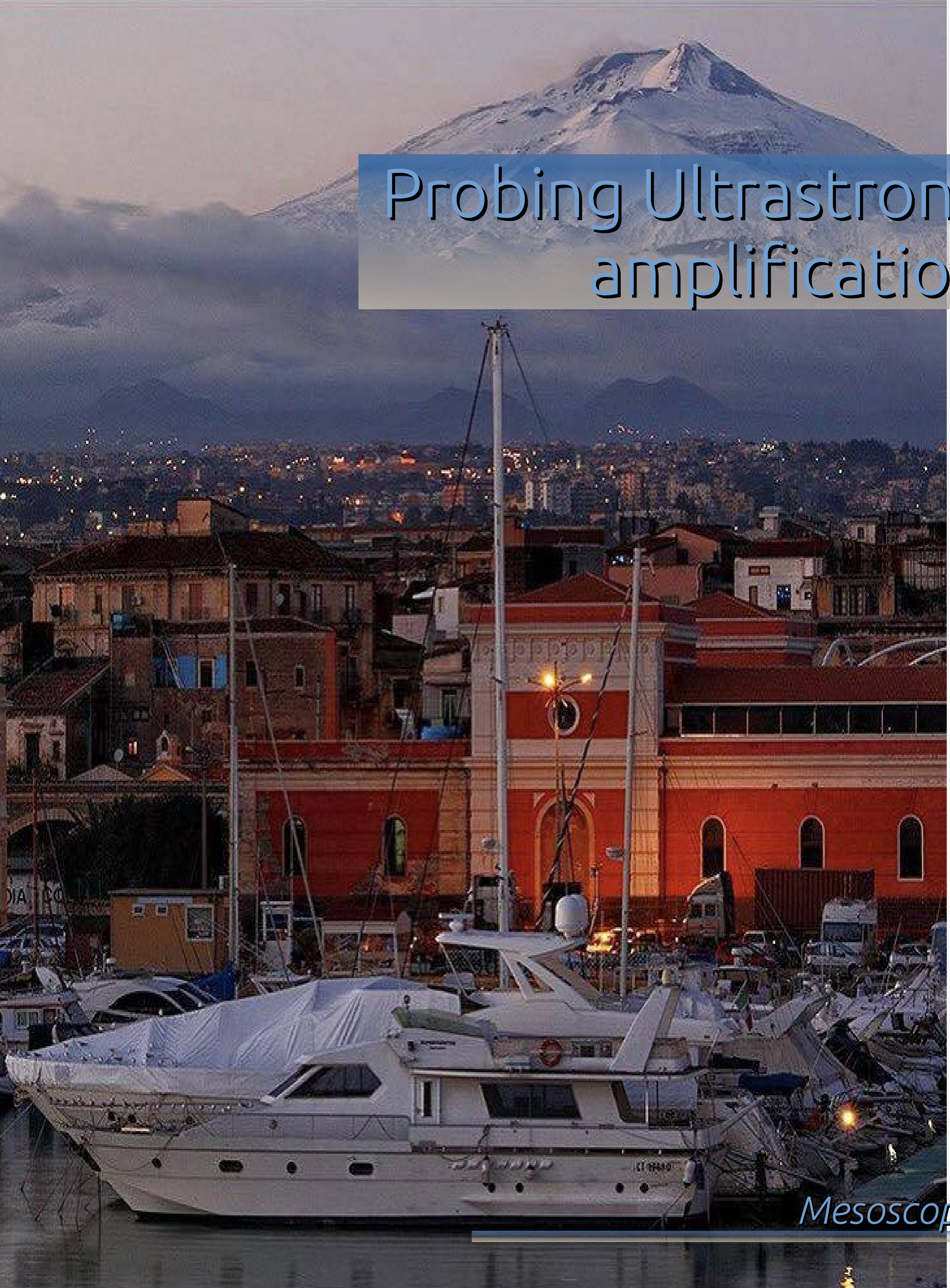

Probing Ultrastrong Coupling by coherent amplification of population transfer

Giuseppe Falci

with E. Paladino, A. Ridolfo, P.G. Di Stefano

Università di Catania
Dipartimento di Fisica e Astronomia

IMM
Istituto per la Microelettronica e Microsistemi

INFN Istituto Nazionale di Fisica Nucleare

Centro Siciliano di Fisica Nucleare e Struttura della Materia

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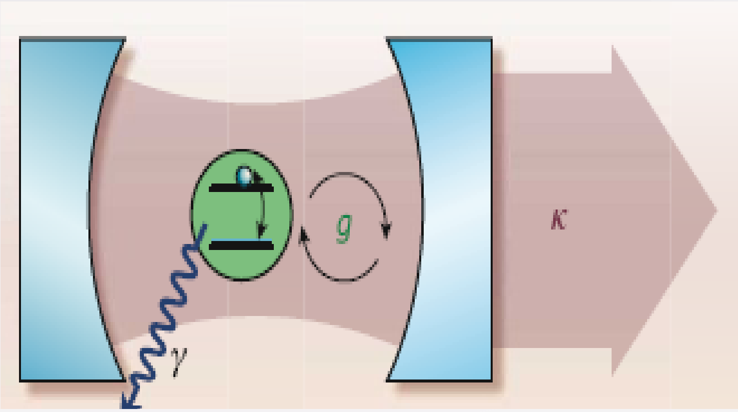
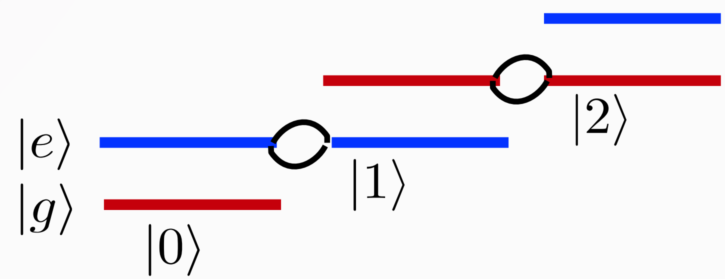
Rabi model



- **Two-level atom** + single **em. cavity mode**

I.I Rabi ,PRB 49, 324 (1936)

$$H_{Rabi} = \varepsilon\, \sigma_+ \sigma_- + \hbar\omega_c\, a^\dagger a + g\,(a\sigma_+ + a^\dagger \sigma_-) + g_c\,(a^\dagger \sigma_+ + a\sigma_-)$$



- atom-oscillator coupling is **coherent**
  → **"strong" coupling regime** $\gamma, \kappa \ll g$

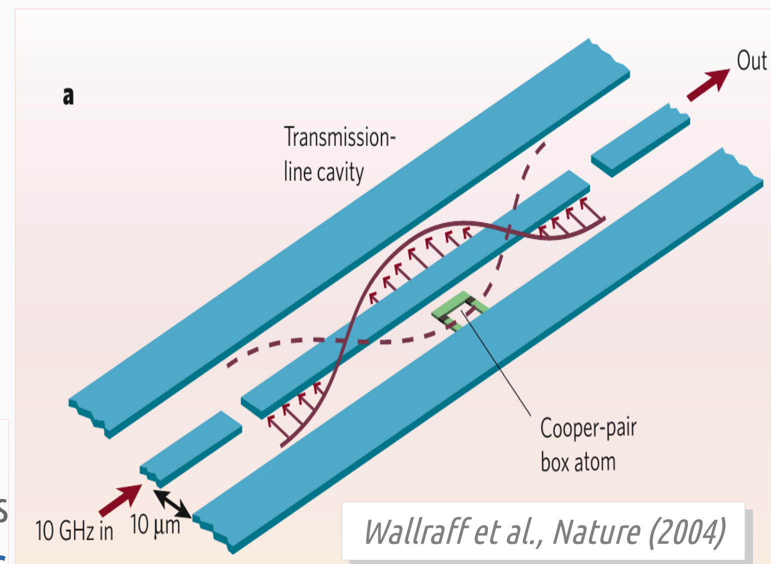
- usually also $g \ll \Omega, \omega_c$ → **RWA**

Jaynes-Cummings model *JC, Proc. IEEE 51, 89–109 (1963)*

- **Eigenstates: entangled doublets** $|\phi_{n\pm}\rangle = \frac{|n+1\,e\rangle \pm |n-1\,g\rangle}{\sqrt{2}}$
  conserving the number of excitations
  factorized ground state $|0\,g\rangle$

- exchanges single quanta atom ↔ cavity mode
  basic building block of several architectures
  for **quantum state processing**

$g \sim 10^{-4}\omega_c$ in natural atoms
$g \sim 10^{-2}\omega_c$ in AAs

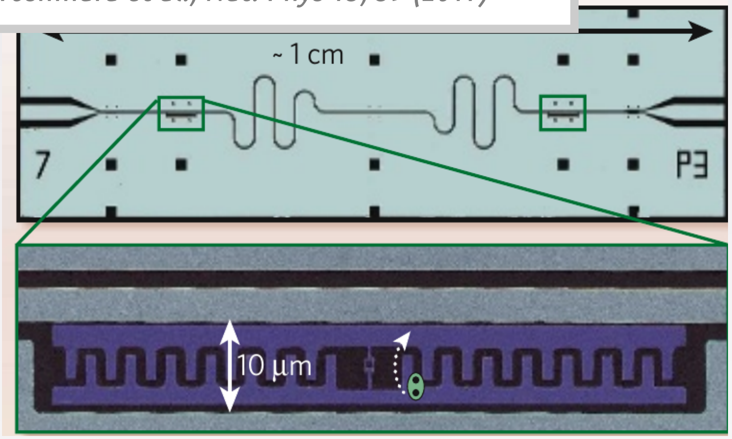


Wallraff et al., Nature (2004)

ultrastrong coupling (USC) in Rabi model

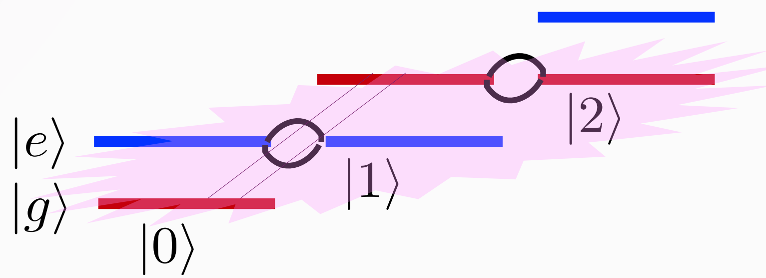
a new regime of light-matter interaction

Yoshihara et al., Nat. Phys 13, 39 (2017)



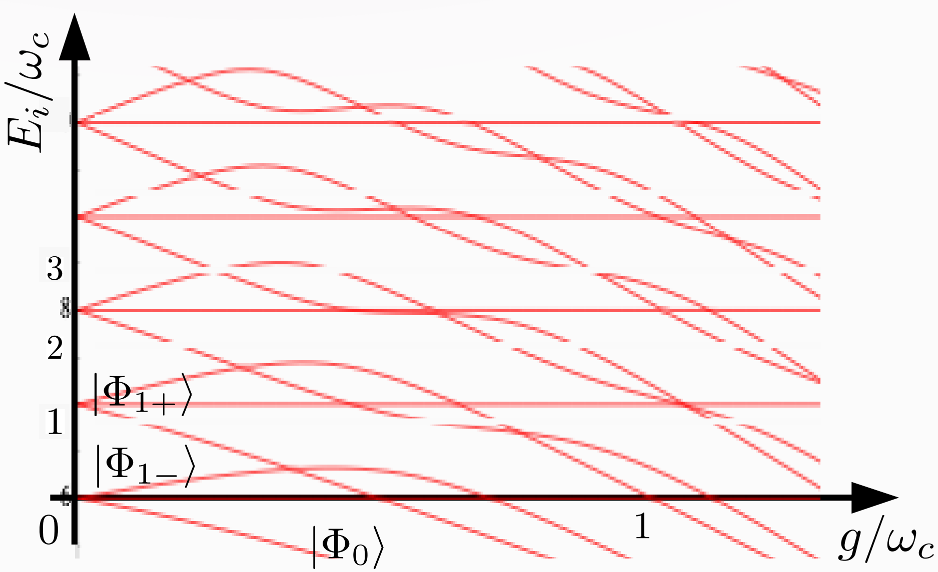
- **beyond JC** $g \sim \varepsilon, \omega_c$

$$H_{Rabi} = \varepsilon\,\sigma_+\sigma_- + \hbar\omega_c\, a^\dagger a$$
$$+g\,(a\sigma_+ + a^\dagger\sigma_-) + g_c\,(a^\dagger\sigma_+ + a\sigma_-)$$



- **Eigenstates** conserving **only** parity of #-excitations $|\Phi_j\rangle = \sum_n c_{j\,n}|n\,g\rangle + d_{j,n}|n,e\rangle$
  - ground state **contains photons**

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



- **Exps: Spectroscopic detection** in archtectures of Artificial Atoms
  - in flux qubits RELEVANT FOR OUR WORK!!

    Niemczyk et al., Nat. Phys. 2010 $g \sim 0.1\,\omega_c$
    Forn-Diaz et al., PRL 2010
    Yoshihara et al., Nat. Phys 2017 $g \sim 1.38\,\omega_c$
  - In semiconductor q-wells

    Todorov et al., PRL 2010 $g \sim 0.48\,\omega_c$
    Scalari et al., Science 2012 $g \sim 0.58\,\omega_c$

- **HERE: dynamical** detection (**STIRAP**)

G. Falci, et al. Fort. Phys. (2016); & GF et al. arxiv 1708.00906

dynamical detection of USC

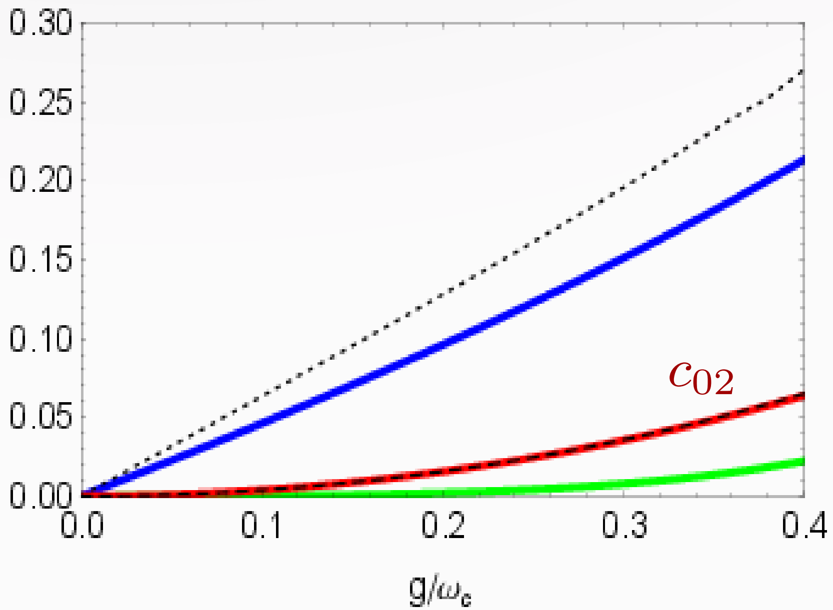
SEP → STIRAP

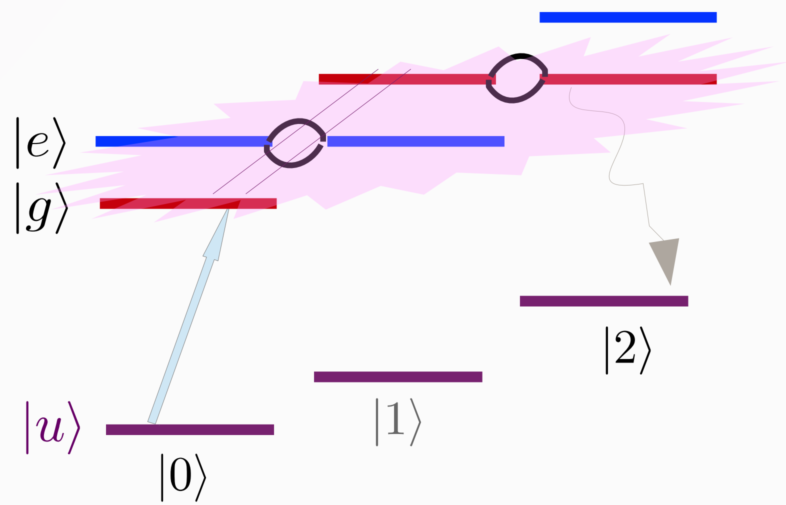
- Detection using a lower energy **atomic ancillary level** $|u\rangle$
  - Theoretical proposal using **spontaneous emission pumping (SEP)**
    → decay of the (false) vacuum $|\Phi_0\rangle$

detecting two-photons is a smoking gun for USC

R. Stassi et al., PRL 2013

- Problem: probability of detecting the two-photon USC channel is **very small**
  - Realistic case of not too large g $\sim |c_{02}|^2 \propto g^4$!!





- cf Raman oscillations *Huang & Law , PRA 2014*

- Our proposal:
  amplify the output signal **by coherence** as in atomic physics: **SEP → STIRAP**

G. Falci, et al. Fort. Phys. (2016); & GF et al. Arxiv 1708.00906

Λ scheme, CPT and STIRAP

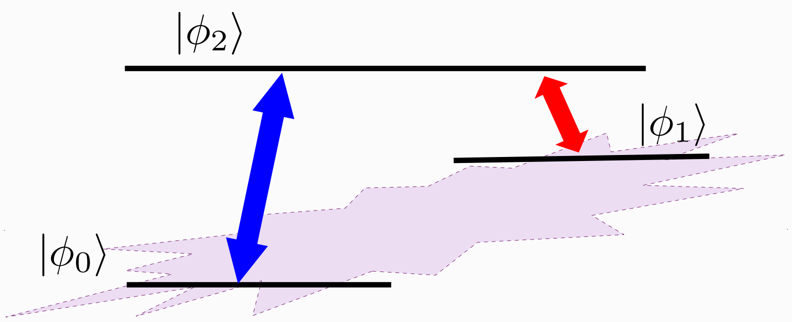
coherent population trapping → stimulated Raman adiabatic passage

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

- 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** $\delta = \delta_p - \delta_s$

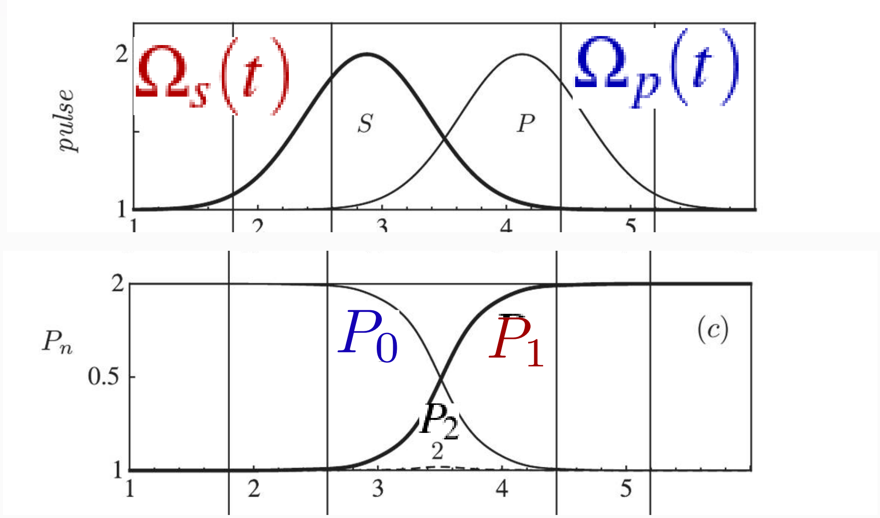
- **@ two-photon** resonance

$\delta = 0$ → **Dark state** $|D\rangle = \dfrac{\Omega_s(t)|\phi_0\rangle - \Omega_p(t)|\phi_1\rangle}{\sqrt{|\Omega_s|^2 + |\Omega_p|^2}}$



Population **coherently trapped** in lowest doublet

Shine fields in the **counterintuitive** sequence

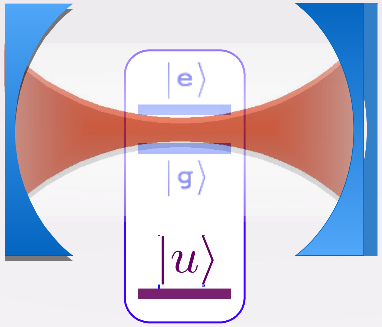


STIRAP
adiabatic following of the **dark state** yields
complete population transfer $|\phi_0\rangle \rightarrow |\phi_1\rangle$
while $|\phi_2\rangle$ remains always unoccupied

Bergmann, Theuer, Shore, RMP 1998
N.V. Vitanov, A.A. Rangelov, B.W. Shore, and K. Bergmann, Rev. Mod. Phys. ***89****, 015006 (2017).*

coherent amplification of the USC channel

ideal Λ-STIRAP Hamiltonian



Falci, Ridolfo, Di Stefano, Paraoanu, Paladino Fort. Phys. (2017)

- Hamiltonian with **additional ancillary level** $|u\rangle$

$$H = -\varepsilon' |u\rangle\langle u| + H_{R2} + H_c(t)$$

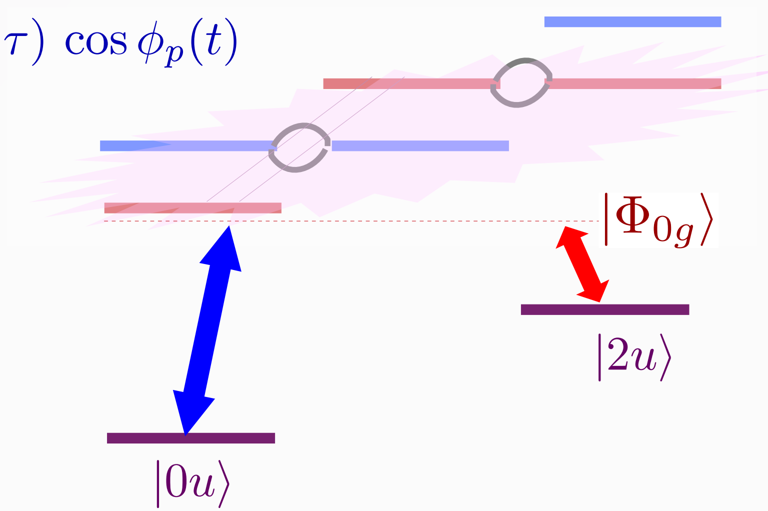
- Two-tone control detuned from the e-g transition

$$H_c = W(t)\,\big(|u\rangle\langle g| + \mathrm{h.c.}\big) = W(t) \textstyle\sum_{nj} |nj\rangle\langle\Phi_j|$$

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

- 3 level truncation → **STIRAP Hamiltonian**

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



- two photon component in the ground state $c_{02} \neq 0$ implies **faithful and selective** population transfer $\rightarrow |2u\rangle$
  - → detecting 2 photons is a **"smoking gun" of USC**
  - **coherent amplification** of USC channel coupling $c_{02}(g)$ large enough to guarantee adiabaticity yields 100% **faithful & robust** population transfer → $c_{02}(g)\Omega_0 T > 10$
  - treshold depends **only linearly** in c_{02} $(\propto g^2)$ (quadratically in SEP)

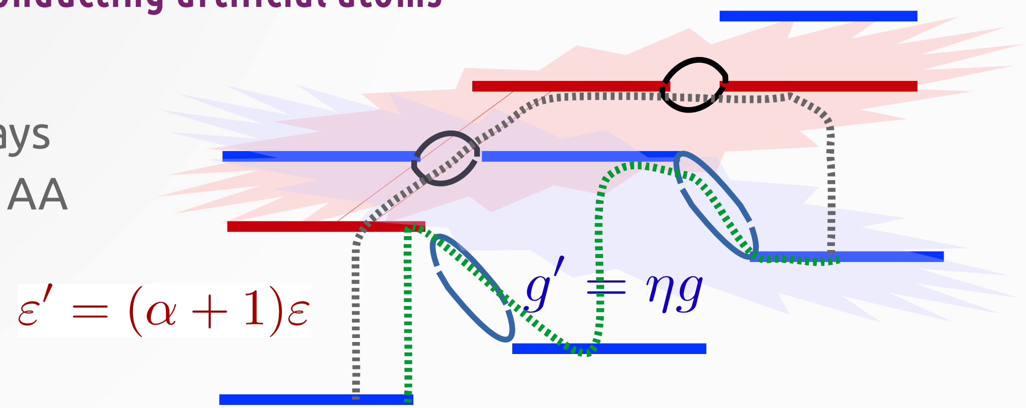
Bergmann, Theuer, Shore, RMP 1998
N.V. Vitanov, A.A. Rangelov, B.W. Shore, and K. Bergmann, Rev. Mod. Phys. 89, 015006 (2017).

implementing in state-of the art devices

limitations in the hardware → SEVERE PROBLEMS

Falci, Ridolfo, Di Stefano, Paladino
arxiv 1708.00906

- **a reliable scheme for detecting the two-photons** left in the cavity is needed.
  - **Rules out semiconductor based devices** where measurement of the number of THz photon is not feasible
  - The number of GHz photons **can be measured in superconducting artificial atoms**



- **BUT** design implies that the cavity may be always coupled also to other transitions of the 3-level AA **involving the ancillary level** $|u\rangle$

- → extra **stray u↔g coupling** to the cavity

opens a **new JC channel** for the $|0u\rangle \to |2u\rangle$ process

$$\Omega_s \to \left[c_{02} - \frac{\sqrt{2} g'^2}{(\varepsilon' - \omega_c)^2 - g^2}\right] \mathscr{W}_s$$

- Necessary condition for "smoking gun" detection of USC

$$A = \frac{1}{2\eta^2} \left| \frac{\alpha^2 - (g/\varepsilon)^2}{2 - (g/\varepsilon)^2} \right| \gg 10$$

large anharmonicity α
& **small couplings ratio** η

- **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

- same argument → USC detection by SEP and Raman is also spoiled by the stray JC channel

stray u-g coupling to the cavity

& compensation of ynamical stark shift and compensation

Falci, Ridolfo, Di Stefano, Paladino
arxiv 1708.00906

$g = 0.25\omega_c$

$$\eta = \frac{g'}{g} \quad \alpha = \frac{\varepsilon'}{\varepsilon} - 1 = 3$$

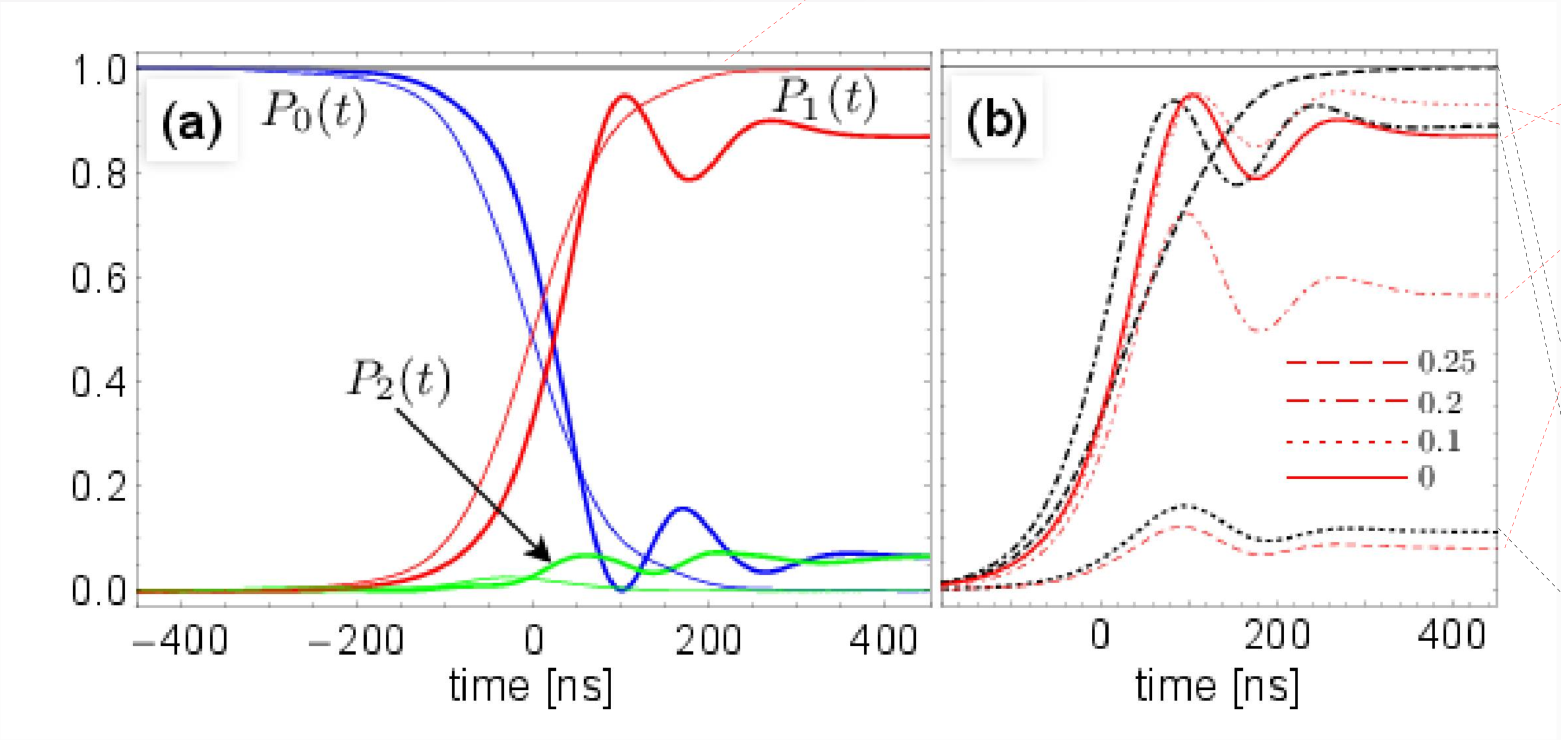
$$A = \frac{1}{2\eta^2} \left| \frac{\alpha^2 - (g/\varepsilon)^2}{2 - (g/\varepsilon)^2} \right| = \frac{2.31}{\eta^2}$$

for the $|0a\rangle \to |2u\rangle$ process $\Omega_s \to \left[c_{02} - \frac{\sqrt{2} g'^2}{(\varepsilon' - \omega_c)^2 - g^2}\right] \mathscr{W}_s$

→ stray JC channel interfering distructively $\langle 2u | H_{JC} | \Phi_0 \rangle \neq 0$

the stray coupling interferes destructively

Compensated dynamical Stark shift



$g = 0.25\omega_c$
$g' = 0.0 \quad A \to \infty$
$g' = 0.1 \quad A = 14.4$
$g' = 0.2 \quad A = 3.6$
$g' = 0.25 \quad A = 2.3$

$g = 0.0$
$g' = 0.25$
$g' = 0.2$
$g' = 0.1$

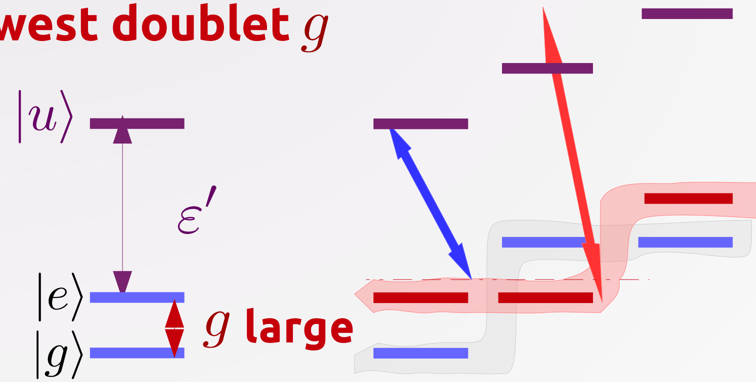
the stray coupling alone can yield population transfer

way out: the Vee-scheme

implementation in flux-based superconducting AAs

Falci, Ridolfo, Di Stefano, Paladino
arxiv 1708.00906

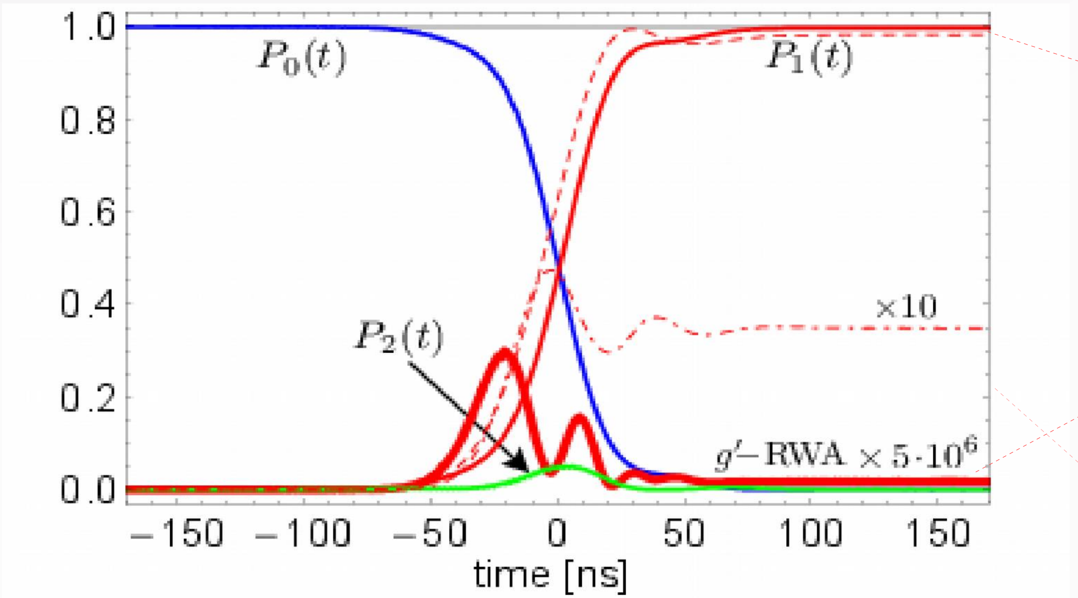
- use the **large lowest doublet** g and the **large** ε' of a flux qutrit



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 USC



~100% efficiency via USC channels (with & without stray coupling)

$$\langle 2u|H_{JC}|\Phi_\pm\rangle = 0$$

NO population transfer due to JC channels **ABSENT FROM DYNAMICS**

the stray coupling alone provides population transfer only via counterrotating term ↔ USC

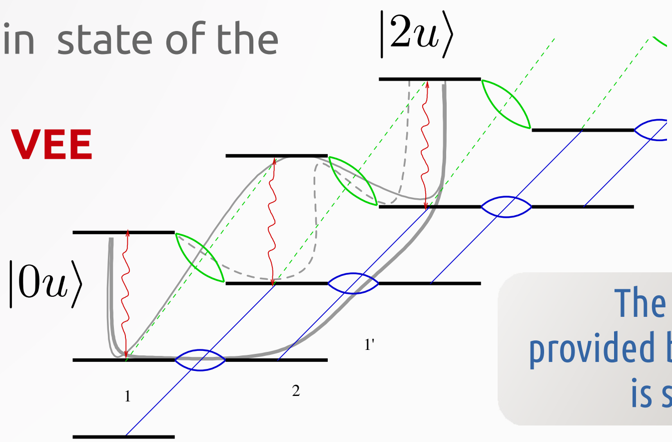
$\alpha = 1.7$
$g' = 2/3\, g$!!

- **Moreover JC channel ABSENT →** less stringent constraint on the spectrum/couplings (very important for experiments!!)

conclusions

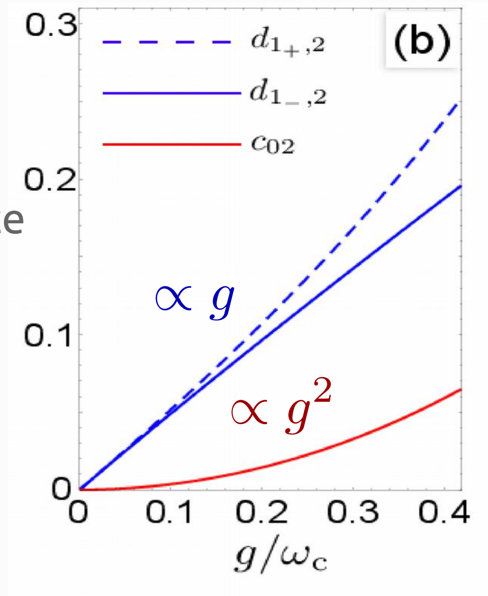
Falci, Ridolfo, Di Stefano, Paraoanu, Paladino Fort. Phys. (2017)
Falci, Ridolfo, Di Stefano, Paladino arxiv 1708.00906

- **Dynamical probe** of USC in architectures of 3-level AAs
  - STIRAP provides **coherent amplification** of the USC channel
  - "Obvious" proposals with Λ-scheme do not work in state of the art quantum hardware
  - limitations **uniquely bypassed by STIRAP in the VEE** configuration.



The alternative path provided by stray coupling is strongly detuned

- Vee STIRAP assets
  - **Absence of the stray JC channel**
  - ideal favorable shape of the spectrum and matrix elements
    - **enhanced USC coupling to** $|\Phi_{\pm,1}\rangle$ with same stray coupling → weaker fiields & shorter times needed
    - Decoherence: limited only by qutrit decay & cavity decoherence



- Benchmark for coherent **control of quantum architectures in the USC regime**
  preparation of nonclassical states, ultrafast gates

- **Advantages** of USC and adiabatics in **more complex architectures** ?

Thanks for your attention

"Quantum Parrot"
David Crooks

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