Strongly Driven Semiconductor Double Quantum Dots

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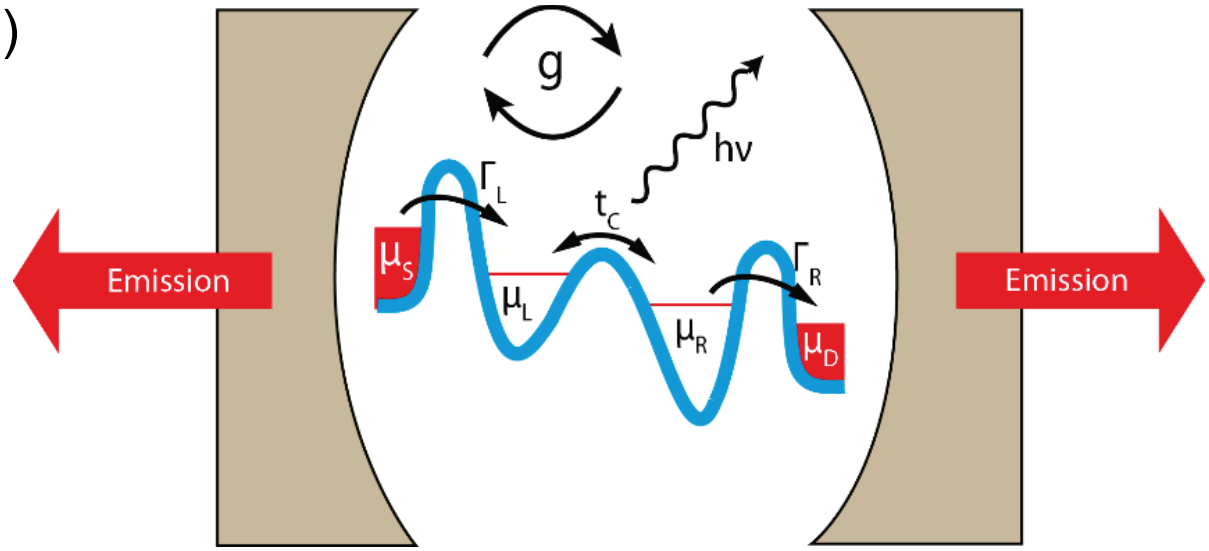
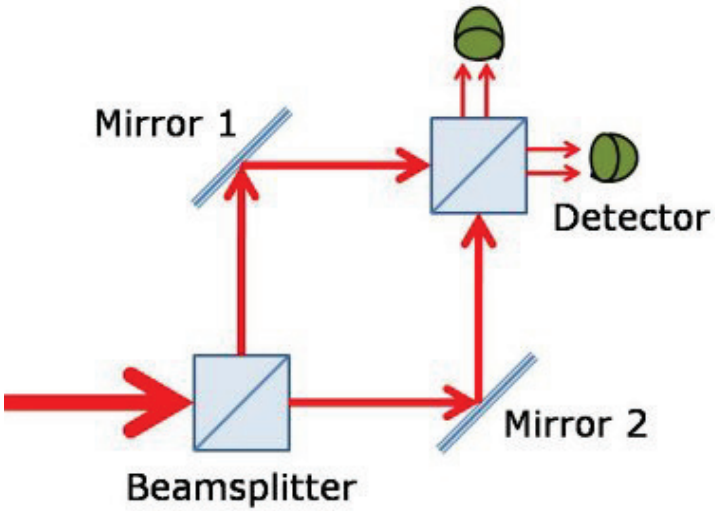
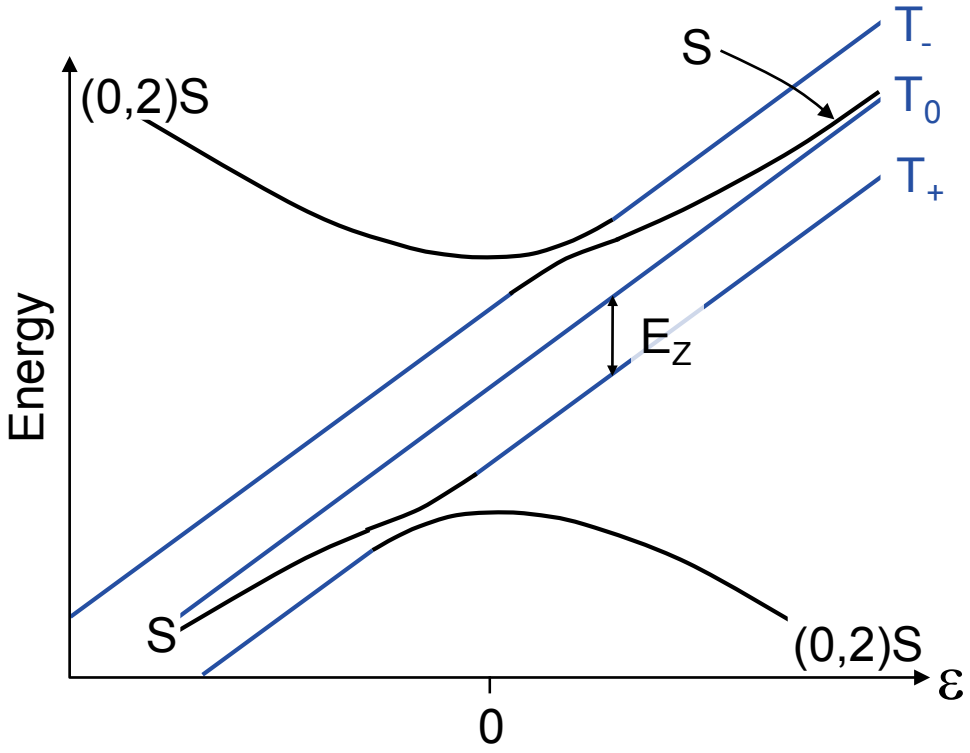


Lecture 1: Landau-Zener Interferometry

Optical interferometer



Quantum dot level diagram



Lecture 2: Spin-Orbit Qubits

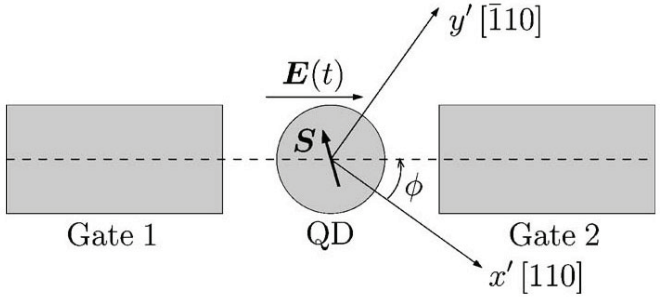
General Spin-Orbit Hamiltonian

$$H_{SO} \propto \left(\nabla V \times \vec{p}\right) \cdot \vec{\sigma}$$

electric field

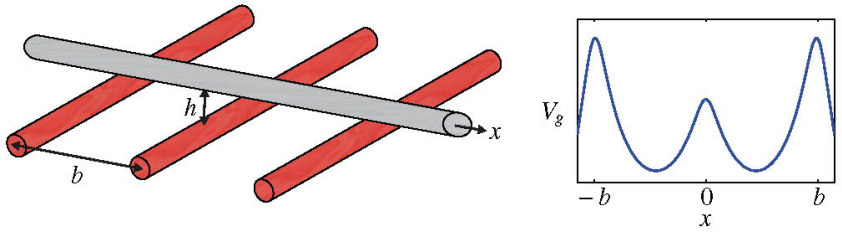
$\vec{B}_E$ = effective B field

Quantum Dots



Golovach *et al.*, PRB (2006)

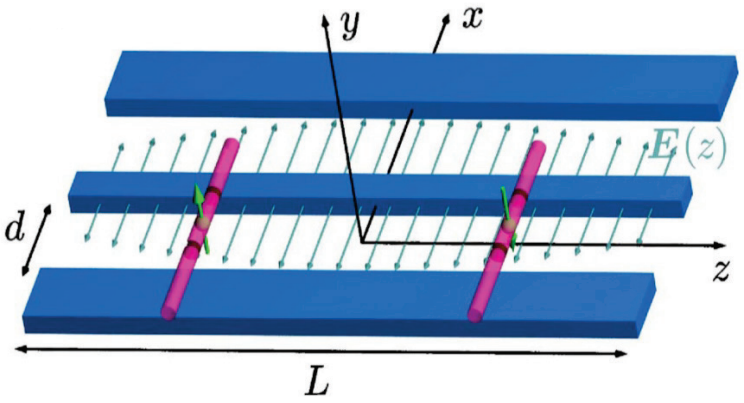
Quantum Wires



Flensberg *et al.*, PRL (2006)

Lecture 3: Cavity-Coupled Double Quantum Dots

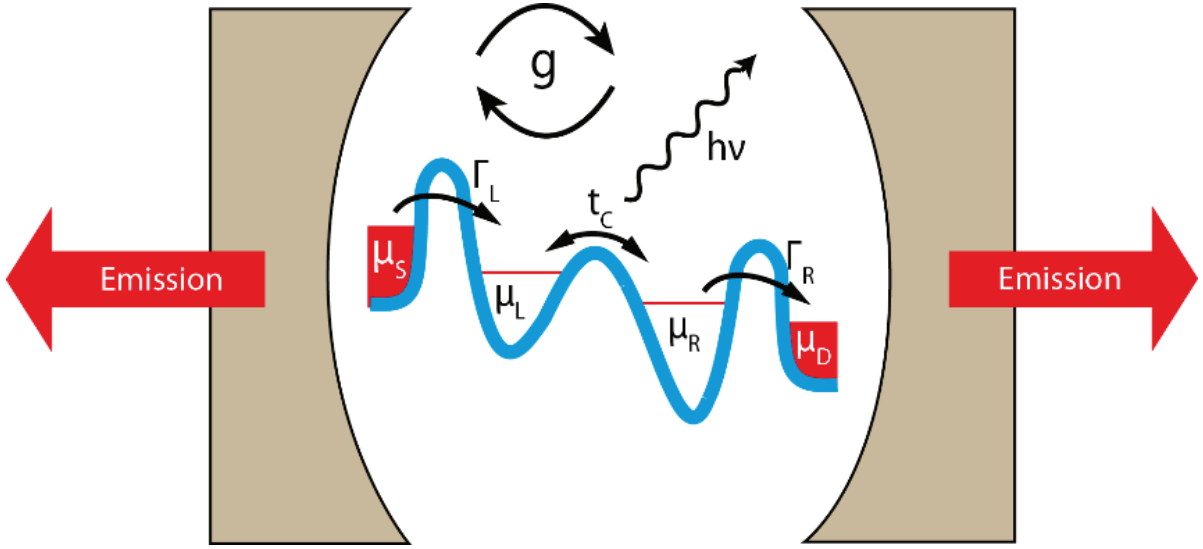
Quantum information science



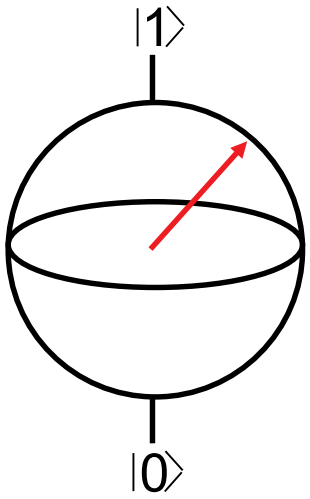
$$J = \nu_1 \nu_2 \left(\frac{1}{\Delta_1} + \frac{1}{\Delta_2} \right)$$

Trif, Golovach, Loss (2008)

Quantum optics with microwave frequency photons



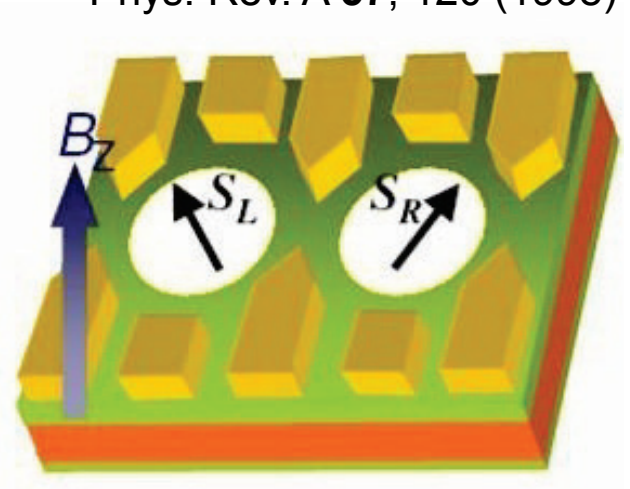
DiVincenzo Criteria



- Efficient initialization
- Readout
- Universal set of gates
- Long decoherence times (T_1,T_2)
- Scalable

Loss & DiVincenzo Proposal

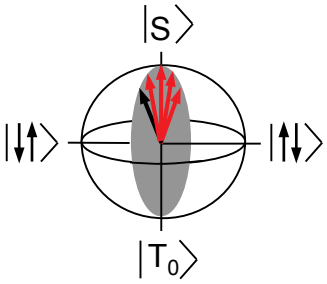
Phys. Rev. A **57**, 120 (1998)



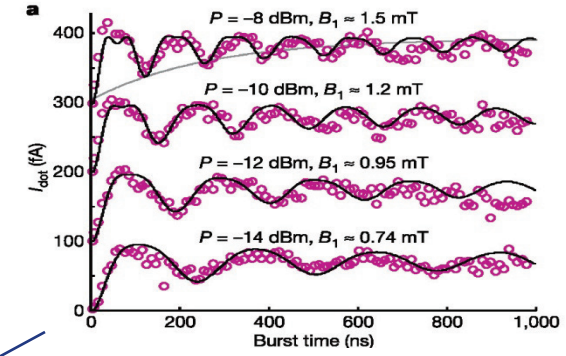
- Prepare spin in ground state
- "Spin to charge conversion"
- ESR for single spin rotations
- Exchange interaction
- T_1 ~ 1 second, T_2 ~ 200 μs
- Standard semiconductor fabrication

Relevant Timescales for GaAs Spin Qubits

Coherence + Quantum Control

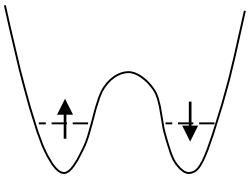


$T_2^* \sim 10$ ns, $T_2 \sim 1$ μs
Petta, Science (2005)

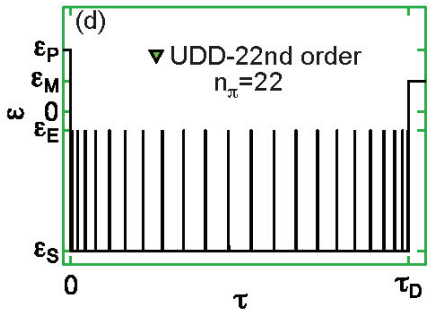


$T_{Rabi} \sim 100$ ns
Koppens, Nature (2006)

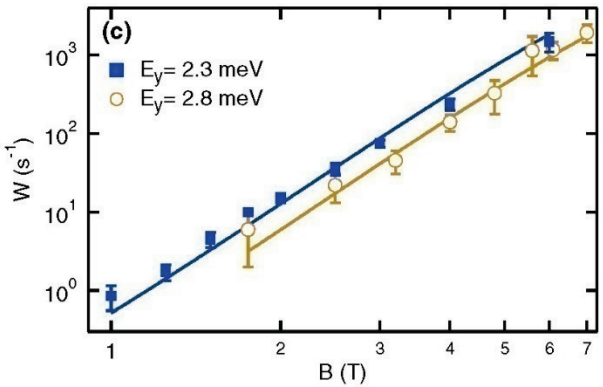
10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} time (sec.)



SWAP ~ 200 ps
Petta, Science (2005)

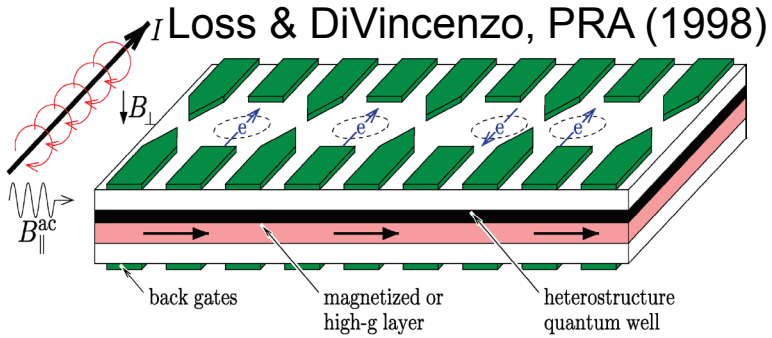


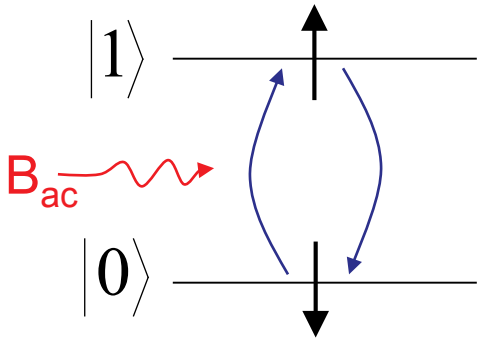
$T_D \sim 200$ μs
Yacoby, Nat. Phy. (2011)
Marcus, PRL (2010)



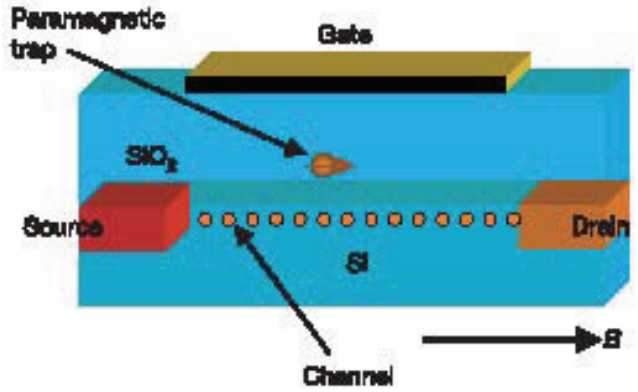
$T_1 > 1$ s
Kastner, PRL (2008)

Challenges of Single Spin Control

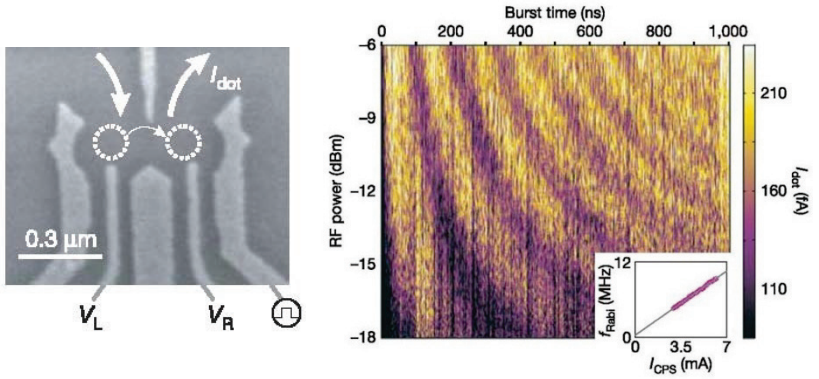




- Selectivity- difficult to localize ac magnetic field on a single spin
- Hyperfine interactions- $B_{ac} \sim B_{nuc}$
- Speed- require 2-5 mT ac magnetic fields for fast control
- Dissipation- mA currents are not compatible with mK temperatures
- Photon assisted tunneling- drives unwanted transitions



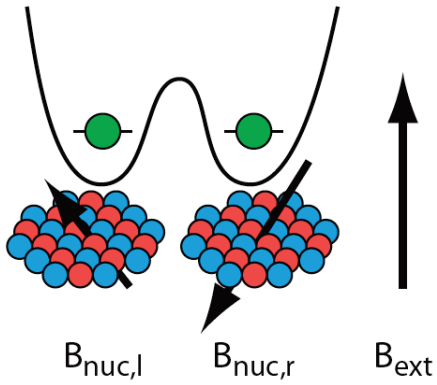
Xiao *et al*., Nature (2004)



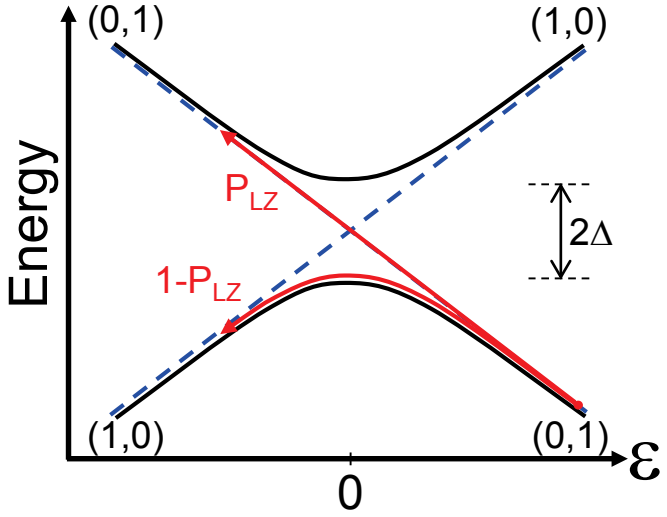
Koppens *et al*., Nature (2006)

Outline

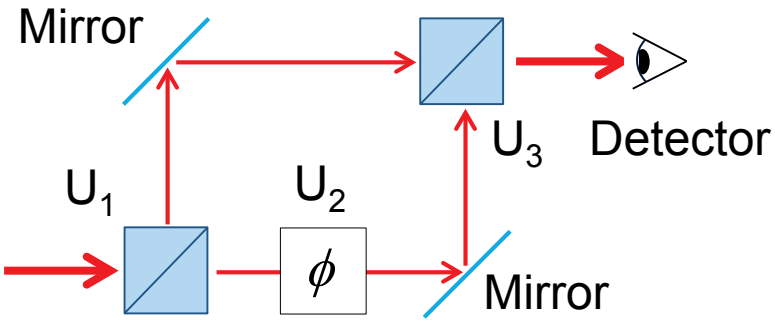
Double Quantum Dots



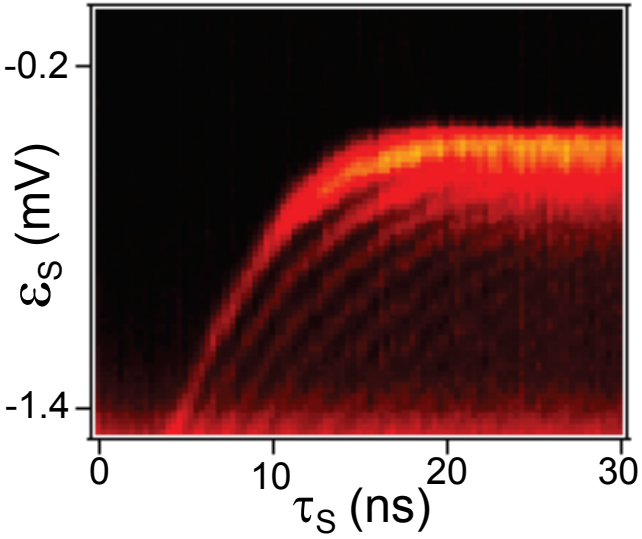
Landau-Zener Physics



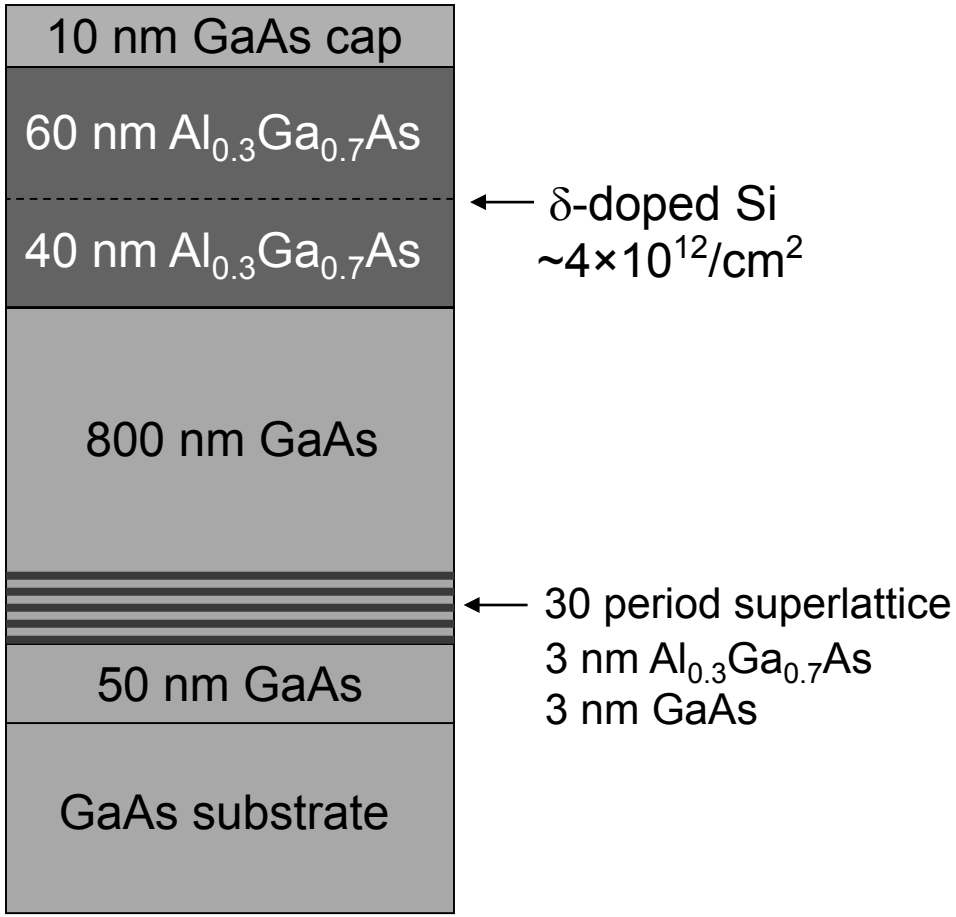
Spin Interferometry



Landau-Zener-Stückelberg Oscillations



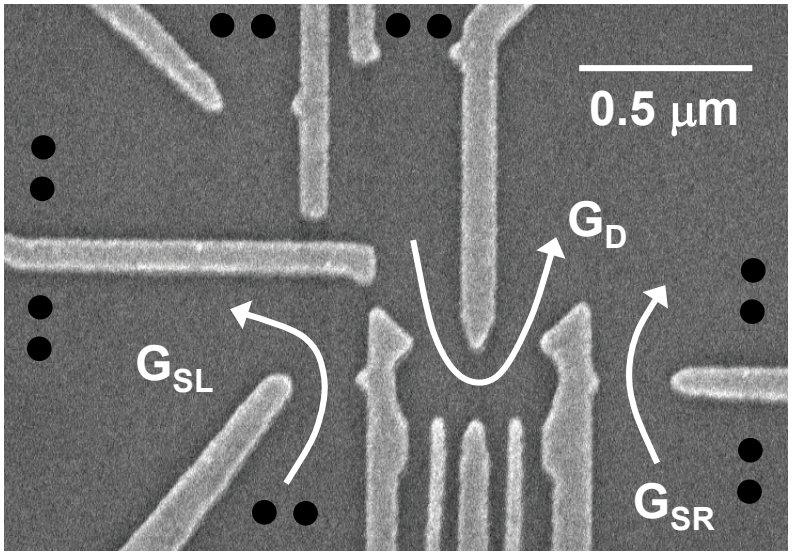
Trapping Single Electrons

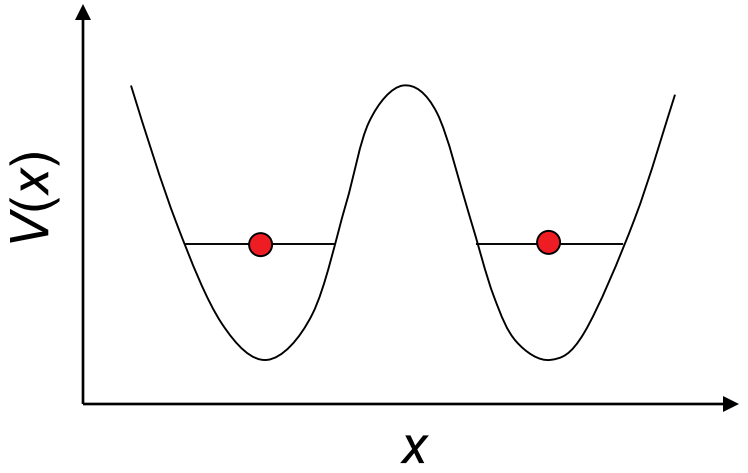


not to scale

Charge density~$2\times10^{11}/cm^2$
Mobility~2×10^5 $cm^2/V\cdot s$
Heterostructure grown by:
H. Lu and A. C. Gossard, UCSB

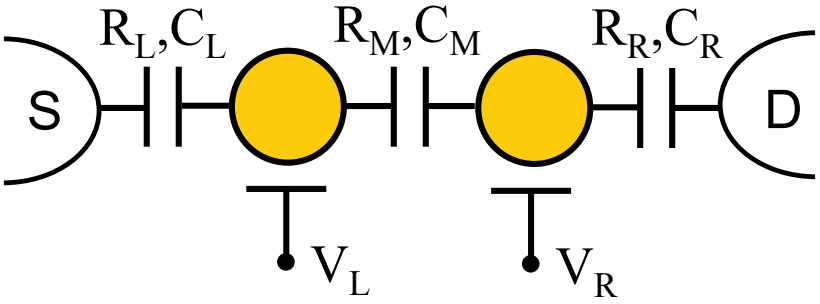
Controlled confinement



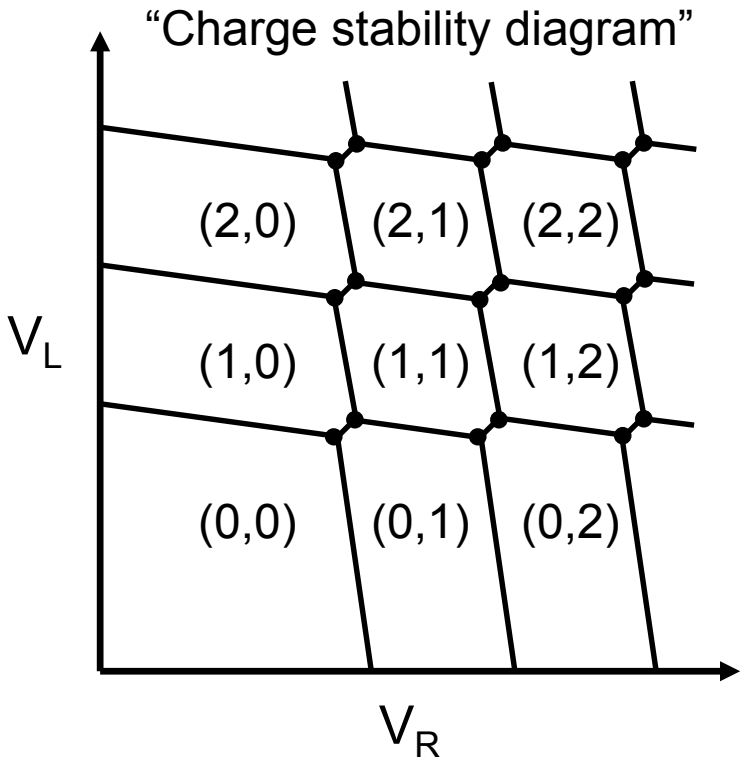


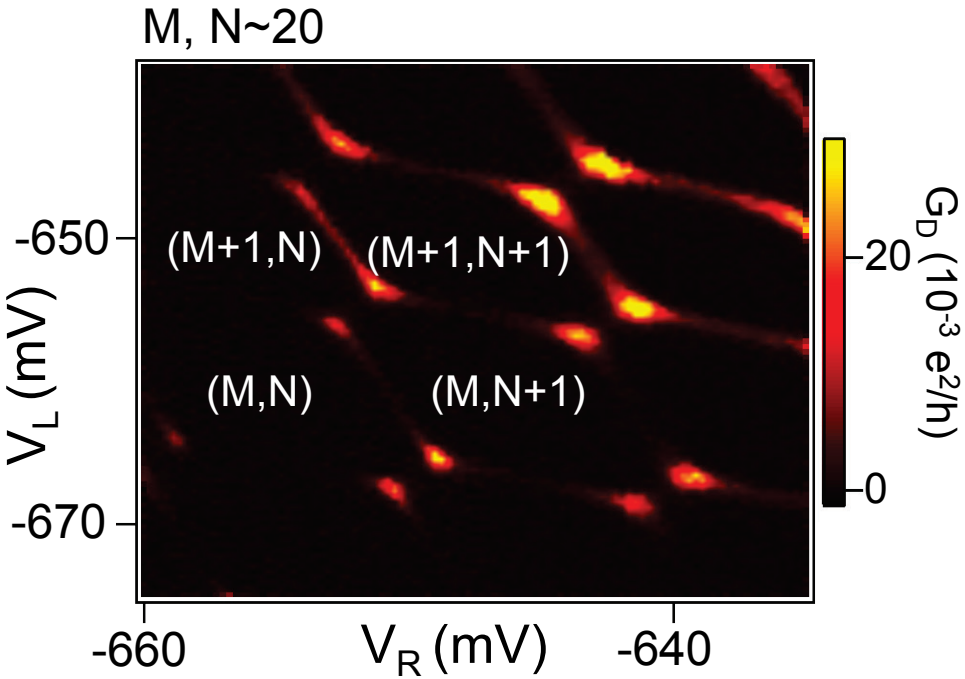
Single dot: Ciorga *et al*., PRB (2000)
Double dot: Elzerman *et al*., PRB (2003)

Transport Spectroscopy of Double Quantum Dots



Charging energy $E_c=e^2/2C$



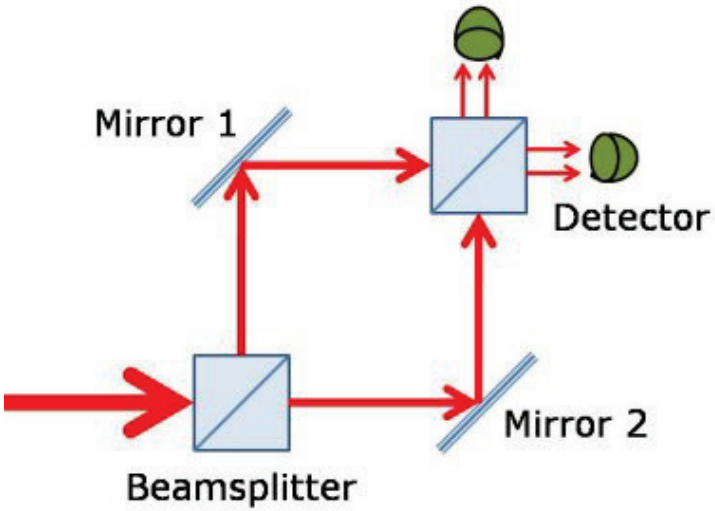


Double dot review article: van der Wiel *et al.,* RMP **75**, 1 (2003)

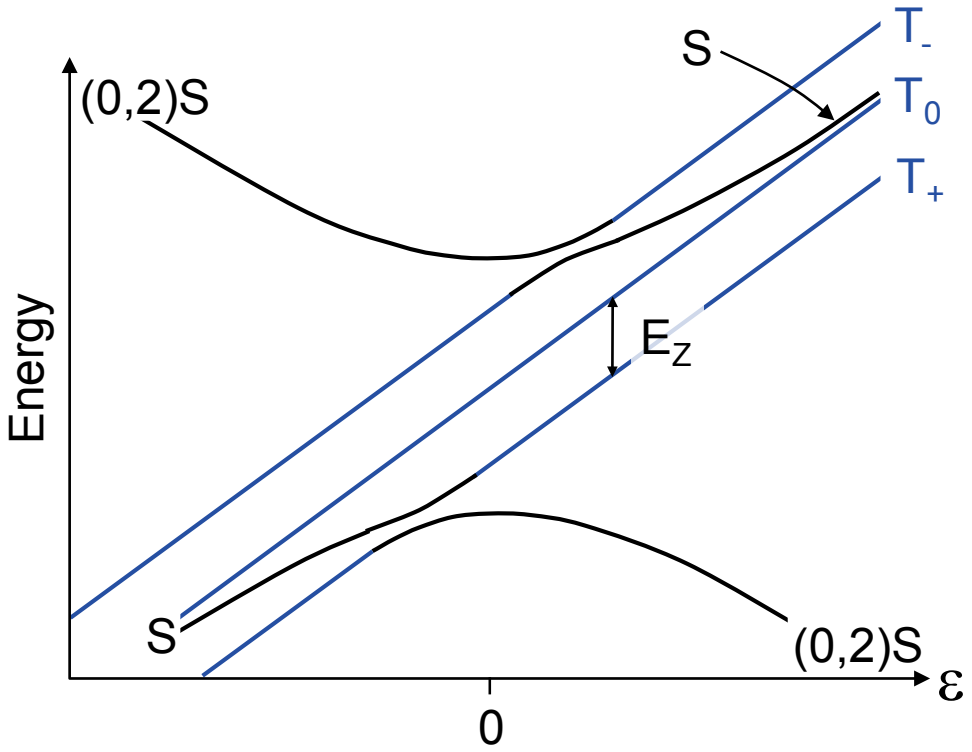
See also: Petta *et al*., PRL **93**, 186802 (2004), Elzerman *et al*., PRB **67**, 161308 (2003)

Single Spin Control Driven by Quantum Interference

Optical interferometer



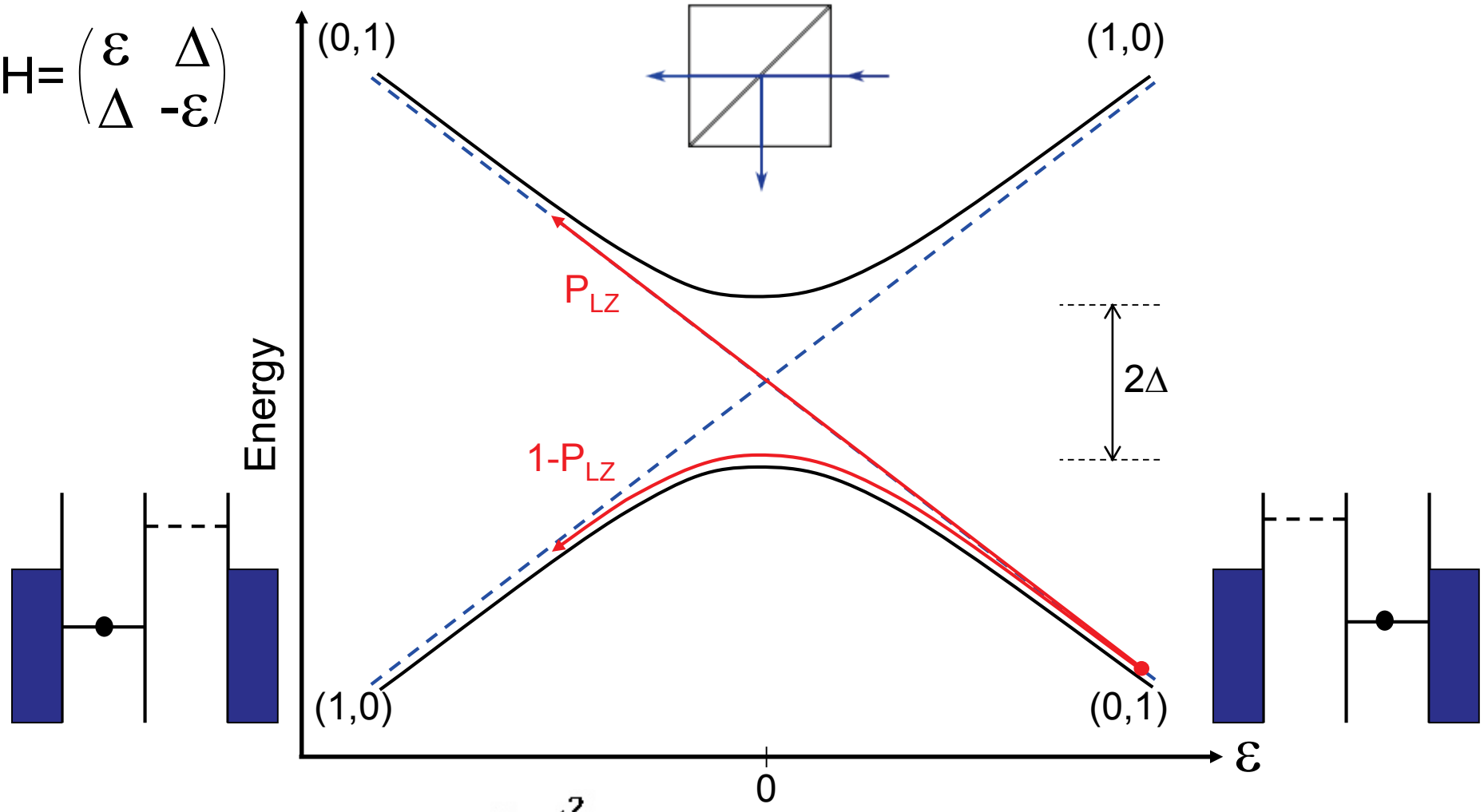
Quantum dot level diagram



Petta, Lu, Gossard, *Science* **327**, 669 (2010)

Avoided Crossing: Quantum Mechanical "Beam Splitter"

$$H=\begin{pmatrix}\varepsilon & \Delta\\ \Delta & -\varepsilon\end{pmatrix}$$



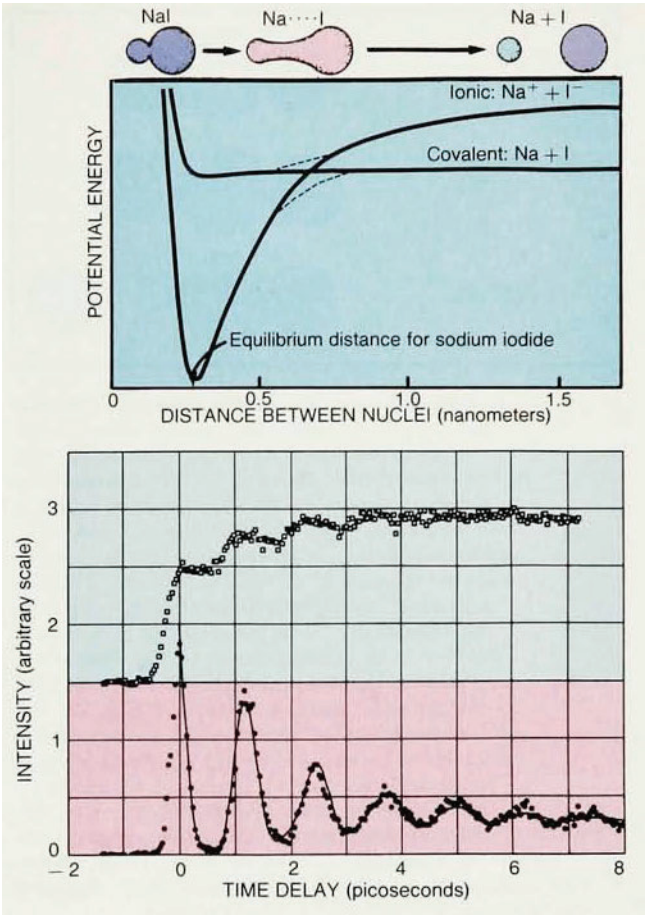
$$P_{LZ} = e^{-\frac{2\pi\Delta^2}{\hbar v}}$$

"Level velocity" $v=\left|d(E_1-E_2)/dt\right|$

Landau (1932), Zener (1932), Stückelberg (1932), Majorana (1932)

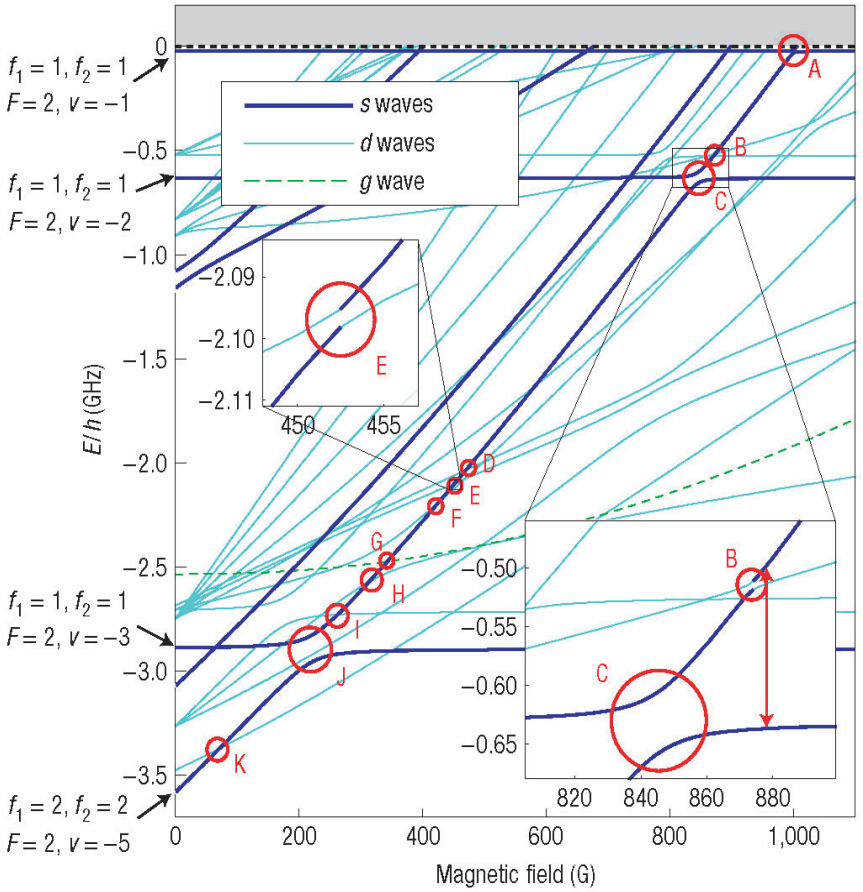
Some Examples of Landau-Zener Physics

ULTRAFAST REACTION DYNAMICS



Zewail, Physics Today (1990)

Cruising through molecular bound-state manifolds with radiofrequency

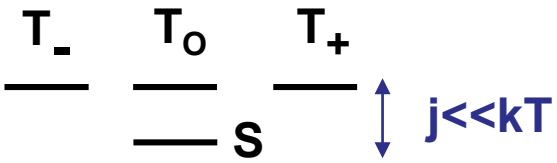


Lang, Nature Physics (2008)

Superconducting qubits:Oliver *et al*., Science (2005), Shevchenko *et al*., Phys. Rep. (2010)

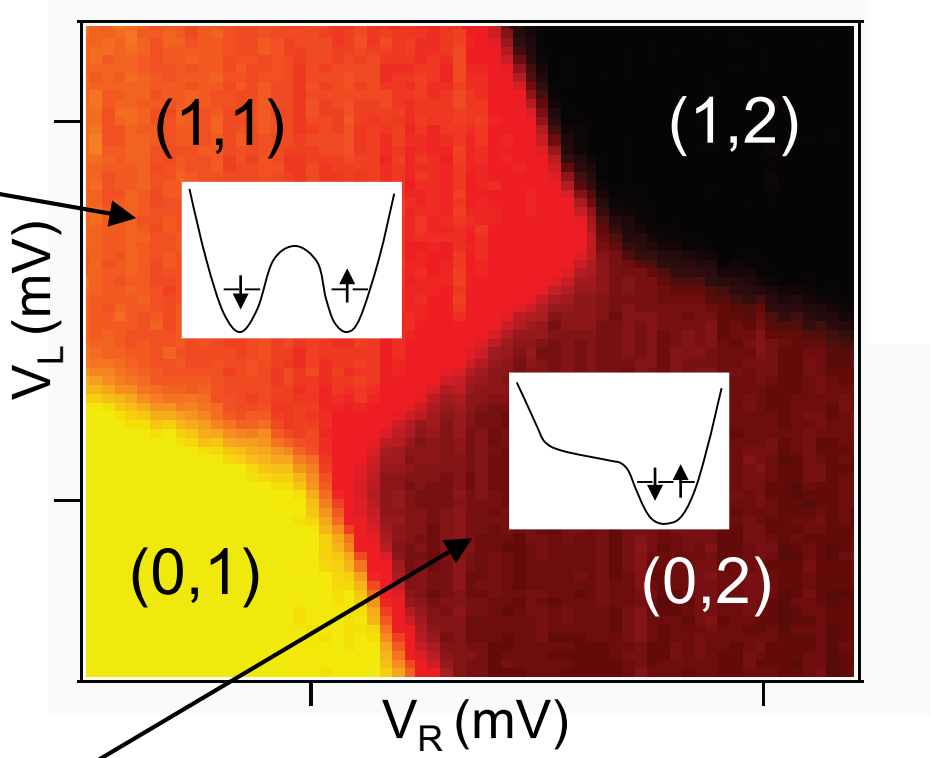
Spin Physics: The Two Electron Regime

(1,1) singlet-triplet splitting:

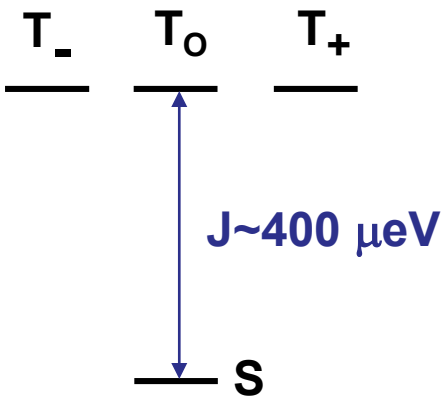


$j=4t^2/U=0.4\ \mu eV<<kT$

with U~4 meV, t~20 μeV



(0,2) singlet-triplet splitting:



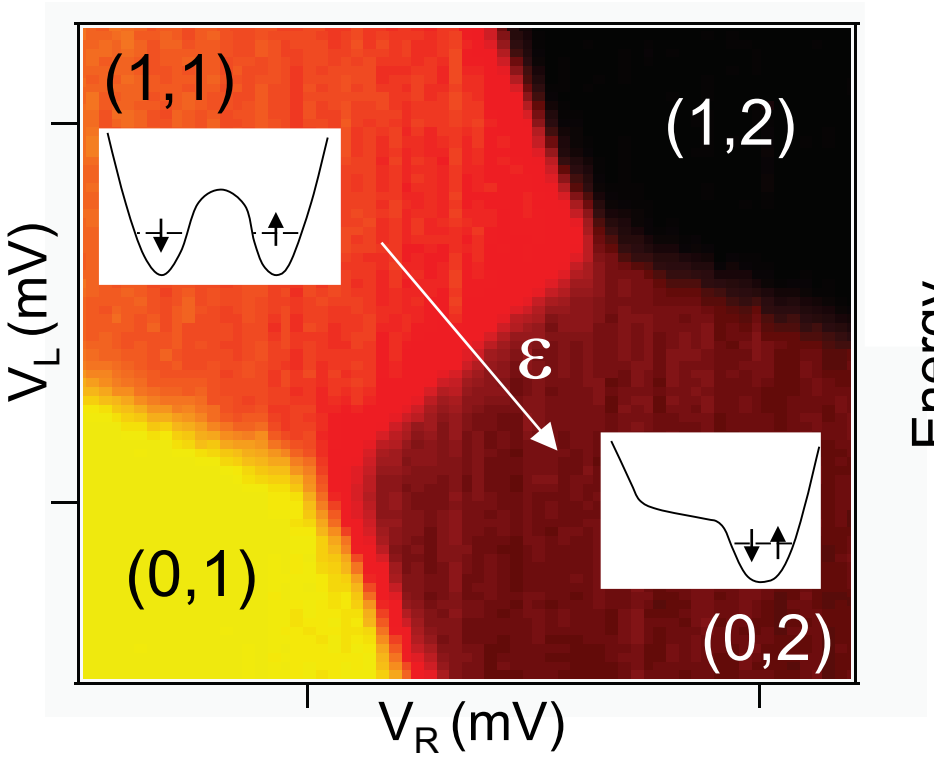
Theory: J~0.3 meV

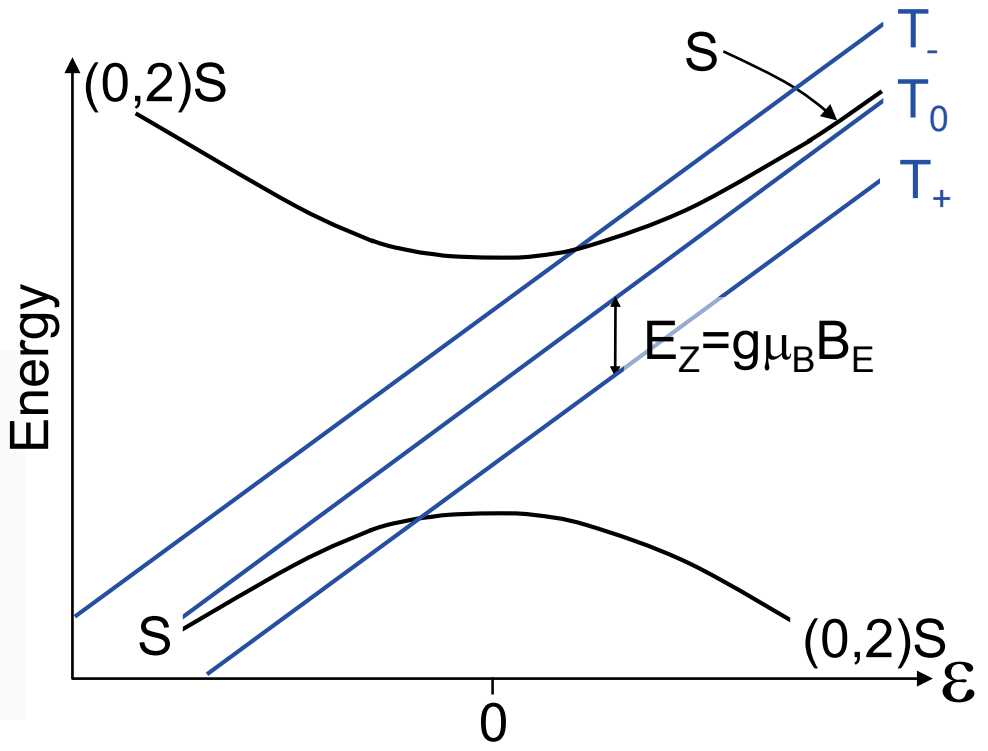
Expt.: J~0.1 to 1 meV

Kyriakidis *et al.*, PRB **66**, 035320 (2002)

Ashoori *et al.*, PRL **71**, 613 (1993)

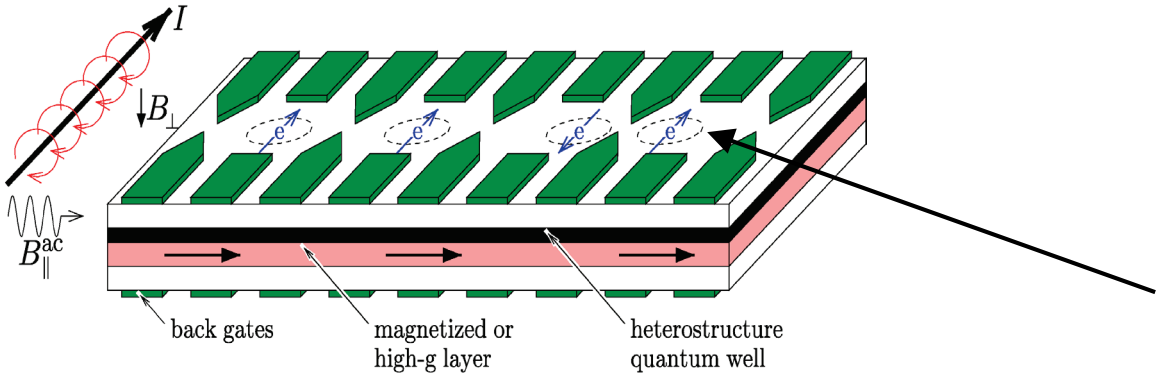
Double Quantum Dot Level Diagram



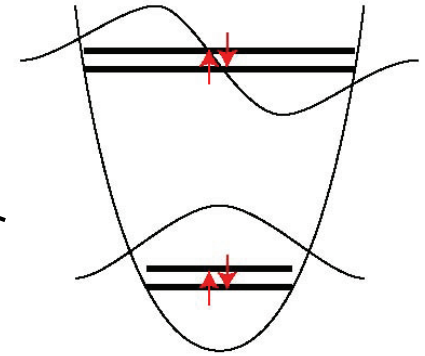


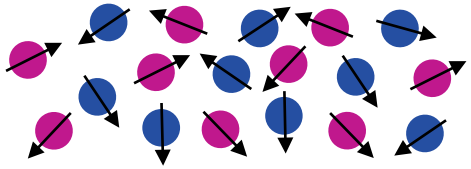
Kyriakidis *et al*., PRB **66**, 035320 (2002)
Ashoori *et al*., PRL **71**, 613 (1993)

Dynamics of the Coupled Electron-Nuclear Spin System



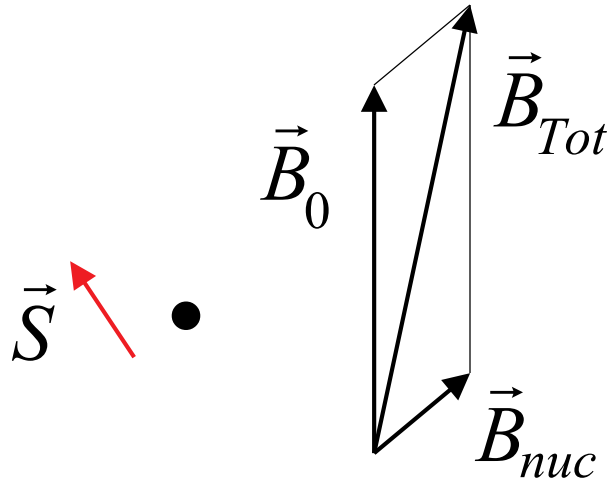
Loss and DiVincenzo, PRA **57**, 120 (1998)





^{75}As, I=3/2, 100%

^{69}Ga, I=3/2, 60% ^{71}Ga, I=3/2, 40%



$$H = \hbar\gamma_e \vec{B}_0 \cdot \vec{S} + \hbar\gamma_e \sum_{\beta,j} b_{\beta,j} \alpha_j \vec{S} \cdot \vec{I}^{\beta,j}$$

Zeeman Hyperfine

$$H = \hbar\gamma_e (\vec{B}_0 + \vec{B}_{nuc}) \cdot \vec{S}$$

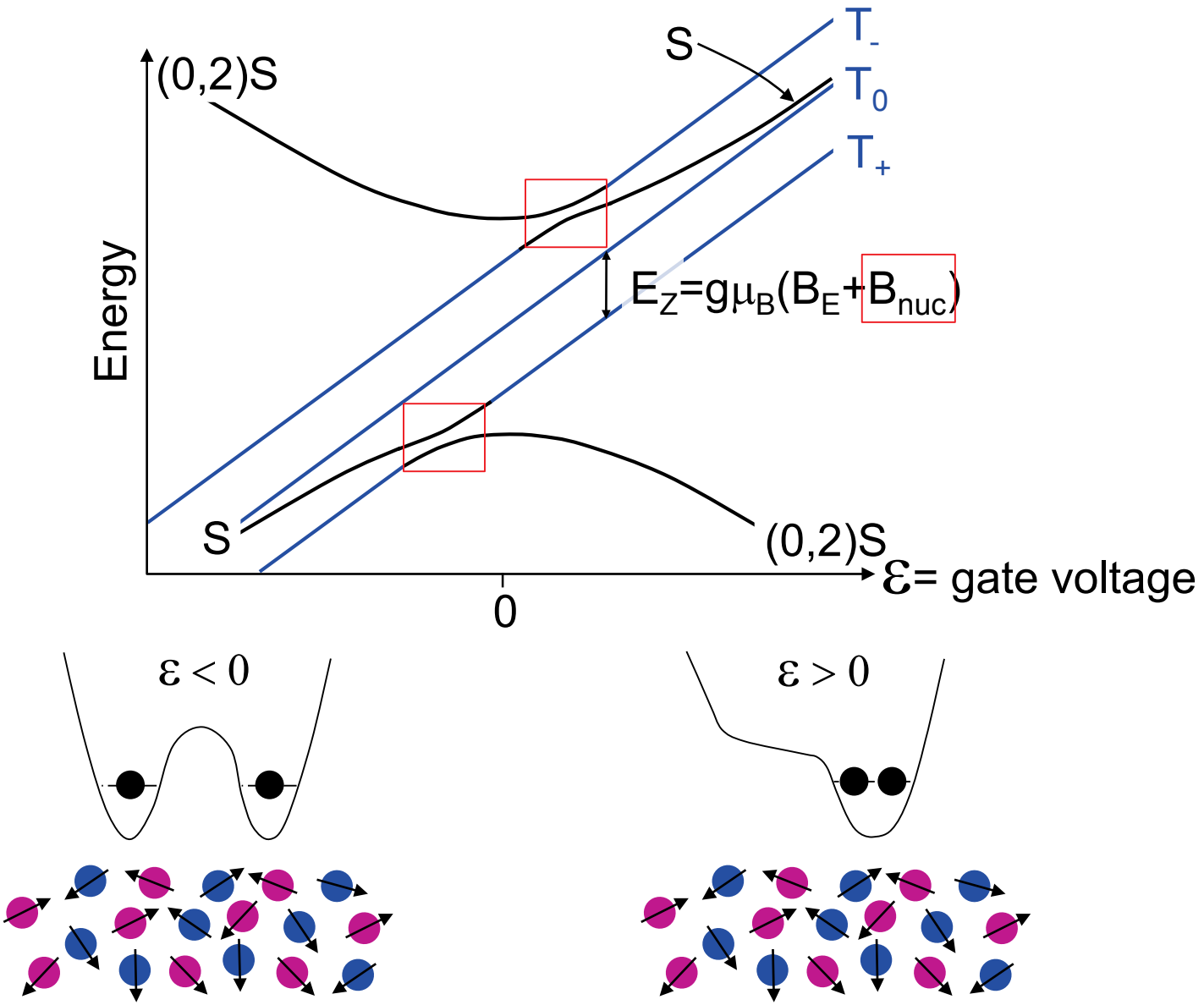
Paget, Lampel, Sapoval, PRB **15**, 5780 (1977)

Khaetskii, Loss, Glazman, PRL **88**, 186802 (2002)

Fully polarized nuclei, B_{nuc}=5.3 T

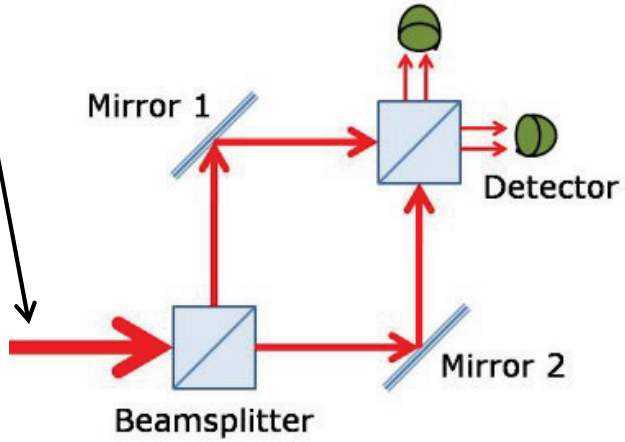
Unpolarized nuclei, B_{nuc}~2 mT

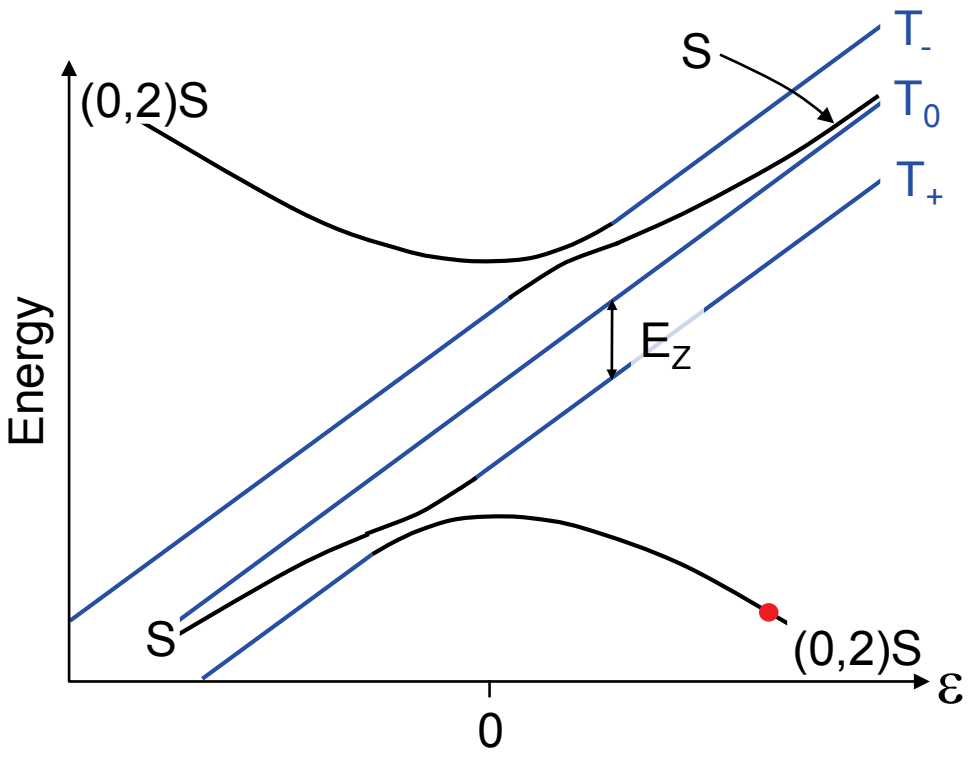
Double Quantum Dot Level Diagram (With Nuclei)



Single Spin Control Driven by Quantum Interference

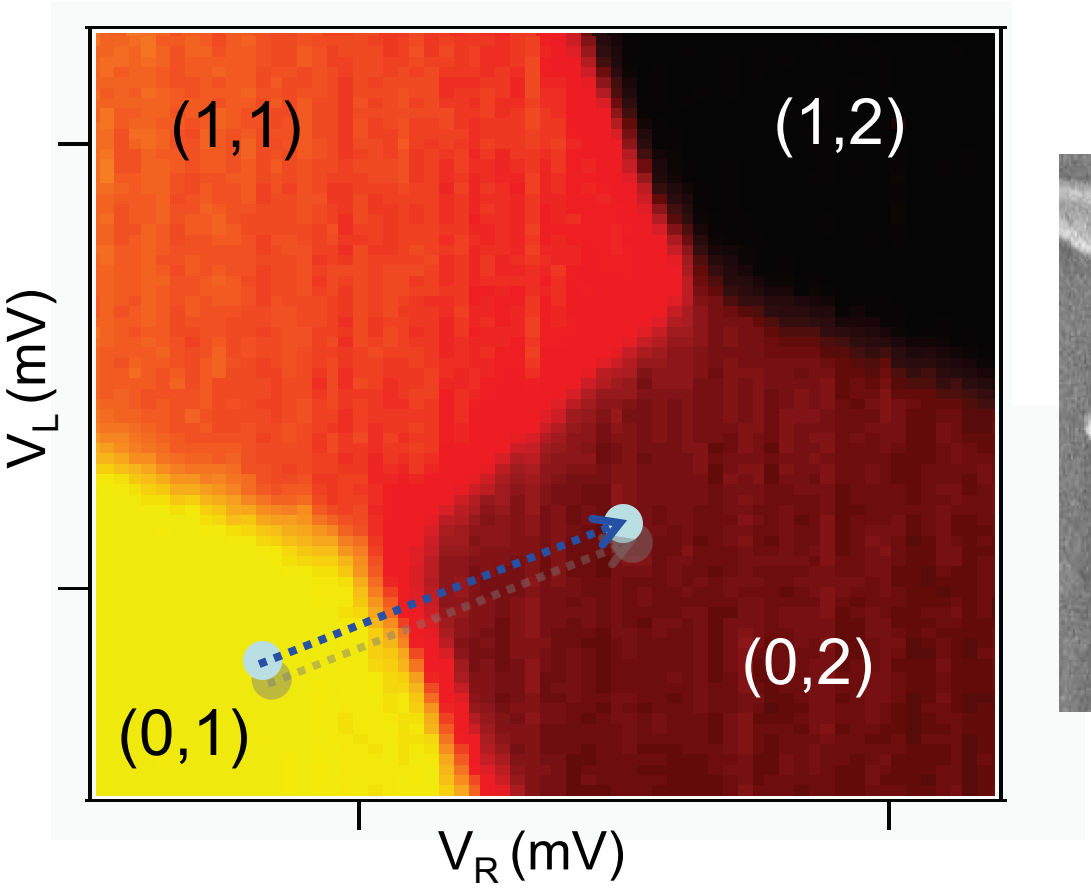
Step 1: Singlet state initialization

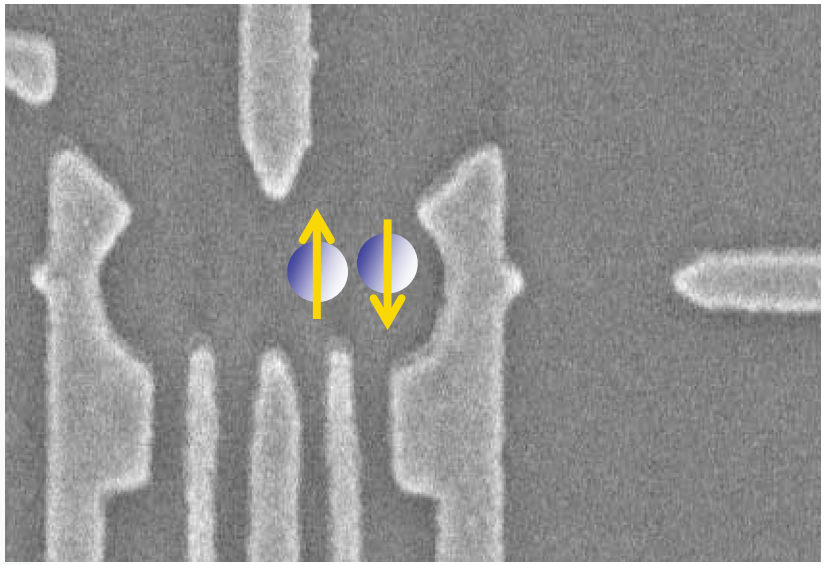




Petta, Lu, Gossard, *Science* **327**, 669 (2010)

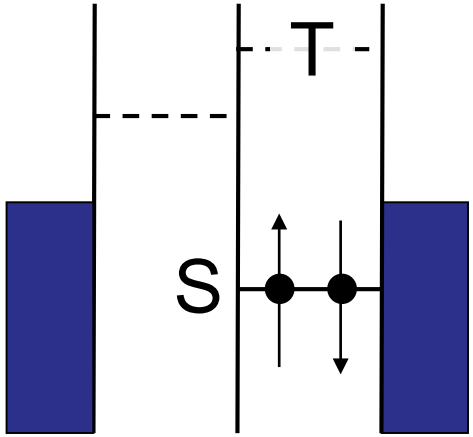
Spin Singlet State Initialization





$$\frac{P_T}{P_S} = e^{-\frac{J}{kT}} \approx 10^{-5}$$

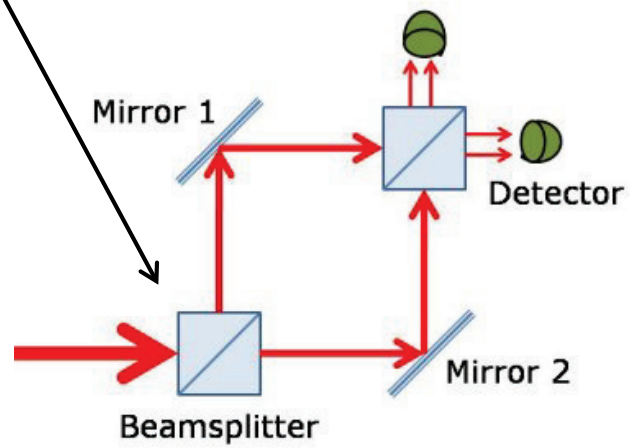
M. Atature *et al.*, Science **312**, *551* (2006)

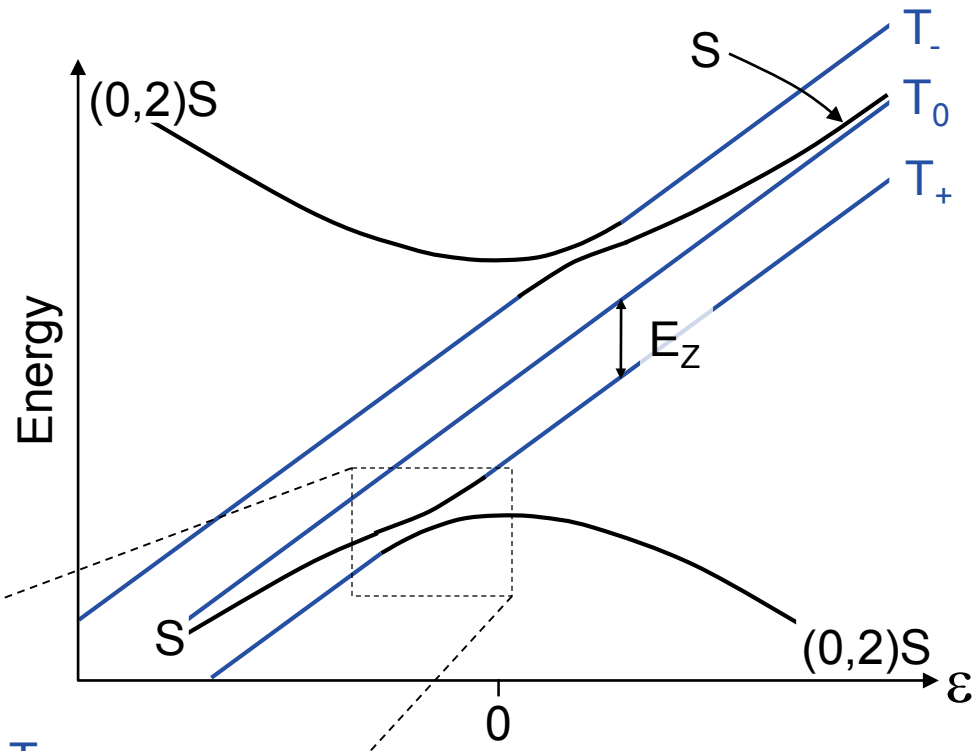


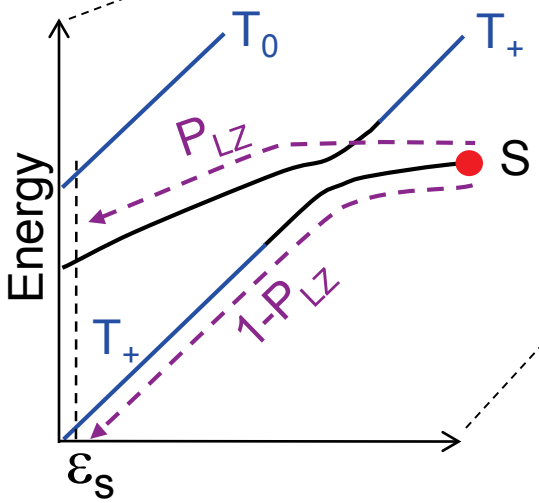
Petta, Lu, Gossard, *Science* **327**, 669 (2010)

Single Spin Control Driven by Quantum Interference

Step 2: Passage through the beam splitter

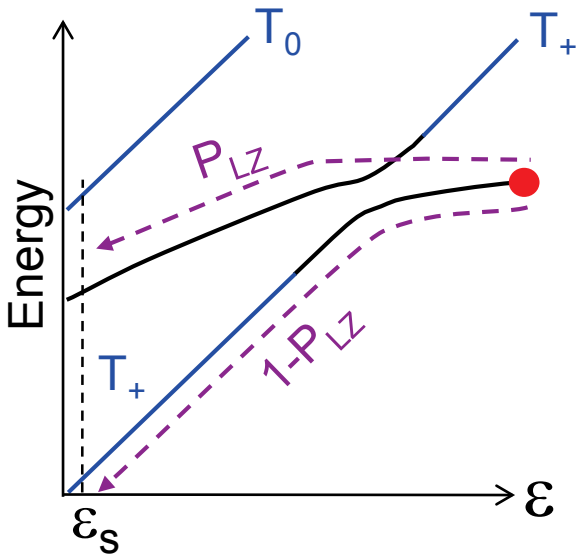






Petta, Lu, Gossard, *Science* **327**, 669 (2010)
Incoherent driving limit: Petta, Taylor, PRL (2008)

Singlet-Triplet Beam Splitter

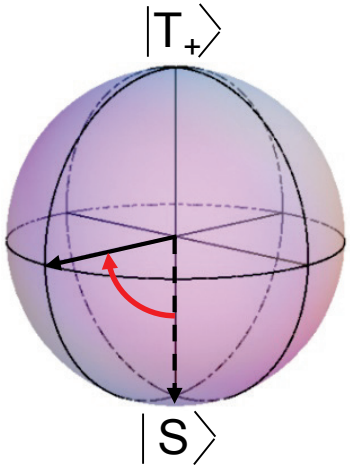


$$U = \begin{pmatrix} \cos[\frac{\theta}{2}]e^{i\tilde{\phi}_S} & i\sin[\frac{\theta}{2}] \\ i\sin[\frac{\theta}{2}] & \cos[\frac{\theta}{2}]e^{-i\tilde{\phi}_S} \end{pmatrix}$$

$$P_{LZ} = \sin^2\left(\frac{\theta}{2}\right)$$

$\tilde{\phi}_S \sim -\pi/2$ Stoke's phase

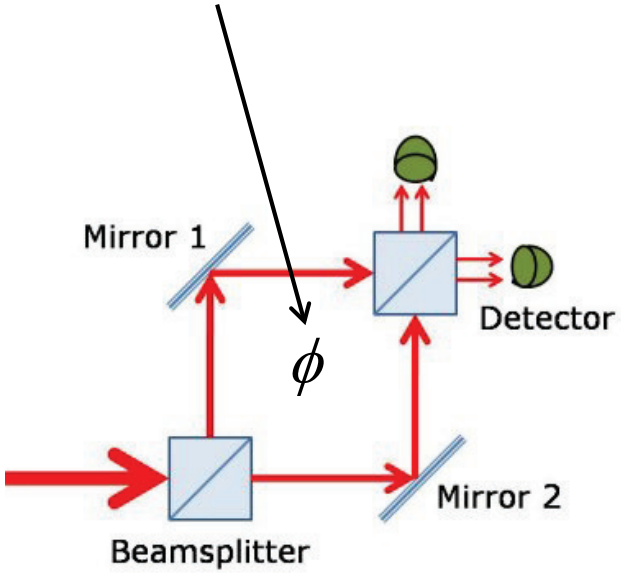
Ideal case: $P_{LZ}=1/2$ → maximum contrast, 50%-50% beam splitter

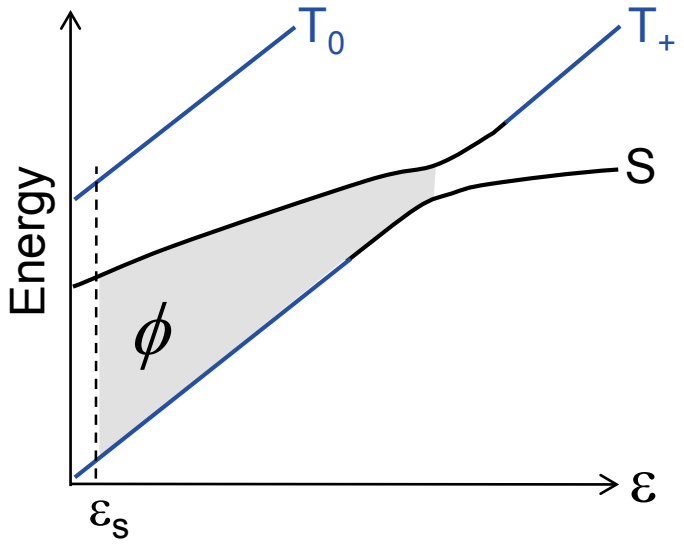


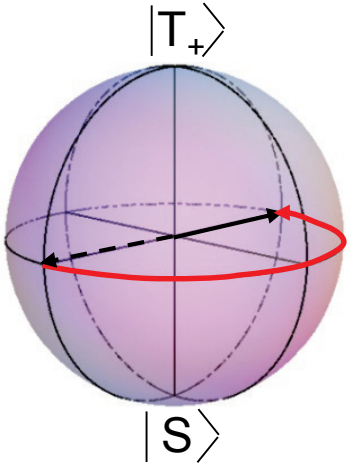
Theory:
Shimshoni *et al*., Ann. Phys. (1991)
Shevchenko *et al*., Phys. Rep. (2010)

Single Spin Control Driven by Quantum Interference

Step 3: Phase accumulation







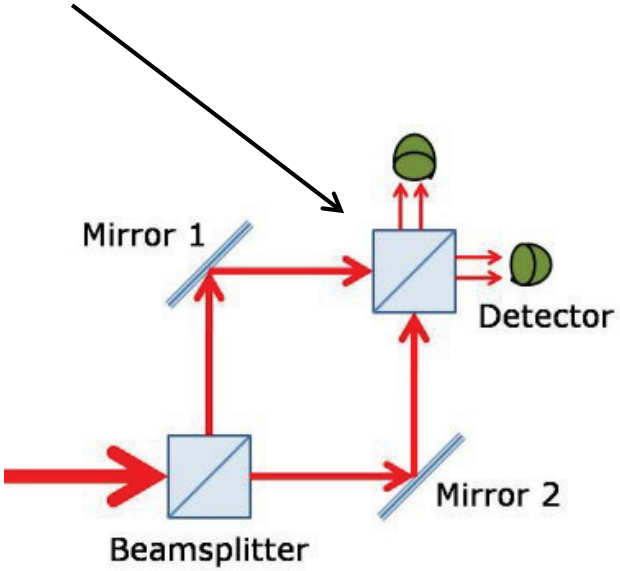
$$U = \exp\left(-\frac{i}{2}\phi\sigma_Z\right)$$

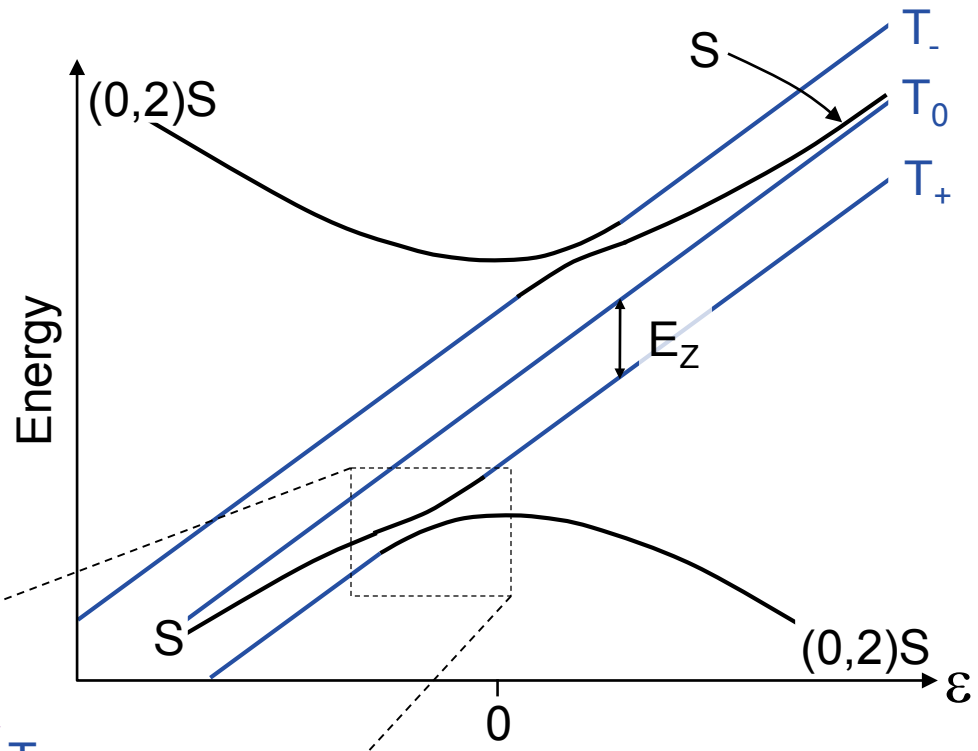
$$\phi = \frac{1}{\hbar}\int\left[E_S\left(\varepsilon(t)\right) - E_{T+}\left(\varepsilon(t)\right)\right]dt$$

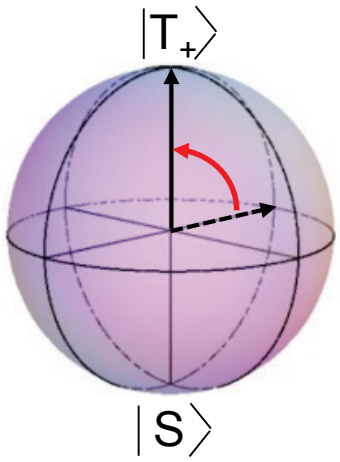
Petta, Lu, Gossard, *Science* **327**, 669 (2010)

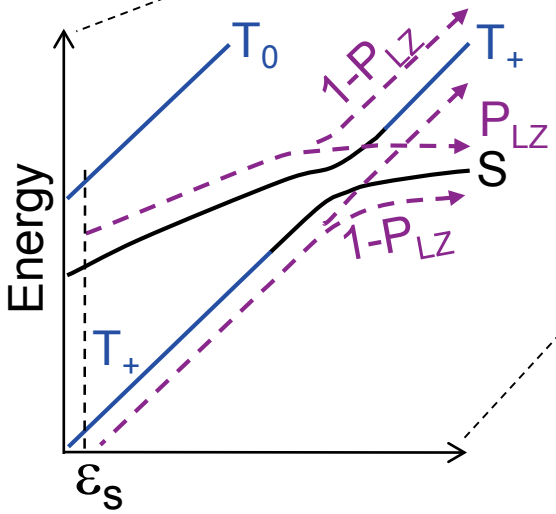
Single Spin Control Driven by Quantum Interference

Step 4: Interference







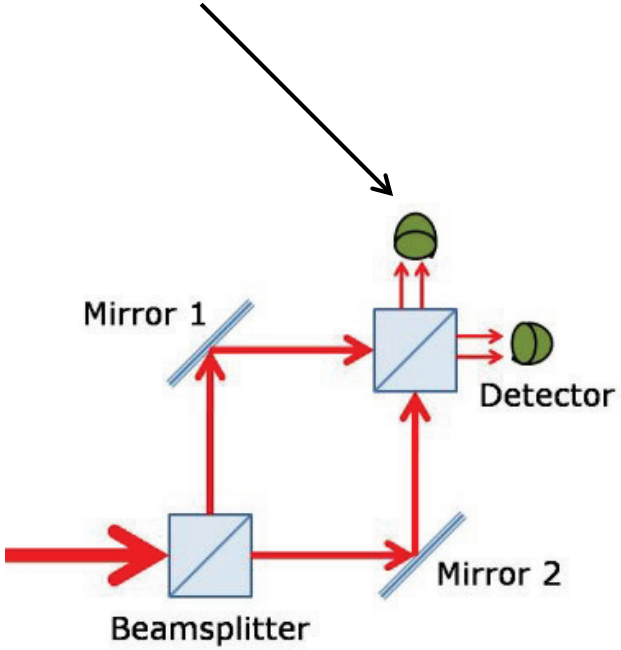


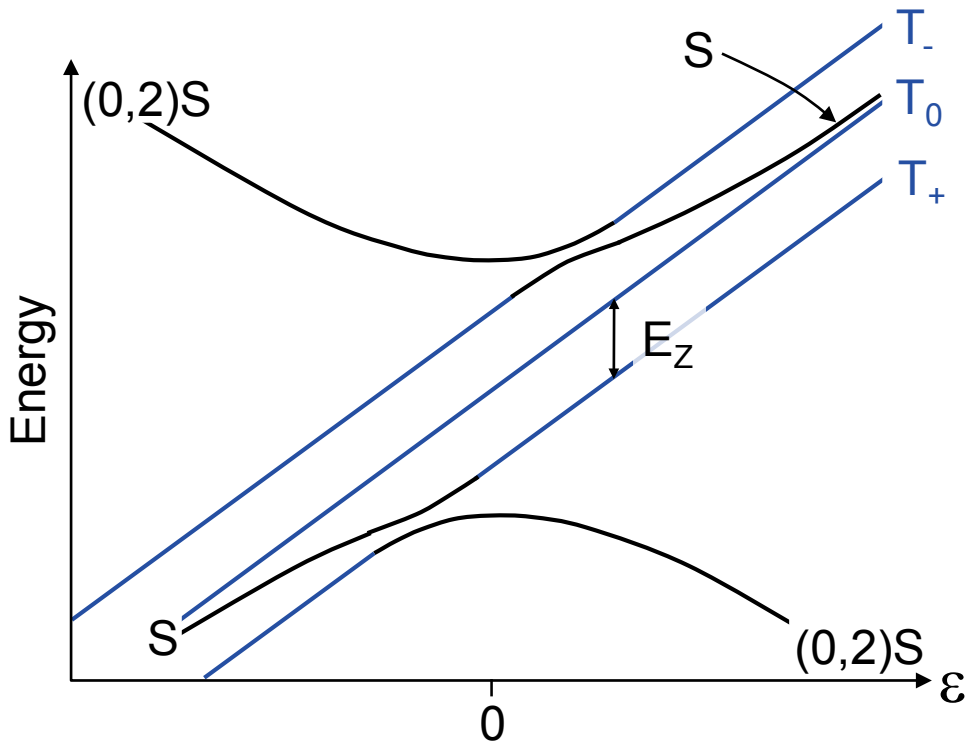
$$U = \begin{pmatrix} \cos[\frac{\theta}{2}]e^{i\tilde{\phi}_S} & i\sin[\frac{\theta}{2}] \\ i\sin[\frac{\theta}{2}] & \cos[\frac{\theta}{2}]e^{-i\tilde{\phi}_S} \end{pmatrix}$$

Petta, Lu, Gossard, *Science* **327**, 669 (2010)

Single Spin Control Driven by Quantum Interference

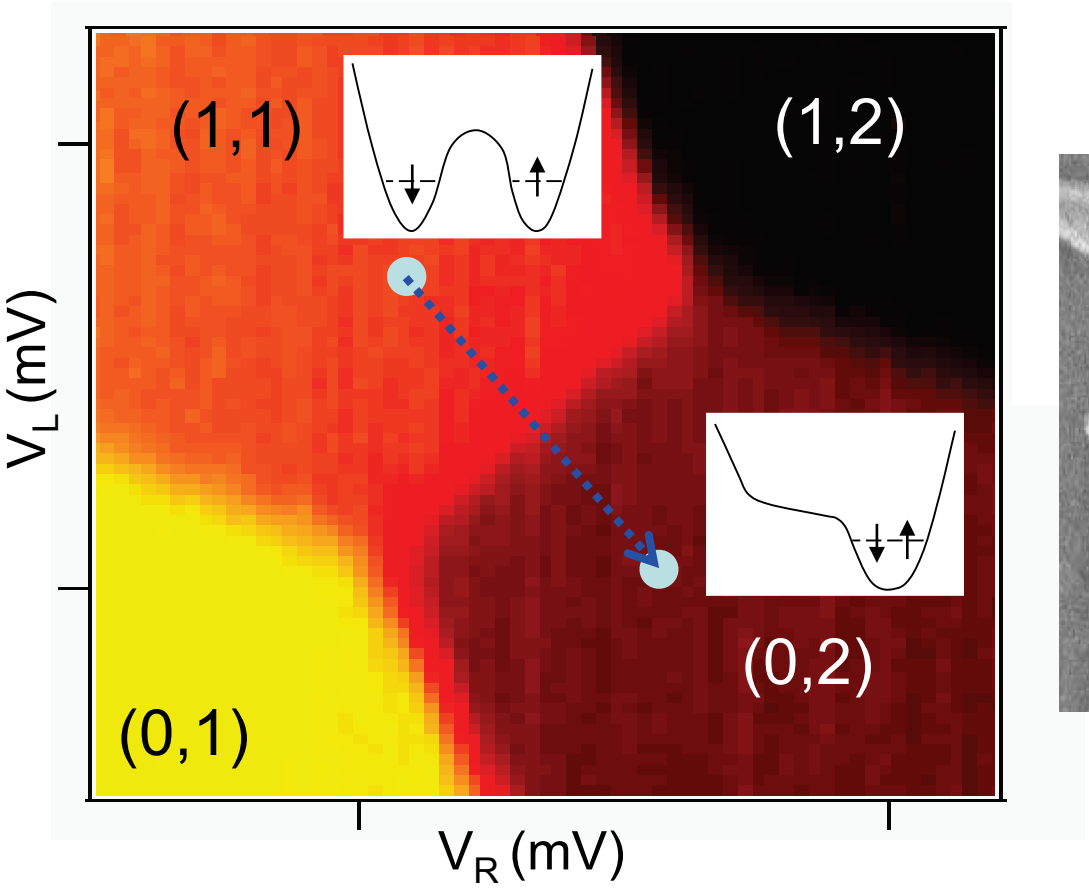
Step 5: Spin state measurement

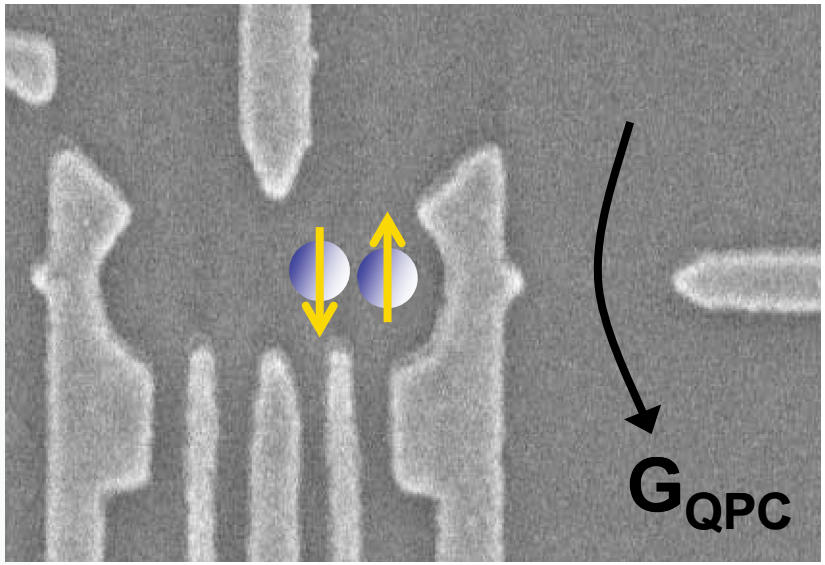




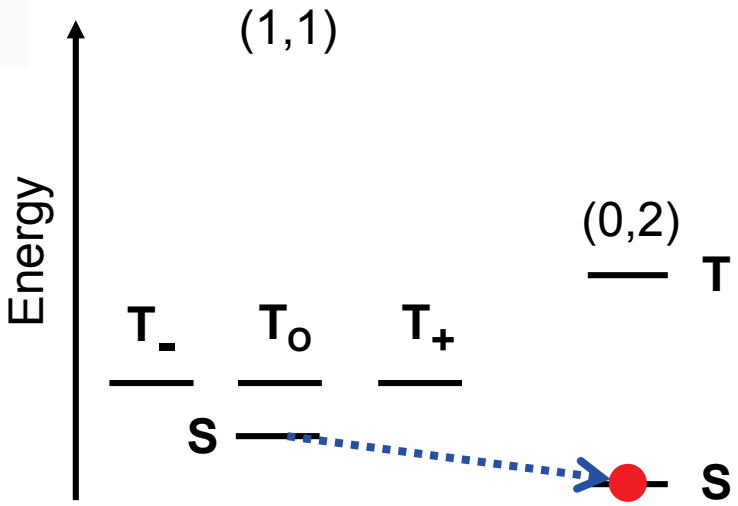
Petta, Lu, Gossard, *Science* **327**, 669 (2010)

Spin State Measurement (Spin-to-Charge Conversion)

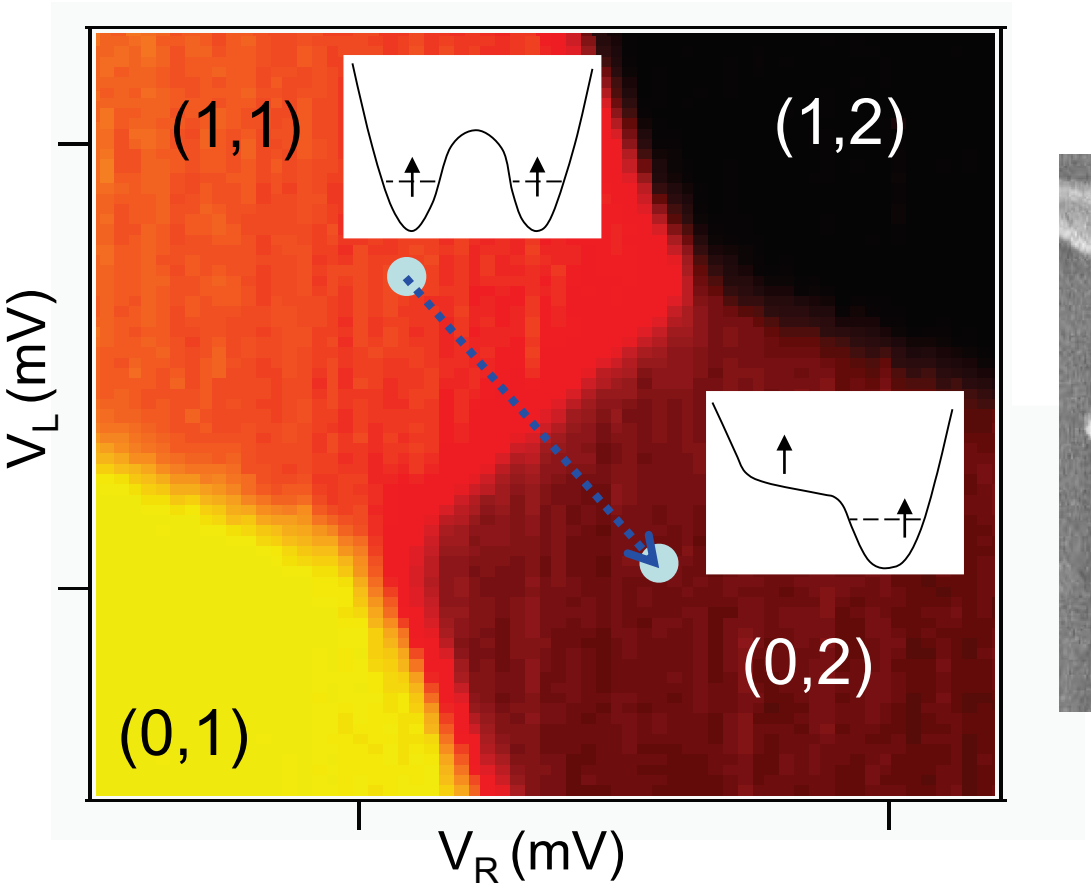


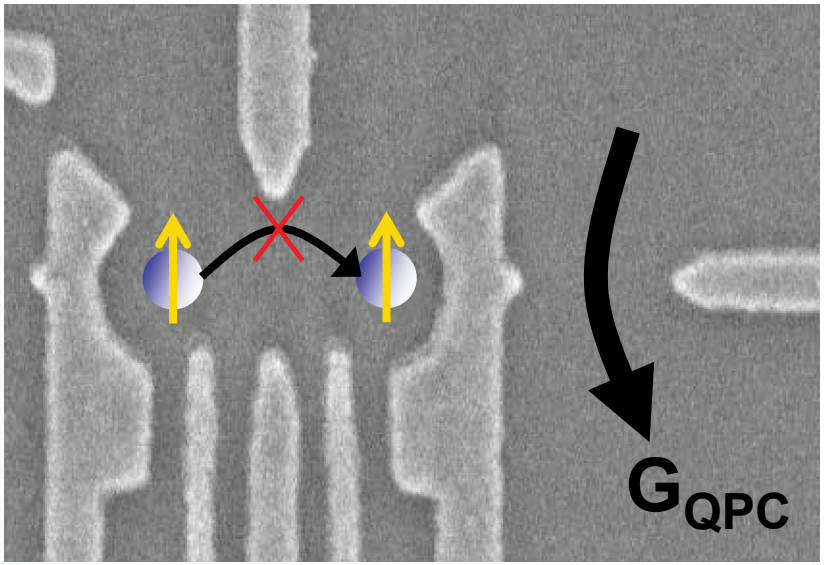


Singlet measurement

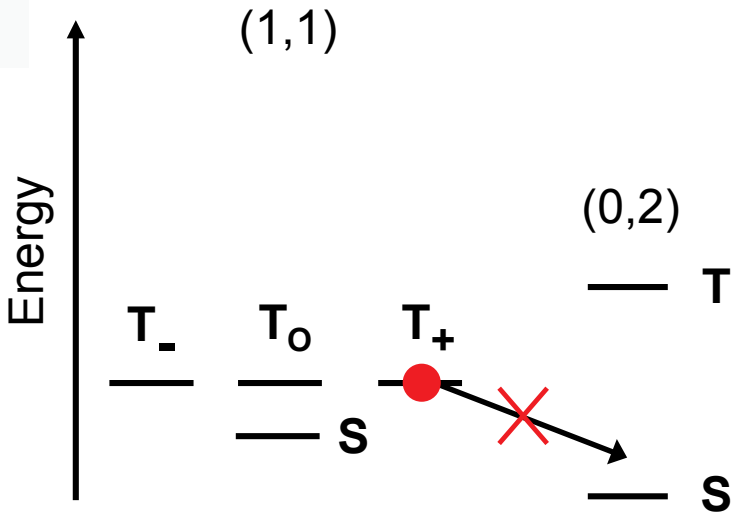


Spin State Measurement (Spin-to-Charge Conversion)

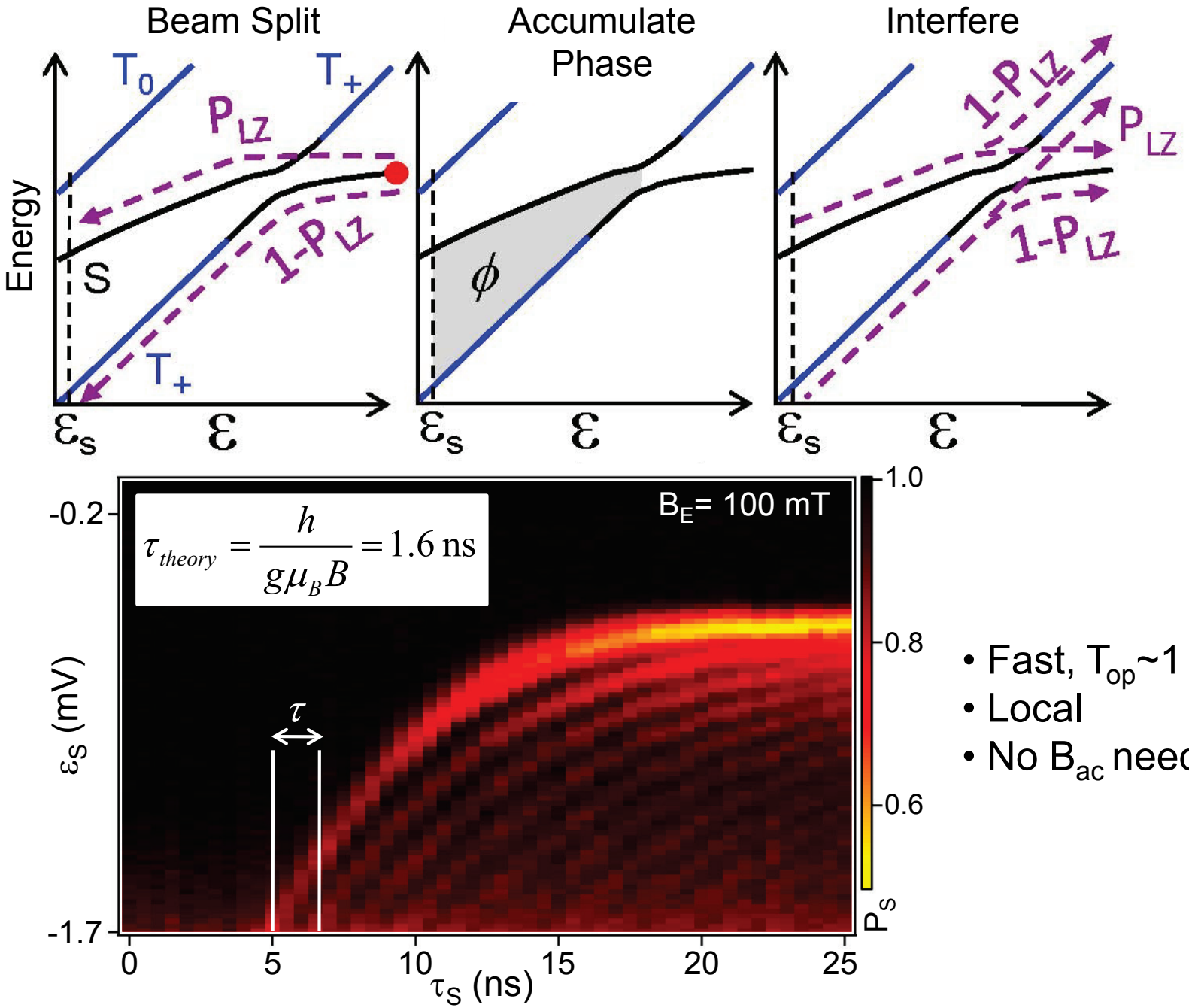




Triplet measurement

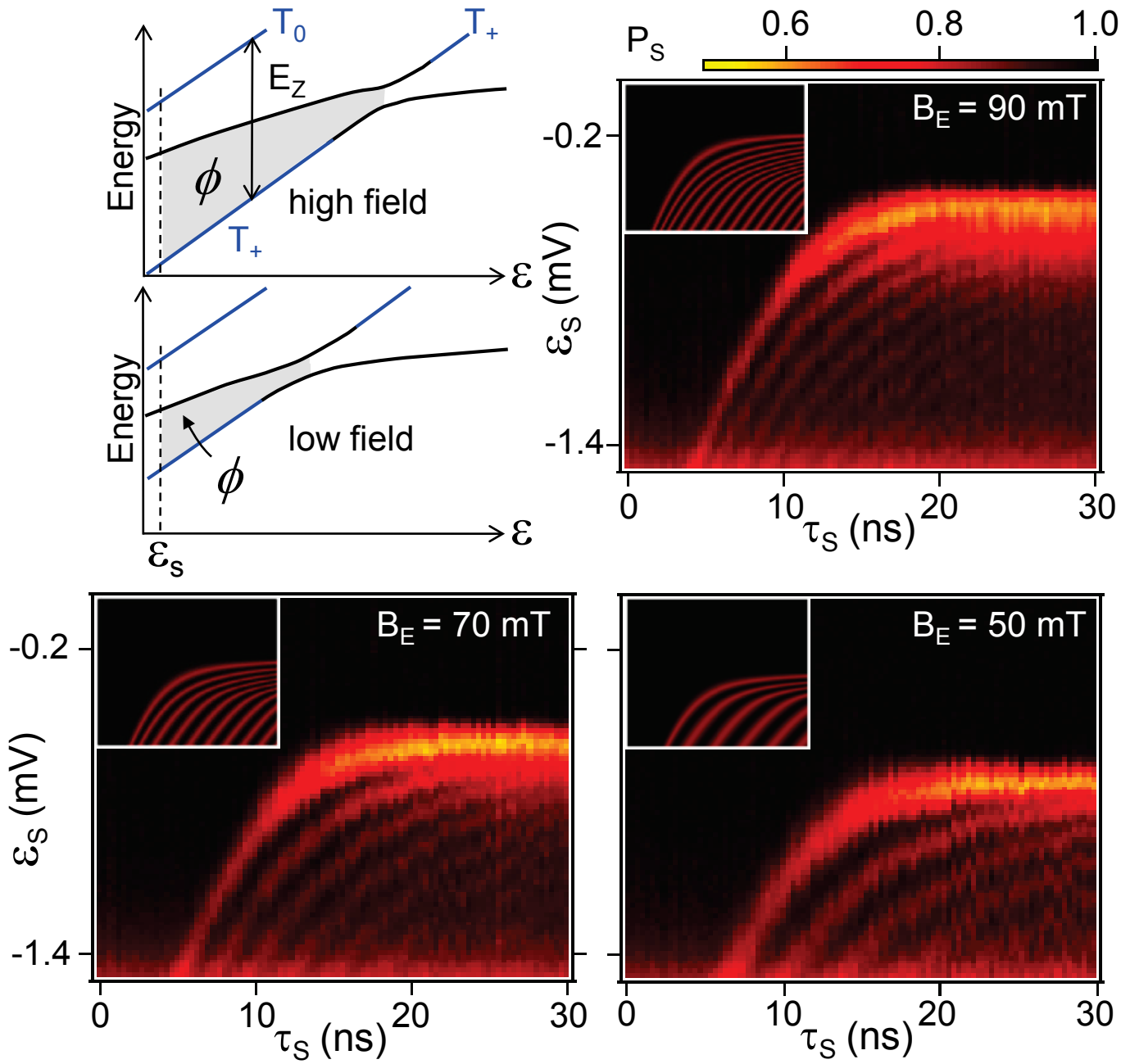


Observation of Landau-Zener-Stückelberg Oscillations

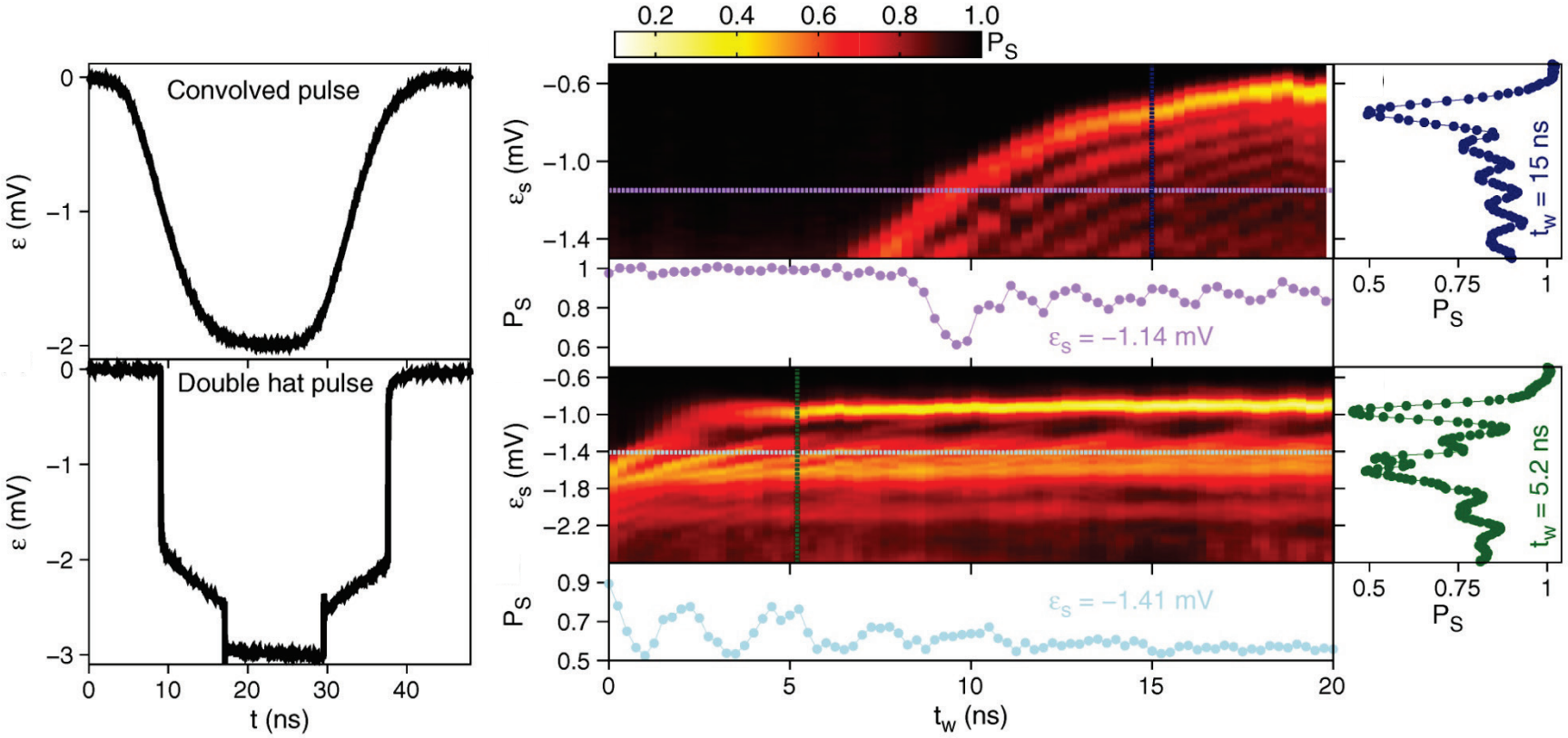


- Fast, T_{op}~1 ns
- Local
- No B_{ac} needed

Magnetic Field Dependence of Stückelberg Oscillations



Tailored Pulses for Quantum Control
"Local Adiabatic Evolution"



Tradeoff between coherence (T_2^*) and adiabaticity (Δ)

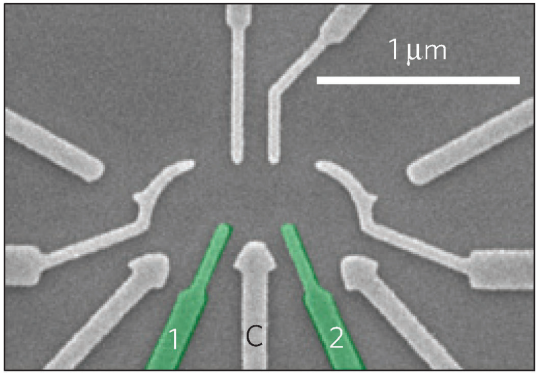
Work with Burkard Group:

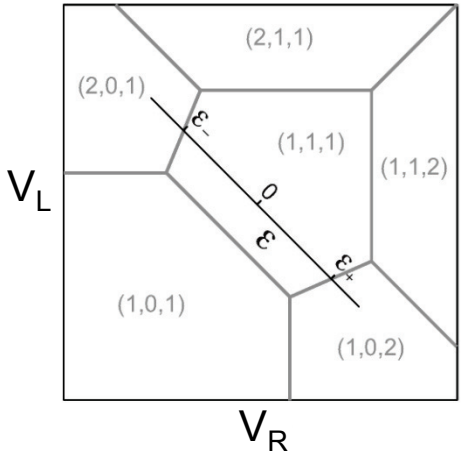
Ribeiro, Petta, Burkard, PRB (2012)

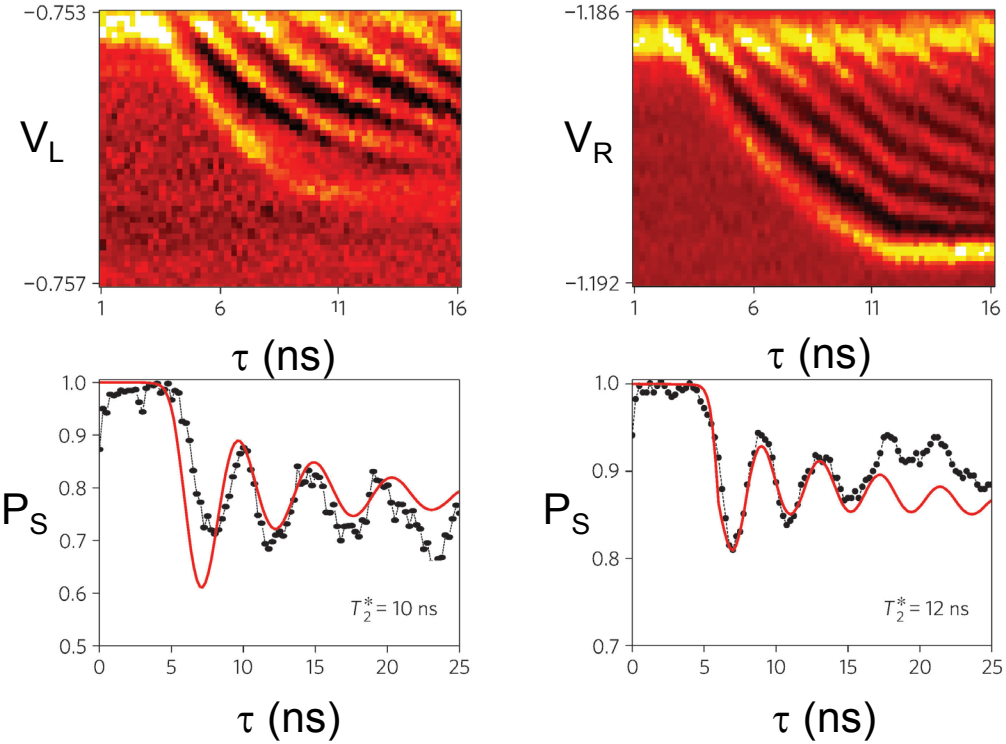
Ribeiro, Burkard, Petta, Lu, Gossard, PRL (2013)

Ribeiro, Petta, Burkard, PRB (2013)

Triple Quantum Dots



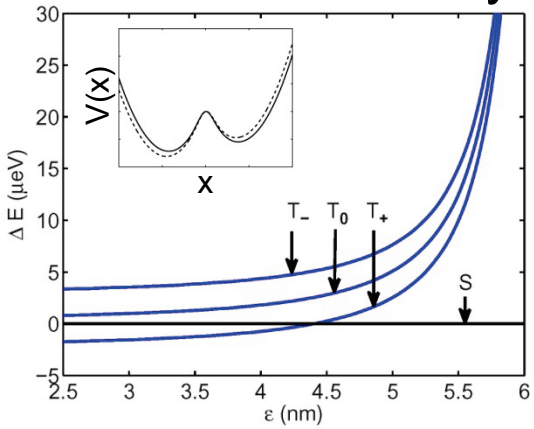


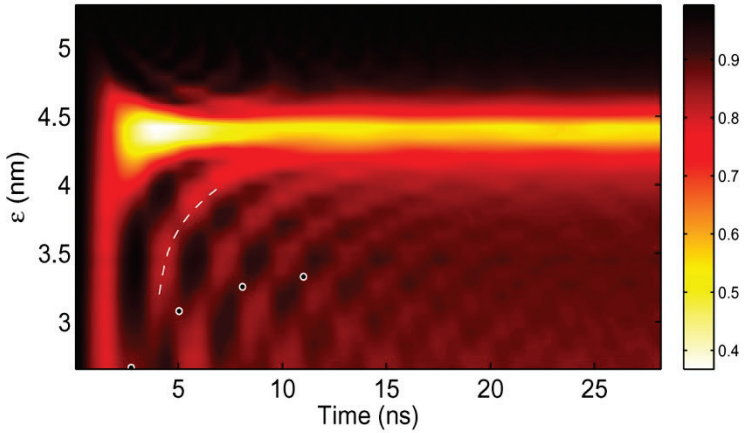


Gaudreau, Sachrajda *et al.*, Nature Phys. **8**, 54 (2012)

Multi-level Interference

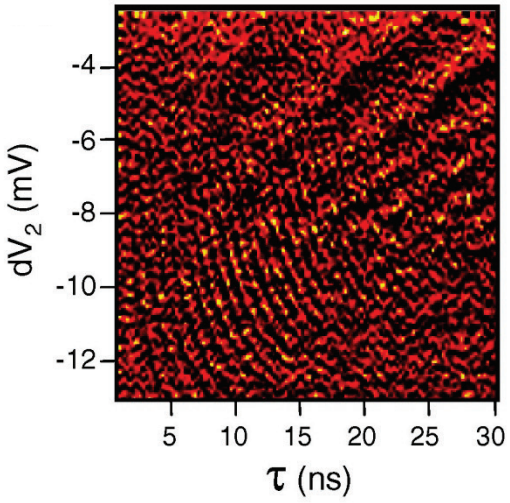
Theory: Full diagonalization

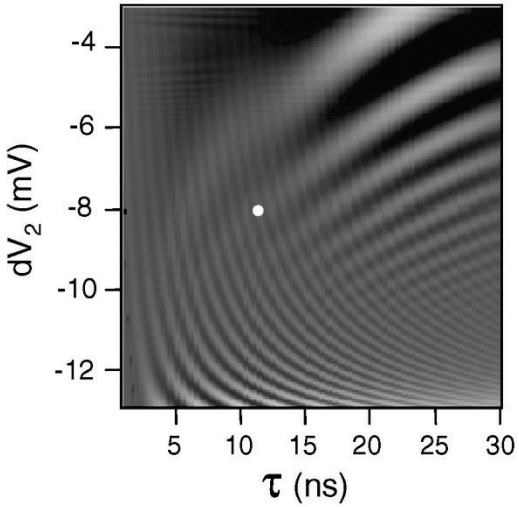




Särkkä and Harju, New J. Phys. **13**, 0430101 (2011)

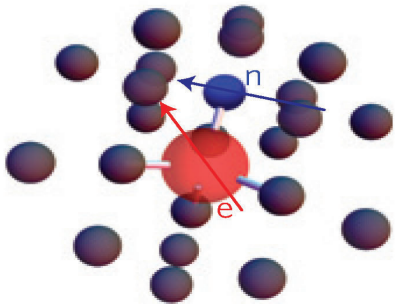
Experiment

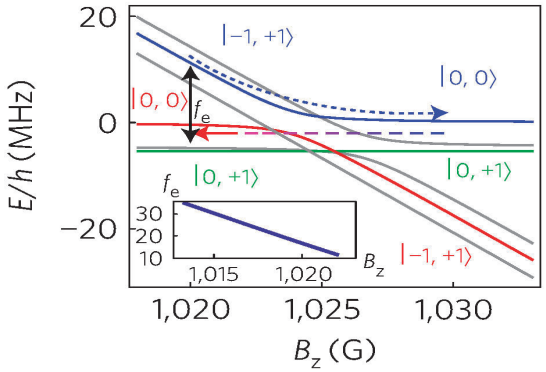


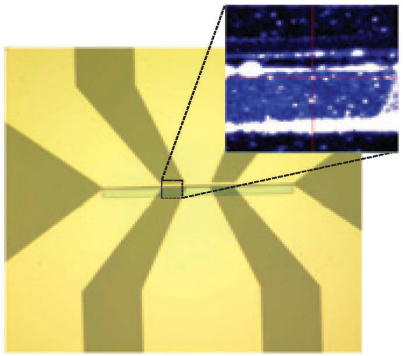


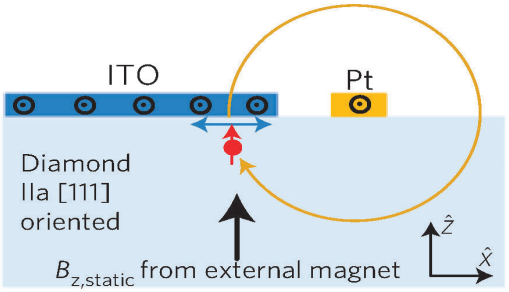
Studenkin, Sachrajda *et al*., Phys. Rev. Lett. **108**, 226802 (2012)

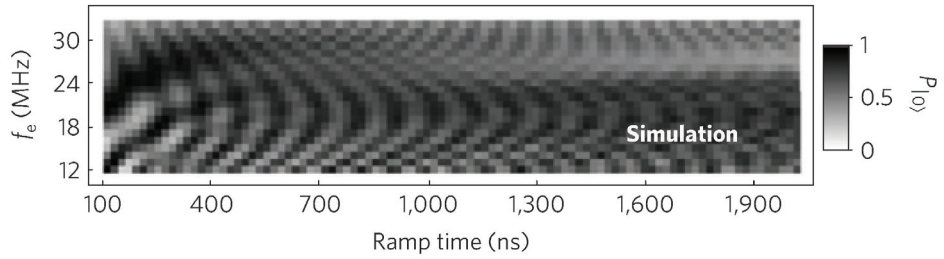
Nitrogen Vacancy Centers in Diamond

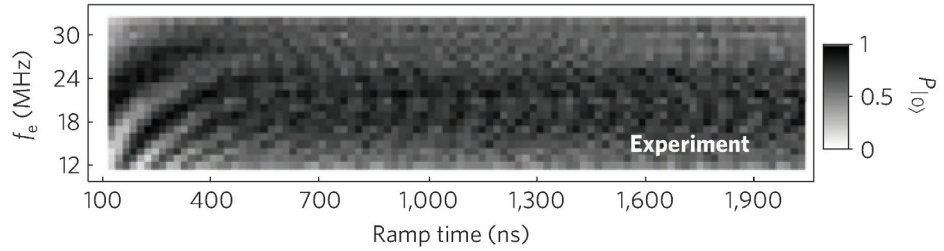








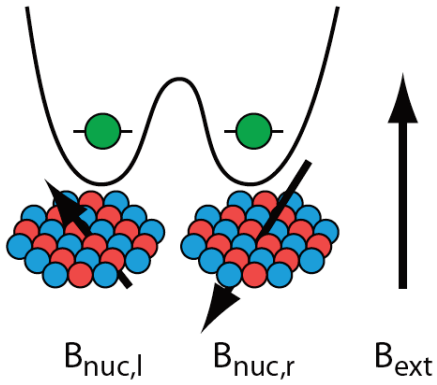




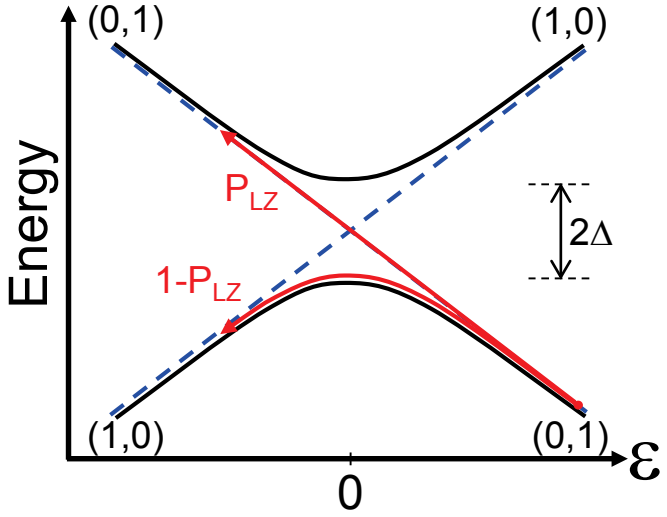
Fuchs, Awschalom *et al.*, Nature Phys. **8**, 54 (2012). See also: Huang *et al*. PRX **1**, 011003 (2011)

Summary

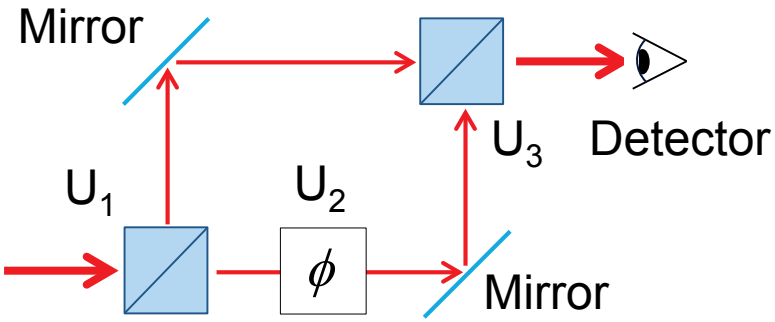
Double Quantum Dots



Landau-Zener Physics



Spin Interferometry



Landau-Zener-Stückelberg Oscillations