

# Coherent Manipulation of Coupled Electron Spins in Semiconductor Quantum Dots

J. R. Petta,<sup>1</sup> A. C. Johnson,<sup>1</sup> J. M. Taylor,<sup>1</sup> E. A. Laird,<sup>1</sup> A. Yacoby,<sup>2</sup>  
M. D. Lukin,<sup>1</sup> C. M. Marcus,<sup>1</sup> M. P. Hanson,<sup>3</sup> A. C. Gossard<sup>3</sup>

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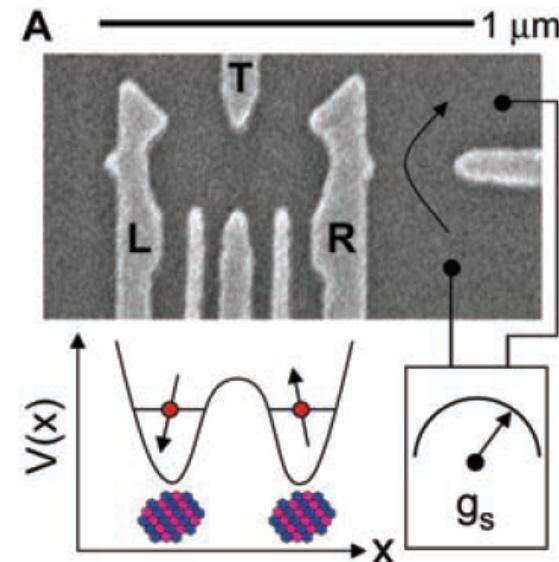
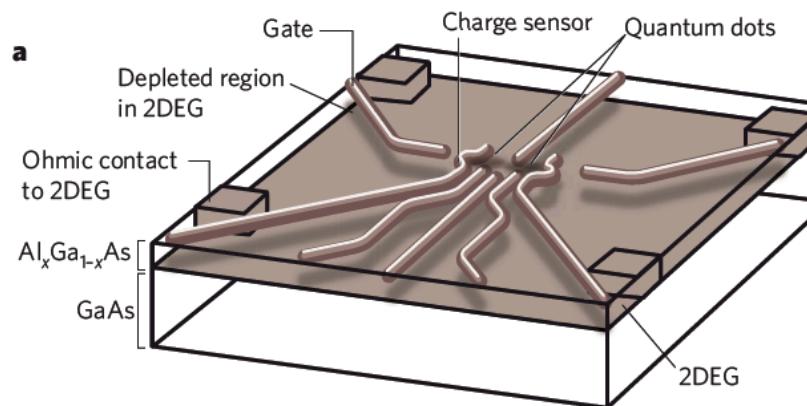
by  
Juan Osorio  
Adrian Stalder

# Overview

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- Experimental setup & basics
- Brief reminder
- Control Cycle
- Energy Diagram and  $J(\varepsilon)$  Exchange Splitting
- Dephasing of separated singlet
- Spin SWAP & Rabi oscillation
- Singlet-triplet spin-echo
- DiVincenzo Criteria

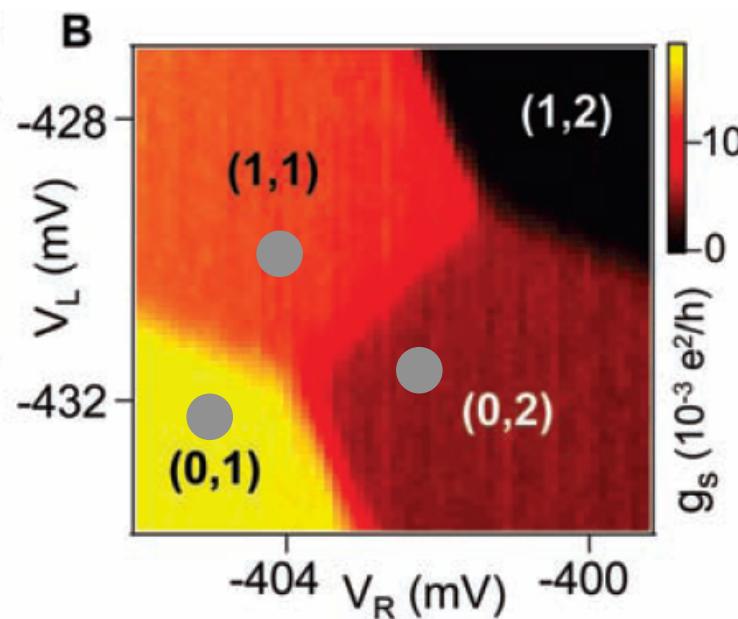
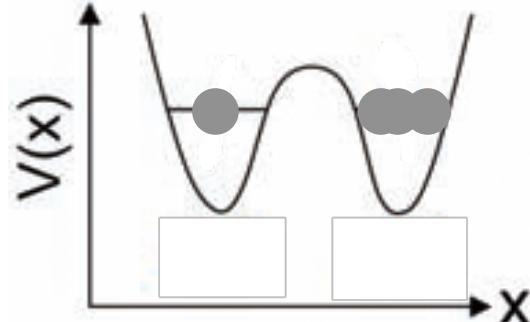
# Experimental Setup & Basics



- GaAs/AlGaAs heterostructure -> 2D EG
- $V_L, V_R$  negative voltages applied  $\varepsilon \sim V_R - V_L$
- Quantum point contact

Hanson et al., NATURE|Vol 453|19 June 2008

# Experimental Setup & Basics (II)



- Quantized conductance  $\frac{2e^2}{h}$   $\rightarrow$  charge states

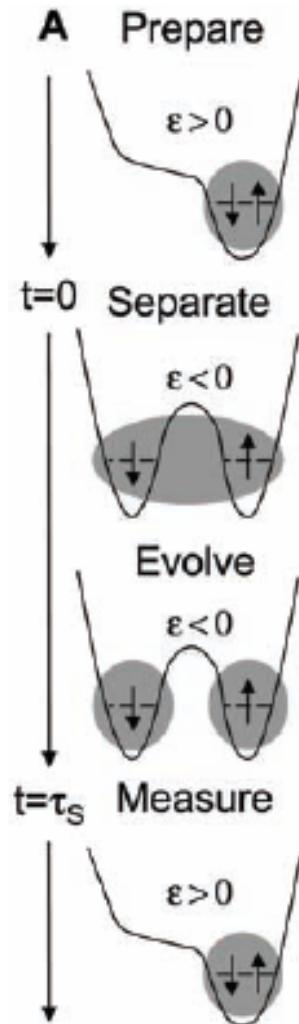
# Brief reminder

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- Singlet
  - $|S\rangle = (1/\sqrt{2}) * (| \uparrow\downarrow \rangle - | \downarrow\uparrow \rangle)$
- Triplet
  - $|T_0\rangle = (1/\sqrt{2}) * (| \uparrow\downarrow \rangle + | \downarrow\uparrow \rangle)$
  - $|T_+\rangle = | \uparrow\uparrow \rangle$
  - $|T_-\rangle = | \downarrow\downarrow \rangle$
- Interaction Hamiltonian
  - $H = J \cdot S_1 \cdot S_2$

# Control Cycle

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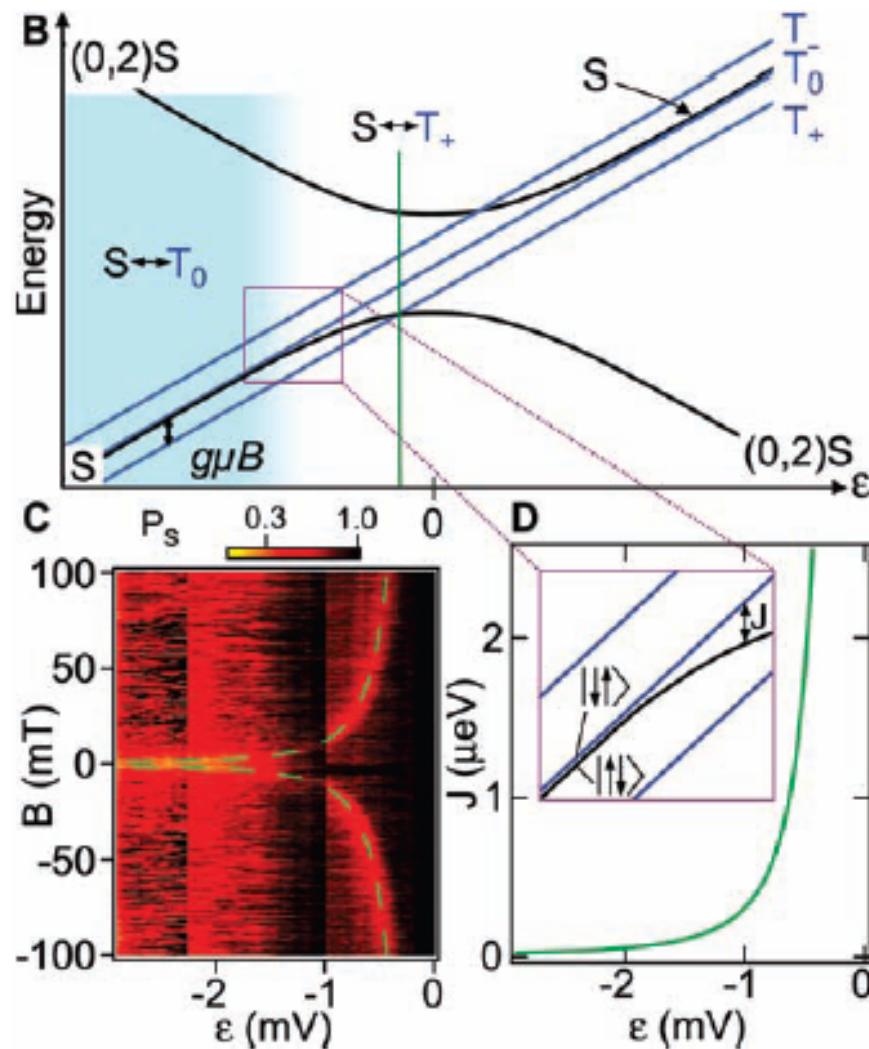
**Preparation:**  
 $\epsilon > 0$ , (0,2)S ground-state configuration.

**Separation:**  
 $\epsilon < 0$ , spatial separation of electrons.

**Evolution:**  
 $\epsilon < 0$ ,  $V_T$  modulates tunneling barrier.

**Measurement:**  
 $\epsilon > 0$ , Projective measurement onto (0,2)S state.

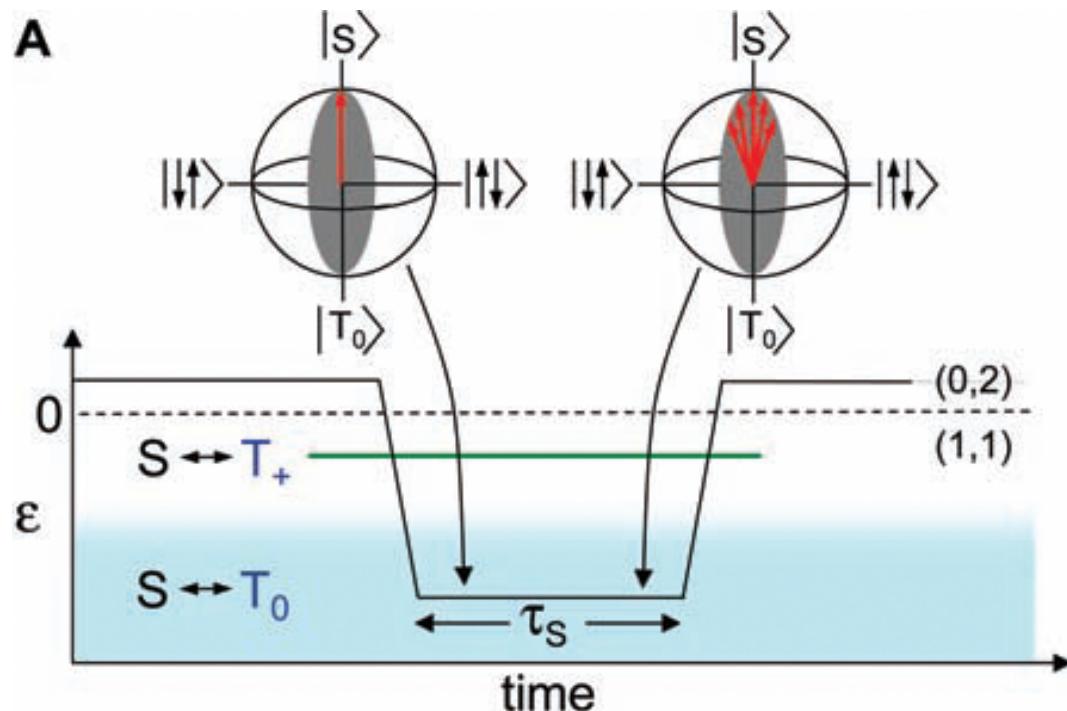
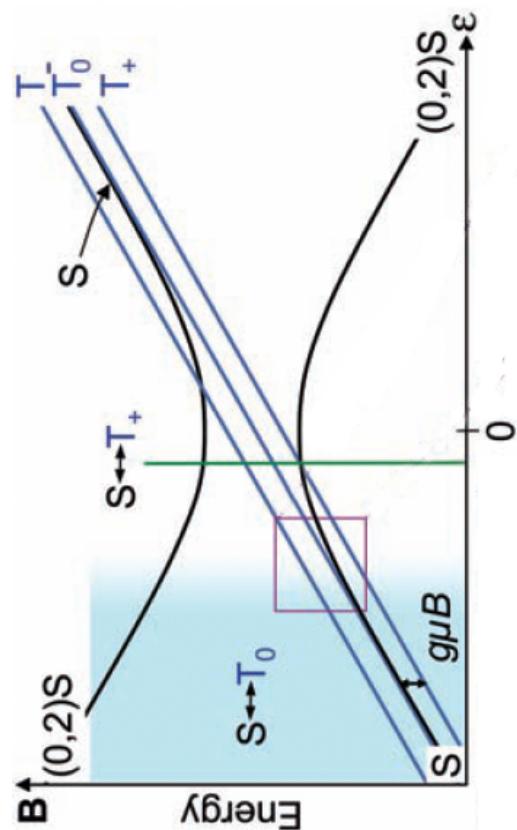
# Energy Diagram and $J(\varepsilon)$ Exchange Splitting



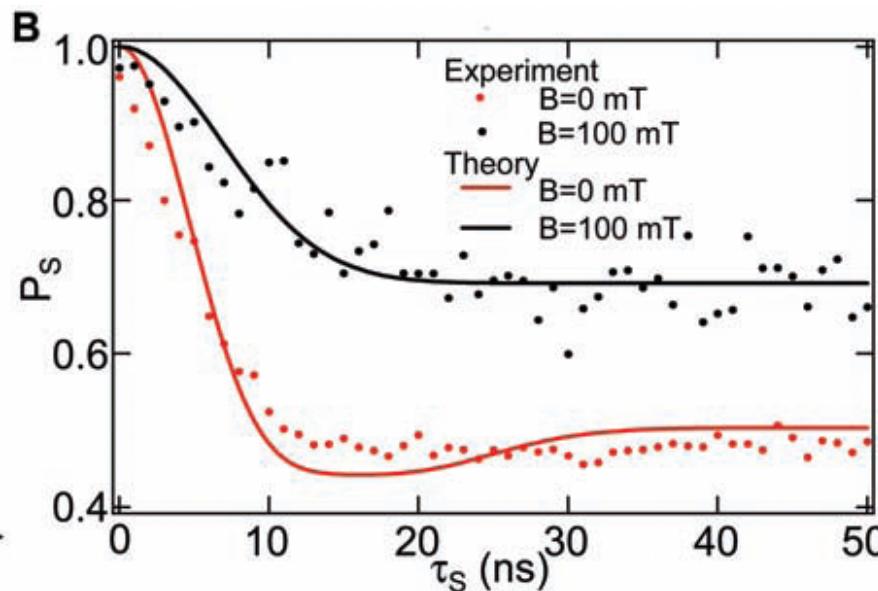
- S-T<sub>+</sub> degeneracy line allows determination of  $J(\varepsilon)$  via  $J(\varepsilon) = g^*\mu_B B$
- (0,2) and (1,1) charge states hybridize, resulting in exchange splitting  $J(\varepsilon)$ .
- Zeeman splitting  $E_Z = \pm g^*\mu_B B$  ( $B = 100$  mT).

$$H = \begin{pmatrix} J(\varepsilon) & \Delta B_{\text{nuc}}^Z \\ \Delta B_{\text{nuc}}^Z & 0 \end{pmatrix}$$

# Dephasing of separated singlet (I)

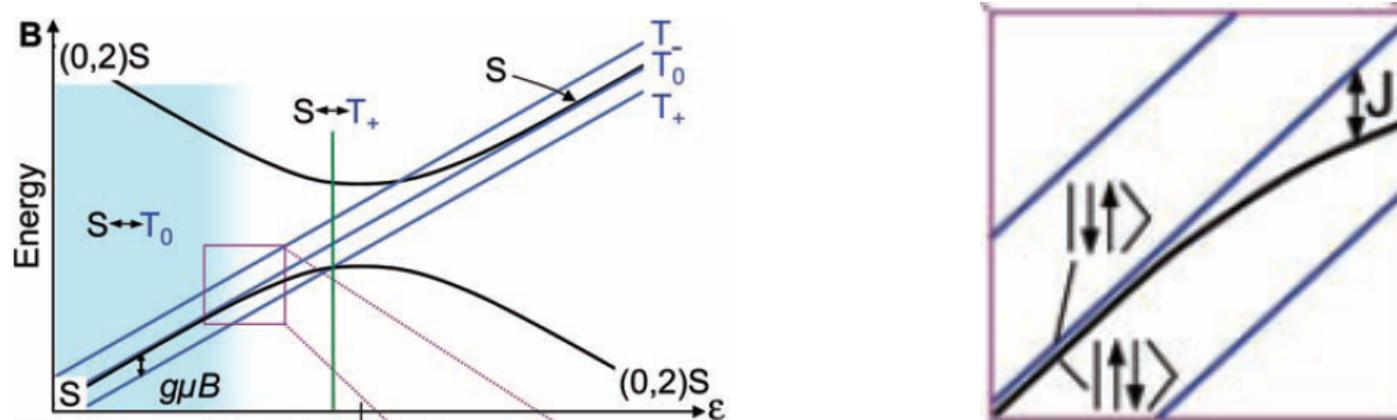
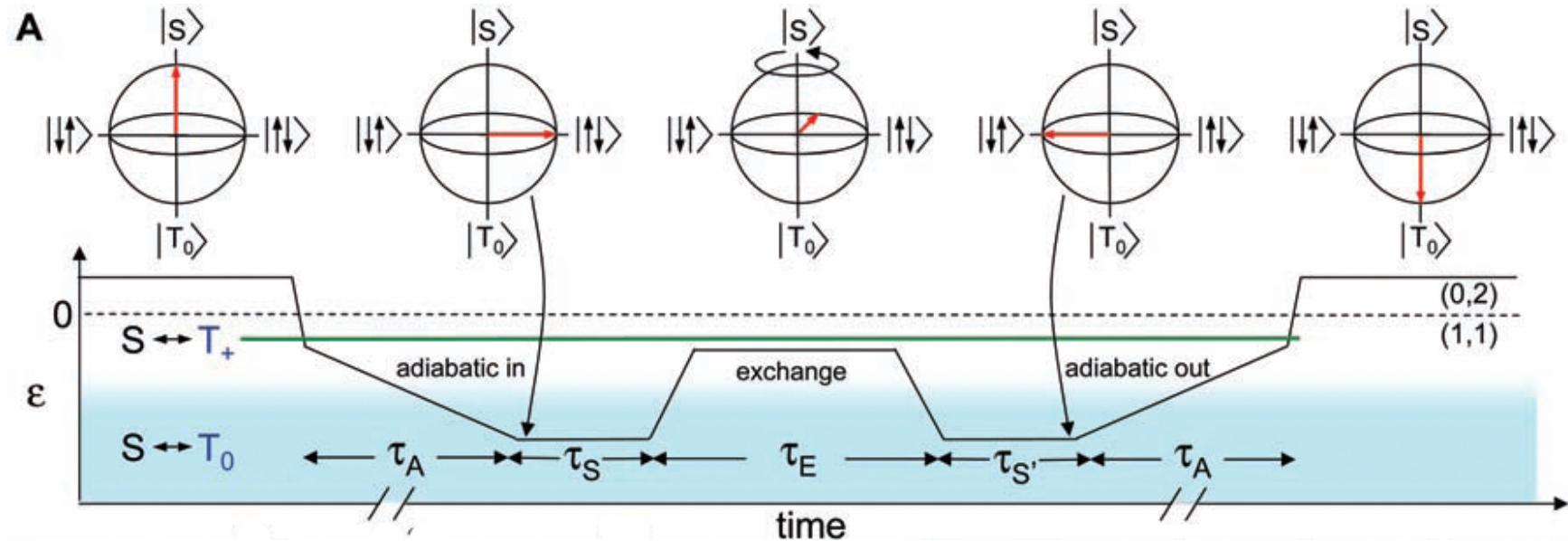


# Dephasing of separated singlet (II)

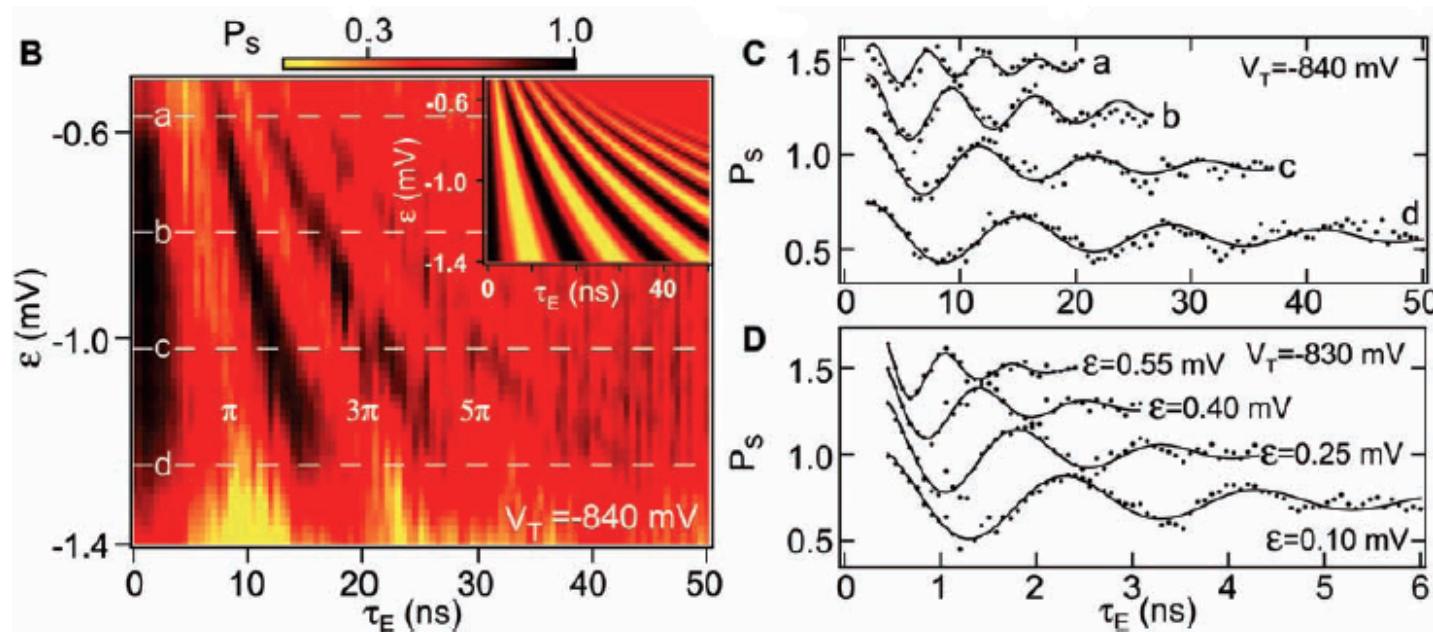


- $T_2^*$  dephasing time for ensemble of dots
- Saturation after 20 ns,  $P_S \sim 0.5$  (0.7) for  $B = 0$  (100) mT
- Semiclassical model  $P_S(\tau_s \gg T_2^*) = 1/3$  ( $B \ll B_{\text{nuc}}$ ),  $P_S(\tau_s \gg T_2^*) = 1/2$  ( $B \gg B_{\text{nuc}}$ )

# Spin SWAP & Rabi oscillations (I)

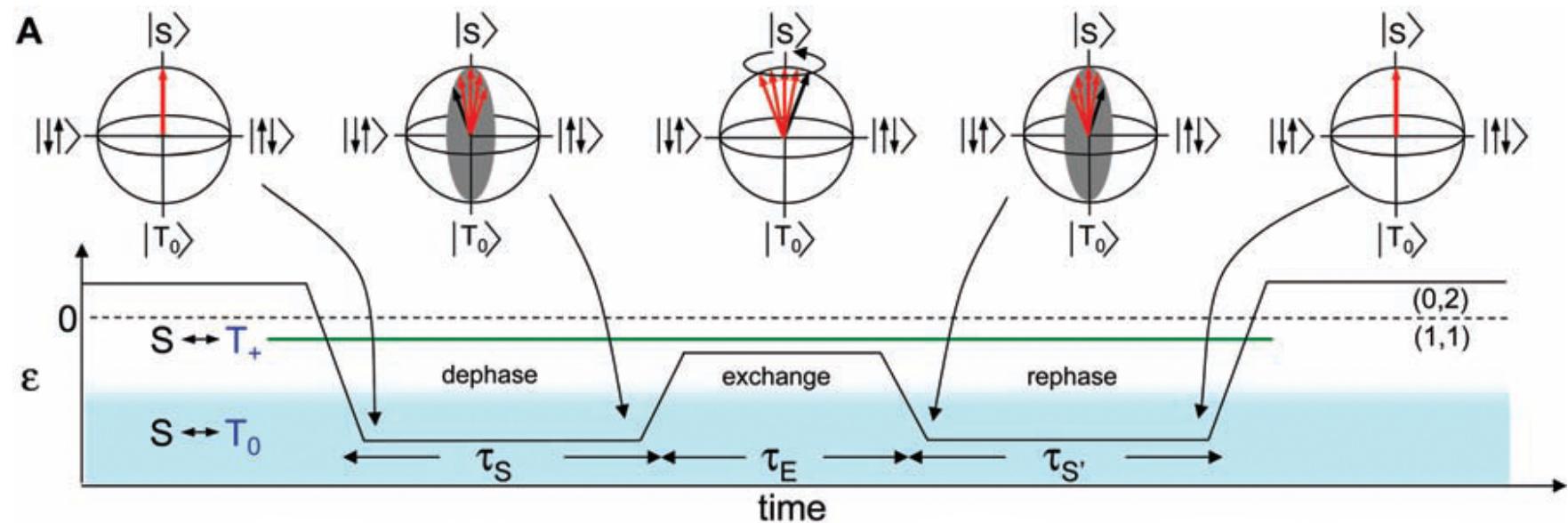


# Spin SWAP & Rabi oscillation (II)

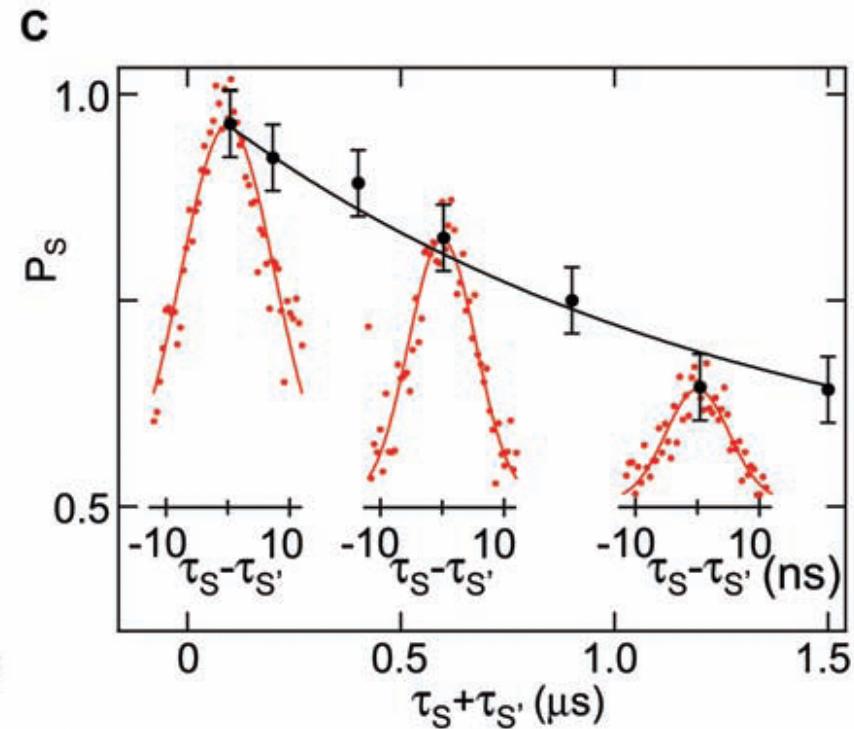
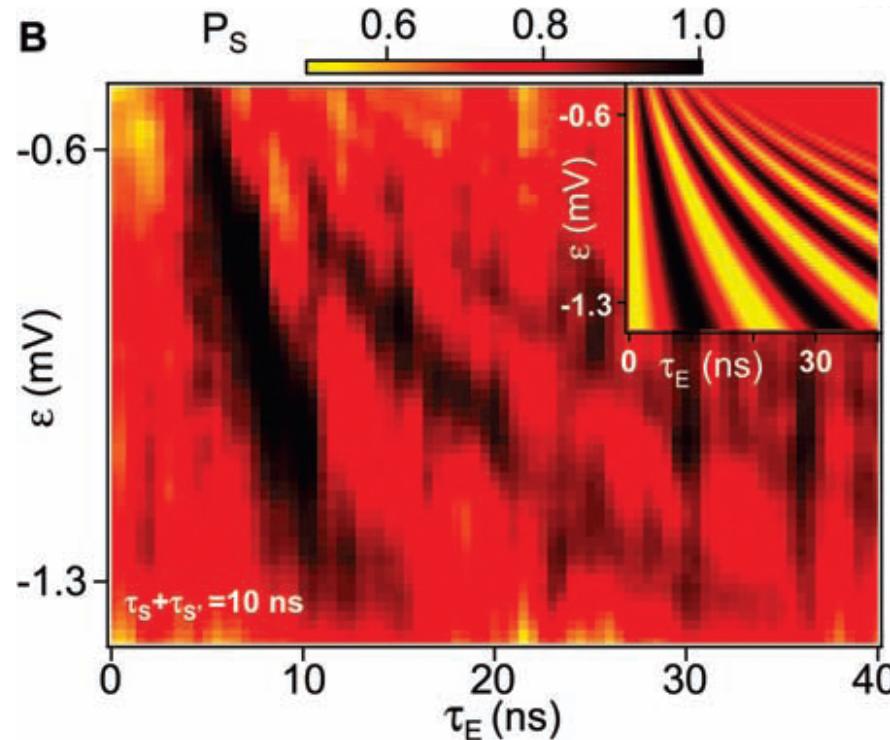


- Theoretical value for  $P_S$  is given by  $P_S = \{1 + \cos[J(\epsilon)\tau_E/\hbar]\}/2$
- Fastest  $\pi$ -pulse  $\sim 350$  ps.
- SWAP operation if  $J(\epsilon)\tau_E/\hbar = \pi, 3\pi, 5\pi, \dots$
- $\sqrt{\text{SWAP}}$  with single qubit gates is universal

# Singlet-triplet spin-echo (I)



# Singlet-triplet spin-echo (II)



- $T_2^* = 9 \pm 2$  ns
- Decoherence time of  $1.2 \mu s$
- 100 times larger
- $\sim 7000 \sqrt{\text{SWAP}}$  operations

# DiVincenzo Criteria

Criterion	✓/✗/-
Scalable with well-characterized qubits.	✓
Initialization to simple fiducial state.	✓
Relatively long coherence times.	✓
Universal gates.	✓
Qubit-specific measurements.	✓
Stationary to flying qubit interconversion.	-
Faithful flying qubit transmission	-