Strongly Driven Semiconductor Double Quantum Dots

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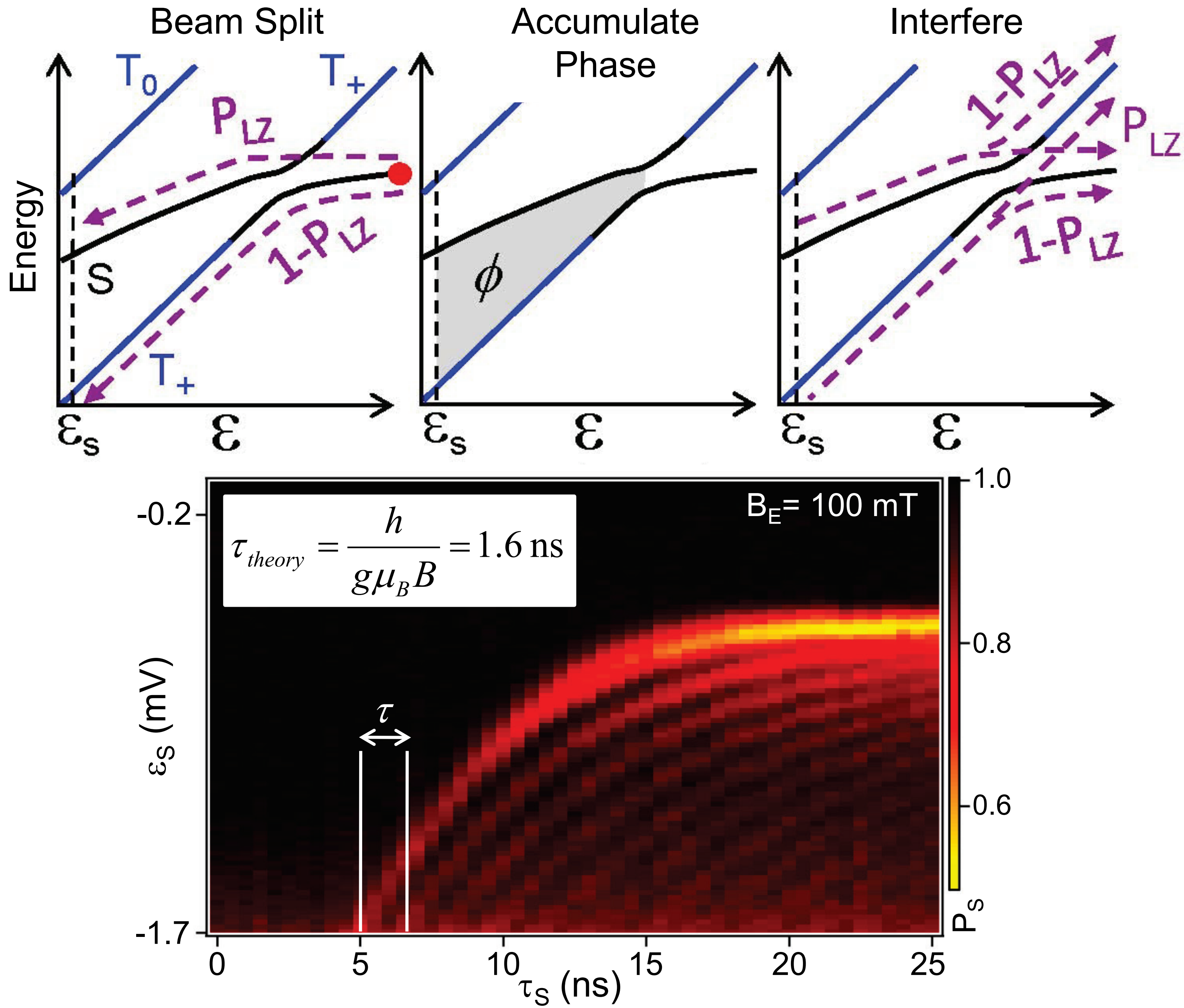
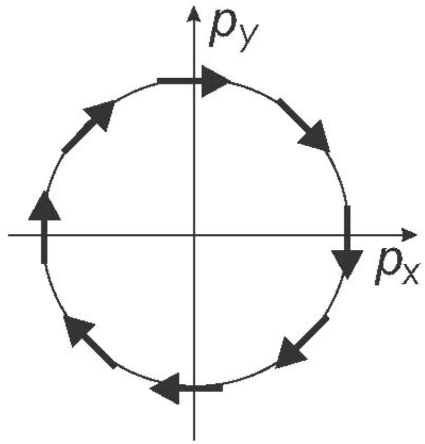
Physics Department, Princeton University

Lecture 1 Review: Landau-Zener Interference

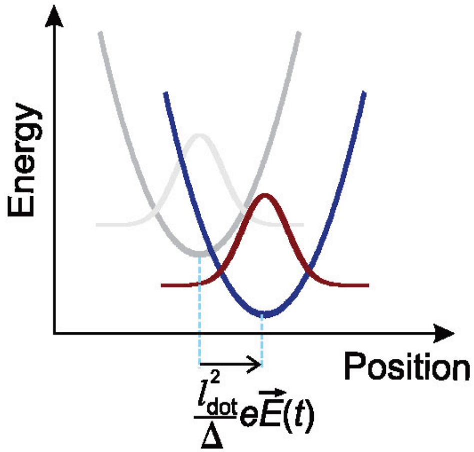


Lecture 2: Strongly Driven Spin-Orbit Qubits

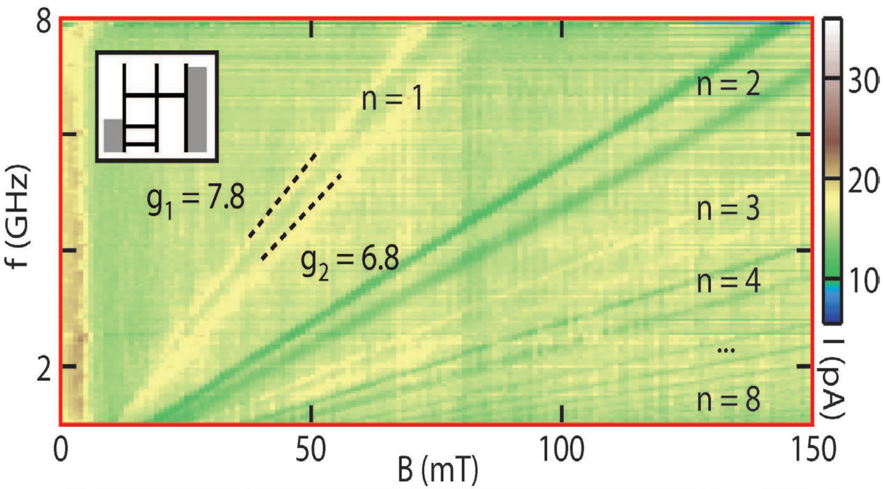
Spin-Orbit Interaction



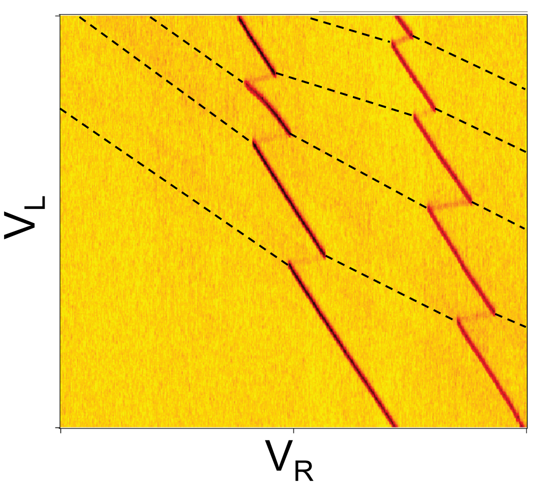
Electric-Dipole Spin Resonance



Extreme Harmonic Generation



Dispersive Readout



Spin-Orbit Interaction

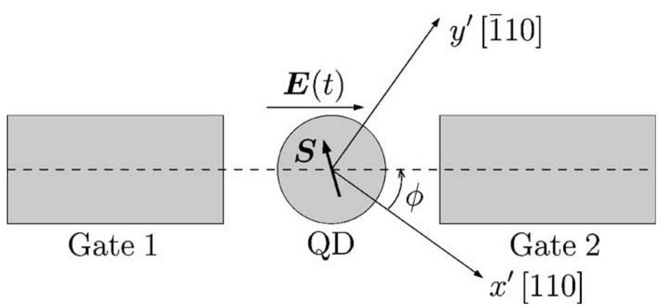
General Spin-Orbit Hamiltonian

electric field

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

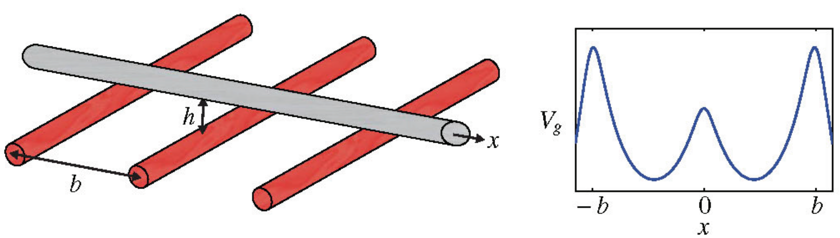
$\vec{B}_E$ = effective B field

Quantum Dots



Golovach *et al*., PRB (2006)

Quantum Wires



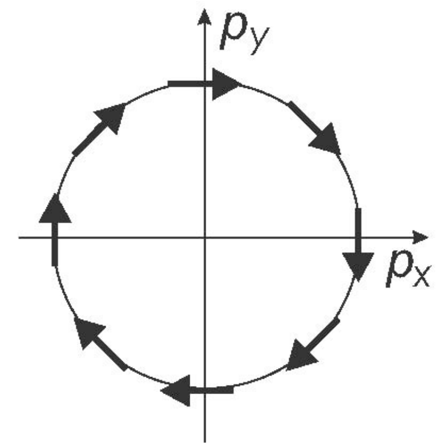
Flensberg *et al*., PRL (2006)

Spin-Orbit Interaction

Effective S-O field

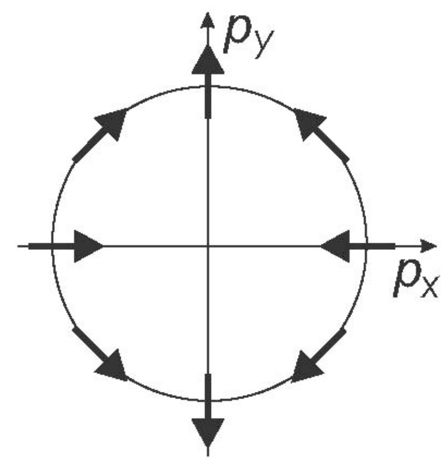
Structural inversion asymmetry – Rashba term

$$H_R = \alpha\left[\sigma_x p_y - \sigma_y p_x\right]$$



Bulk inversion asymmetry – Dresselhaus term

$$H_D = \beta\left[-\sigma_x p_x + \sigma_y p_y\right]$$



Hanson *et al.,* "Spins in few electron quantum dots," Rev. Mod. Phys. **79**, 1217 (2007)

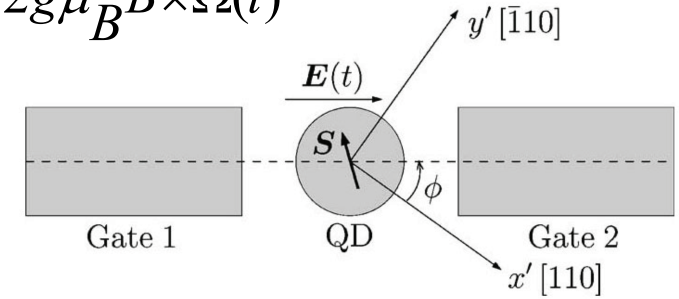
Electric Dipole Spin Resonance Theory

Effective Hamiltonian

$$H_{eff} = \frac{1}{2} g\mu_B \vec{B}\cdot\vec{\sigma} + \frac{1}{2}\vec{h}(t)\cdot\vec{\sigma} \quad \text{with} \quad \vec{h}(t) = 2g\mu_B \vec{B}\times\vec{\Omega}(t)$$

Static Zeeman term

ac driven spin-orbit term



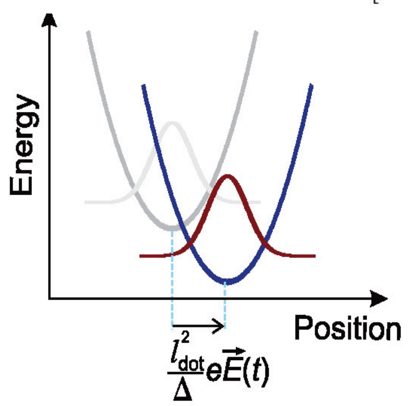
$$\vec{\Omega}(t) = \frac{-e}{m_e\omega_o^2}\left[\lambda_{so}^{-1}E_y(t), \lambda_{so}^{-1}E_x(t), 0\right]$$

m_e= effective mass

$\hbar\omega_o$~1 meV, confinement energy

$E_{x,y}$= ac field magnitude

λ_{so}= spin-orbit length



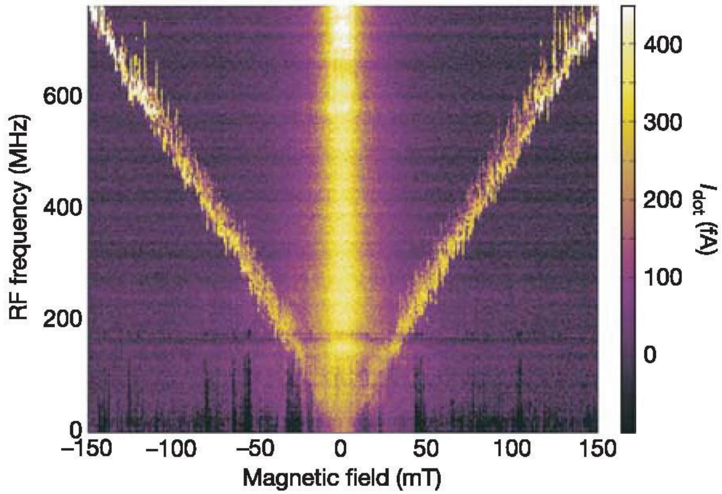
$E_{ac} \rightarrow B_{ac}$

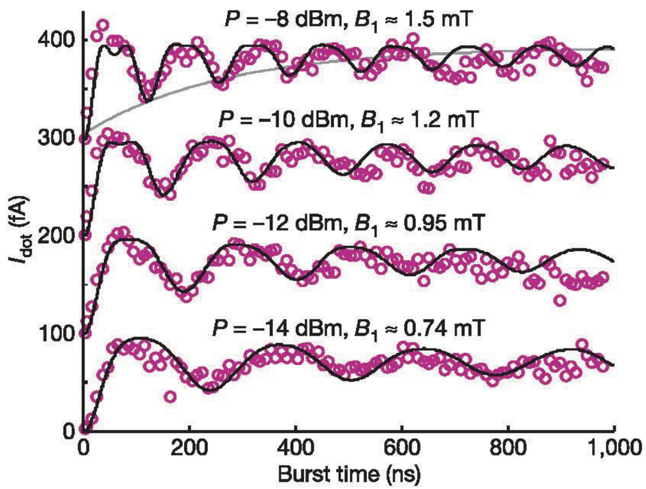
Theory: Golovach *et al*., PRB (2006)
Flindt *et al*., PRL (2006)

Experiment: Nowak *et al*., Science (2007)

Maximum Rabi Frequency

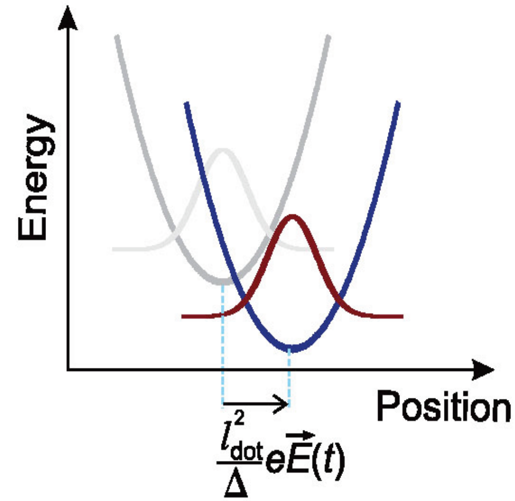
Conventional ESR

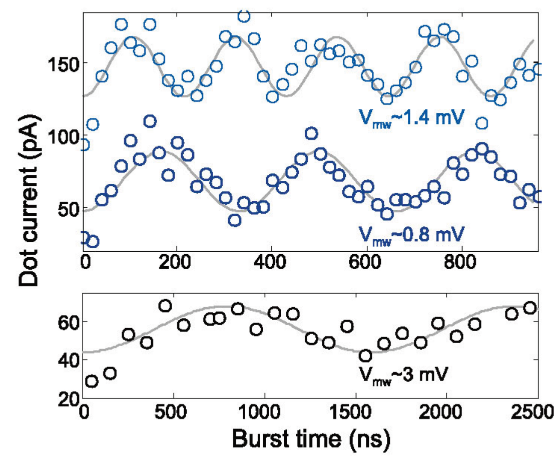




Koppens *et al*., Nature (2006)

EDSR



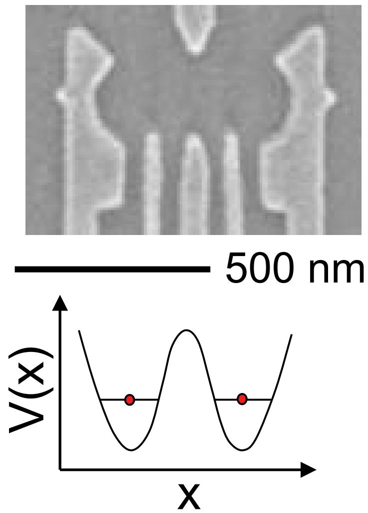


Nowack *et al*., Science (2007)

GaAs EDSR 2x slower

Strong Spin-Orbit Coupling

GaAs Double Quantum Dot

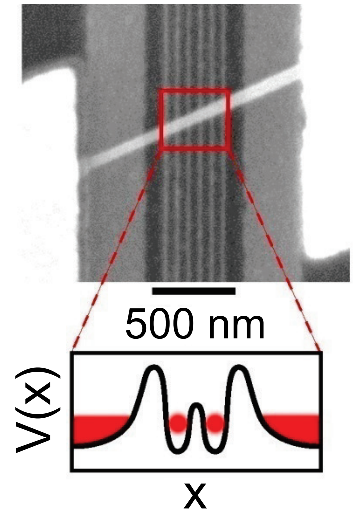


Ga Z = 31

GaAs m^* = 0.063 m_0

λ_{so} ~ 8 μm

InAs Double Quantum Dot



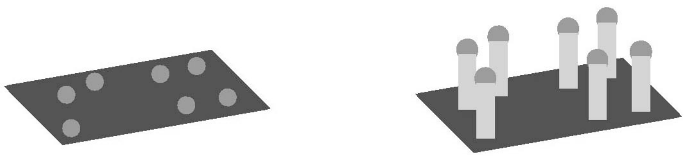
In Z = 49

InAs m^* = 0.023 m_0

λ_{so} ~ 200 nm

InAs Nanowire Double Quantum Dot

Vapor-Liquid-Solid (VLS)
growth process

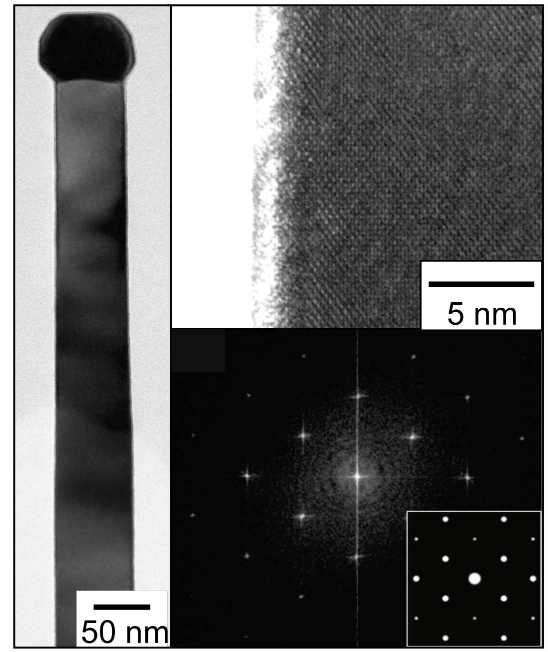


Au catalyst pads

Final product

References:
Wagner and Ellis (1965)
Samuelson Group (Lund)
Lieber Group (Harvard)

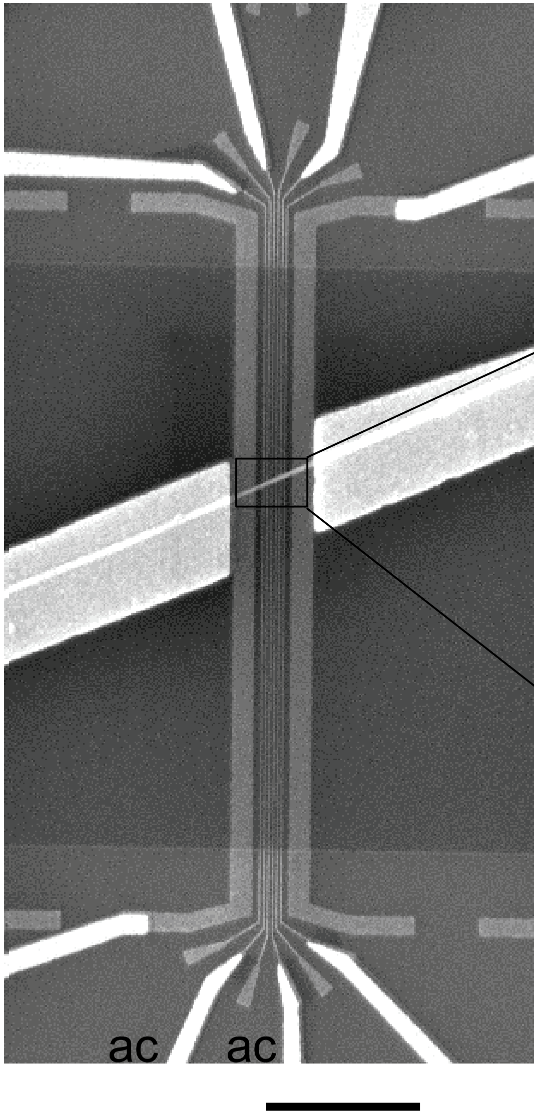
Single InAs nanowire

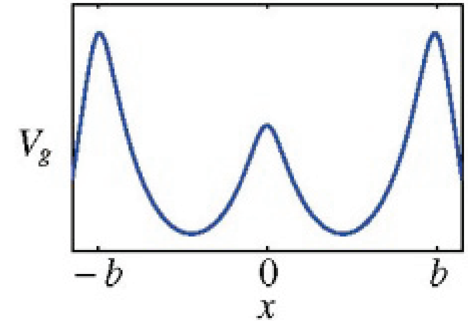


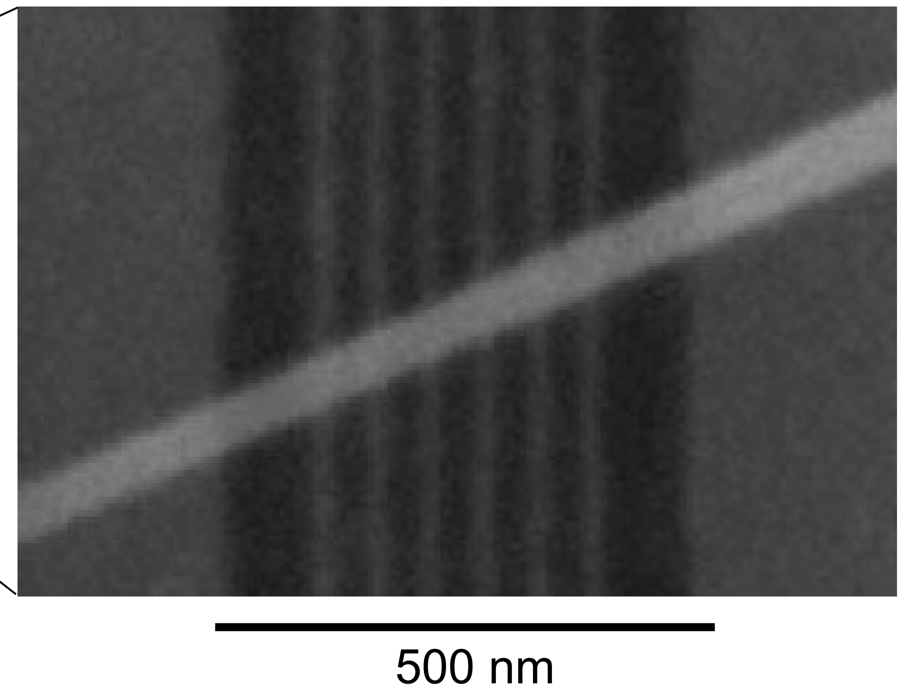
Schroer and Petta, Nano Lett. (2010)

Bottom Gated InAs Nanowire Double Quantum Dots

Bottom Gated DQD

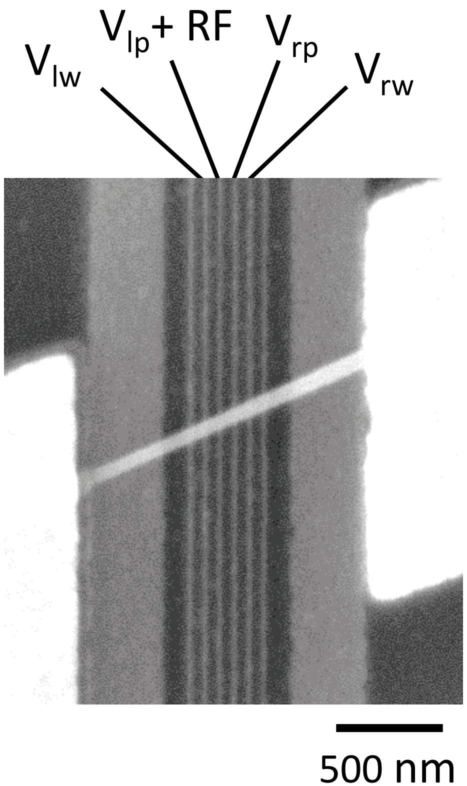


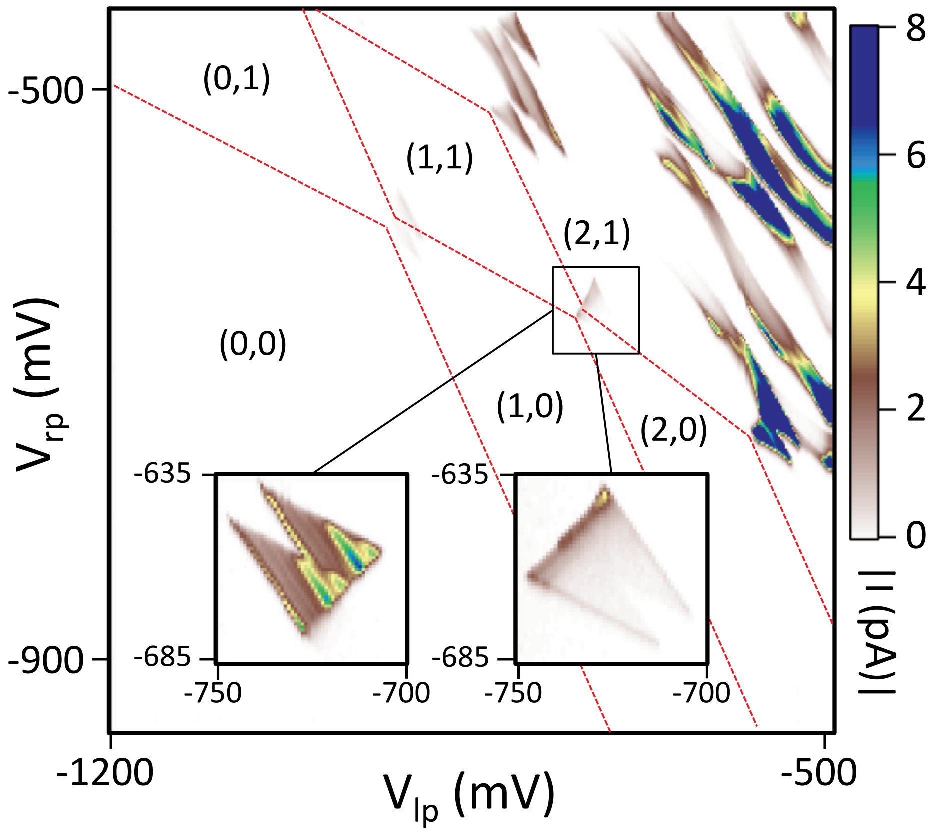




References:
Nadj-Perge *et al*., Nature (2010)
Schroer and Petta, Nano Lett. (2010)
Schroer, Petersson, Jung, Petta, PRL (2011)

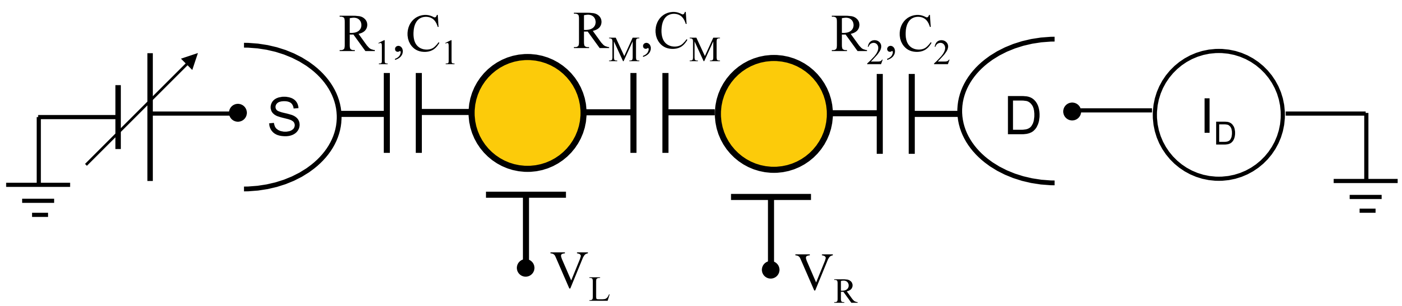
Few-Electron Regime

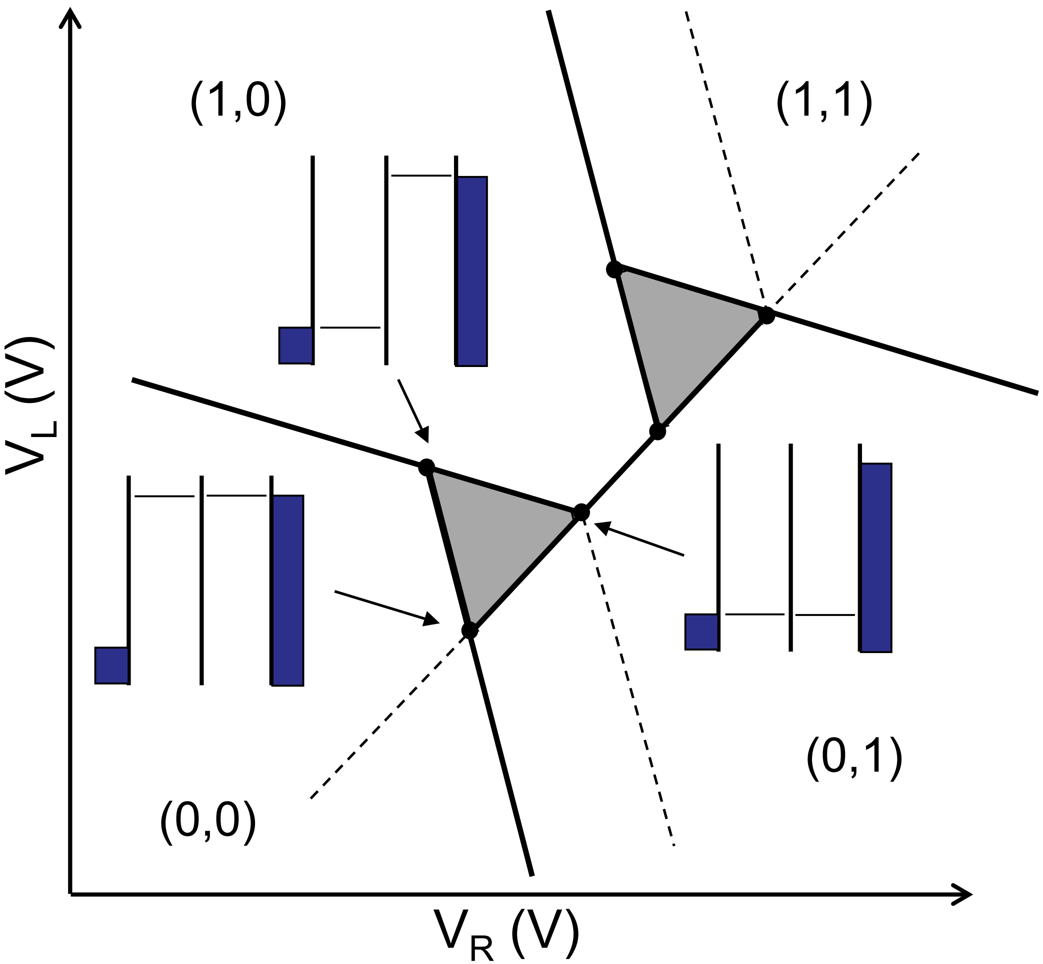




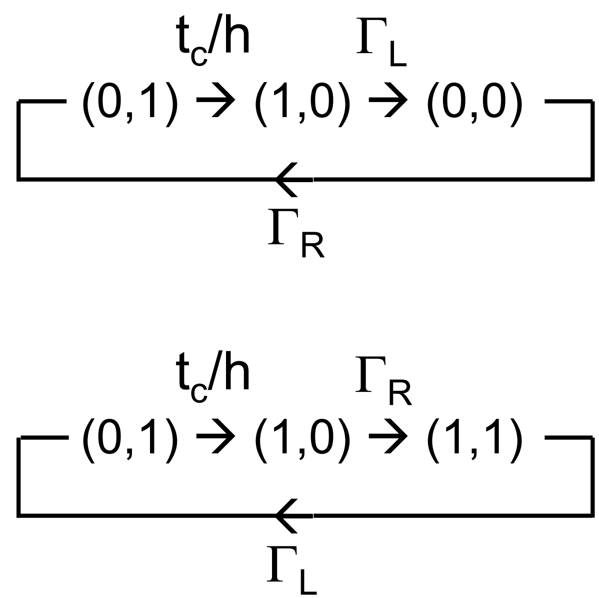
Schroer, Petersson, Jung, Petta, PRL (2011)

DC Transport in Double Quantum Dots

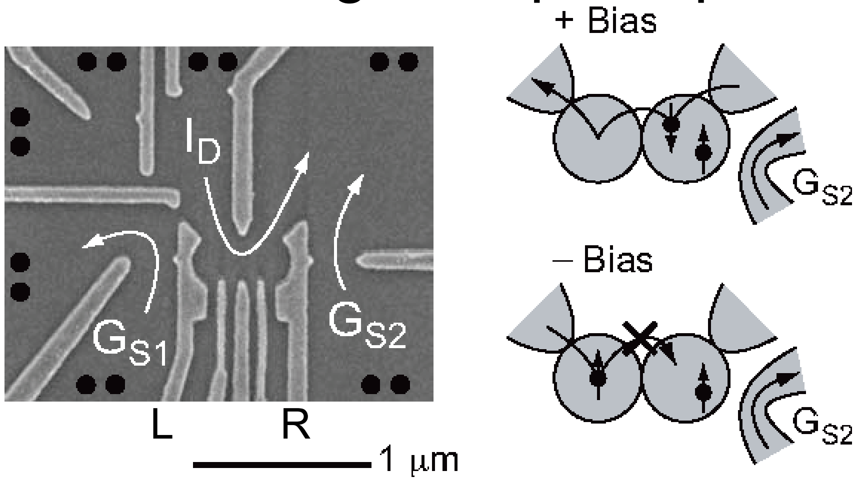




Finite bias “triangles”

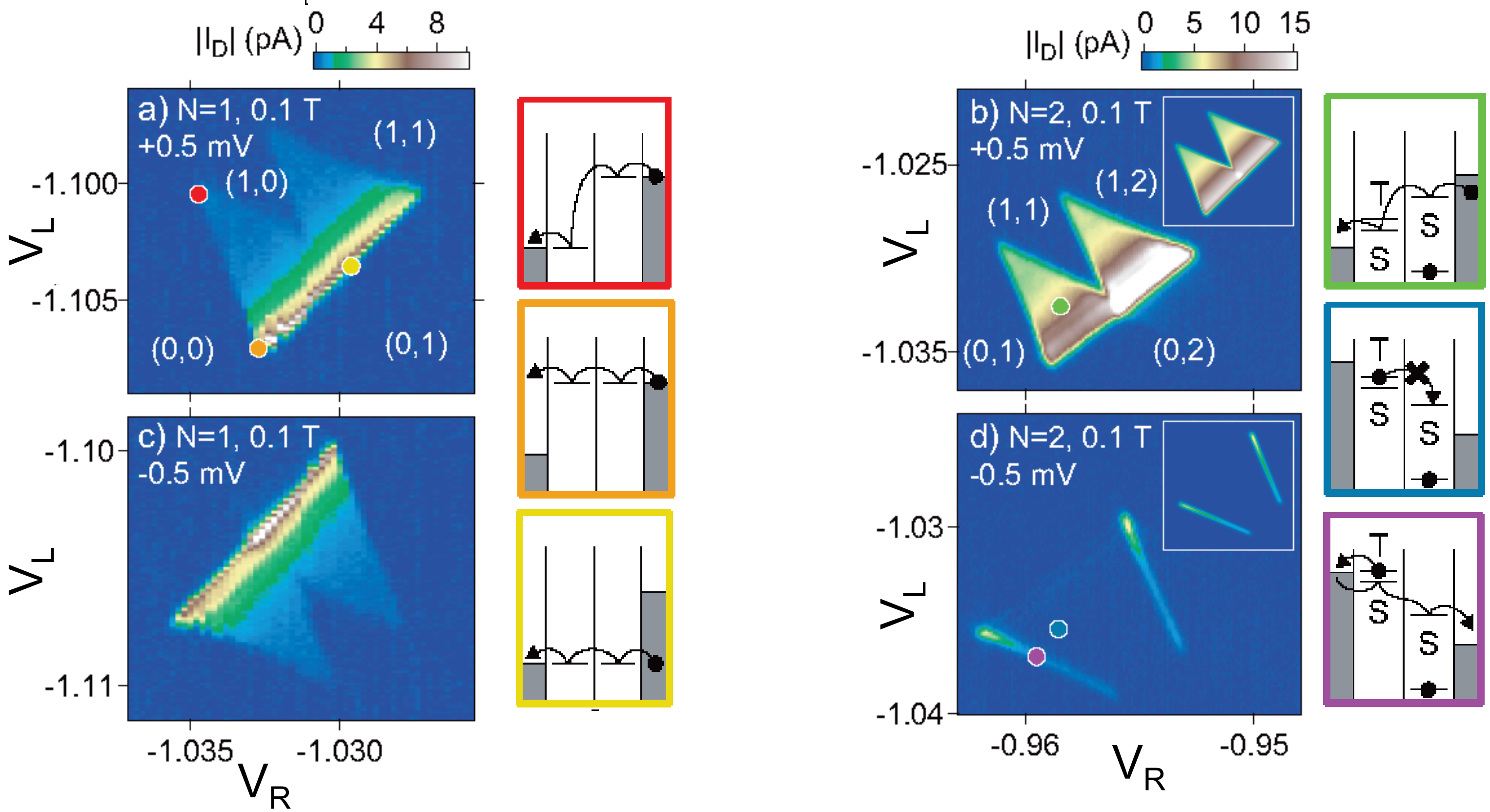


Singlet-Triplet Spin Blockade in dc Transport



(0,2) → (1,1) transport is allowed

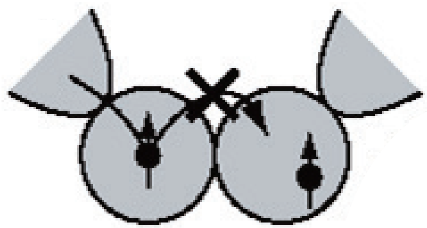
(1,1) → (0,2) transport is spin blocked

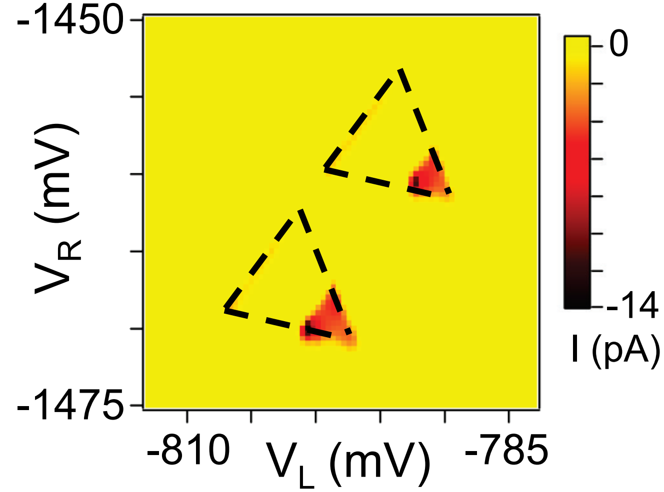


Johnson, Petta, Marcus, PRB (2005). See also Ono *et al.*, Science (2002).

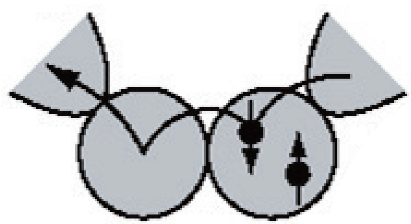
Spin Dependent Transport in InAs Double Dots

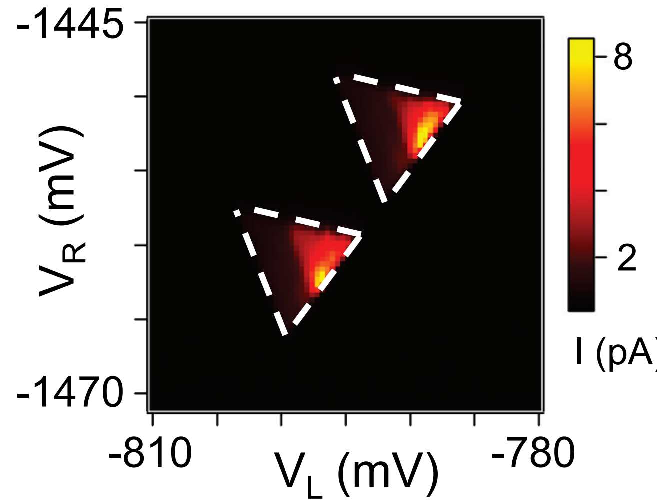
Negative Bias





Positive Bias

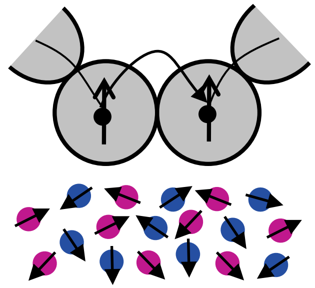


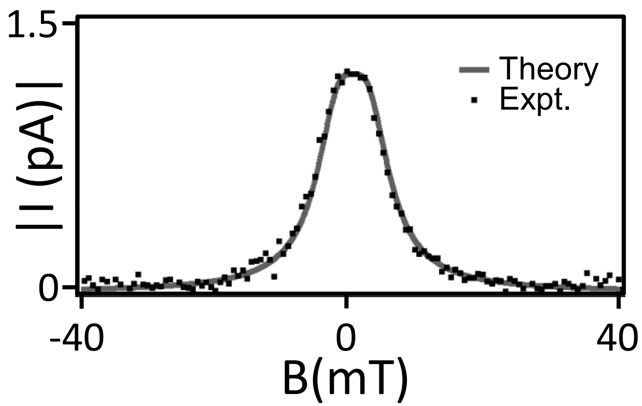


Ono, Austing, Tokura, Tarucha, Nature (2002)
Schroer, Petersson, Jung, Petta, PRL (2011)

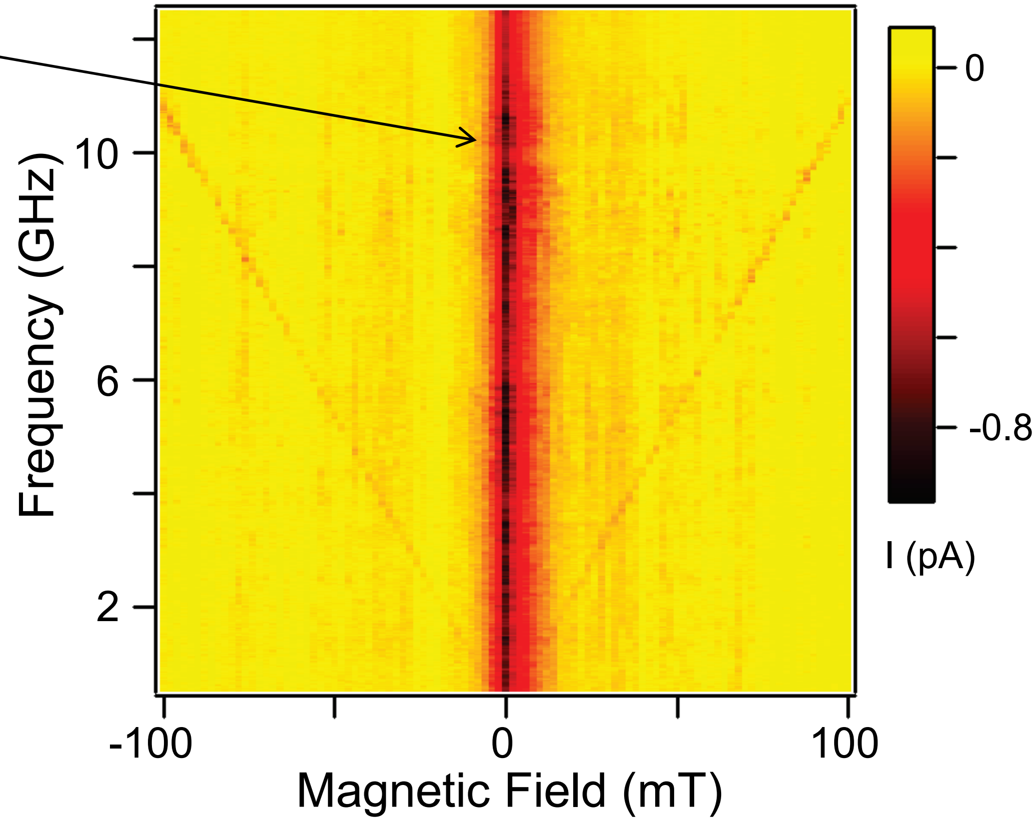
InAs EDSR

Hyperfine “mixing”
of spin states





B_{nuc} = 3.3 mT

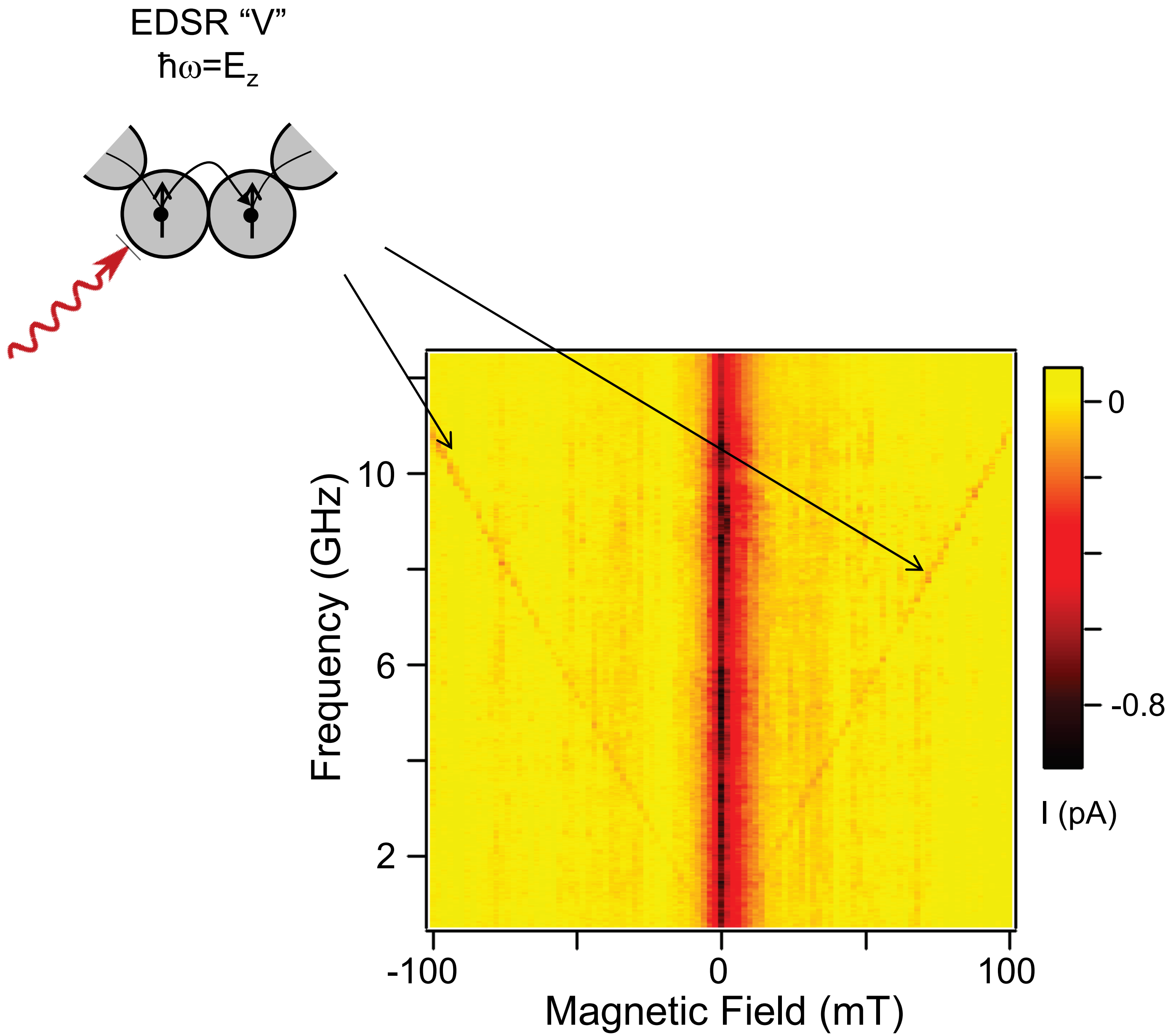


Koppens *et al*., Science (2005)

Schroer, Petersson, Jung, Petta, PRL (2011)

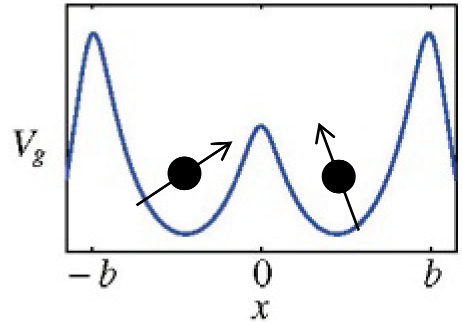
Theory: Jouravlev *et al*., PRL (2006)

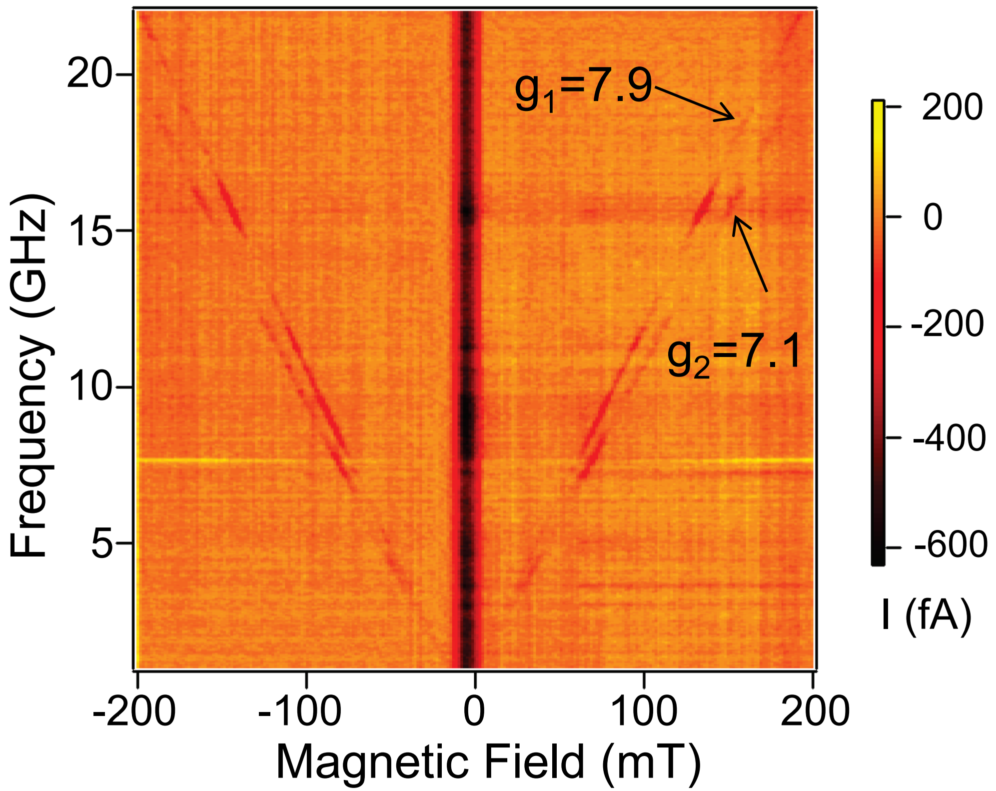
InAs EDSR



Schroer, Petersson, Jung, Petta, PRL (2011)

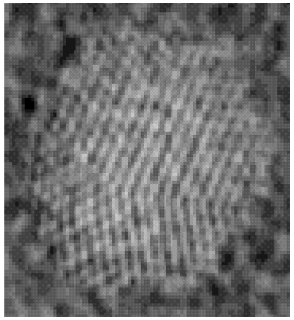
Spin-Selective EDSR in InAs





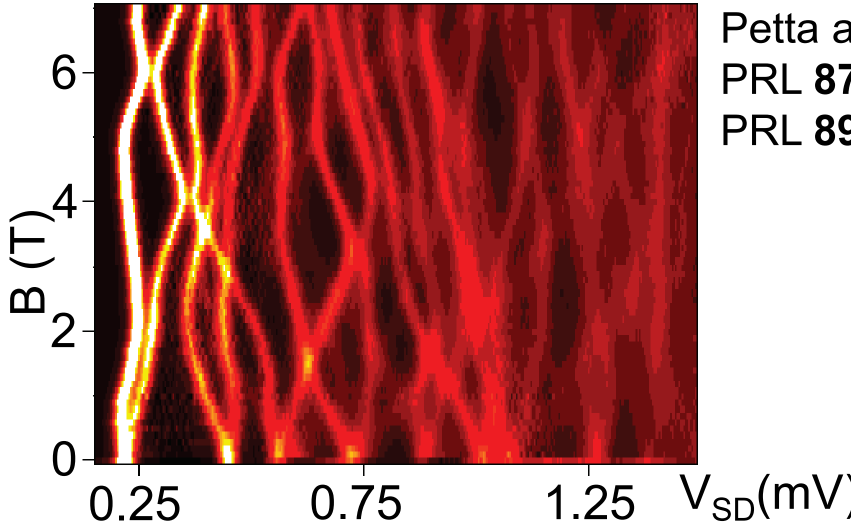
Schroer, Petersson, Jung, Petta, PRL (2011)

Evidence for Strong Spin-Orbit Interactions



Metal nanoparticle
N~10^4

Energy levels in a Cu nanoparticle

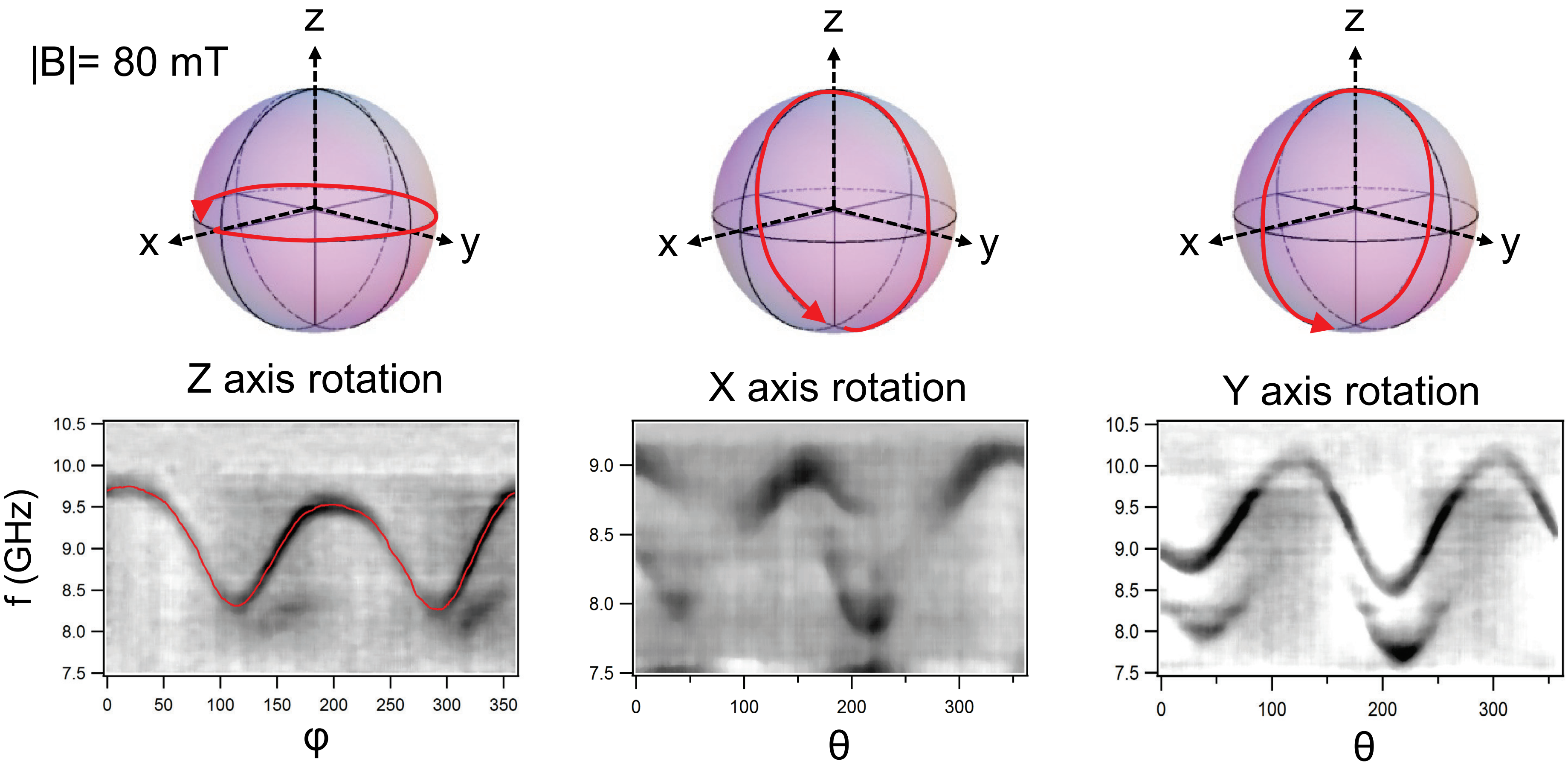


Petta and Ralph
PRL **87**, 266801 (2001)
PRL **89**, 156802 (2002)

- g-factors fluctuate
- g-factors are anisotropic
- level avoided crossings “spaghetti”

InAs Single Dot References:
Bjork *et al.*, PRB **72**, 201307 (2005)
Fasth *et al.*, PRL **98**, 266801 (2007)
Takahashi *et al.*, PRL **104**, 246801 (2010)

g-factor Anisotropy



General model for 3D anisotropic g factor:

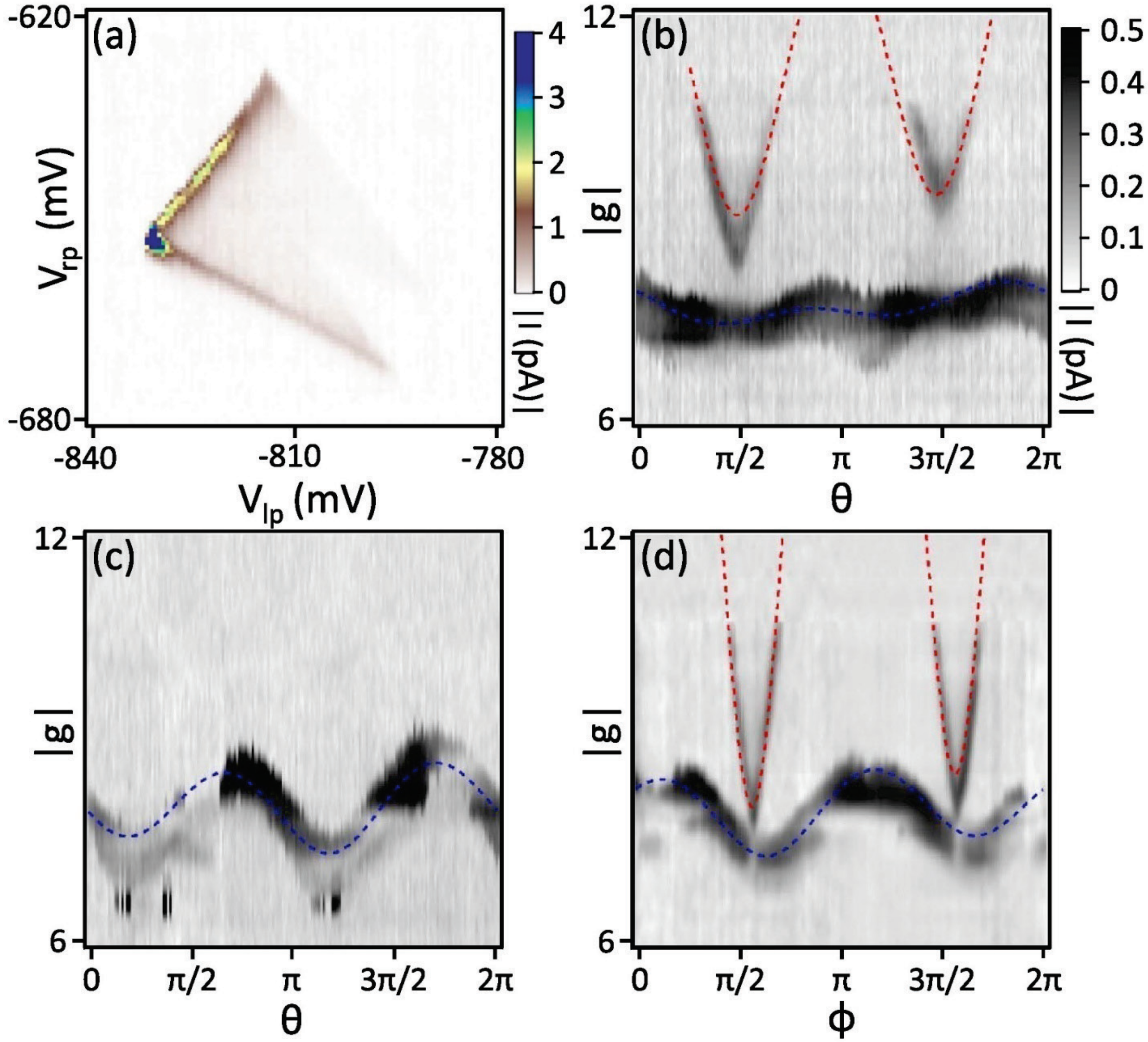
$$g(\hat{B}) = (g_1{}^2 B_1{}^2 + g_2{}^2 B_2{}^2 + g_3{}^2 B_3{}^2)^{1/2} \Big/ \left|\vec{B}\right|^2$$

$g_1 = 7.1$, $g_2 = 7.5$, $g_3 = 9.1$

Theory: Brouwer, PRL **85**, 369 (2000)

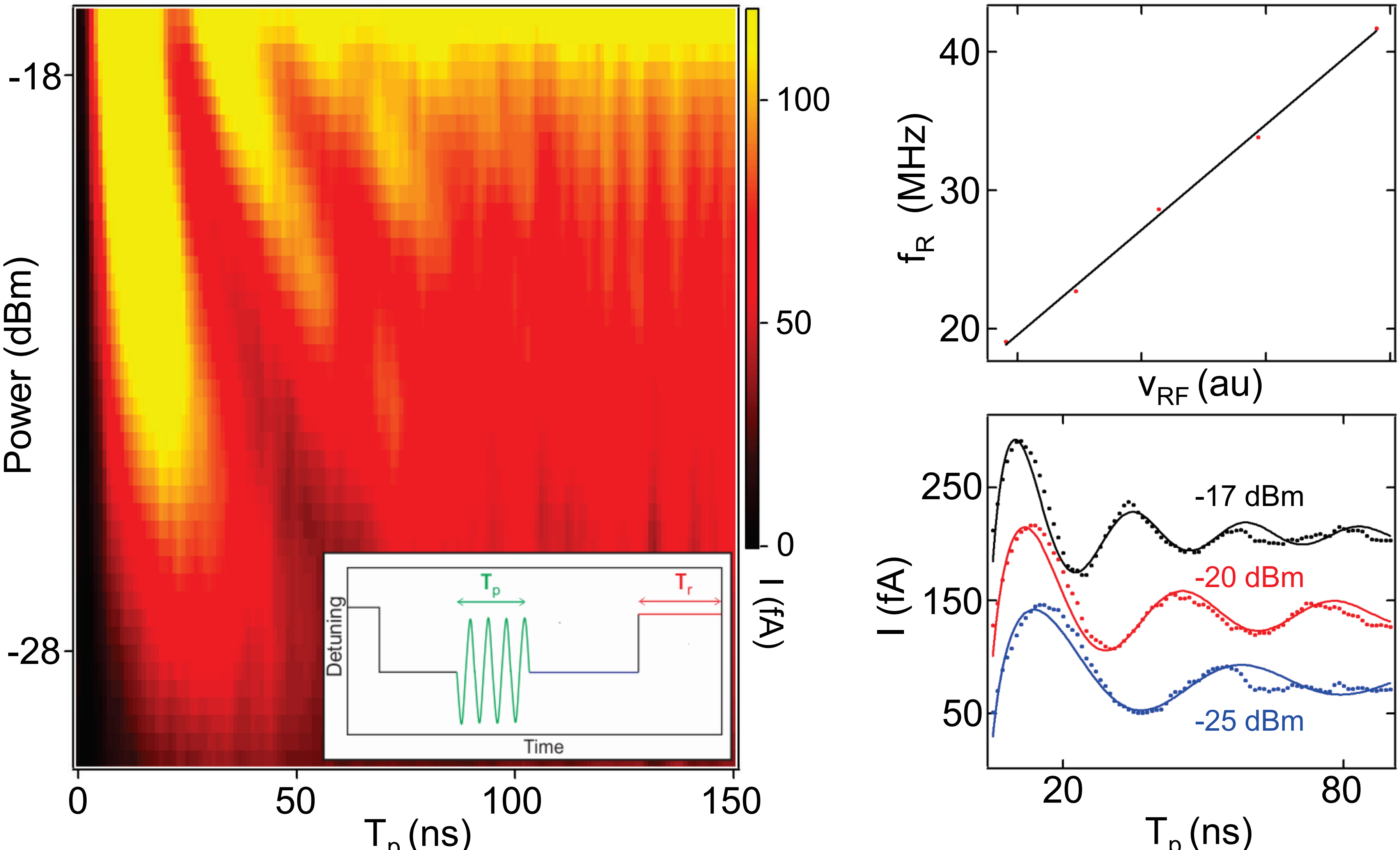
- g-factor is anisotropic
- g-factor is dot dependent
- EDSR amplitude is anisotropic

Electrically Tunable G-Factor



$g_1 = 22$, $g_2 = 12.0$, $g_3 = 8.0$

Driven Rabi Oscillations

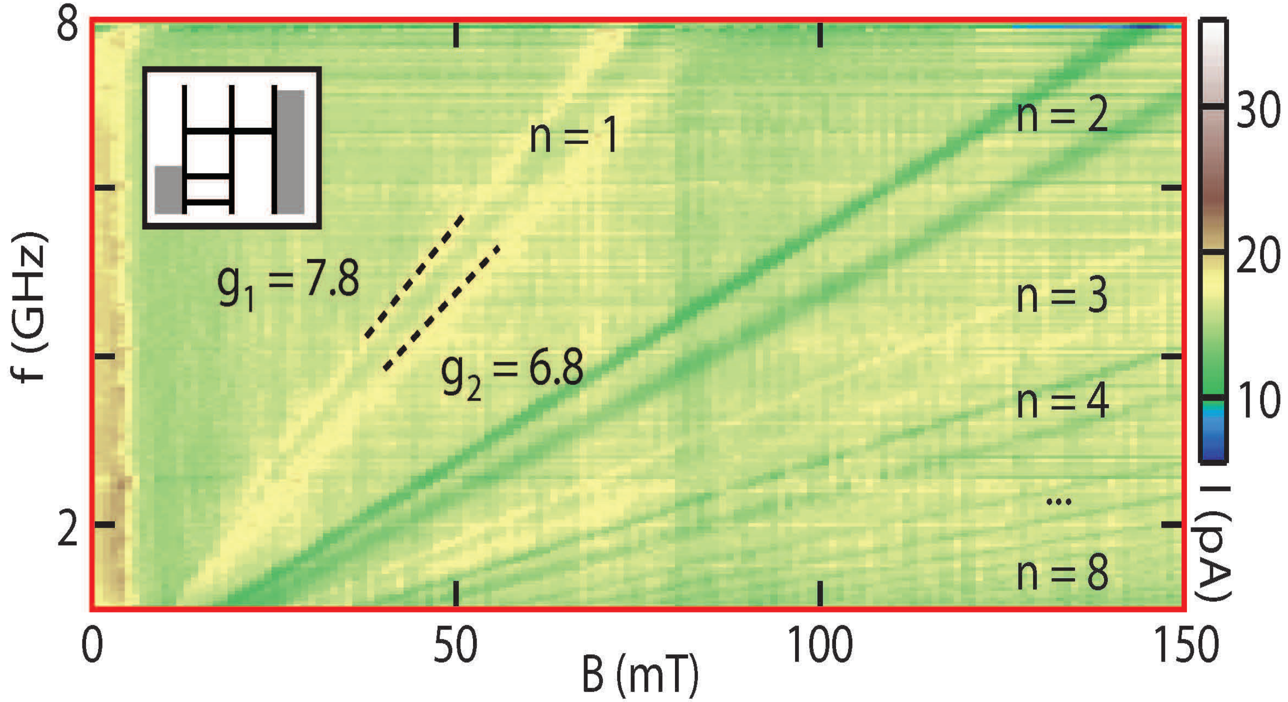


See also: Nadj-Perge *et al.*, Nature (2010)

Landau-Zener Interferometry in EDSR

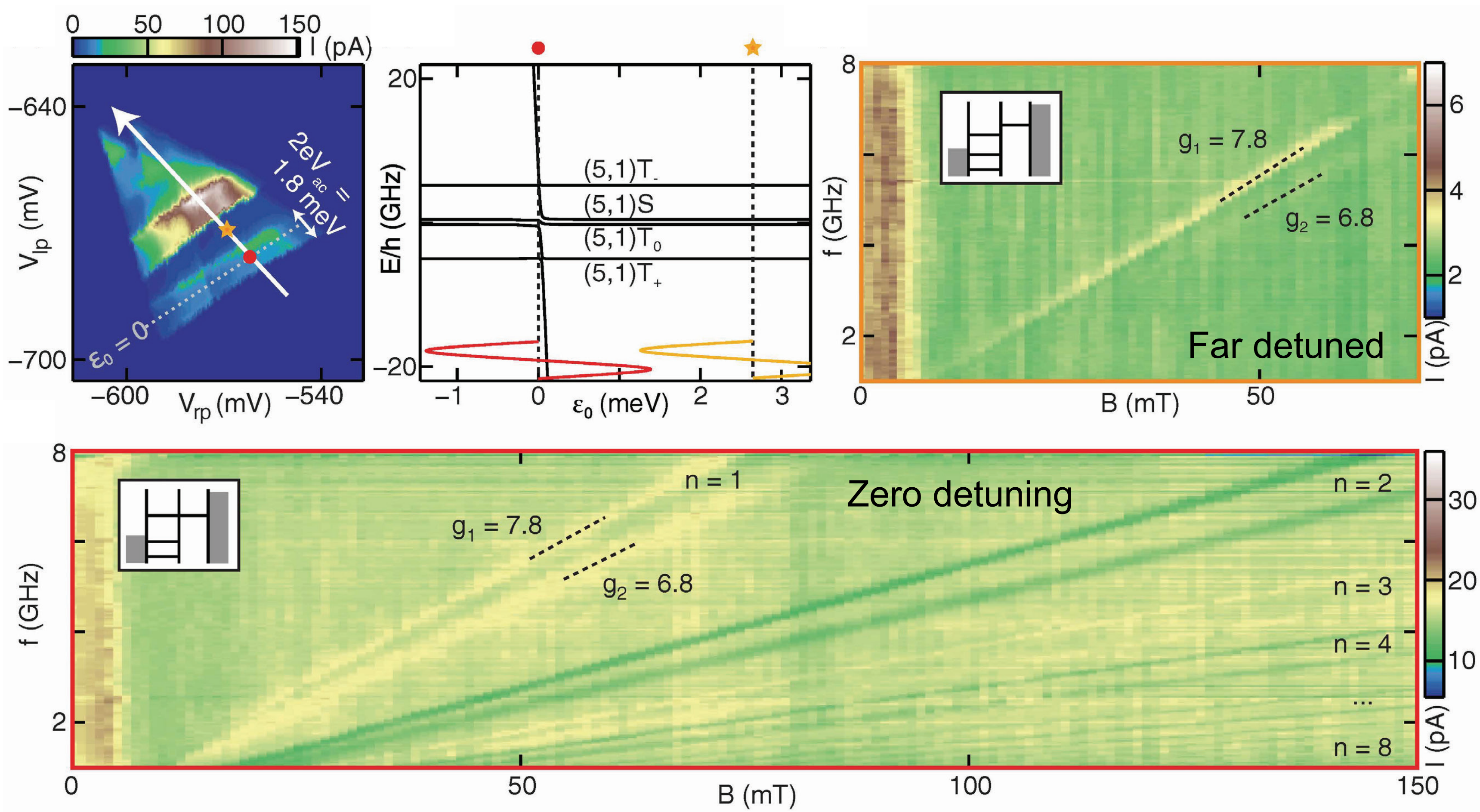
ESR response when $E_z = n\hbar\omega$

- n as large as 8
- striking even-odd dependence



Stehlik, Schroer, Maialle, Degani, Petta, Phys. Rev. Lett. (2014)

Detuning Dependence



Multilevel Interference Resonances in Strongly Driven Three-Level Systems

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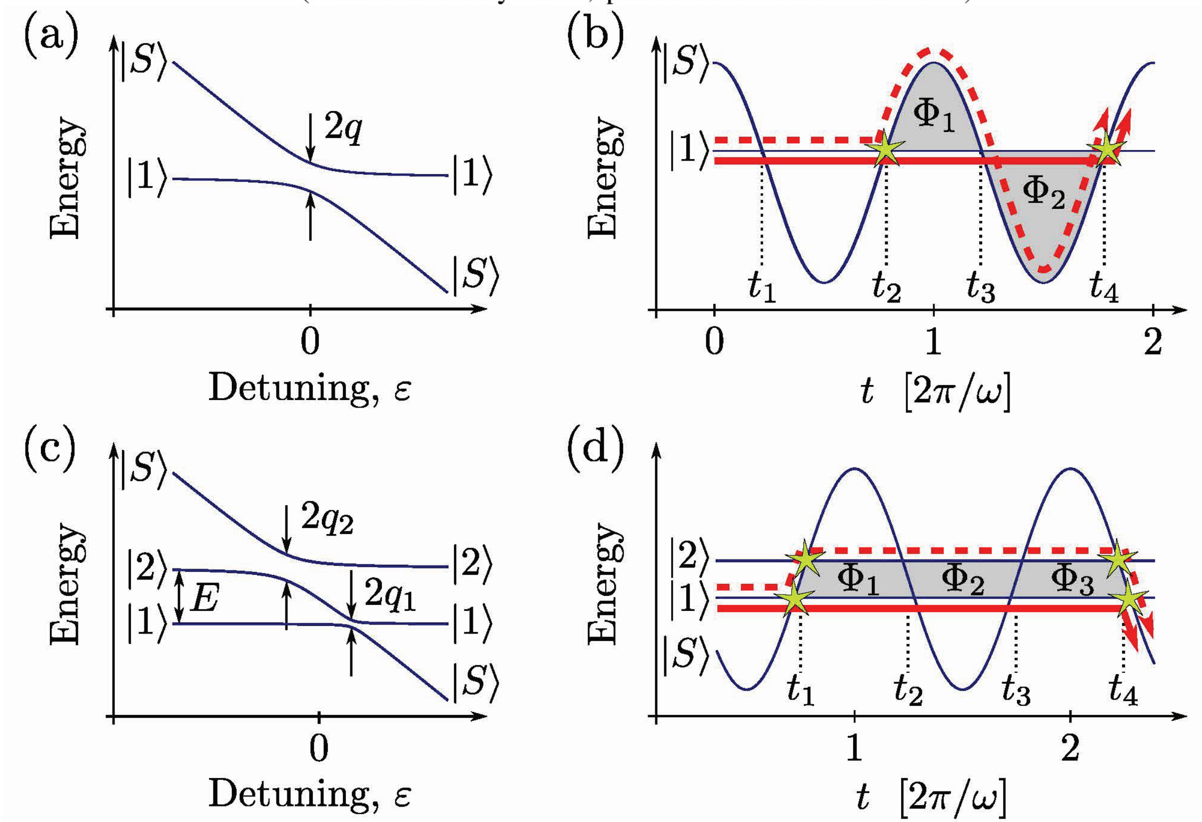
Niels Bohr International Academy, and the Center for Quantum Devices, Niels Bohr Institute, University of Copenhagen, 2100 Copenhagen, Denmark

(Received 8 July 2014; published 9 December 2014)

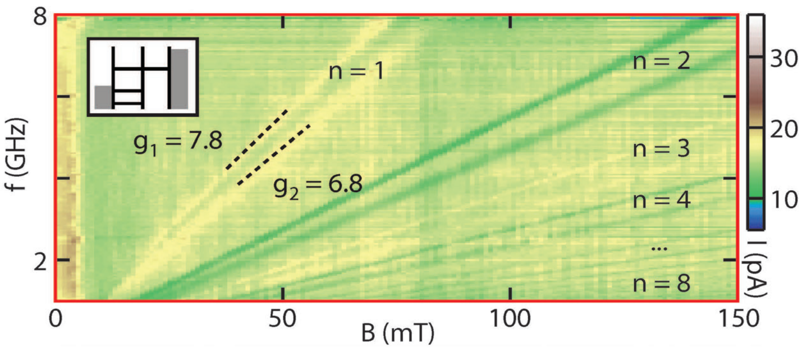


Analyze interferences to 4th order:

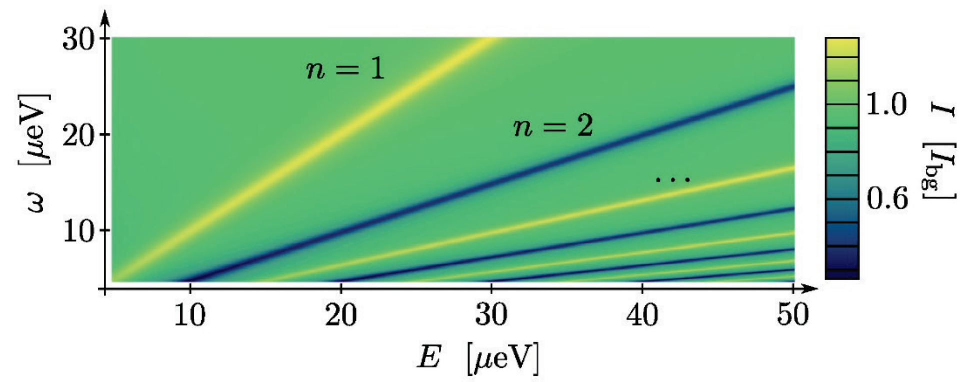
1) Trajectories that couple |1> to |2>
2) Trajectories that couple |1> to |S>

Comparison of Experiment and Theory

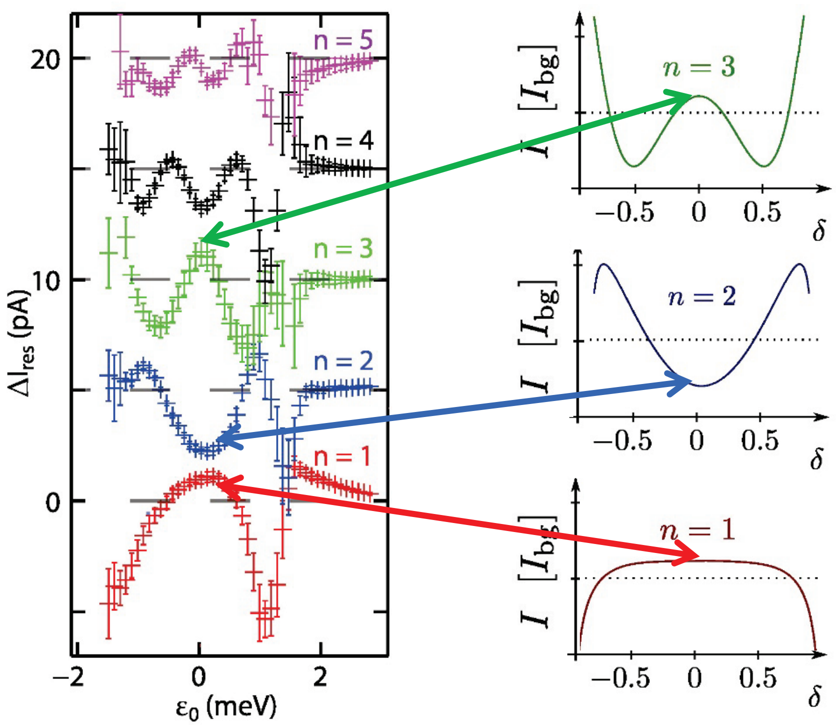
Experiment: Stehlik *et al.*, PRL (2014)



Theory: Danon and Rudner, PRL (2014)

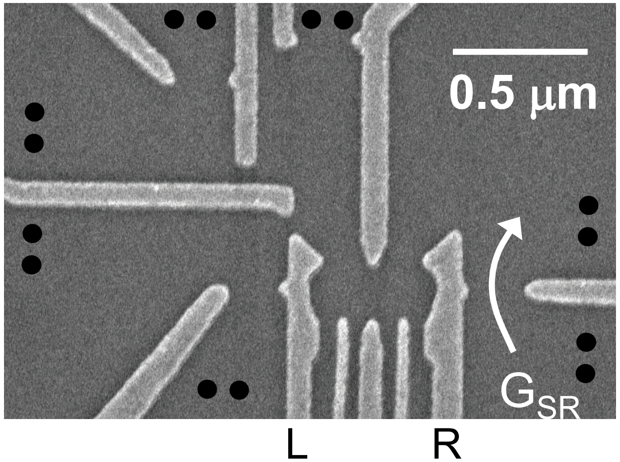


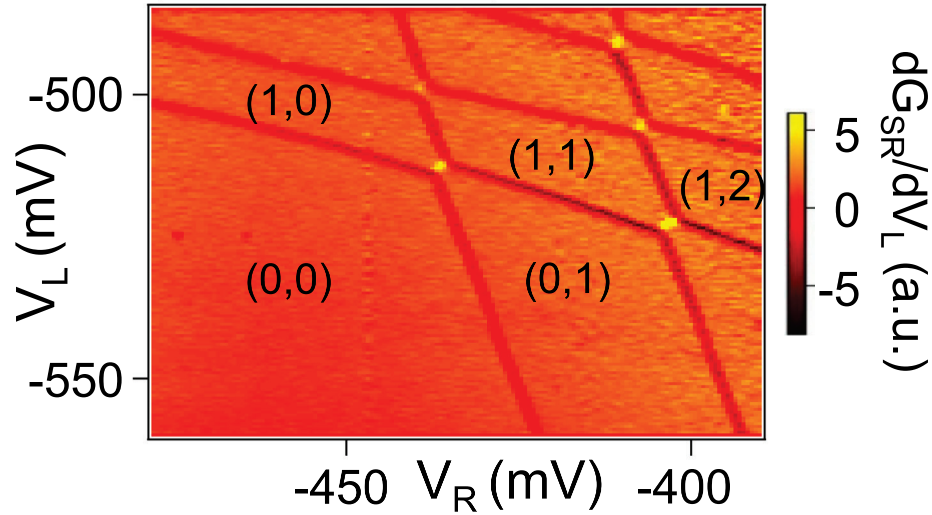
Detailed detuning dependence



Charge Detection/Spin Readout

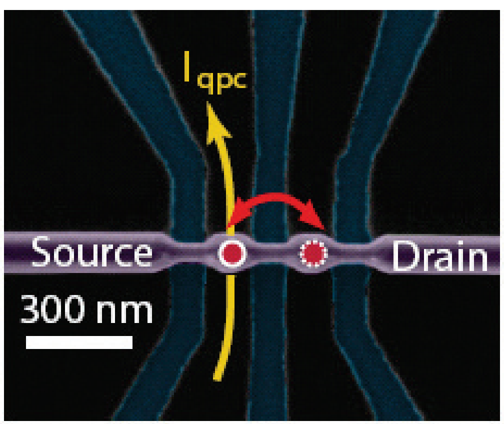
GaAs/AlGaAs 2DEG (easy)





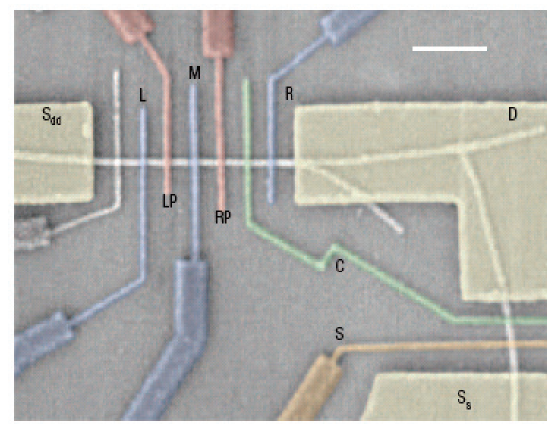
Nanowires (hard)

Self-alignment with QPC



Shorubalko *et al.*, Nano Lett. **8**, 382 (2008)

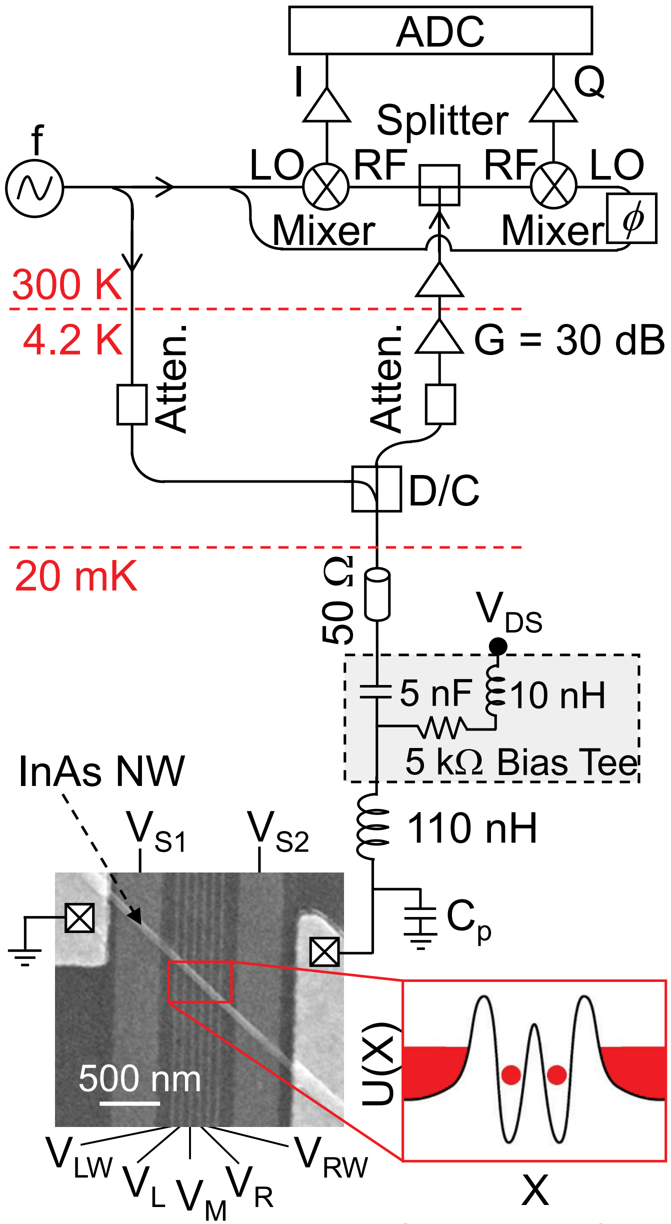
DQD + Single Dot Detector



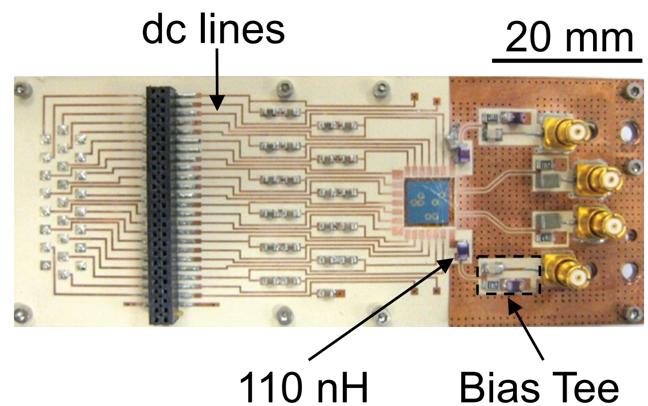
Hu *et al.*, Nature Nanotech. **2**, 622 (2007)

rf-Reflectometry

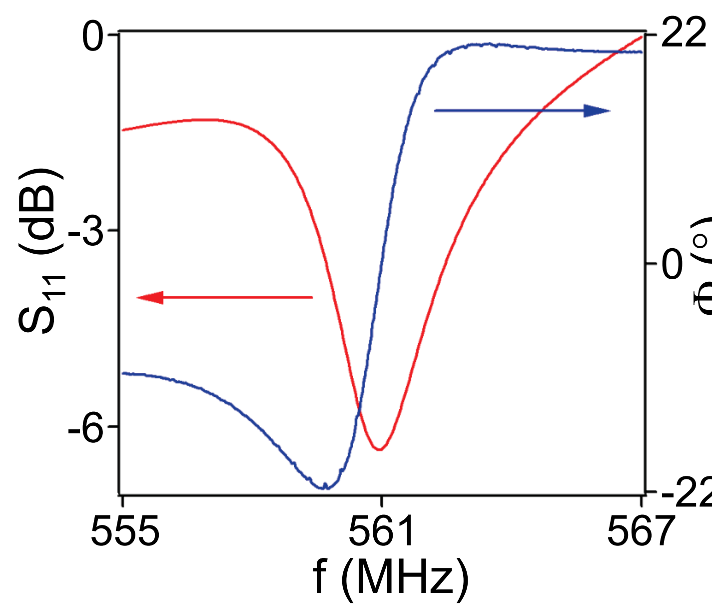
Lumped Element Resonator



Sample Holder

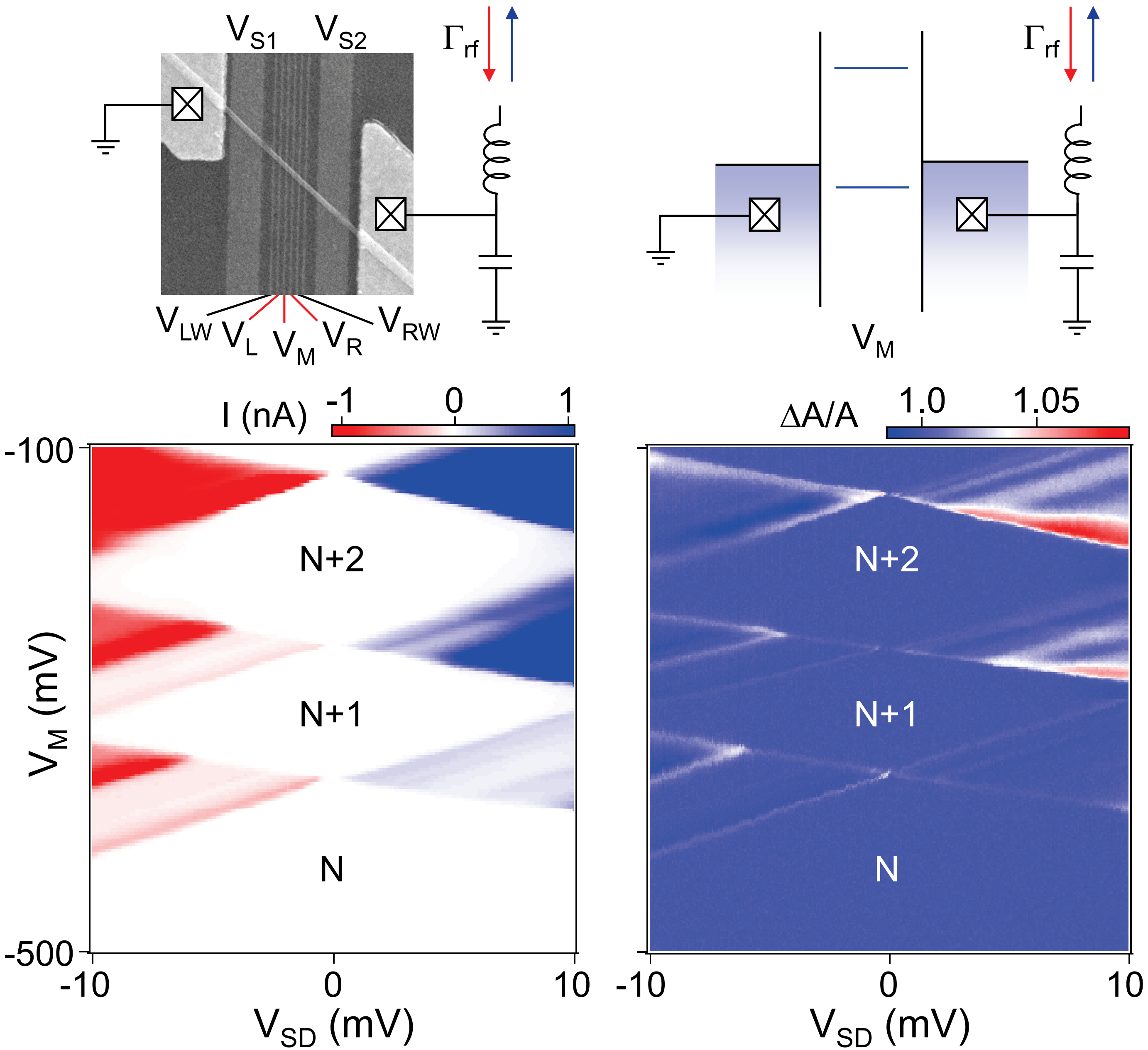


Microwave Response



Schoelkopf *et al.*, Science **280**, 1238 (1998)

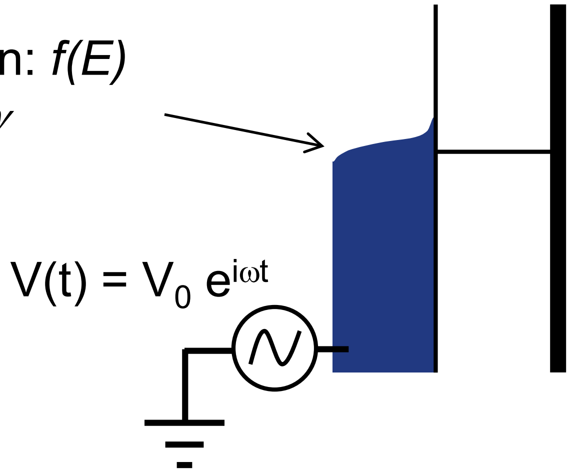
Charge Detection/Spin Readout



Jung, Schroer, Petersson, Petta, Appl. Phys. Lett. **100**, 253508 (2012)

Single Electron Box Model

Fermi function: *f(E)*
Tunnel rate: γ
Lever arm: α



Single level is either empty or occupied with one electron

Rate for tunneling off of the dot: $\gamma_{off} = \gamma(1 - f(E))$

Rate for tunneling onto the dot: $\gamma_{on} = \eta\gamma f(E)$

η = level degeneracy
(take η = 1 for simplicity)

Rate equations: $\dot{P}_0 = \gamma_{off} P_1 - \gamma_{on} P_0$

$$\dot{P}_1 = \gamma_{on} P_0 - \gamma_{off} P_1$$

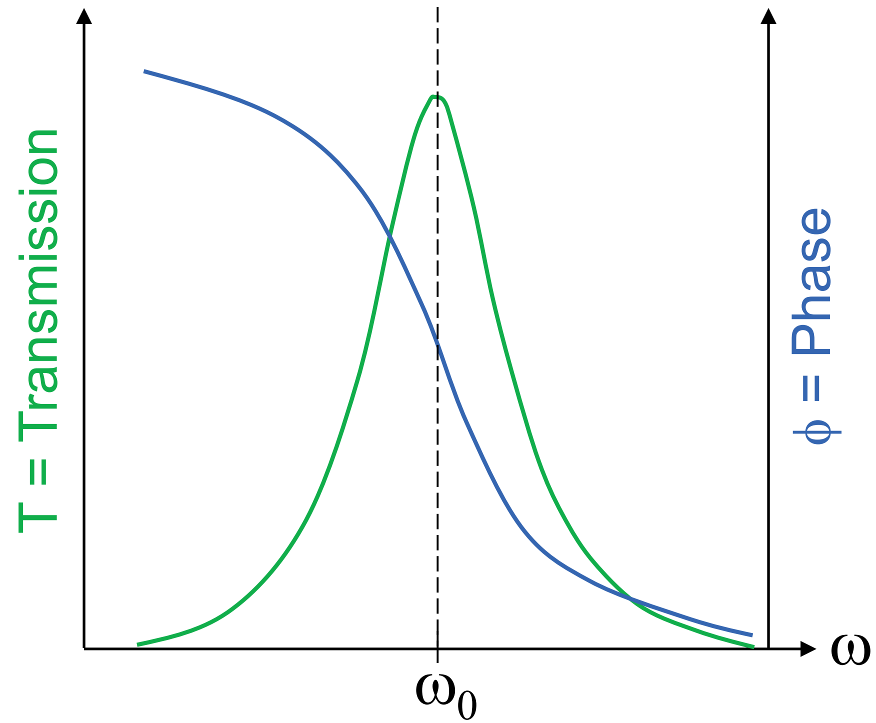
Current: $I_D(t) = \dfrac{dQ_D}{dt}$

Solve for the effective impedance:

$$R_{eff} = \frac{4k_B T}{e^2\alpha^2\gamma}\left(1 + \frac{\gamma^2}{\omega_0^2}\right) \qquad C_{eff} = \frac{e^2\alpha^2}{4k_B T}\frac{1}{1+\omega_0^2/\gamma^2}$$

Persson *et al.*, Nano Lett. **10**, 963 (2010)

Single Electron Box Model



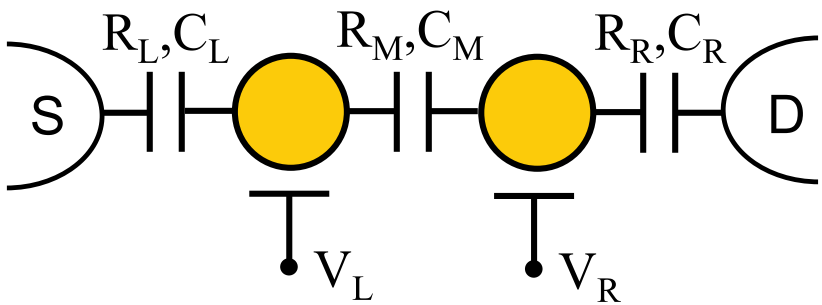
R_{eff} damps the resonator

- Strong amplitude response
- Phase response is first-order insensitive

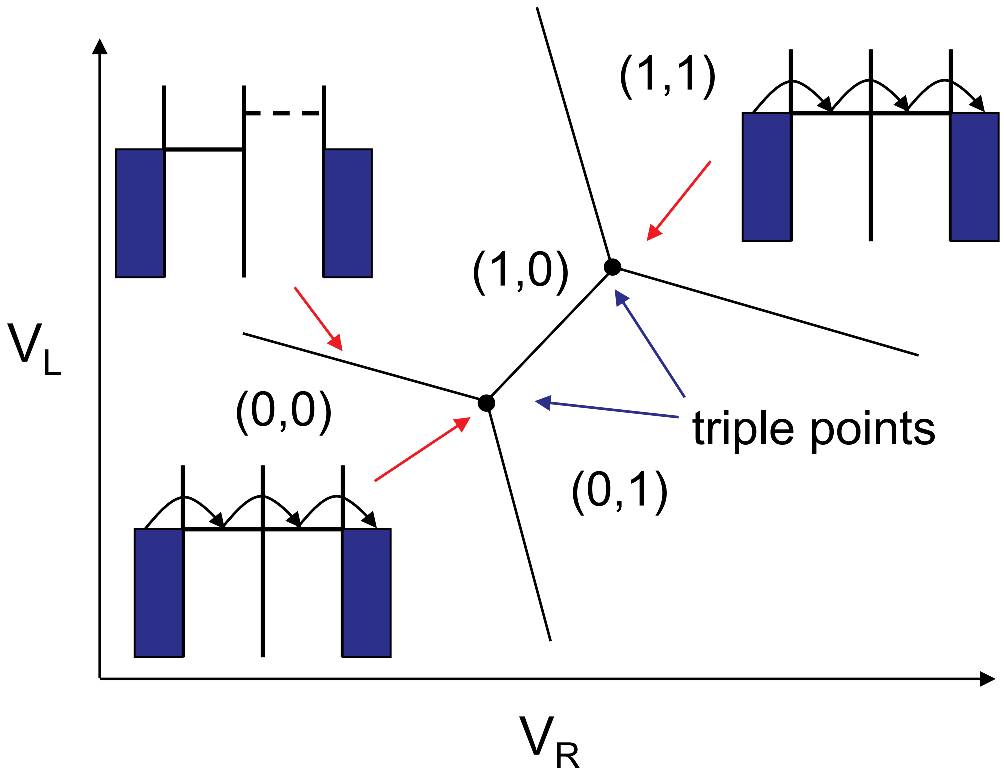
C_{eff} shifts the resonance frequency $\omega_0 = 1/\sqrt{LC}$

- Strong phase response
- Amplitude response is first-order insensitive

Double Dot Charge Transitions

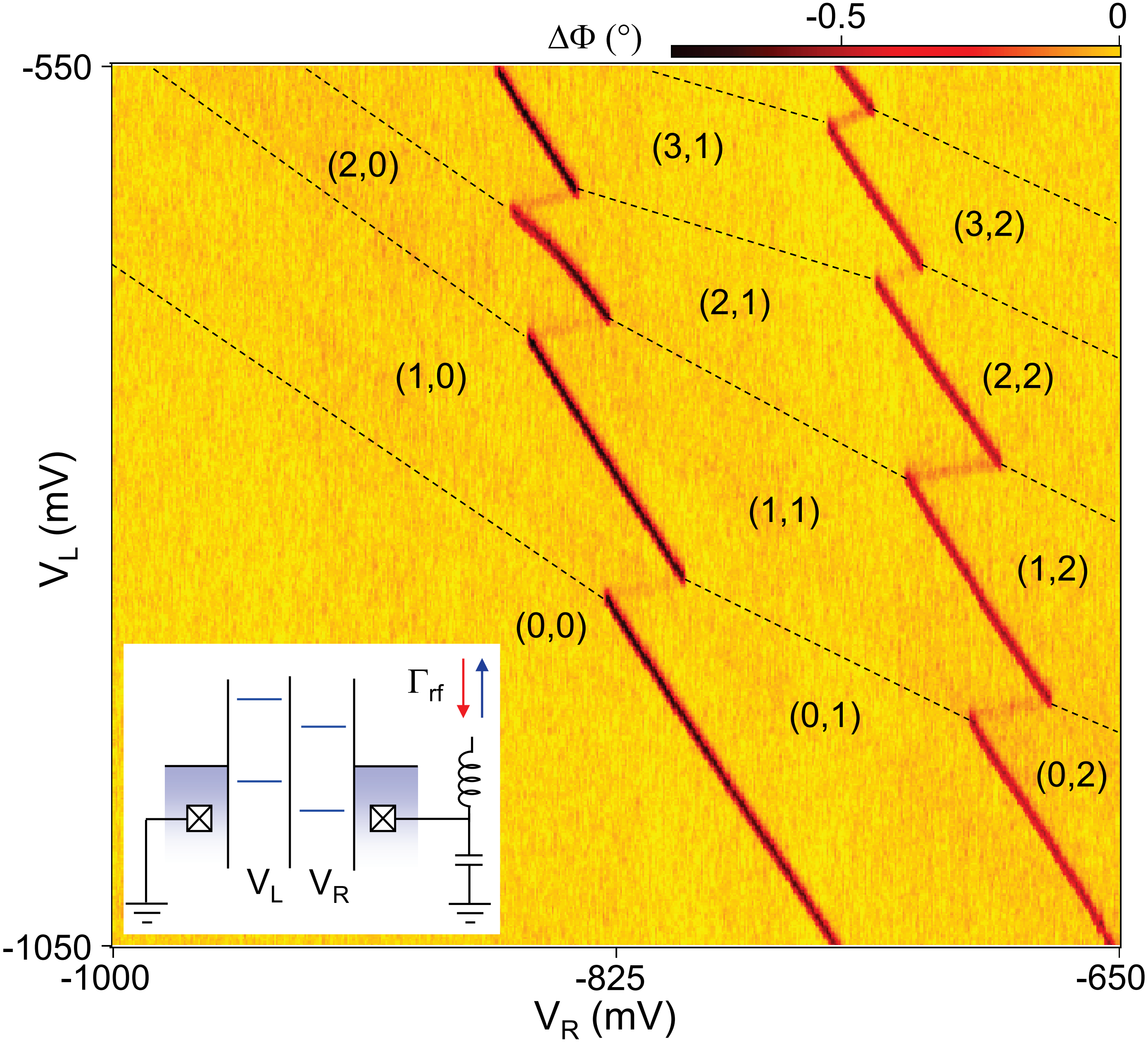


charging energy $E_c = e^2/2C$



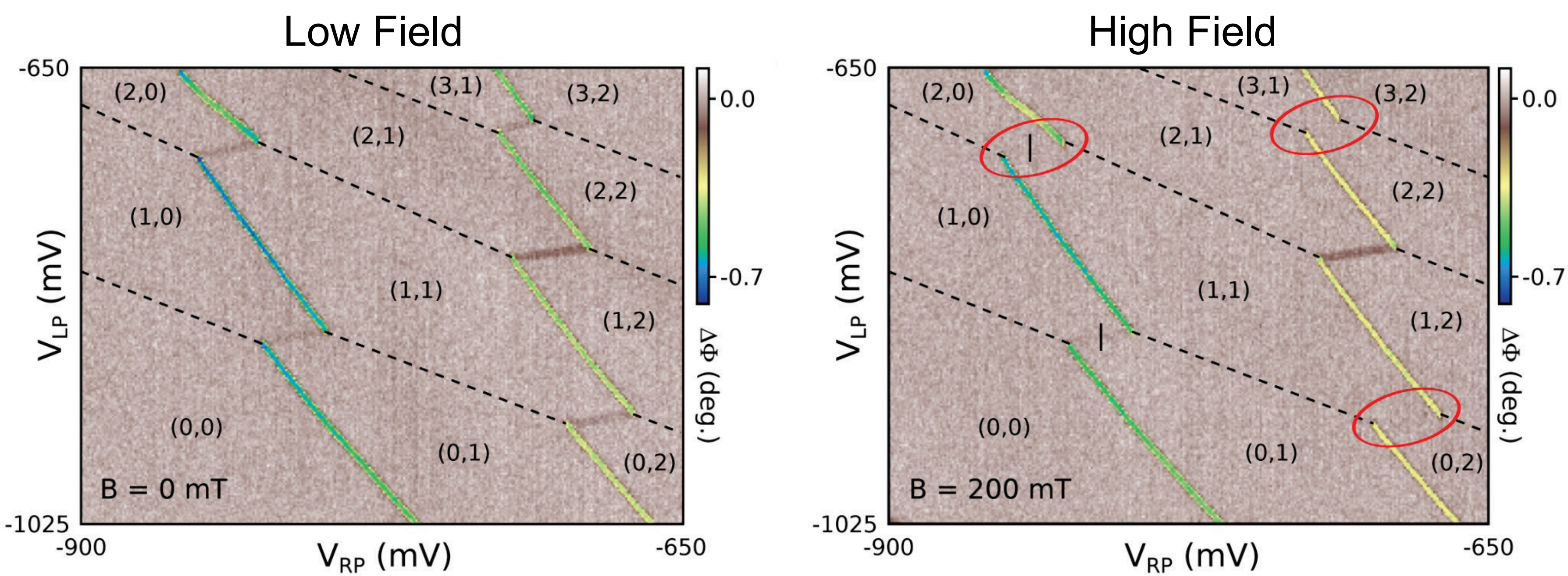
Double dot review article: van der Wiel *et al.,* RMP **75**, 1 (2003)

Double Dot Charge Sensing



Jung, Schroer, Petersson, Petta, Appl. Phys. Lett. **100**, 253508 (2012)

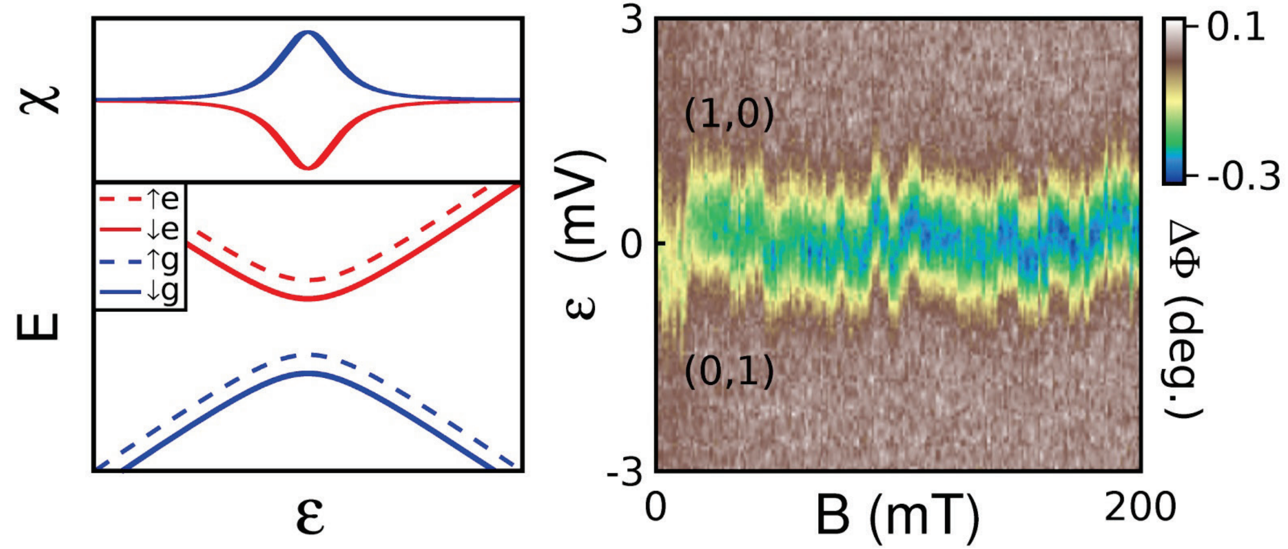
Charge Parity Meter: Magnetic Field Dependence



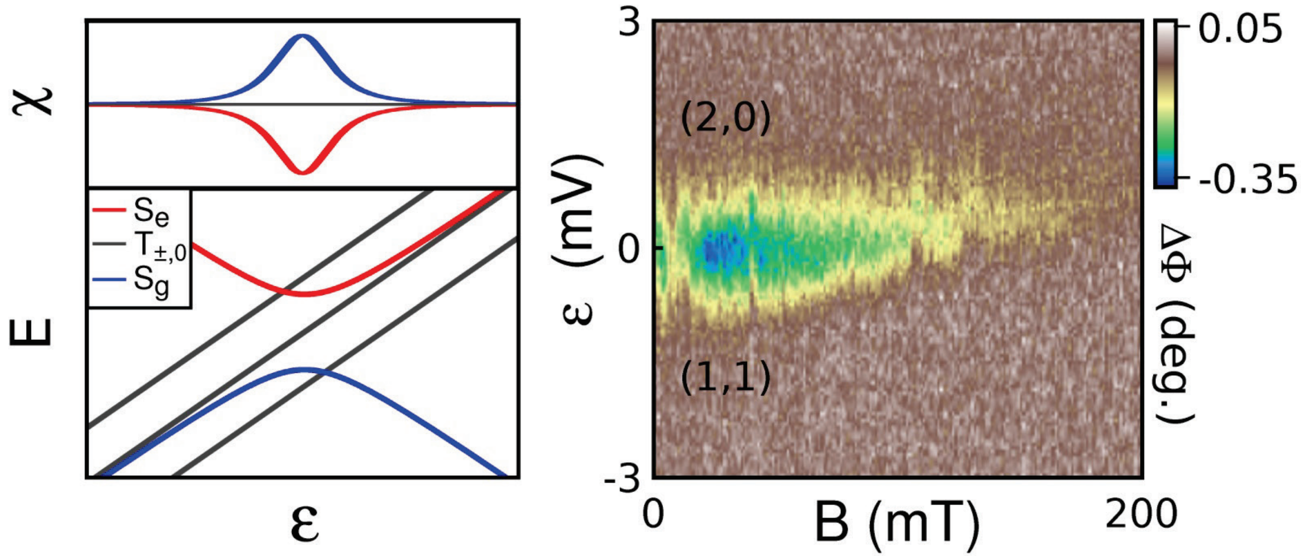
Schroer, Petersson, Jung, Petta, Phys. Rev Lett. **109**, 166804 (2012)

Spin-Dependent Quantum Capacitance

Odd Parity

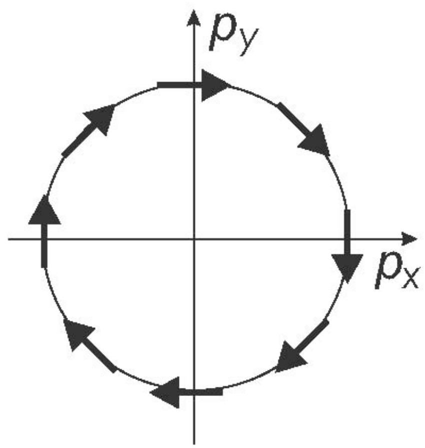


Even Parity

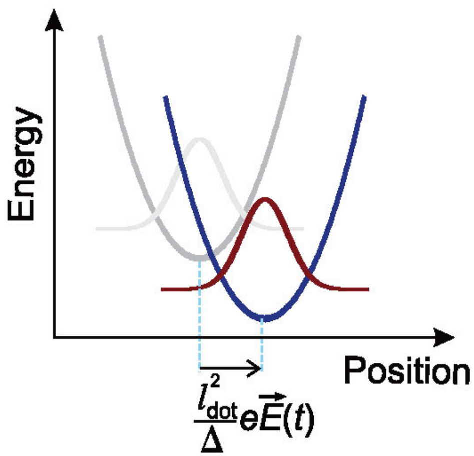


Summary

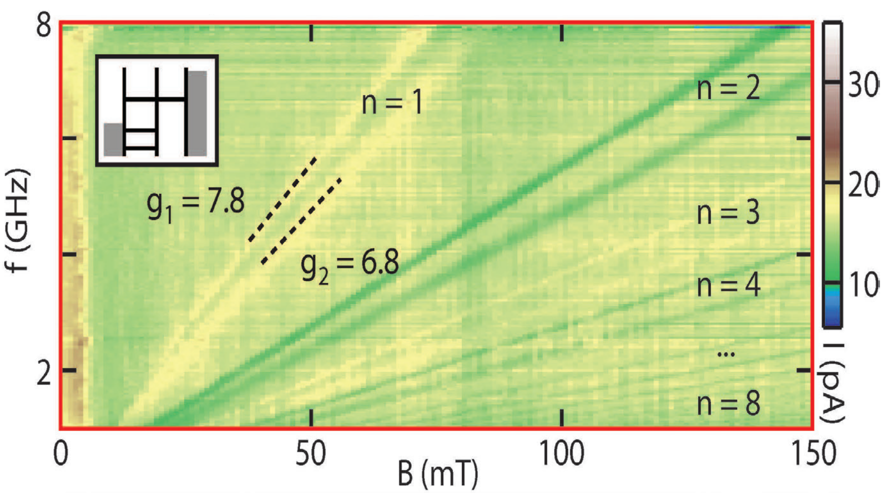
Spin-Orbit Interaction



Electric-Dipole Spin Resonance



Extreme Harmonic Generation



Dispersive Readout