Spin-Based Qubits:
Recent Experiments and Integration Scenarios

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Material:
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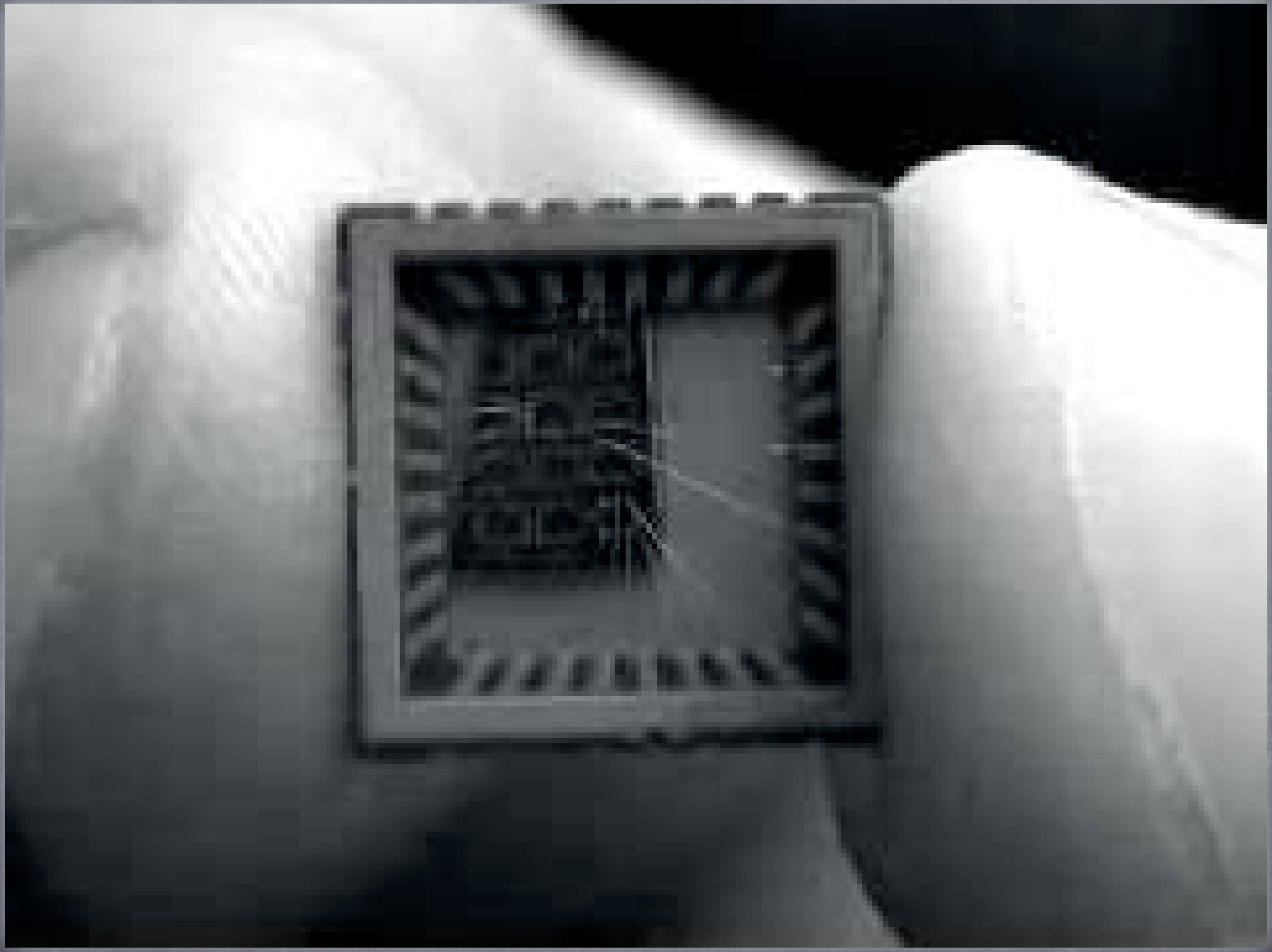
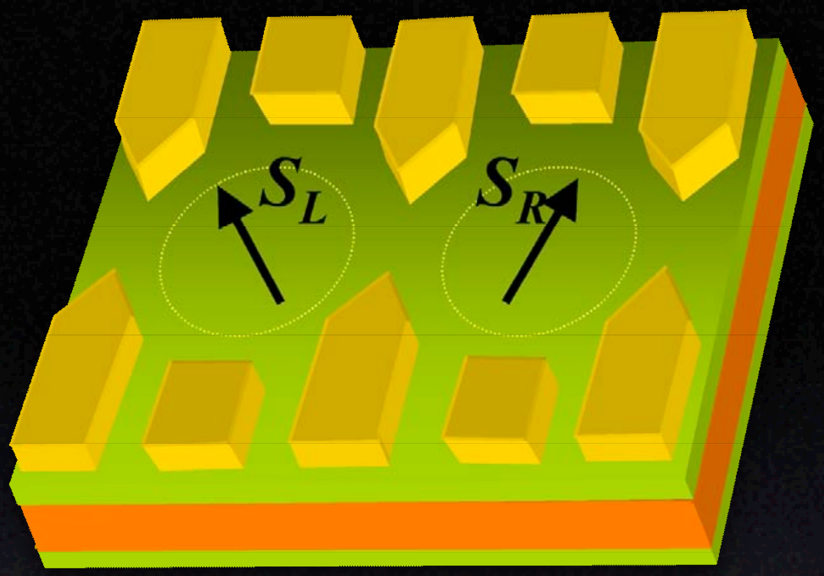
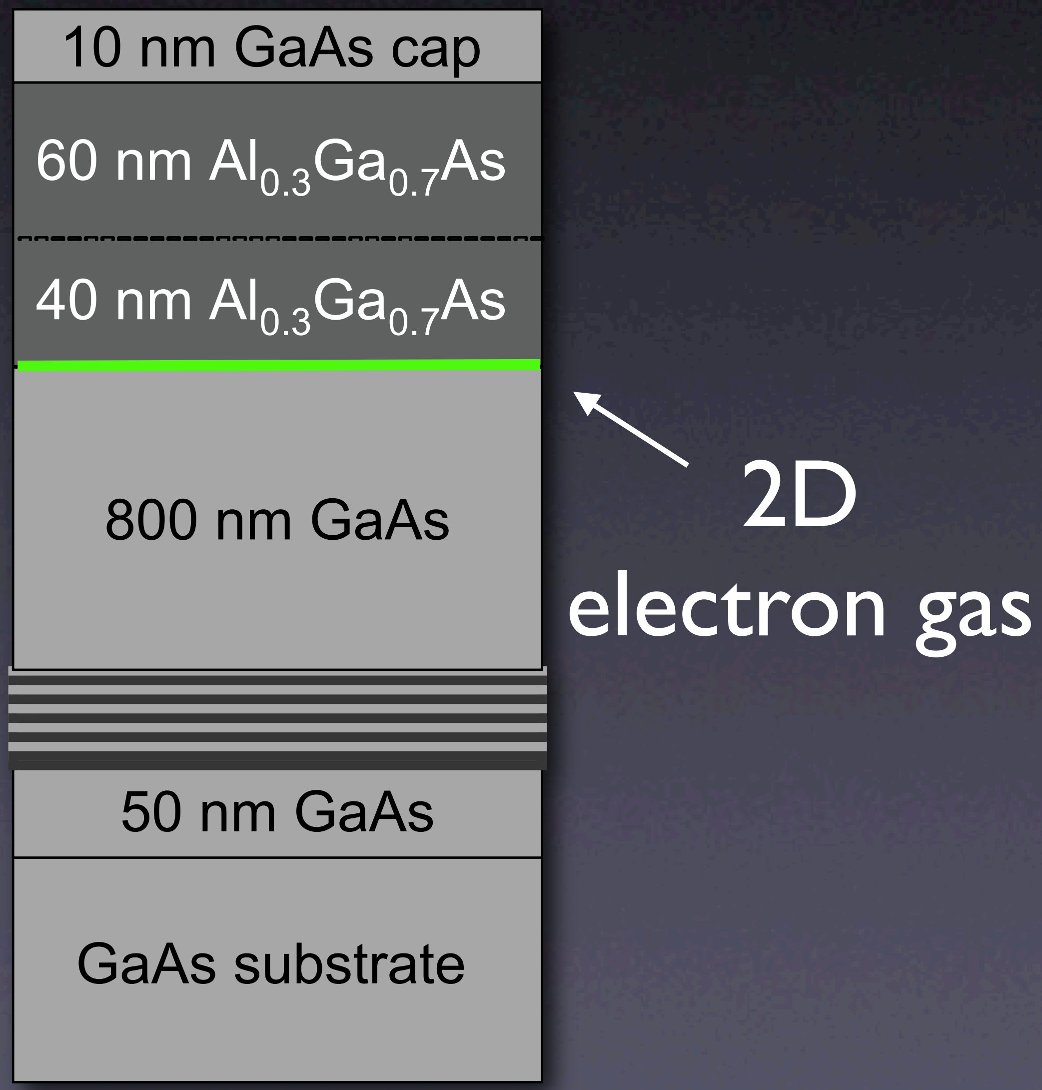
Support:
DARPA, ARO/DTO, NSA-LPS, NSF



Semiconductor Doublet Dot Device




10 nm GaAs cap

60 nm $Al_{0.3}Ga_{0.7}As$

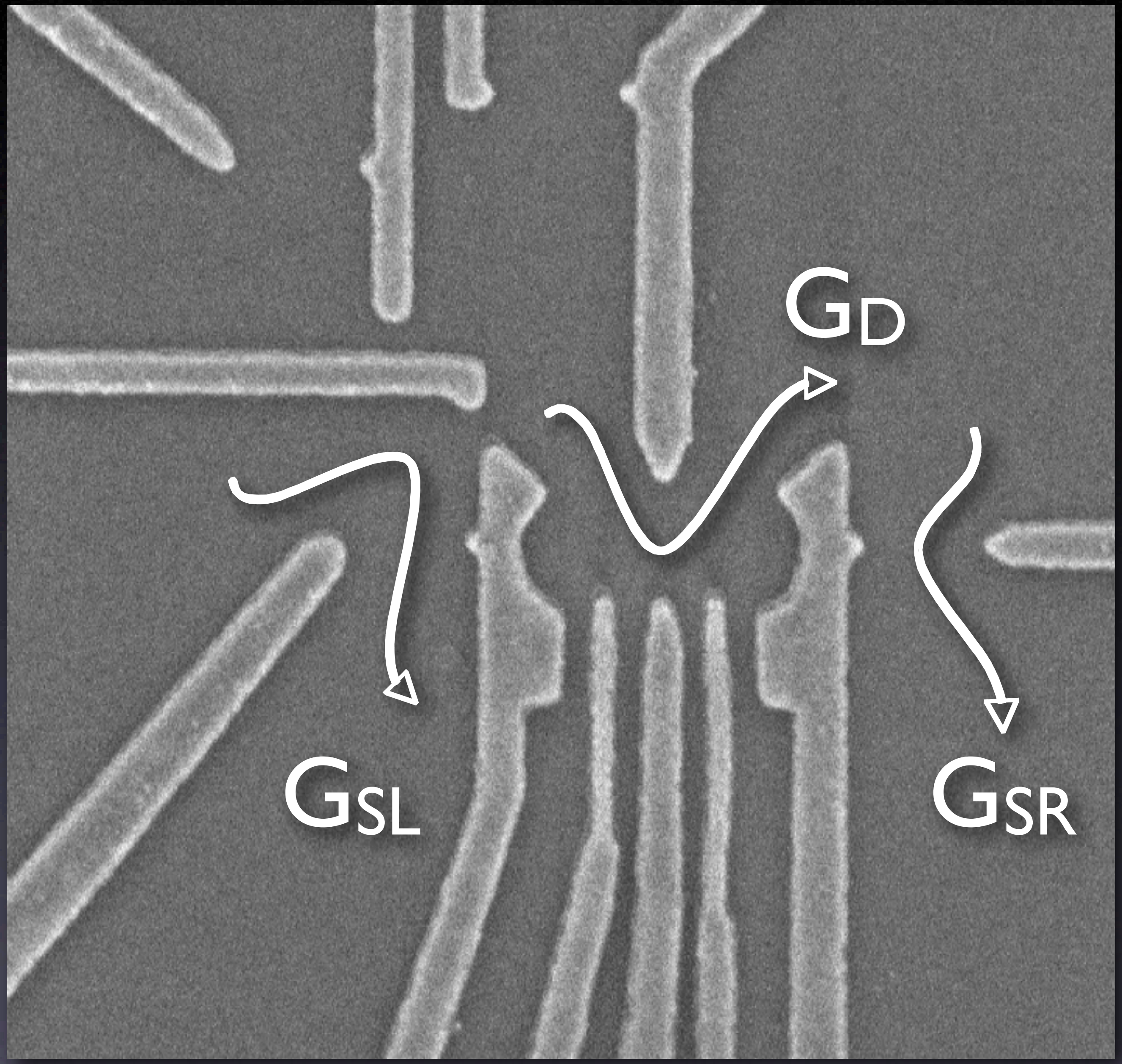
40 nm $Al_{0.3}Ga_{0.7}As$

800 nm GaAs

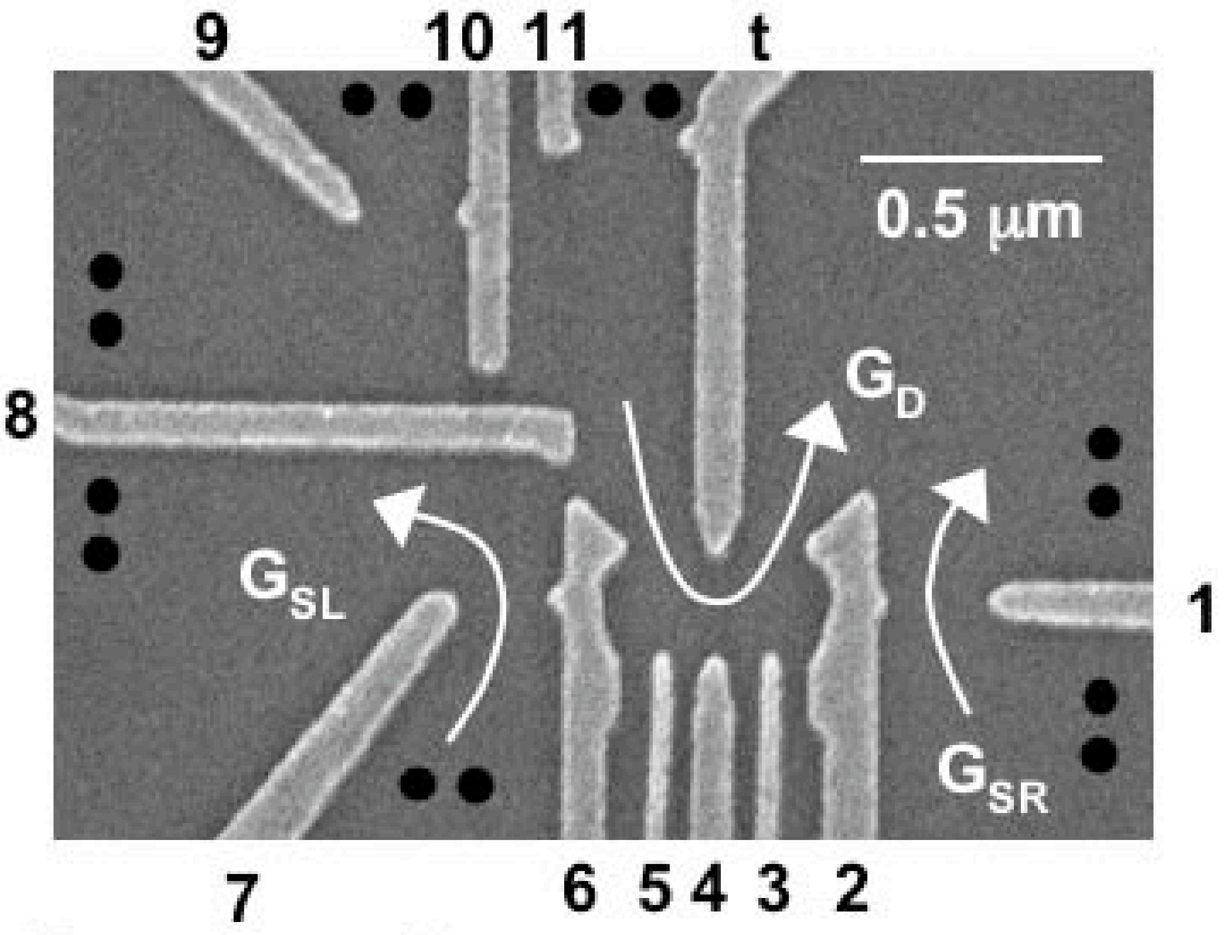
50 nm GaAs

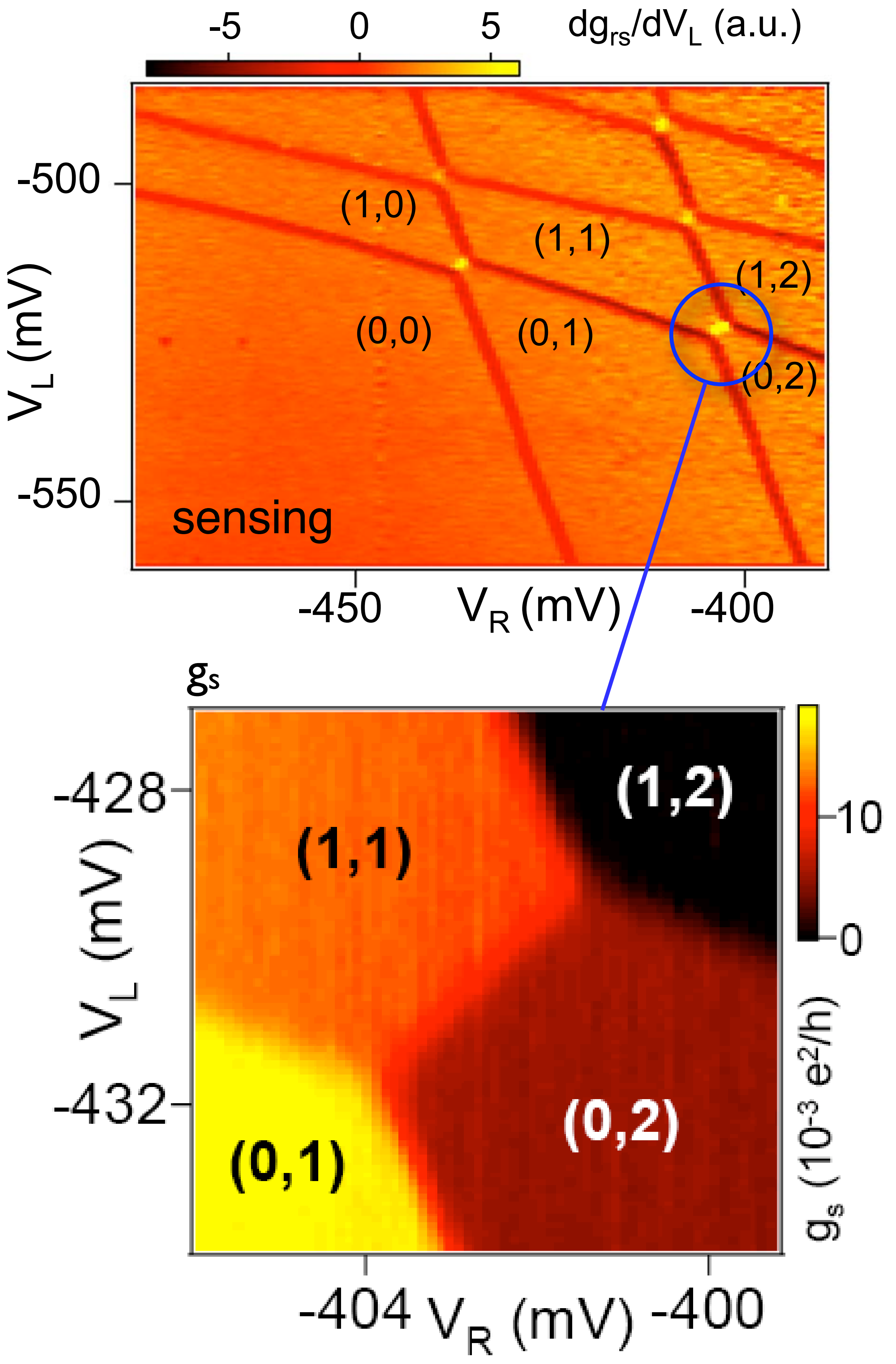
GaAs substrate

2D electron gas

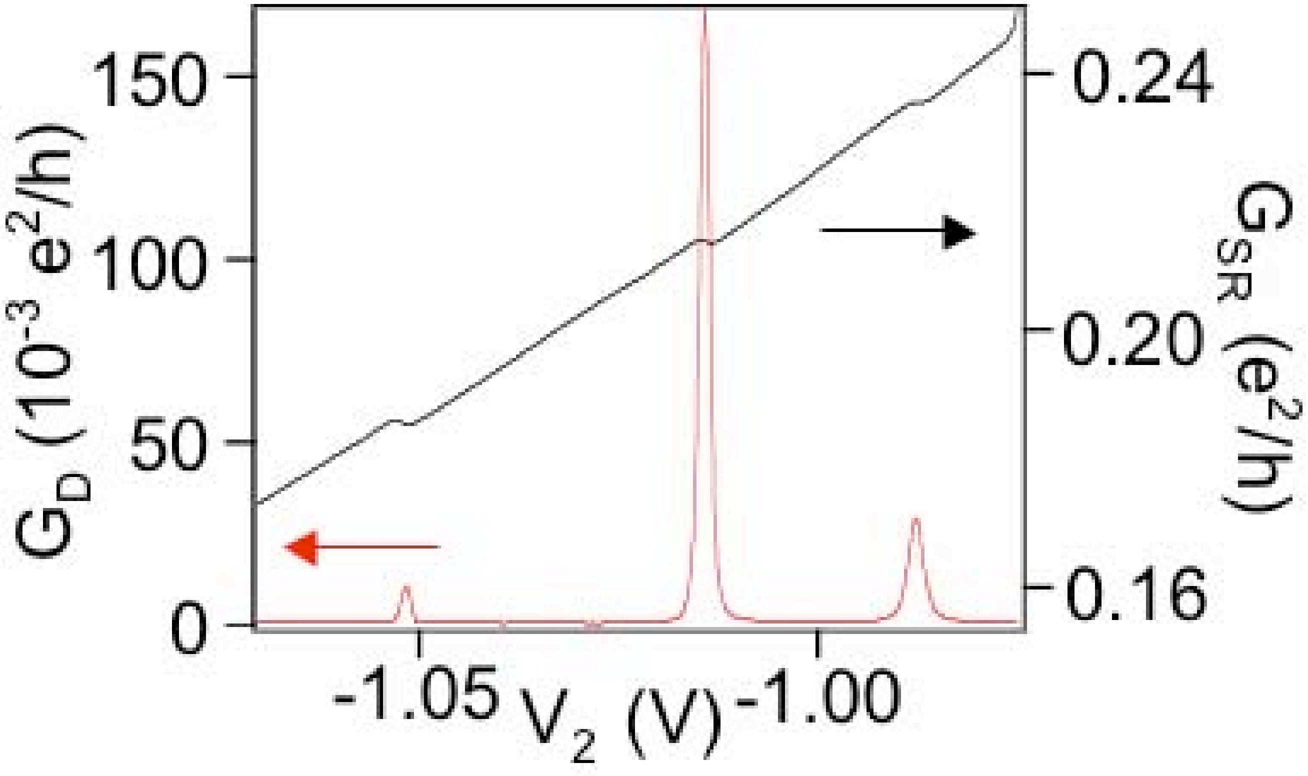


Charge transport in a double dot



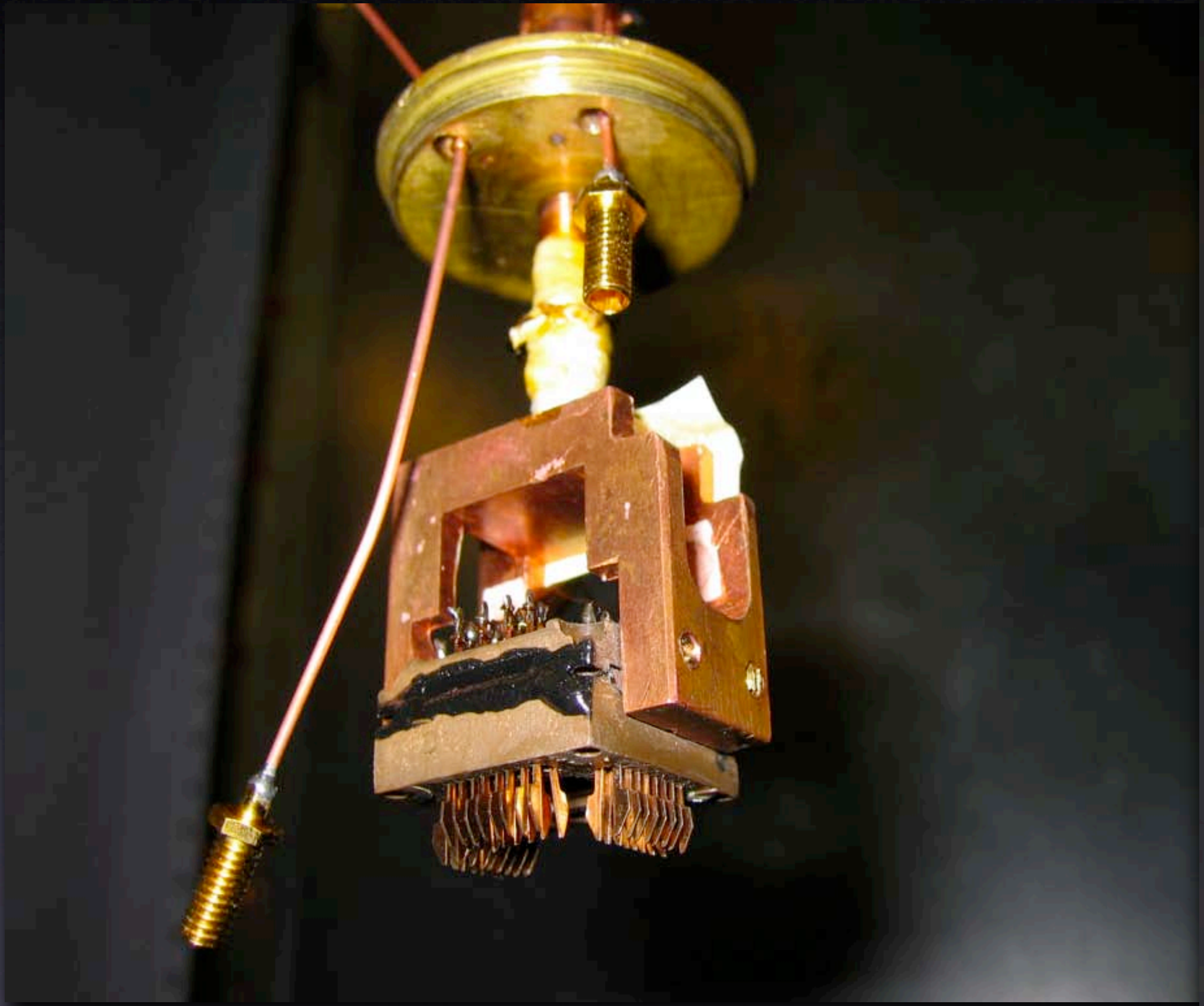


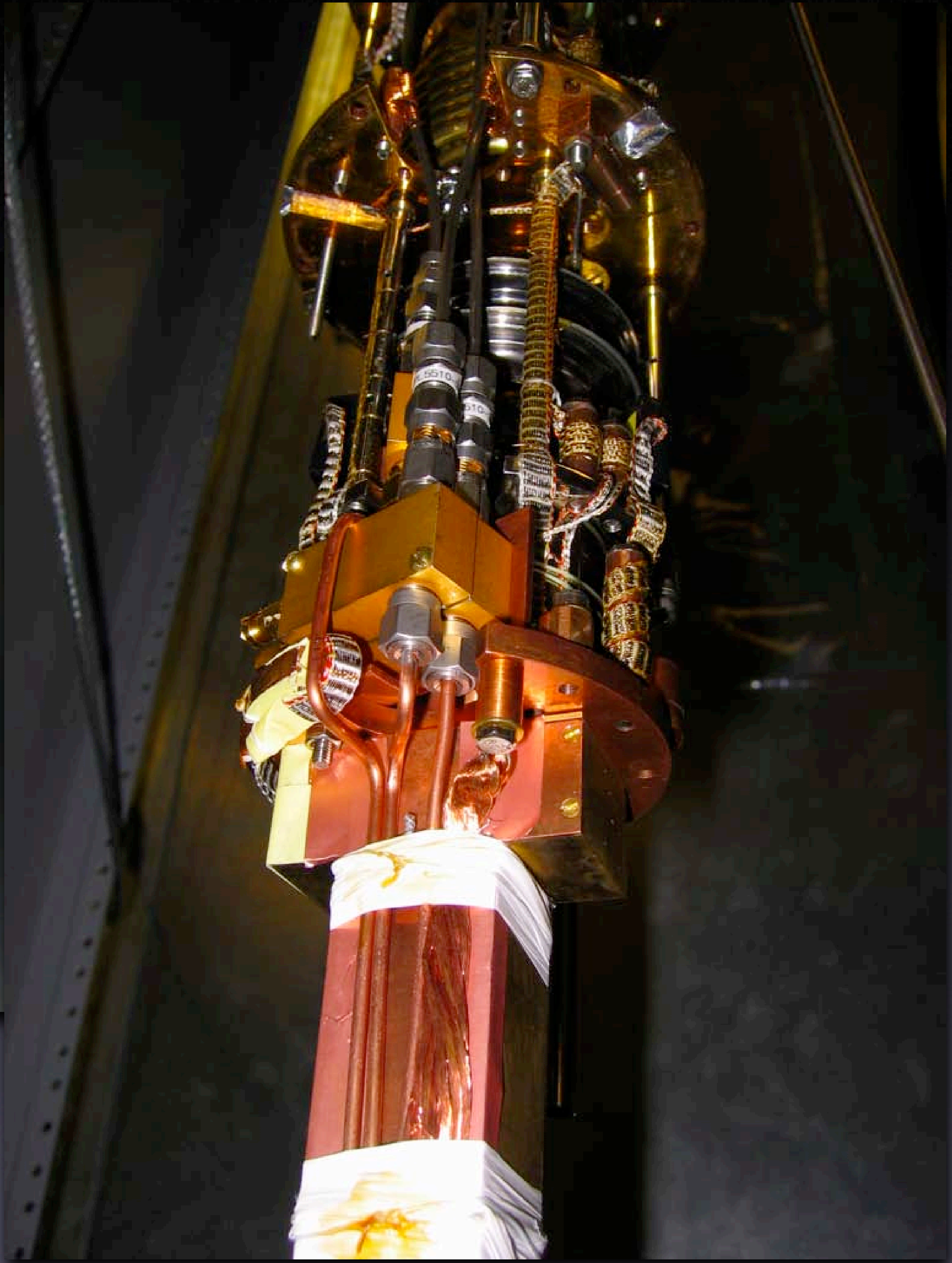
Charge sensing



QPC sensing: Field *et al*., PRL **70**, 1311 (1993)

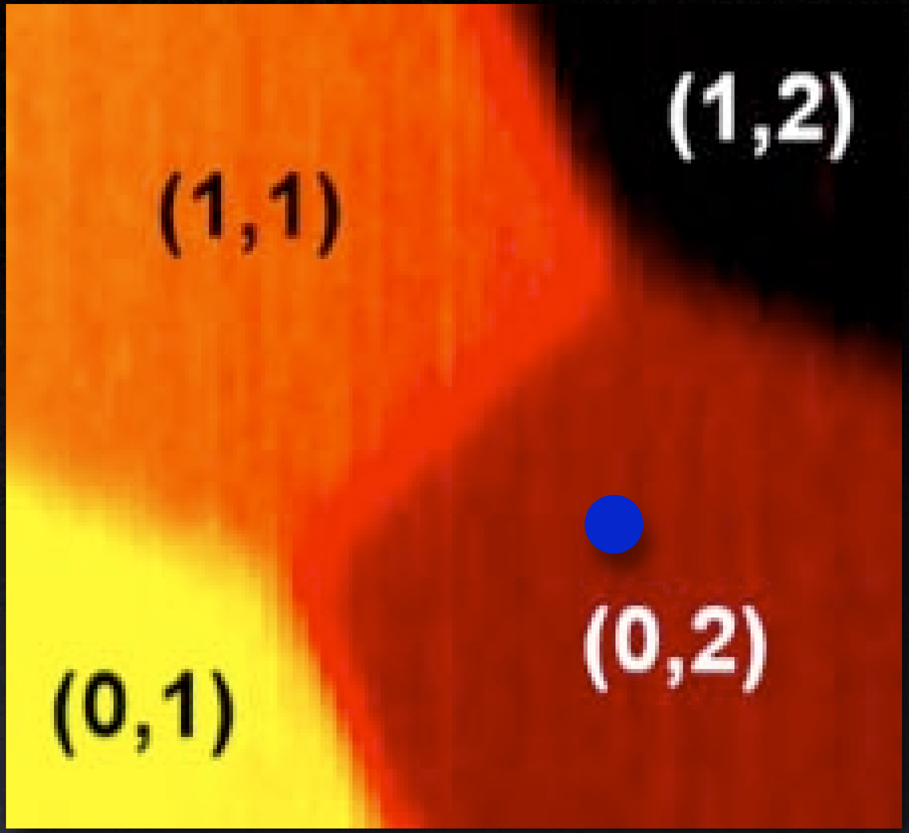
High-bandwidth dilution refrigerator

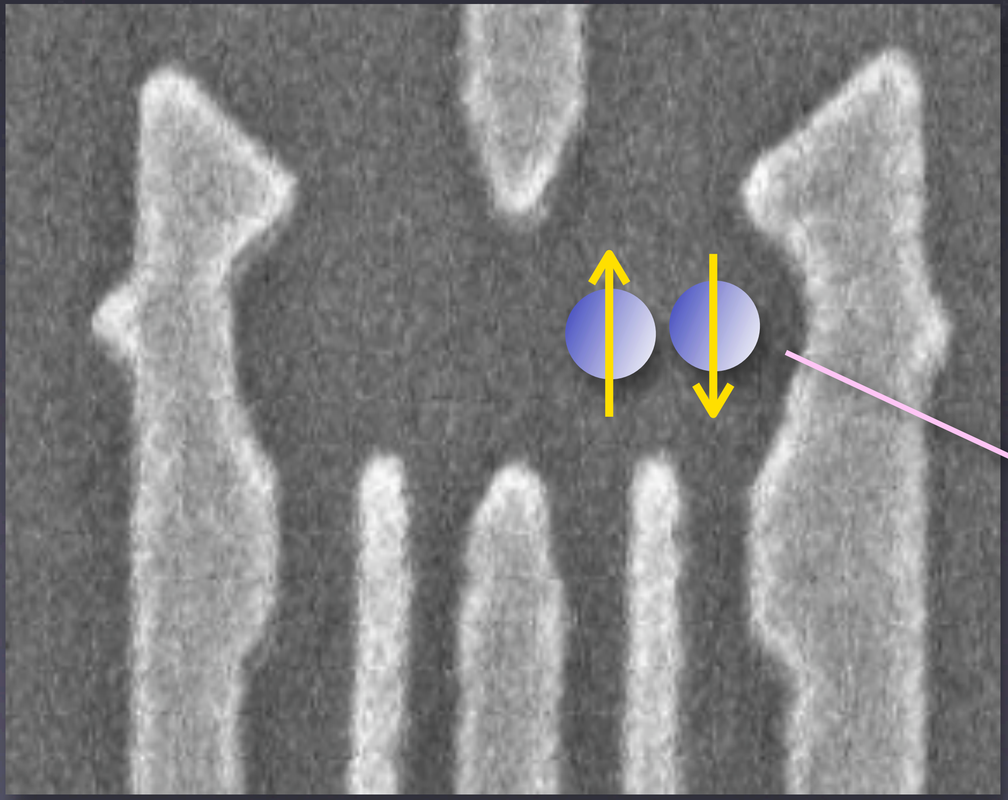


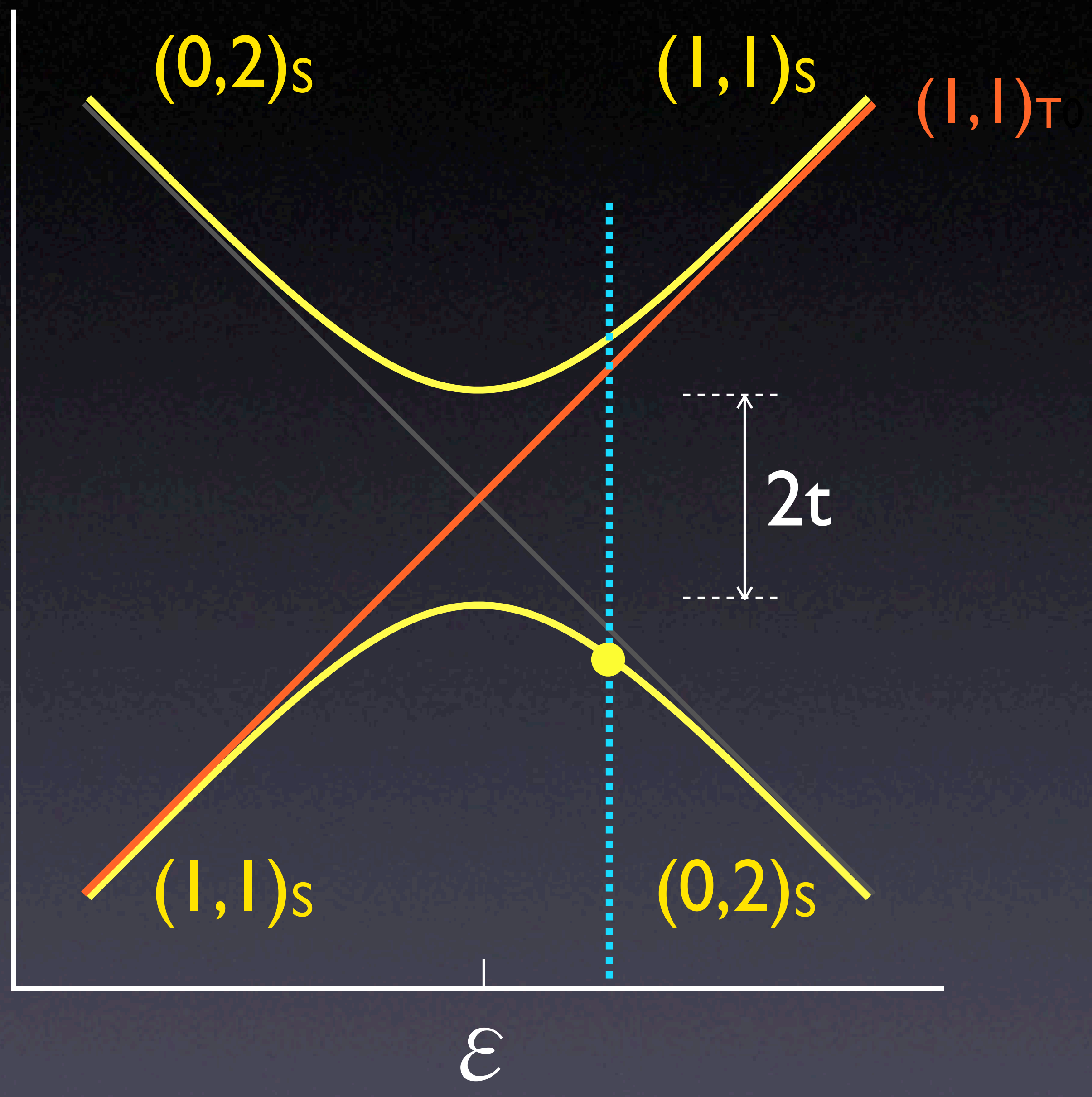


Pulses with 1ns rise time applied
using Tektronix AWG 520
arbitrary waveform generators

Measuring Spin Dephasing (T2*): Time-domain Interferometry



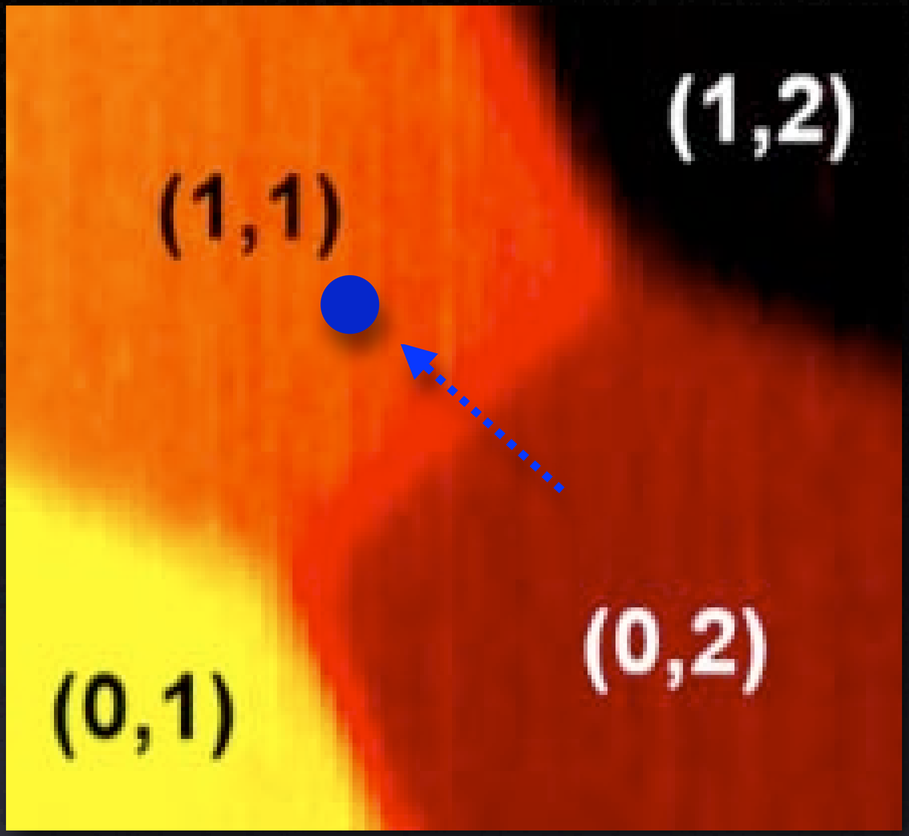


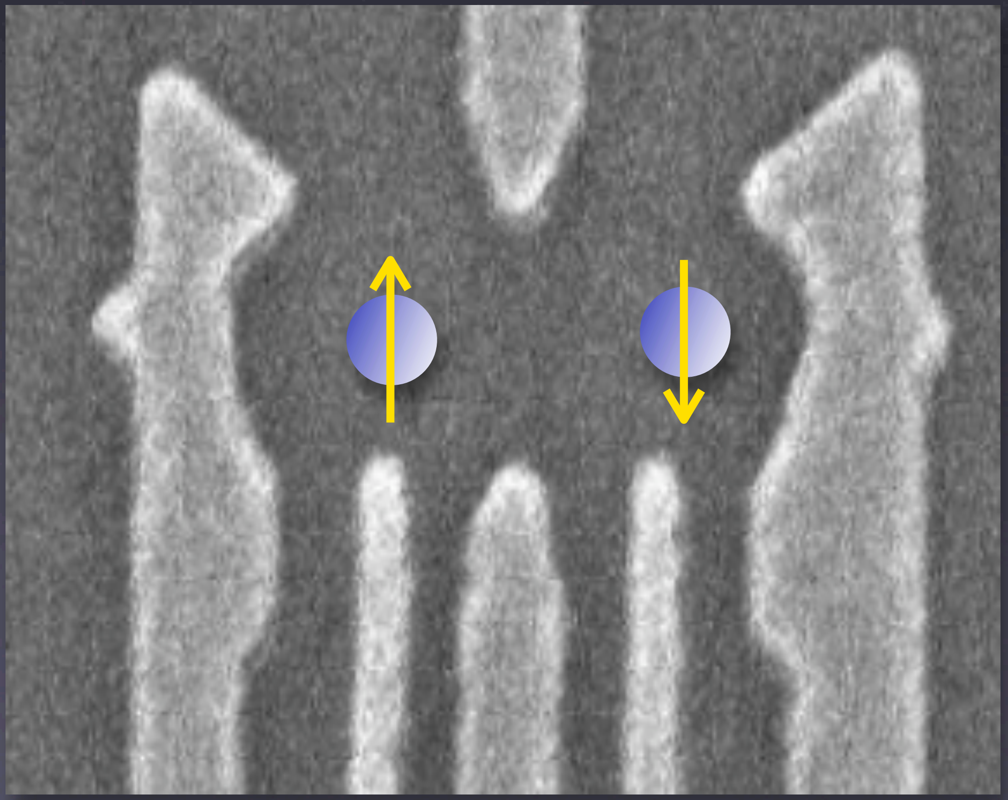


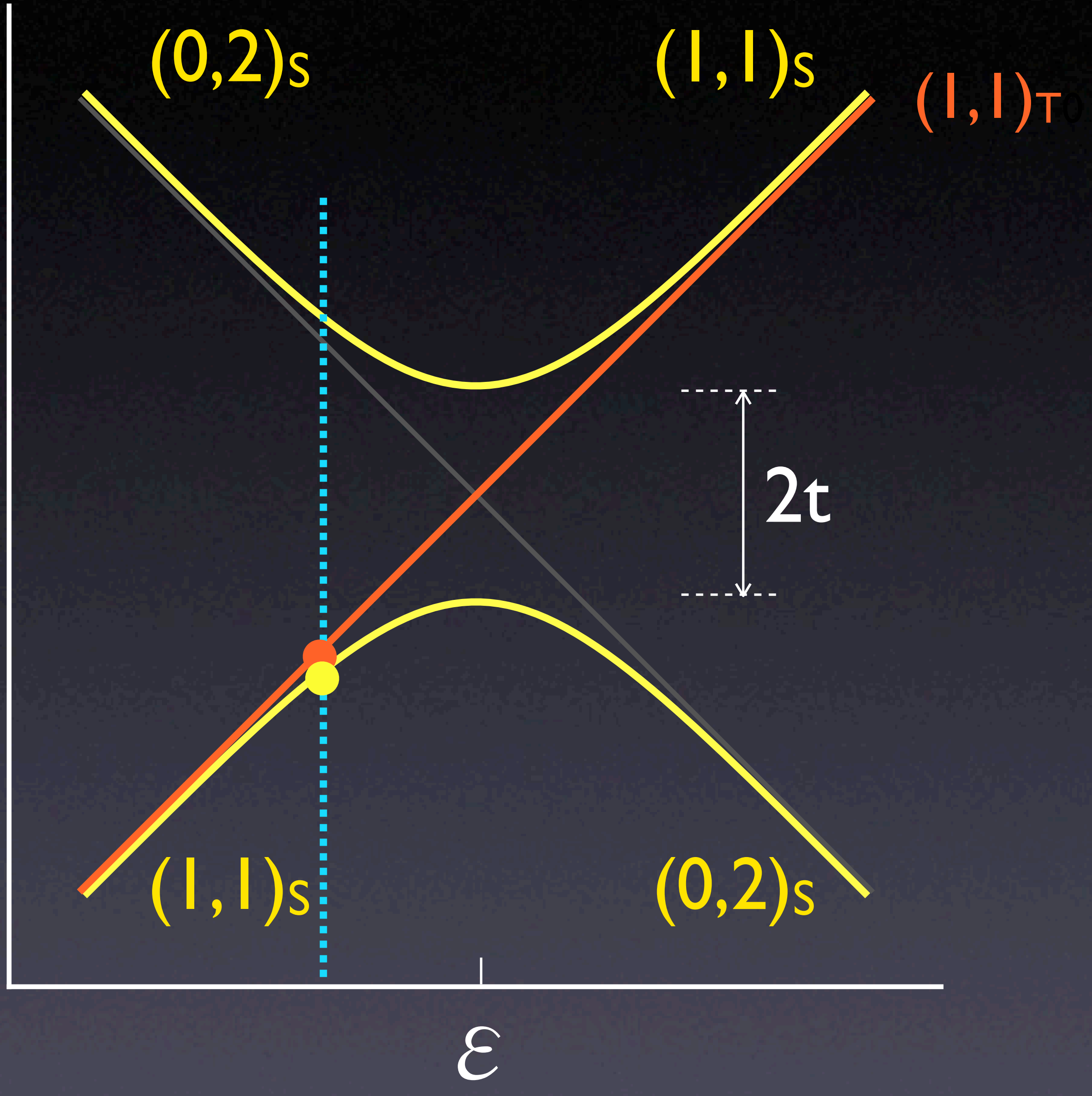
(0,2) triplets are unavailable
~ 4K above (0,2)S.

J. R. Petta, A. C. Johnson, J. Taylor, A. Yacoby, M.D. Lukin,
M. Hanson, A. C. Gossard, CMM Science **309** 2180 (2005)

Measuring Spin Dephasing ($T2^*$): Time-domain Interferometry

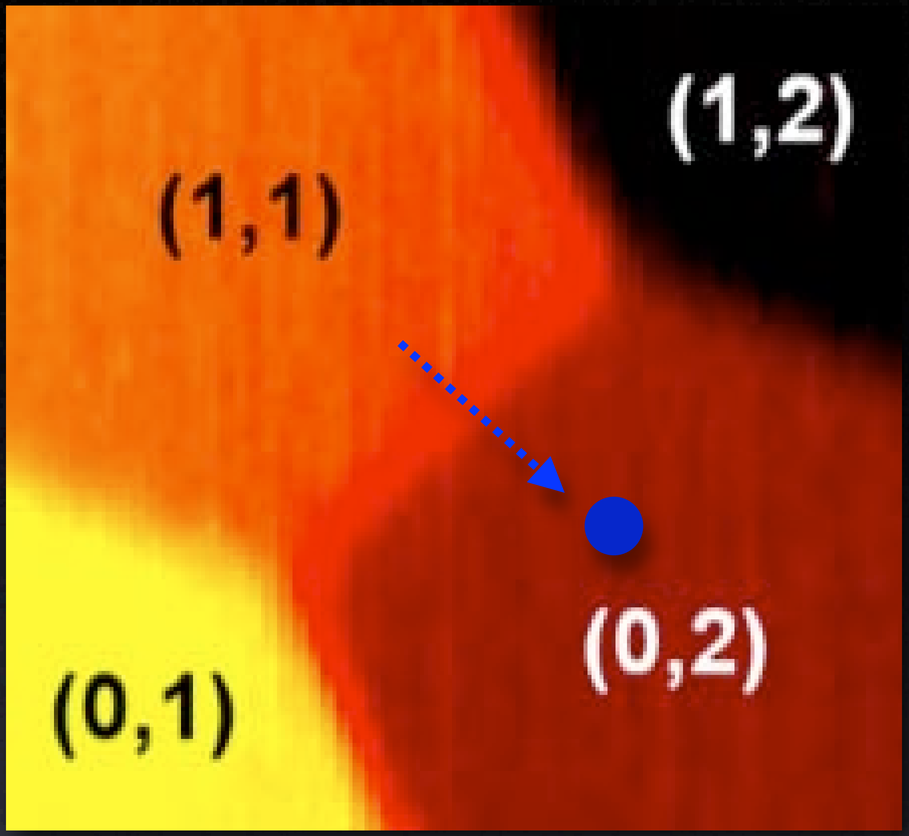


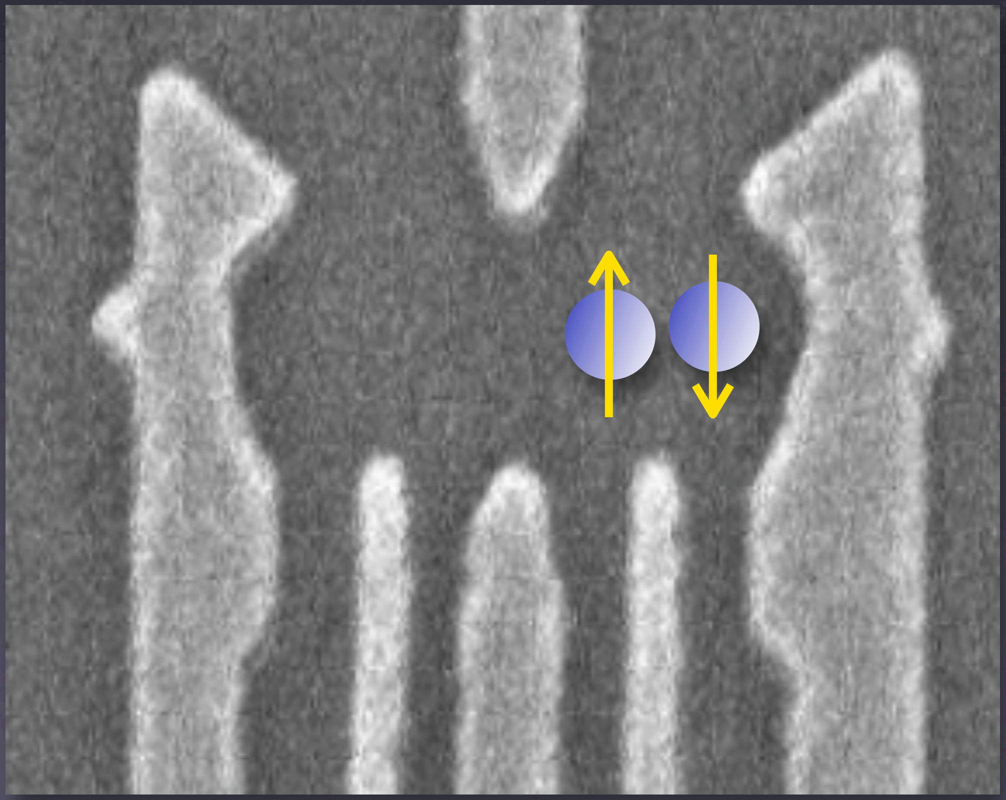


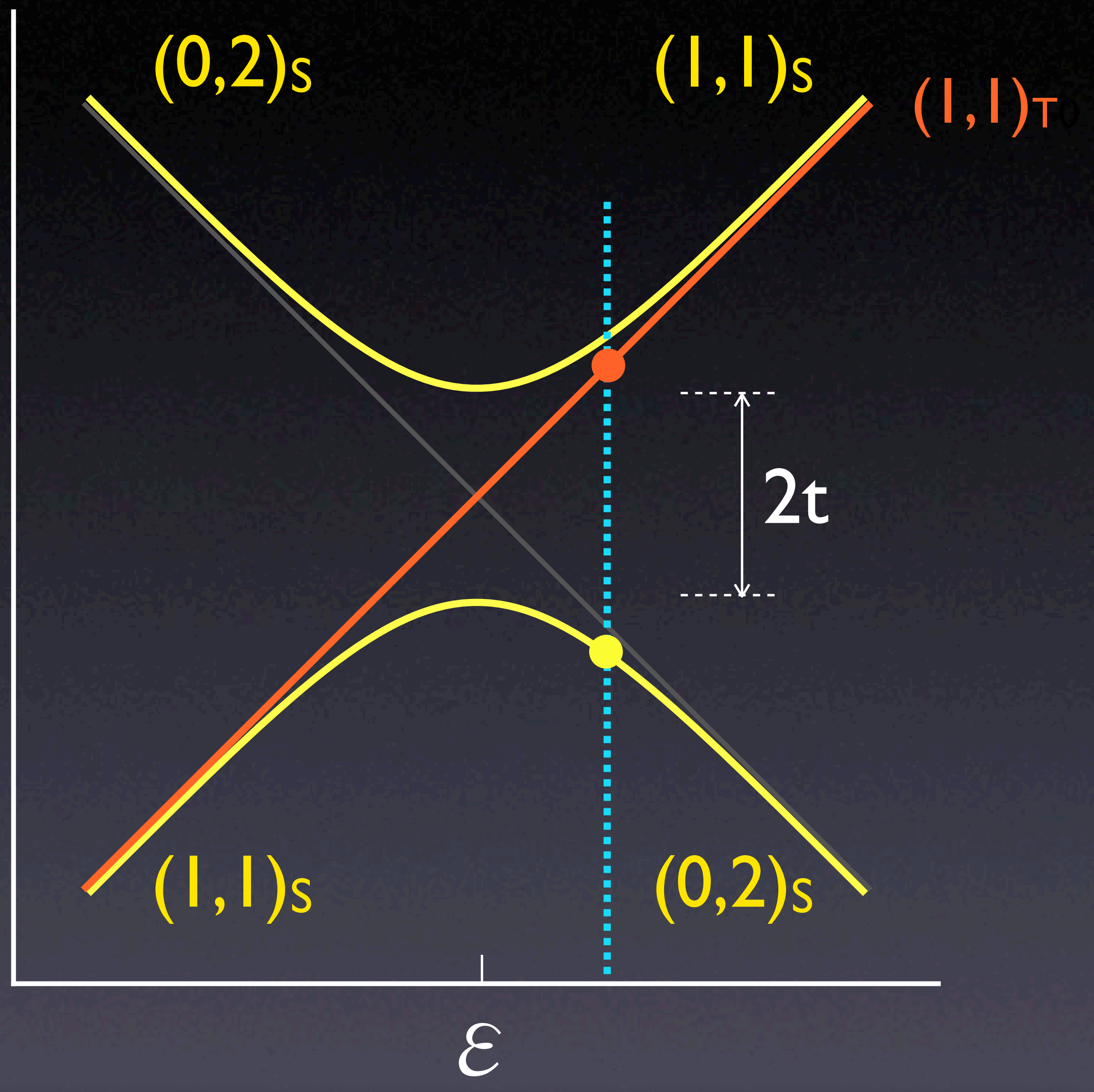


J. R. Petta, A. C. Johnson, J. Taylor, A. Yacoby, M.D. Lukin,
M. Hanson, A. C. Gossard, CMM Science **309** 2180 (2005)

Measuring Spin Dephasing (T2*): Time-domain Interferometry







singlet-to-charge conversion

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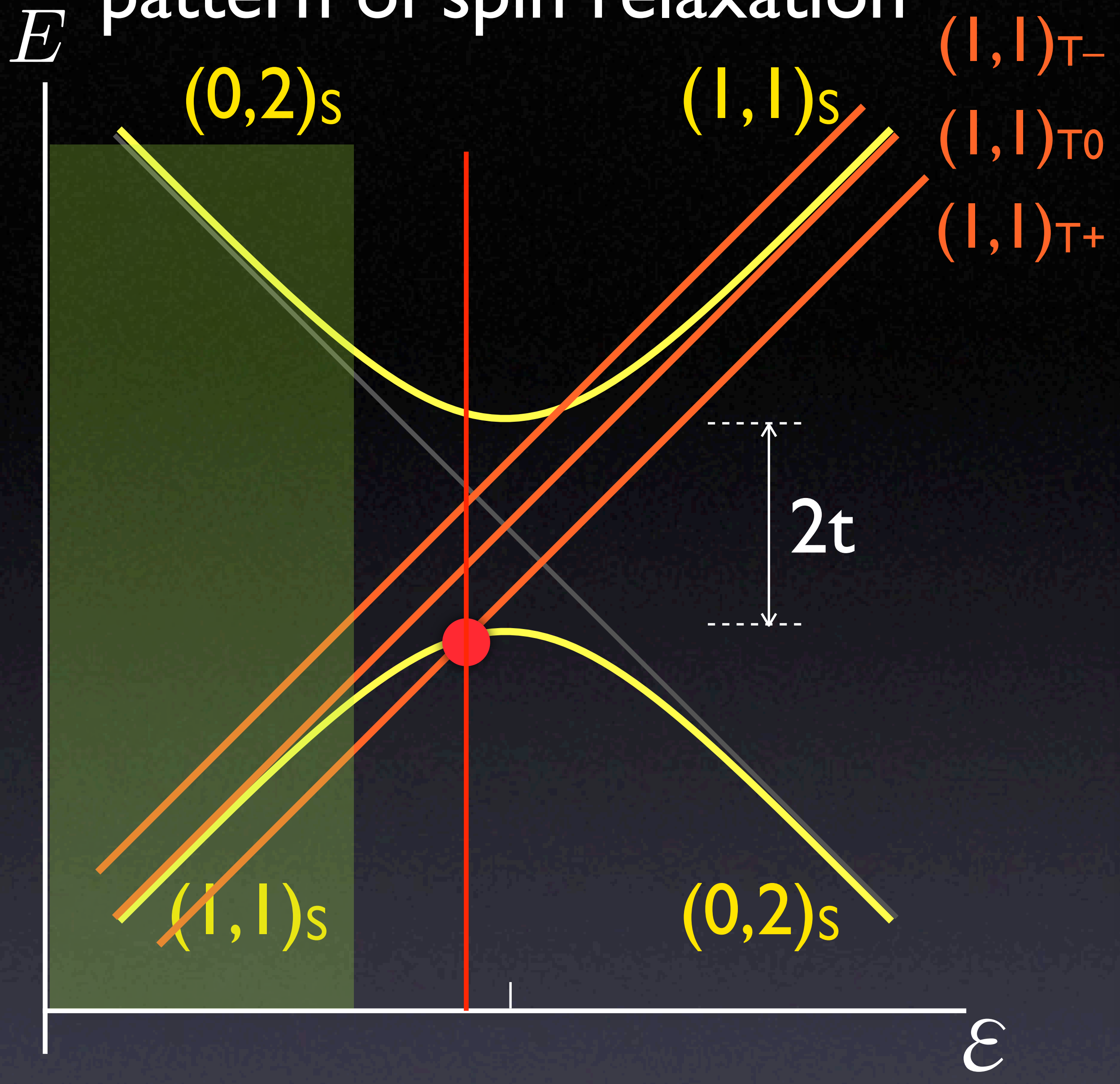
M. Hanson, A. C. Gossard, CMM Science **309** 2180 (2005)

pattern of spin relaxation



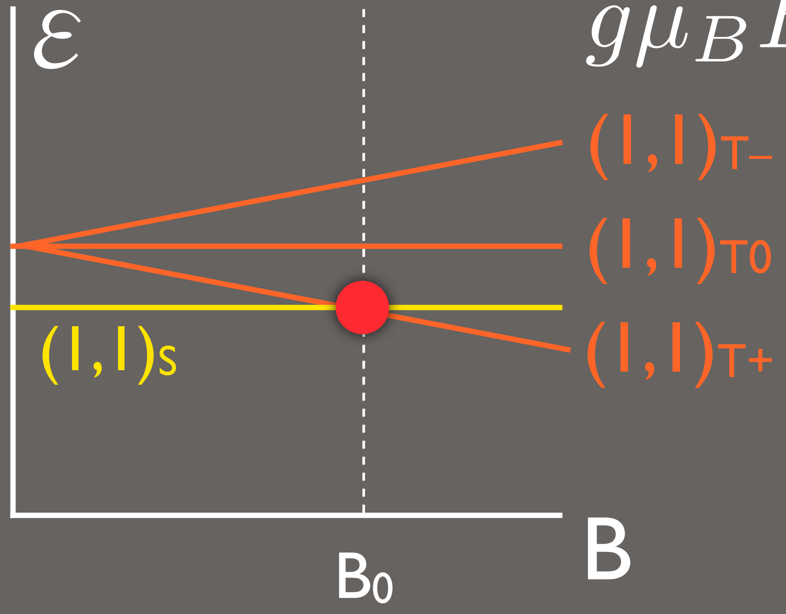
● S - T+ degeneracy

$$E_{(1,1)_S} = E_{(1,1)_{T+}} \quad \text{where}$$

$$E_{(1,1)_S} = -\sqrt{(\epsilon/2)^2 + t^2},$$

$$E_{(1,1)_{T+}} = -\epsilon/2 - mg\mu_B B\,.$$

$$g\mu_B B_0 \approx t^2/|\epsilon|$$

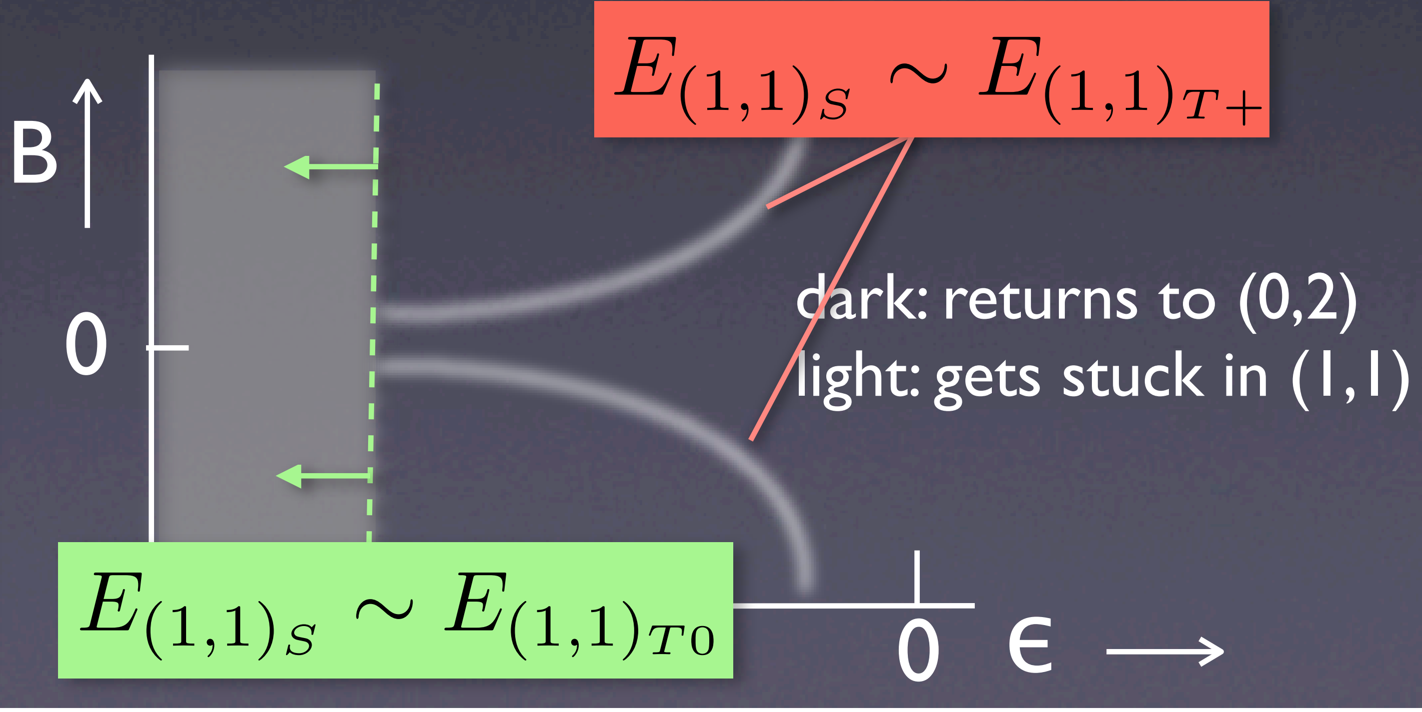


● S - T0 degeneracy

$$E_{(1,1)_S} \sim E_{(1,1)_{T0}}$$

at large ϵ

so that $t^2/|\epsilon| \approx g\mu_B B_{nuc.}$



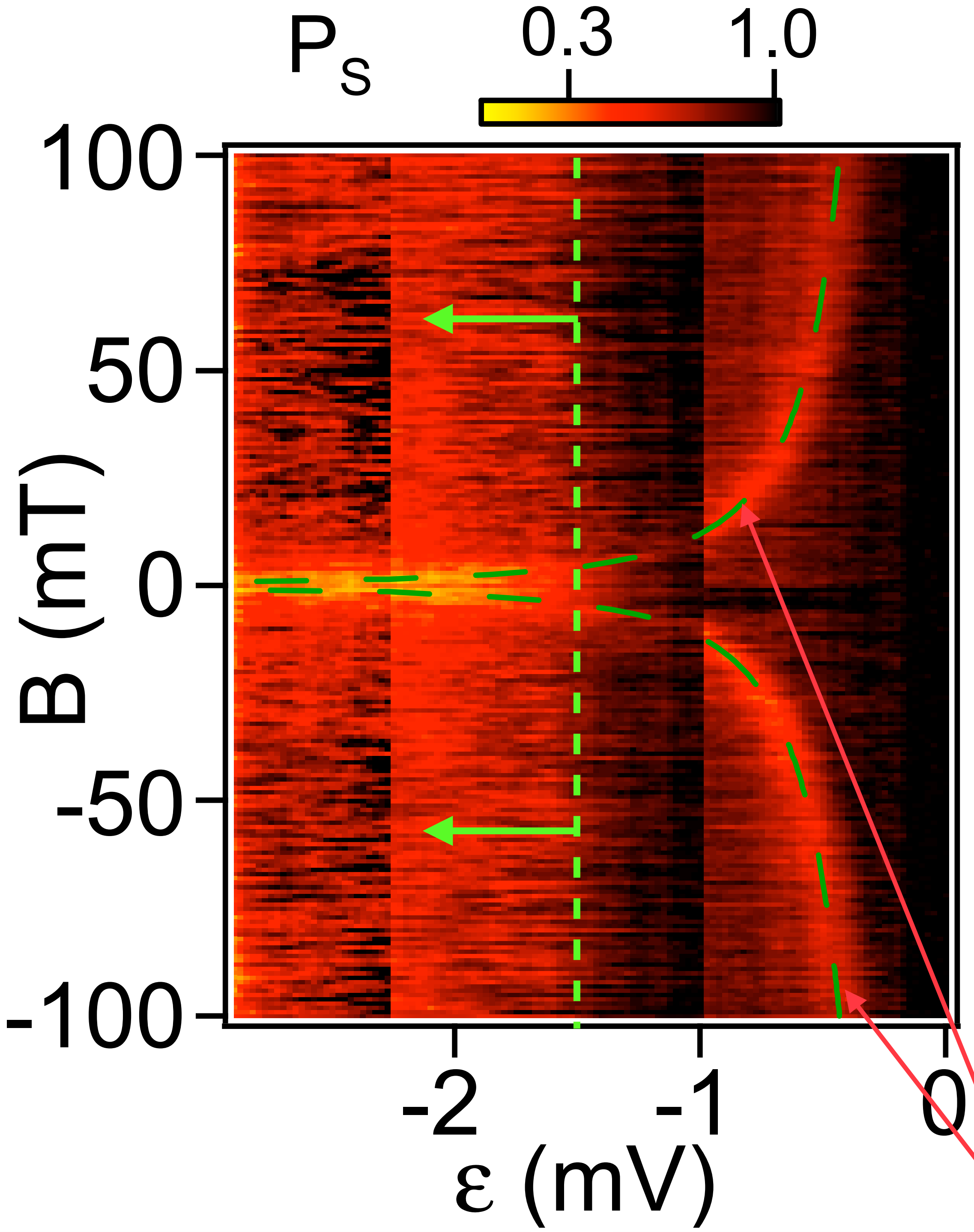
$E_{(1,1)_S} \sim E_{(1,1)_{T+}}$

dark: returns to (0,2)

light: gets stuck in (1,1)

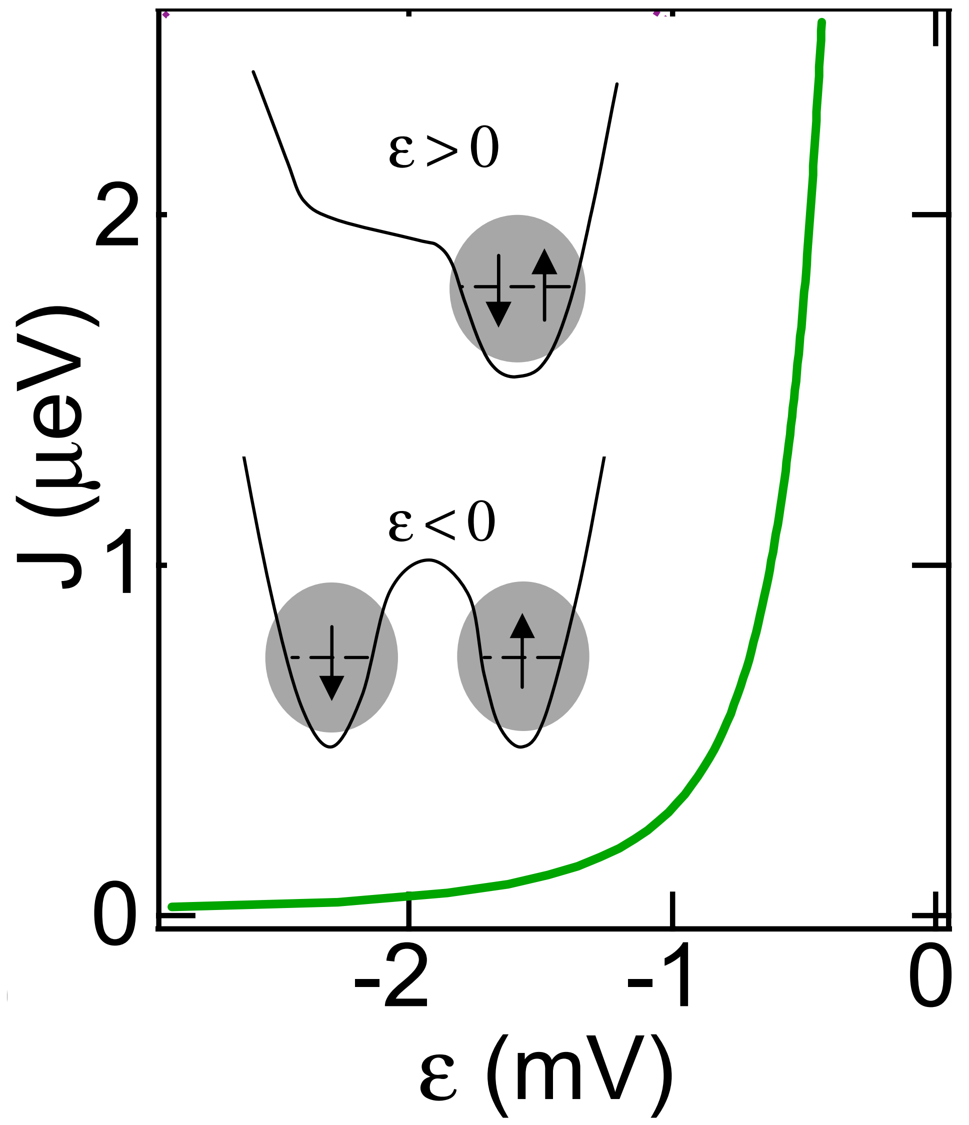
$E_{(1,1)_S} \sim E_{(1,1)_{T0}}$

Probability for separated singlet to be in a found in a singlet state after 200 ns.



S - T₊ degeneracy occurs at

$$J(\epsilon) = g\mu_B B$$

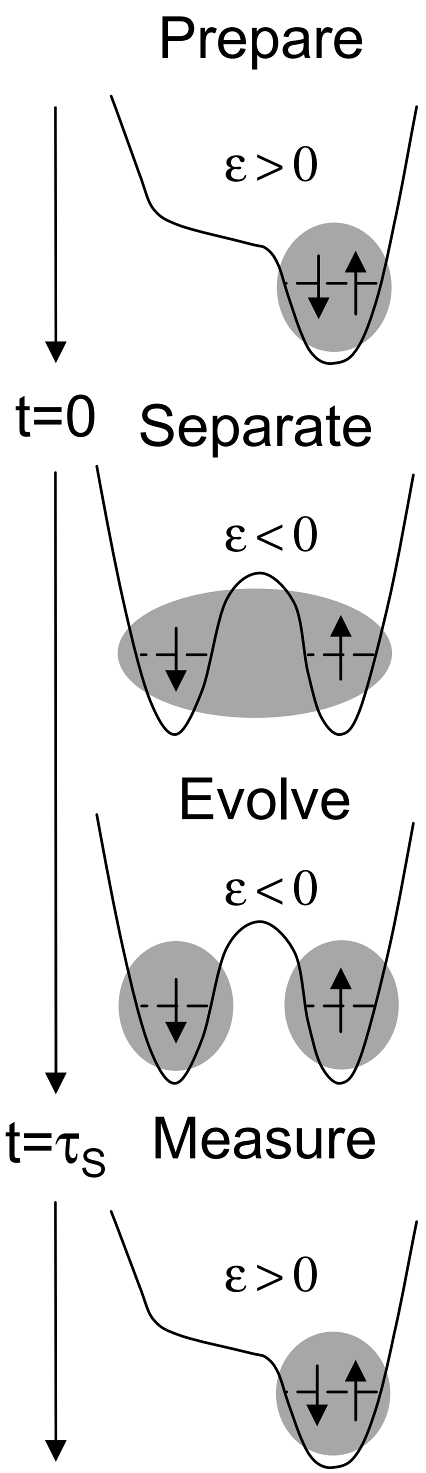


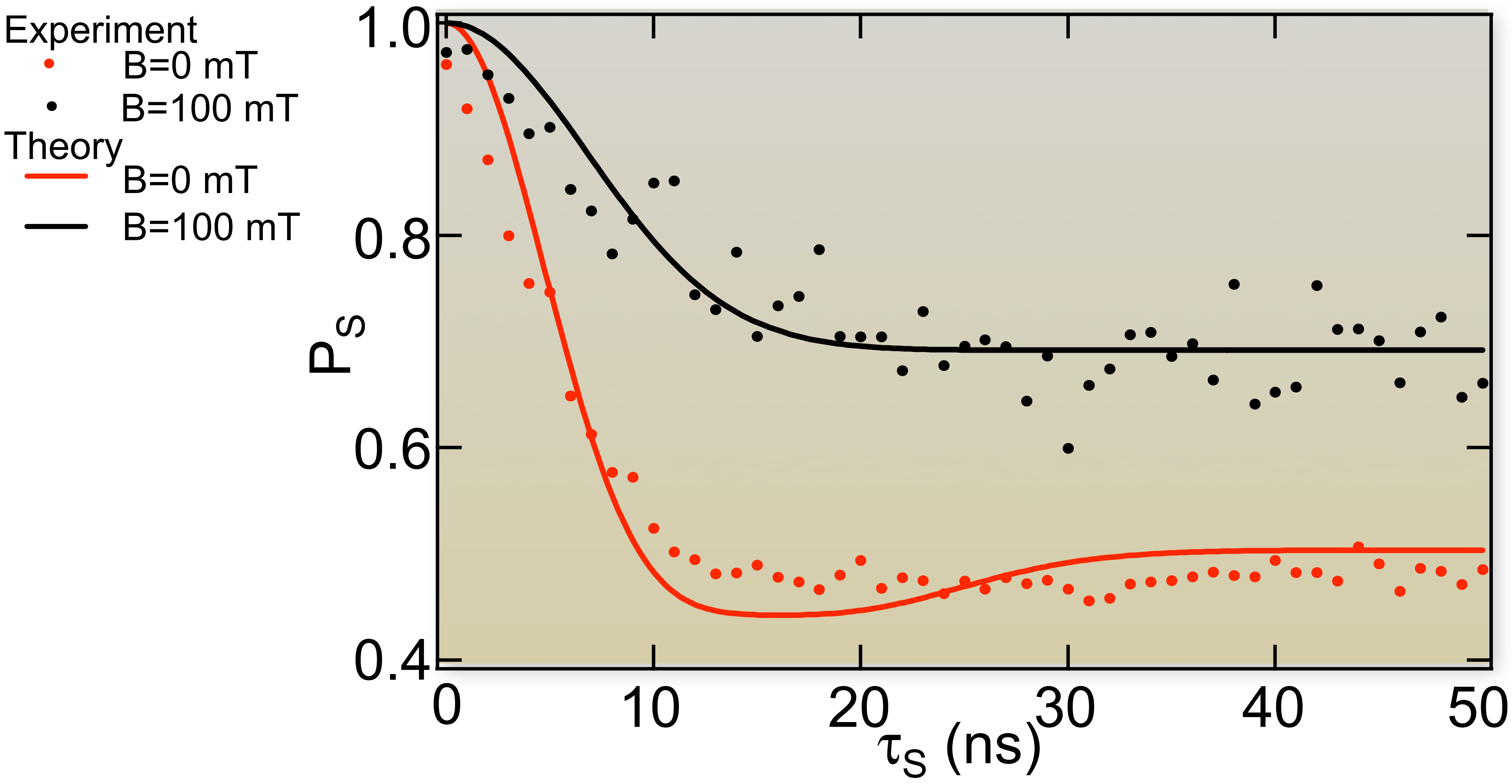
$E_{(1,1)_S} \sim E_{(1,1)_{T0}}$

$E_{(1,1)_S} \sim E_{(1,1)_{T+}}$

R. Petta, A. C. Johnson, J. Taylor, A. Yacoby, M.D. Lukin, M. Hanson, A. C. Gossard, CMM Science **309** 2180 (2005)

Measuring Spin Dephasing (T2*)





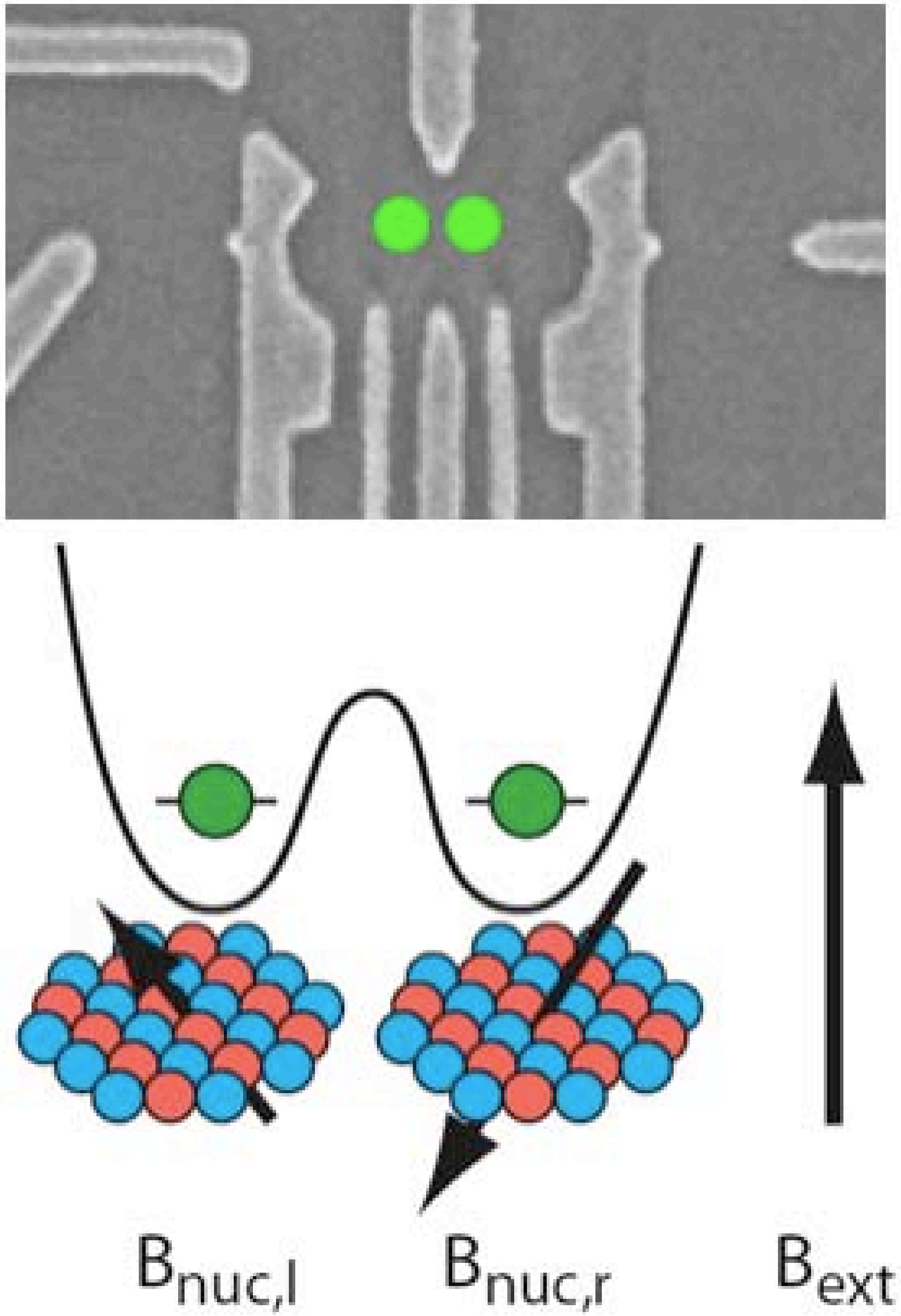
$$P_S(\tau_S) = 1 - \frac{C_1}{2}\left(1 - e^{-(\tau_S/T_2^*)^2}\right) \text{ for } B \gg B_{\text{nuc}}$$

$$P_S(\tau_S) = 1 - \frac{3}{4}C_2\left\{1 - \frac{1}{9}\left(1 - 2e^{-\frac{1}{2}(\tau_S/T_2^*)^2}\left\{(\tau_S/T_2^*)^2 - 1\right\}\right)^2\right\} \text{ for } B \ll B_{\text{nuc}}.$$

See: K. Schulten and P. G. Wolynes, J. Chem. Phys. **68** 3292 (1978); J. M. Taylor, *et al.* (in prep).

J. R. Petta, A. C. Johnson, J. Taylor, A. Yacoby, M.D. Lukin,
M. Hanson, A. C. Gossard, CMM Science **309** 2180 (2005)

Effective nuclear field from Hyperfine interaction



Large ensemble with random spin orientations, slow internal dynamics...

Quasistatic effective field

$$\mathbf{B}_{nuc} = b_0 \sum_k \left|\psi(r_k)\right|^2 \mathbf{I}_k$$

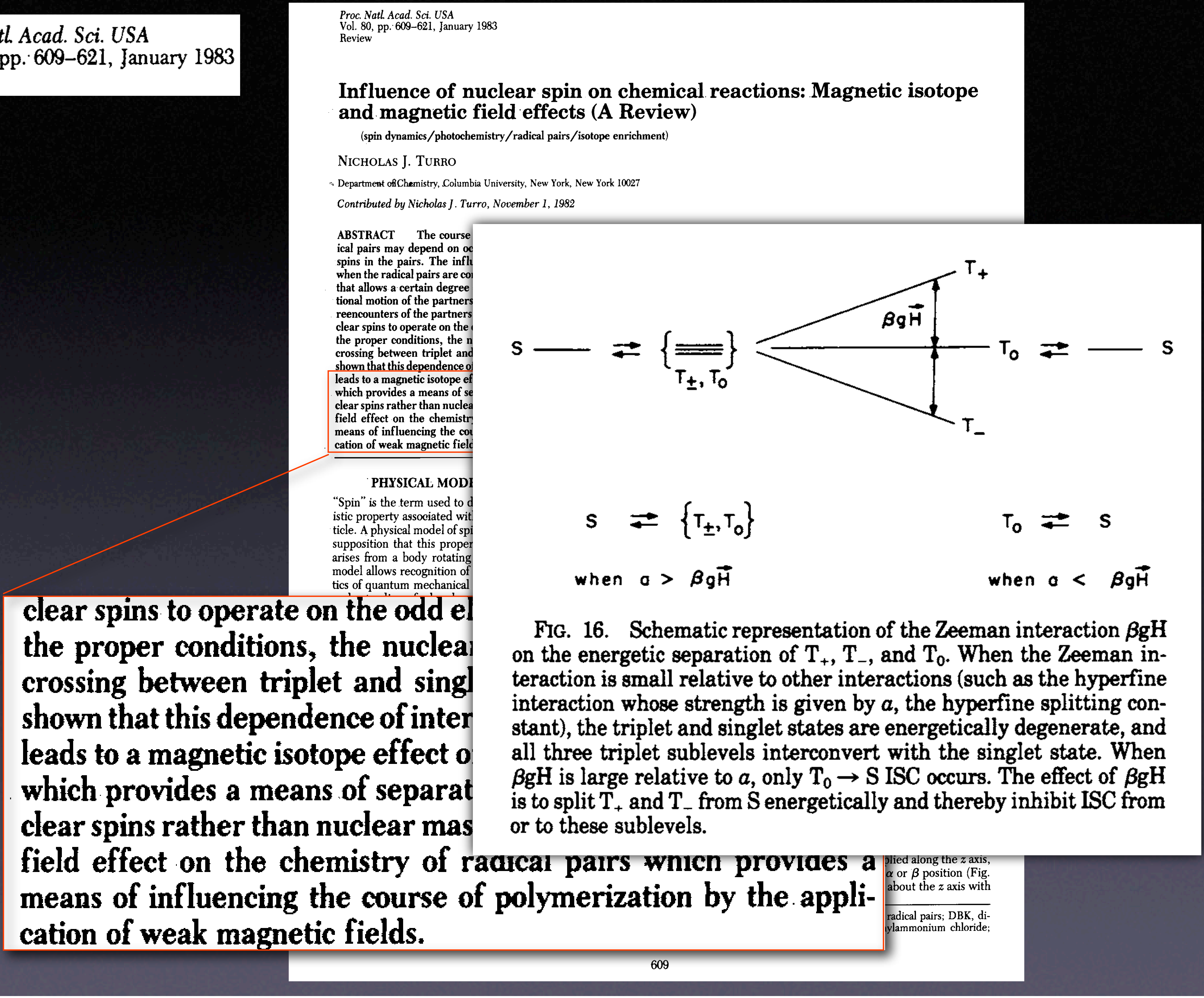
$$rms\ B_{nuc} = b_0\sqrt{I_0(I_0+1)/N}$$

GaAs: b_0=3.47 T, I_0 =3/2

Our device: N~10^6-10^7

B_{nuc}~2-6 mT, t_{nuc}~3-10 ns

Proc. Natl. Acad. Sci. USA
Vol. 80, pp. 609–621, January 1983
Review



Proc. Natl. Acad. Sci. USA
Vol. 80, pp. 609–621, January 1983
Review

Influence of nuclear spin on chemical reactions: Magnetic isotope and magnetic field effects (A Review)

(spin dynamics/photochemistry/radical pairs/isotope enrichment)

NICHOLAS J. TURRO

Department of Chemistry, Columbia University, New York, New York 10027

Contributed by Nicholas J. Turro, November 1, 1982

ABSTRACT The course
ical pairs may depend on oc
spins in the pairs. The influ
when the radical pairs are co
that allows a certain degree
tional motion of the partners
reencounters of the partners
clear spins to operate on the
the proper conditions, the n
crossing between triplet and
shown that this dependence o
leads to a magnetic isotope ef
which provides a means of se
clear spins rather than nuclea
field effect on the chemistry
means of influencing the cou
cation of weak magnetic field

PHYSICAL MODE

"Spin" is the term used to d
istic property associated wit
ticle. A physical model of spi
supposition that this proper
arises from a body rotating
model allows recognition of
tics of quantum mechanical

clear spins to operate on the odd el
the proper conditions, the nuclea
crossing between triplet and singl
shown that this dependence of inter
leads to a magnetic isotope effect o
which provides a means of separat
clear spins rather than nuclear mas
field effect on the chemistry of radical pairs which provides a
means of influencing the course of polymerization by the application of weak magnetic fields.

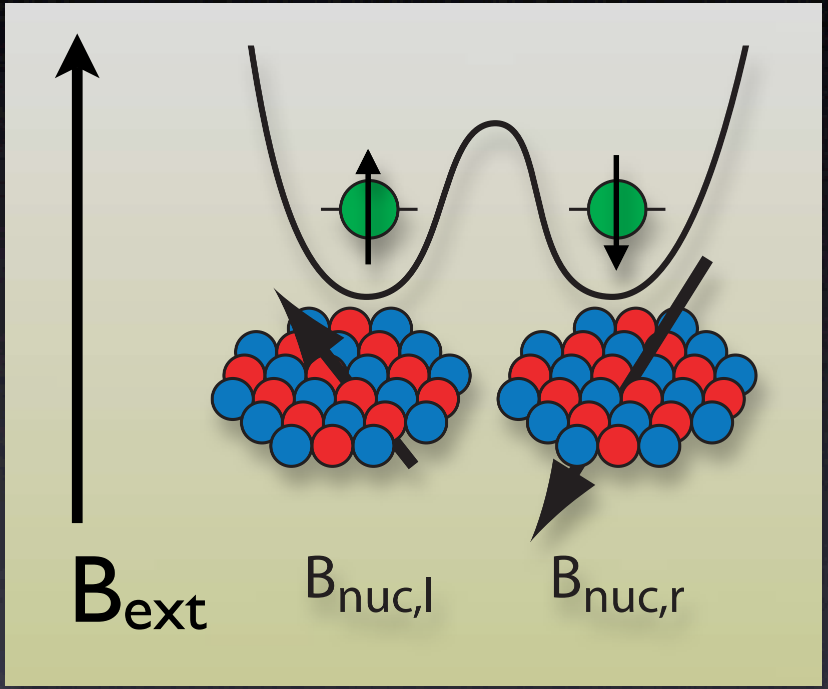
FIG. 16. Schematic representation of the Zeeman interaction βgH on the energetic separation of T_+, T_-, and T_0. When the Zeeman interaction is small relative to other interactions (such as the hyperfine interaction whose strength is given by a, the hyperfine splitting constant), the triplet and singlet states are energetically degenerate, and all three triplet sublevels interconvert with the singlet state. When βgH is large relative to a, only $T_0 \rightarrow S$ ISC occurs. The effect of βgH is to split T_+ and T_- from S energetically and thereby inhibit ISC from or to these sublevels.

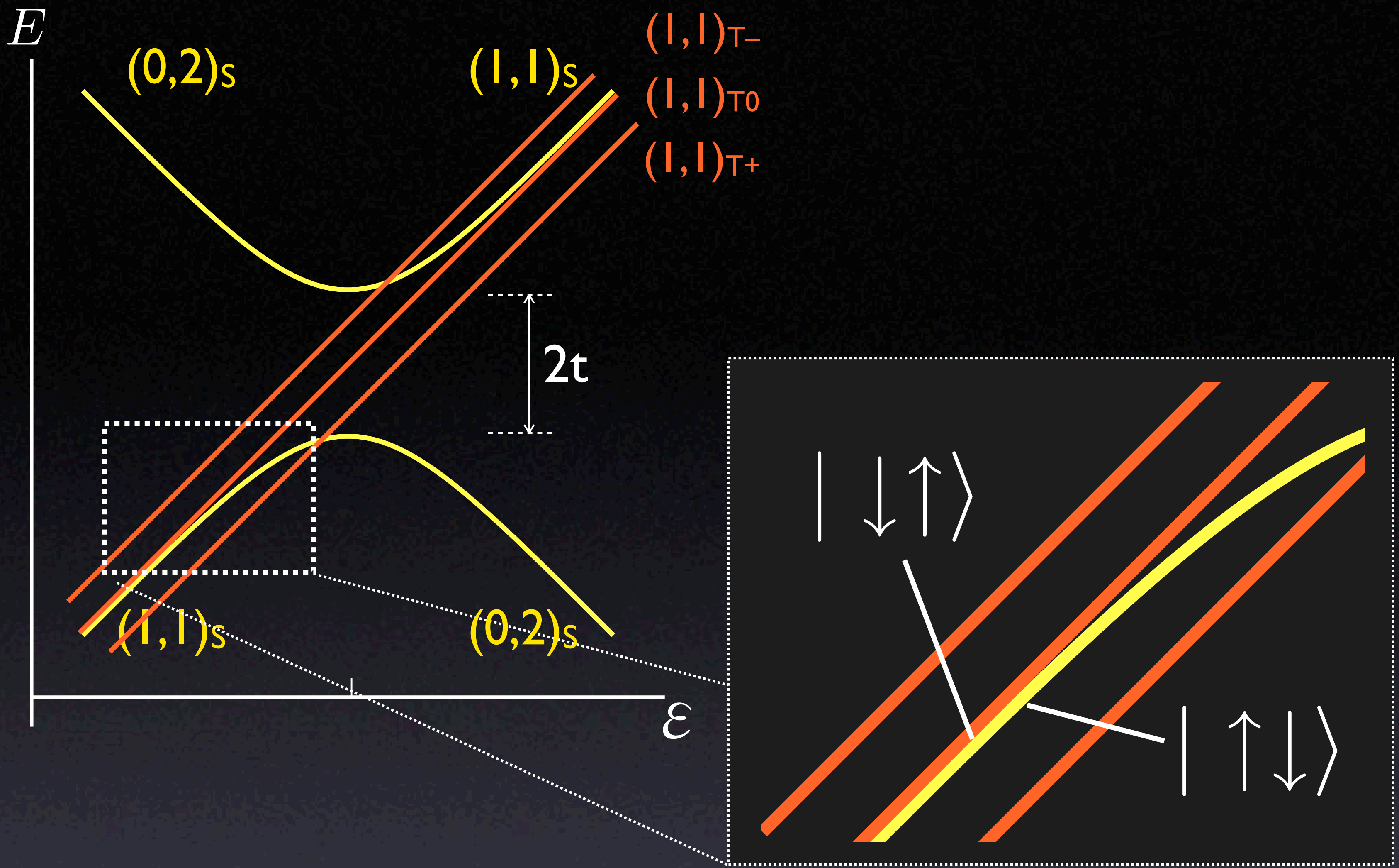
plied along the z axis,
α or β position (Fig.
about the z axis with

radical pairs; DBK, di-
ylammonium chloride;

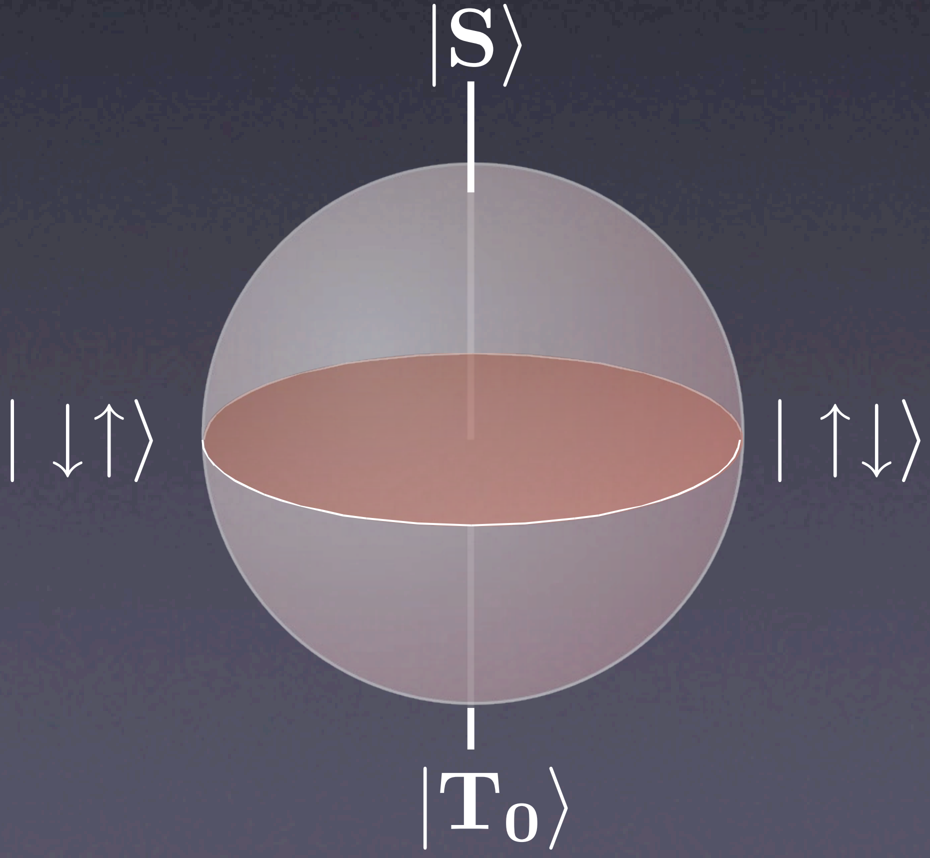
609

In the (1,1) S - T_0 subspace, the eigenstates of the nuclear fields are $|\uparrow\downarrow\rangle$ and $|\downarrow\uparrow\rangle$.

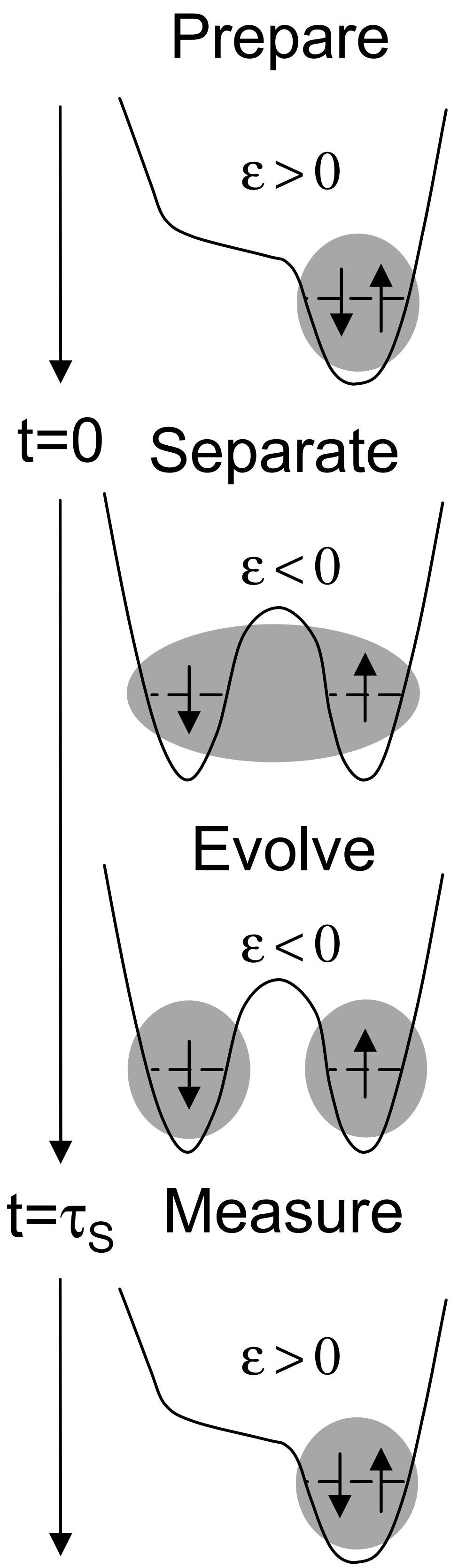


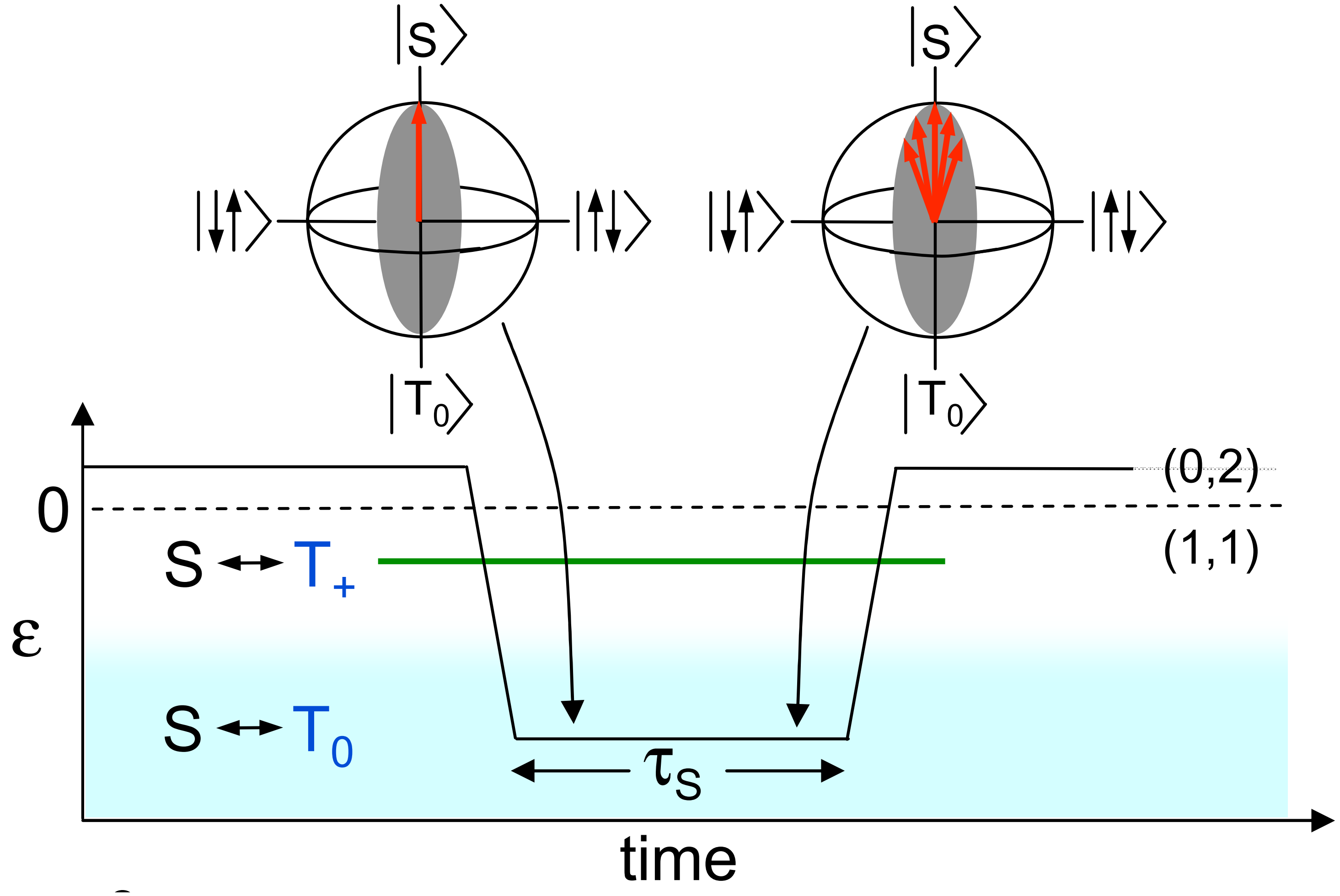


Bloch sphere in (1,1) S - T_0 subspace



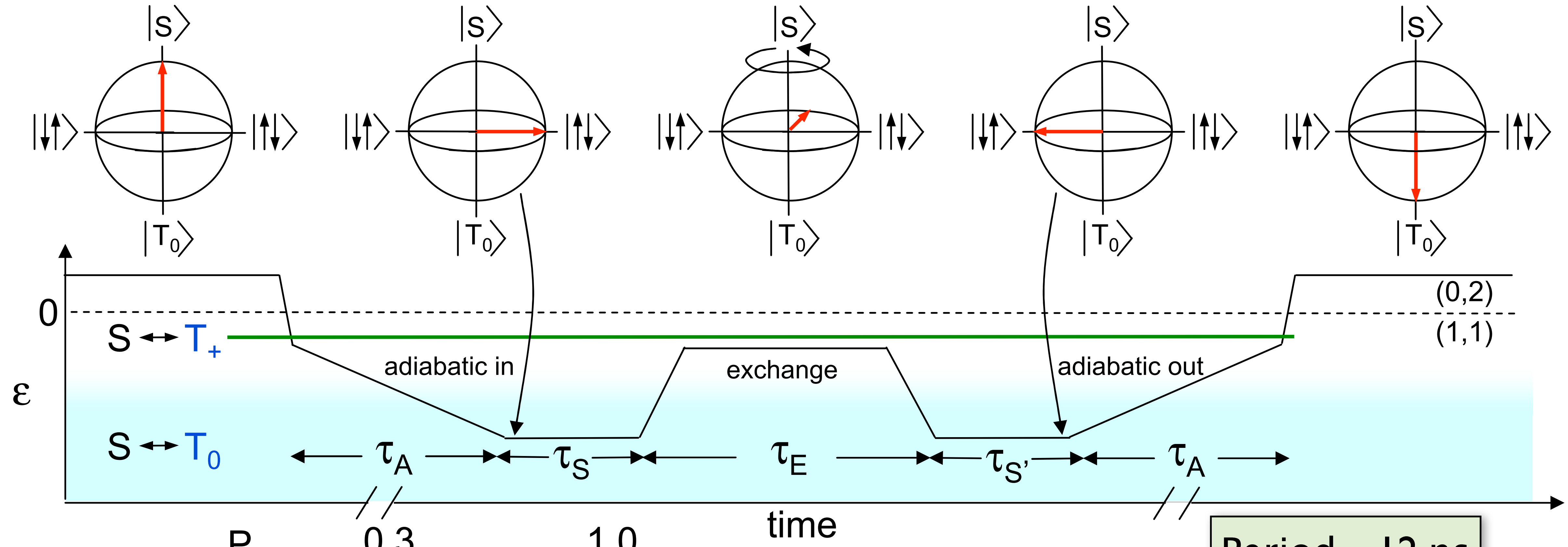
Probability for separated singlet to be found in a singlet after time τ_S

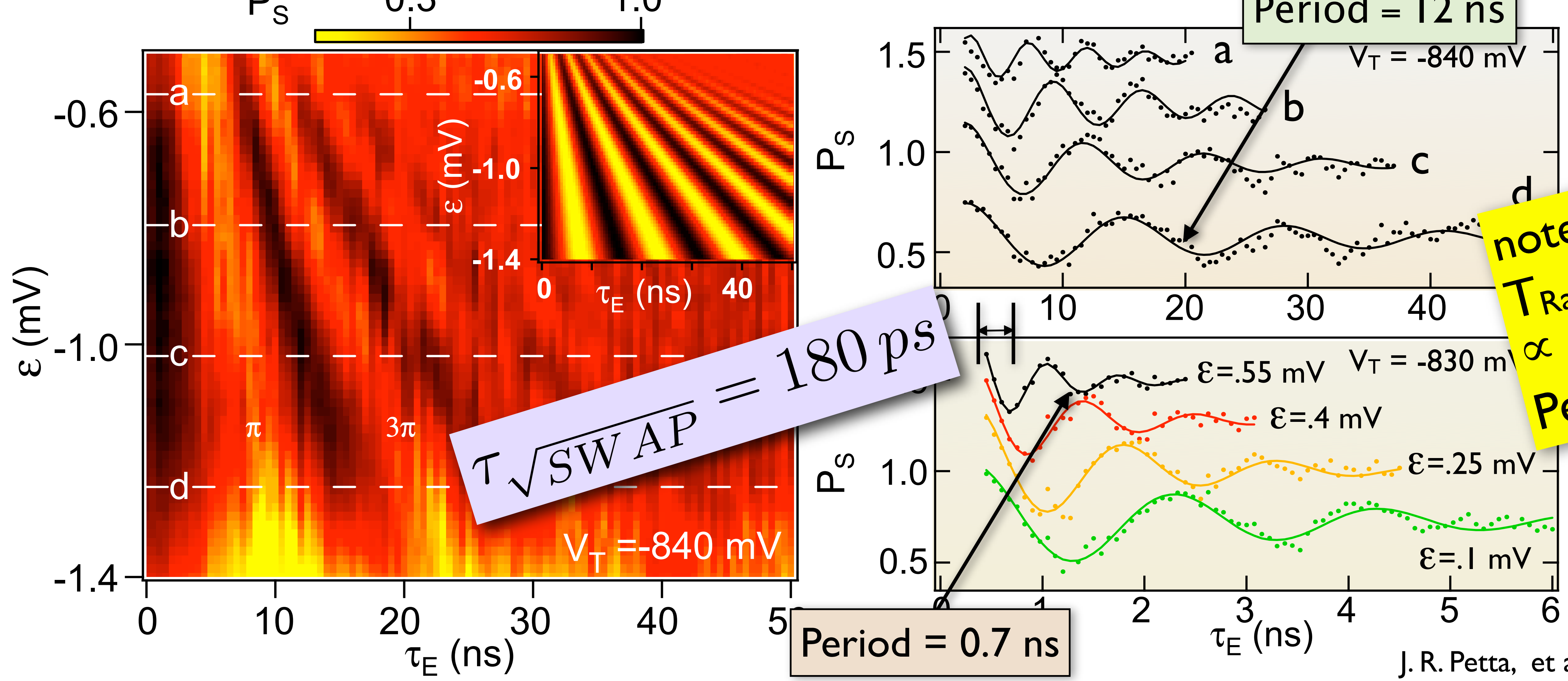




J. R. Petta, A. C. Johnson, J. Taylor, A. Yacoby, M.D. Lukin,
M. Hanson, A. C. Gossard, CMM Science **309** 2180 (2005)

Exchange Control: Rabi oscillations between ↑↓ and ↓↑ states





Period = 12 ns

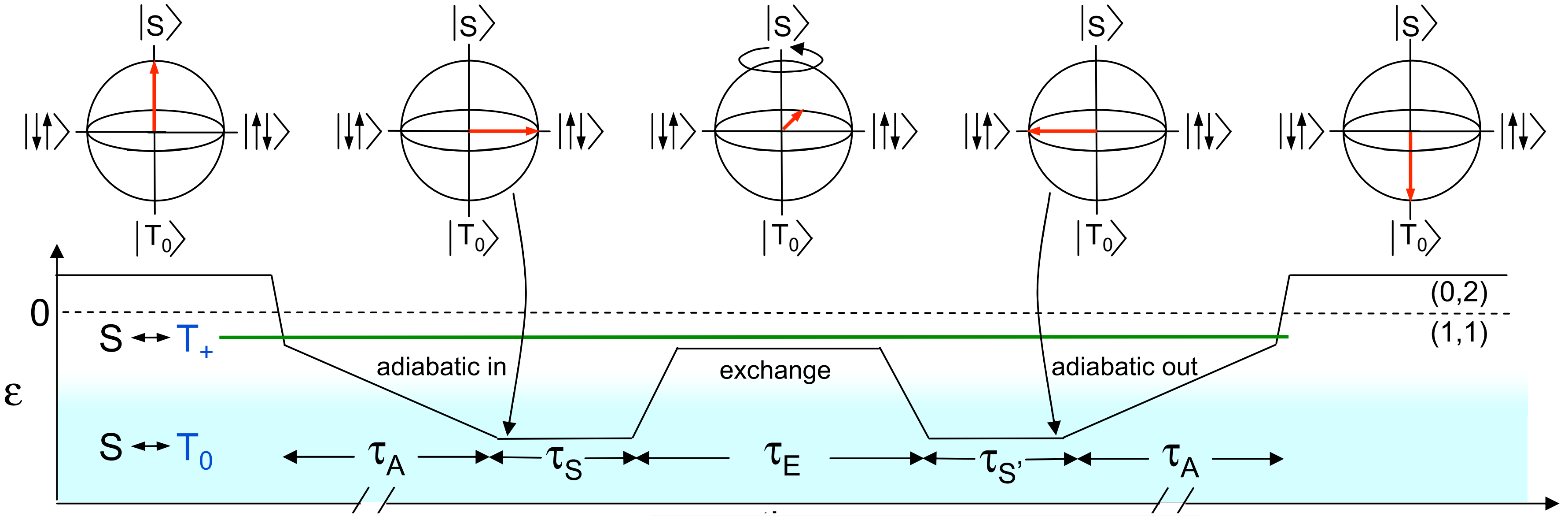
$\tau_{\sqrt{SWAP}} = 180\ ps$

note: T_{Rabi} ∝ Period

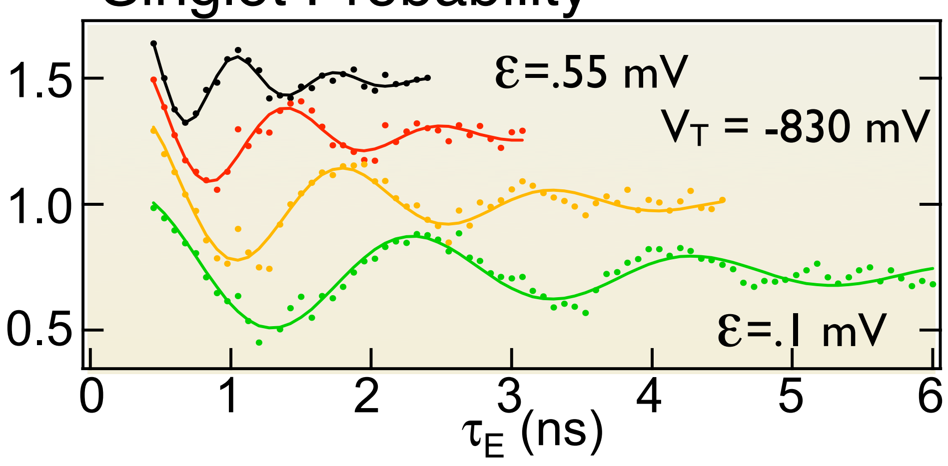
Period = 0.7 ns

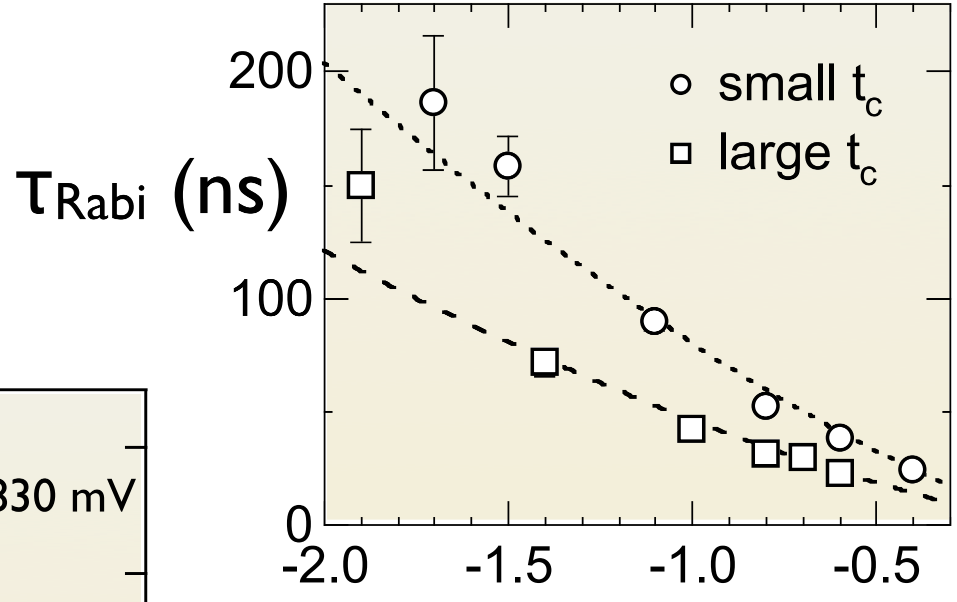
J. R. Petta, et al. (2005)

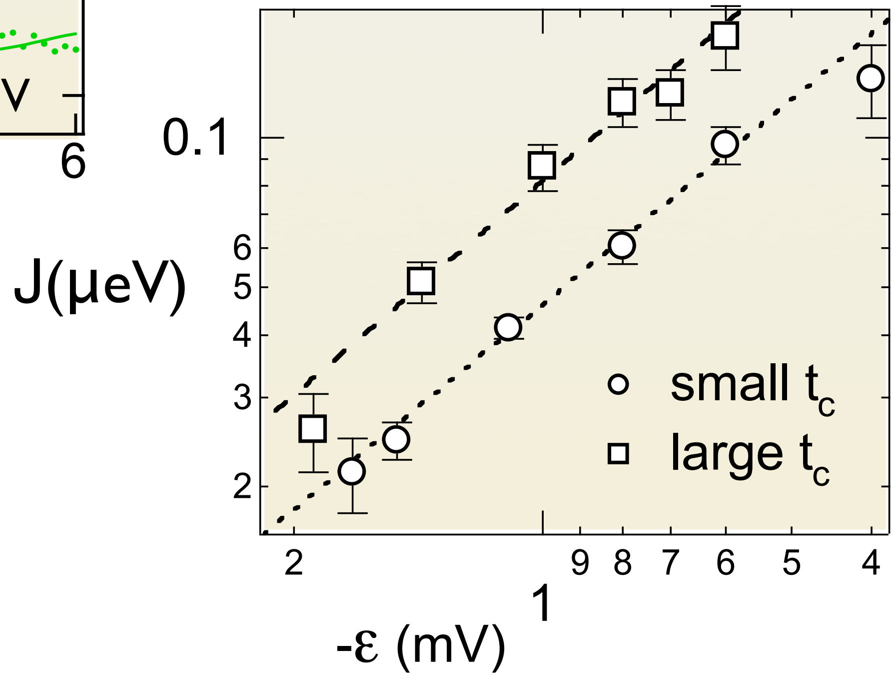
Gate control of SWAP speed

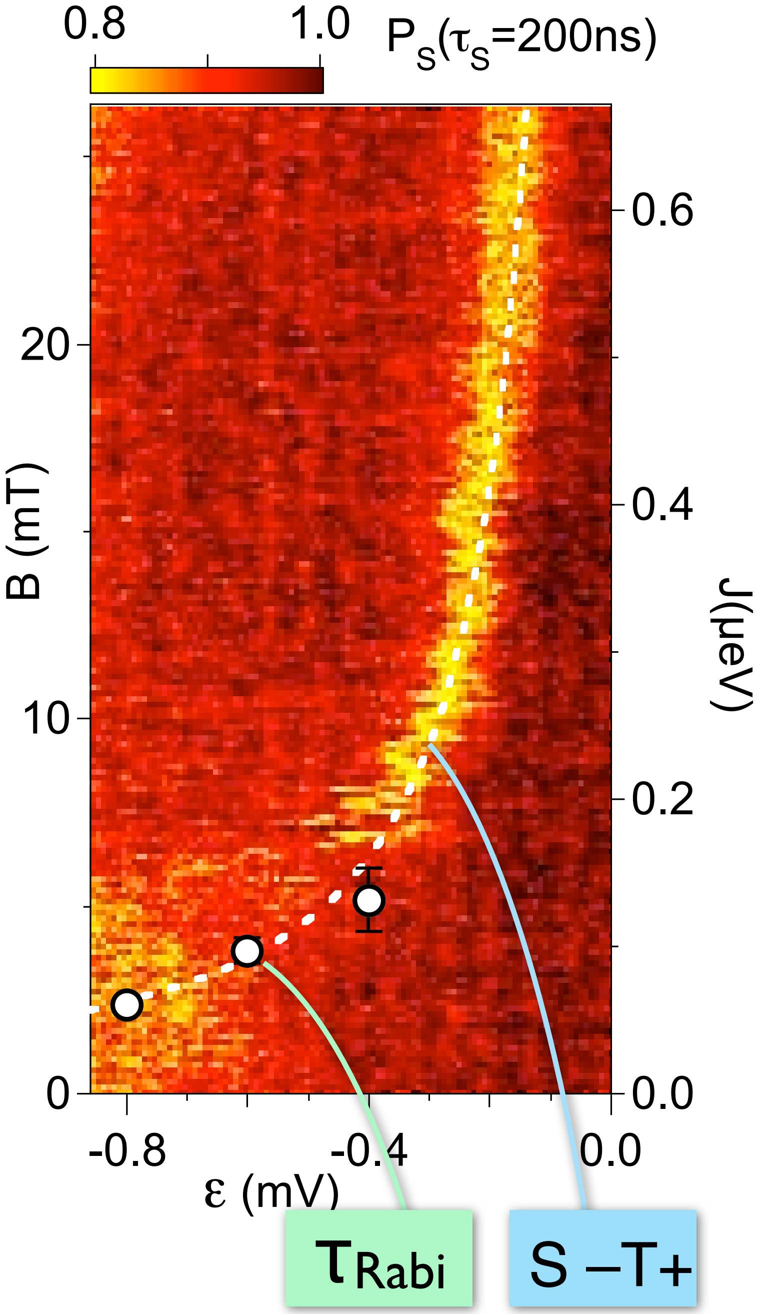


Singlet Probability



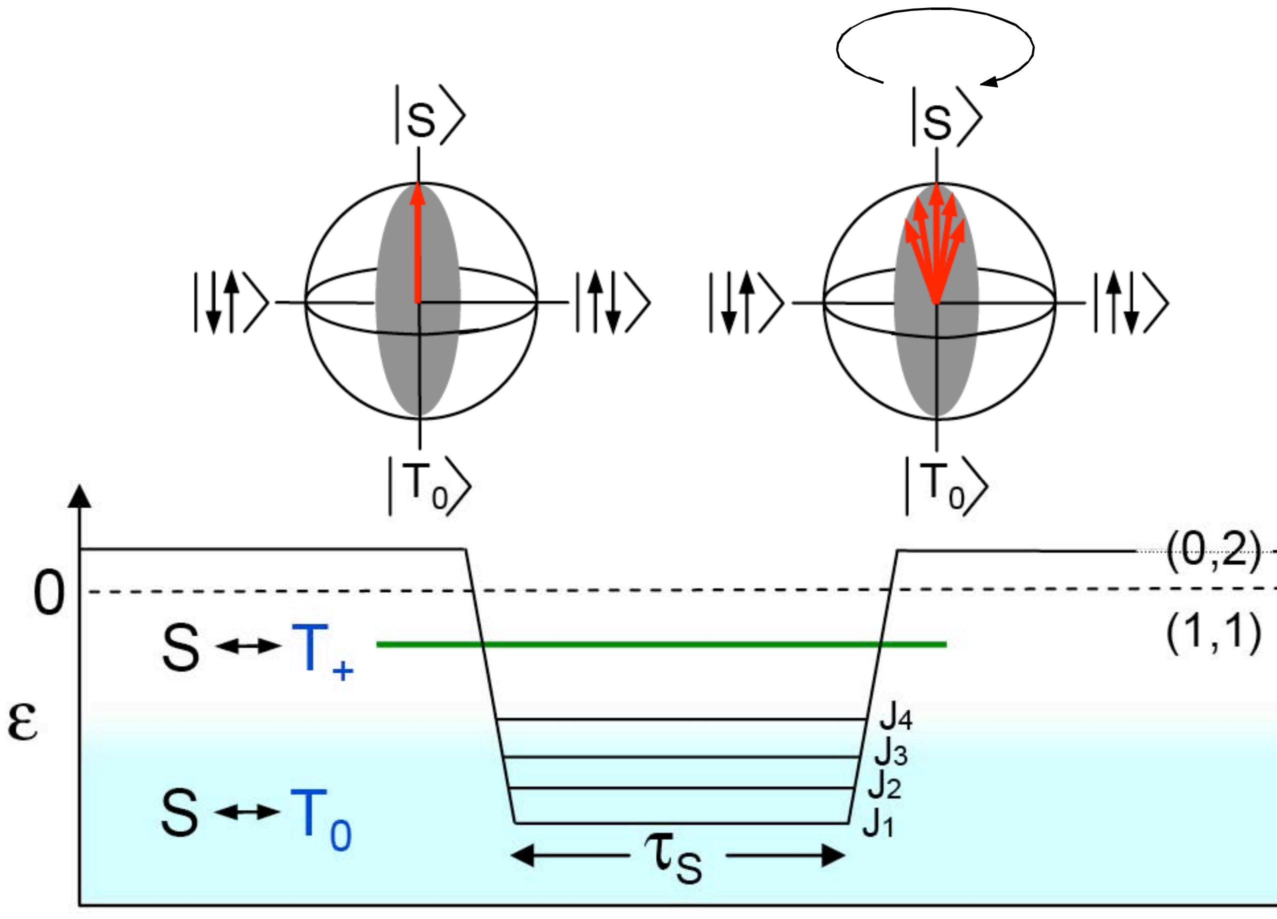


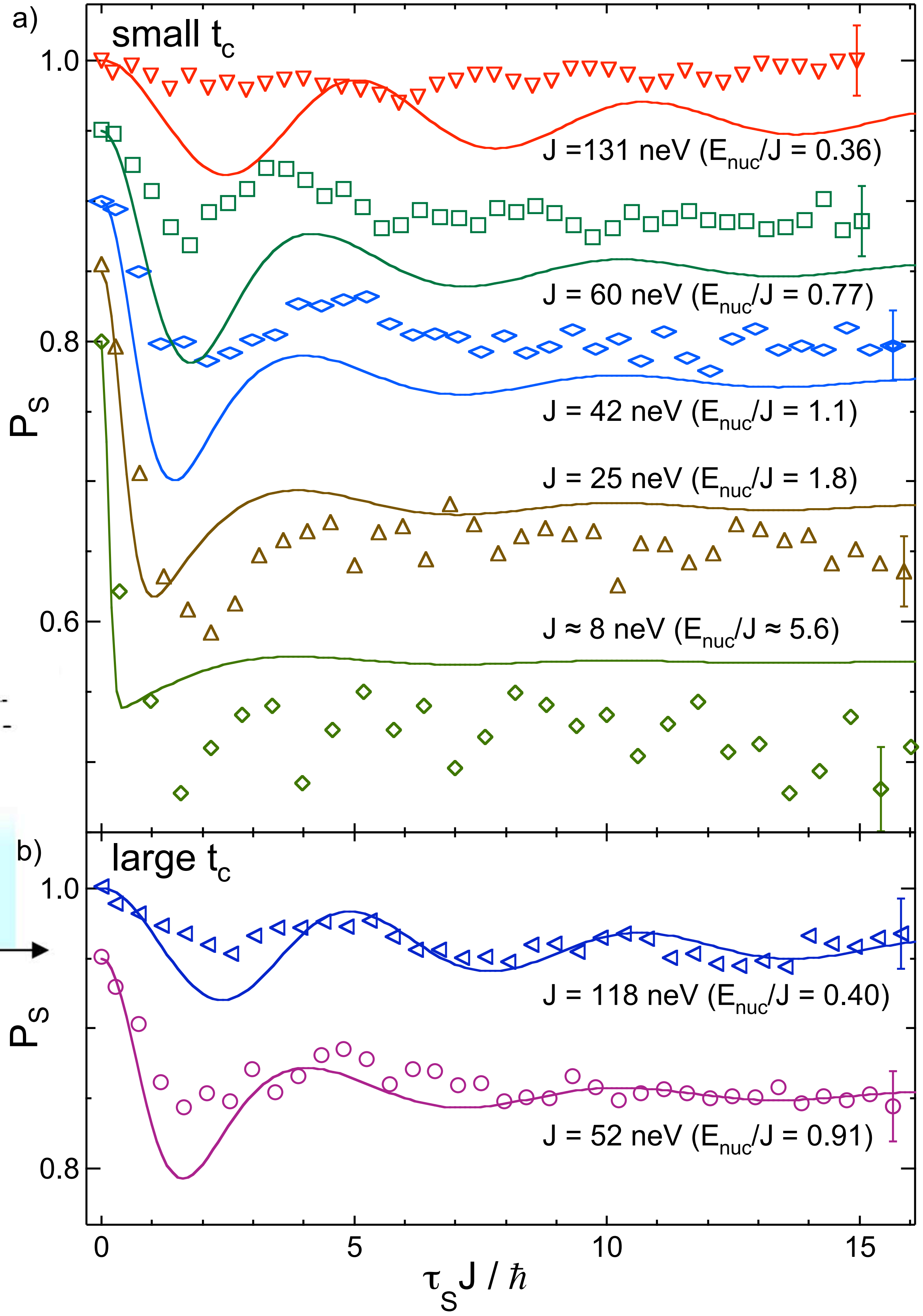




J. R. Petta, et al. (2005); E. Laird, et al. (2006)

Hyperfine dephasing with finite exchange interaction

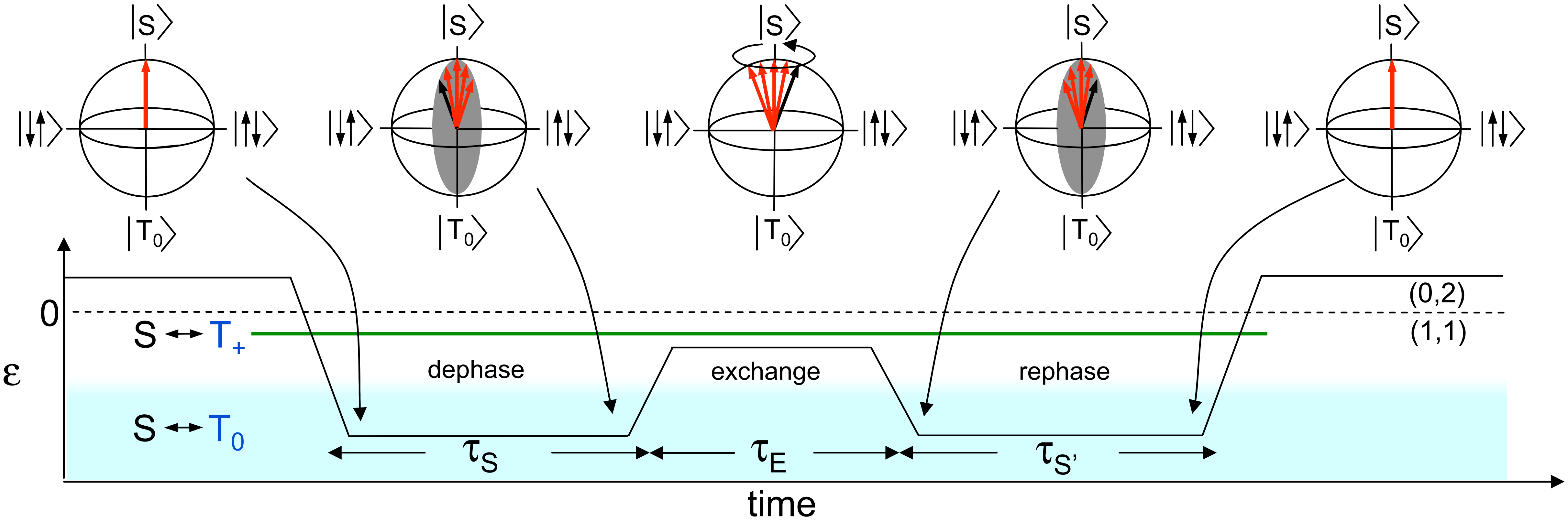


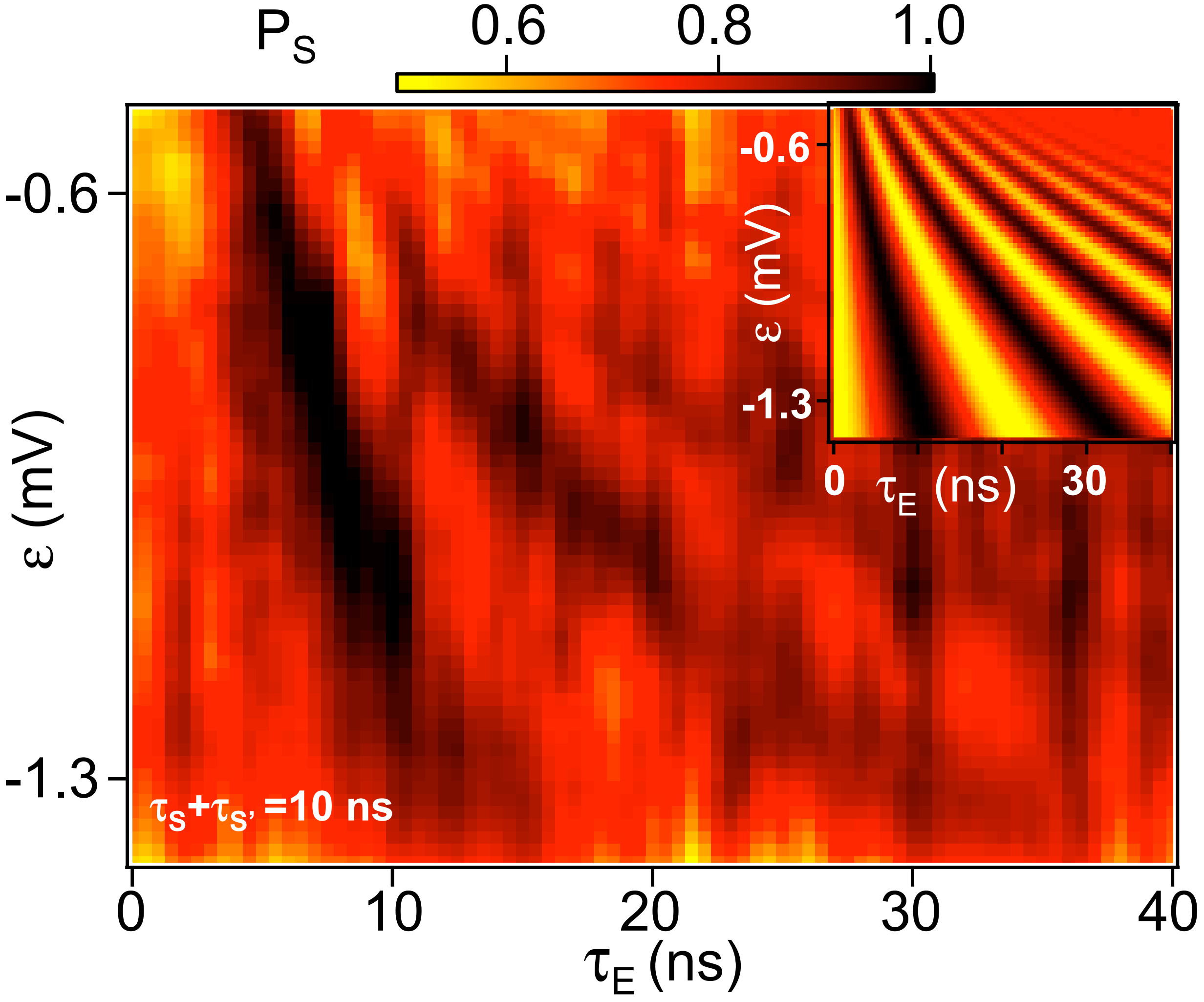


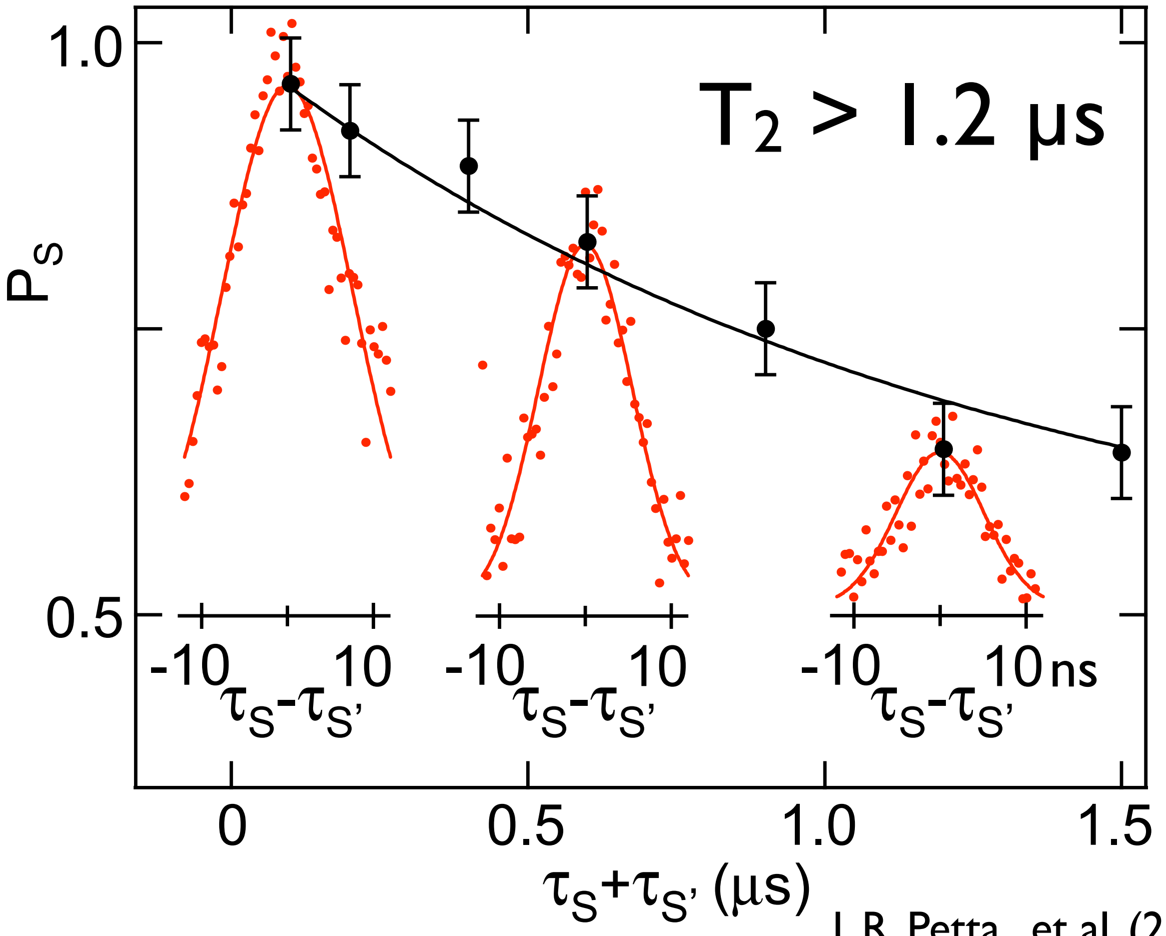
theory
W. Coish and D. Loss, Phys. Rev. B **72**, 125337 (2005).

experiment
E. A. Laird, J. Petta, CMM et al. cond-mat/0512077 (2005).

Hahn Echo in S - T_0 basis

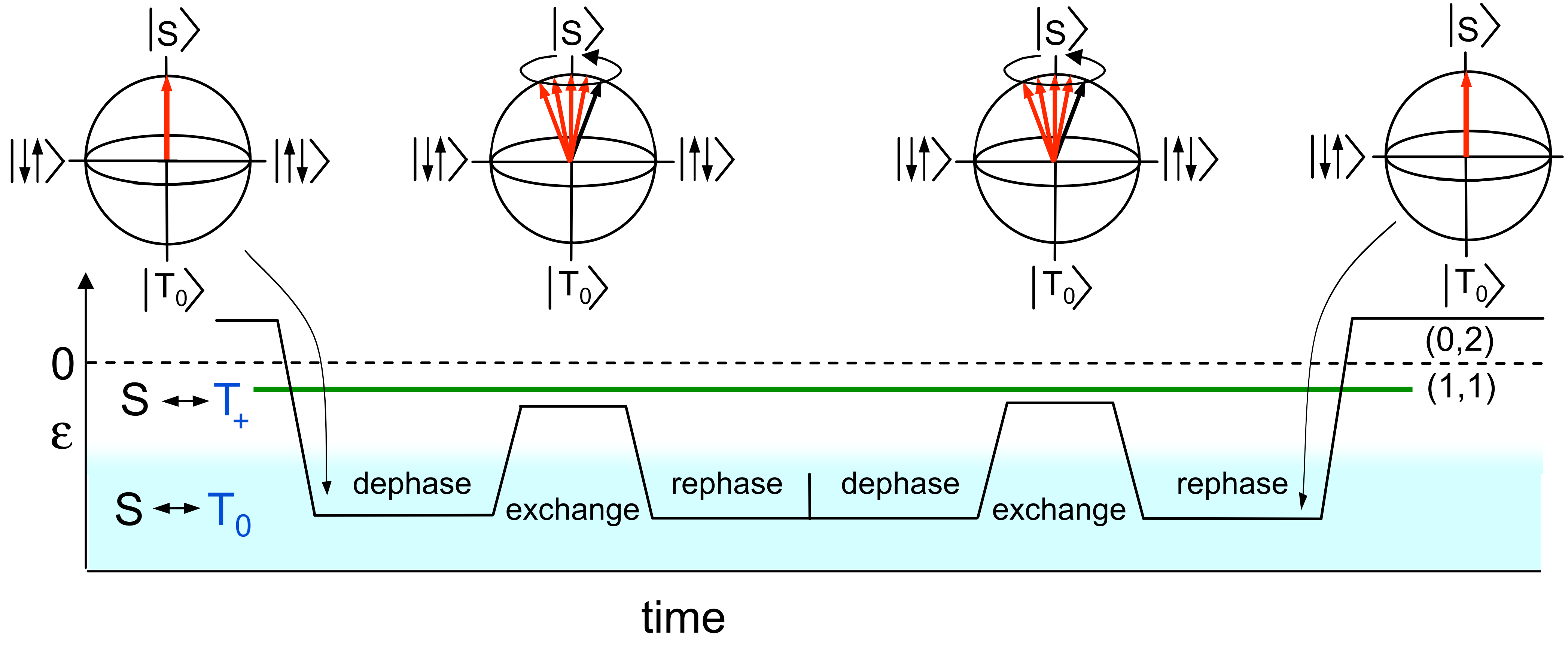


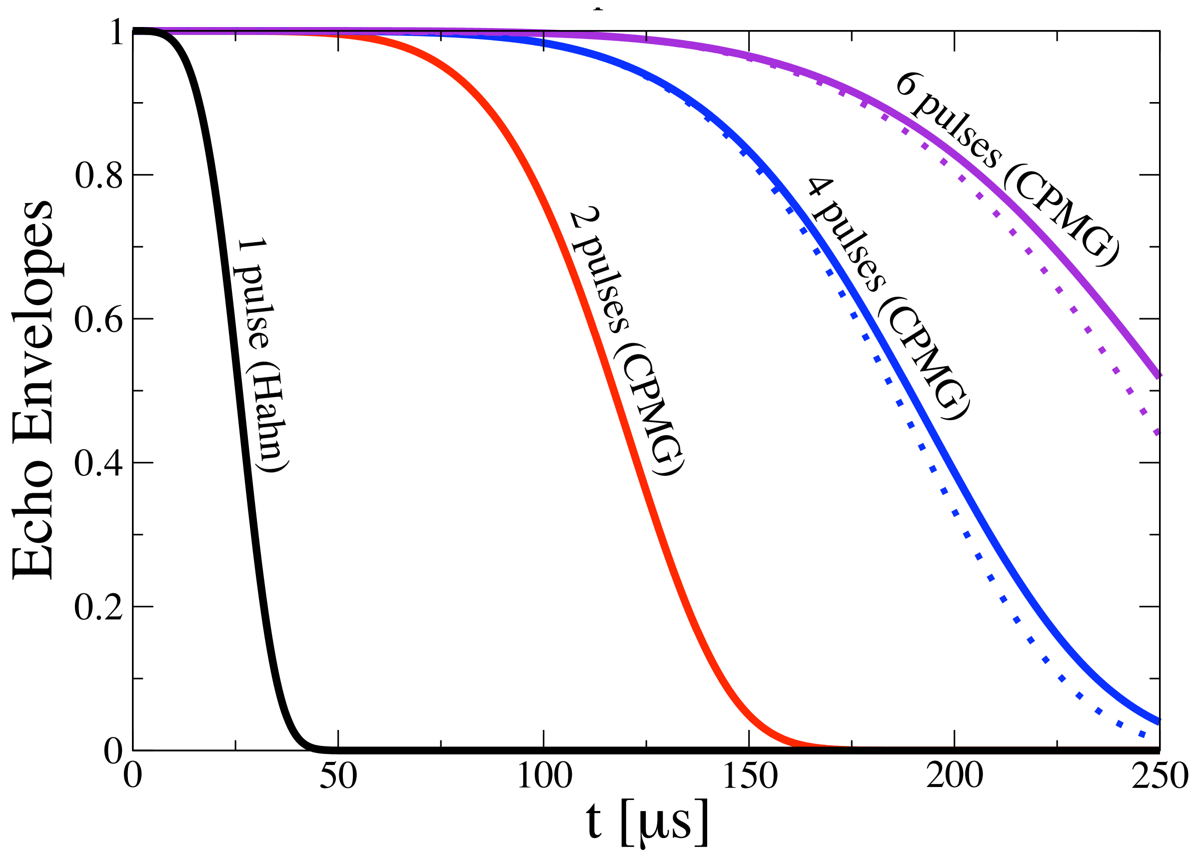




J. R. Petta, et al. (2005)

Carr-Purcell Echo in S - T_0 basis



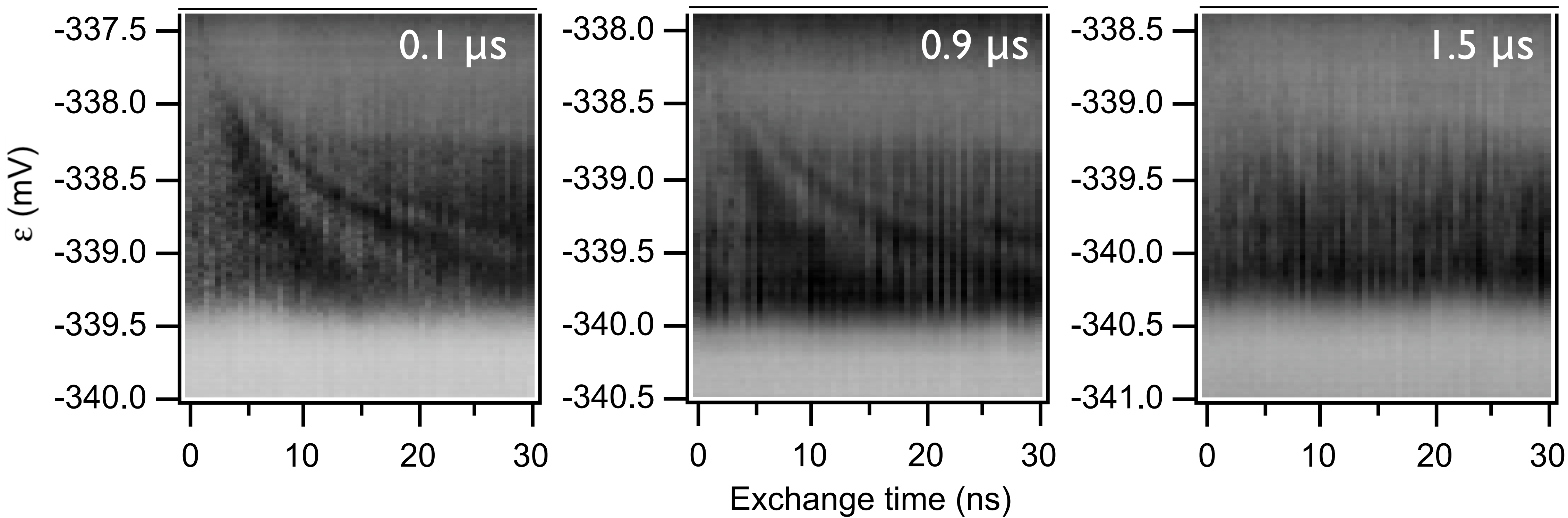


Theory: W. M. Witzel and S. Das Sarma cond-mat/0604577

Carr-Purcell Pulse Sequences

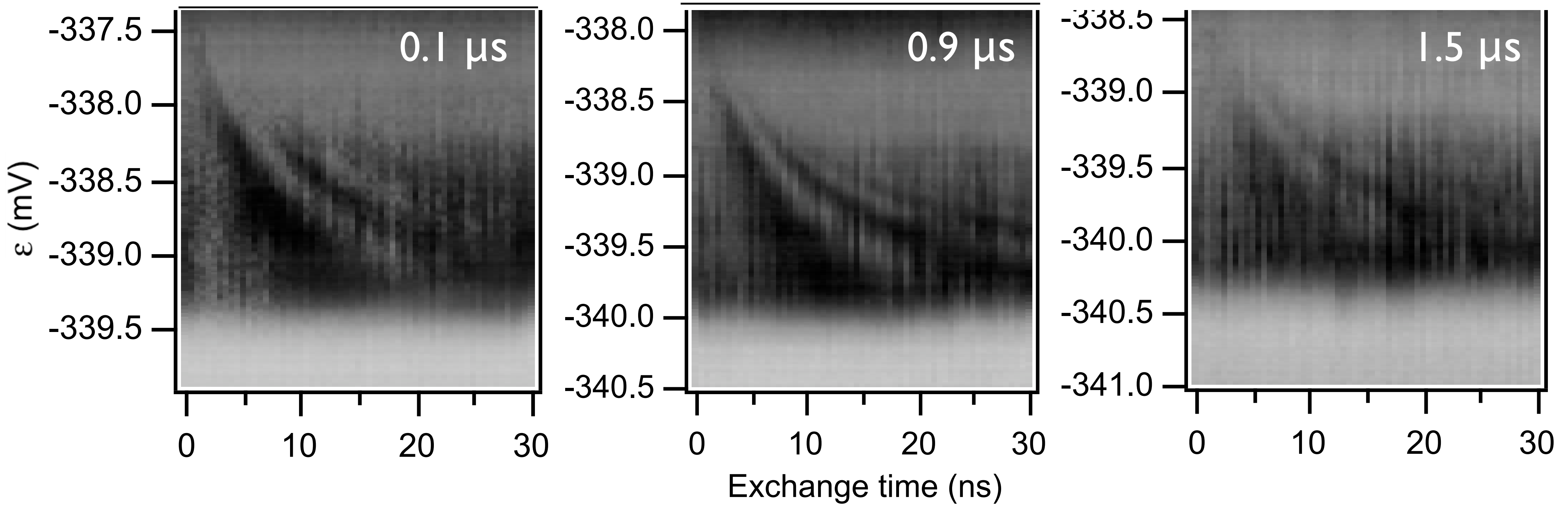
1-pulse (Hahn)

T2 ~ 1.2 μs



2-pulse (Carr-Purcell)

T2 > 5 μs

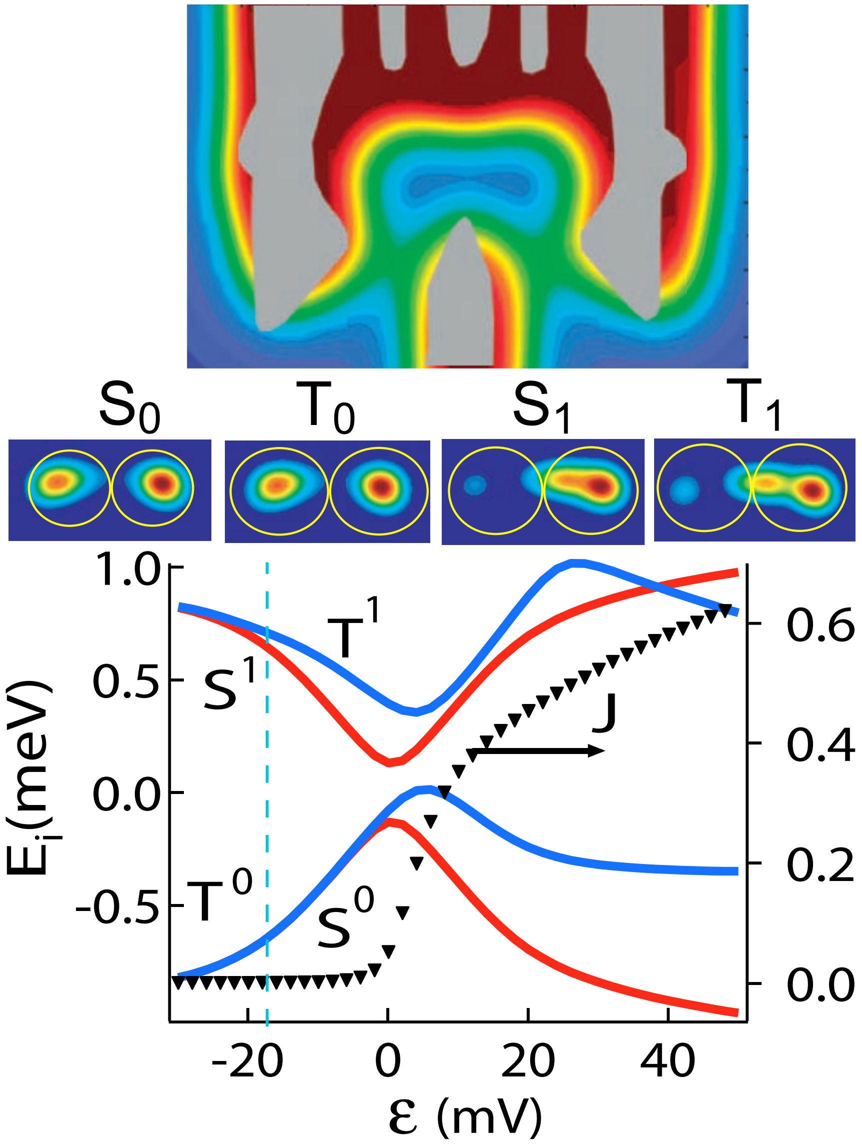


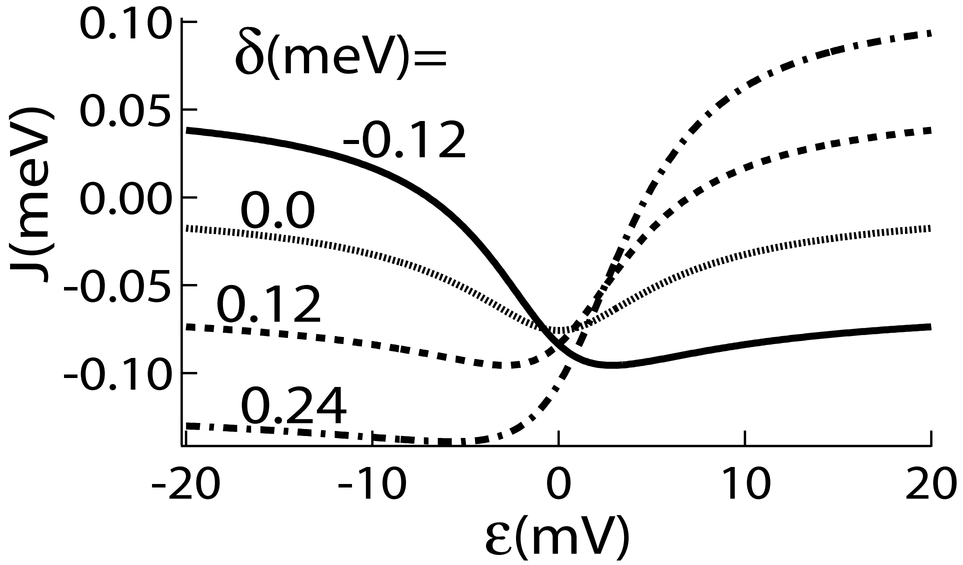
Magnetic Field Control of Exchange and Noise Immunity in Double Quantum Dots

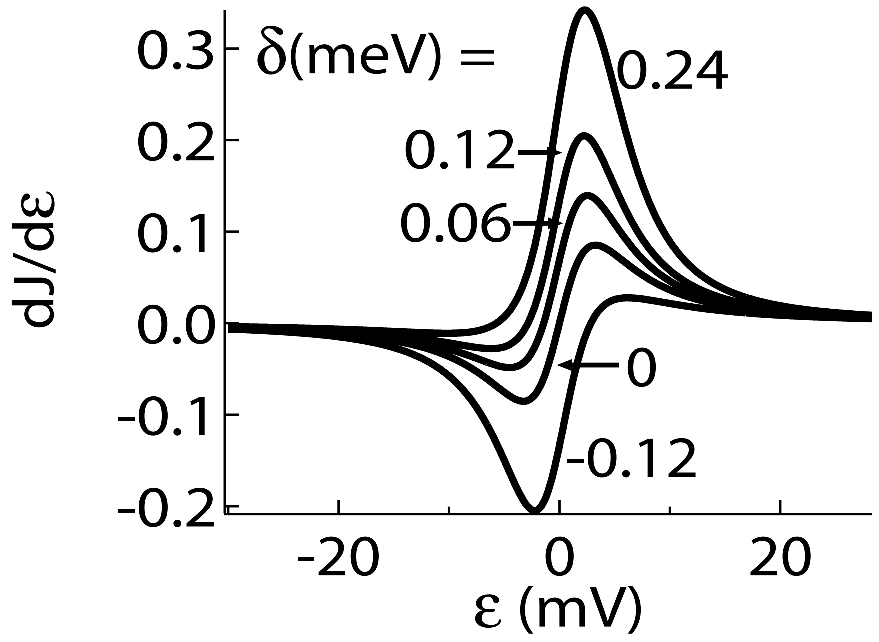
M. Stopa[1, *] and C. M. Marcus[2]

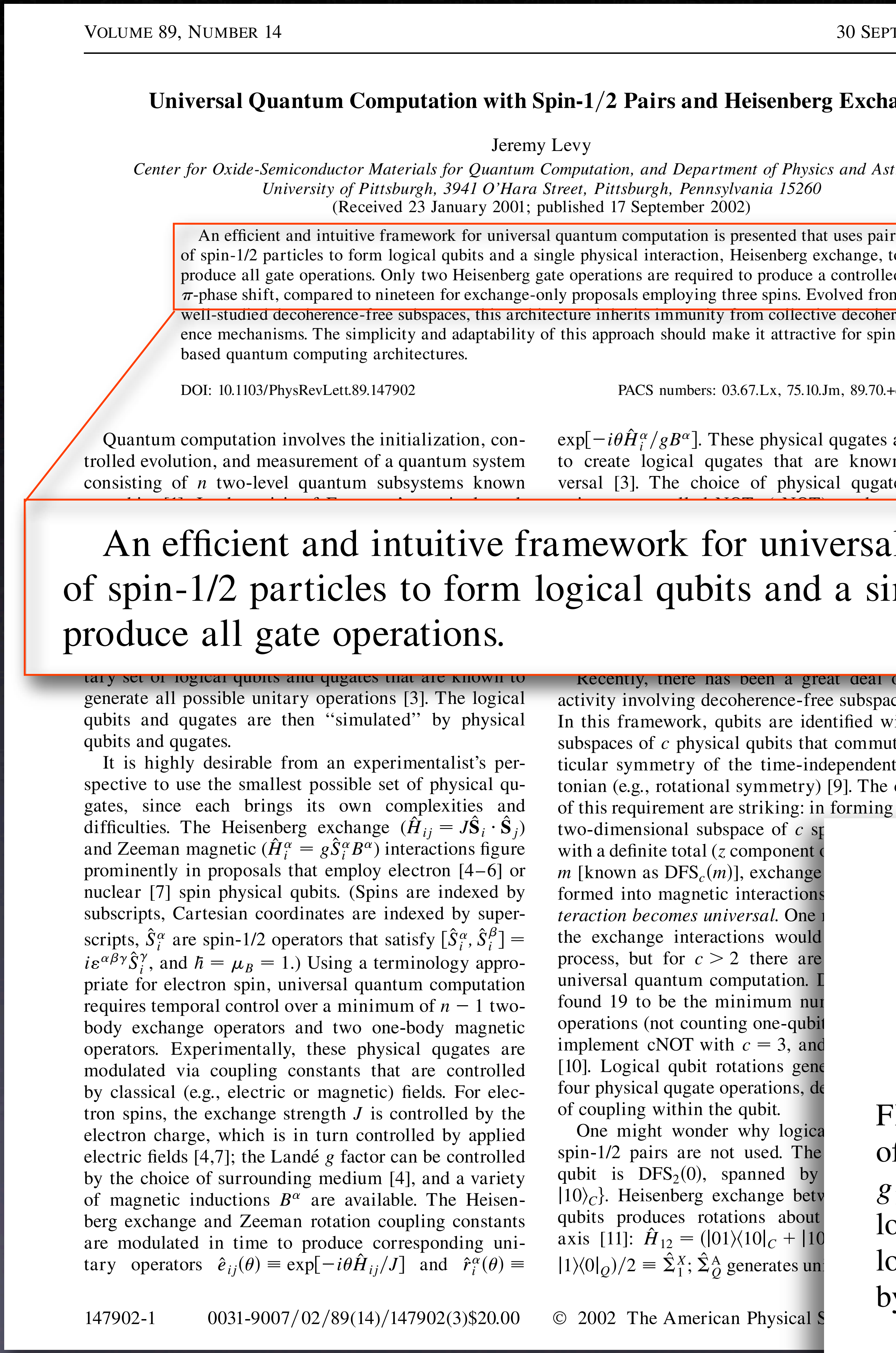
[1] *Center for Nanoscale Systems, Harvard University, Cambridge, MA 02138*
[2] *Department of Physics, Harvard University, Cambridge, MA 02138*

We employ density functional calculated eigenstates as a basis for exact diagonalization studies of semiconductor double quantum dots, with two electrons, through the transition from the symmetric bias regime to the regime where both electrons occupy the same dot. We calculate the singlet-triplet splitting $J(\varepsilon)$ as a function of bias detuning ε and explain its functional shape with a simple, double anti-crossing model. A voltage noise suppression "sweet spot," where $dJ(\varepsilon)/d\varepsilon = 0$ with nonzero $J(\varepsilon)$, is predicted and shown to be tunable with a magnetic field B.









VOLUME 89, NUMBER 14 30 SEPTEMBER 2002

Universal Quantum Computation with Spin-1/2 Pairs and Heisenberg Exchange

Jeremy Levy
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An efficient and intuitive framework for universal quantum computation is presented that uses pairs of spin-1/2 particles to form logical qubits and a single physical interaction, Heisenberg exchange, to produce all gate operations. Only two Heisenberg gate operations are required to produce a controlled π-phase shift, compared to nineteen for exchange-only proposals employing three spins. Evolved from well-studied decoherence-free subspaces, this architecture inherits immunity from collective decoherence mechanisms. The simplicity and adaptability of this approach should make it attractive for spin-based quantum computing architectures.

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Quantum computation involves the initialization, controlled evolution, and measurement of a quantum system consisting of n two-level quantum subsystems known

tary set of logical qubits and qugates that are known to generate all possible unitary operations [3]. The logical qubits and qugates are then "simulated" by physical qubits and qugates.

It is highly desirable from an experimentalist's perspective to use the smallest possible set of physical qugates, since each brings its own complexities and difficulties. The Heisenberg exchange ($\hat{H}_{ij} = J\hat{\mathbf{S}}_i \cdot \hat{\mathbf{S}}_j$) and Zeeman magnetic ($\hat{H}_i^\alpha = g\hat{S}_i^\alpha B^\alpha$) interactions figure prominently in proposals that employ electron [4–6] or nuclear [7] spin physical qubits. (Spins are indexed by subscripts, Cartesian coordinates are indexed by superscripts, $\hat{S}_i^\alpha$ are spin-1/2 operators that satisfy $[\hat{S}_i^\alpha, \hat{S}_i^\beta] = i\varepsilon^{\alpha\beta\gamma}\hat{S}_i^\gamma$, and $\hbar = \mu_B = 1$.) Using a terminology appropriate for electron spin, universal quantum computation requires temporal control over a minimum of $n-1$ two-body exchange operators and two one-body magnetic operators. Experimentally, these physical qugates are modulated via coupling constants that are controlled by classical (e.g., electric or magnetic) fields. For electron spins, the exchange strength J is controlled by the electron charge, which is in turn controlled by applied electric fields [4,7]; the Landé g factor can be controlled by the choice of surrounding medium [4], and a variety of magnetic inductions B^α are available. The Heisenberg exchange and Zeeman rotation coupling constants are modulated in time to produce corresponding unitary operators $\hat{e}_{ij}(\theta) \equiv \exp[-i\theta\hat{H}_{ij}/J]$ and $\hat{r}_i^\alpha(\theta) \equiv$ $\exp[-i\theta\hat{H}_i^\alpha/gB^\alpha]$. These physical qugates are combined to create logical qugates that are known to be universal [3]. The choice of physical qugate sets is not

Recently, there has been a great deal of theoretical activity involving decoherence-free subspaces [8] (DFS). In this framework, qubits are identified with particular subspaces of c physical qubits that commute with a particular symmetry of the time-independent full Hamiltonian (e.g., rotational symmetry) [9]. The consequences of this requirement are striking: in forming qubits from a
two-dimensional subspace of c sp
with a definite total (z component
m [known as $\mathrm{DFS}_c(m)$], exchange
formed into magnetic interactions
teraction becomes universal. One
the exchange interactions would
process, but for $c > 2$ there are
universal quantum computation. I
found 19 to be the minimum nu
operations (not counting one-qubit
implement cNOT with $c = 3$, and
[10]. Logical qubit rotations gene
four physical qugate operations, de
of coupling within the qubit.

One might wonder why logica
spin-1/2 pairs are not used. The
qubit is $\mathrm{DFS}_2(0)$, spanned by
$|10\rangle_C\}$. Heisenberg exchange betw
qubits produces rotations about
axis [11]: $\hat{H}_{12} = (|01\rangle\langle 10|_C + |10$
$|1\rangle\langle 0|_Q)/2 \equiv \hat{\Sigma}_1^X$; $\hat{\Sigma}_Q^A$ generates un

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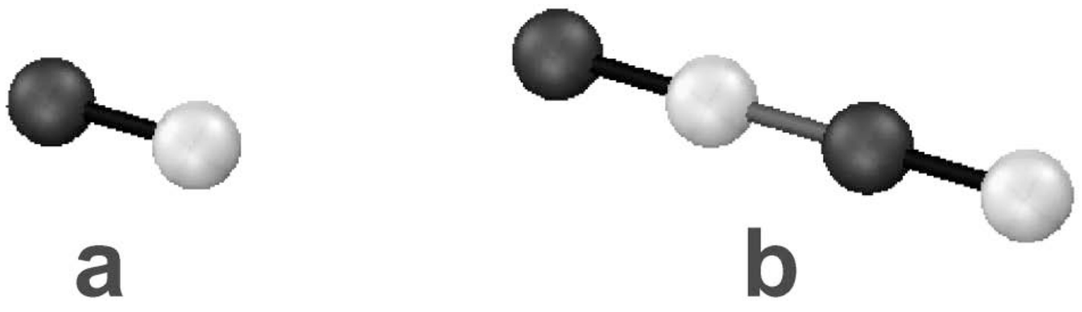

FIG. 1. (a) Logical qubit Q formed from the $S_z = 0$ subspace of two spin-1/2 physical qubits with different Landé g factors g_1 (gray) and g_2 (white). Heisenberg coupling within the logical qubit is represented by a solid black line. (b) Two logical qubits coupled via Heisenberg exchange, represented by a solid gray line.

Fault-tolerant architecture for quantum computation using electrically controlled semiconductor spins

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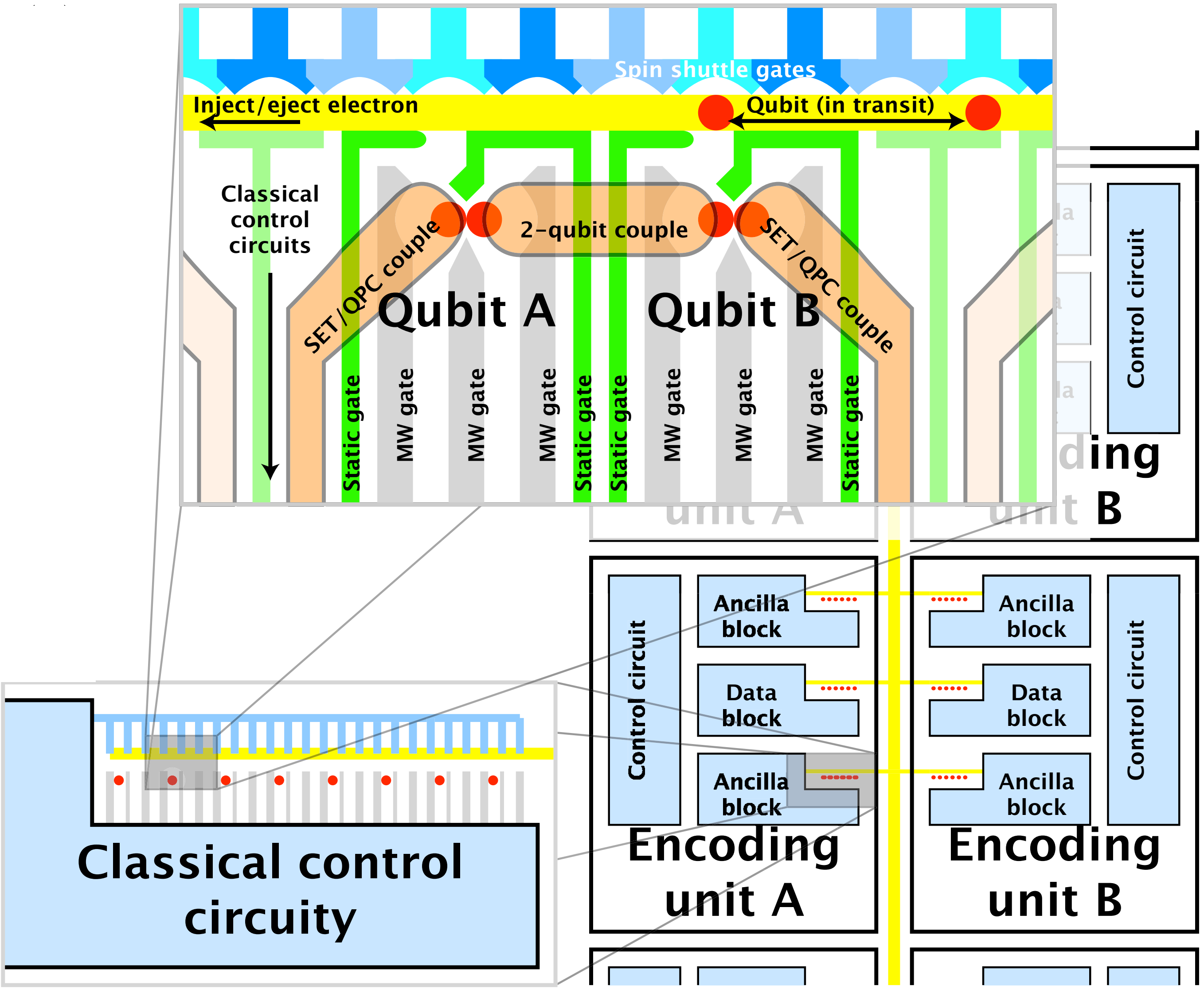
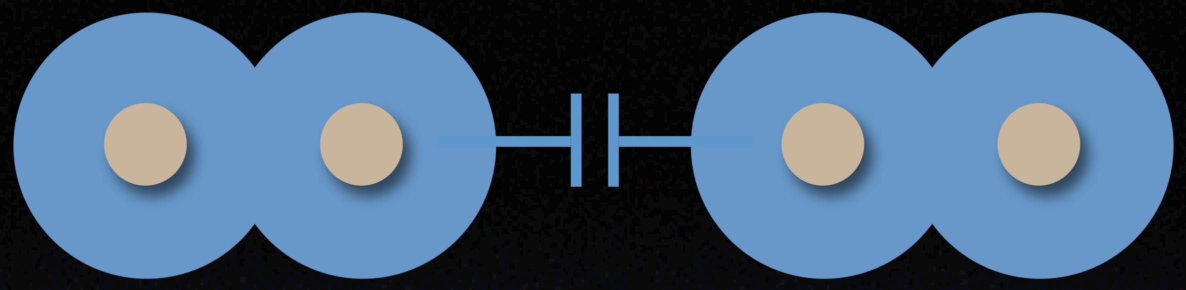
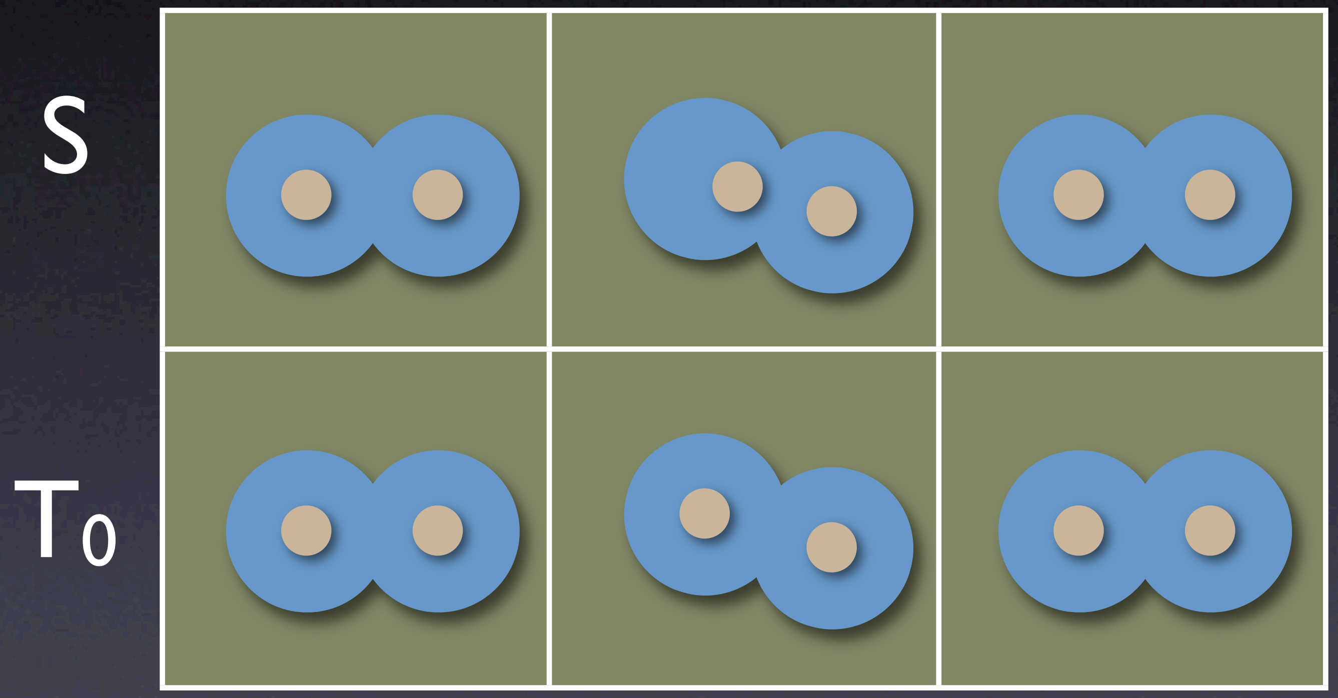
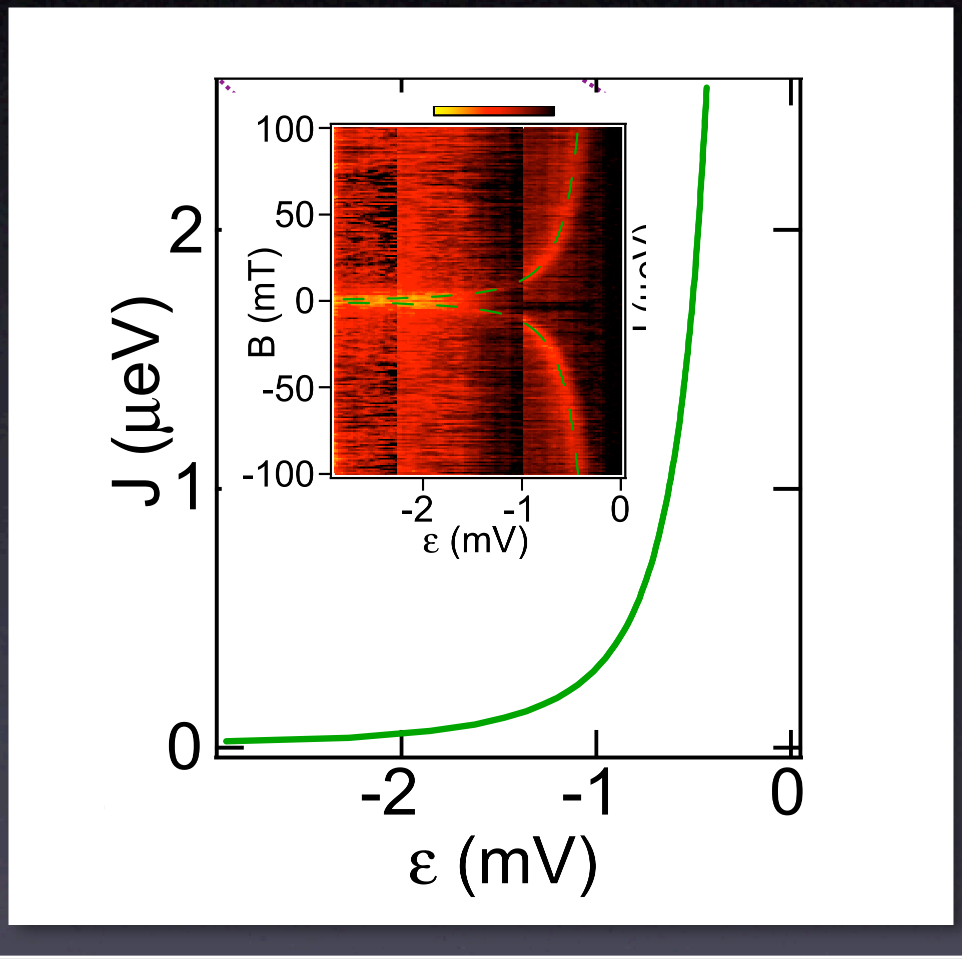
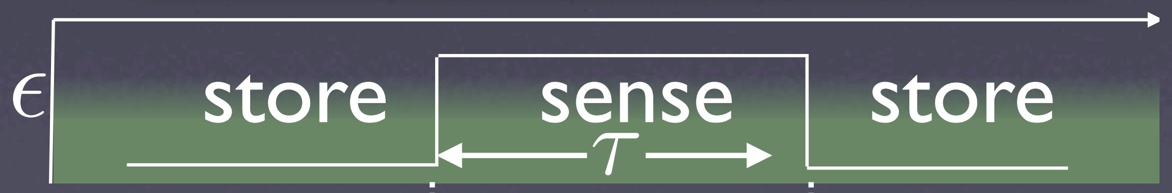


Electrostatic Two-Qubit Gate



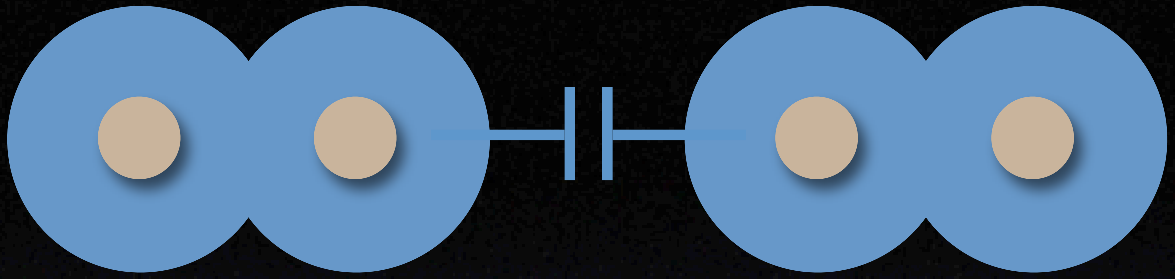


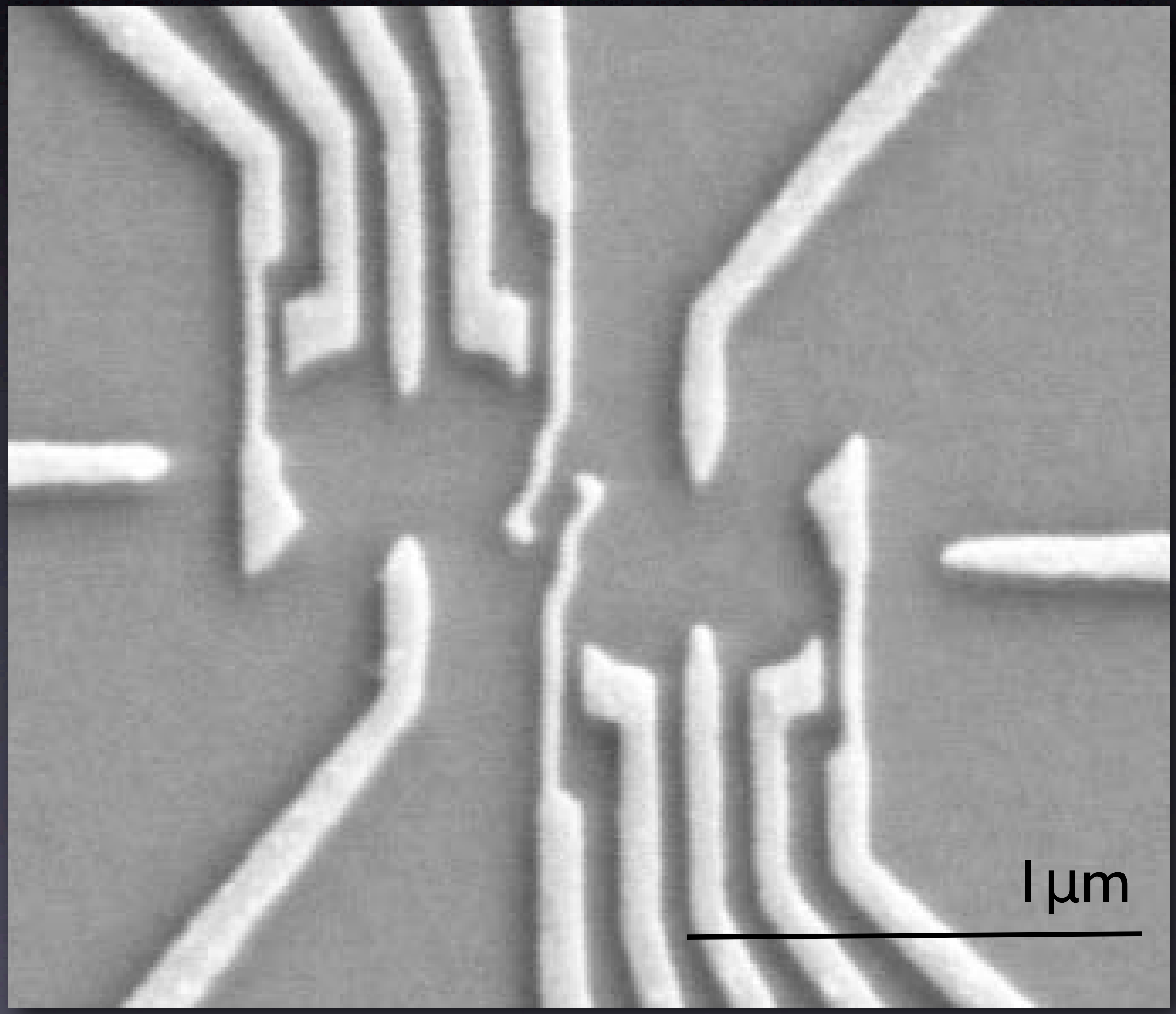




$$\frac{dJ}{d\epsilon} \sim 0 \qquad \frac{dJ}{d\epsilon} \sim \frac{\pi d}{e\tau} \qquad \frac{dJ}{d\epsilon} \sim 0$$

Electrostatic Two-Qubit Gate

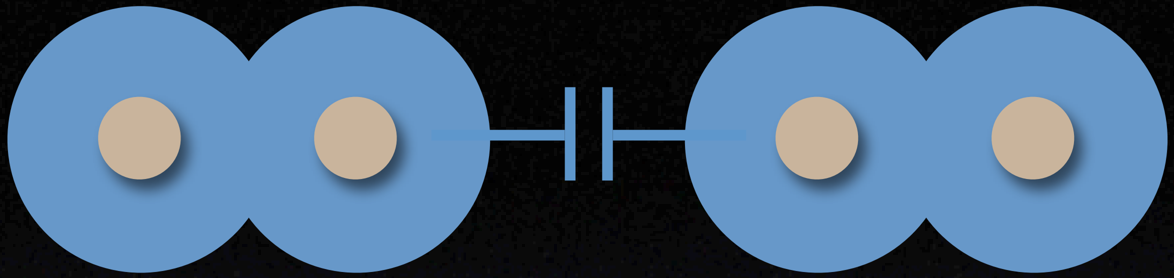


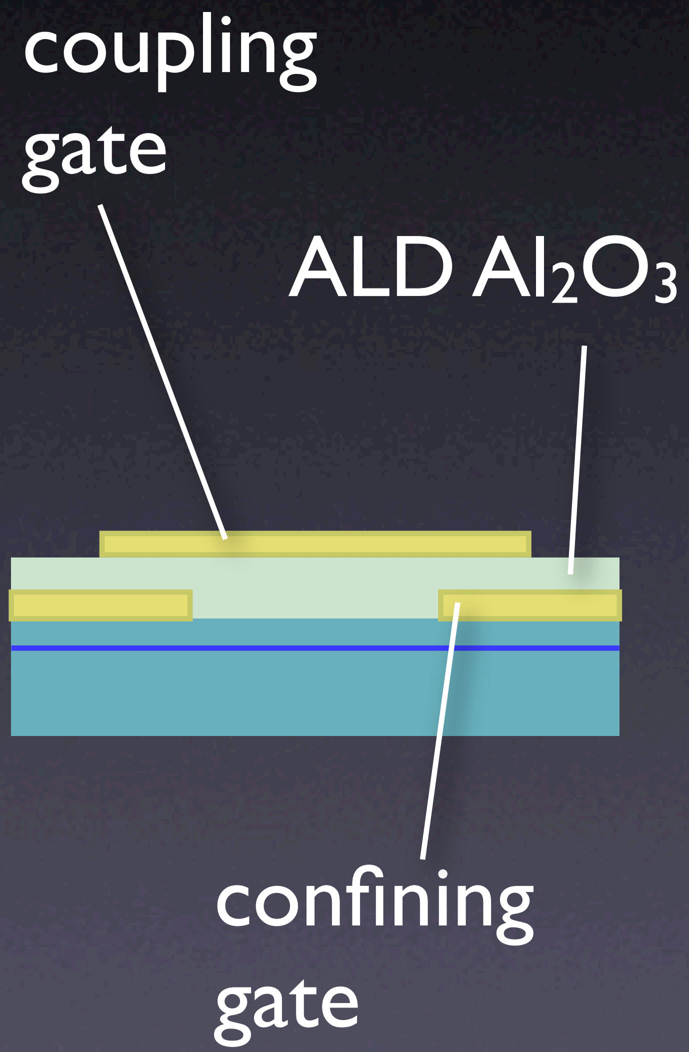


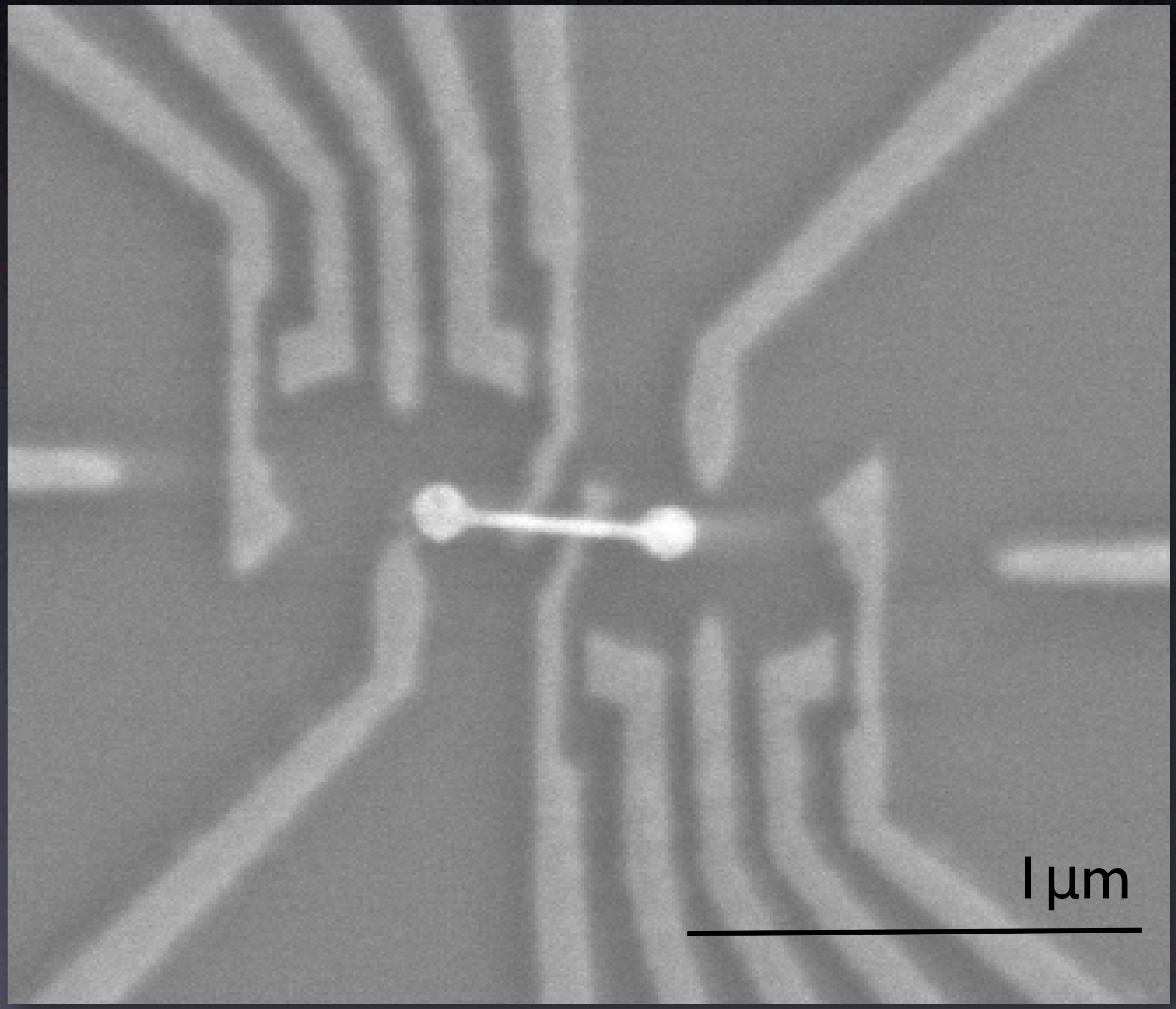
first generation

J. R. Petta, et al. (2005)

Electrostatic Two-Qubit Gate







second generation

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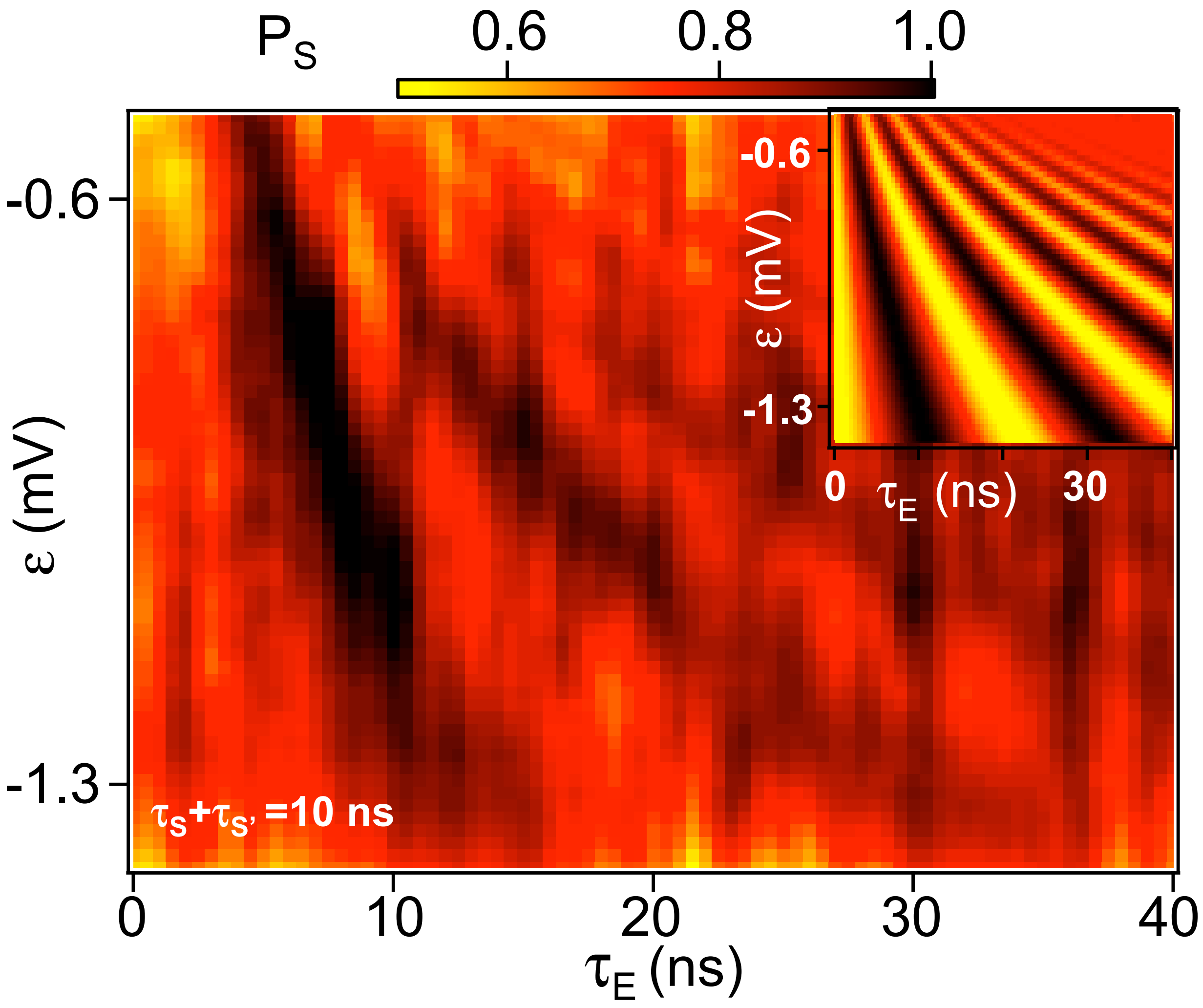
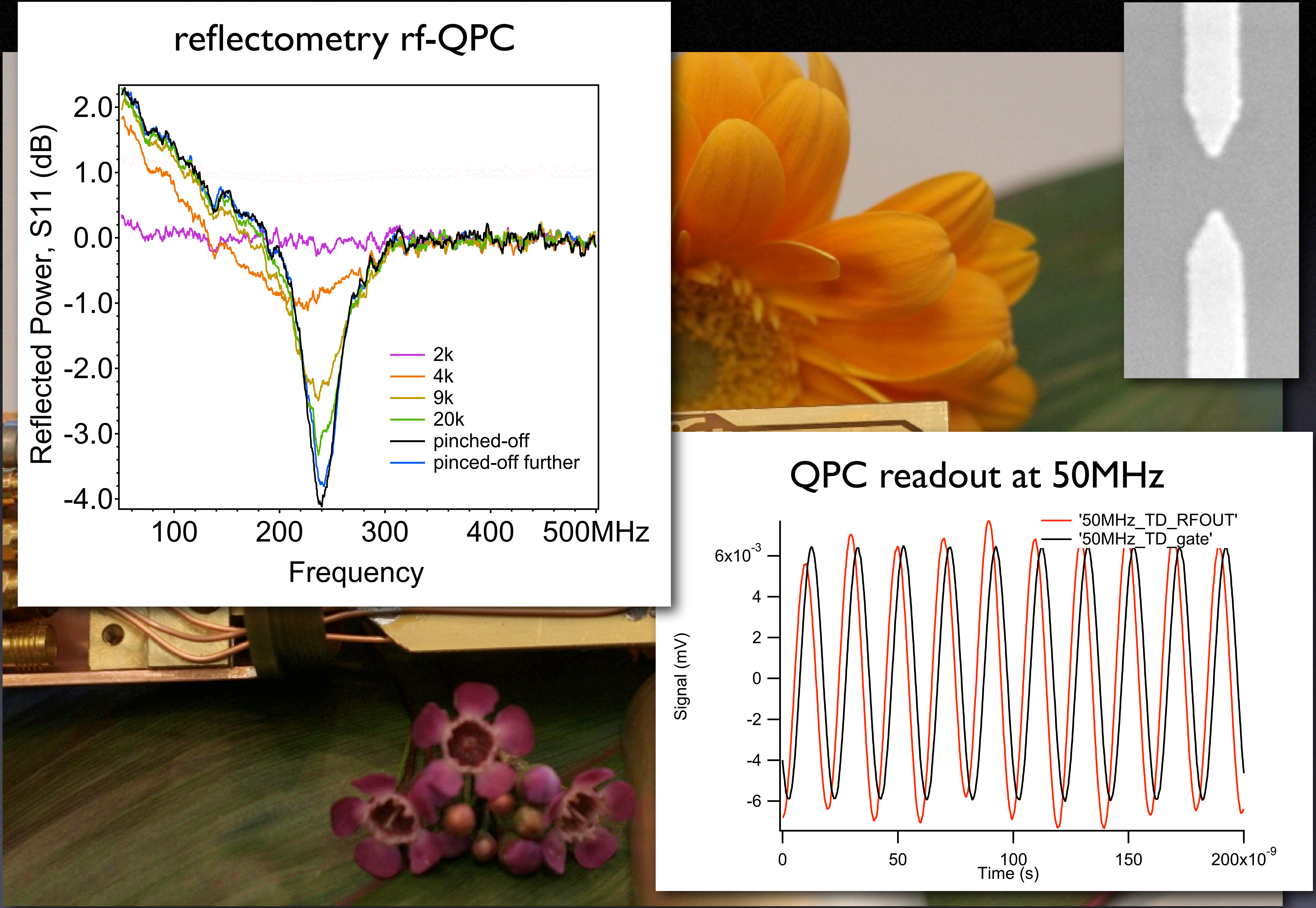
Noisy Data: Nuclear Memory

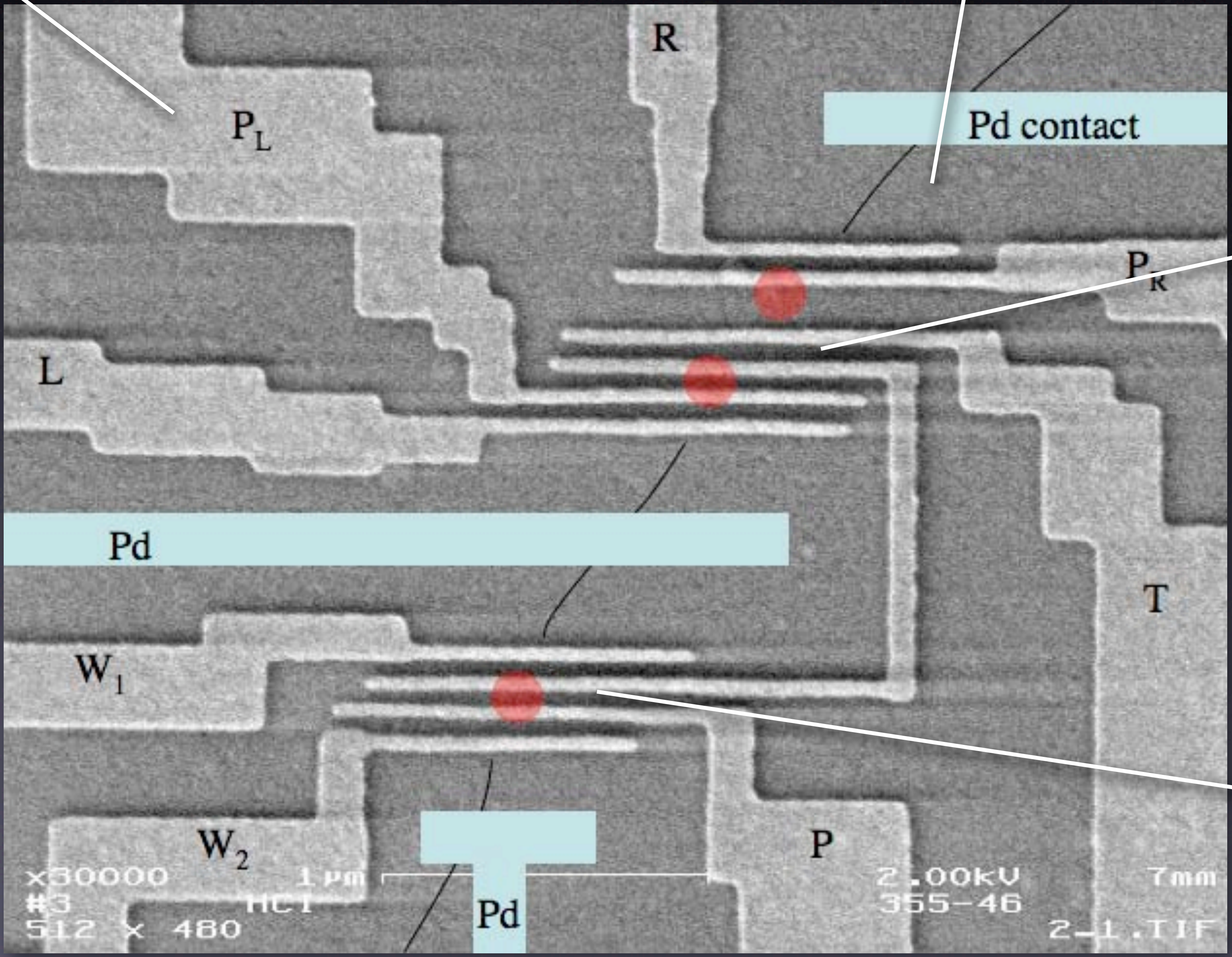


High Bandwidth Readout

High Bandwidth Readout



The Nuclear-Free Zone:
Nanotube double dot with charge sensors



depletion gates

carbon nanotube

double-dot

charge sensor

Gate-Defined Quantum Dots on Carbon Nanotubes

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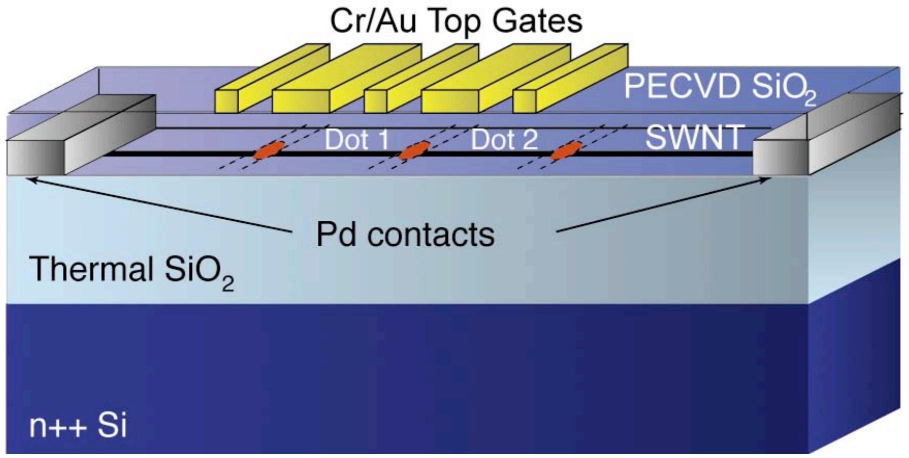
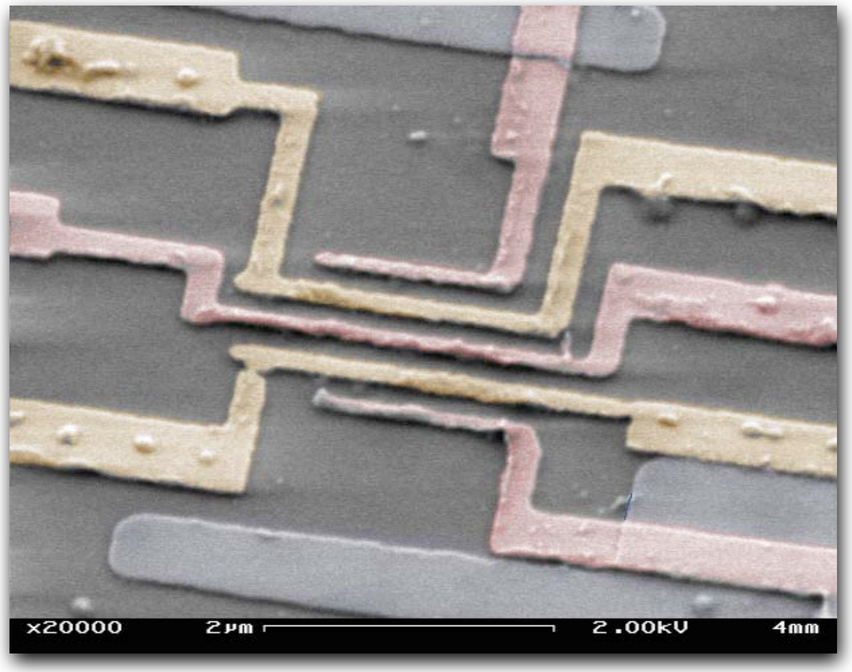
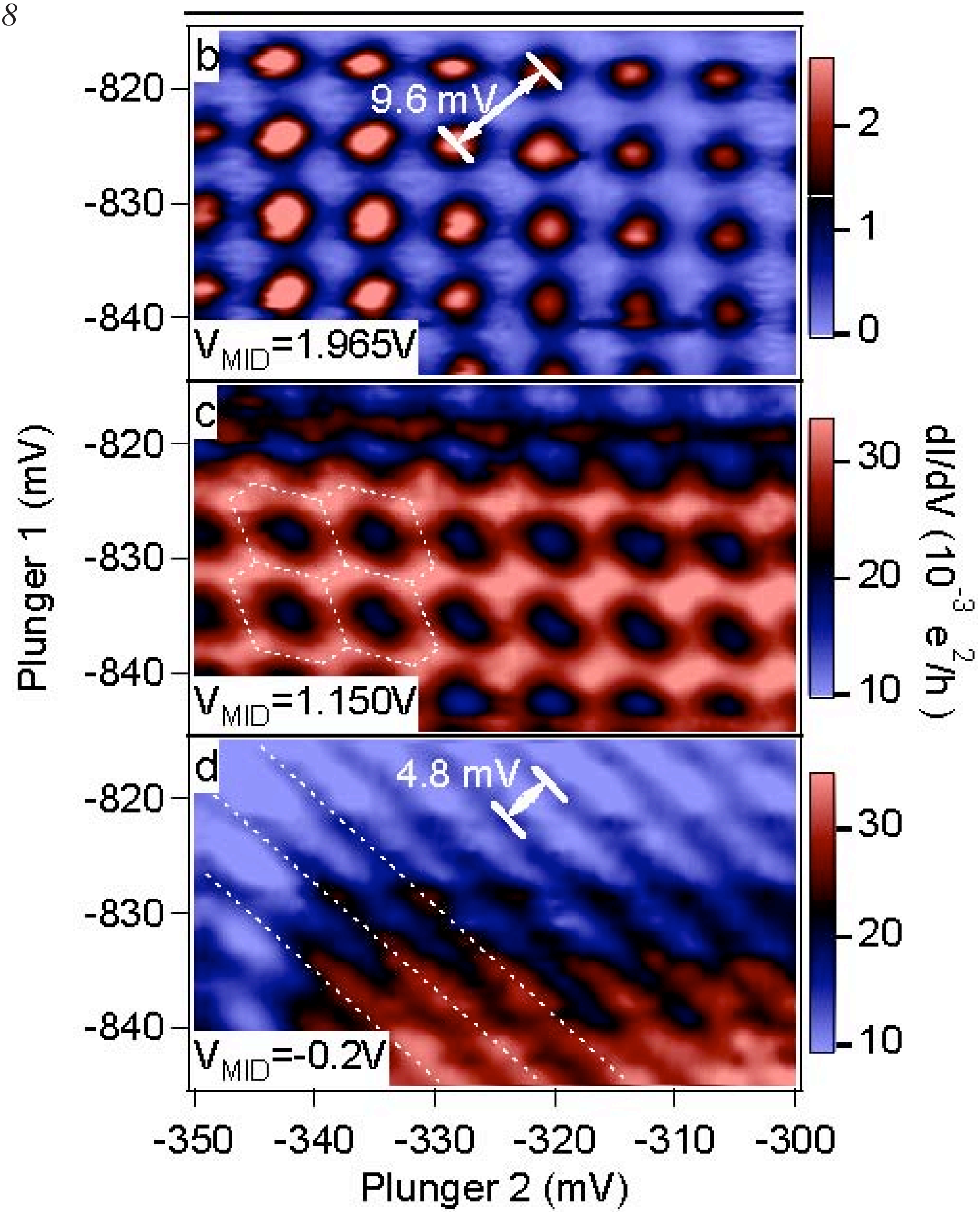
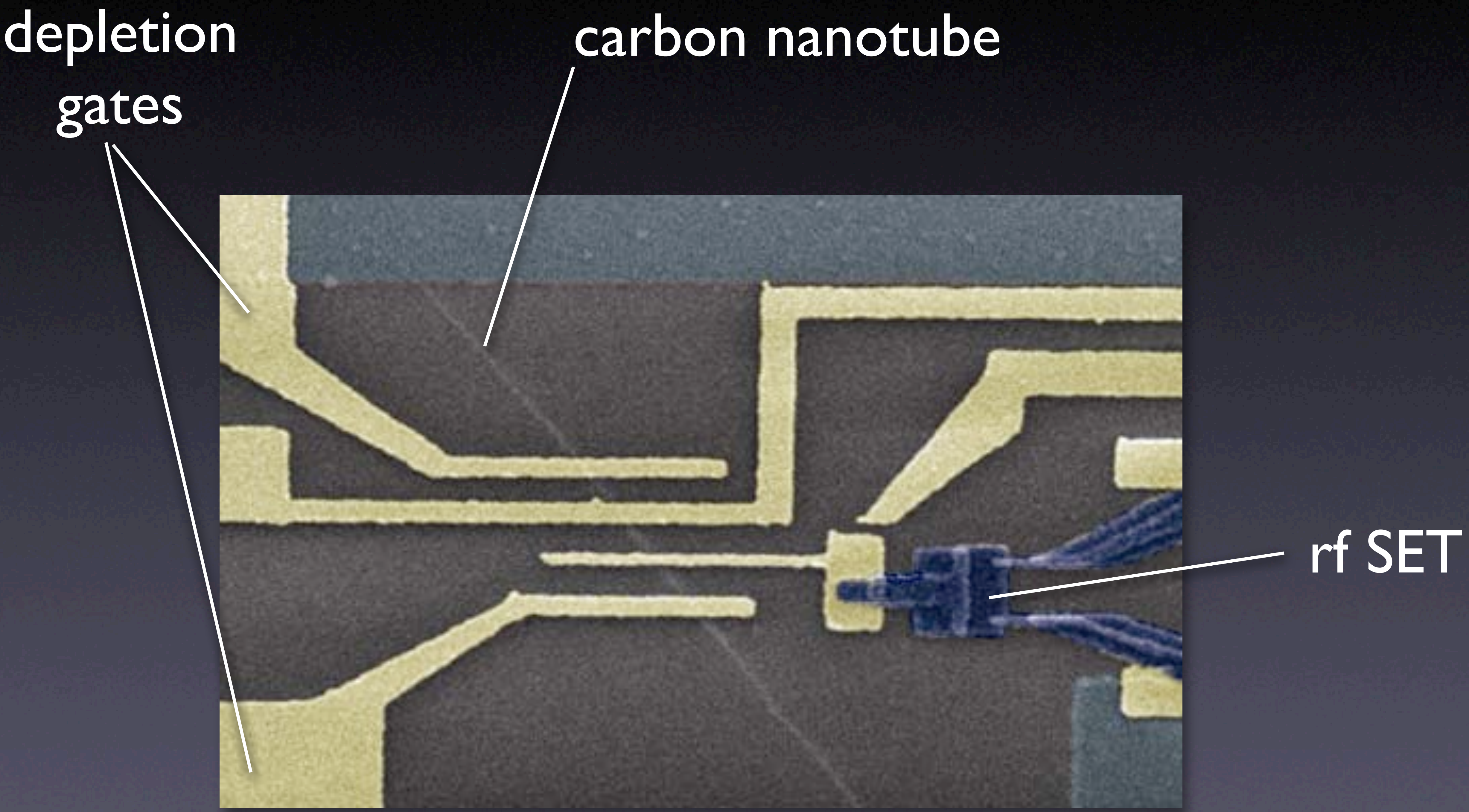




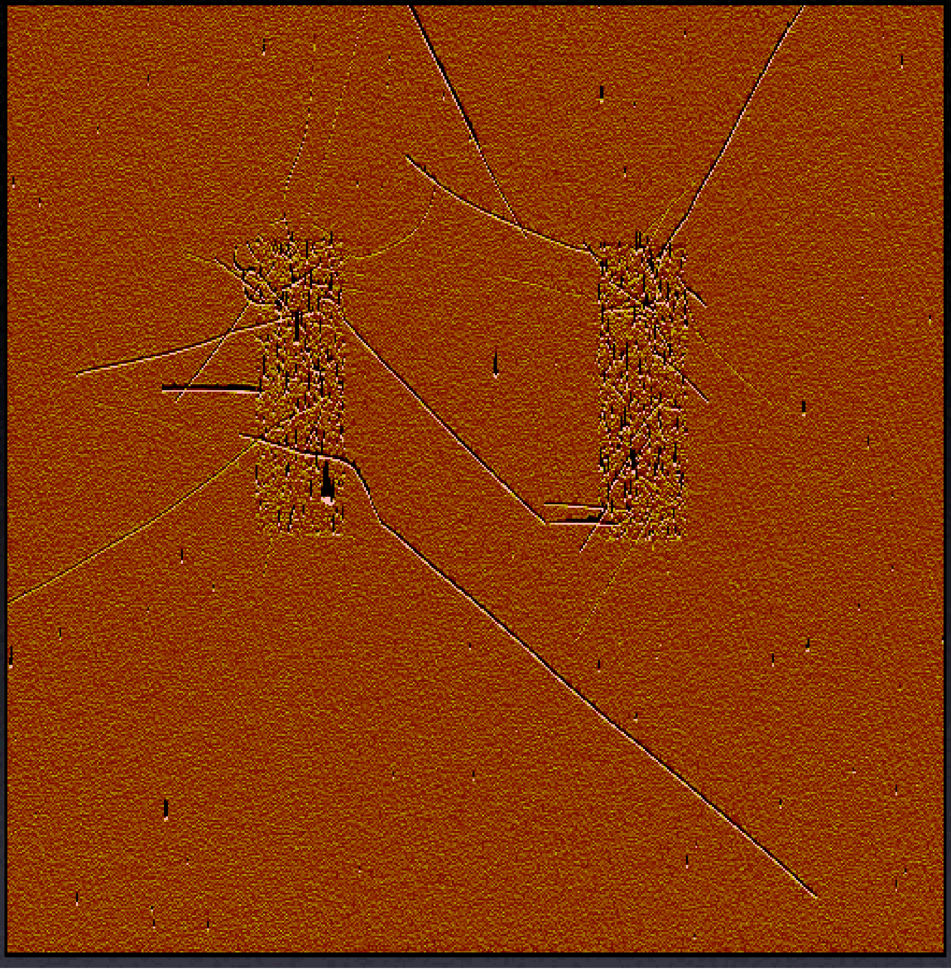


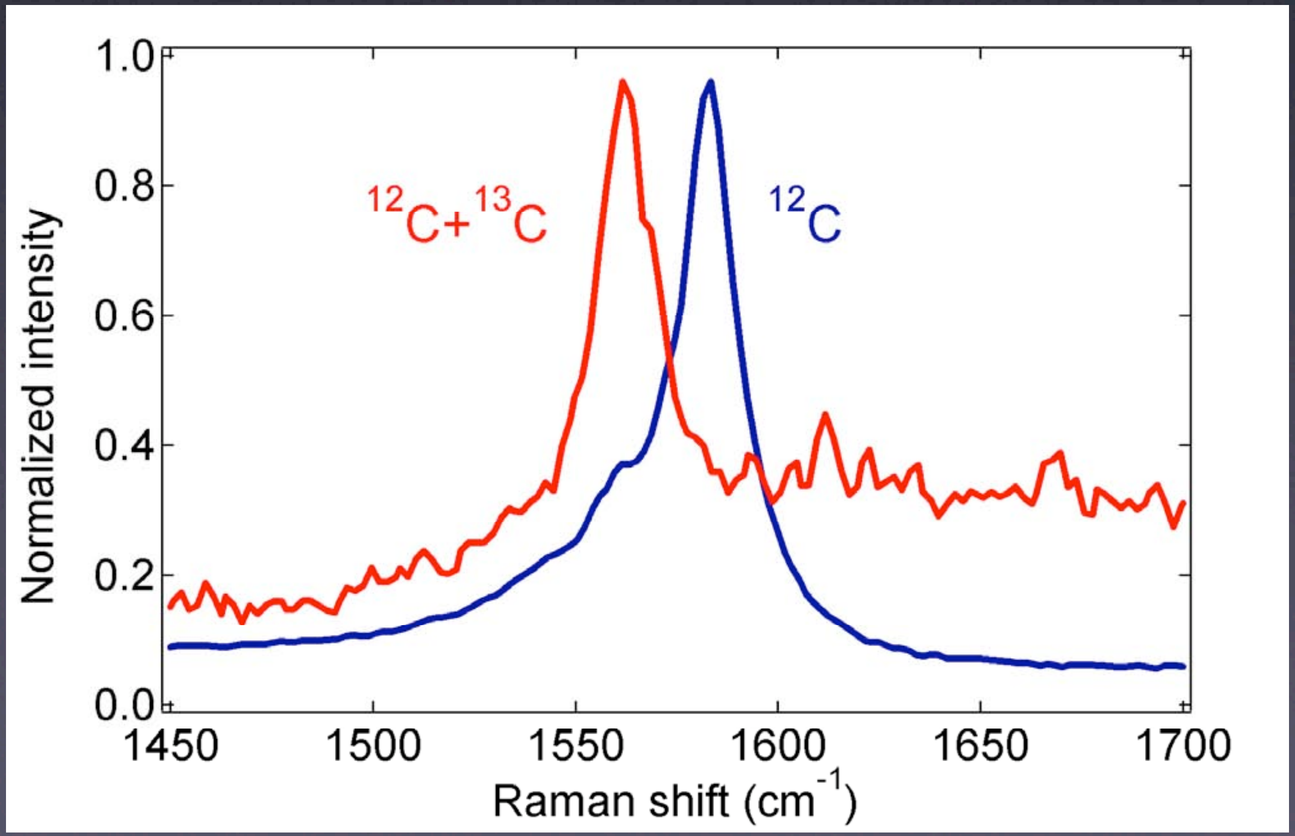
Nanotube-Based Single Electron Device with Fast Charge Sensor



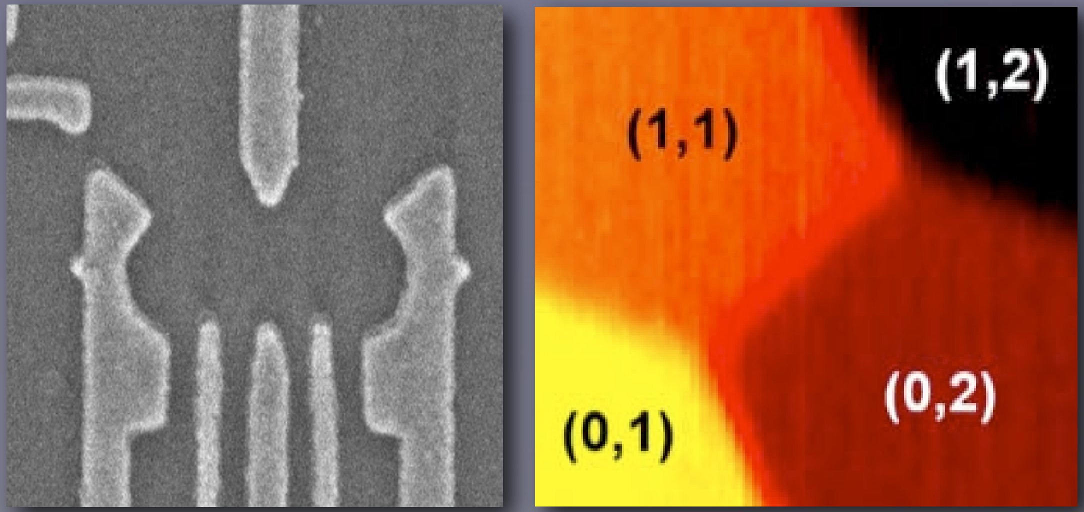
M. J. Biercuk, D. J. Reilly, et al. cond-mat/0510550 (PRB-RC, in press (2006)).

99% ^{13}C Methane feedstock
50% ^{12}C, 50% ^{13}C mixture

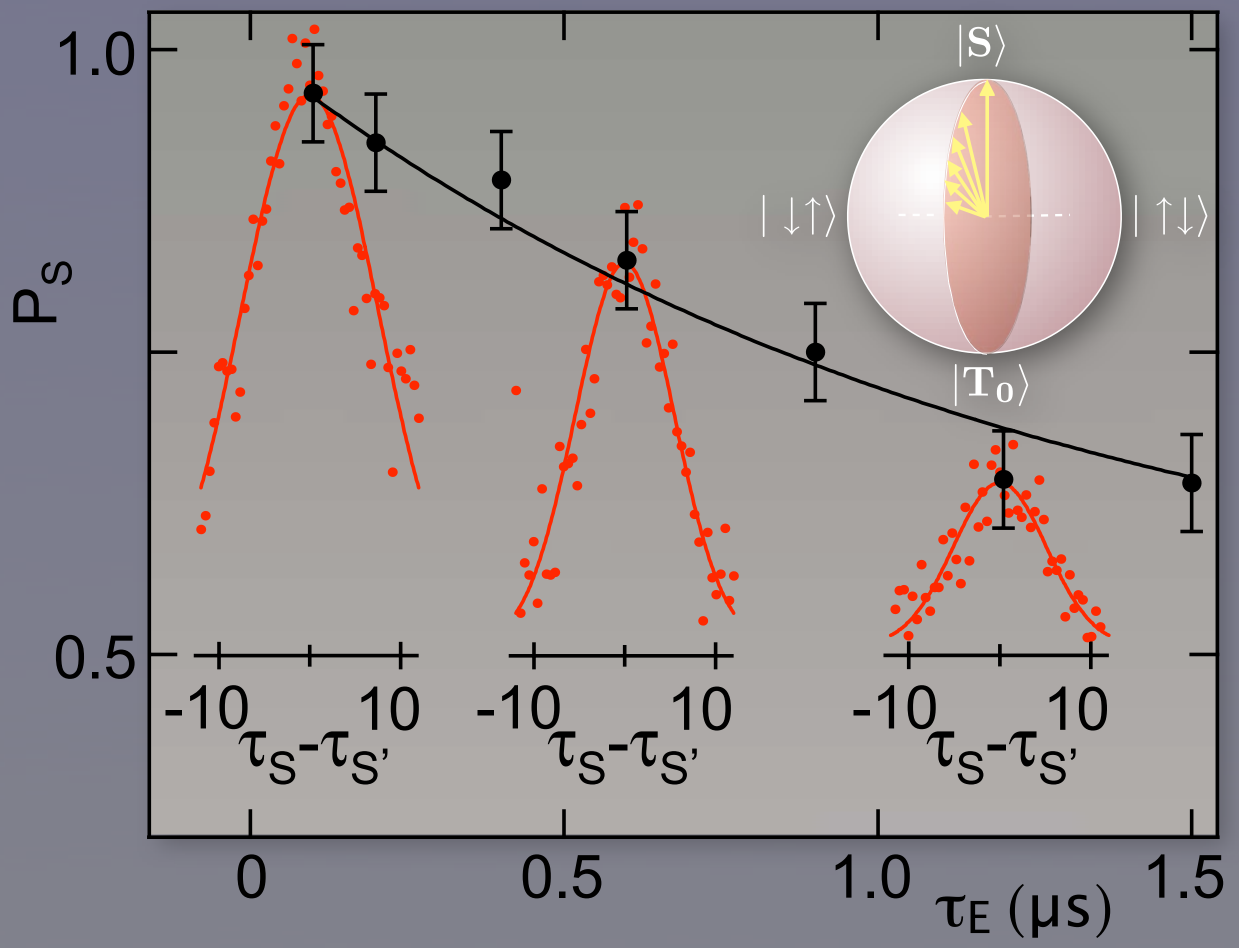




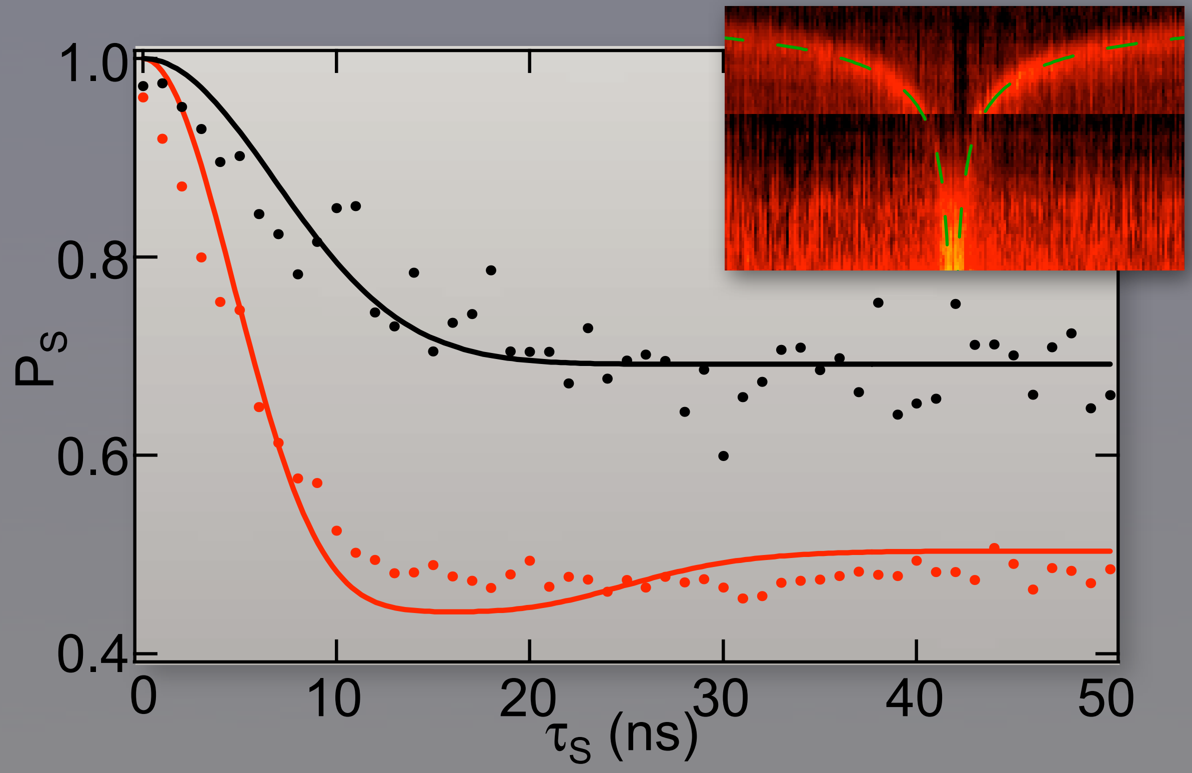
Summary



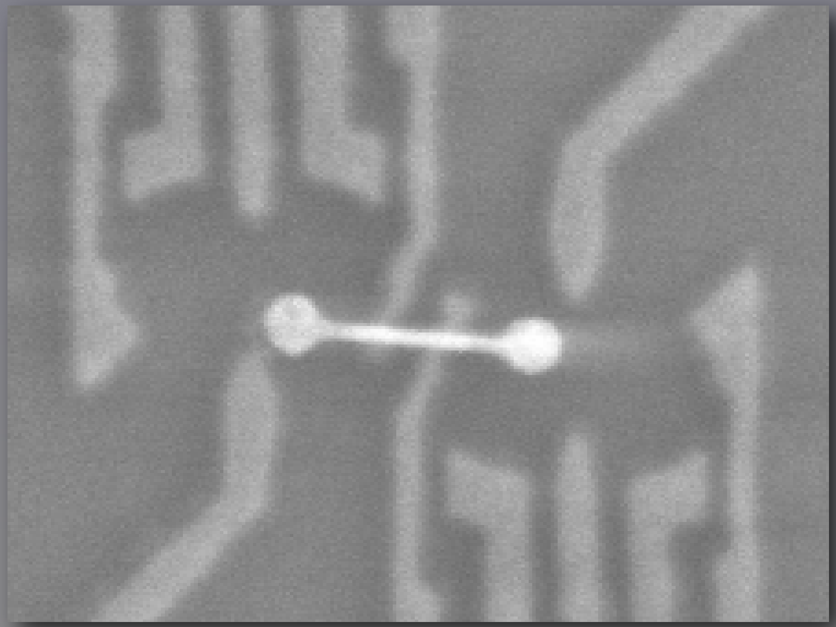
fast, single electron control



Spin Echo - Spin T2 > 1μs



Spin T2* ~ 10ns



two qubit gates