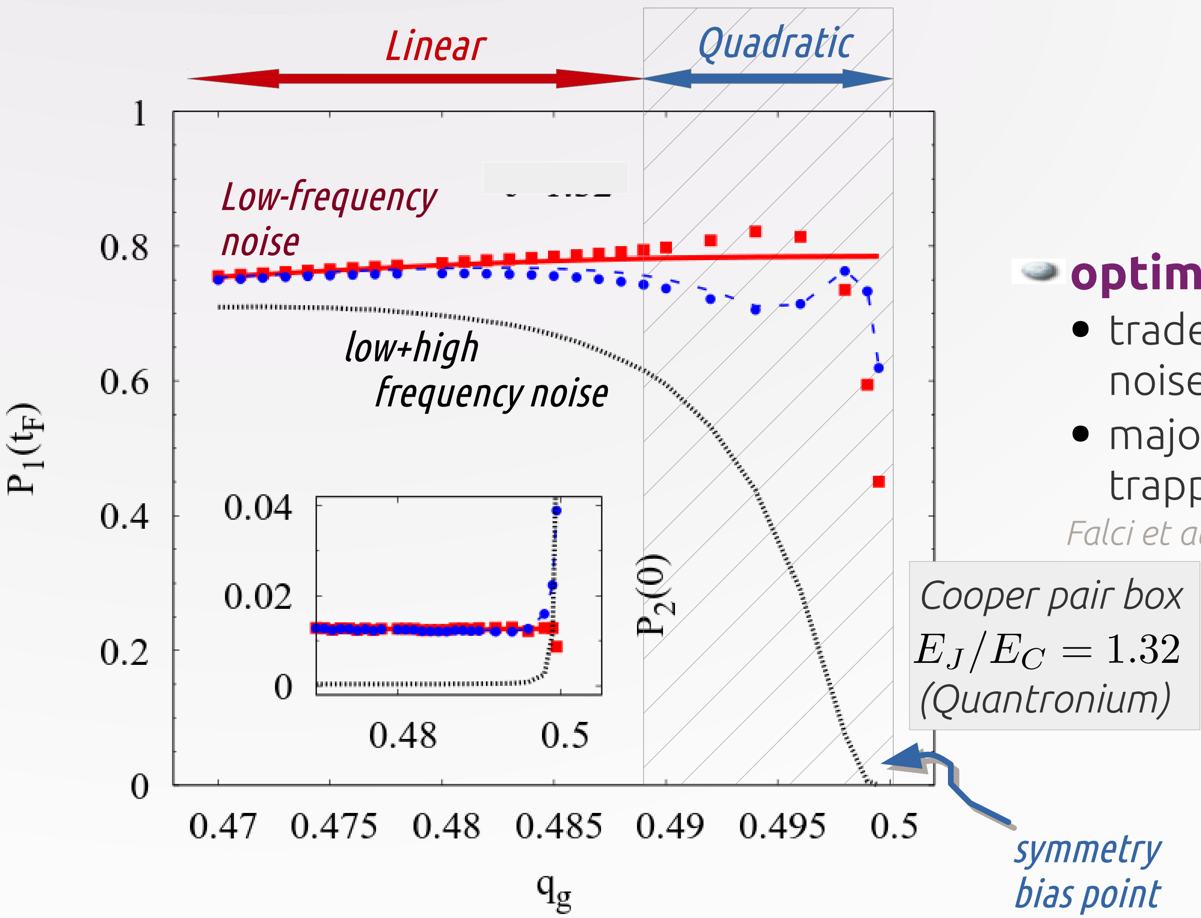
- **fundamental reason**
  - large decoherence times reqire **protection** against low-frequency noise
    Paladino, Galperin, Falci, Altshuler, RMP 2014
  - → design a device Hamiltonian with symmetries and work at **symmetry point.**
    Vion et al., Science 2002; Paladino et al., RMP 2014
  - ↔ **selection rules** limiting the control
    - in superconducting artificial atoms **parity symmetry cancels pump field**

    Liu et al., PRL 2005; Siewert Brandes Falci, Opt. Comm. 2006; You-Nori, Nature 2011; Falci et al., PRB 2103

- same physics for devices where symmetries hold approximately

Λ-STIRAP not yet observed in artificial atoms

possible ways out



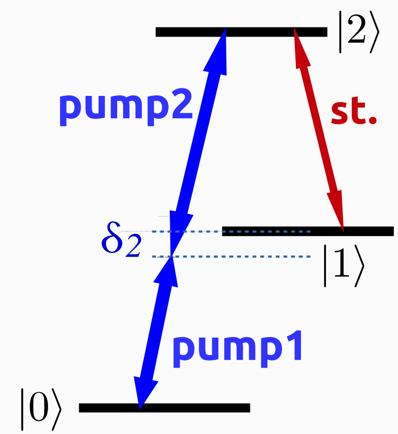
- breaking (parity) symmetry

  Liu et al., PRL 2005; Siewert, Brandes, Falci, Opt. Comm. 2006 & PRB 2009; You-Nori, Nature 2011;

- **optimal breaking** of (parity) symmetry
  - tradeoff between coupling and low-frequency noise → ~ 70% efficiency
  - major drawback is low-frequency noise in the trapped subspace

  Falci et al., PRB 2103

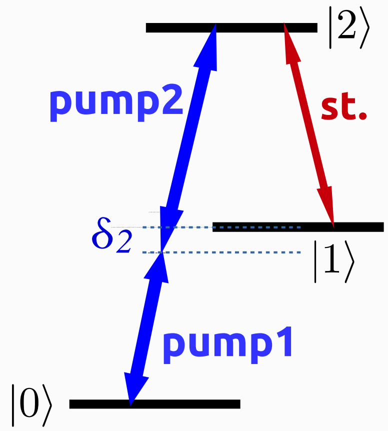
- **"2+1" Lambda scheme** operated at **symmetry**
  - Good in principle but known to yield poor efficency
  - Combine with **advanced control** allows to operate with **~100% efficiency** in high-quality devices **keeping high protection** against low-frequency noise.



Falci et al., Phys. Scr. 2102

Di Stefano et al., preprint 2015

2+1 Λ-STIRAP



Falci et al., Phys. Scr. 2102
Di Stefano et al., preprint 2015

2+1 Λ-STIRAP effective Hamiltonian

$$\mathrm{H}_3 = H_0 + \hat{\mathcal{Q}}\, A(t) \qquad A(t) = \mathcal{A}_s(t)\cos\phi_s(t) + \underbrace{\mathcal{A}_{p1}(t)\cos\phi_{p1}(t) + \mathcal{A}_{p2}(t)\cos\phi_{p2}(t)}_{\to two-photon\ pump\ pulse}$$

selection rules

$$\mathrm{H}_3 \equiv \begin{bmatrix} 0 & \mathcal{Q}_{01}A(t) & 0 \\ & \varepsilon_{10} & \mathcal{Q}_{12}A(t) \\ & & \varepsilon_{21} \end{bmatrix} \leftarrow \mathcal{Q}_{02} = 0$$

$\phi_k(t) = \omega_k t + \tilde{\phi}_k(t)$ for $k = p1, p2, s$

slowly varying

Goal: find H_3 **equivalent** to H_{RWA} of Λ scheme, $H_3 \to H_{eff} = H_{RWA}$

- Take effective resonance.................................... $\omega_{p1} + \omega_{p2} = \varepsilon_{20}$; $\omega_s = \varepsilon_{21}$
- Take **slightly detuned** pump frequencies...... $\omega_{p1} = \varepsilon_{10} - \delta_2$; $\omega_{p2} = \varepsilon_{21} + \delta_2$
  → ensuring the **dispersive** regime................. $\delta_2 \gg \mathcal{A}_{p1,p2}\mathcal{Q}_{ij} =: \Omega_{p1,p2}$

Effective Hamiltonian (by Magnus expansion with **quasi-resonant terms only**)

$$H_{eff} = [(\dot{\tilde{\phi}}_{p2} - \dot{\tilde{\phi}}_s) - (S_2 + 2S_1)]|1\rangle\langle 1| + (\dot{\tilde{\phi}}_{p2} + S_2 - S_1)|2\rangle\langle 2|$$
$$+ \tfrac{1}{2}\left[\left(\Omega_p|0\rangle\langle 2| + \Omega_s|1\rangle\langle 2|\right) + \text{h.c.}\right]$$

with **same structure** of desired H_{RWA}

$$\boxed{\Omega_p(t) = -\Omega_{p1}(t)\Omega_{p2}(t)/(2\delta_2)}$$

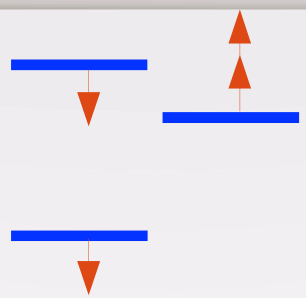
effective two-photon pump

$$\boxed{S_k(t) = -[\Omega_{pk}(t)]^2/(4\delta_2)}$$

dynamical Stark shifts

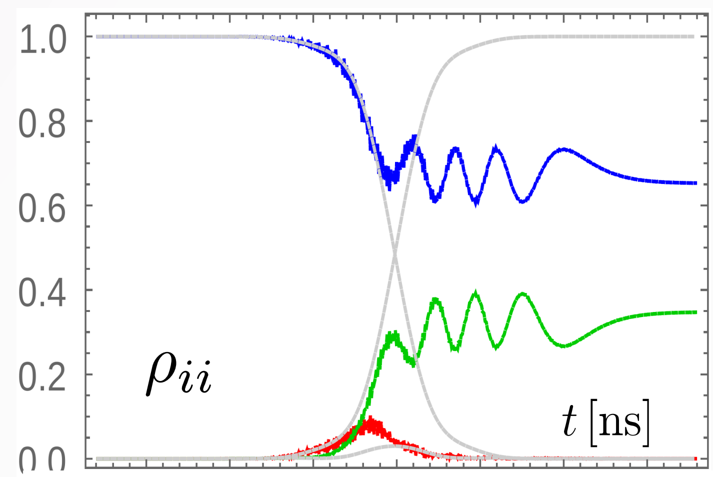
2+1 Λ-STIRAP

two-photon pump induced Stark shift



$$H_{eff} = [(\dot{\tilde{\phi}}_{p2} - \dot{\tilde{\phi}}_s) - (S_2 + 2S_1)]|1\rangle\langle 1| + (\dot{\tilde{\phi}}_{p2} + S_2 - S_1)|2\rangle\langle 2| + \frac{1}{2}\left[\left(\Omega_p|0\rangle\langle 2| + \Omega_s|1\rangle\langle 2|\right) + \text{h.c.}\right]$$

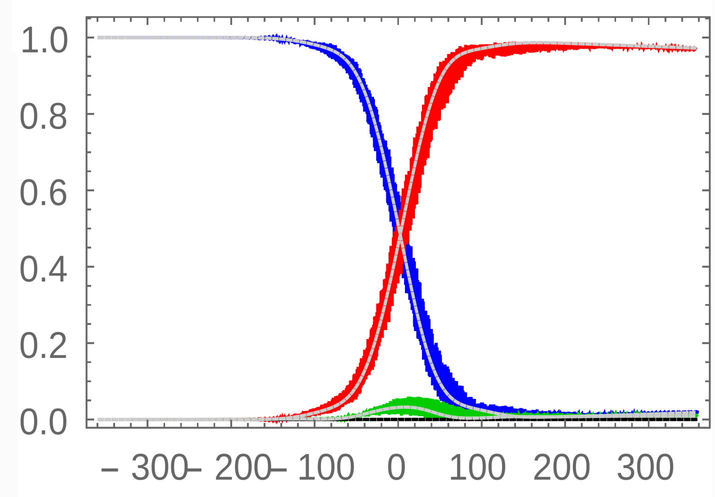
- the two-photon pump-induced **Stark shifts** yield a **stray two-photon detuning** spoiling STIRAP



- suitable **phase modulated control** cancels the effect of dynamically induced shifts

$$\dot{\tilde{\phi}}_{p2} = 0 \quad , \quad \dot{\tilde{\phi}}_{p2} = S_1 - S_2 \quad , \quad \dot{\tilde{\phi}}_s = -(S_1 + 2S_2)$$

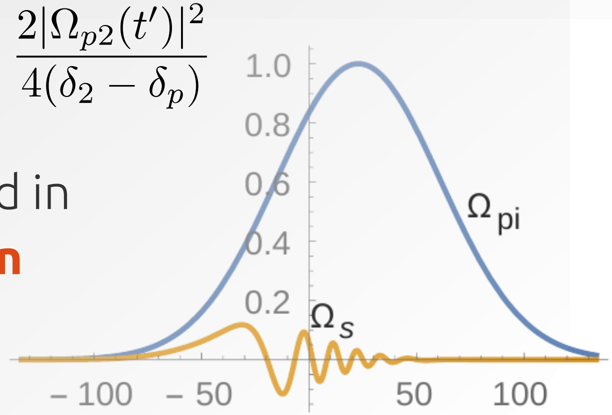
- **yielding 100% recovery of the efficiency**



- Phase modulation is **slowly varying** e.g.

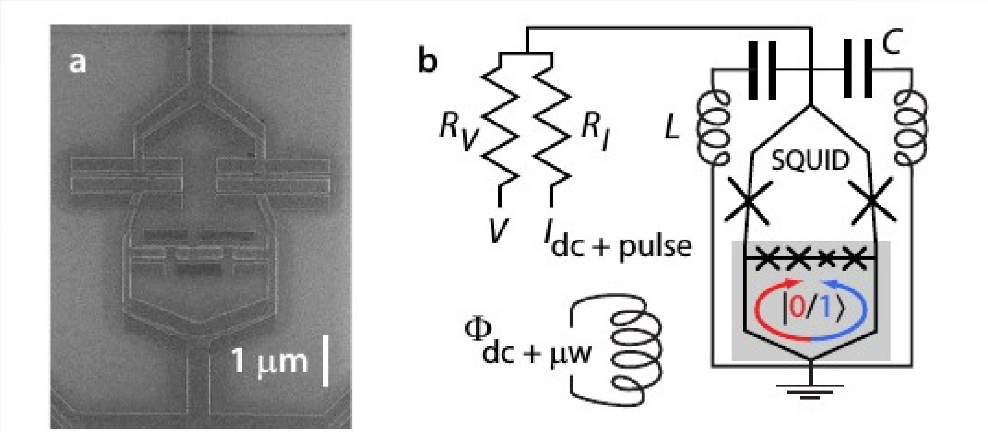
$$\tilde{\phi}_s(t) = \int_0^t dt' \frac{|\Omega_{p1}(t')|^2}{4\delta_2} + \frac{2|\Omega_{p2}(t')|^2}{4(\delta_2 - \delta_p)}$$

and easily implemented in the **microwave domain**

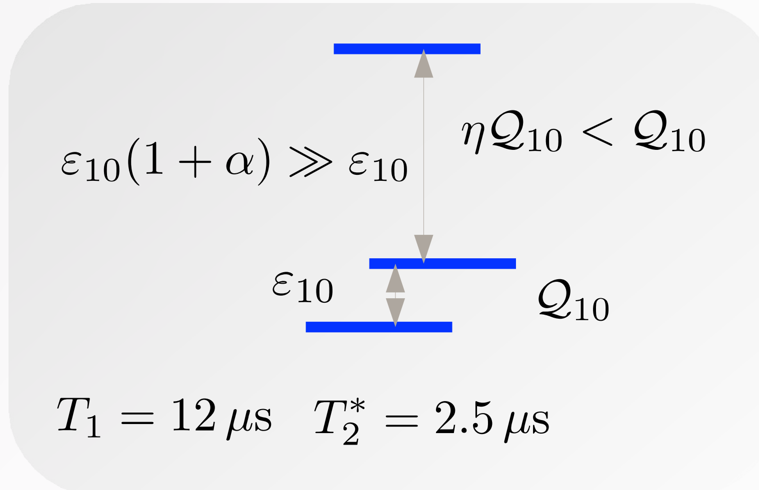


2+1 STIRAP in highly anharmonic qutrits

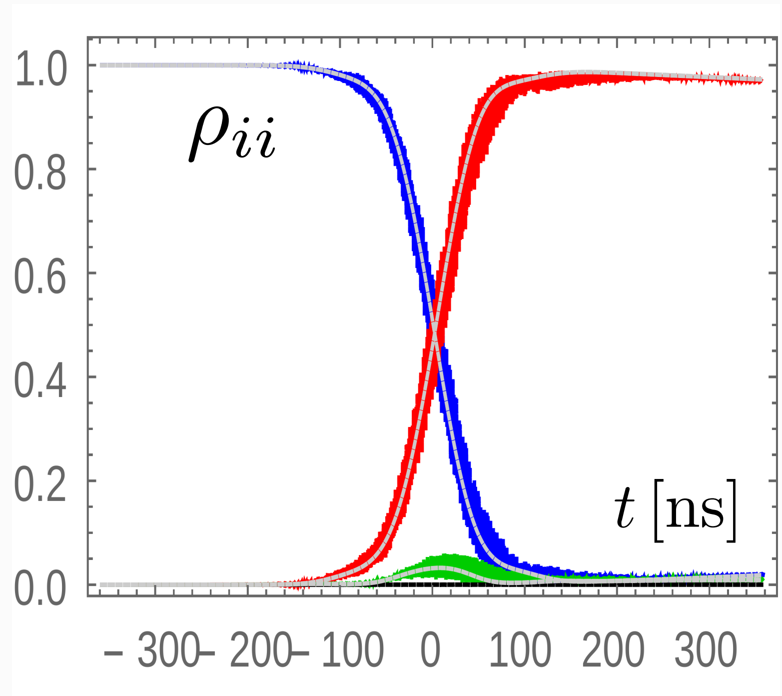
flux-based superconducting artificial atoms



Bylander et al., Net. Phys. 2011



- 6-level simulation → no leakage
- Includes effects of **decoherence**
  - High-freq. noise by Lindblad eqs. → few percent loss
  - Low-freq. noise in quasistatic approx. → irrelevant

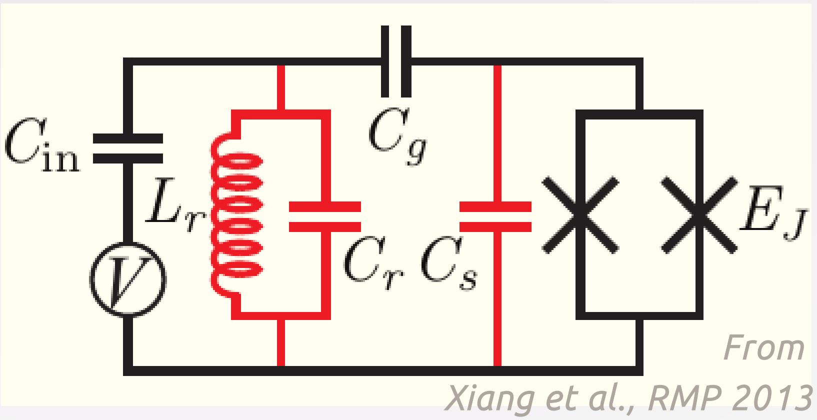


- **Large transfer efficiency** can be demonstrated in **in high quality devices**
- **remarkable agreement** with 3-level effective H by Magnus expansion.

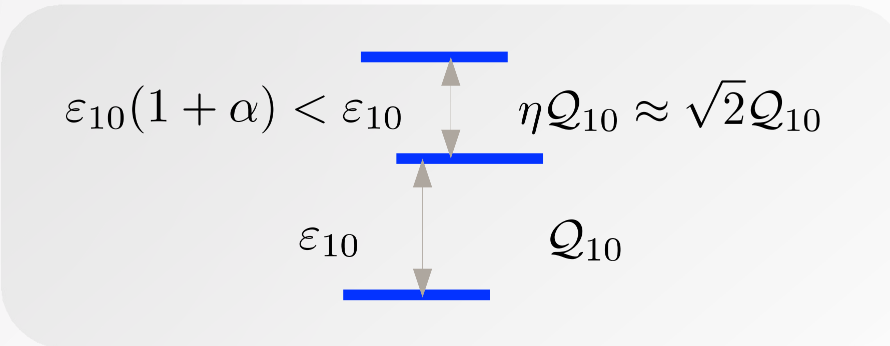
- Applications to Q-networks requiring larger field strength **→ Bloch-Siegert shifts** compensated by the same recipe

2+1 STIRAP in ~ harmonic qutrits

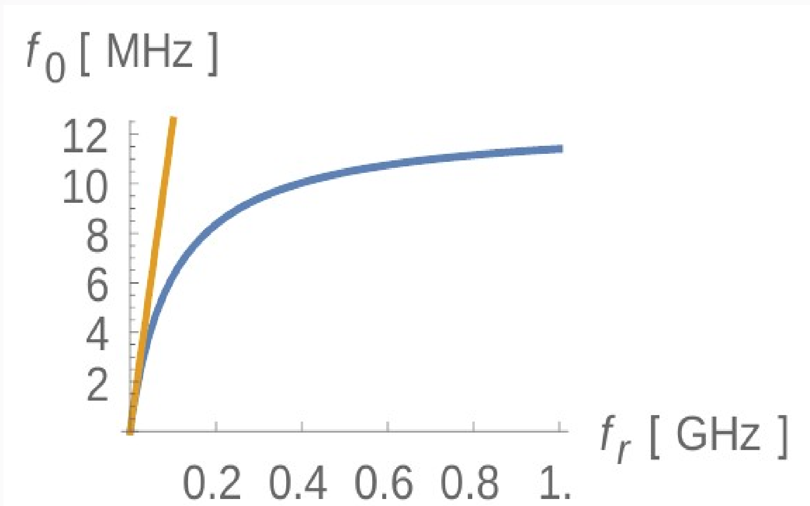
superconducting artificial atoms in transmon design



From Xiang et al., RMP 2013



- design yielding the **largest decoherence times** so far: up to $T_1 = 70\,\mu\mathrm{s}$ decay-limited
- small anharmonicity → **off-resonant terms** of the pump drives become relevant for the effective Hamiltonian



$$\Omega_p(t) = -\frac{\Omega_{p1}\Omega_{p2}}{2\delta_2}\,\frac{\alpha\varepsilon_{10}}{\alpha\varepsilon_{10}+\delta_2}$$

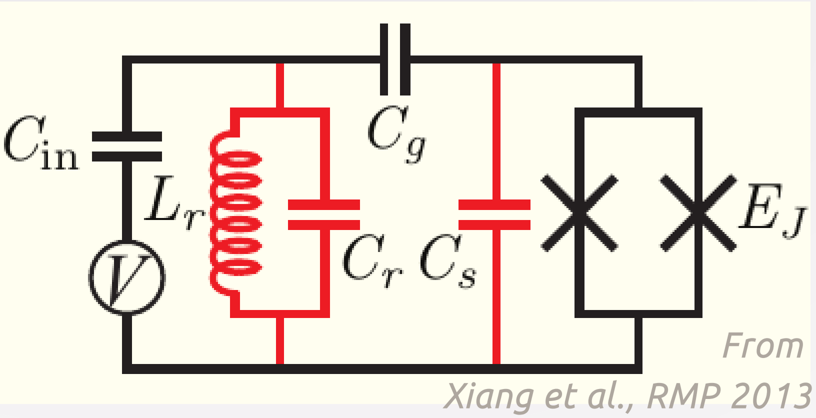
saturating effective two-photon pump

$$S_{ij}^k(t) := \left|\frac{A_{pk}(t)\mathcal{Q}_{ij}}{2}\right|^2\left(\frac{1}{\varepsilon_{ij}-\omega_{pk}}+\frac{1}{\varepsilon_{ij}+\omega_{pk}}\right)$$

dynamical Stark shift of splitting *ij* due to pump field *k*

2+1 STIRAP in ~ harmonic qutrits

superconducting artificial atoms in transmon design



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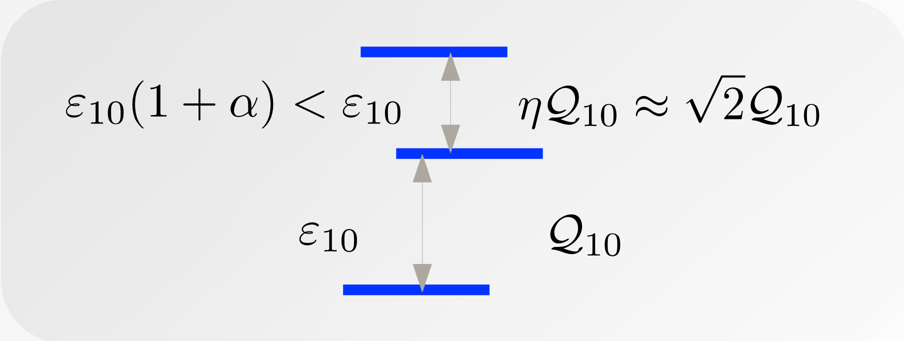

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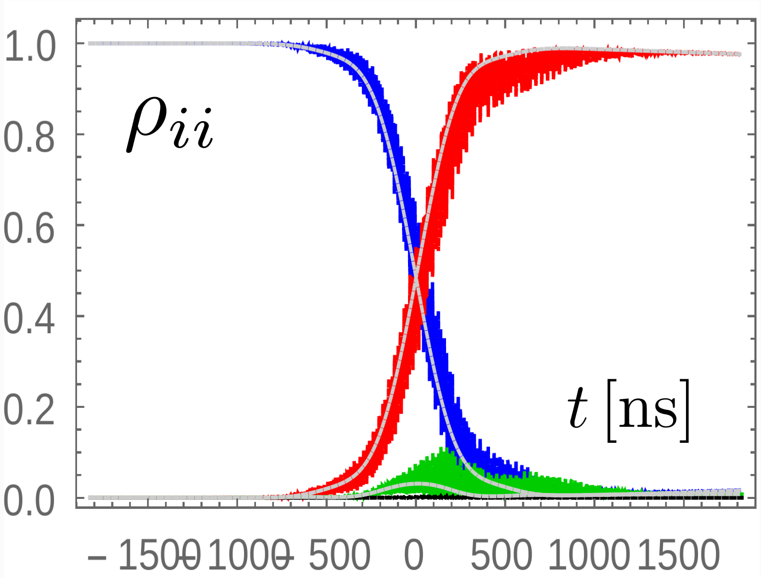
- small anharmonicity → **off-resonant terms** of the pump drives become relevant for the effective Hamiltonian
  - again suitable **phase modulation control** cancels dynamical shifts

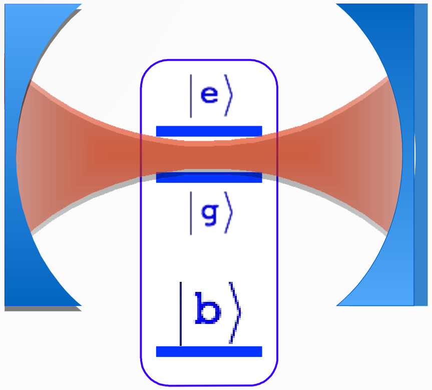
$$\dot{\tilde{\phi}}_{p2} = \sum_{k,j} (S^k_{j0} - S^k_{j2}) \;,\; \dot{\tilde{\phi}}_s = \sum_{k,j} (S^k_{j1} - S^k_{j2})$$

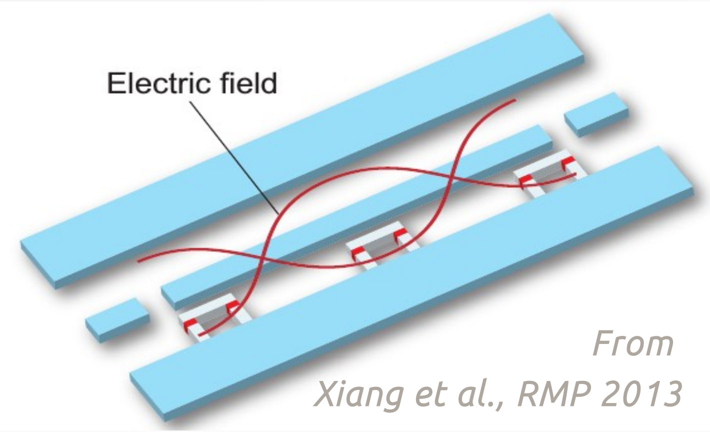
yielding ~100% efficiency

  - large decoherence times allow more complicated multiple cycle control protocols

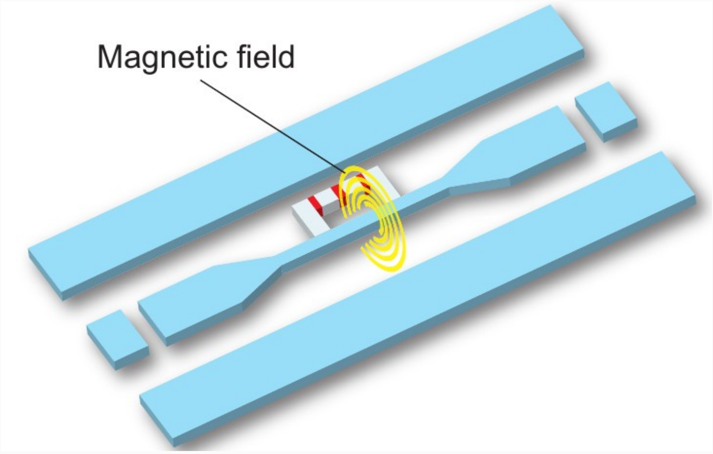


detection of ultrastrong coupling

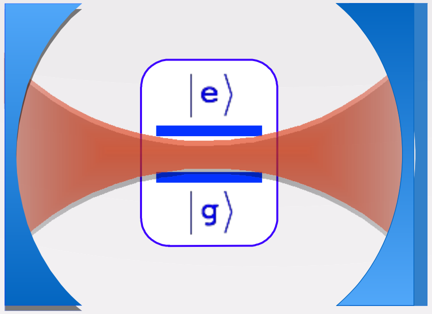




From
Xiang et al., RMP 2013



ultrastrong coupling in Rabi Hamiltonian

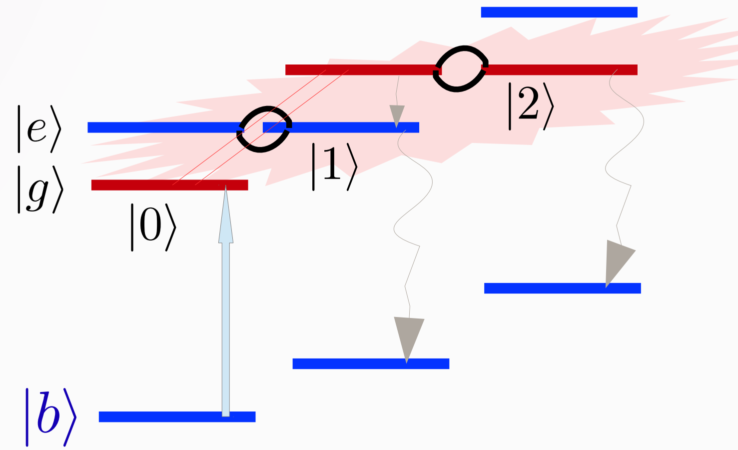


- Rabi Hamiltonian **beyond JC** $g \sim \omega_c$

$$\mathrm{H}_{R2} = \varepsilon\,|e\rangle\langle e| + \omega_c\, a^\dagger a + g\,\left[\left(a^\dagger|g\rangle\langle e| + a|g\rangle\langle e|\right) + \mathrm{h.c.}\right]$$

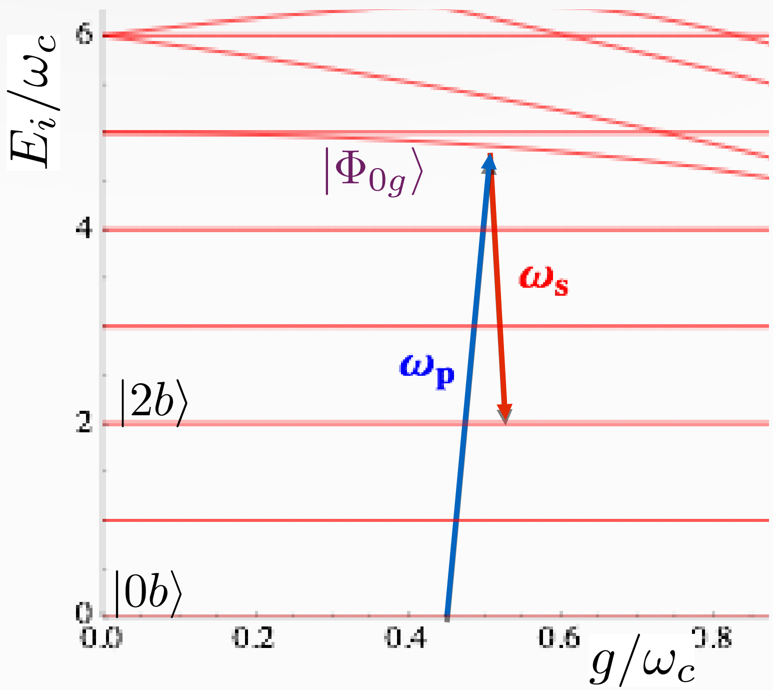
- **Eigenstates** conserving **only** parity of number of excitations

$$|\Phi_j\rangle = \sum_n c_{j\,n}|n\,g\rangle + d_{j,n}|n,e\rangle$$



- ground state **contains photons**

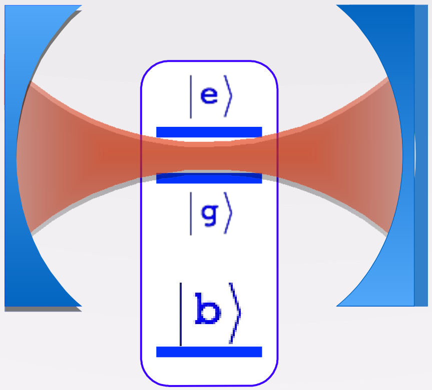
$$|0g\rangle \rightarrow \quad |\Phi_0\rangle \overset{g\ll\omega_c}{\approx} c_{00}|0g\rangle + c_{02}|2g\rangle + d_{01}|1e\rangle$$



- **Spectroscopic detection**
  - in flux qutrits $g \sim 0.1\,\omega_c$ *Niemczyk et al., Nat. Phys. 2010*
  - In semiconductor q-wells $g \sim 0.48\,\omega_c$ *Todorov et al., PRL 2010*

- Detection using **decay to a third atomic level** $|b\rangle$ of the false vacuum $|\Phi_0\rangle$
  - Theoretical proposal *R. Stassi et al., PRL 2013*
    but very small probability $\sim |c_{02}|^2$
  - Here: **amplify** the output signal **by coherence**

coherent amplification of the ultrastrong coupling channel



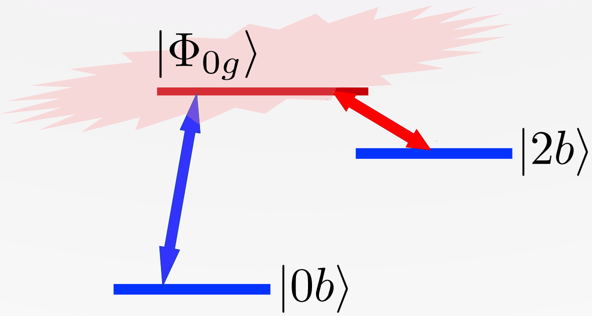
- Hamiltonian with **additional level** $|b\rangle$

$$H = -\varepsilon_b |b\rangle\langle b| + H_{R2} + H_c(t)$$

- Two-tone control detuned from the e-g transition

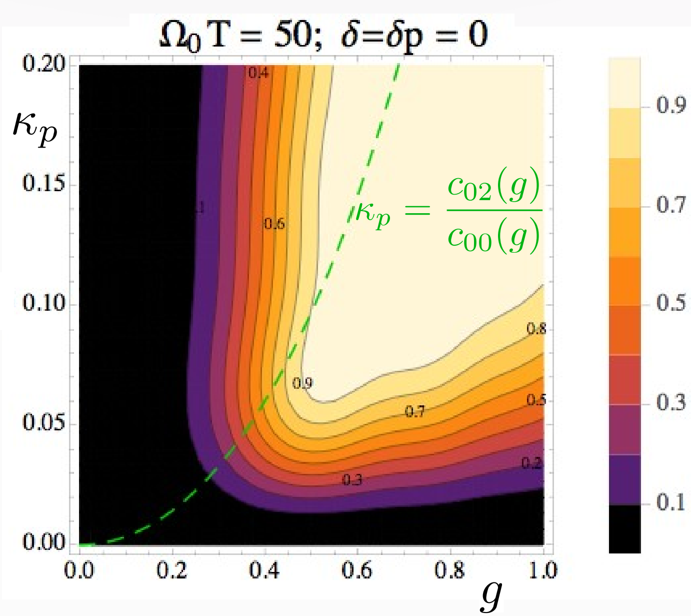
$$H_c = W(t)\,(|b\rangle\langle g| + \text{h.c.}) = W(t) \sum_{nj} |nb\rangle\langle\Phi_j|$$

$$W(t) = \Omega_0 \mathcal{F}(t+\tau)\,\cos\phi_s(t) + \kappa_p \Omega_0 \mathcal{F}(t-\tau)\,\cos\phi_p(t)$$



- 3 level truncation and STIRAP

$$H_3 = \begin{bmatrix} 0 & 0 & c_{00}W(t) \\ 0 & 2\omega_0 & c_{02}W(t) \\ c_{00}W(t) & c_{02}W(t) & E_0 \end{bmatrix}$$



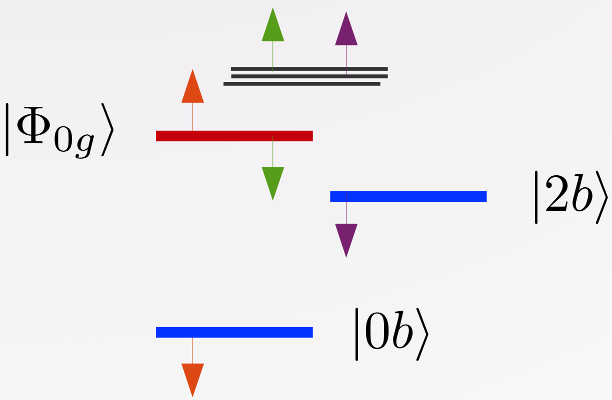
- two photon component in the ground state $c_{02} \neq 0$
  implies **faithful and selective** population transfer $\to |2b\rangle$

  → "smoking gun" of **ultrastrong coupling**

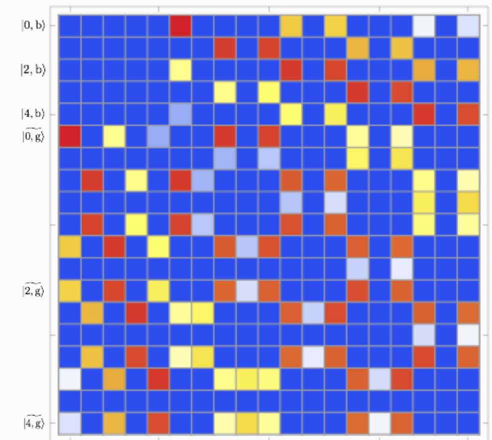
- optimal attenuation $\kappa_p = c_{02}(g)/c_{00}(g)$

- small c_{02} → **large Stokes** needed
  - huge Stark shifts at the 3LS truncation

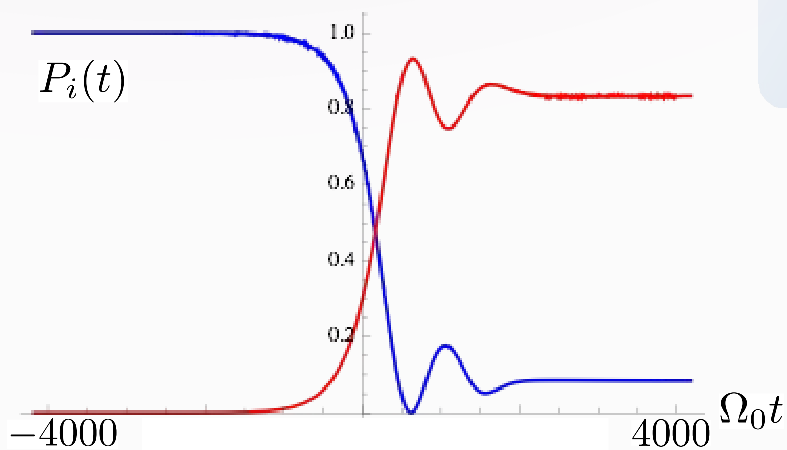
$$H_3 = \begin{bmatrix} 0 & 0 & c_{00}W(t) \\ 0 & 2\omega_0 & c_{02}W(t) \\ c_{00}W(t) & c_{02}W(t) & E_0 \end{bmatrix}$$



- Stray g↔e couplings to the field

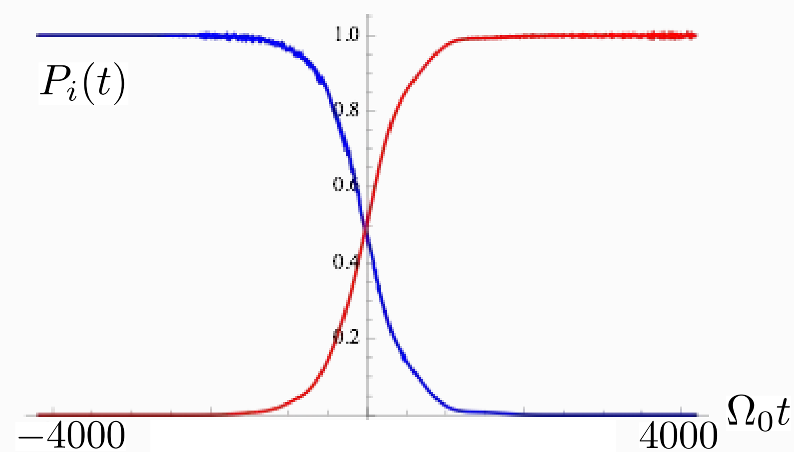


- **partly autocompensated** by multilevel structure



g=0.2ω_c; Ω_0=0.1ω_c; κ_p=0.01436; T=20/($\kappa_p\Omega_0$); Ω_0T=1393.11

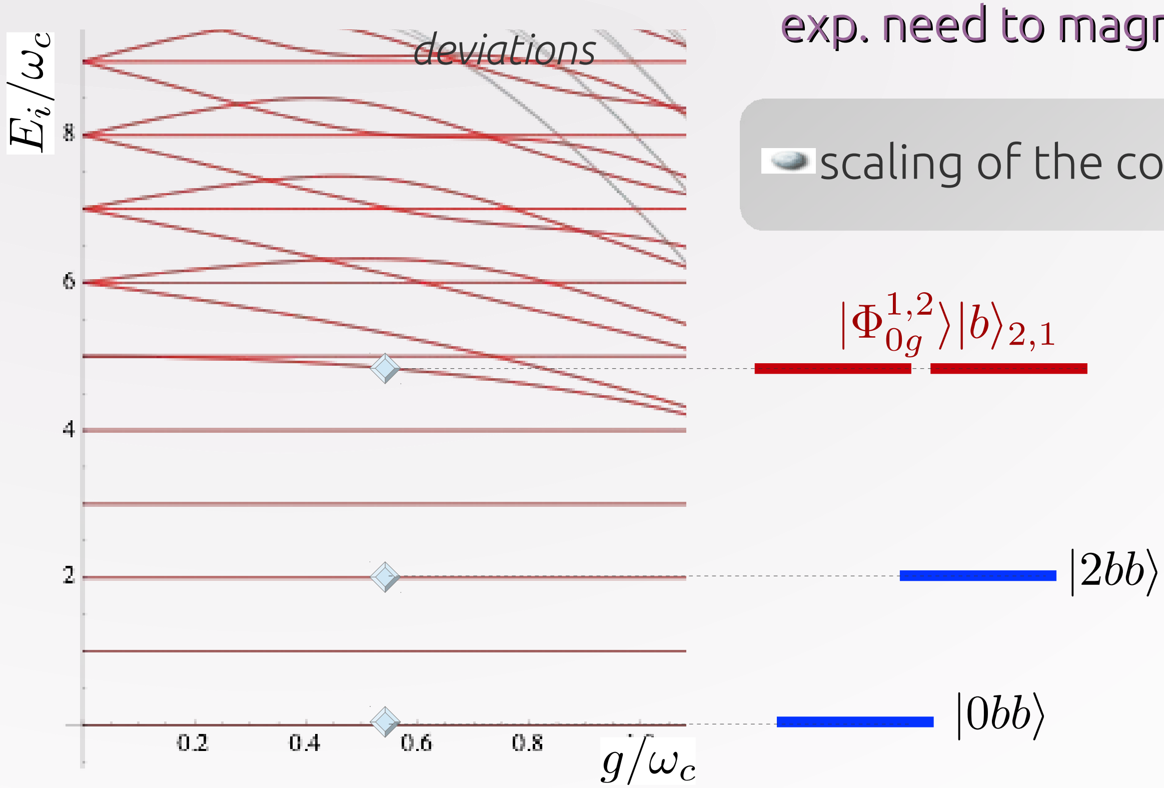
- **Totally compensated** by phase modulation (3LS) or by wistle (multilevel)



many coupled atoms

exp. need to magnify coupling to cavity → ultrastrong limit

- scaling of the coupling constant $g \to \sqrt{N}\, g$



- STIRAP via **two** intermediate levels

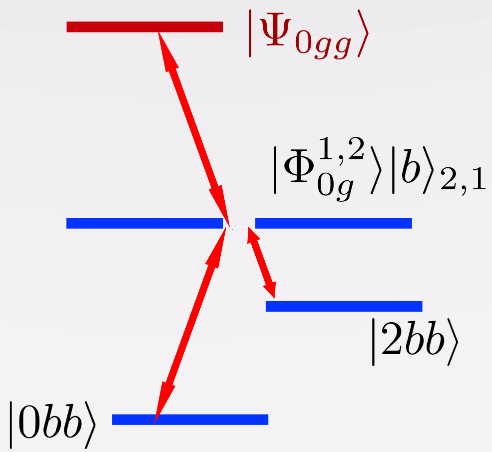
$$H_4 = \begin{bmatrix} 0 & 0 & c_{00}W & c_{00}W \\ 0 & 2\omega_0 & c_{02}W & c_{02}W \\ c_{00}W & c_{02}W & E_{0gb} & 0 \\ c_{00}W & c_{02}W & 0 & E_{0bg} \end{bmatrix}$$

- and of STIRAP → effective c_{02} **increases**

$$\begin{bmatrix} \mathbb{1} & 0 \\ 0 & \mathbb{H} \end{bmatrix} H_4 \begin{bmatrix} \mathbb{1} & 0 \\ 0 & \mathbb{H} \end{bmatrix} = \begin{bmatrix} 0 & 0 & \sqrt{2}\, c_{00}W & 0 \\ 0 & 2\omega_0 & \sqrt{2}\, c_{02}W & 0 \\ \sqrt{2}\, c_{00}W & \sqrt{2}\, c_{02}W & E_0 & 0 \\ 0 & 0 & 0 & E_0 \end{bmatrix}$$

Hadamard transform

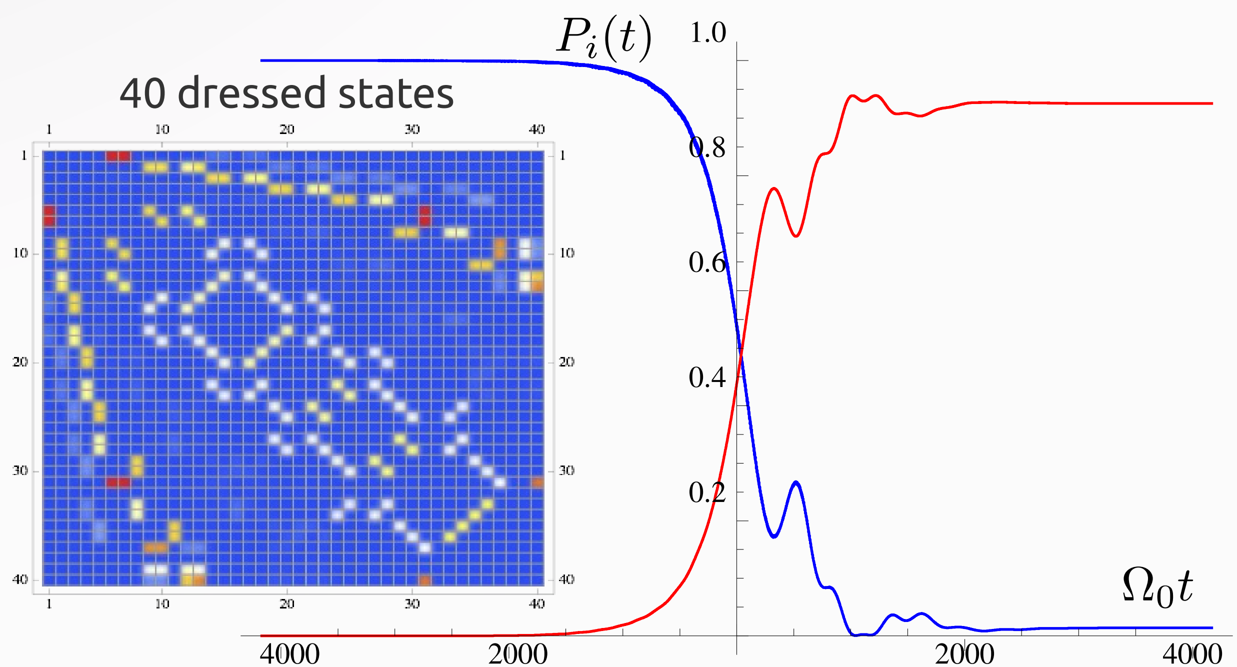
- STIRAP via a **Bell-like virtual state** $|\Phi^1_{0g}\rangle|b\rangle_2 + |\Phi^2_{0g}\rangle|b\rangle_1/\sqrt{2}$



- not trivial generalization because of stray ~resonant processes
  - pump-induced **two-photon ladder transition**
    - → tripod configuration, spoiling population transfer
    - ↔ **detune** transition by $\delta_p \neq 0$
- 5LS approx: Stark shifts compensated by phase modulation

- **many dressed states**
  - autodetune ladder transition
  - autocompensate Stark shifts

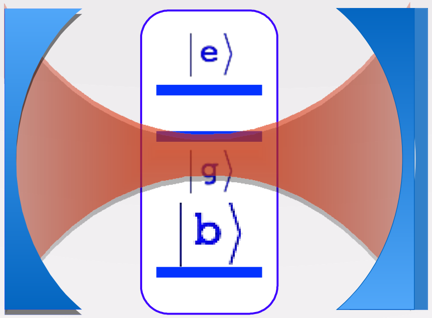
remarkably
92% efficiency
with no compensation



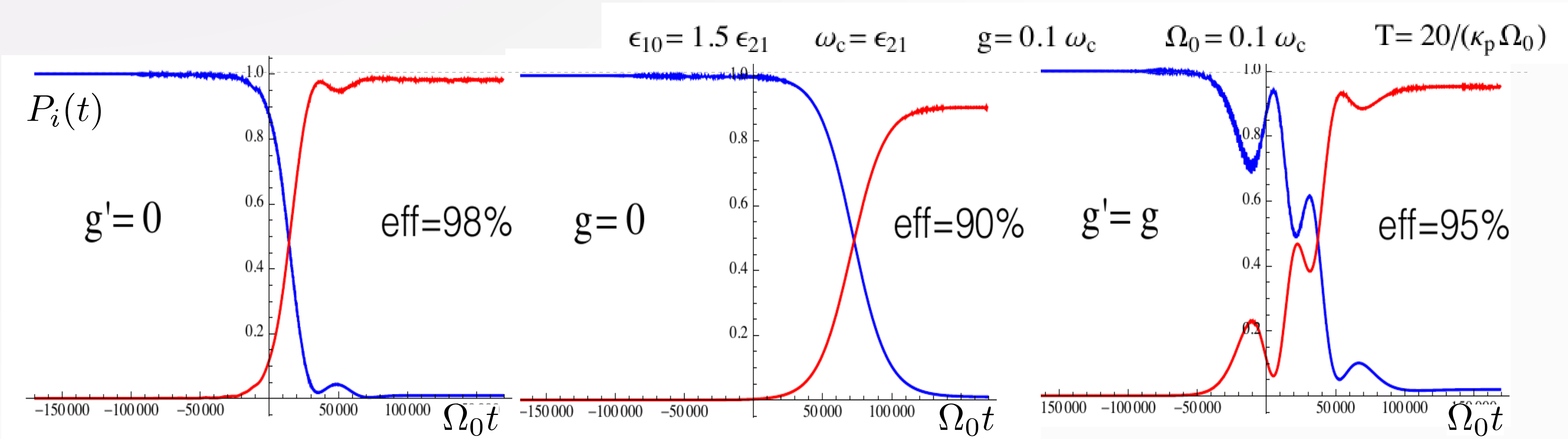
g=0.2ω_c; Ω_0=0.1ω_c; T=20/(κ_p*Ω_0);

implementation in superconducting artificial atoms

unfavorable characteristics of the spectra

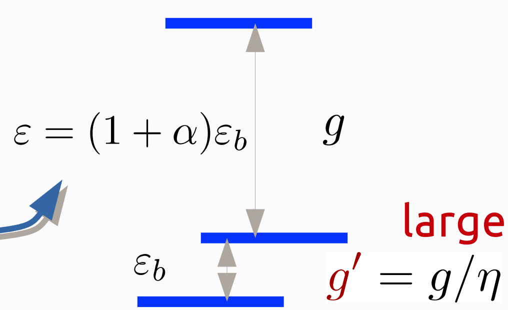


- design implies extra **stray b↔g coupling** with the cavity
  - opens a **new JC channel** for the $|0b\rangle \to |2b\rangle$ process



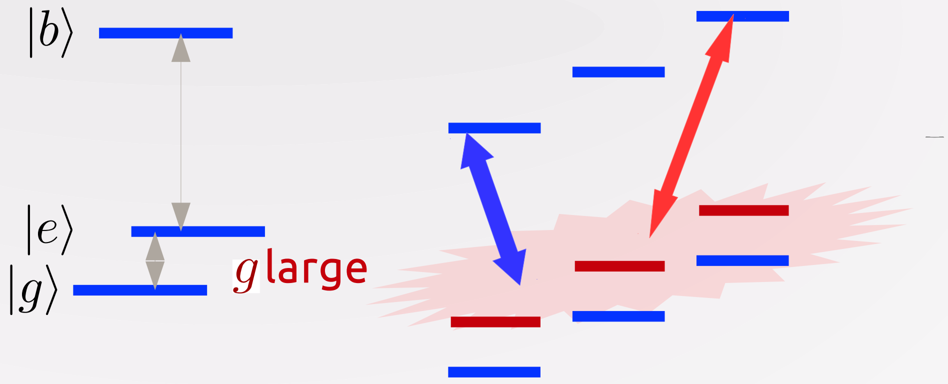
- For "smoking gun" detection **we need**
  - suppression of new channel ← only if $\dfrac{g}{\varepsilon} \lesssim 0.1\,\eta^2\,|\alpha|\dfrac{2+\alpha}{1+\alpha}$
  - **AND** strong coupling ← $g/\varepsilon \gtrsim 0.1$

- **never met** in superc. high-quality artificial atoms
  - Highy anharmonic (flux) – large α but too small η
  - Nearly harmonic (transmon) large η but α too small



way out: the Vee scheme

implementation in flux superconducting qutrits

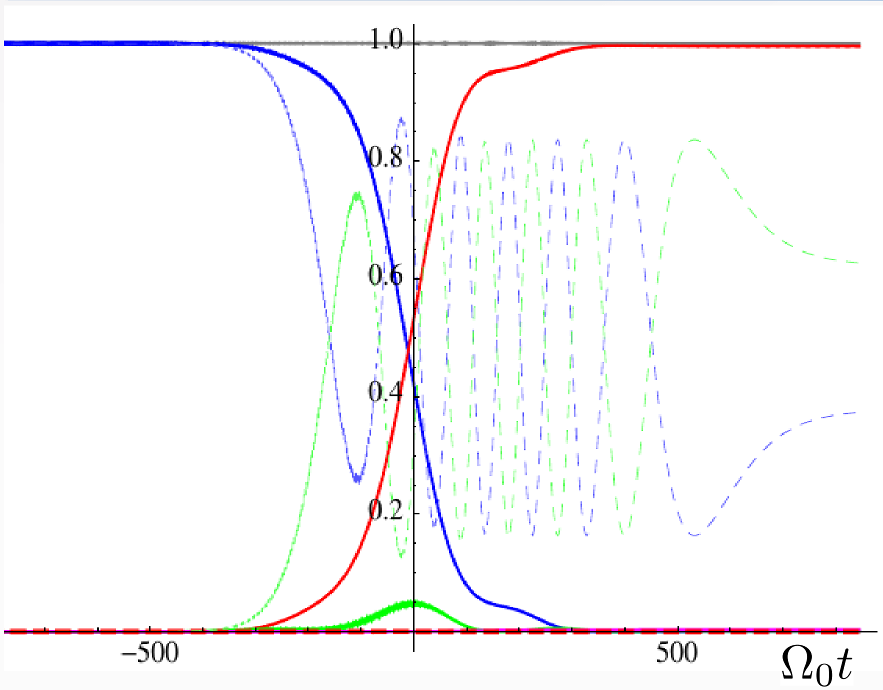


- use the **large lowest doublet coupling** in flux qutrits to couple to the cavity

→ **VEE scheme** via intermediate state

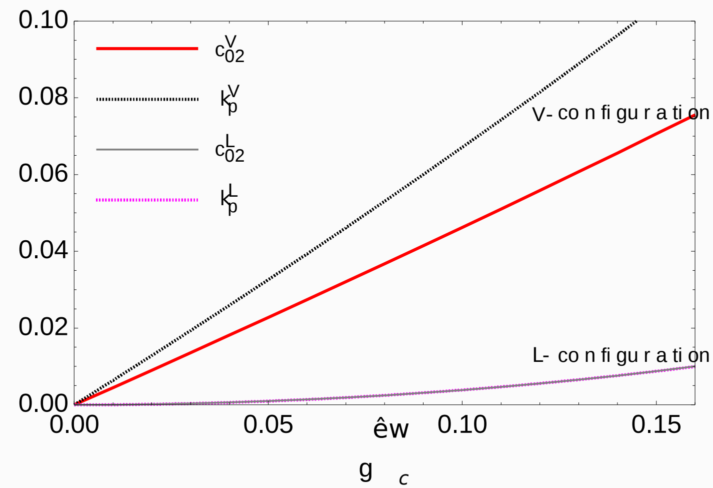
$$|\Phi_1^{\pm}\rangle \approx d_{10}|0e\rangle \pm c_{11}|1g\rangle + d_{12}|2e\rangle$$

- population transfer → a **smoking gun** for ultrastrong coupling



- Larger couplings a priori available

$d_{12} \sim 2\, c_{02}$



- limited only by qutrit decay γ_b besides cavity decoherence

- **multilevel coherence v**in artificial atoms may allow quantum control in highly integrated Q-networks

- **benchmarked by STIRAP**

  - not a mere translation of q-optics: **new elements** come into play
    - symmetries & **tradeoff** between efficient control and protection from noise *Falci et al., PRB 2103*
    - **Phase modulated** control in the microwave regime allows to operate **Λ-STIRAP in highly symmetry-protected superconducting artificial atoms**
      Di Stefano et al., preprint 2015

  - **new physical phenomena**/regimes in sold-state
    - "smoking gun" detection of **ultrastrong coupling by coherent amplification** of the $|0b\rangle \to |2b\rangle$ channel
      Ridolfo et al., preprint 2015

… cento di questi giorni, Boris !