LECTURE II: BIFURCATION READOUT FOR SUPERCONDUCTING QUBITS

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ARDA
W. M. KECK FOUNDATION

OUTLINE

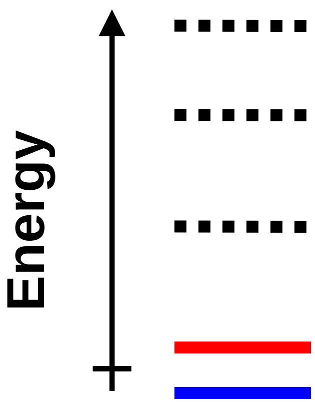
Lecture I: Metastable States of the Josephson Junction

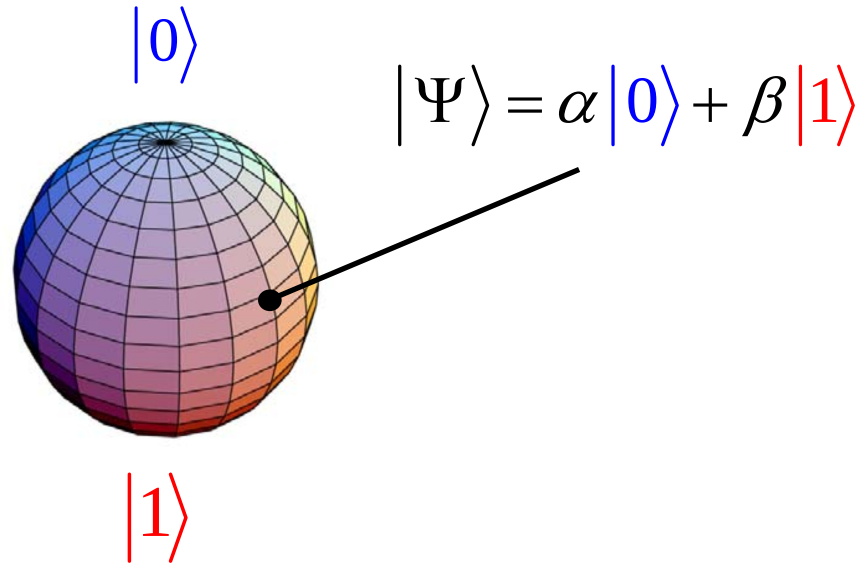
- Josephson junction dynamics
- Non-linear Josephson inductance
- DC / RF current biased junction
  - metastable states
  - escape dynamics
- Bifurcation amplification

Lecture II: Bifurcation Readout for Superconducting Qubits

- Quantum information and superconducting qubits
- Quantronium qubit
  - DC switching readout
  - RF bifurcation readout
- Coherence measurements
- Information flow
- Stark shift spectroscopy and relaxation

QUANTUM INFORMATION





classical bit

write: 0 or 1
read: 0 or 1

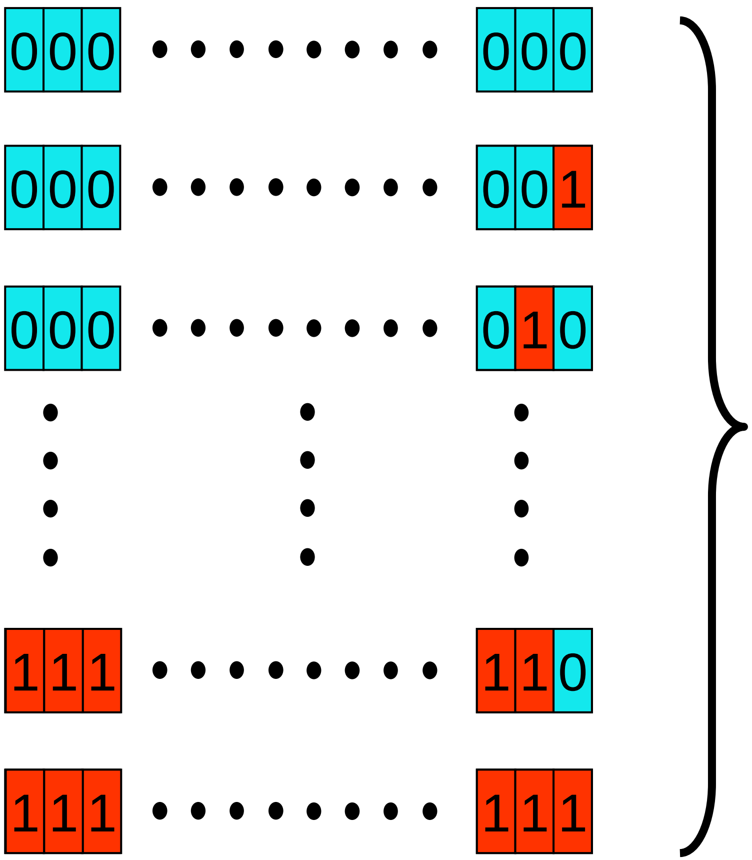
quantum
two level systems

- atoms, ions
- NMR systems
- semiconductor dots, spins
- superconducting circuits…

qubit

write: |0> and |1>
read: |0> or |1>

REGISTER WITH N BITS



THE POWER OF SUPERPOSITION

2^N POSSIBLE CONFIGURATIONS

- classically, can write only one number
- **"quantally", can write all numbers!**
- **"entangled" wavefunction**

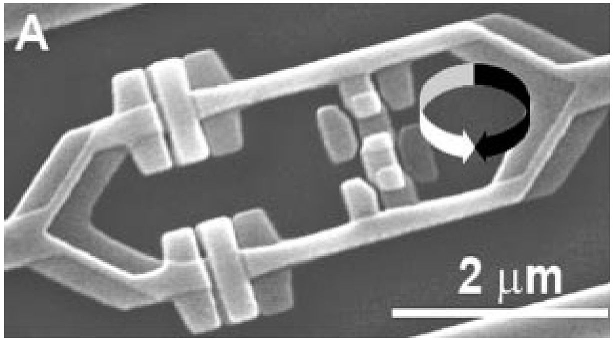
$$|\Psi\rangle = a_0|0\ldots00\rangle + a_1|0\ldots01\rangle + \ldots\ a_{2^N-1}|1\ldots11\rangle$$

MIRACLE or MIRAGE ?

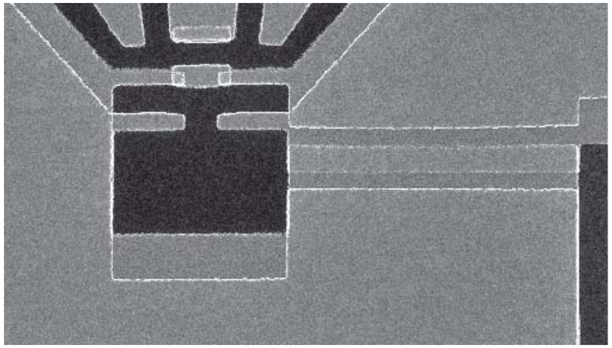
- computation
- communication
- precision measurements

- entanglement of > 10^5 qubits ?
- can you apply it ?
  - -solve quantum control problem
  - -solve decoherence problem
  - -solve scaling problem

SUPERCONDUCTING QUBITS



Chiorescu et al. (DELFT)
Science 299 (5614): 1869, 2003.



Vion et al. (SACLAY)
Science 296 (5569): 886, 2002.

Advantages

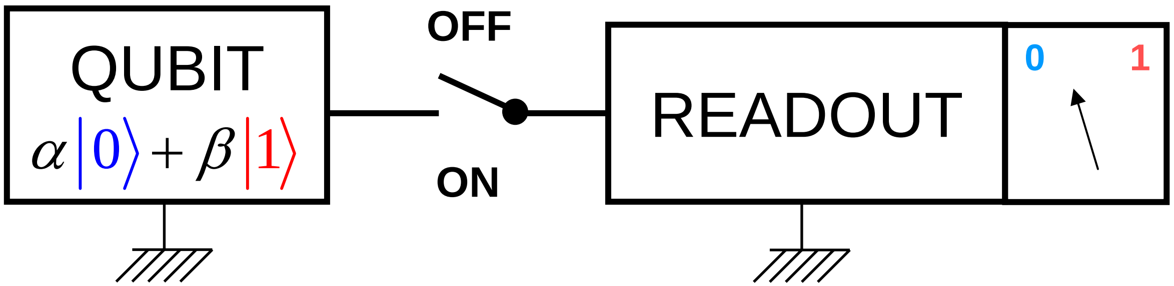
- engineered
- scalable
- electrical control
- strong coupling

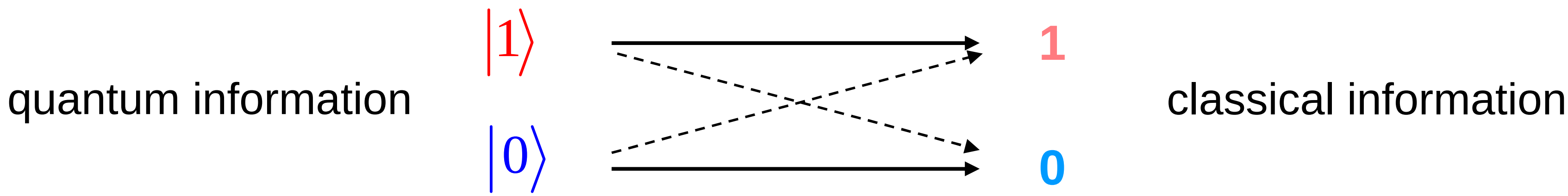
Challenge: Decoherence

- isolate noisy env't
  → use symmetry (Vion, Ioffe)
- **readout**

THE READOUT PROBLEM FOR SQUBITS

Devoret & Schoelkopf (2000)



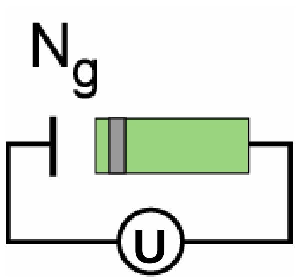


WANT:

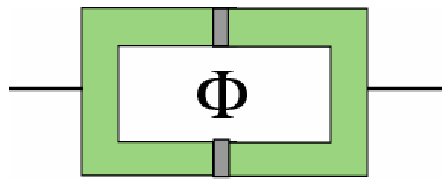
- Readout ON: $T_1 / \tau_{meas} >> 1$ (sensitivity)
- Readout OFF: T_1, T_2 not reduced (low back-action)
- Short duty cycle (speed to fight drifts)
- No energy dissipated on chip (no spurious noise)

JOSEPHSON QUBITS & READOUT STRATEGY

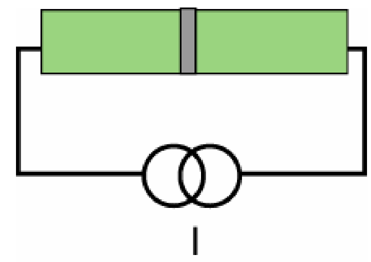
BOX (Charge)



SQUID (Flux)



JUNCTION (Current)



Can't Use Qubit Symmetry

Box + SET (Chalmers/NEC)
(charge/charge)

SQUID + SQUID (DELFT/MIT)
(flux/flux)

Junction (NIST)
(current/current)

Use Qubit Symmetry

Box + Cavity (Yale/Schoelkopf)
(charge/oscillator phase)

SQUID + Oscillator (DELFT)
(flux/oscillator phase)

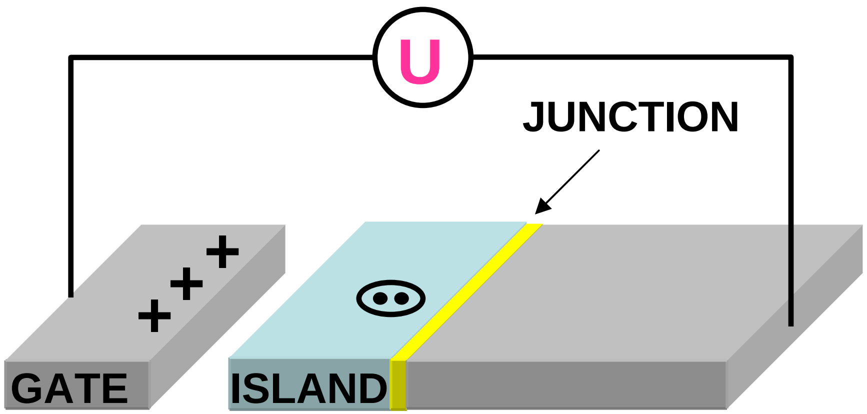
} **linear**

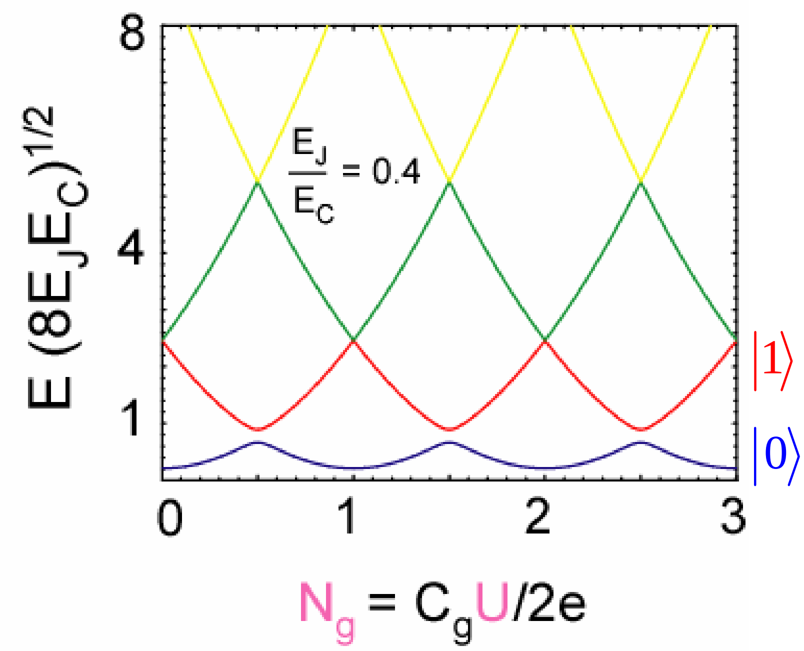
Box + Junction (Saclay)
(charge/junction phase)

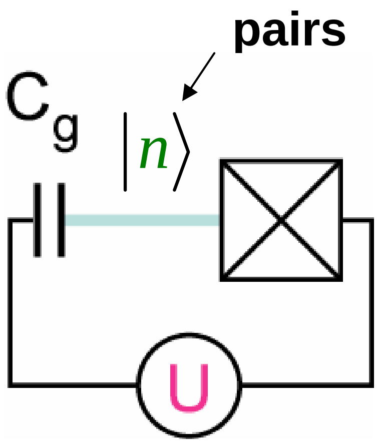
dissipative

BOX + NON-LINEAR OSCILLATOR (YALE)

CHARGE QUBIT: COOPER PAIR BOX





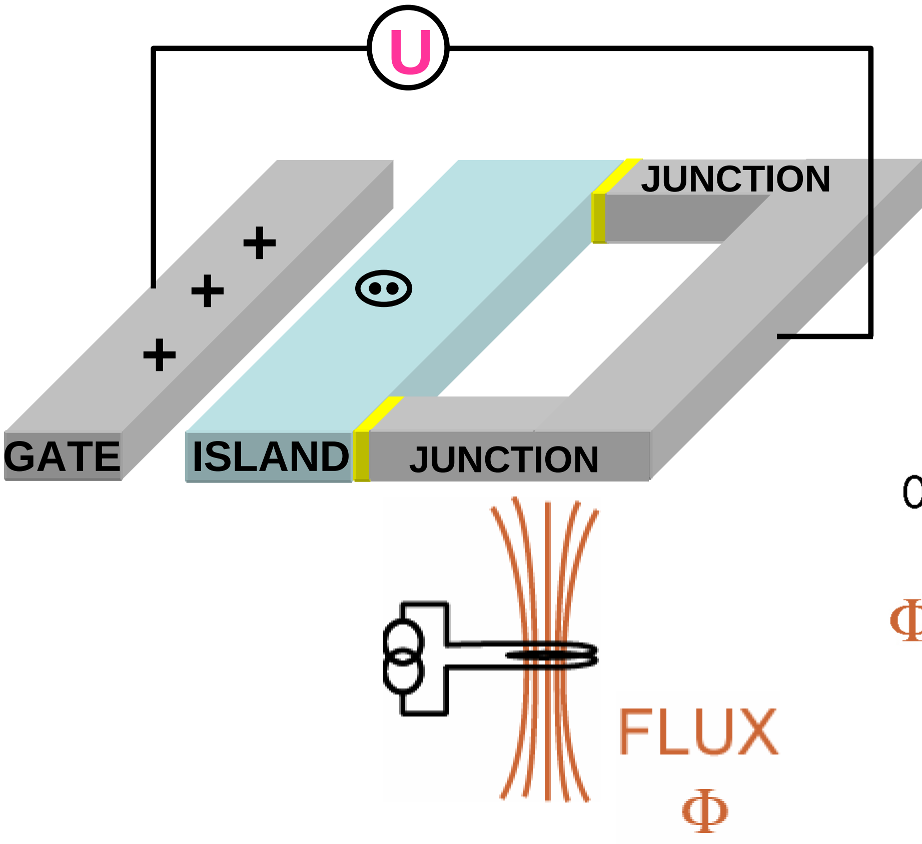


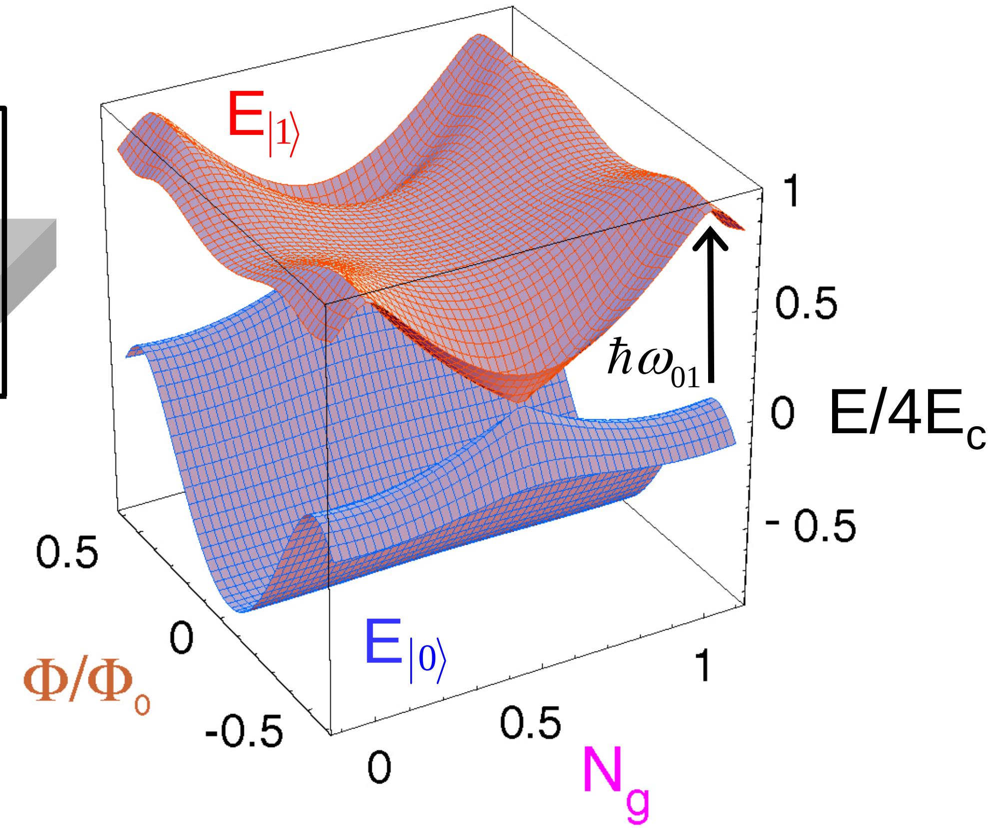
$$\hat{H} = \hat{H}_{el} + \hat{H}_J$$

$$\hat{H}_{el} = 4E_c \sum_n \left(n - \frac{C_g U}{2e} \right)^2 |n\rangle\langle n|$$

$$\hat{H}_J = \frac{E_J}{2} \sum_n \left(|n\rangle\langle n+1| \right) + h.c.$$

SPLIT COOPER PAIR BOX





$$\hat{H} = \sum_n \left[E_C (n - N_g)^2 |n\rangle\langle n| \quad - \quad \tfrac{1}{2} E_j \cos\left(\frac{\pi\Phi}{\Phi_0}\right)\left(|n\rangle\langle n+1| + |n+1\rangle\langle n|\right)\right]$$

READOUT STRATEGIES

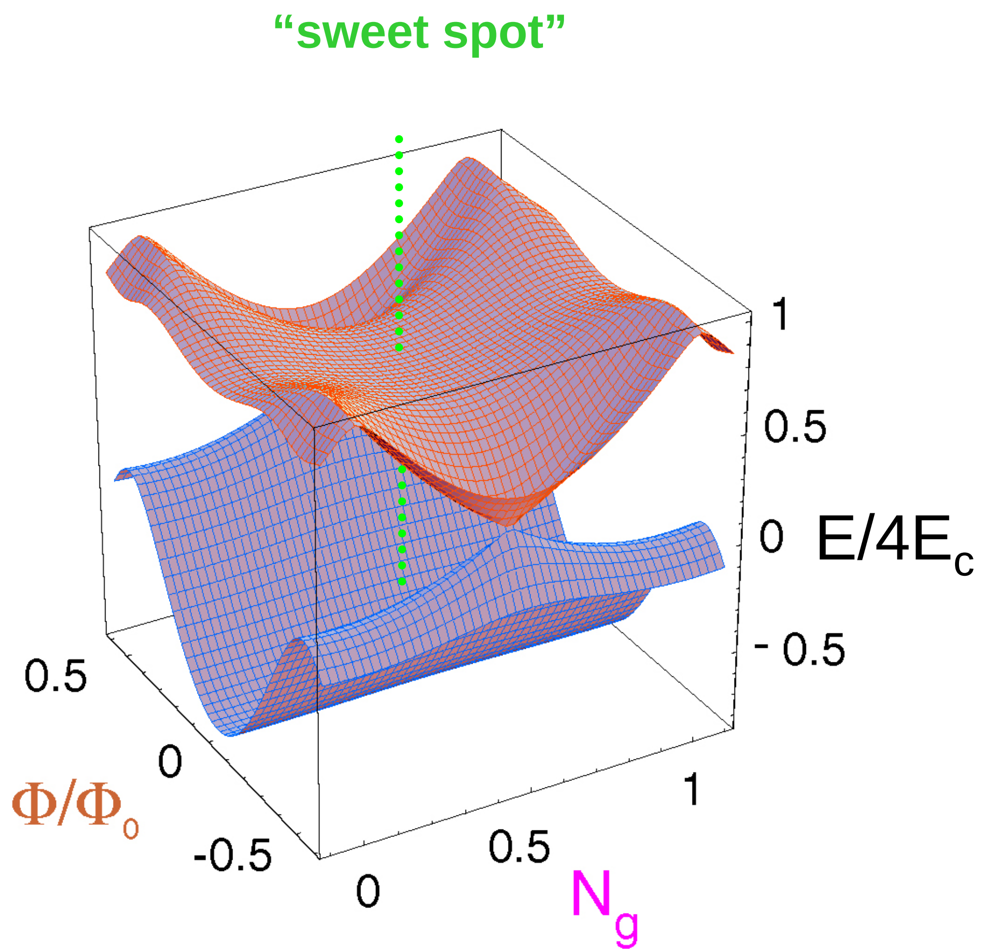
charge	capacitance
$Q_k \propto \frac{\partial E_k}{\partial N_g}$	$C_k \propto \frac{\partial^2 E_k}{\partial N_g^{\ 2}}$

CPB + SET   cQED , QC

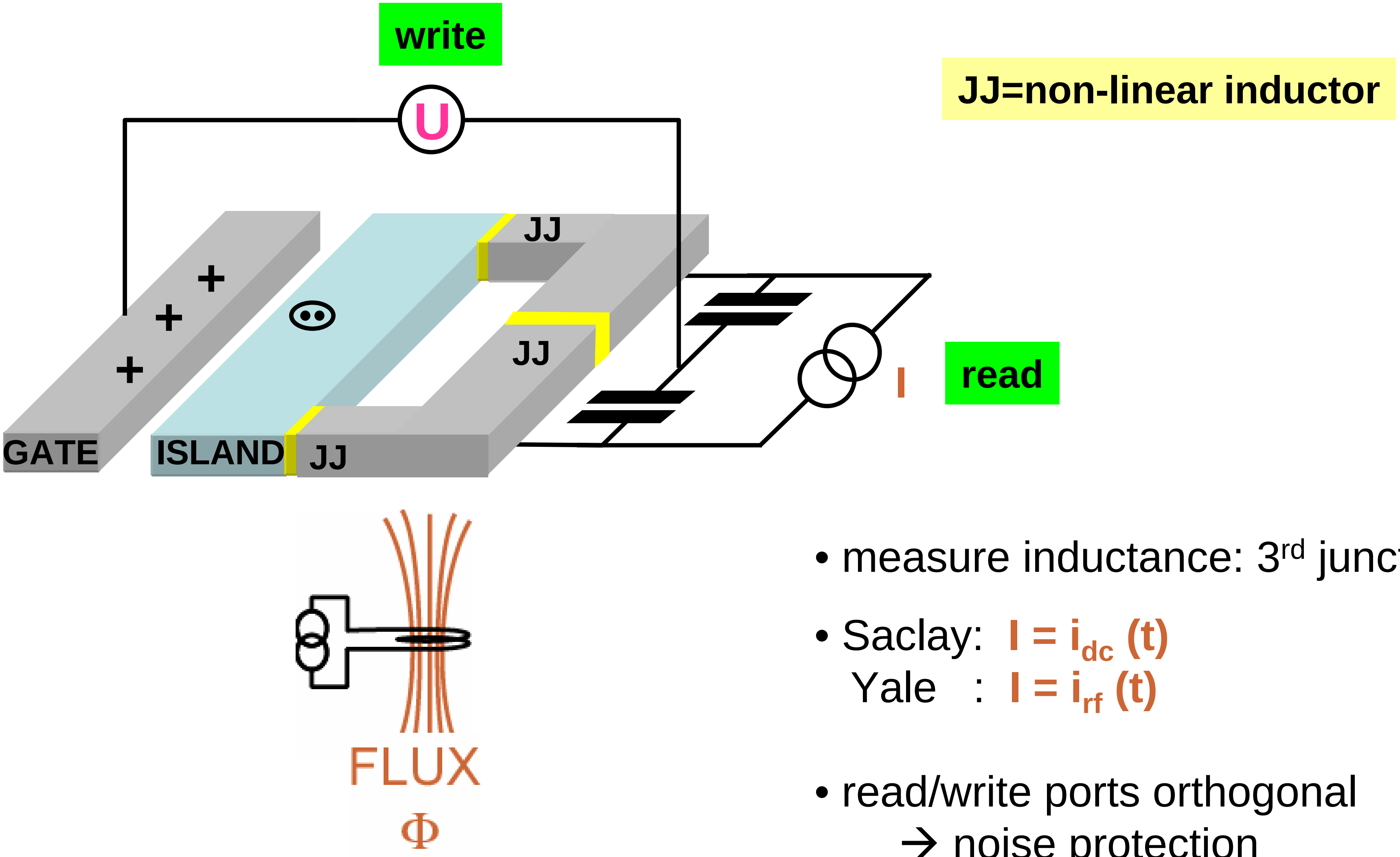
current	inductance
$I_k \propto \frac{\partial E_k}{\partial \Phi}$	$L_k \propto \left(\frac{\partial^2 E_k}{\partial \Phi^2} \right)^{-1}$

Quantronium   **Quantronium + JBA**

- work @ sweet spot
- readout @ sweet spot

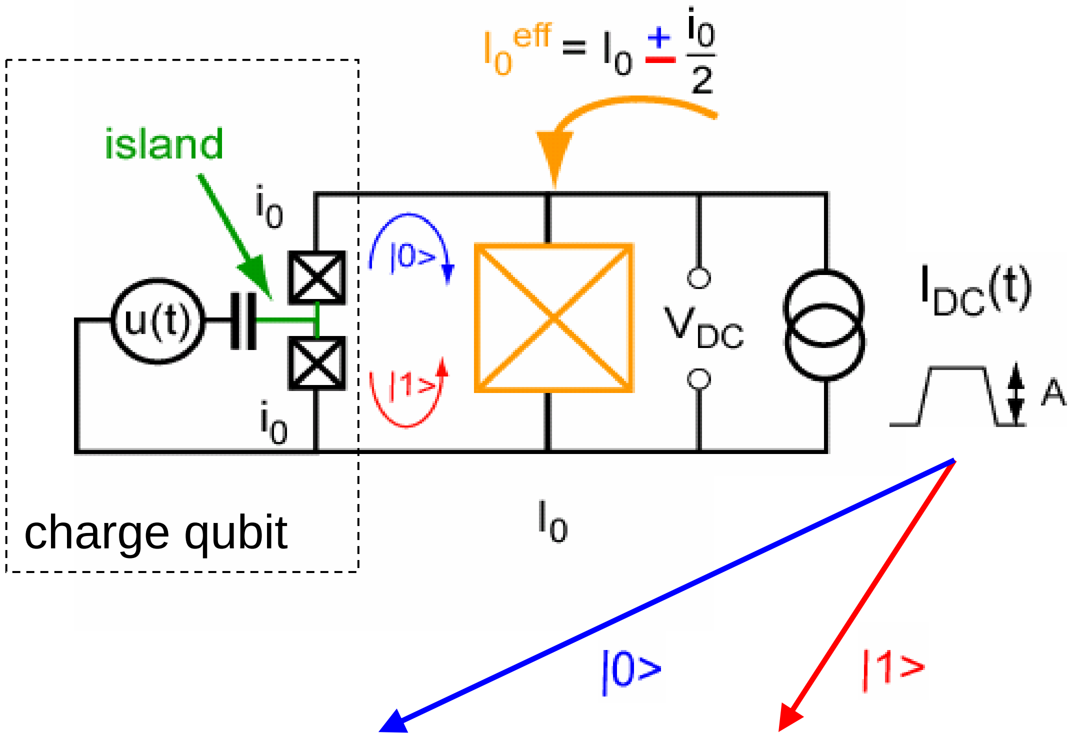


NON-LINEAR INDUCTIVE READOUT: QUANTRONIUM



- measure inductance: 3rd junction
- Saclay: $I = i_{dc}\ (t)$
  Yale : $I = i_{rf}\ (t)$
- read/write ports orthogonal
  → noise protection
  → indep. frequencies

QUANTRONIUM with DC Switching Readout



A < I_0^{eff}

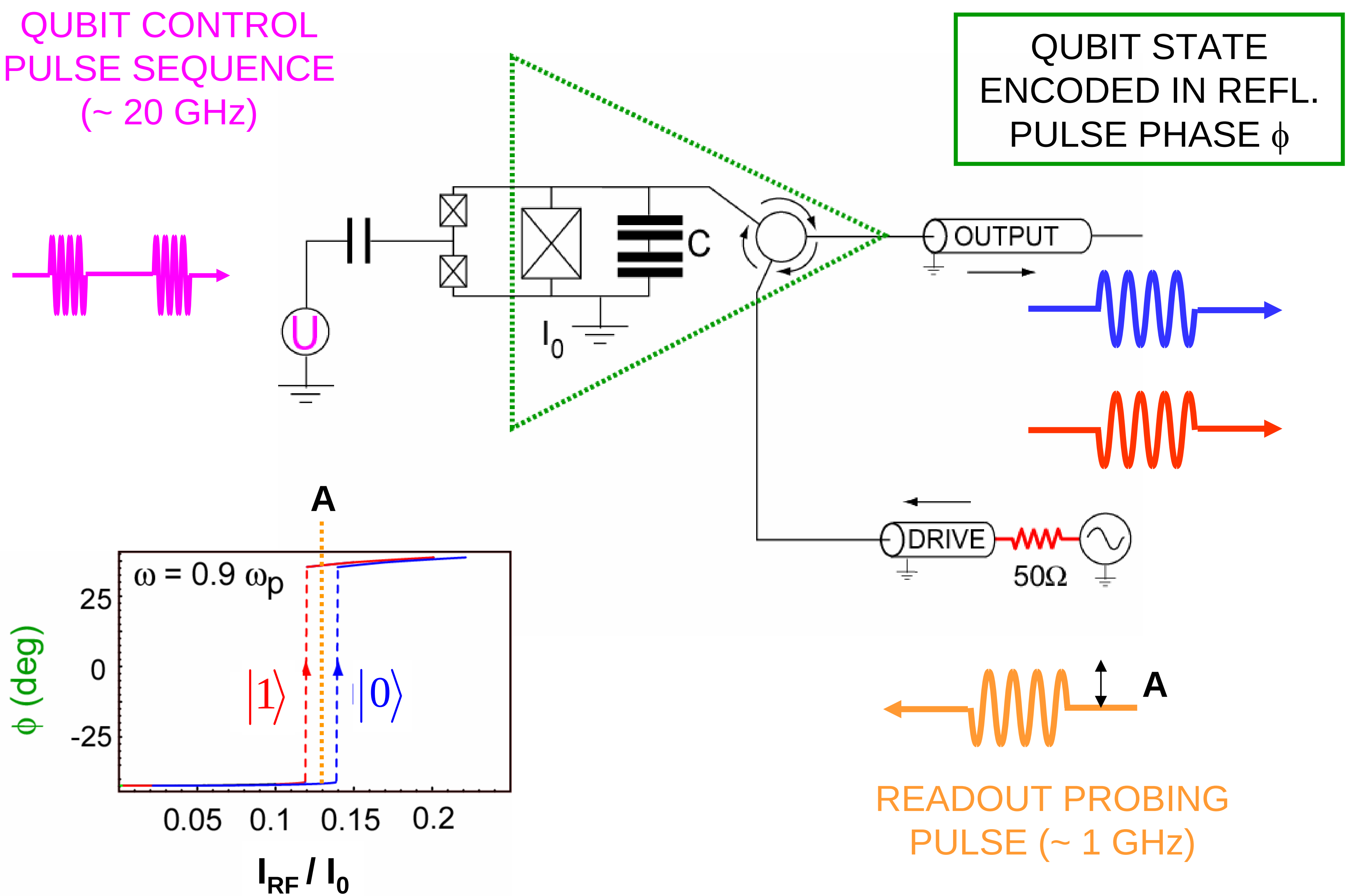
Superconducting
V_{DC}=0
(DC Readout 0)

A > I_0^{eff}

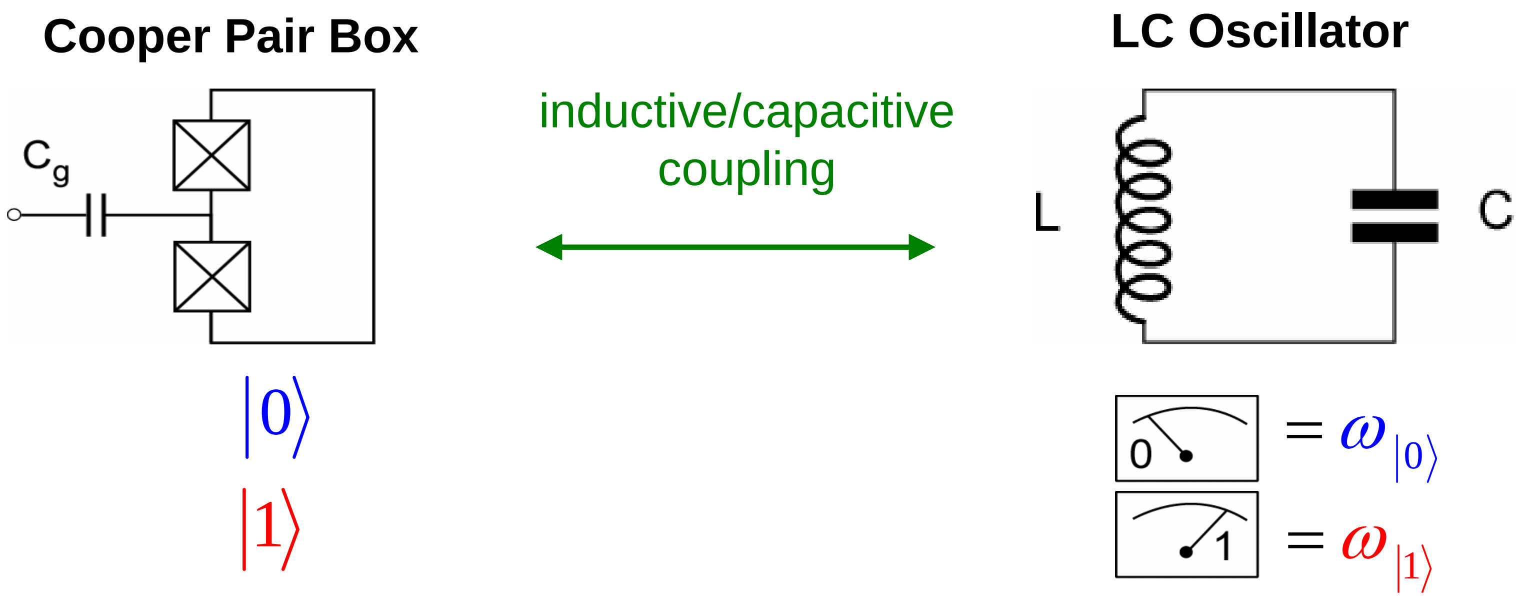
Dissipative
$V_{DC}=2\Delta/e$
(DC Readout 1)

- I_{DC}=0 → Readout off
- 1/f charge & flux noise immunity
- T_1 = 1.8 μs
  T_2= 500 ns ~10^3 ops!
  (D. Vion et al., Science 2002)
- **Quasiparticles**
  -slow reset (>10μs)
- **Reduced Visibility**

QUANTRONIUM with RF Bifurcation Readout



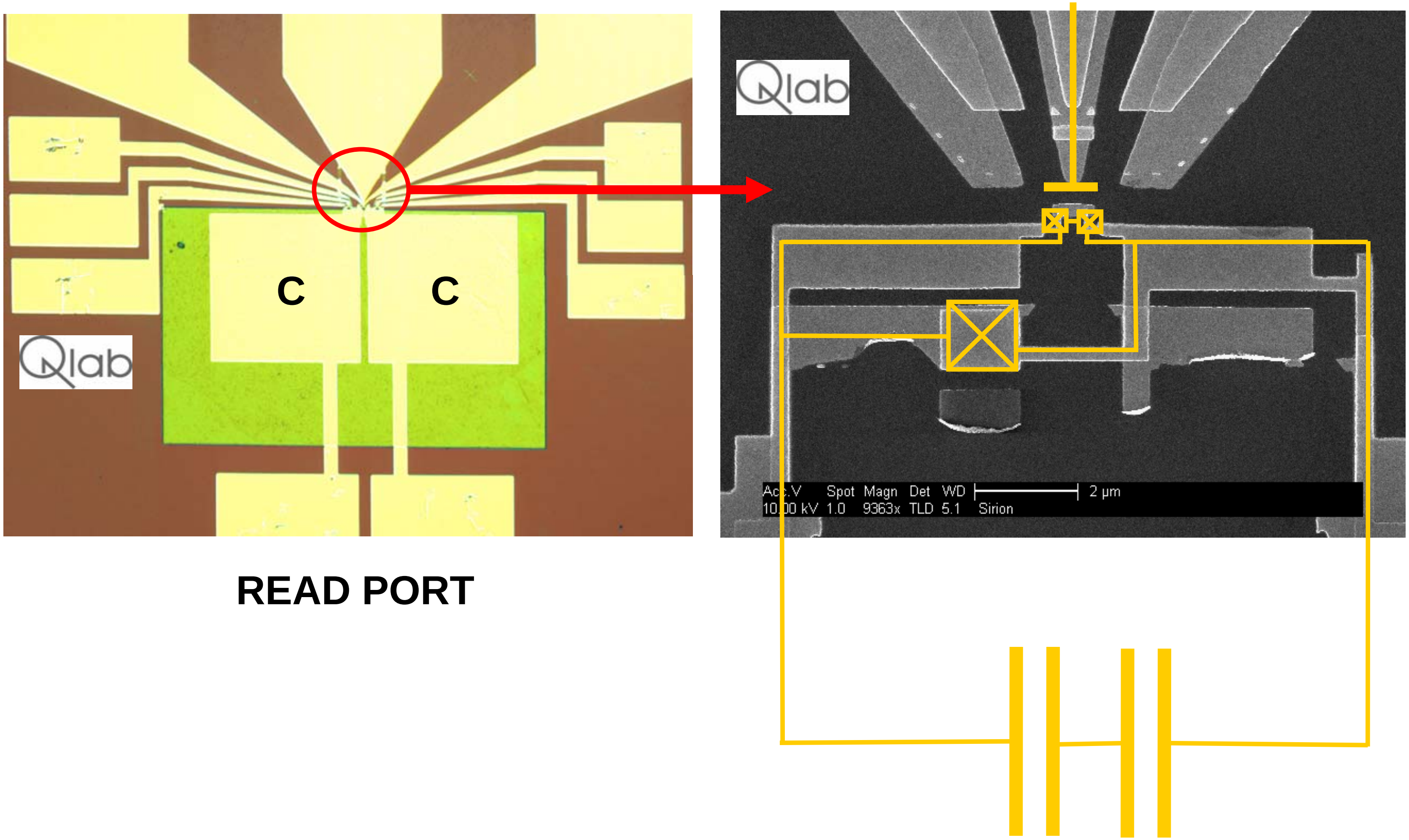
DISPERSIVE READOUT



- qubit state modifies oscillator frequency
- measure susceptibility, not loss
- cQED: high Q coplanar waveguide resonator
  → weak, continuous measurement
- Quantronium + JBA: anharmonic Josephson oscillator
  → strong, projective measurement

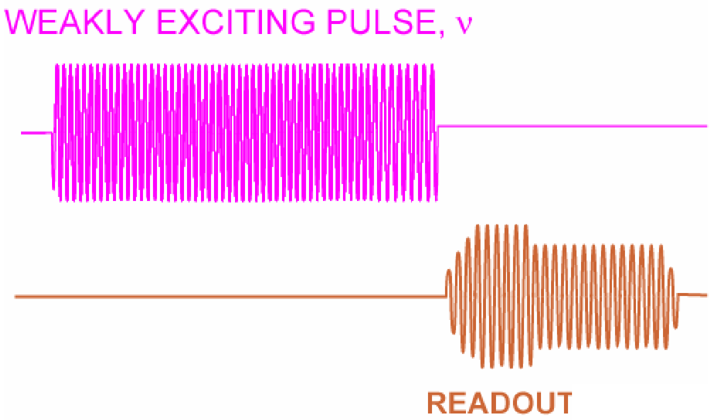
QUANTRONIUM + JBA CHIP

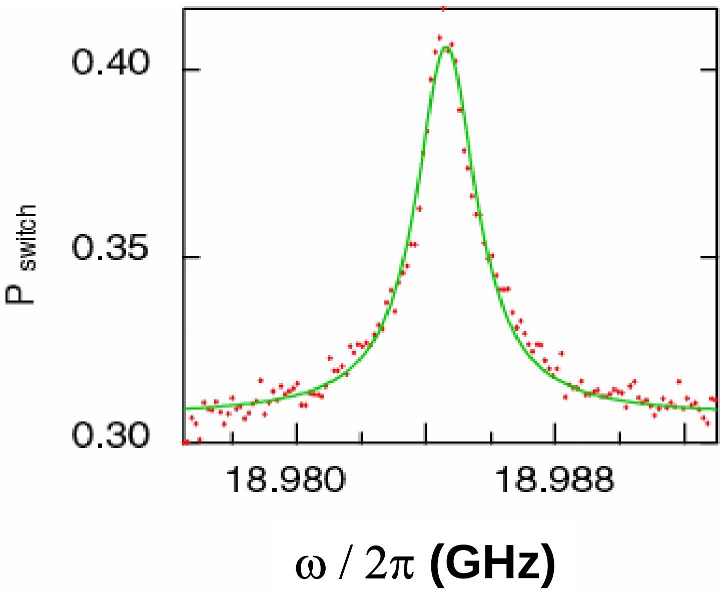
WRITE PORT

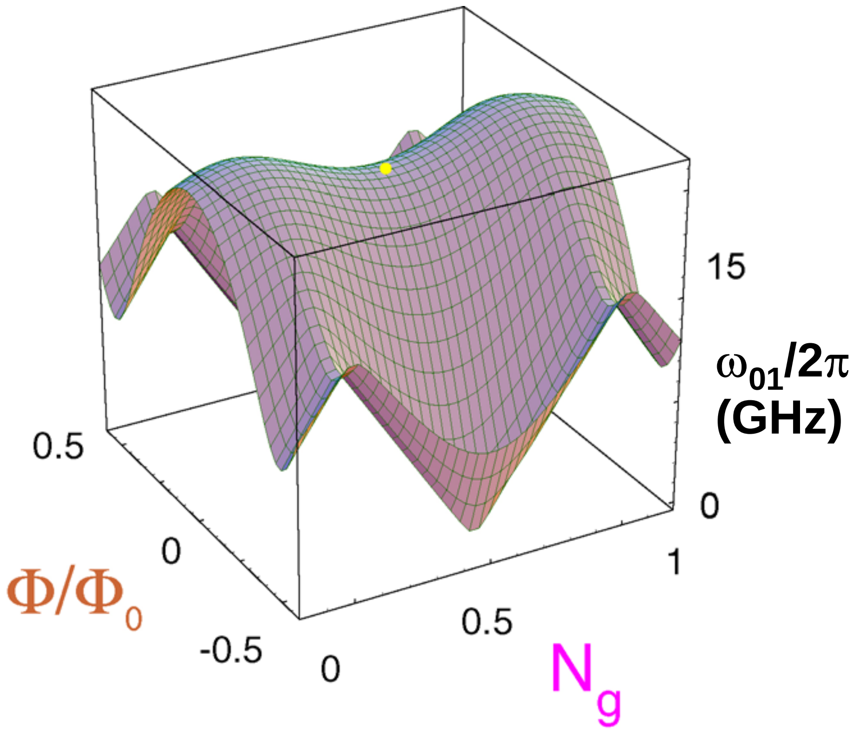


READ PORT

SPECTROSCOPIC FINGERPRINT





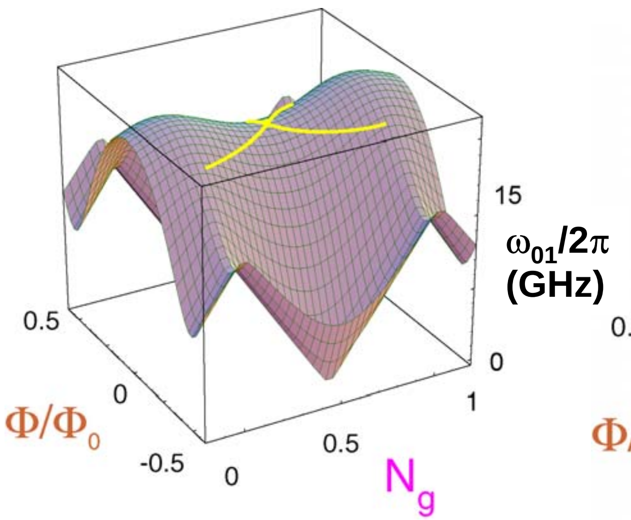


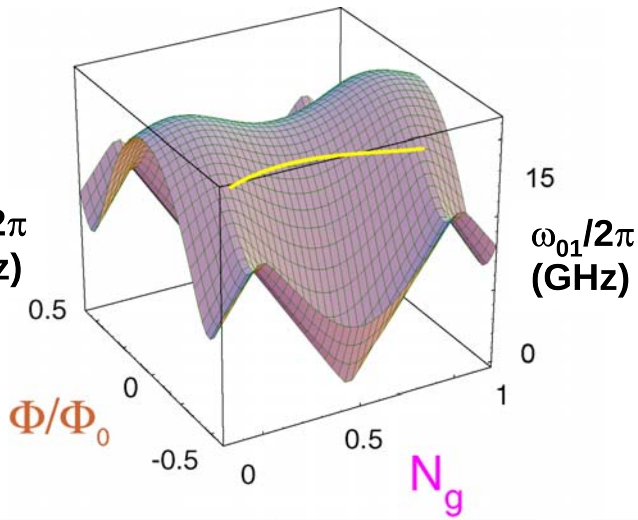
$$\frac{\omega_{01}^{\text{sweet spot}}}{2\pi} = 18.983\,\text{GHz}$$

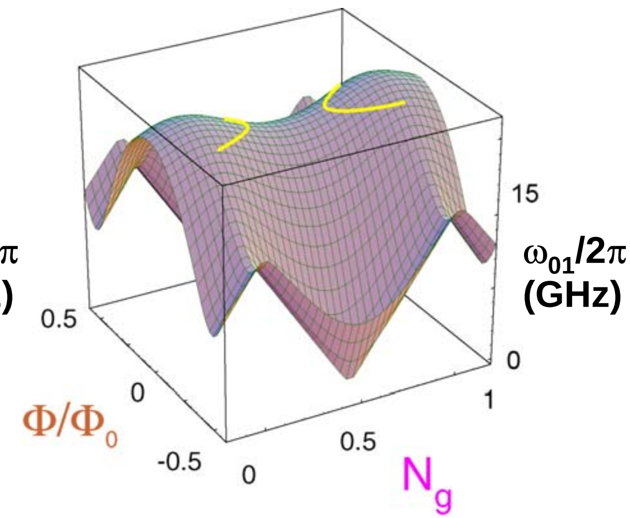
$\omega = \omega_{sweet\ spot}$

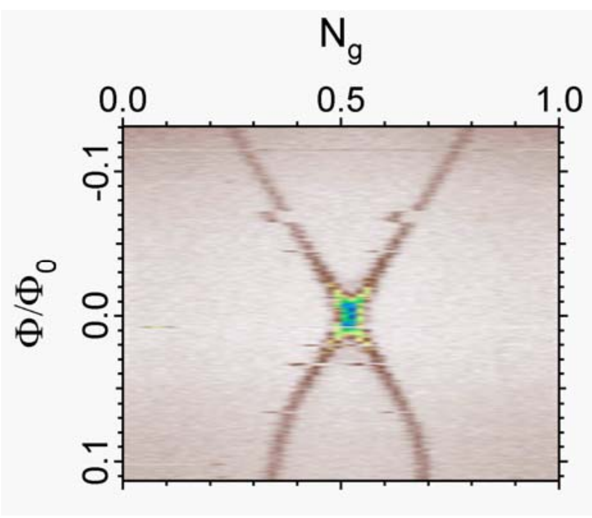
$\Delta\omega/2\pi = -\ 100\text{MHz}$

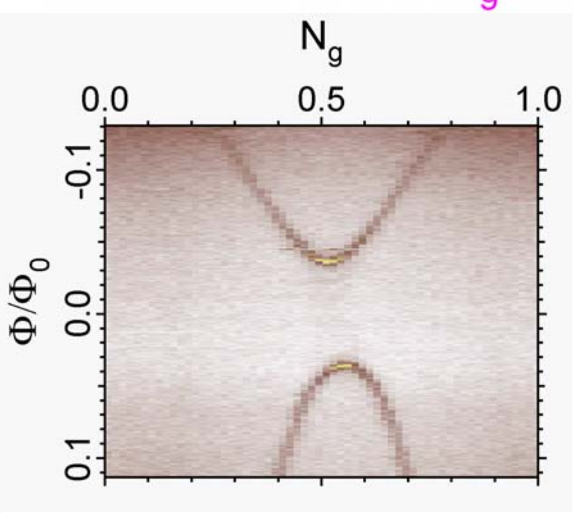
$\Delta\omega/2\pi = +\ 100\text{MHz}$

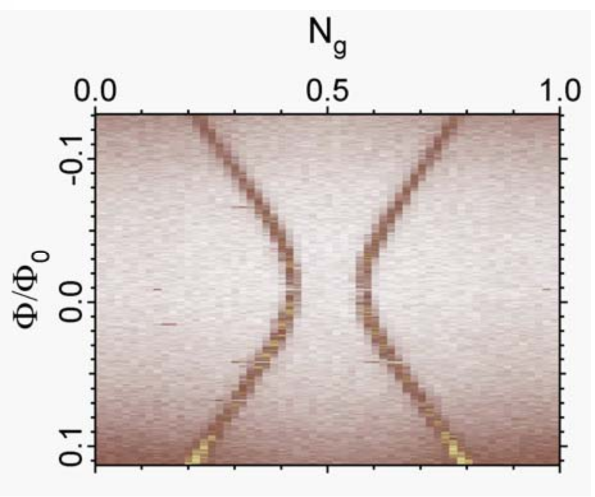


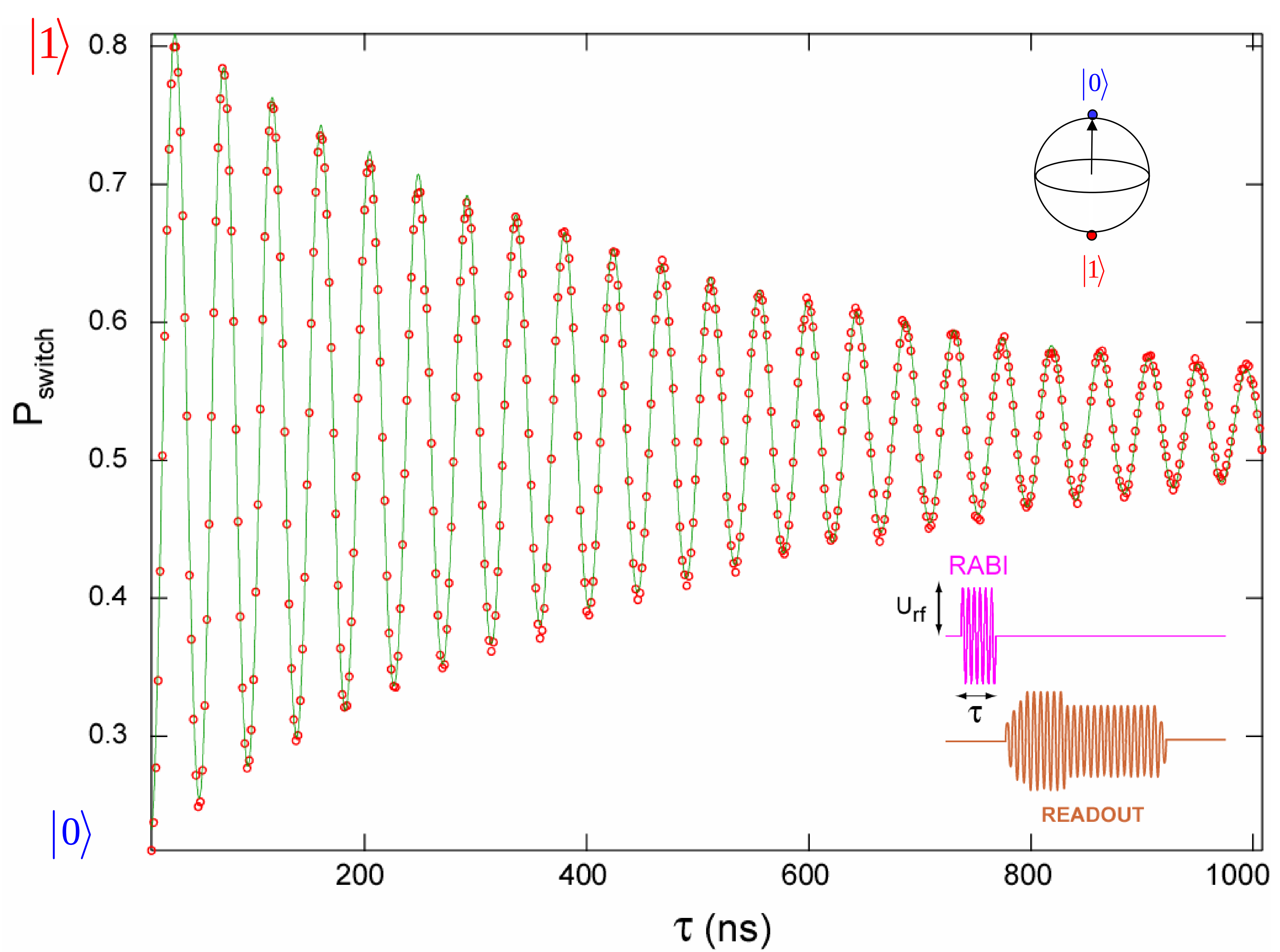






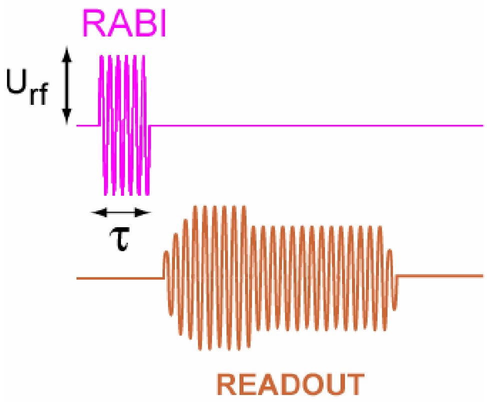


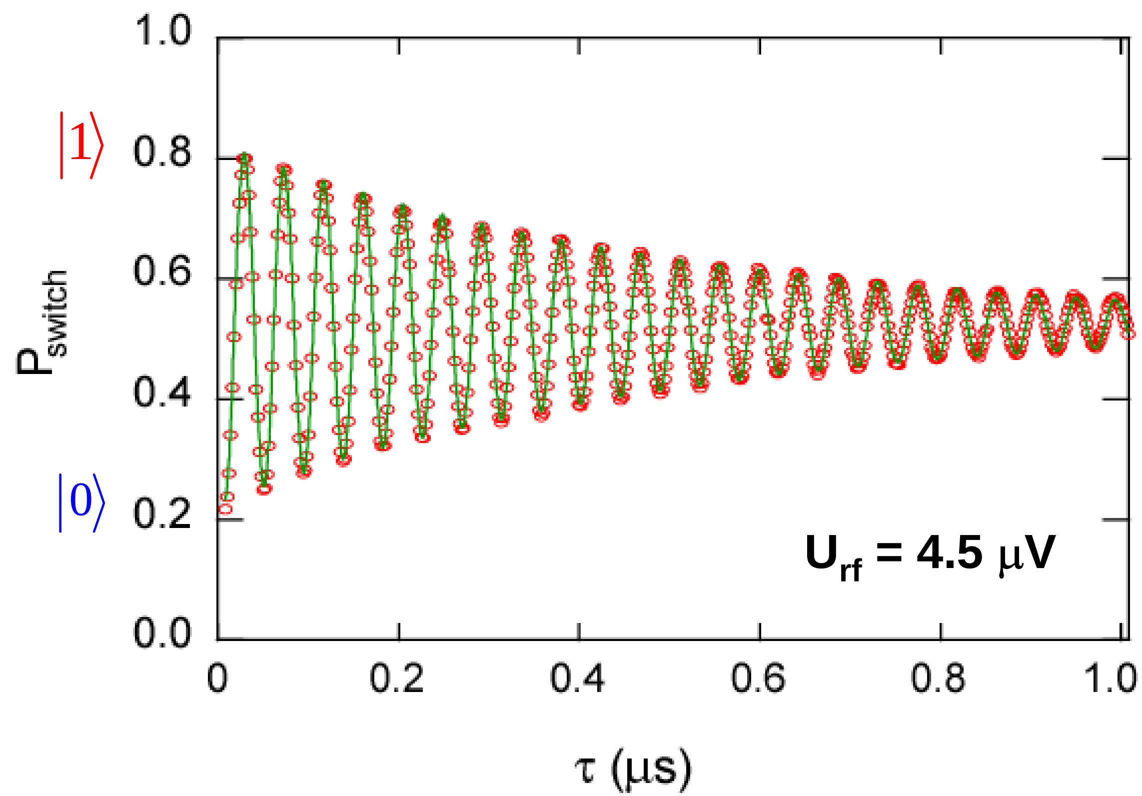


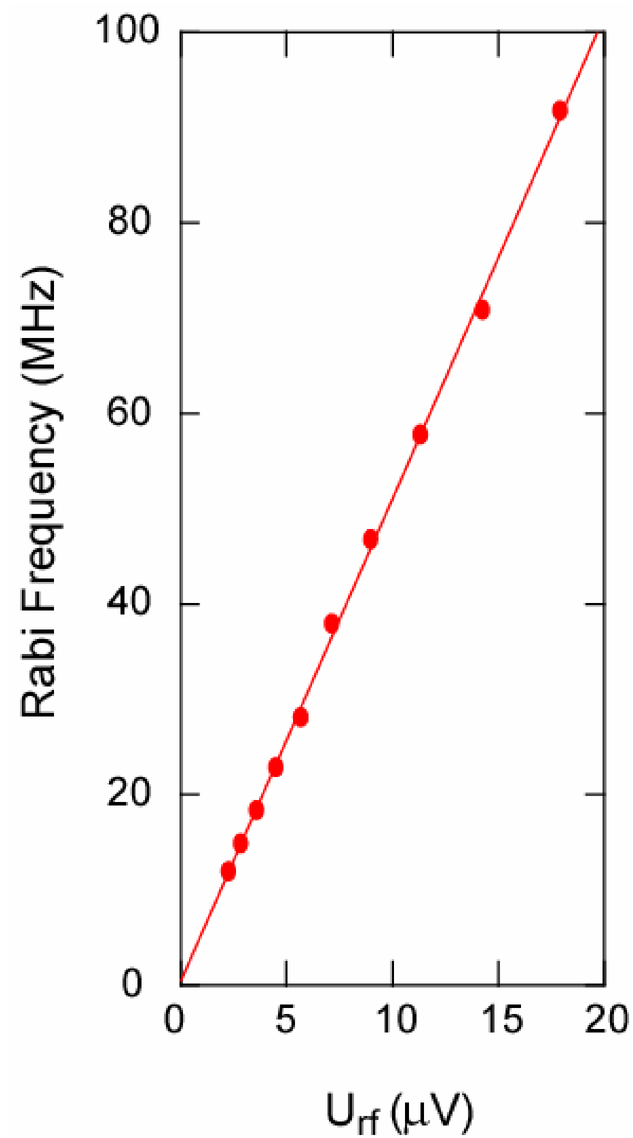


|1⟩
|0⟩
0.8
0.7
0.6
0.5
0.4
0.3
P switch
200
400
600
800
1000
τ (ns)
|0⟩
|1⟩
RABI
U rf
τ
READOUT

RABI OSCILLATIONS

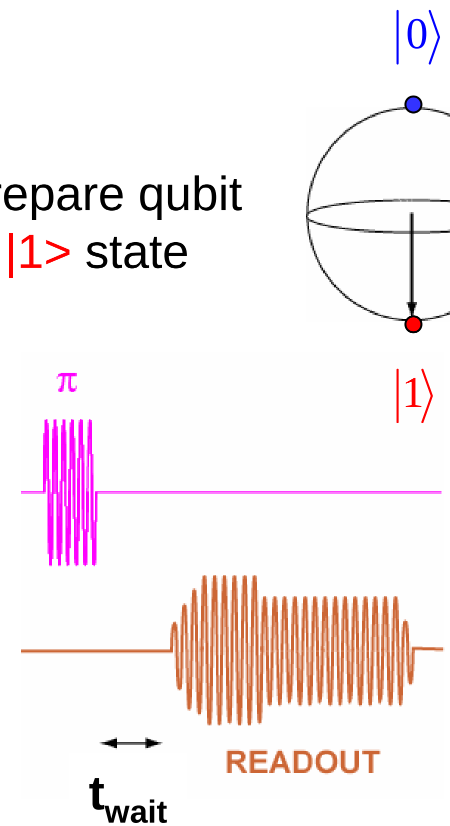


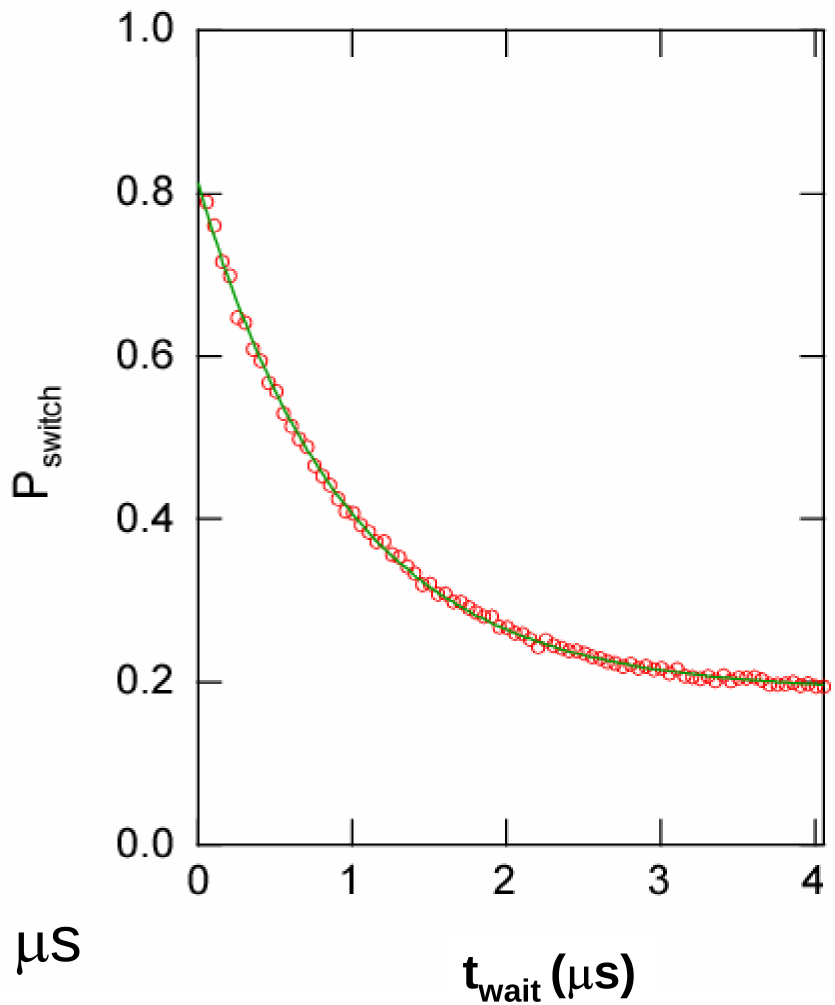




EXCITED STATE LIFETIME – T_1

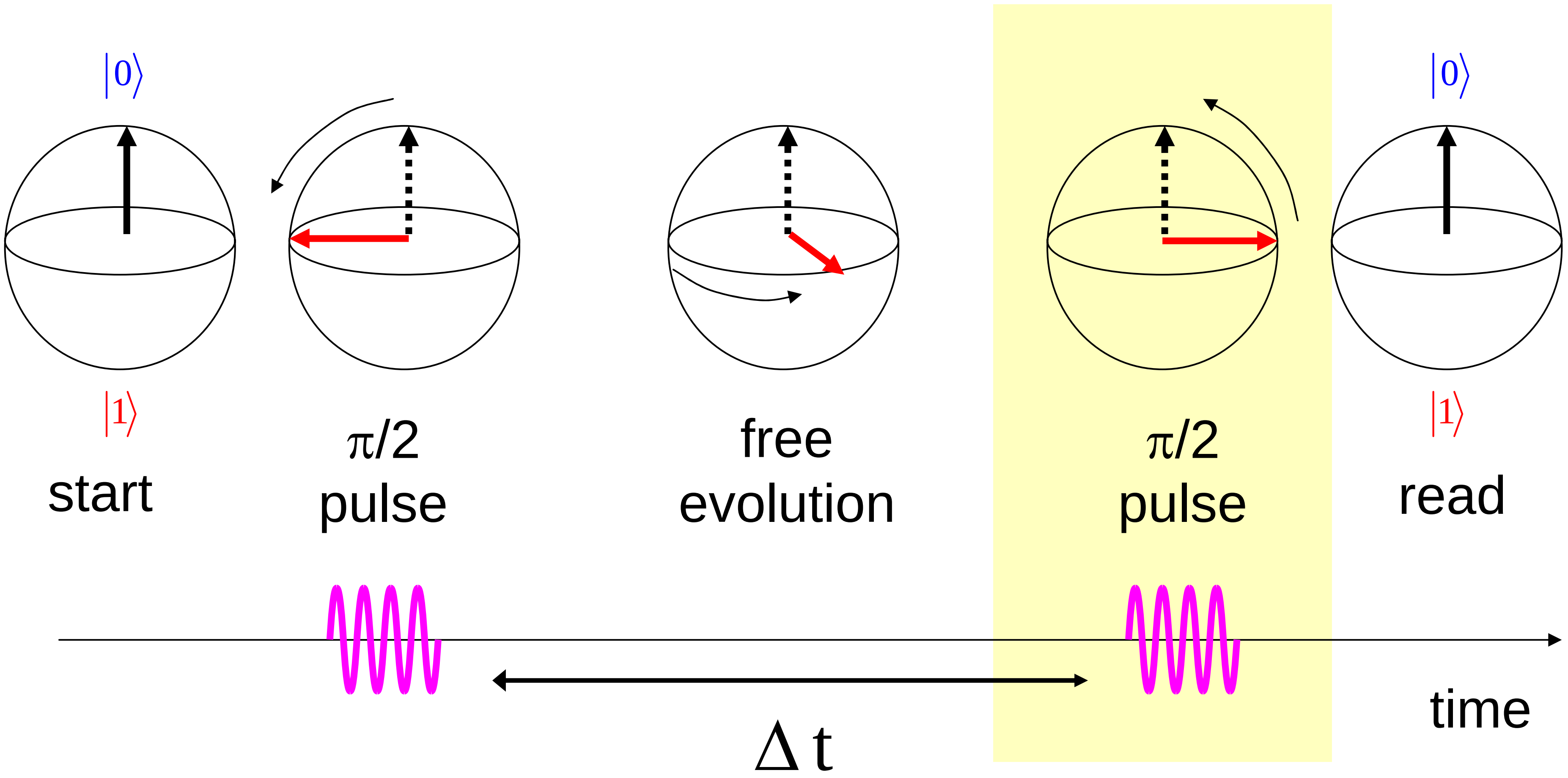
Prepare qubit in |1> state



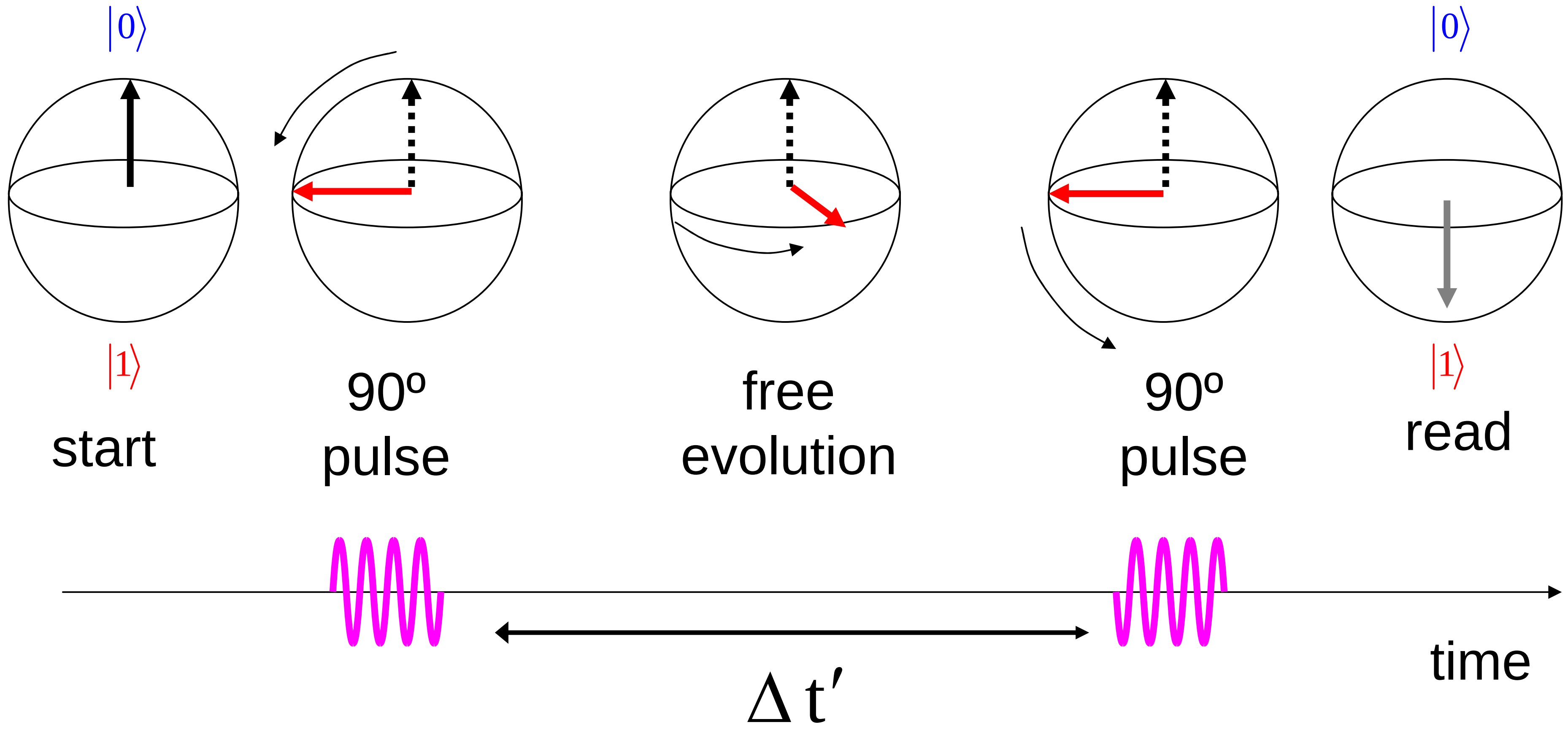


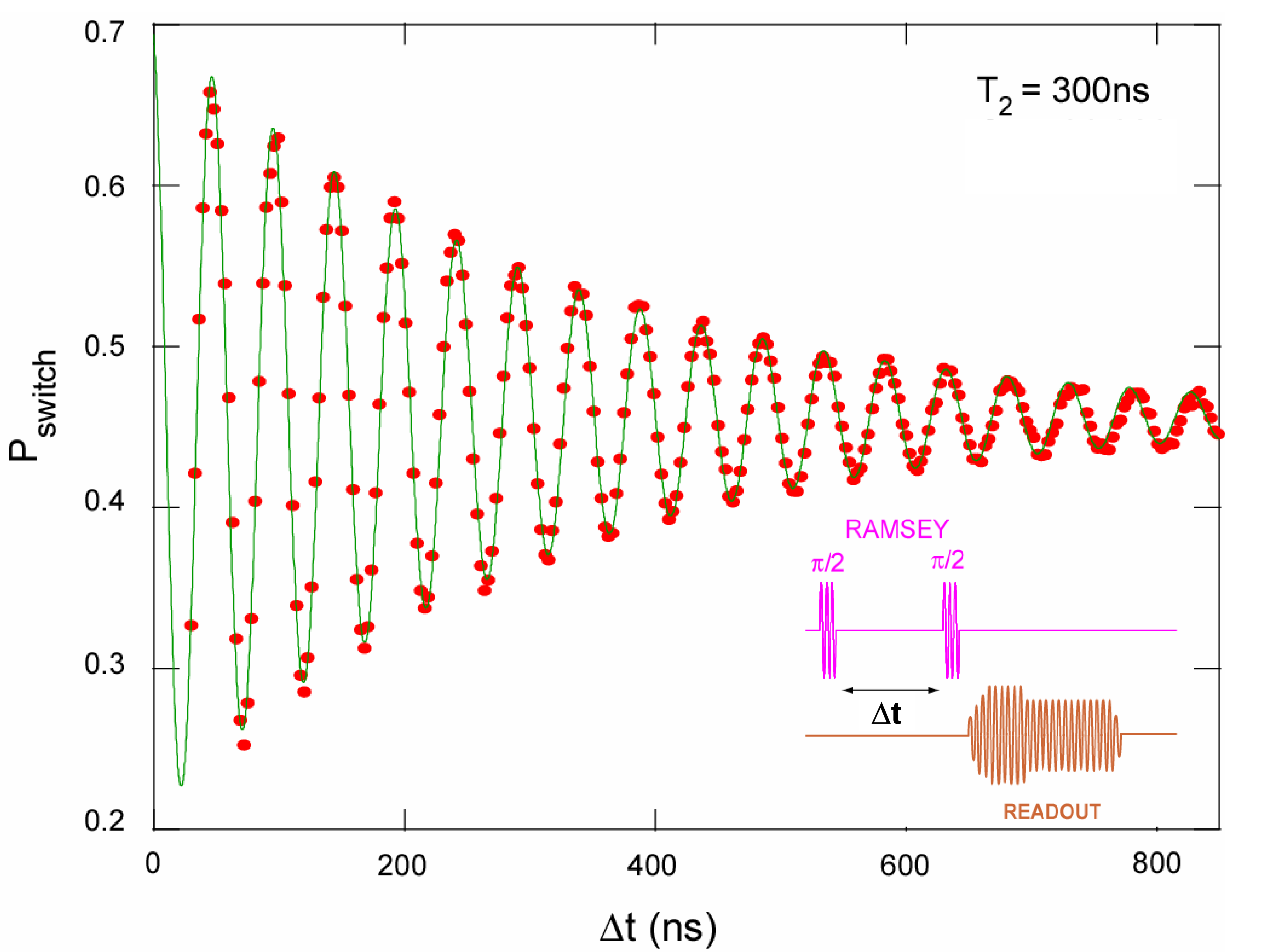
- Exponential decay, T_1 = 1-5 μs
- T_1 >> readout time

PRINCIPLE OF RAMSEY EXPERIMENT (1)



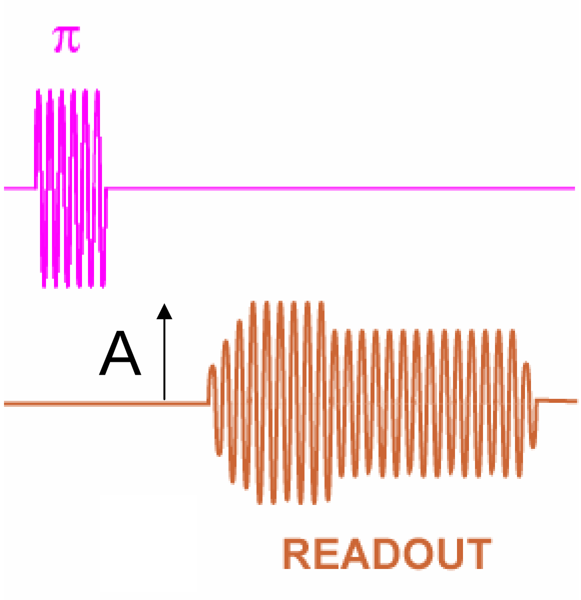
PRINCIPLE OF RAMSEY EXPERIMENT (2)

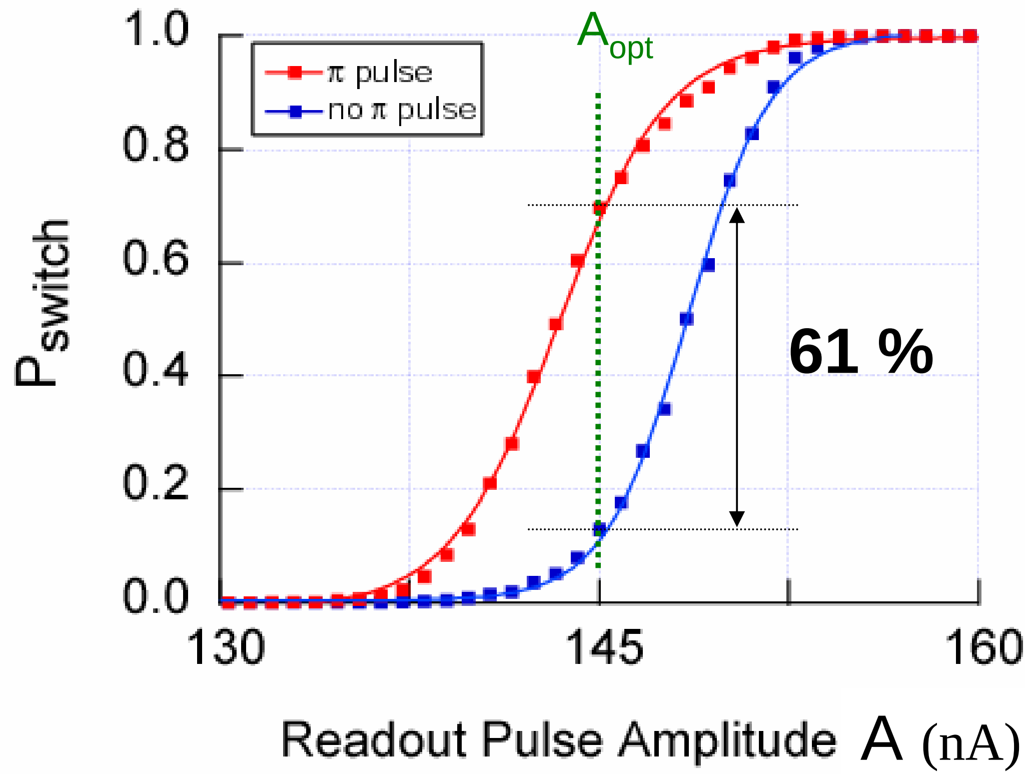




T$_2$ = 300ns
RAMSEY
π/2
π/2
Δt
READOUT
0.7
0.6
0.5
0.4
0.3
0.2
P$_{switch}$
0
200
400
600
800
Δt (ns)

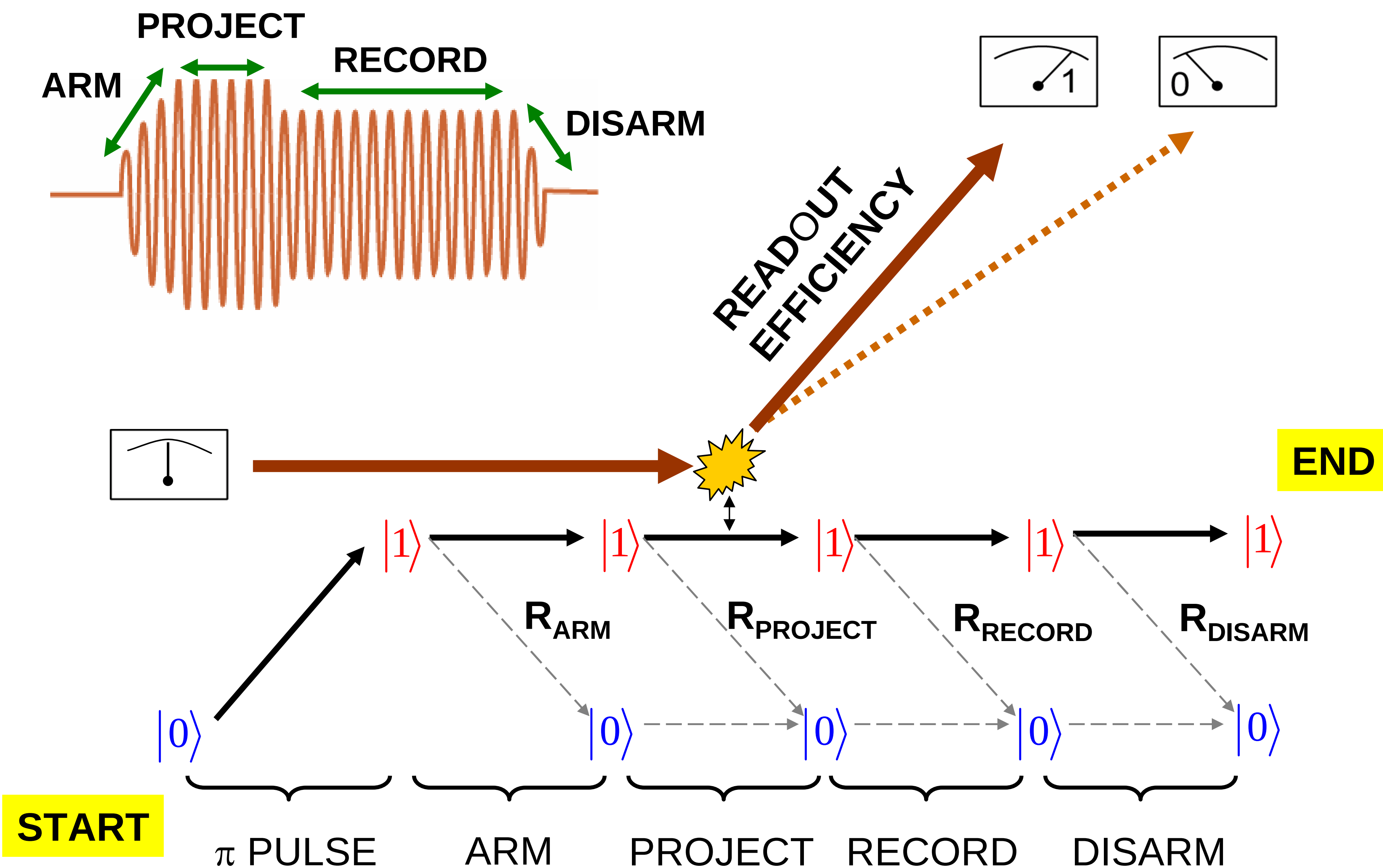
SINGLE READOUT EFFICIENCY



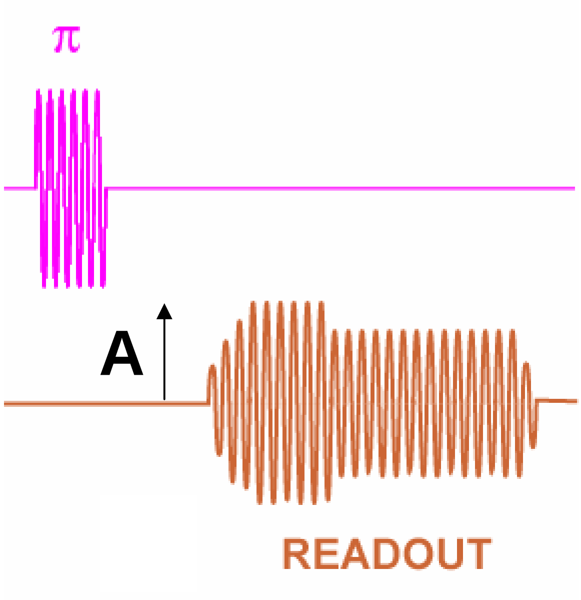


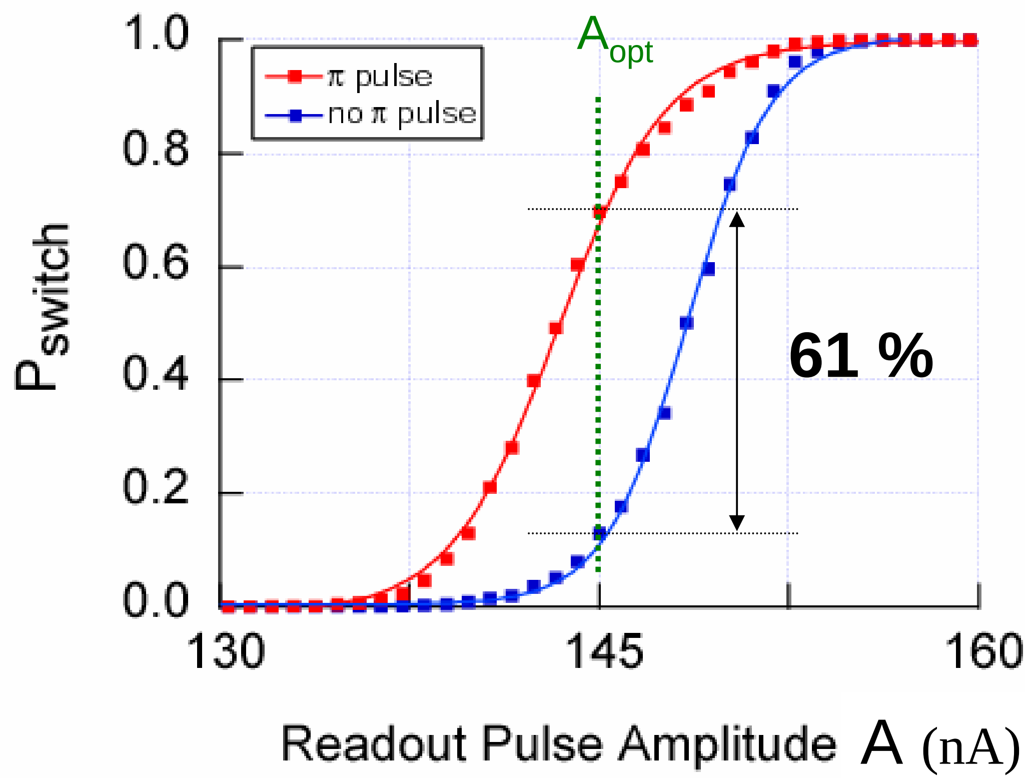
OBSERVED CONTRAST = 61%

INFORMATION FLOW DURING MEASUREMENT



SINGLE READOUT EFFICIENCY

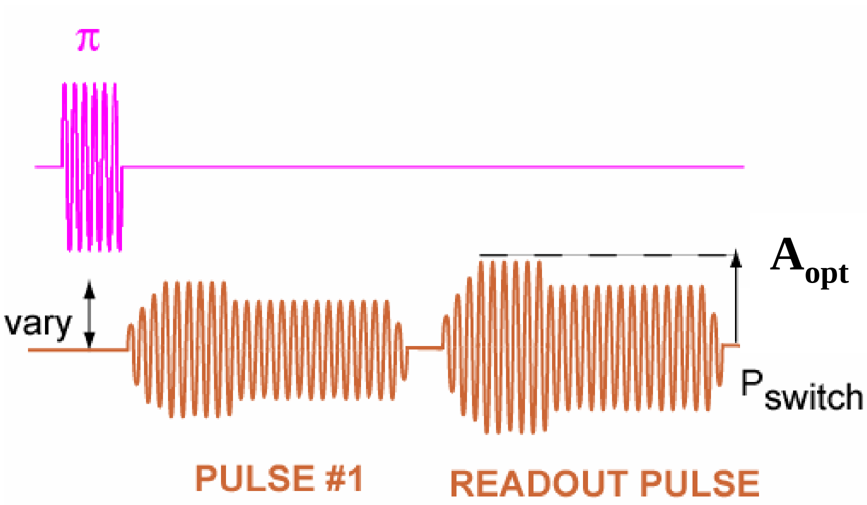


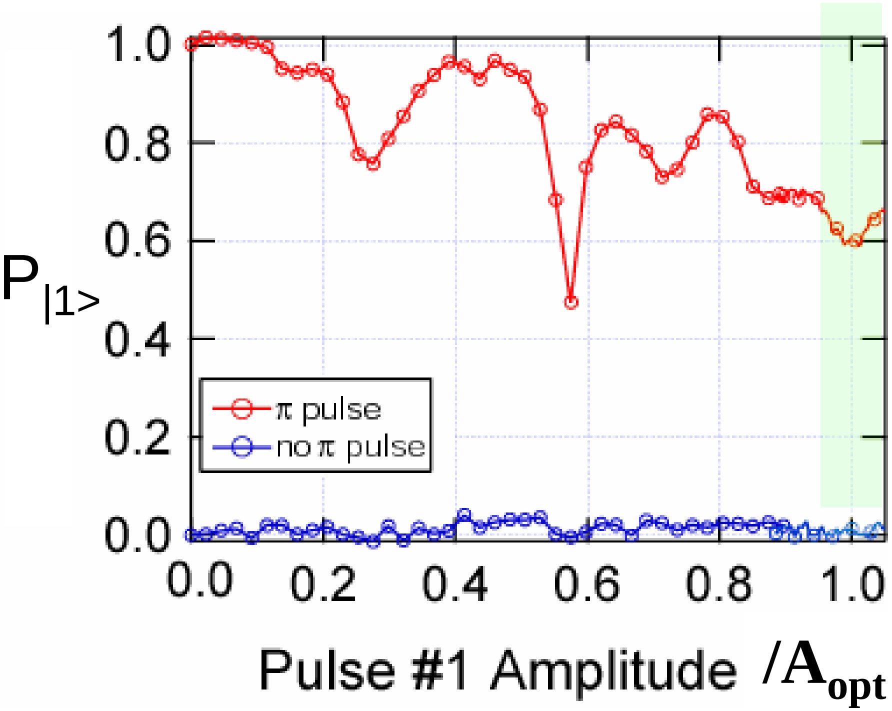


OBSERVED CONTRAST = 61%

$= (1-R_{ARM}) \times (1-R_{PROJECT}) \times (\text{READOUT EFFICIENCY})$

PRE-MEASUREMENT RELAXATION & CONTRAST





- $R_{PROJECT} = 0$ %
- $R_{ARM} = R_{DISARM}$

  (other measurements)

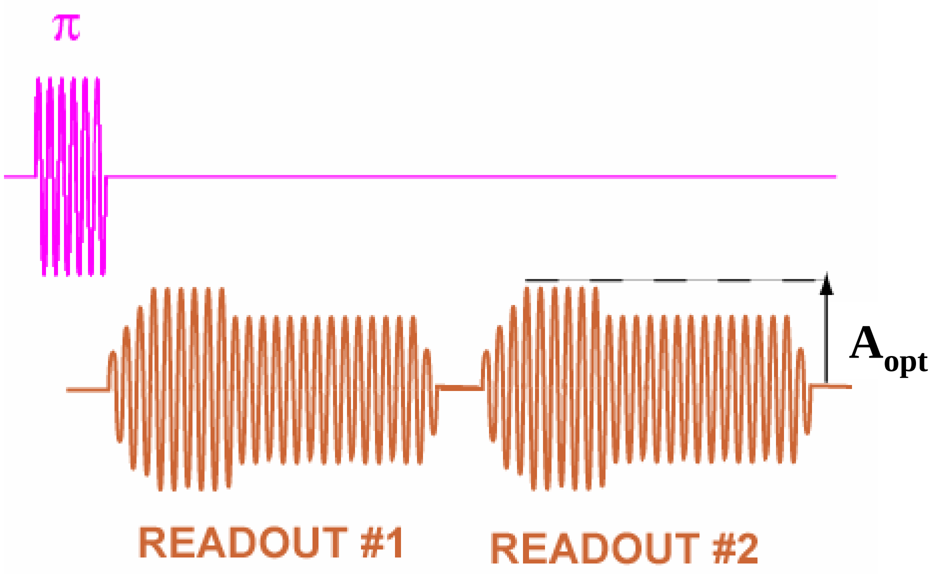
- no excitation of $|0\rangle$
- $(1-R_{ARM}) \times (1-R_{DISARM}) = 66\%$

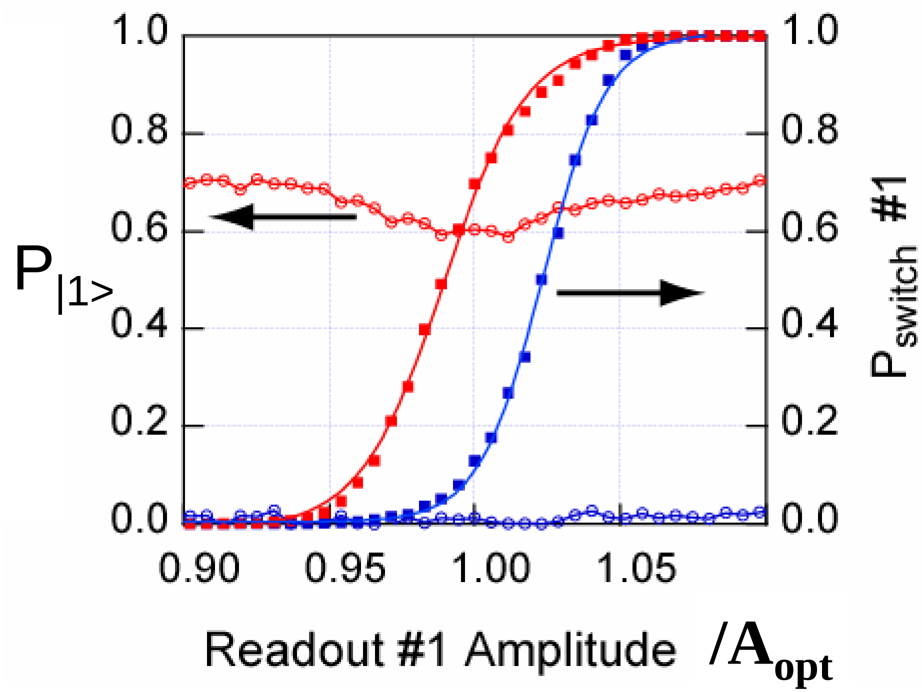
OBSERVED CONTRAST = 61%

R_{ARM} = 19%
(SPURIOUS RESONANCES)

READOUT EFFICIENCY = 75%

POST-MEASUREMENT RELAXATION





R_{RECORD} = 9%

no excitation of $|0\rangle$ due to switching

QND FRACTION =

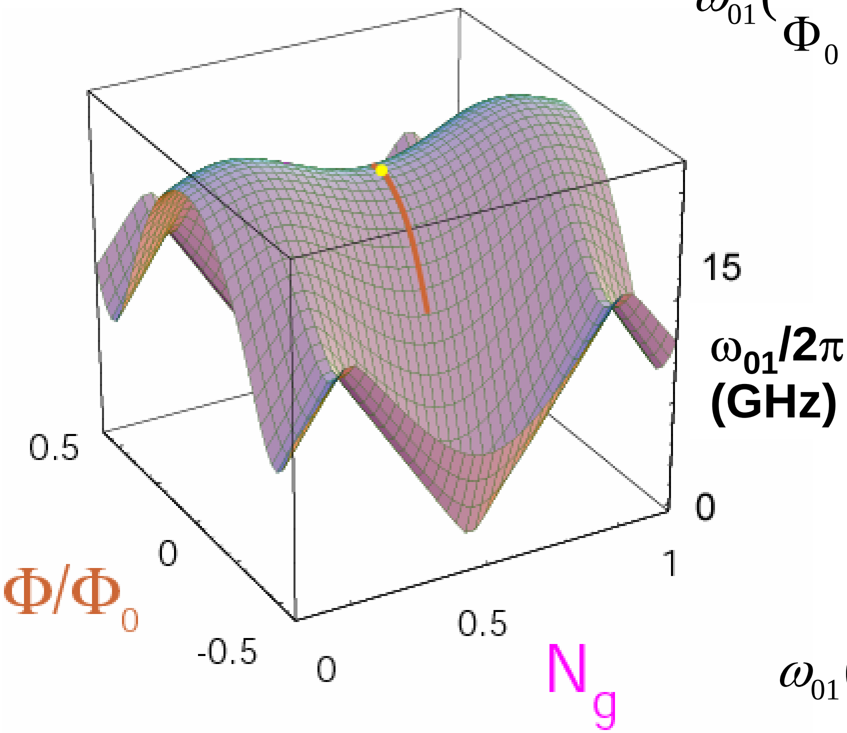
$(1\text{-}R_{ARM})(1\text{-}R_{DISARM})(1\text{-}R_{PROJECT})(1\text{-}R_{RECORD}) = 60\%$

66% 100% 91%

"UNKNOWN DEFECTS" "MEASUREMENT"

PHASE PORT STARK SHIFT

$$\omega_{01}\left(\frac{\Phi}{\Phi_0}, N_g\right) \approx \omega_{01}^{N_g=1/2,\ \Phi=0}\left[1 - a\left(\frac{\Phi}{\Phi_0}\right)^2 + b\left(N_g - \frac{1}{2}\right)^2\right]$$



Readout

$$N_g = \frac{1}{2}$$

$$\delta(t) = \delta_{\max}\sin(\omega t) \Rightarrow \Phi(t) = \Phi_{\max}\sin(\omega t)$$

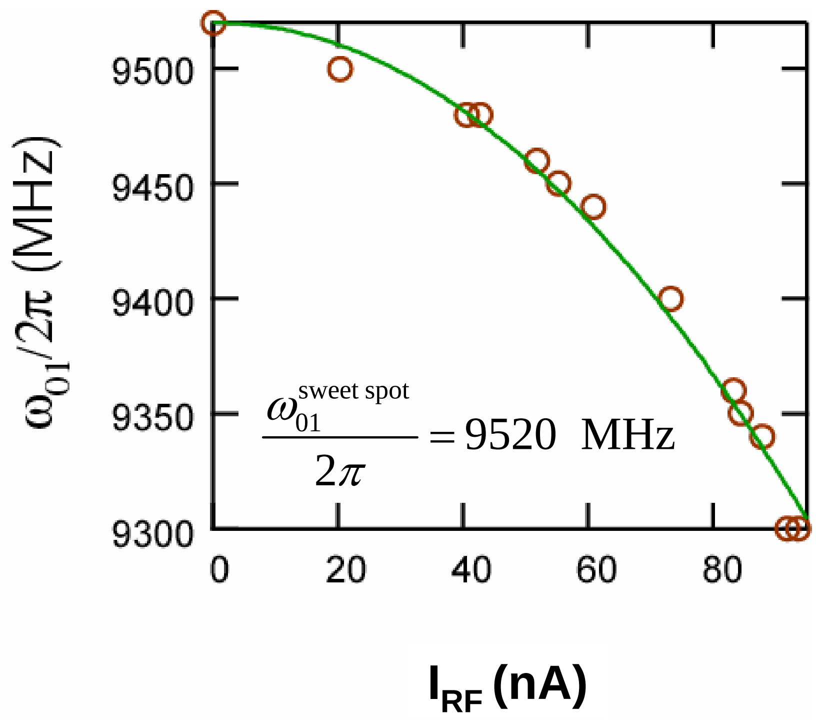
$$\omega_{01}\left(\frac{\Phi}{\Phi_0}, N_g\right) \approx \omega_{01}^{N_g=1/2,\ \Phi=0}\left[1 - a\left(\frac{\Phi_{\max}}{\Phi_0}\right)^2 \sin^2(\omega t)\right]$$

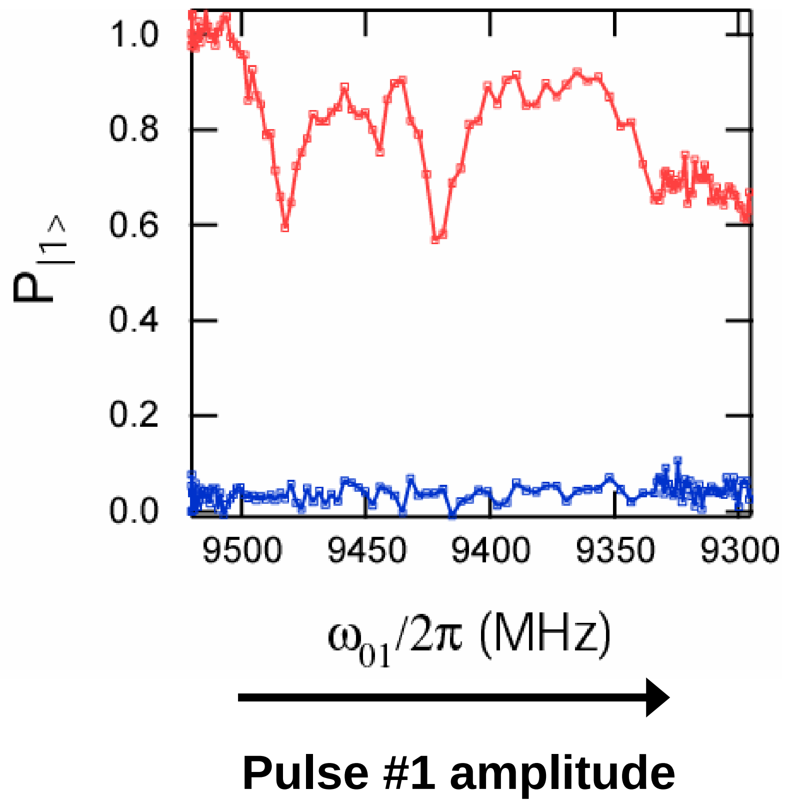
$$(\omega_{01} - \omega) \gg \frac{\omega_{01}}{Q_{01}}$$

$$\tau_{\text{operation}} \gg \frac{2\pi}{\omega}$$

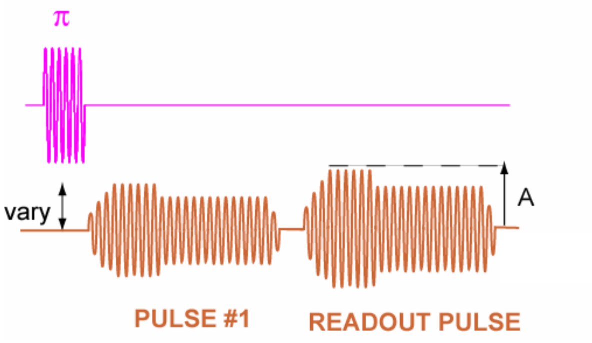
$$\omega_{01}\left(\frac{\Phi}{\Phi_0}, N_g\right) \approx \omega_{01}^{N_g=1/2,\ \Phi=0}\left[1 - \frac{a}{2}\left(\frac{\Phi_{\max}}{\Phi_0}\right)^2\right]$$

FLUCTUATORS at $\omega < \omega_{01}$



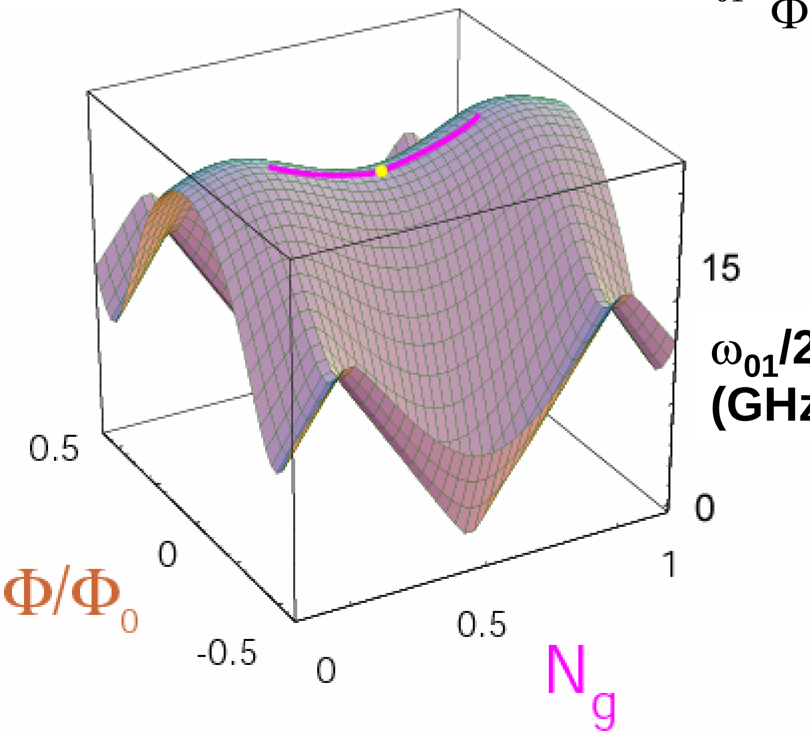


- **Readout pulse lowers ω_{01}**
- **When $\omega_{01}=\omega_{fluctuator}$ → relaxation**



CHARGE PORT STARK SHIFT

$$\omega_{01}(\frac{\Phi}{\Phi_0}, N_g) \approx \omega_{01}^{N_g=1/2,\ \Phi=0}\left[1 - a\left(\frac{\Phi}{\Phi_0}\right)^2 + b\left(N_g - \frac{1}{2}\right)^2\right]$$



$$\Phi = 0$$

$$N_g(t) = N_{g0}\sin(\Omega t) + \frac{1}{2}$$

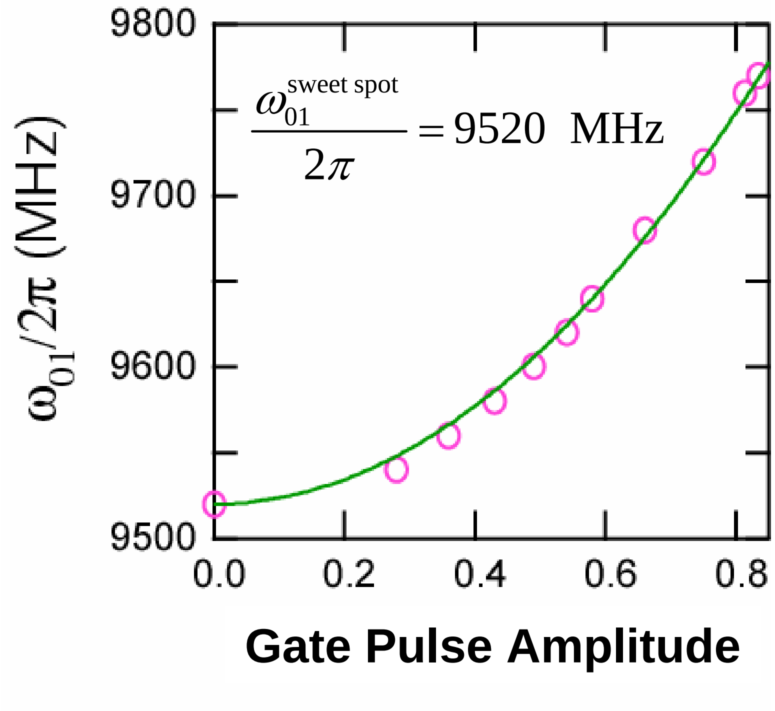
$$\omega_{01}(\frac{\Phi}{\Phi_0}, N_g) \approx \omega_{01}^{N_g=1/2,\ \Phi=0}\left[1 + bN_{g0}^{\ 2}\sin^2(\Omega t)\right]$$

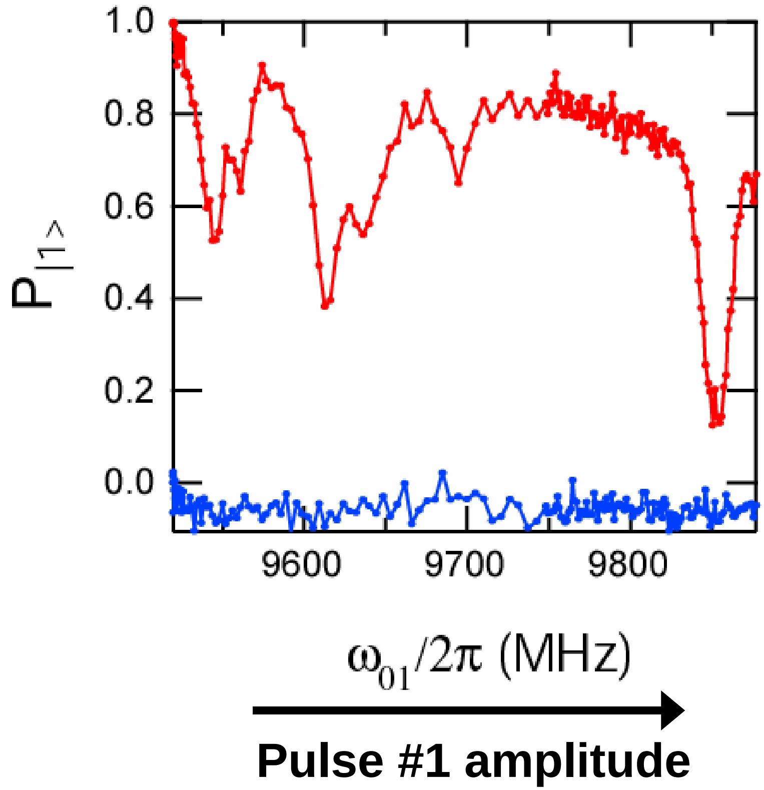
$$(\omega_{01} - \Omega) \gg \frac{\omega_{01}}{Q_{01}}$$

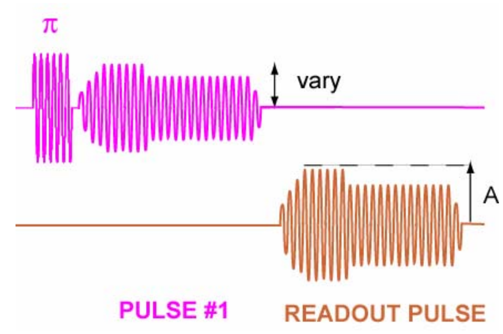
$$\tau_{\text{operation}} \gg \frac{2\pi}{\Omega}$$

$$\omega_{01}(\frac{\Phi}{\Phi_0}, N_g) \approx \omega_{01}^{N_g=1/2,\ \Phi=0}\left[1 + \frac{b}{2}\left(N_{g0}\right)^2\right]$$

FLUCTUATORS at $\omega > \omega_{01}$

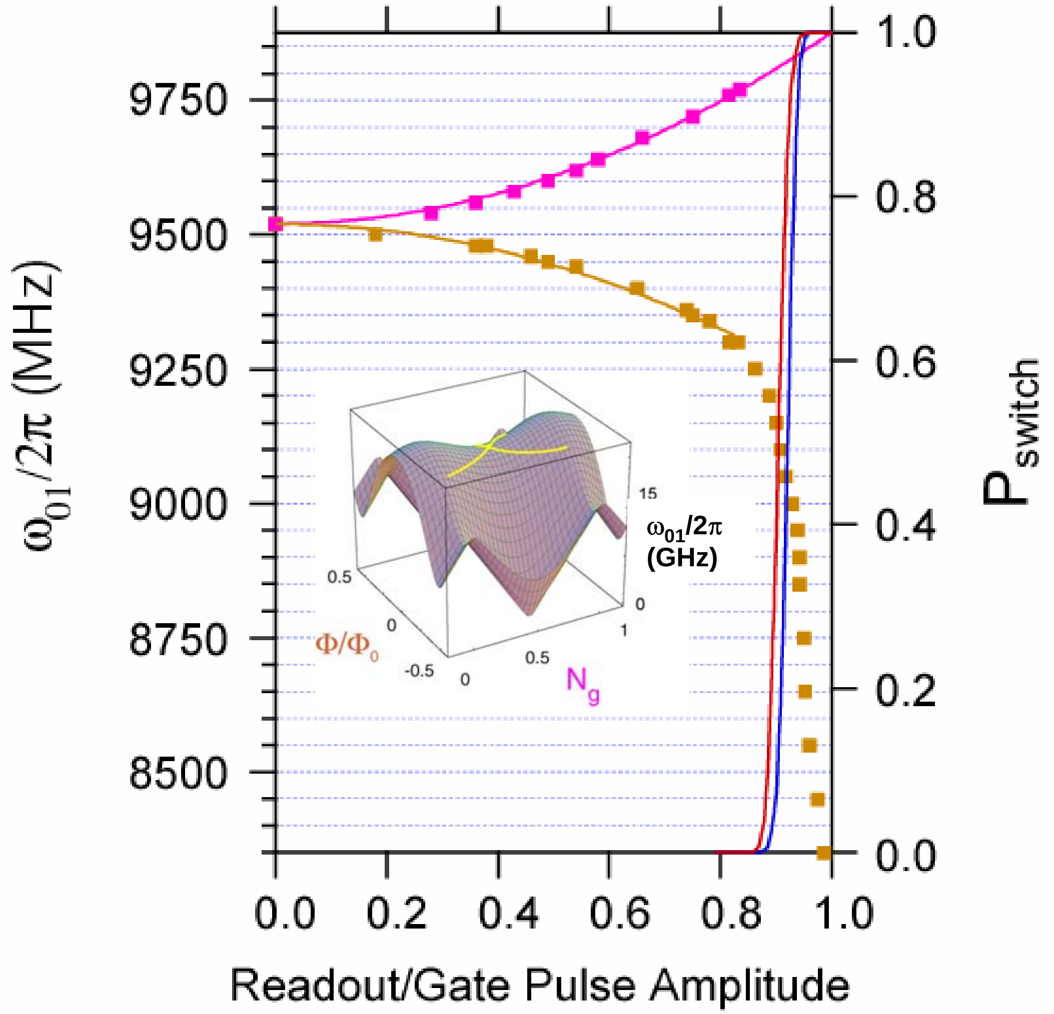


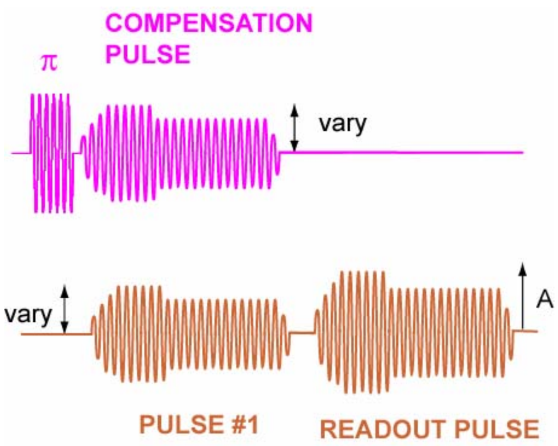


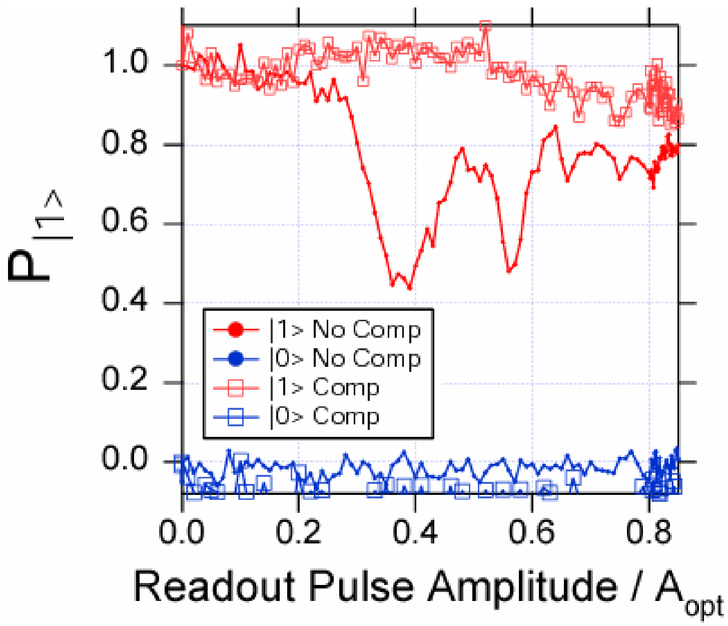


- **Gate pulse raises ω_{01}**
- **When $\omega_{01}=\omega_{fluctuator} \rightarrow$ relaxation**

STARK COMPENSATION







SUMMARY

HIGH SPEED QUBIT READOUT:

- Readout ON: $T_1 / \tau_{meas} >> 1$ ☑ (4-20)
- Readout OFF: T_1, T_2 not reduced ☑
- Short duty cycle ☑ (4 MHz)
- No energy dissipated on chip ☑

COHERENCE MEASUREMENTS:

- T_1 = 1-5 μs
- T_2 = 300 ns

INFORMATION FLOW:

- Observed Contrast = 61% (Predict 75%)
- Characterize Pre/Post Measurement Relaxation
- Spectroscopy of Qubit Environment
- Stark Shift Compensation