The Abdus Salam
International Centre
for Theoretical Physics

2451-2

Workshop on Interferometry and Interactions in Non-equilibrium Meso- and Nano-systems

8 - 12 April 2013

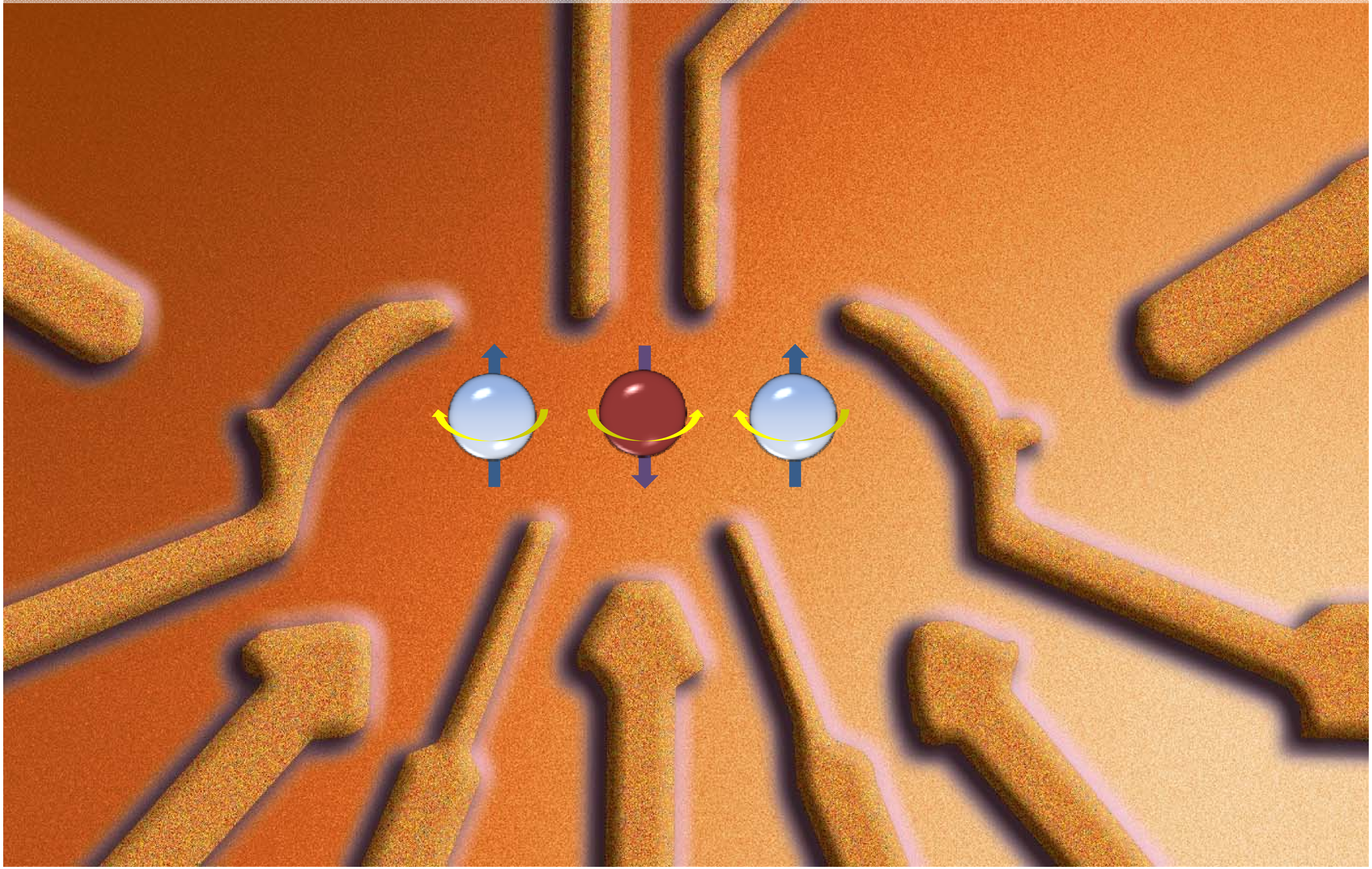
Quantum Interference Phenomena in Triple Quantum Dot Circuits

Andy SACHRAJDA

University of Waterloo, National Research Council
1200 Montral Road, Ottawa, KIA 0R6
Ontario
CANADA

Quantum Interference Phenomena in Triple Quantum Dot Circuits

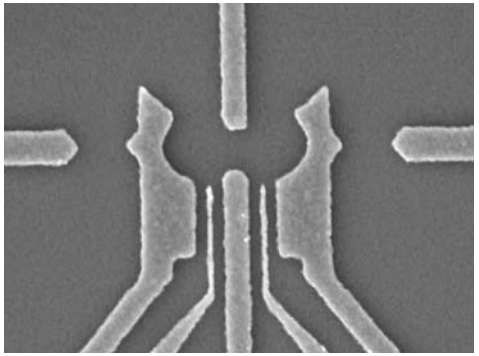
Andy Sachrajda, NRC Canada

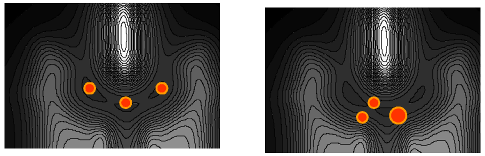


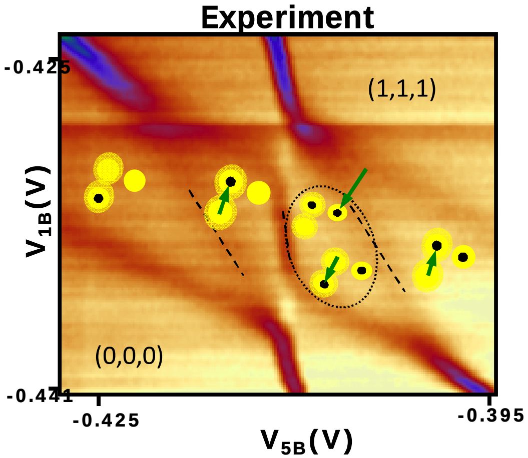
Transport Through an ‘incidental’ Ring of Quantum Dots

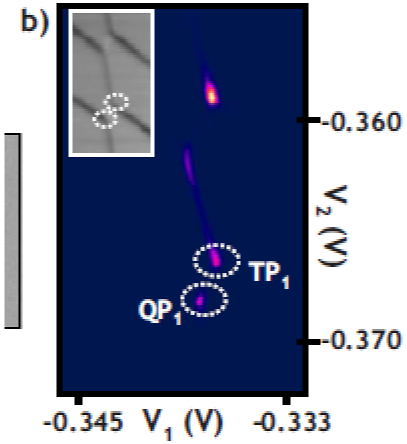
L. Gaudreau *et al*. Phys. Rev. Lett. 97, 036807 (2006) and PRB 80 075415 (2009)

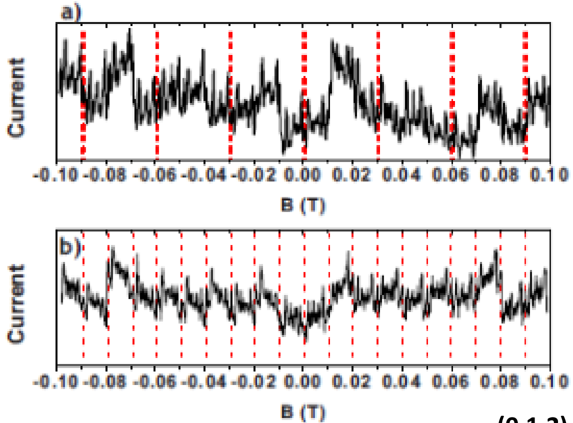
D.Schroer et al. PRB 76 075306 (2007)



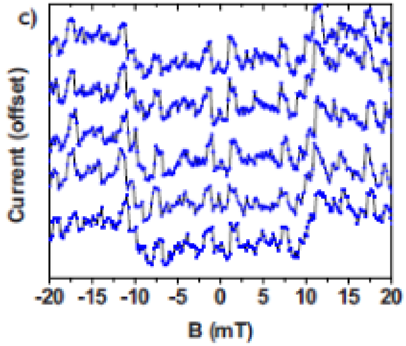


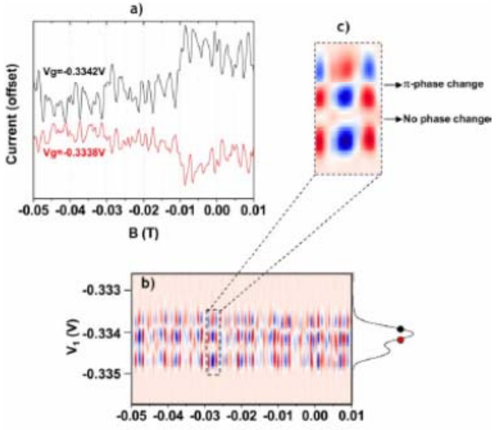


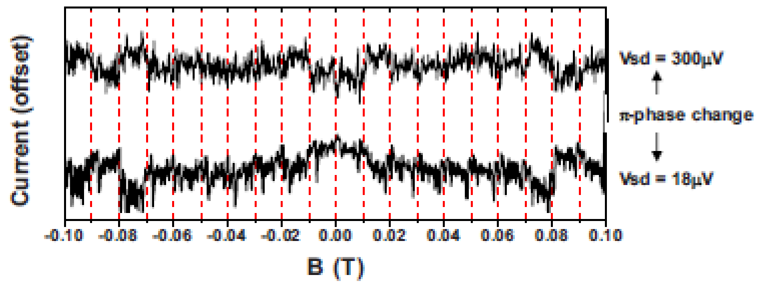




(0,1,2) (1,1,2), (0,2,2) (0,1,3)







Outline

(1) Quantum Backaction due to Absorption of Phonons via Quantum Interference – Single Phonon Detector (collaboration with groups of Stefan Ludwig and Aash Clerk)

(2) Transferring electrons between distant qubits (collaboration with group of Gloria Platero)

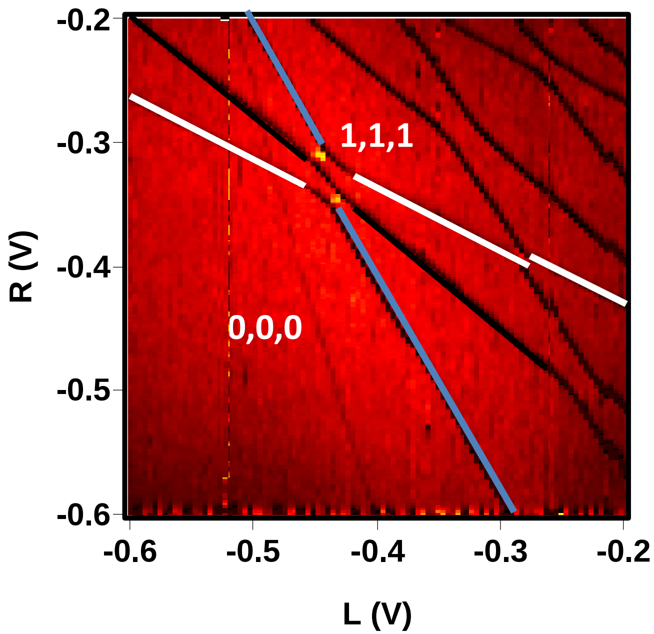
Quantum Superpositions overcoming Spin Blockade

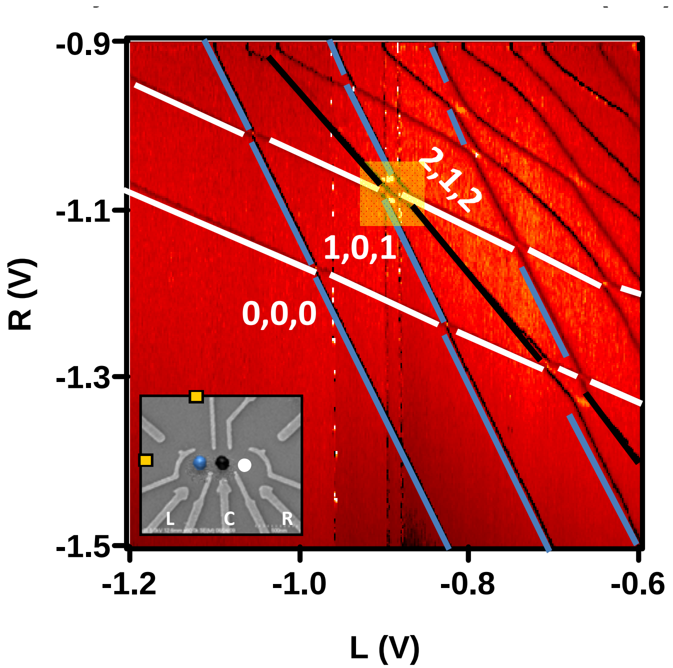
(3) Interplay between 3 spin Qubits

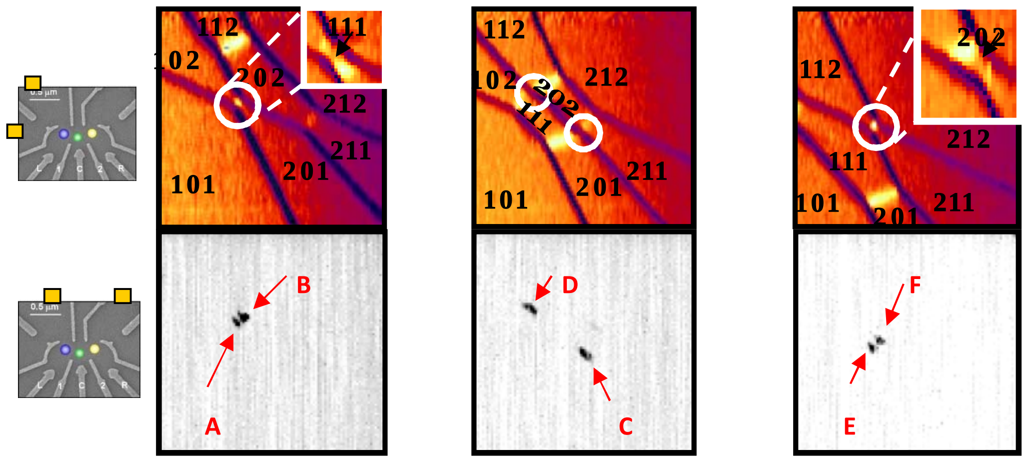
(LZS and all exchange)

Stability Diagram / Transport Regimes

L. Gaudreau et al. APL 99 193101 (2009)





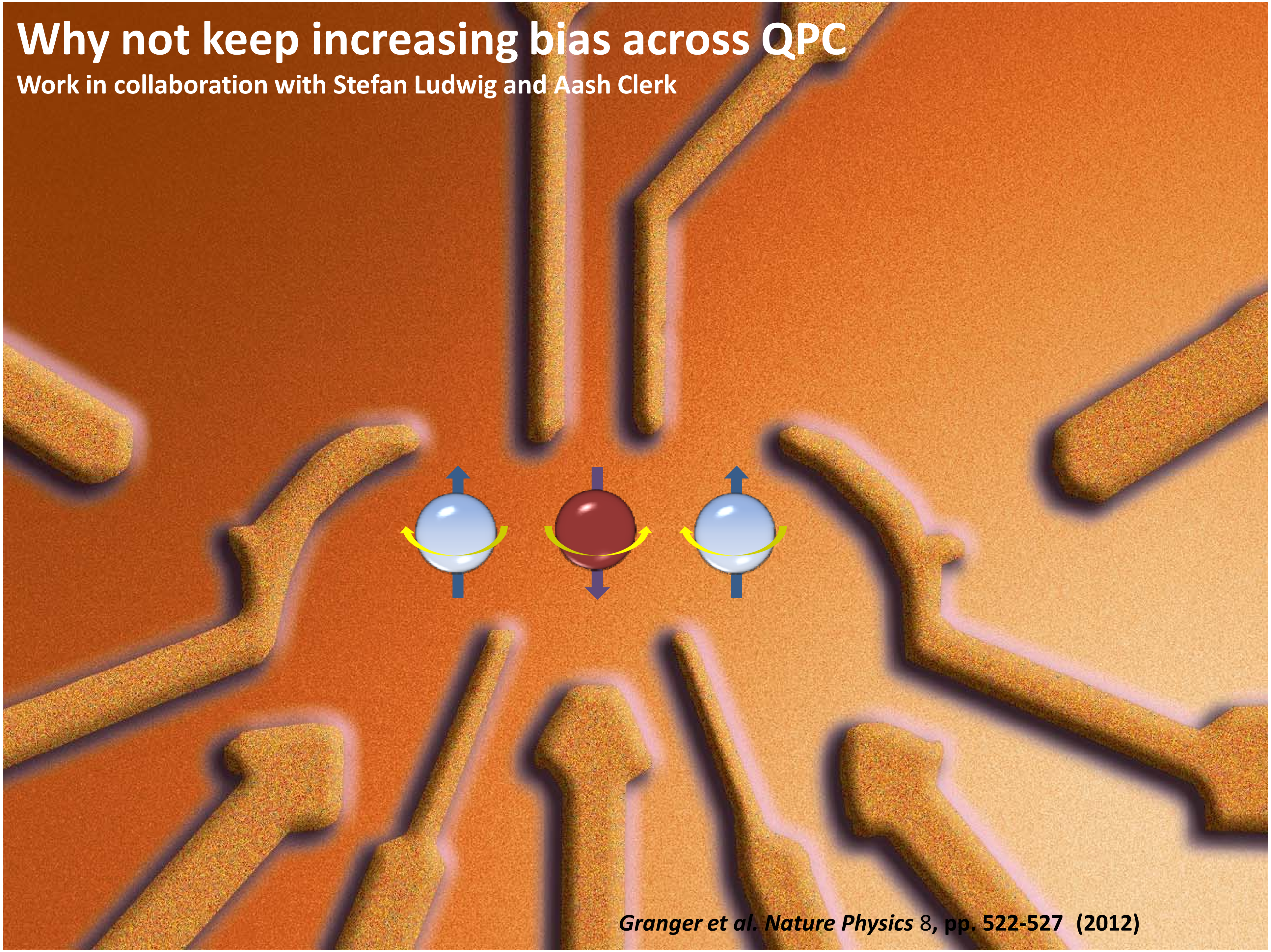


G.Granger *et al.*, PRB 82, 075304 (2010).

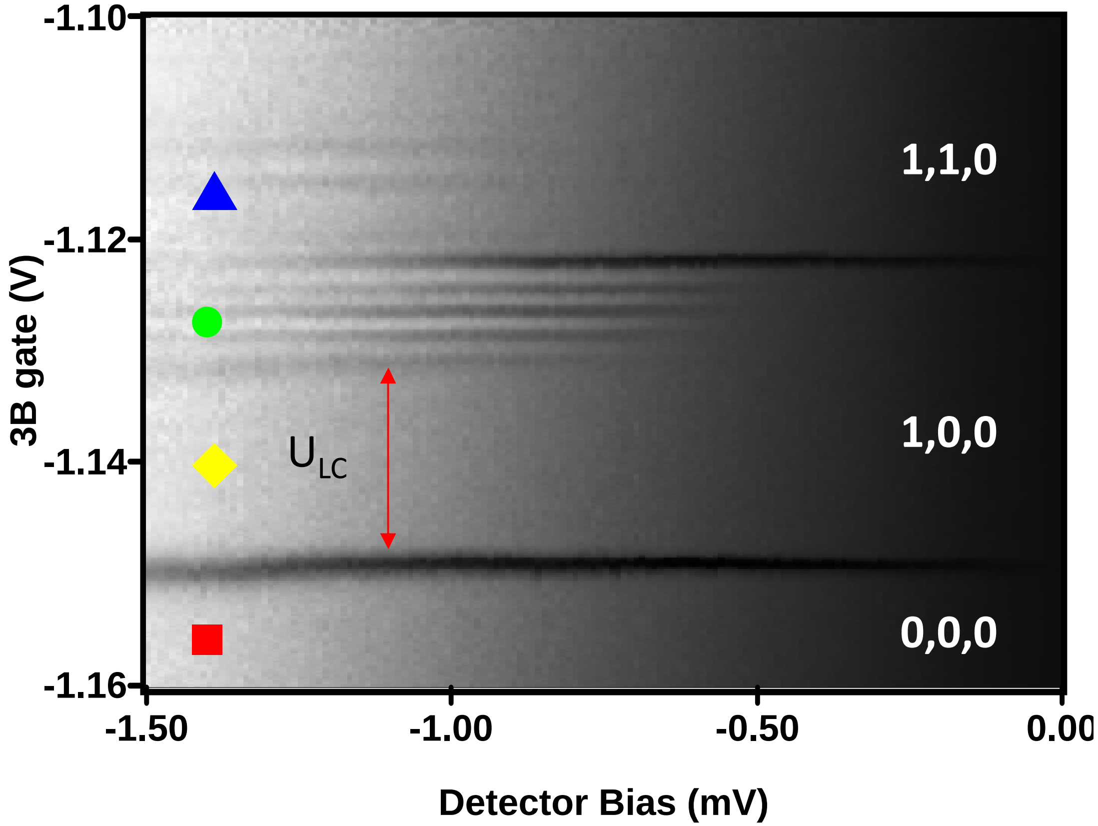
Predicted by M. Rogge, R. Haug. New Journal of Physics, **11** 113037 (2009)

Why not keep increasing bias across QPC

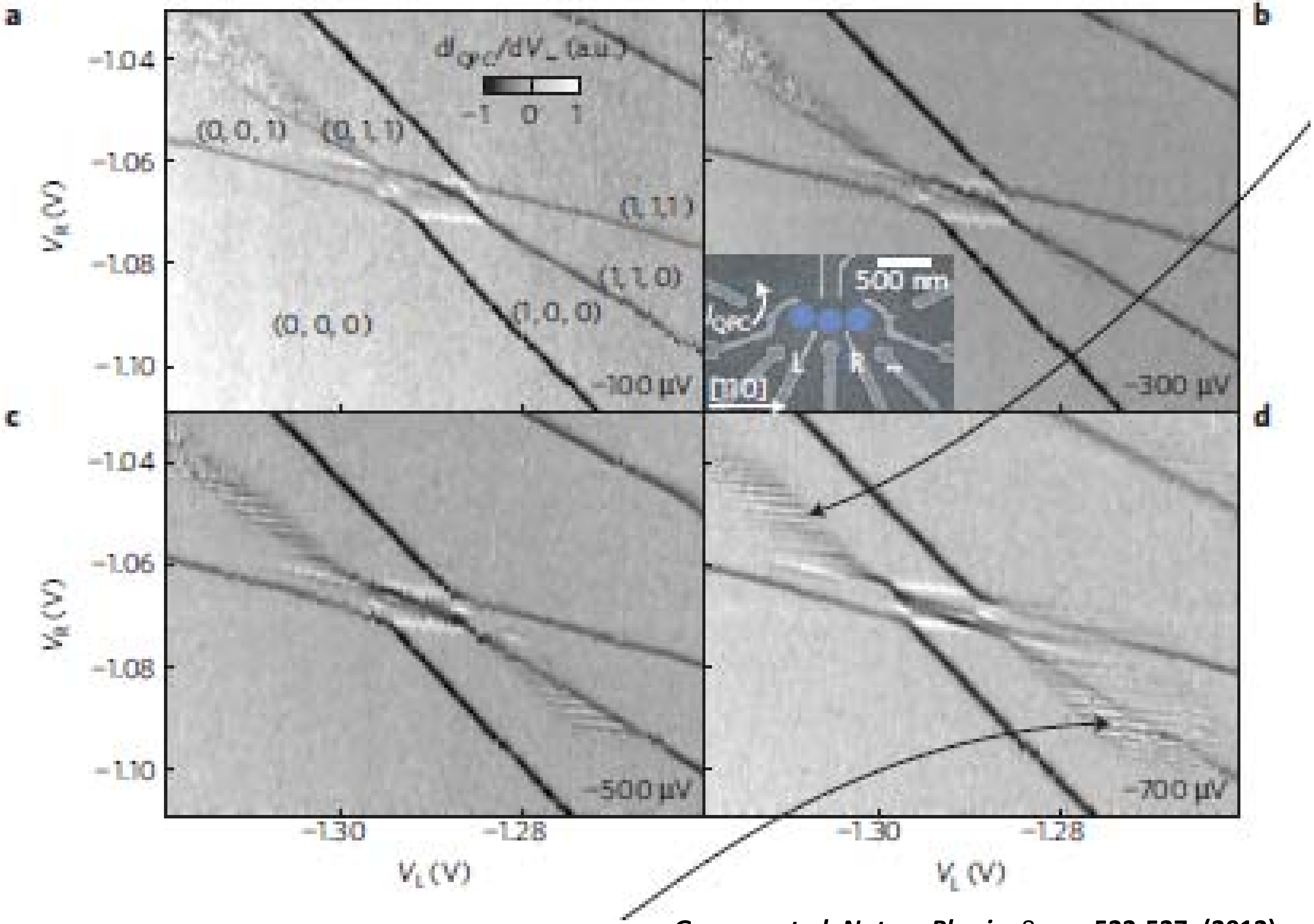
Work in collaboration with Stefan Ludwig and Aash Clerk



***Granger et al. Nature Physics* 8, pp. 522-527 (2012)**



-1.10
-1.12
-1.14
-1.16
3B gate (V)
1,1,0
1,0,0
0,0,0
U_{LC}
-1.50
-1.00
-0.50
0.00
Detector Bias (mV)

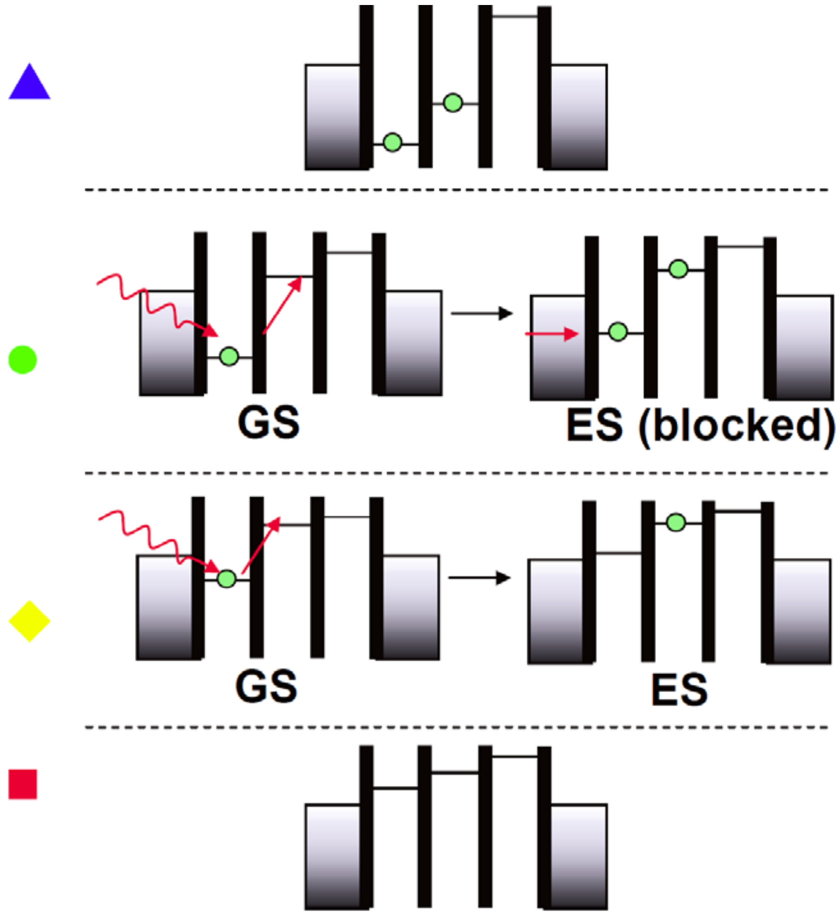


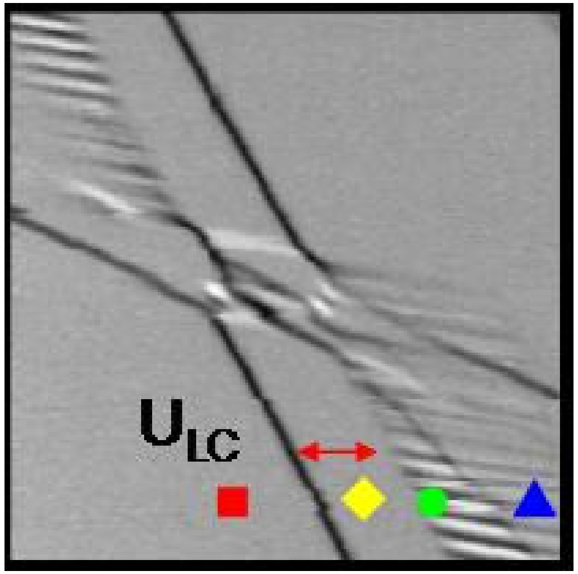
Granger et al. Nature Physics **8, pp. 522-527 (2012)**

Harbusch, D et al. Phys. Rev. Lett. 104, 196801 (2010).

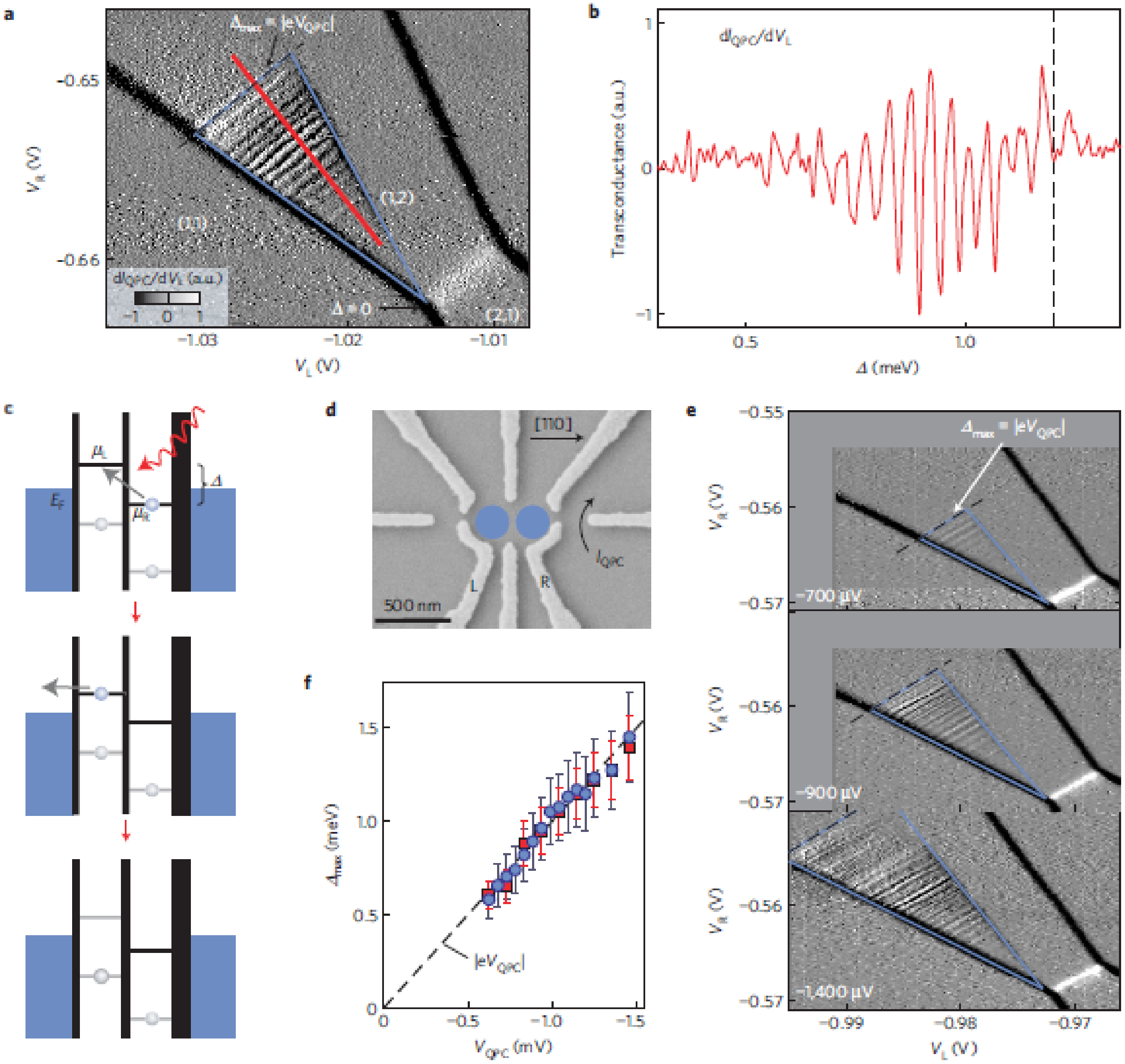
Taubert, D. et al. Phys. Rev. Lett. 100, 176805 (2008).

Young, C. E. & Clerk, A. A. Phys. Rev. Lett. 104, 186803 (2010).





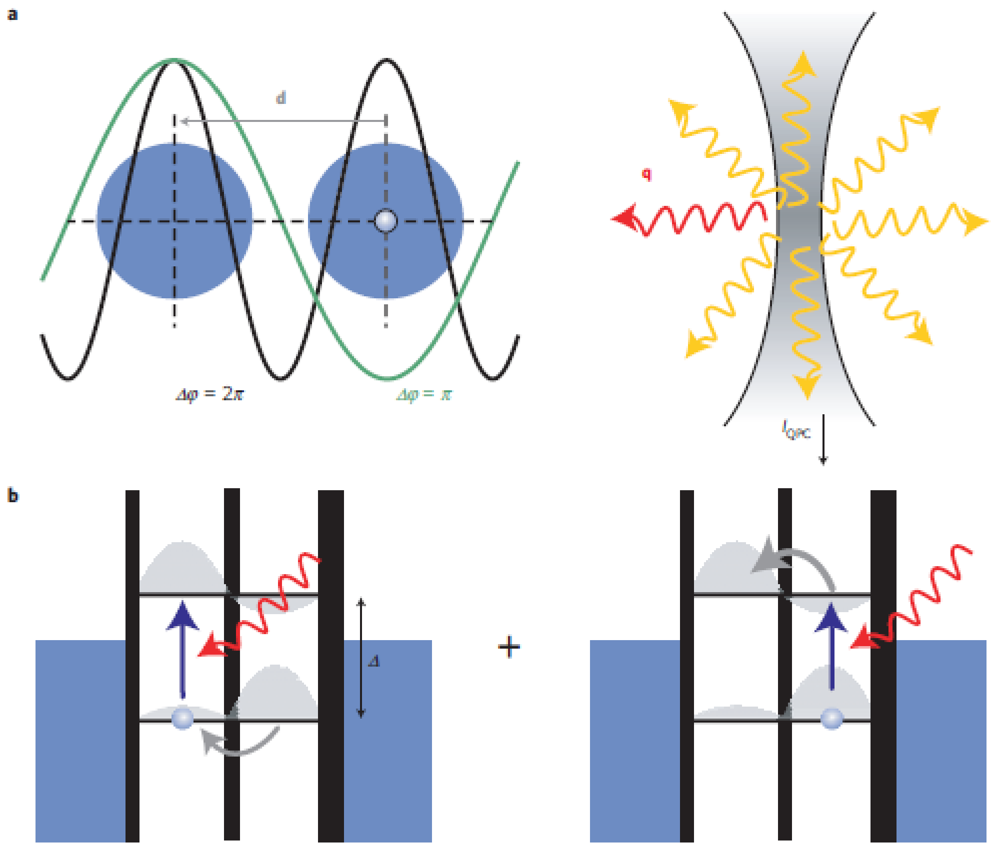
Granger et al. Nature Physics **8, pp. 522-527 (2012)**



***Granger et al. Nature Physics* 8, pp. 522-527 (2012)**

Why Periodic Pattern?
Why Stronger than emission equivalent?

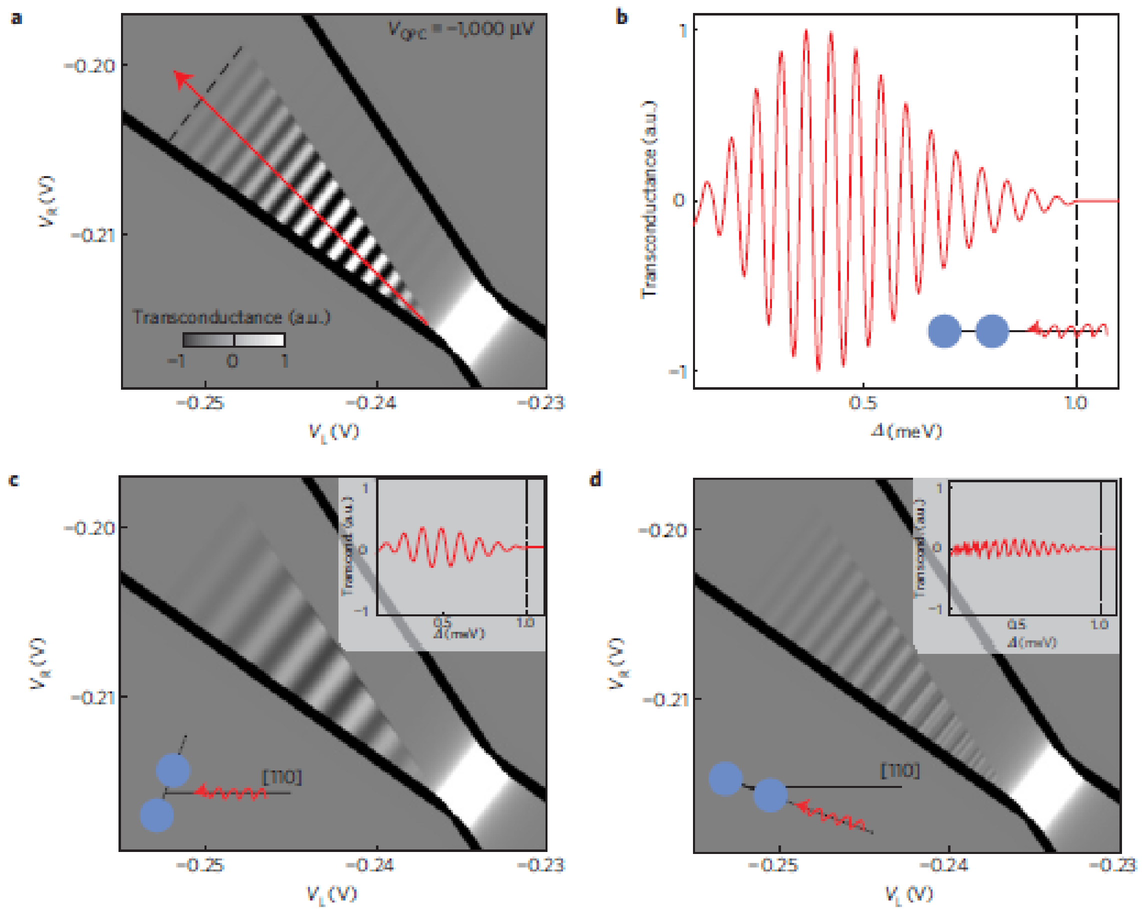
Equivalent Emission Mechanism
Fujisawa, T. et al. Science 282, 932935 (1998).
Roulleau, P. et al. Nature Commun. 2, 239 (2011)



$$\Delta = \hbar |q| v_{ph}$$

$$\Delta\varphi = d.q$$ $$\Delta\varphi = (2n+1)\pi$$ Constructive Interference

Granger et al. Nature Physics 8, **pp. 522-527 (2012)**



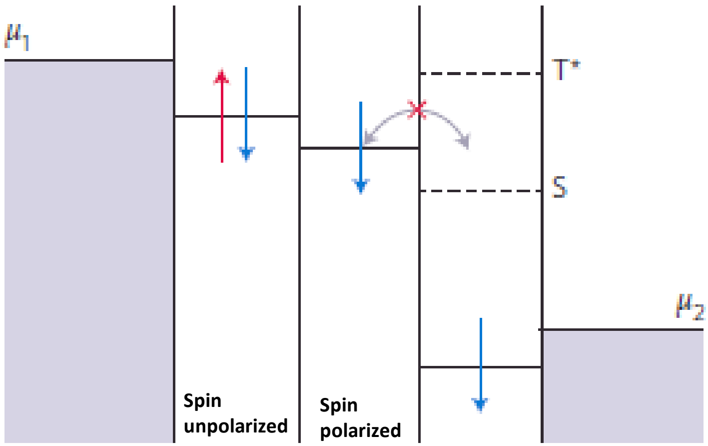
$$\hat{H}_{\text{int}} = \frac{t_c}{\Delta} \sum_{\mathbf{q},\mu} \lambda_{\mathbf{q},\mu} \left(e^{i\mathbf{q}\cdot\mathbf{r}_L} - e^{i\mathbf{q}\cdot\mathbf{r}_R}\right) \left(\hat{a}_{\mu,\mathbf{q}} + \hat{a}^{\dagger}_{\mu,-\mathbf{q}}\right) \Big(|g\rangle\langle e| + \text{h.c.} \Big)$$

Granger et al. Nature Physics **8, pp. 522-527 (2012)**

Bipolar spin blockade in the serial triple quantum dot

e.g. (1,1,1) to (2,1,1) to (2,0,2) to (1,1,2) to (1,1,1)

c



two spin blockade rectifiers placed back to back, forming a spinsulator

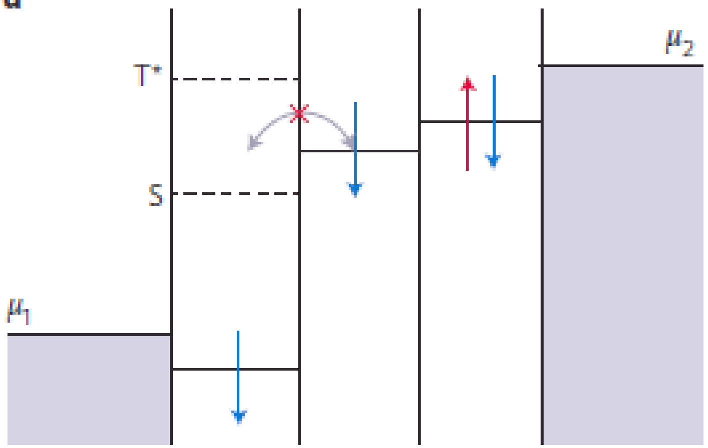
B=0

Due to the nuclear Overhauser fields that spins in neighboring dots experience, the singlet and triplet states of these spins are mixed, and spin blockade is lifted.

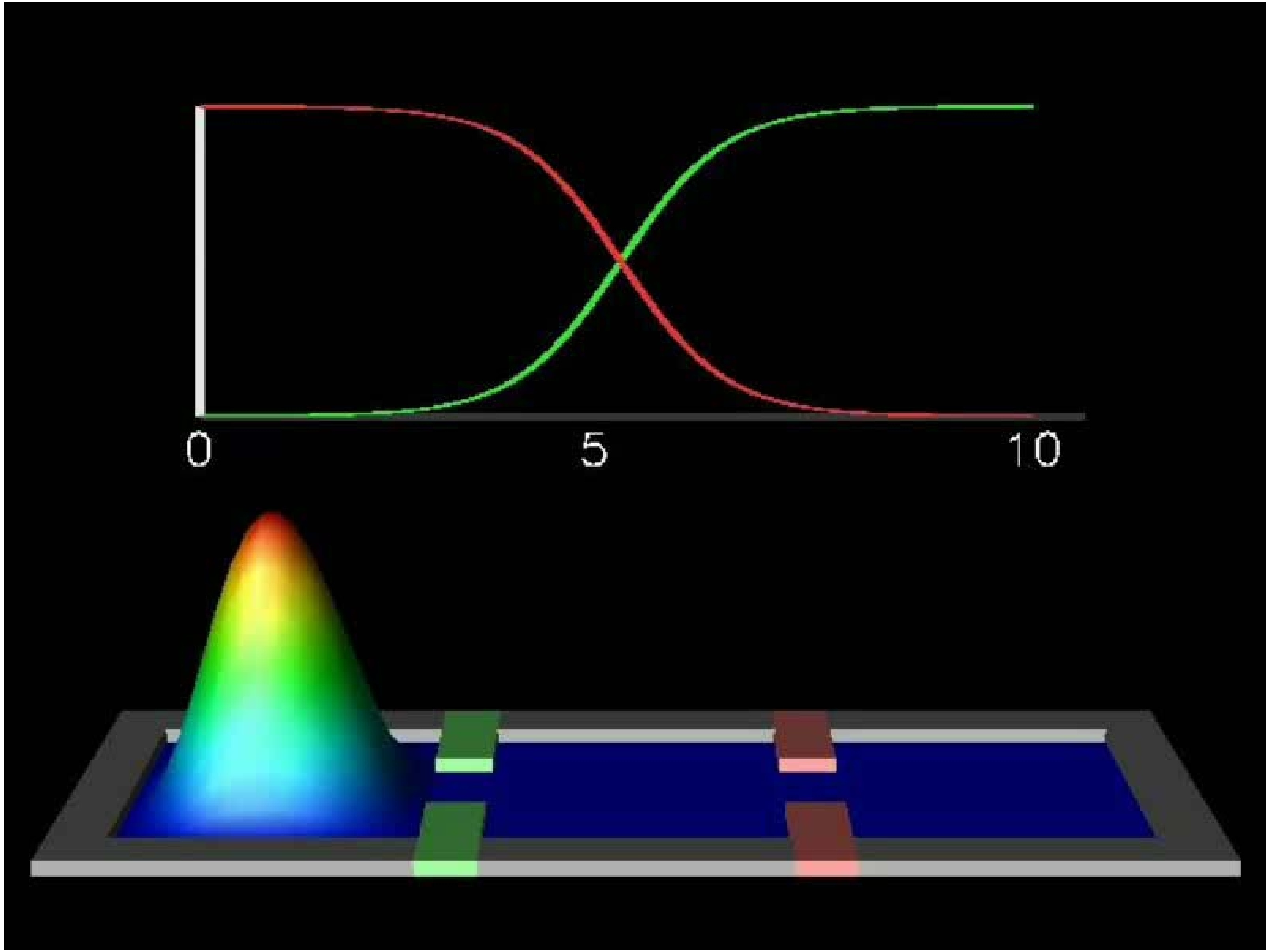
B>10mT

For an external magnetic field larger than the Overhauser field, triplet states with parallel spins provide unmixed spin blockade channels and the leakage current is suppressed.

d

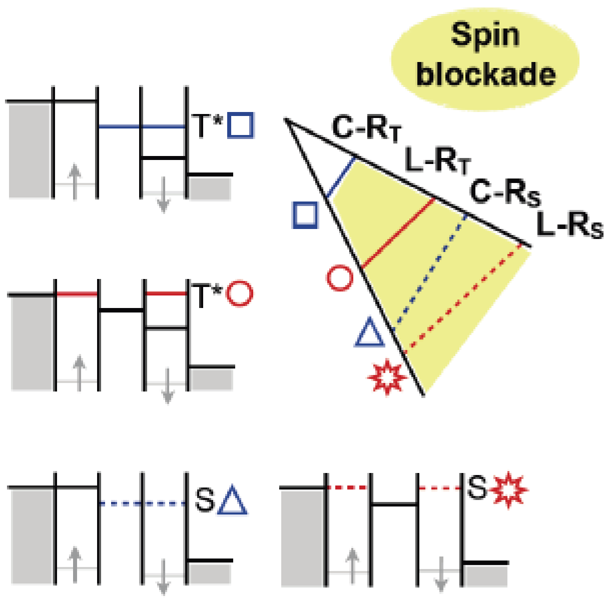


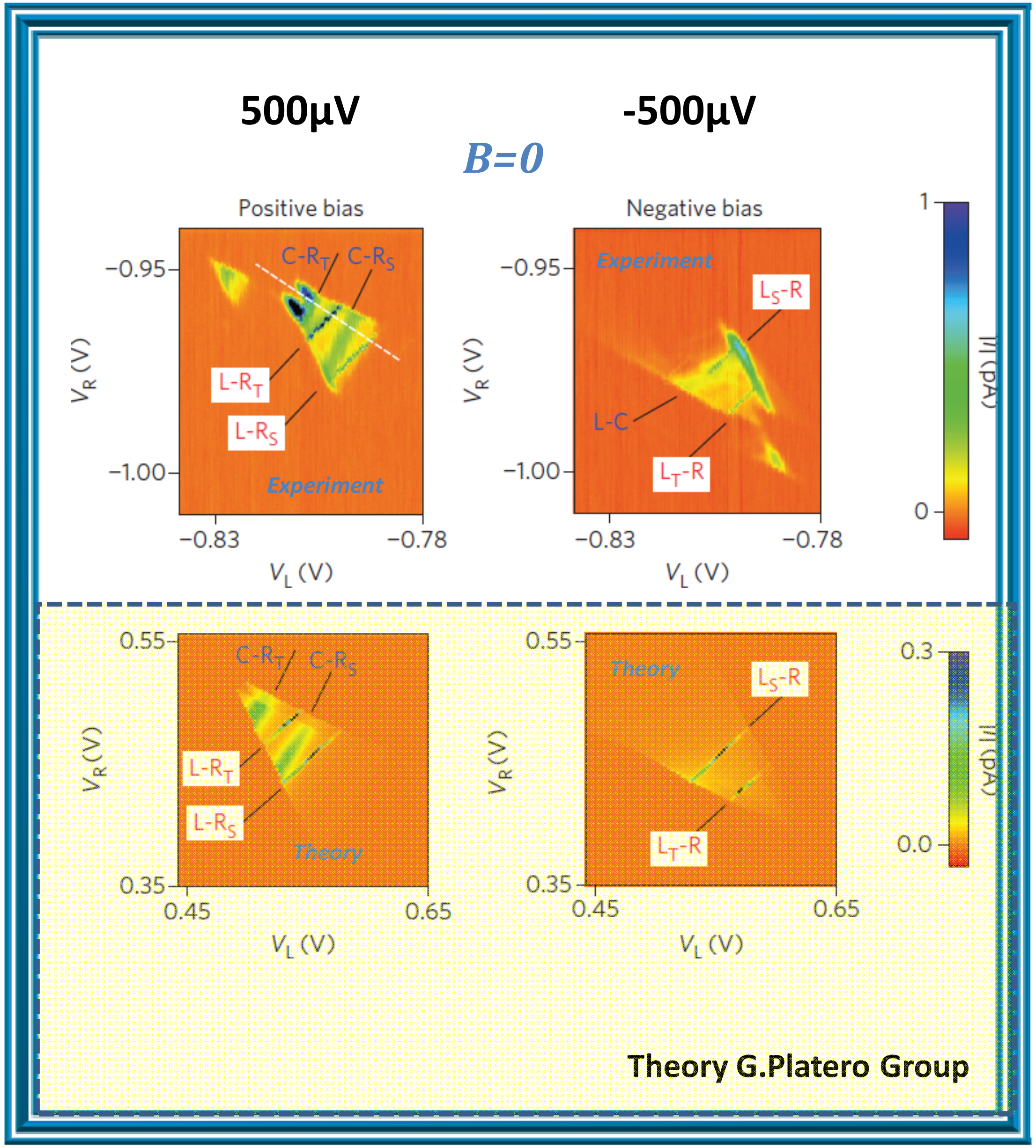
A.D. Greentree, J.H. Cole, A.R. Hamilton, and L.C.L. Hollenberg, Phys. Rev. B 70, 235317 (2004).



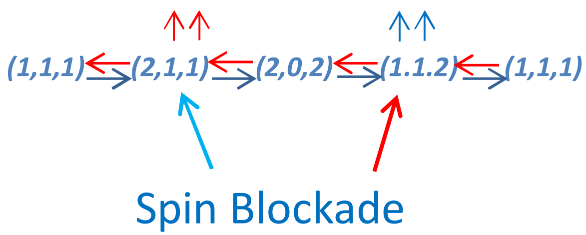
$$A|1\rangle + 0|2\rangle + C|3\rangle$$

Bipolar Spin Blockade (Spinsulator) and Leakage Paths at B=0





Sequential Transport Sequence



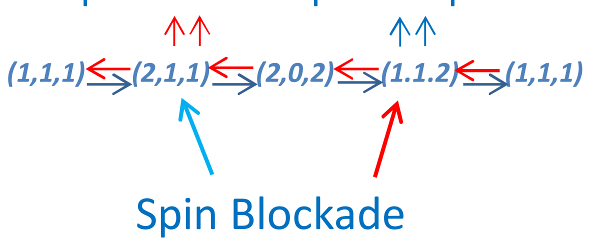
M.Busl et al Nature Nanotechnology (2013)

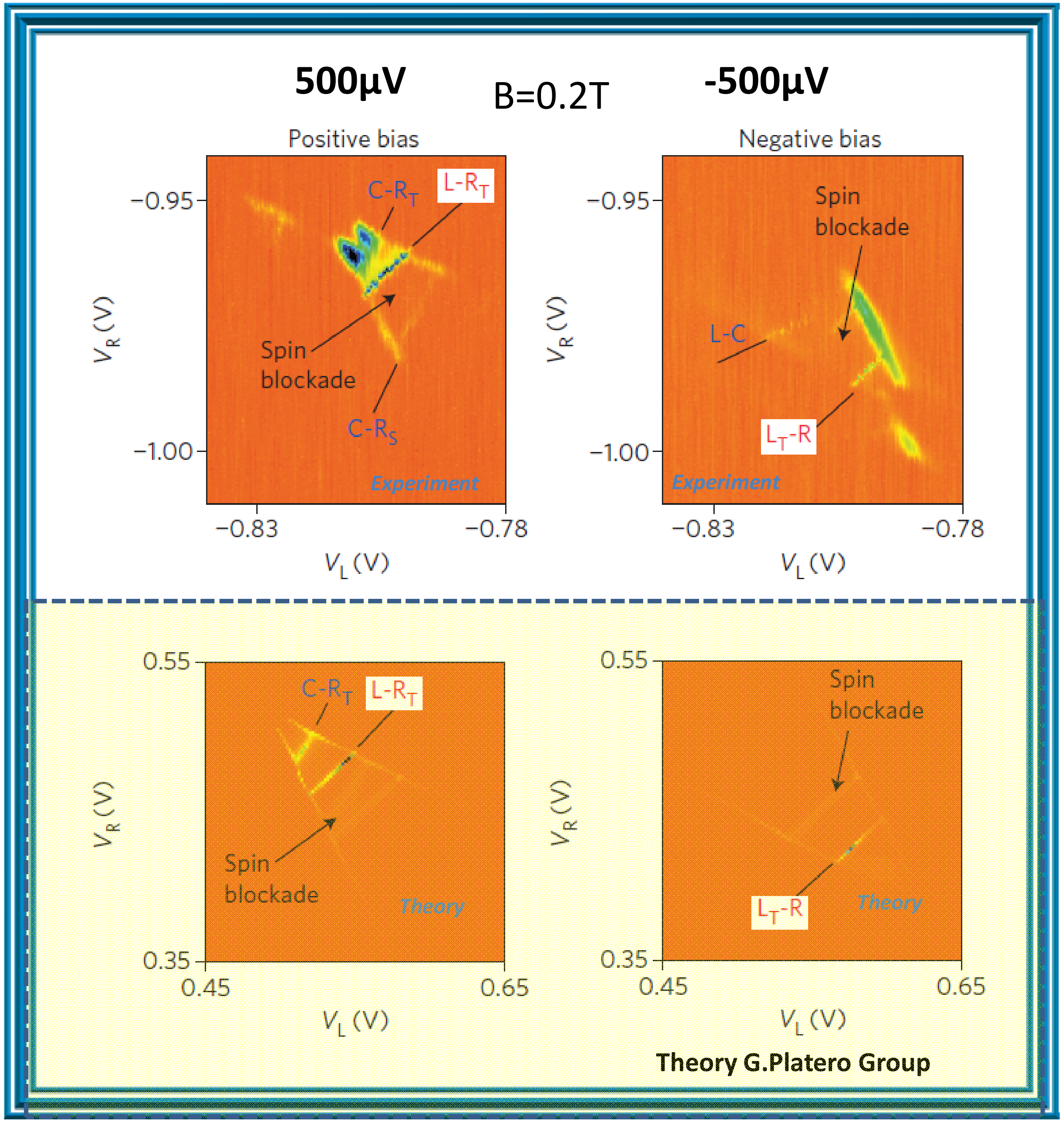
Bipolar Spin Blockade (Spinsulator) and Leakage Paths at B=0.2T

Quadruple Point

(1,1,1), (2,1,1), (2,0,2) (1,1,2)

Sequential Transport Sequence



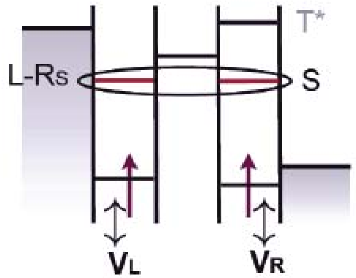


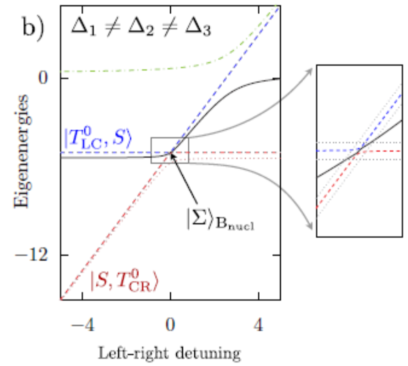
M.Busl et al Nature Nanotechnology (2013)

L-Rs resonance

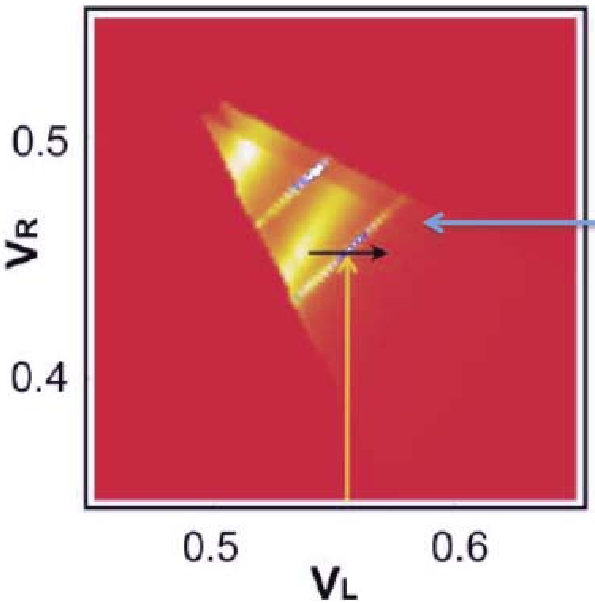
Off-resonance

$$(2,1,1) \rightarrow (2,0,2) \rightarrow (1,1,2)$$



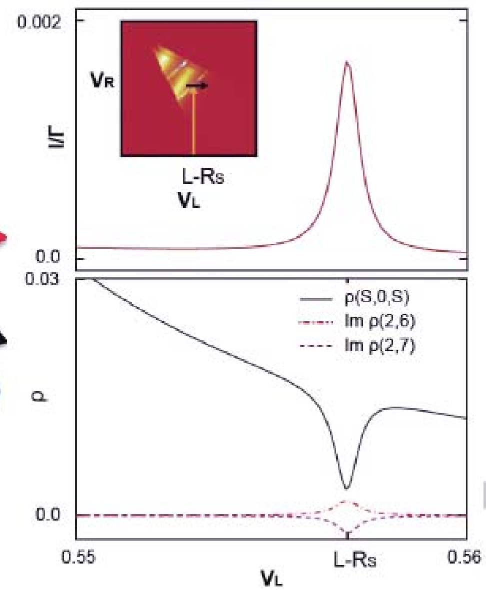


B = 0 T

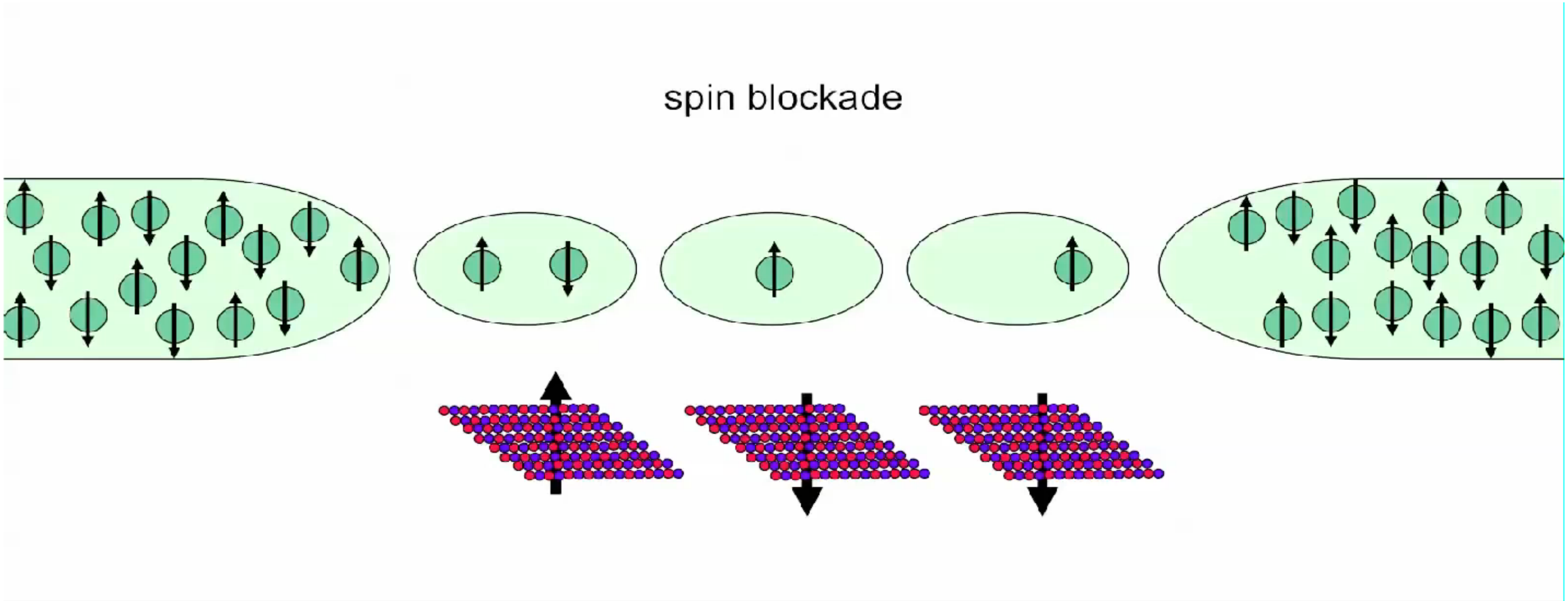


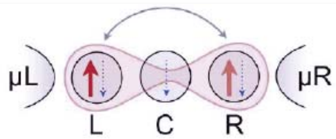
High current peak without participation of The intermediate state

$$|\uparrow\downarrow, 0, \uparrow\downarrow\rangle = |S, 0, S\rangle$$



Spin blockade and Coherent Superpositions



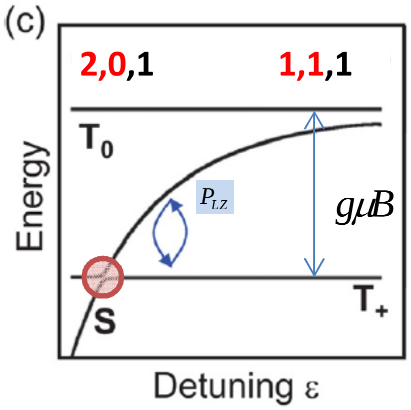


coherent superposition

$$|\Sigma_2\rangle = \frac{1}{2}\left(|\uparrow\downarrow,\downarrow,\uparrow\rangle - |\uparrow\downarrow,\uparrow,\downarrow\rangle - |\downarrow,\uparrow,\uparrow\downarrow\rangle + |\uparrow,\downarrow,\uparrow\downarrow\rangle\right)$$

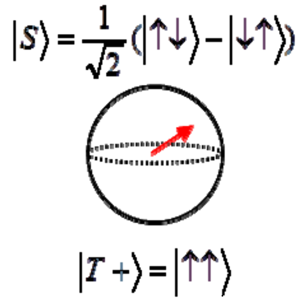
$|\uparrow\downarrow,0,\uparrow\downarrow\rangle = |S,0,S\rangle$ not involved

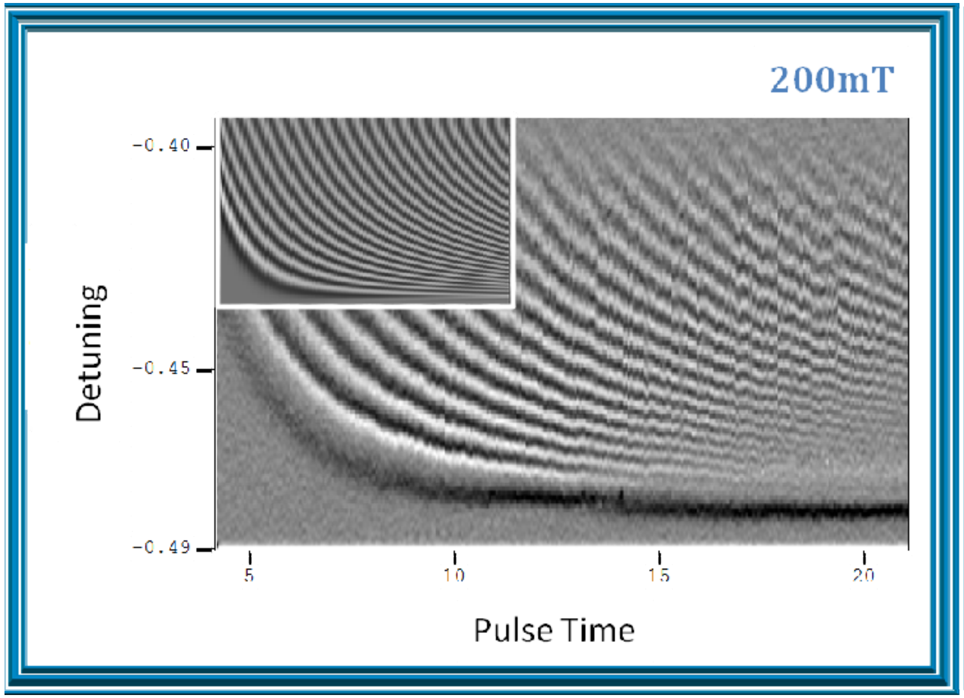
Two Spin Landau-Zener-Stückelberg Oscillations

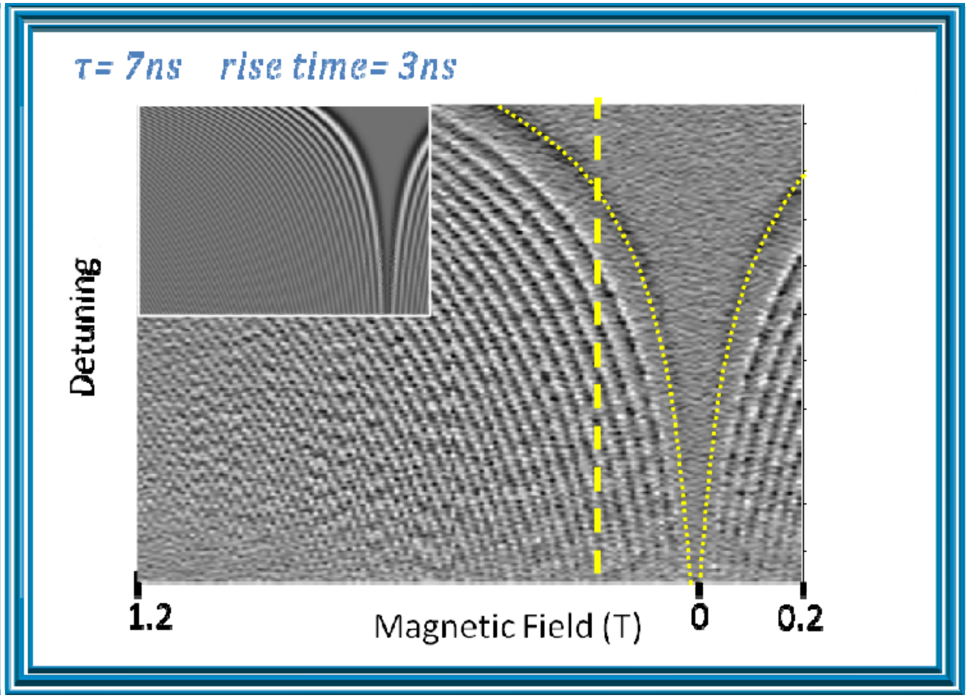


$$P_{LZ} = e^{-2\pi\Delta^2/\hbar v},$$

$$v = \frac{d(E_+ - E_-)}{dt}$$

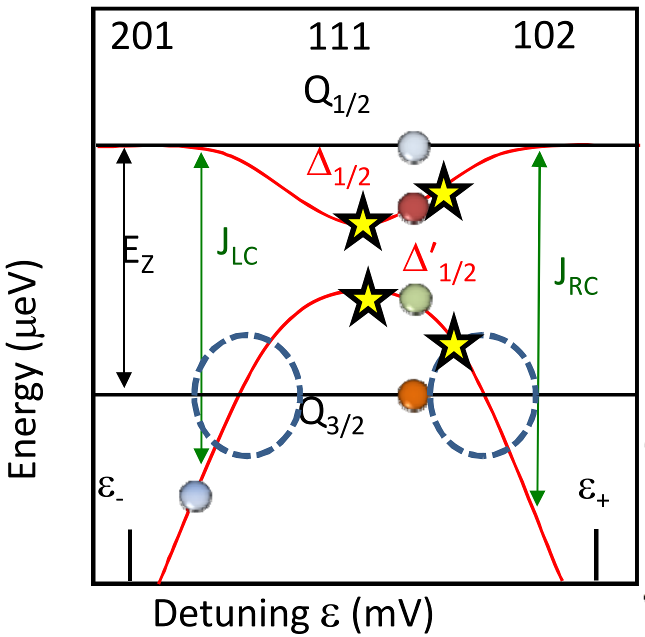


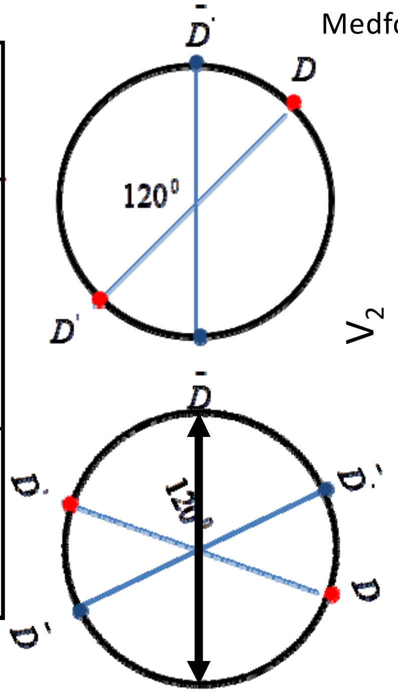


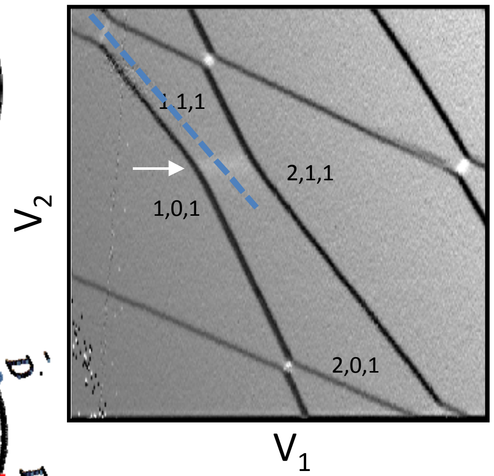


Measurements Made with the Harvard Protocol

Petta et al., Science 309, (2005) 2180
Petta et al., Science 327, (2010) 669
DiVincenzo et al. Science 408 (2000) 339)
Medford et al. Cond-mat arXiv:1392.1933







$$|Q_{1/2}\rangle = \frac{1}{\sqrt{3}}(|\uparrow\uparrow\downarrow\rangle + |\uparrow\downarrow\uparrow\rangle + |\downarrow\uparrow\uparrow\rangle)$$

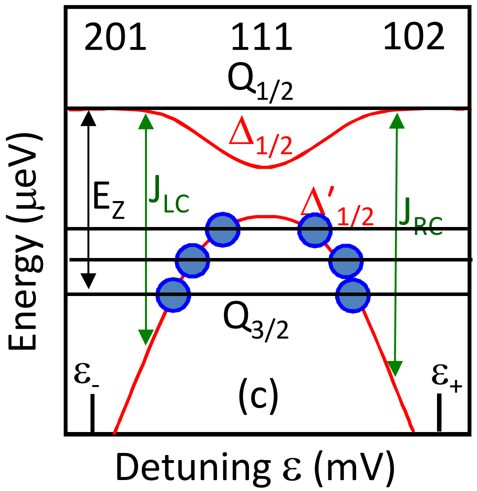
$$|\Delta_{1/2}\rangle = \frac{1}{\sqrt{4\Omega^2 + 2\Omega(J_{LC} - 2J_{RC})}}((J_{LC} - J_{RC} + \Omega)|\uparrow\uparrow\downarrow\rangle + (J_{RC} - \Omega)|\uparrow\downarrow\uparrow\rangle - J_{LC}|\downarrow\uparrow\uparrow\rangle)$$

$$|Q_{3/2}\rangle = |\uparrow\uparrow\uparrow\rangle$$

$$|\Delta'_{1/2}\rangle = \frac{1}{\sqrt{4\Omega^2 + 2\Omega(2J_{RC} - J_{LC})}}((-J_{LC} + J_{RC} + \Omega)|\uparrow\uparrow\downarrow\rangle - (J_{RC} + \Omega)|\uparrow\downarrow\uparrow\rangle + J_{LC}|\downarrow\uparrow\uparrow\rangle)$$

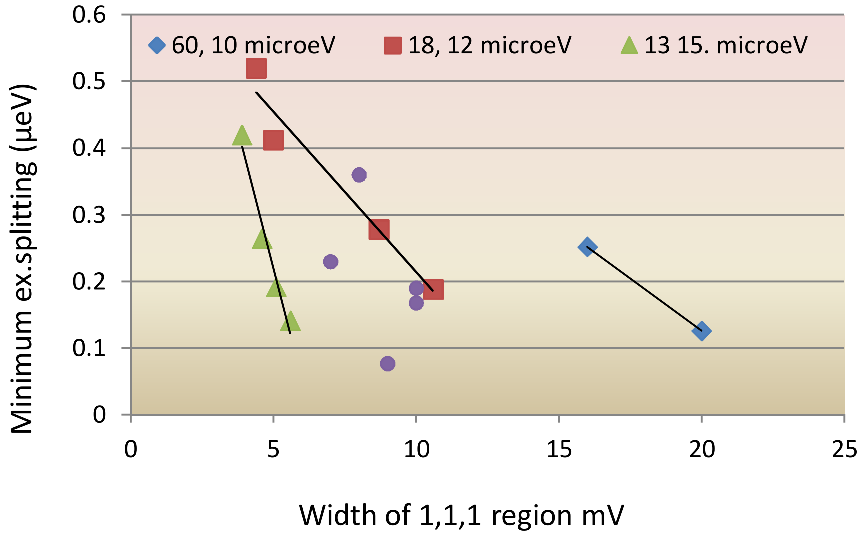
$$\Omega = \sqrt{J_{LC}^2 + J_{RC}^2 - J_{LC}J_{RC}}$$

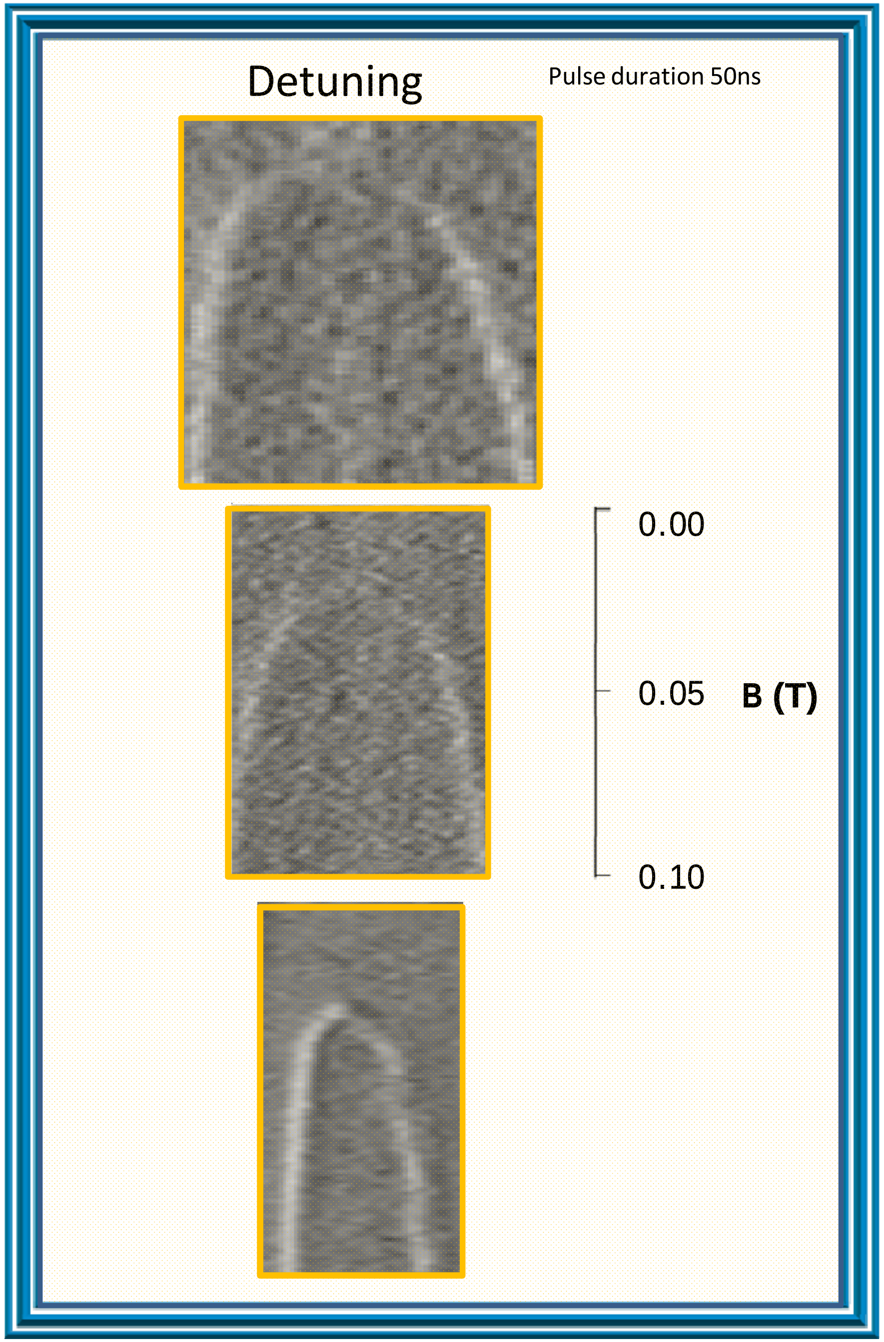
Spin Arch – back to back spin funnels



$$T_{LC}(\epsilon) = \begin{cases} T_{LC}\exp[C_{LC}(\epsilon - \epsilon_+)], & \epsilon < \epsilon_+ \\ T_{LC}, & \epsilon \geq \epsilon_+ \end{cases}$$

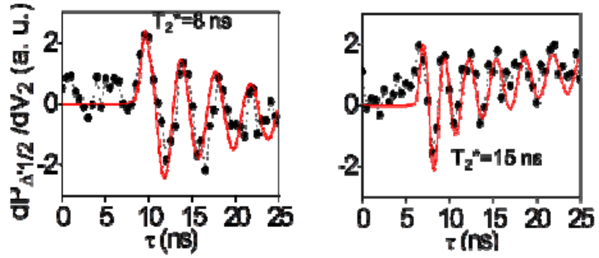
$$T_{RC}(\epsilon) = \begin{cases} T_{RC}\exp[C_{RC}(\epsilon_- - \epsilon)], & \epsilon > \epsilon_- \\ T_{RC}, & \epsilon \leq \epsilon_- \end{cases}$$





Three Spin LZS

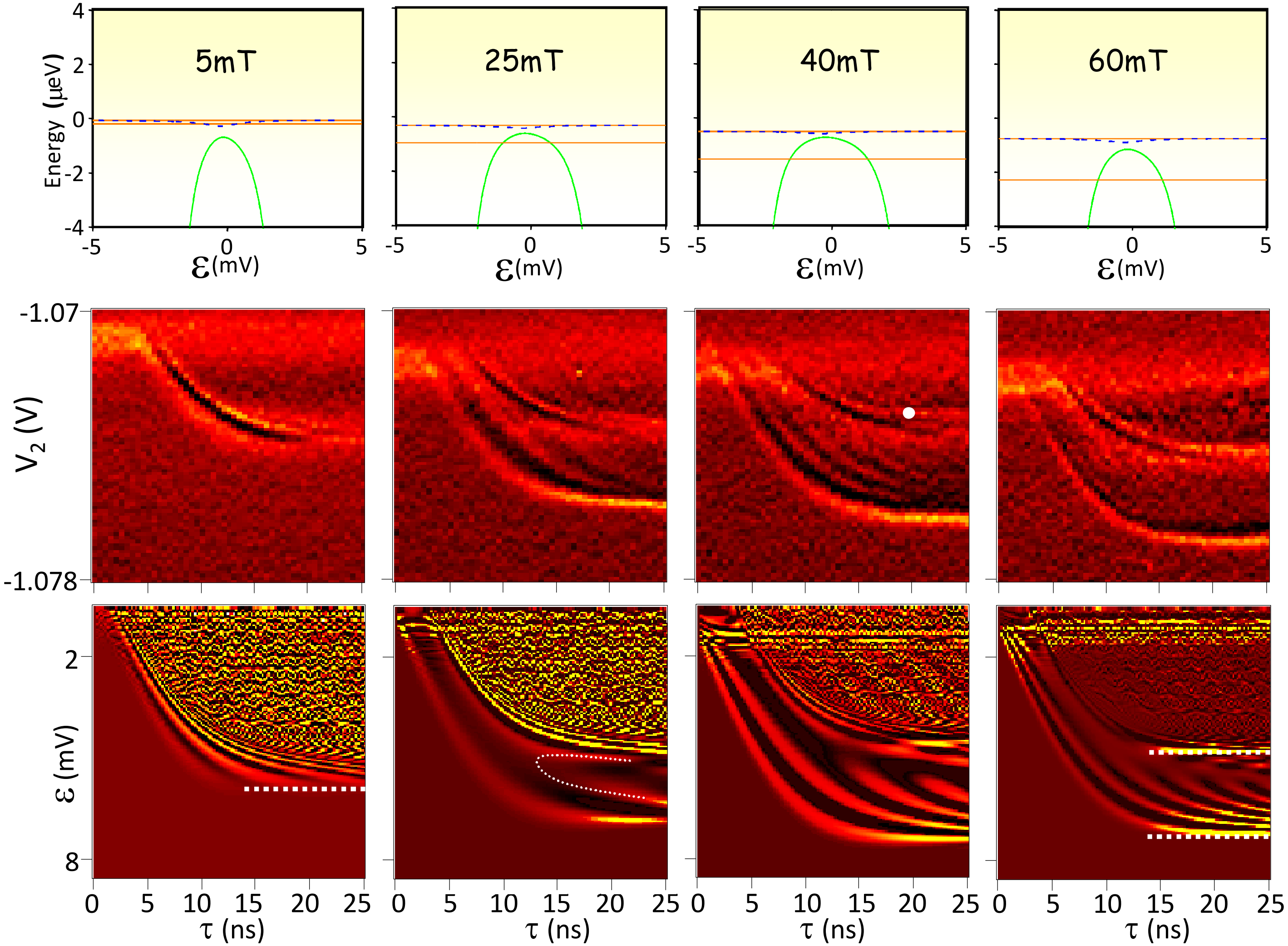
Rise time ~ 6.6 ns



Level spectrum

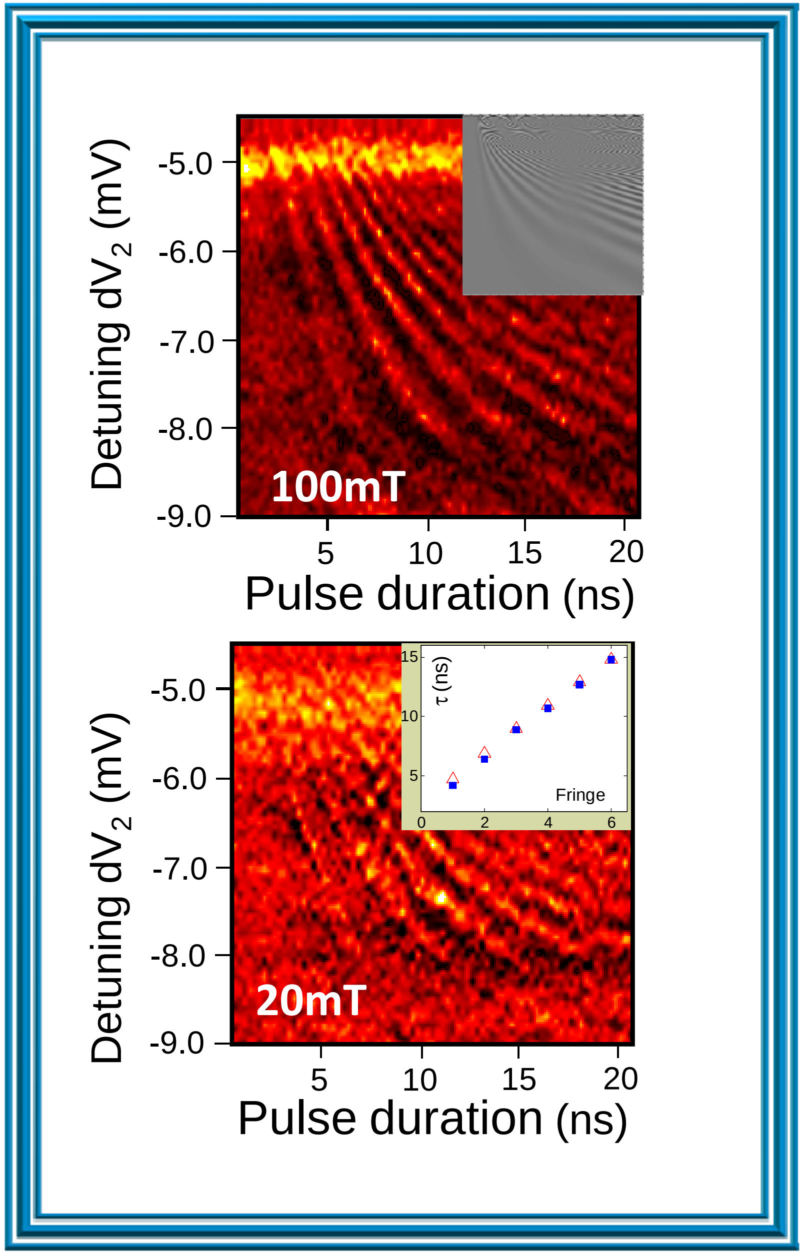
Experiment

Theory



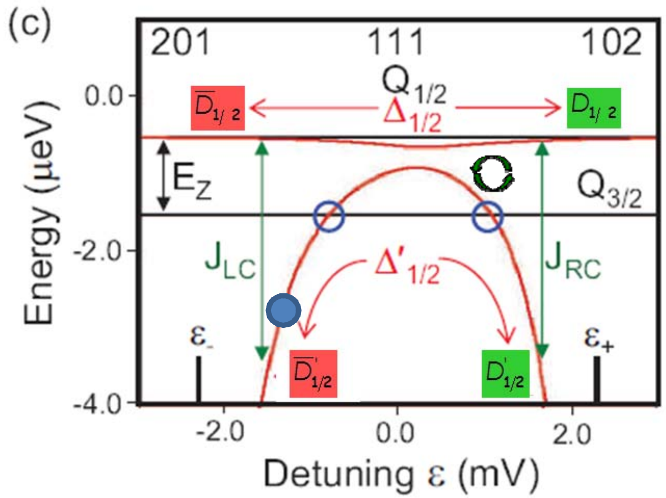
Gaudreau et al. Nature Physics 8, 54–58 (2012)

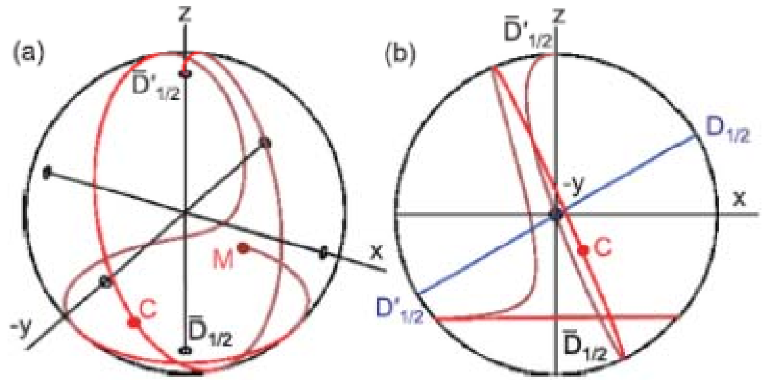
Exchange oscillations - 1ns rise time



$$|\bar{D}_{1/2}\rangle = \frac{-1}{\sqrt{6}}(2|\uparrow\uparrow\downarrow\rangle - |\uparrow\downarrow\uparrow\rangle - |\downarrow\uparrow\uparrow\rangle),$$

$$|\bar{D}'_{1/2}\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\uparrow\rangle - |\downarrow\uparrow\uparrow\rangle).$$





G.C.Aers et al. Phys. Rev. B 86, p. 45316 (2012)

DiVincenzo et al. Science 408 (2000) 339
Laird et al. PRB 82 075403 (2010)
Medford et al. Cond-mat arXiv:1392.1933

Summary

(1) Spin Blockade Leakage via Coherent Superpositions

M.Busl et al Nature Nanotechnology –on line February 2013

(2) Quantum Backaction related to coherent absorption of phonons

Granger et al. Nature Physics 8, pp. 522-527 (2012)

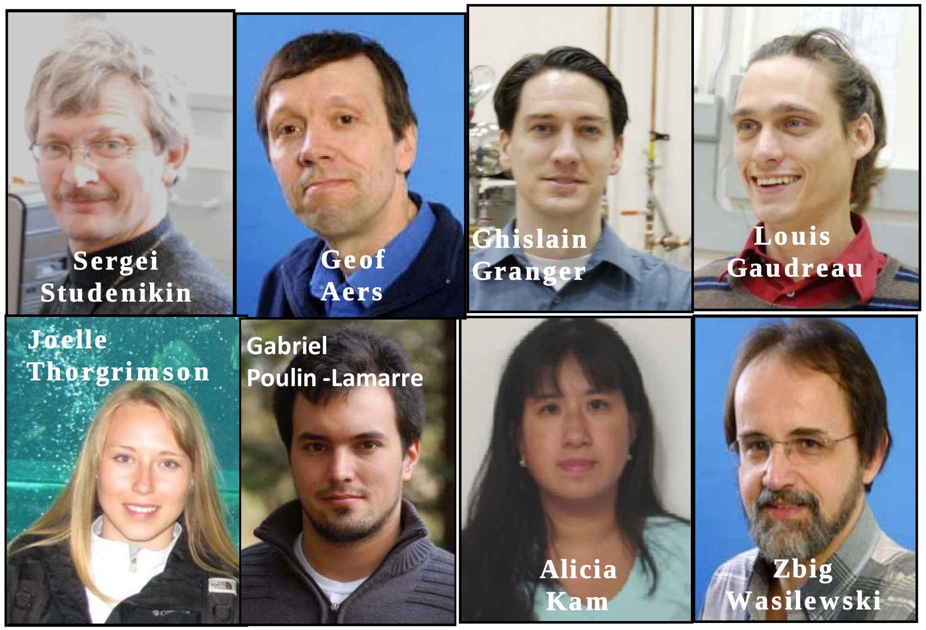
(3) **Holistic View of Possible Coherent Behaviours with 3 spins in Triple Quantum Dots**

Gaudreau et al. Nature Physics 8, 54–58 (2012)

Studenikin et al. Phys. Rev. Lett. 108, (2012) 226802

G.C.Aers et al. Phys. Rev. B 86, p. 45316 (2012)

Acknowledgements



NRC·CNRC NSERC CRSNG CIFAR CANADIAN INSTITUTE for ADVANCED RESEARCH