The Three Spin System

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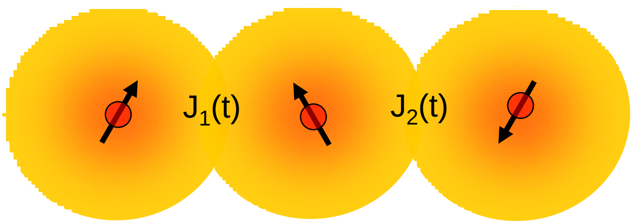

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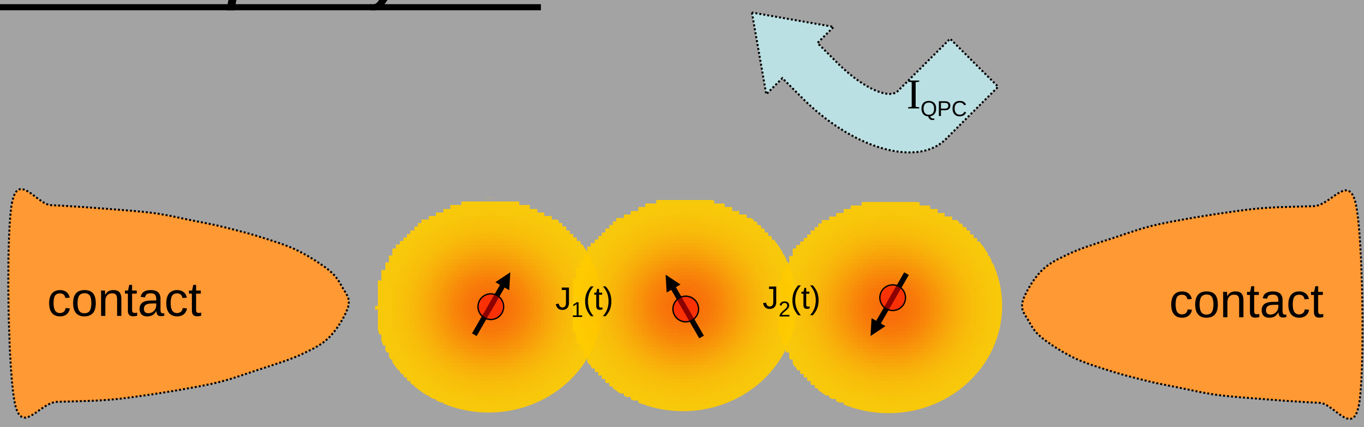
The Three Spin System



- All electrical control of spin states using J_1 and J_2 (*DiVincenzo et al. 2000*)

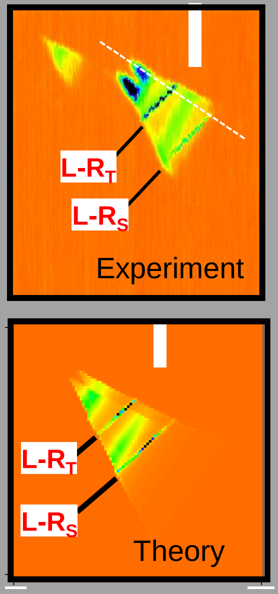
The exchange-only qubit:

- Separate control of J_1 and J_2 allow easy manipulation around the Bloch sphere
- Solves single qubit addressability problem
- Does not require B-field gradients as in case of the ST_0 and ST_+ qubits
- Directly couples spin states to electric field, e.g. superconducting cavities

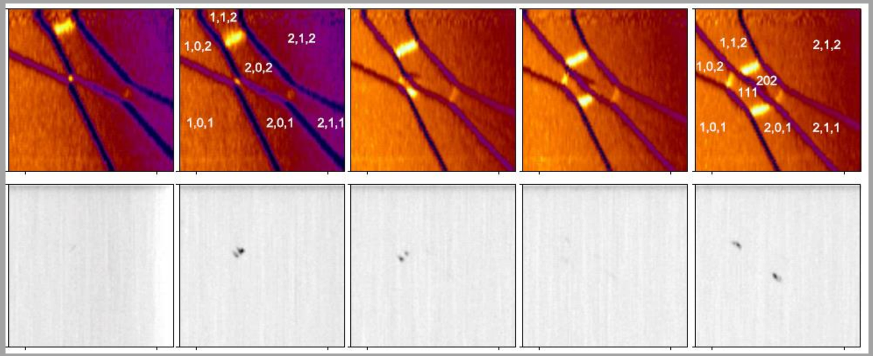
- New phenomena: bipolar spin blockade, coherent electron transfer between distant dots (*Nat. Phys. 2013*), enhanced spin-state and single-phonon detection via meta-stable states *(APL 2013, Nat. Phys. 2012)*, rich coherent behaviour *(Nat. Phys. 2011)* ...

Overview of the triple-dot results

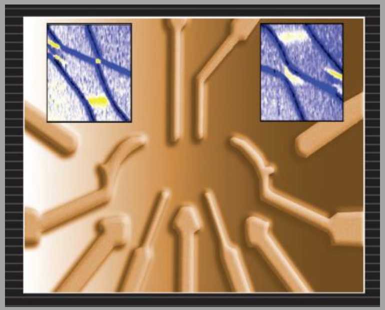
Busl et al. Nat. Nano. **2013**



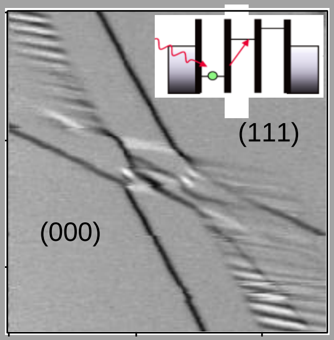
Granger et al. PRB **2010**



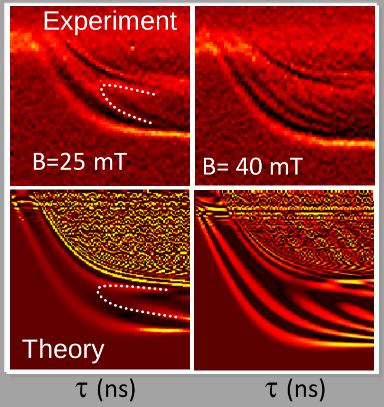
Gaudreau et al. APL **2009**



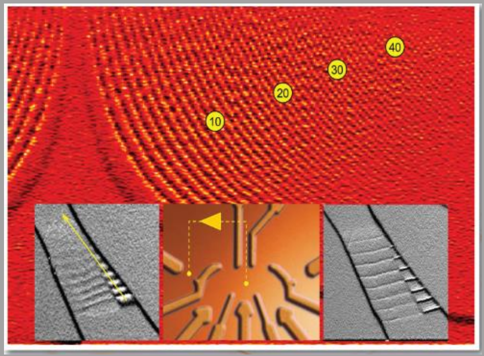
Granger et al. *Nat. Phys*. **2012**



Gaudreau et al. Nat. Phys. **2012**

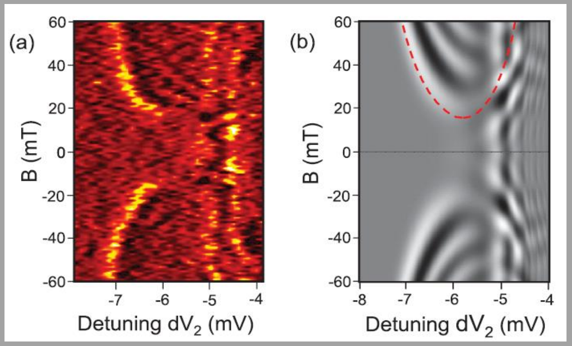


S.S. et al. APL **2012**

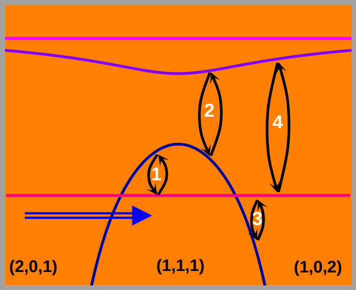


S.S. et al. PRL **2012**, *phys. stat. sol.* **2013**

Aers et al. PRB **2012**



New, 2013



The Three-Spin System

Outline

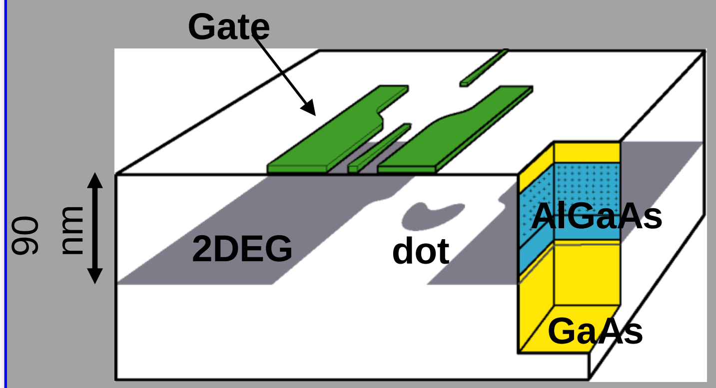
1) The 3-dot sample, 3D stability diagram
2) Transport measurements at quadruple points

Coherent 3-spin state manipulation

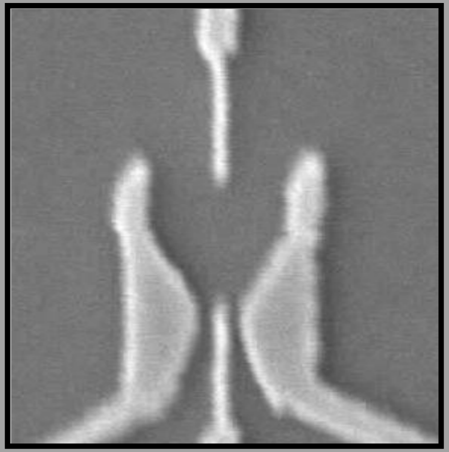
3) The energy diagram
4) Hyperfine-driven LZS: pair-wise control of J_{12} and J_{23}
5) All-exchange oscillations
6) Interplay between various qubits
7) Summary

Lateral split gate technology

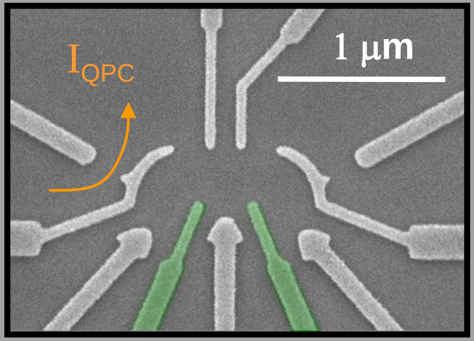
M. Pepper et al. PRL 1986



3D layout of a lateral QD sample formed by surface gates from 2DEG at the hetero-interface in GaAs/AlGaAs stucture.

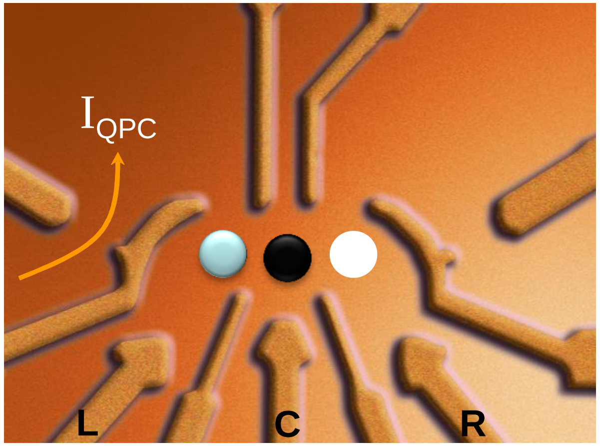


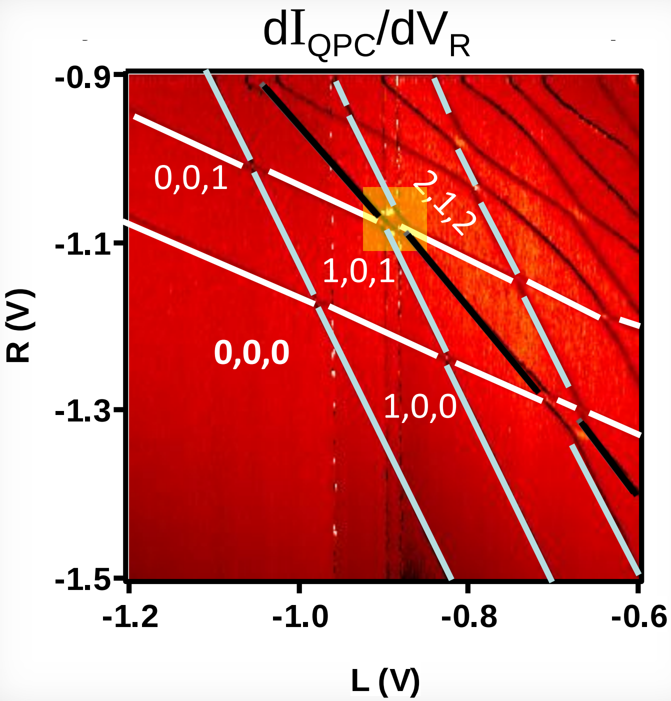
Single electron regime reached:
Ciorga, Sachrajda et al. (NRC)
Phys. Rev. ***B* 61**, R16315 (2000).



Lateral Triple Dot
L. Gaudreau *et al*.
APL **99** 193101 (2009)

Stability diagram of a triple QD



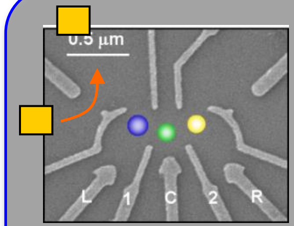


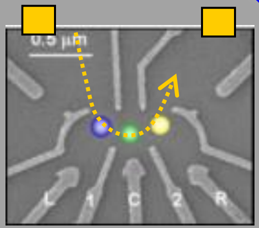
Charge detection is important technology:
(M.Field et al. PRL **70**, 1311 (1993))

- *Allows to map out stability diagrams*
- *Can be used for spin-state readout using Pauli blockade, e.g.* (↑,↑)→ (0,↑↓)

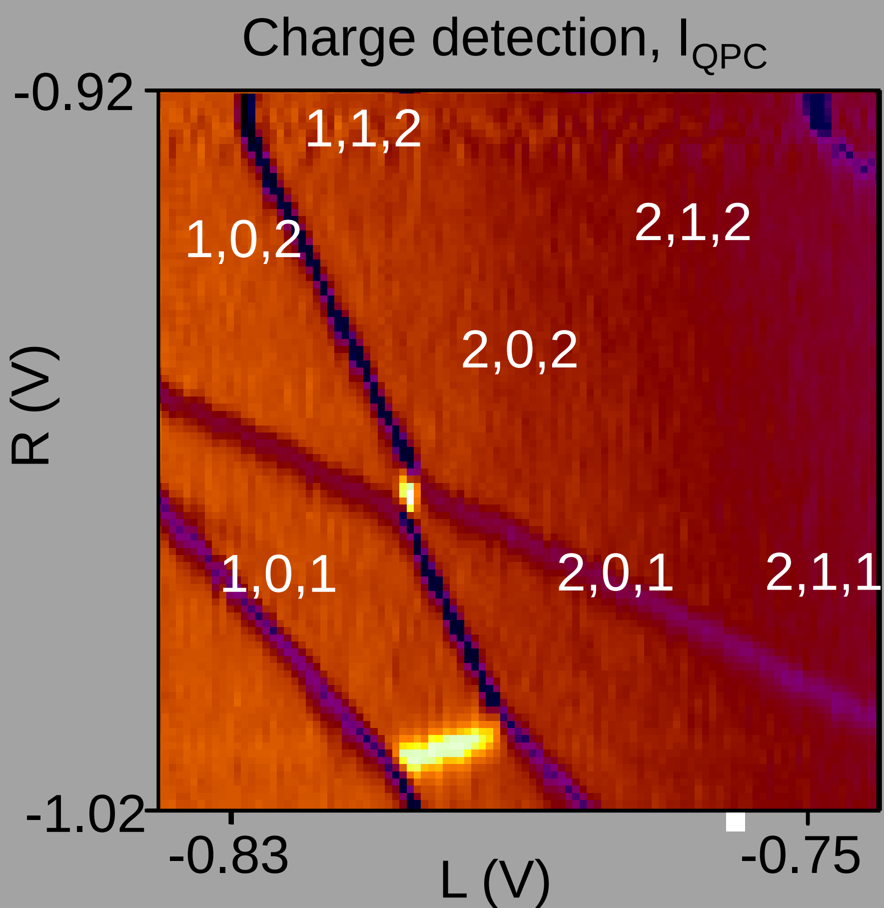
A stability diagram measured by the QPC charge detector, dI_{QPC}/dV_R

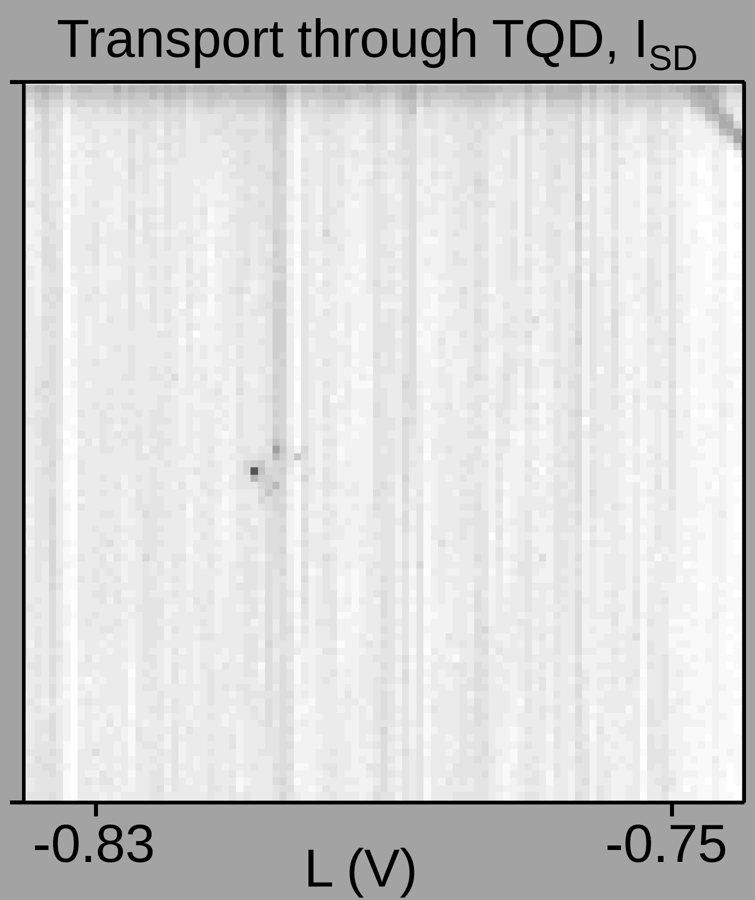
3D stability diagram and transport measurements at quadruple points





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



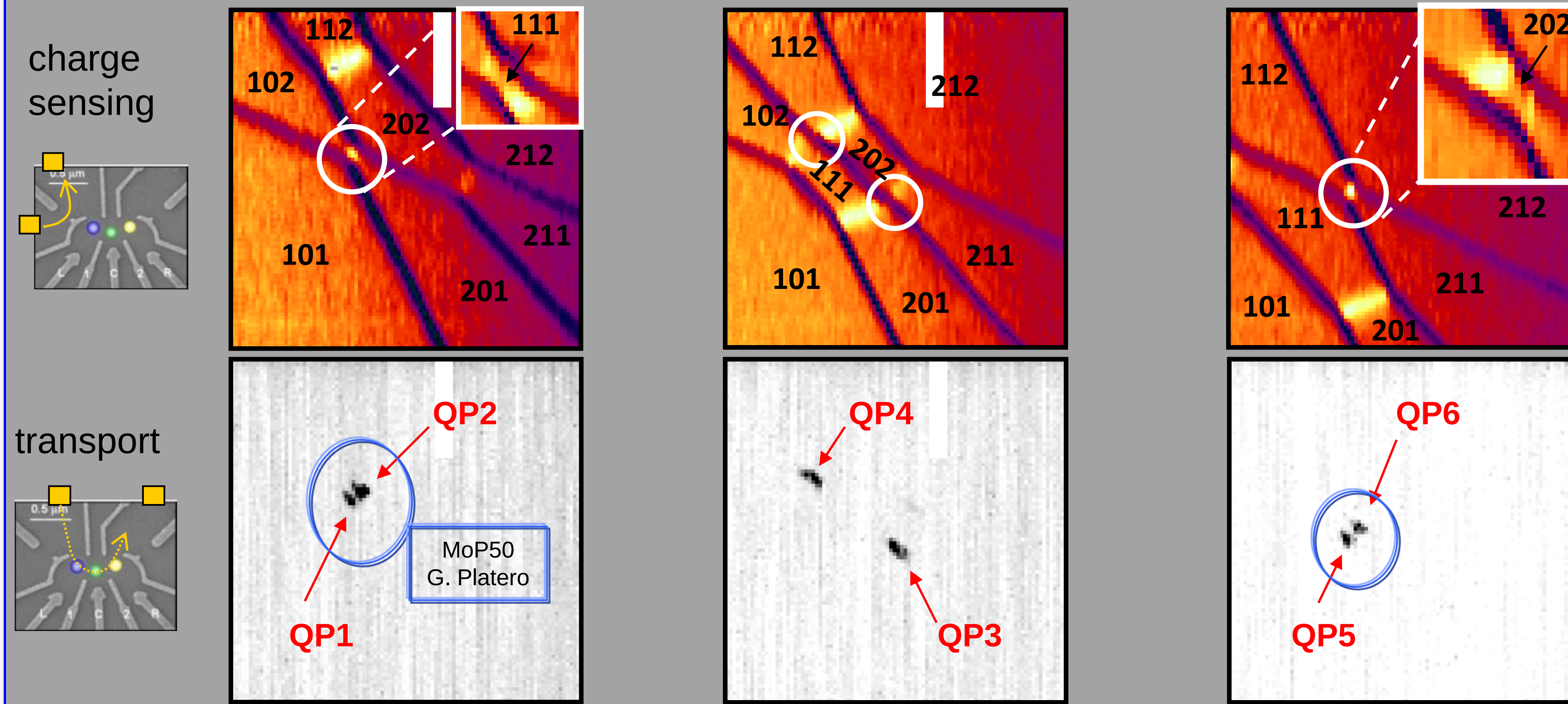


2D slices of the 3-dimentional SD stepping V_C

Transport at quadruple points

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

Six quadrupole points predicted in : M. Rogge, R. Haug. New Journal of Physics **11,** 113037 (2009)



QP1: 101 ↔ 201 → 111 ← 102 ↔ 101

Spin blockade

QP3: 111 ↔ 211 ← 202 ↔ 201 → 111

Spin blockade

QP6: 212 ↔ 112 ← 202 → 211 ↔ 212

Spin blockade

Example of bipolar spin blockade at QPs 5,6

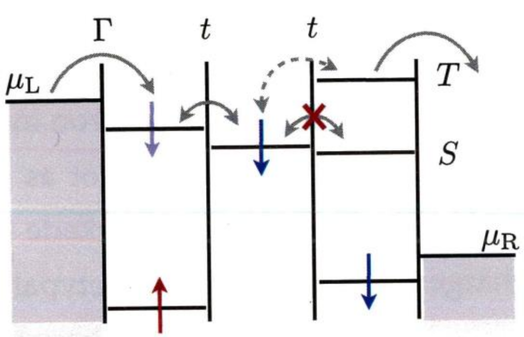
M. Busl et al. *Nature Nanotechnology* **8**, 261 (2013)

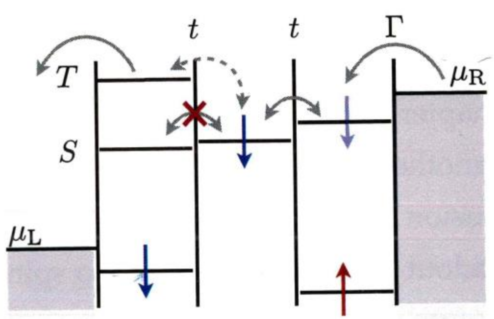
QP5: 111 ↔ 112 ← 202 → 211 ↔ 111

Spin blockade

QP6: 212 ↔ 112 ← 202 → 211 ↔ 212

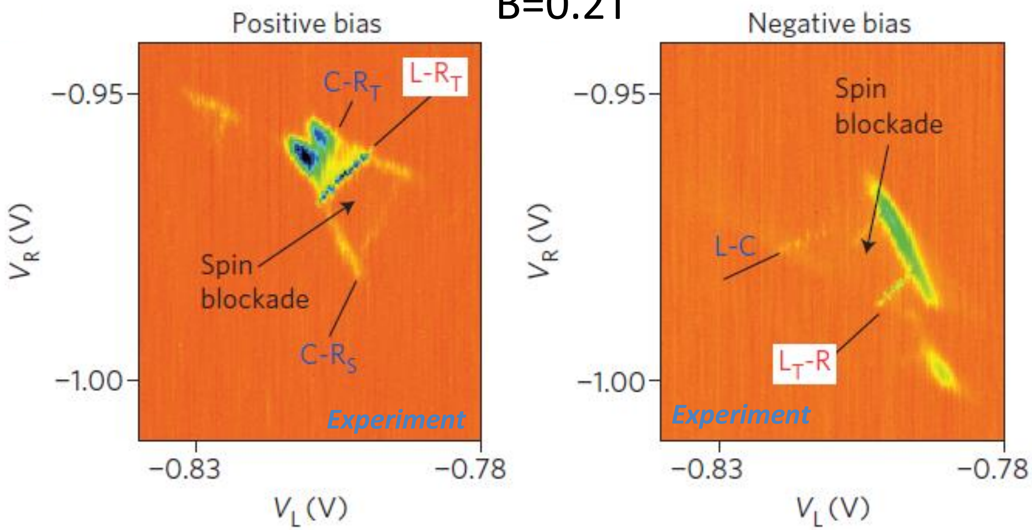
Spin blockade

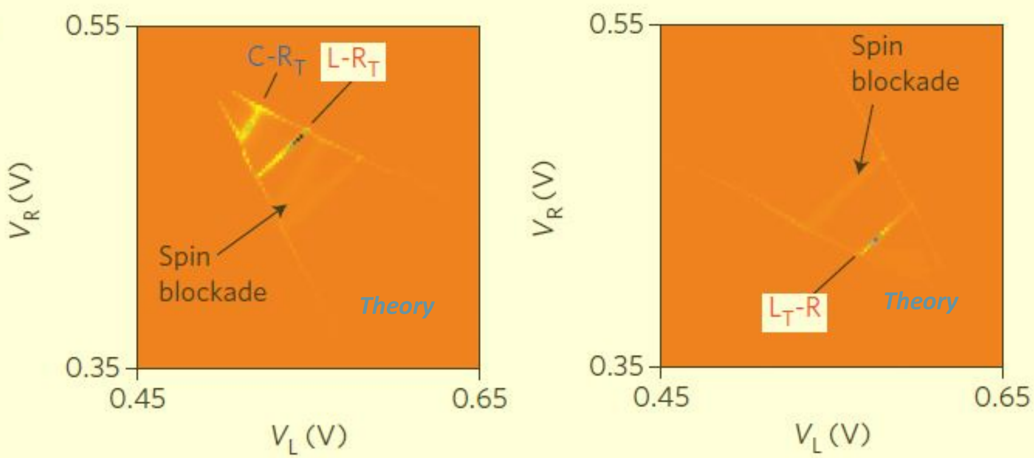




V_{SD}= 500μV **V_{SD}= -500μV**

B=0.2T





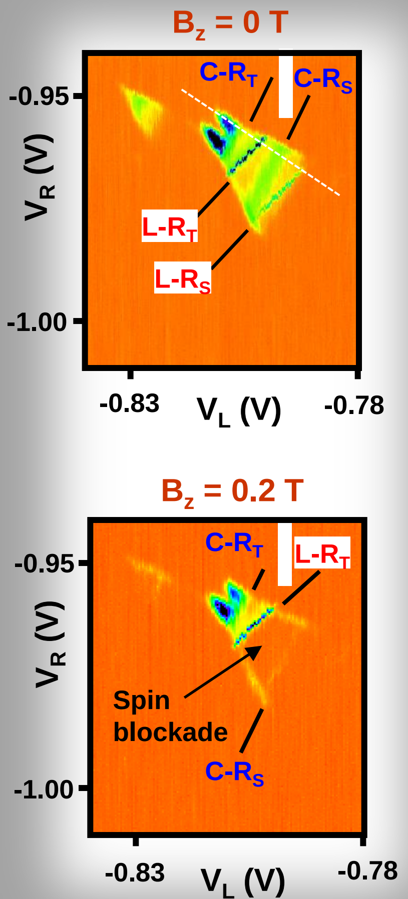
Theory G.Platero Group

QP5&6

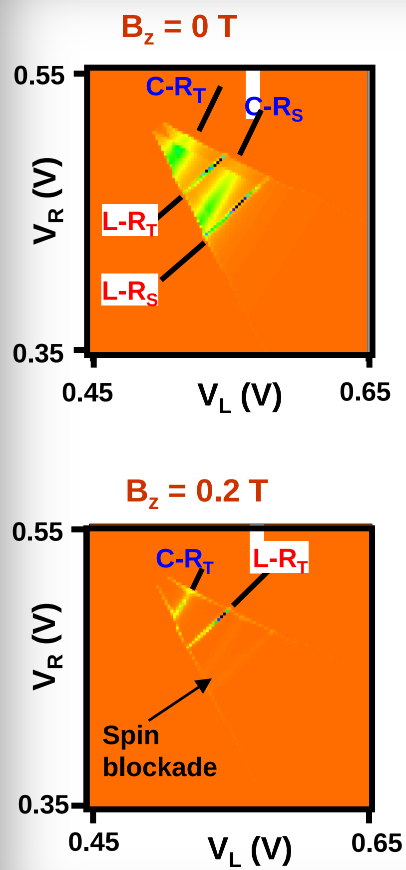
Resonant electron transfer

M. Busl et al. Nat. Nanotechnol. **8**, 261 (2013)

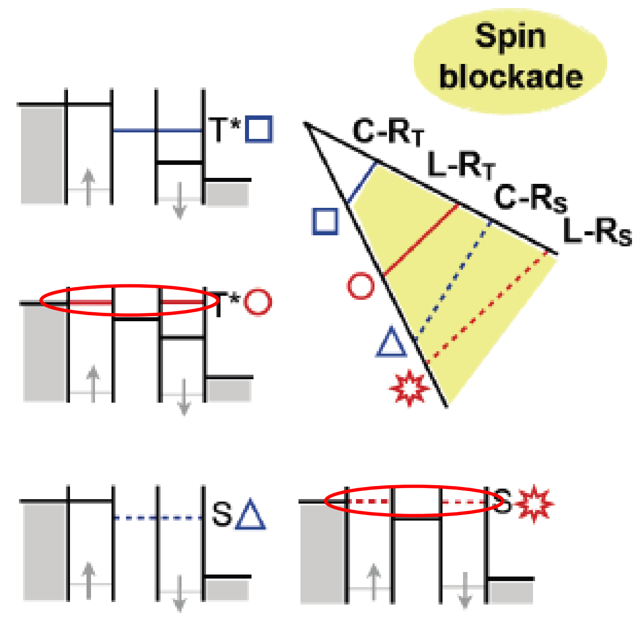
Experiment:



Theory:



Leakage currents along resonances:



Poster MoP50 by G. Platero

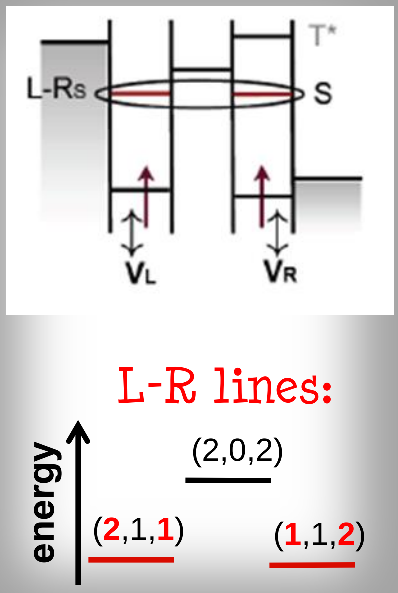
Electron transfers from L to R via the following coherent state superposition (center dot is not envolved):

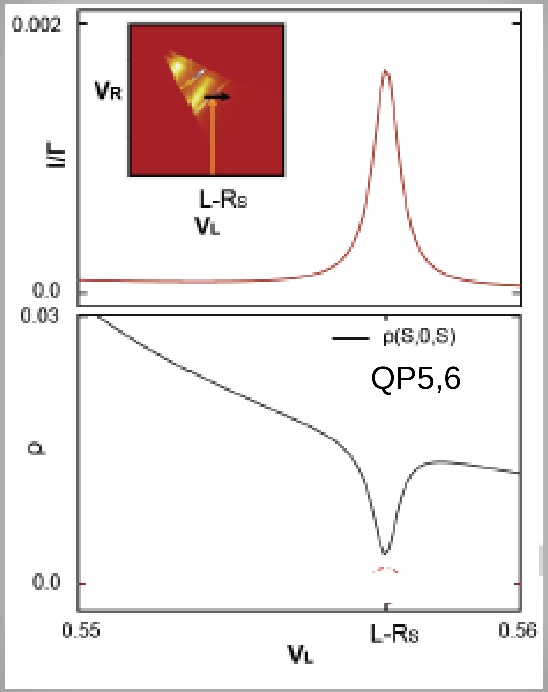
$$|\Sigma\rangle = \frac{1}{2}\left(|\uparrow\downarrow,\downarrow,\uparrow\rangle - |\uparrow\downarrow,\uparrow,\downarrow\rangle - |\downarrow,\uparrow,\uparrow\downarrow\rangle + |\uparrow,\downarrow,\uparrow\downarrow\rangle\right)$$

Braakman et al, *Nature Nanotechnology* **8**, 432 (2013) and Poster MoP59

Transport through long-range coherent superpositions

Busl *et al*., *Nature Nanotechnology* **8**, 261 (2013)
Braakman et al, *Nature Nanotechnology* **8**, 432 (2013)





New transport data at QP1,2:
Poster MoP50:

QP1: (1,0,1)→(2,0,1)→(1,0,2)→(1,0,1)…
QP2: (2,0,2)→(2,0,1)→(1,0,2)→(2,0,2)…

Important: state (1,1,1) is not involved

Charge is transferred from one end of the linear triple dot circuit to the other via coherent superpositions involving only the virtual occupation of the centre site.

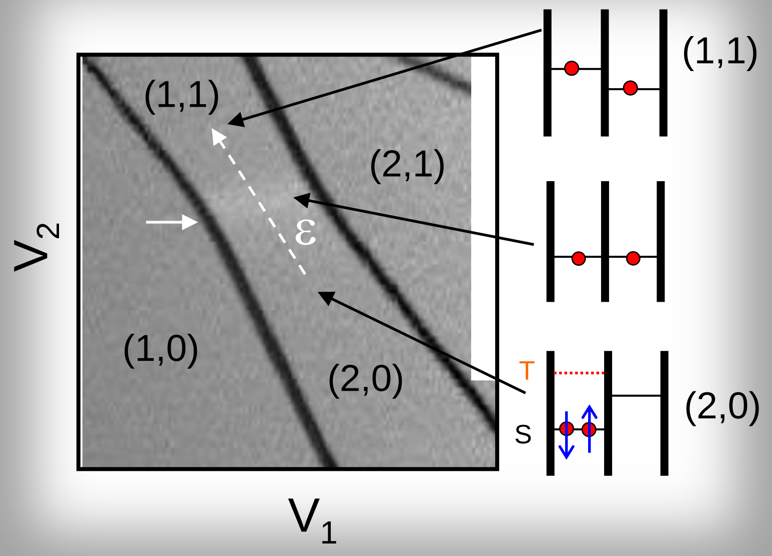
$$|\Sigma_2\rangle = \frac{1}{2}\left(|\uparrow\downarrow,\downarrow,\uparrow\rangle - |\uparrow\downarrow,\uparrow,\downarrow\rangle - |\downarrow,\uparrow,\uparrow\downarrow\rangle + |\uparrow,\downarrow,\uparrow\downarrow\rangle\right)$$

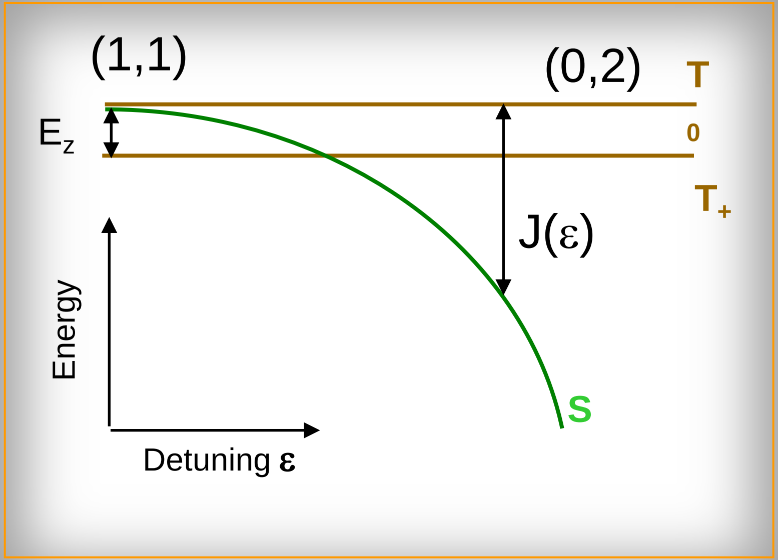
$|\uparrow\downarrow,0,\uparrow\downarrow\rangle = |S,0,S\rangle$ not involved

Coherent manipulation of 3-spin states

- The 3-spin energy diagram
- Hyperfine-driven LZS: pair-wise control of J_{12} and J_{23}
- All-exchange oscillations
- Interplay between different qubits

Energy diagram of a double quantum dot





$$T_- = |\downarrow\downarrow\rangle$$

$$T_0 = \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle\right)$$

$$T_+ = |\uparrow\uparrow\rangle$$

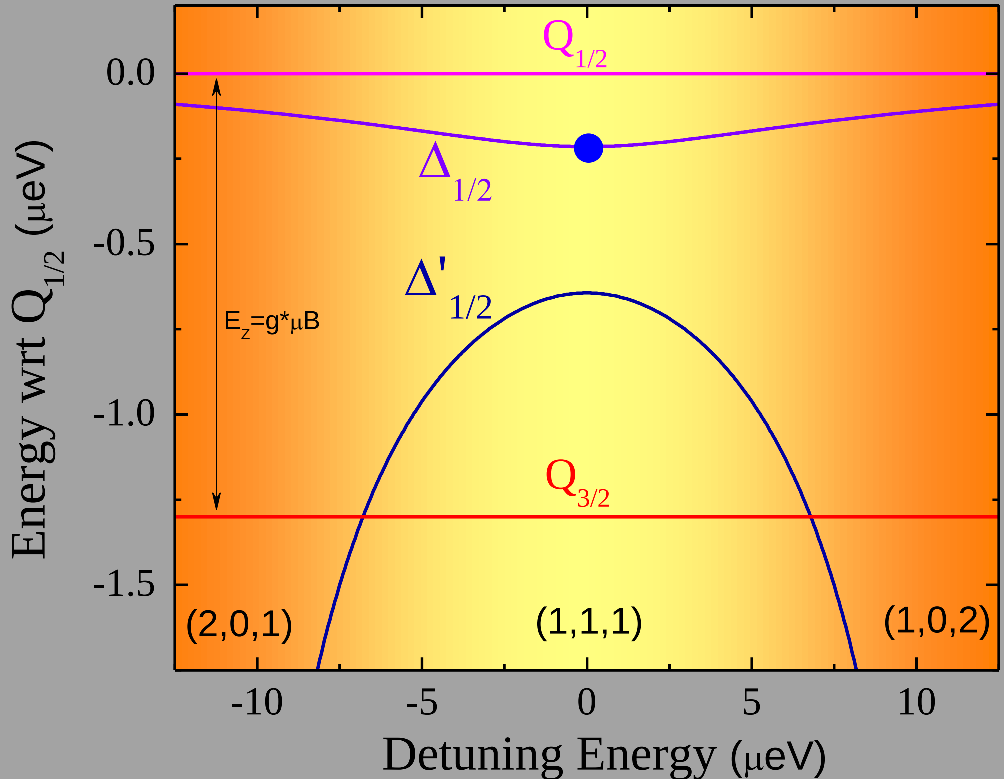
$$S = \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)$$

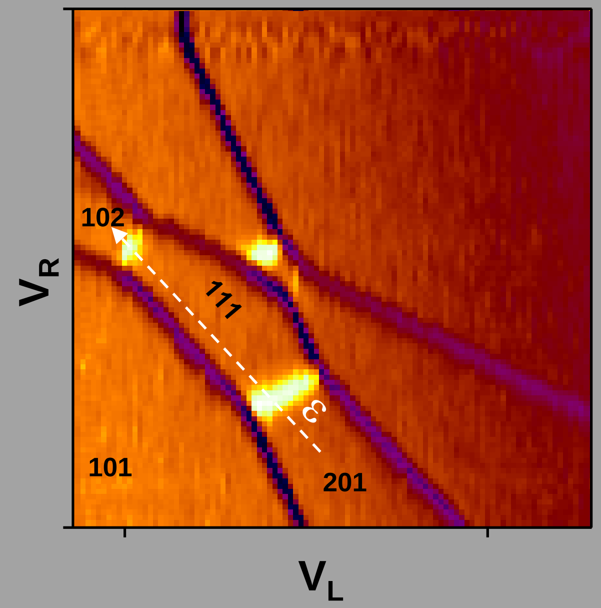
Three-spin energy diagram

Notations from:

Laird *et al.*, PRB **82,** 075403 (2010)

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





$$Q_{1/2} = \frac{1}{\sqrt{3}}\left(\left|\uparrow\uparrow\downarrow\right\rangle + \left|\uparrow\downarrow\uparrow\right\rangle + \left|\downarrow\uparrow\uparrow\right\rangle\right) \quad \sim T_0$$

$$Q_{3/2} = \left|\uparrow\uparrow\uparrow\right\rangle \quad \sim T_+$$

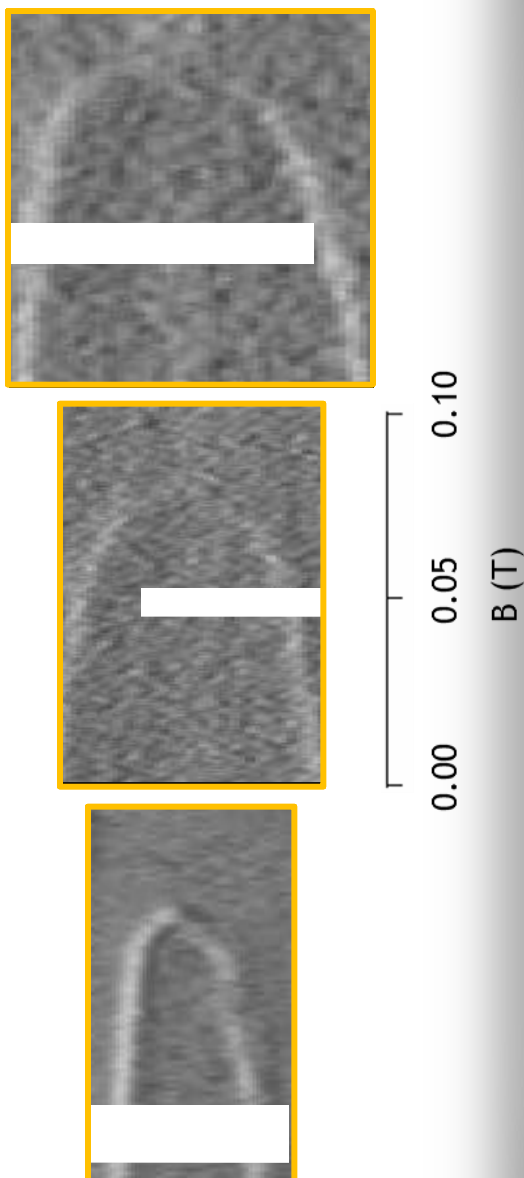
Right side:

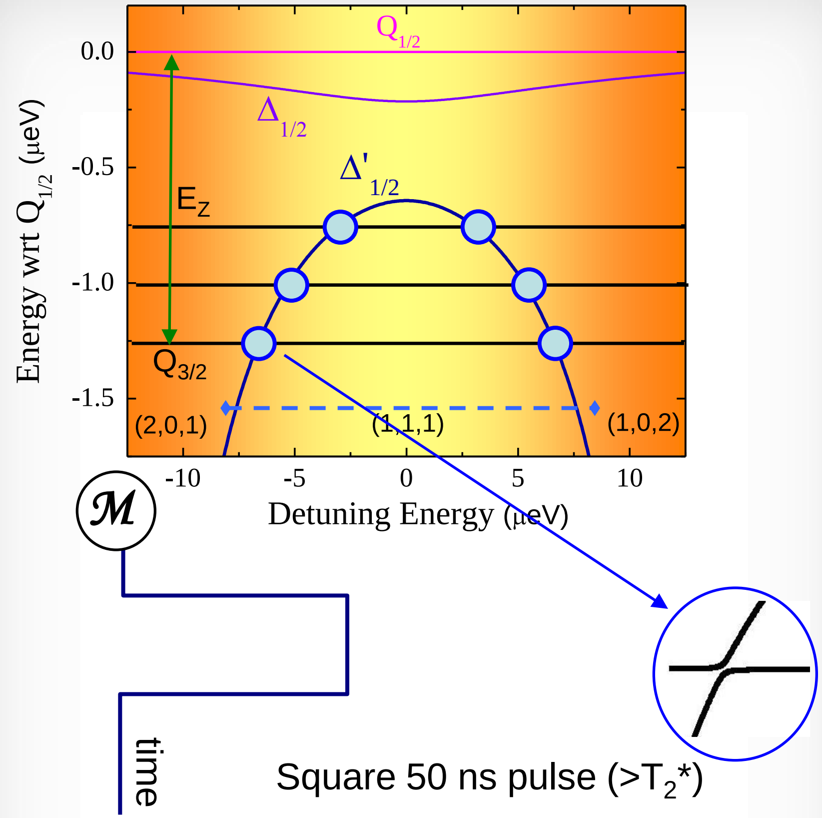
$$\Delta'_{1/2} \rightarrow D'_{1/2} = \frac{1}{\sqrt{2}}\left(\left|\uparrow\uparrow\downarrow\right\rangle - \left|\uparrow\downarrow\uparrow\right\rangle\right) \Rightarrow \left|\uparrow S^R\right\rangle \quad \sim S$$

$$\Delta_{1/2} \rightarrow D_{1/2} = \frac{1}{\sqrt{6}}\left(\left|\uparrow\uparrow\downarrow\right\rangle + \left|\uparrow\downarrow\uparrow\right\rangle - 2\left|\downarrow\uparrow\uparrow\right\rangle\right) \sim \sum T_i$$

center $\left|S_{13}\right\rangle\left|\uparrow\right\rangle_2$ (Taylor et al. arXiv:1304.3407)

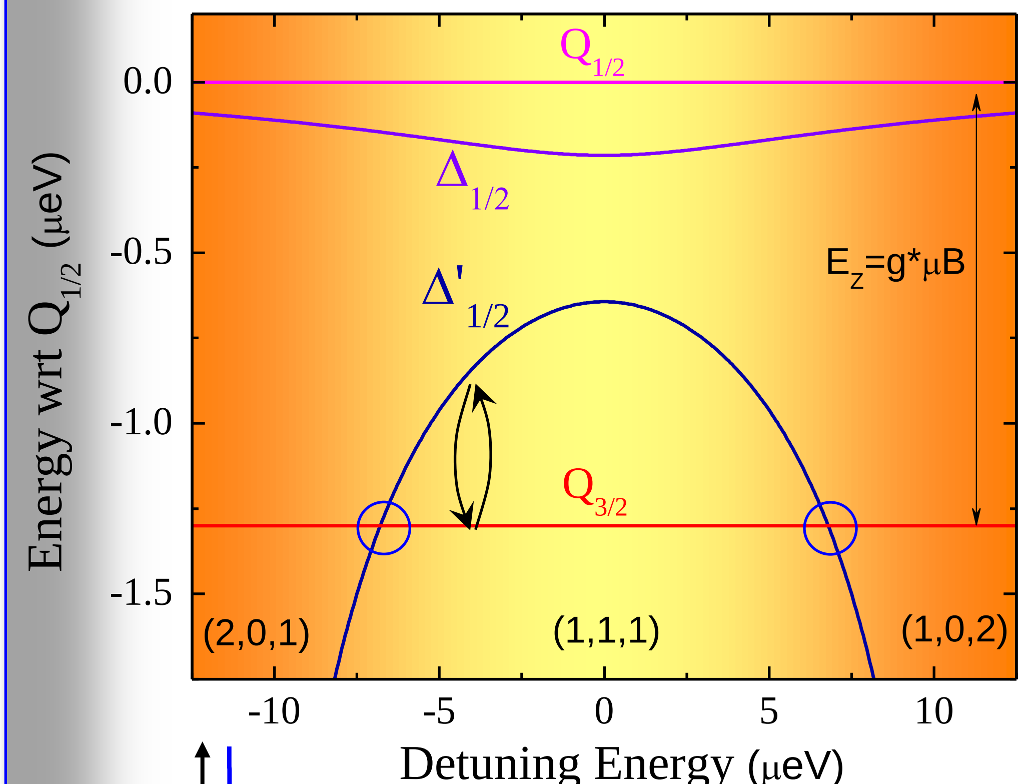
Calibration of the 3-spin energy spectrum

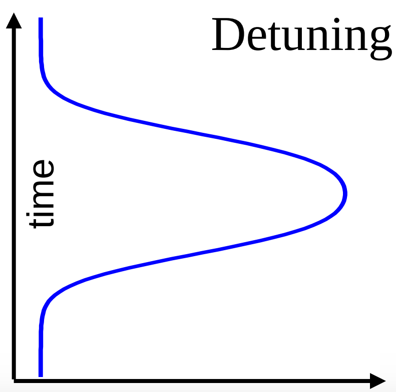


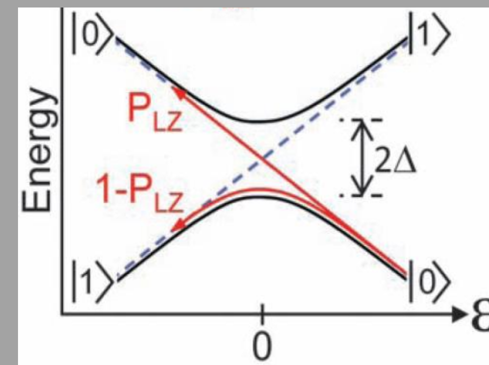


- sweep range of the pulse end point

Landau-Zener-Stückelberg (LZS) oscillations







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

where

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

LZS in double dot:
Petta *et al.*, Science **327**, 669 (2010)

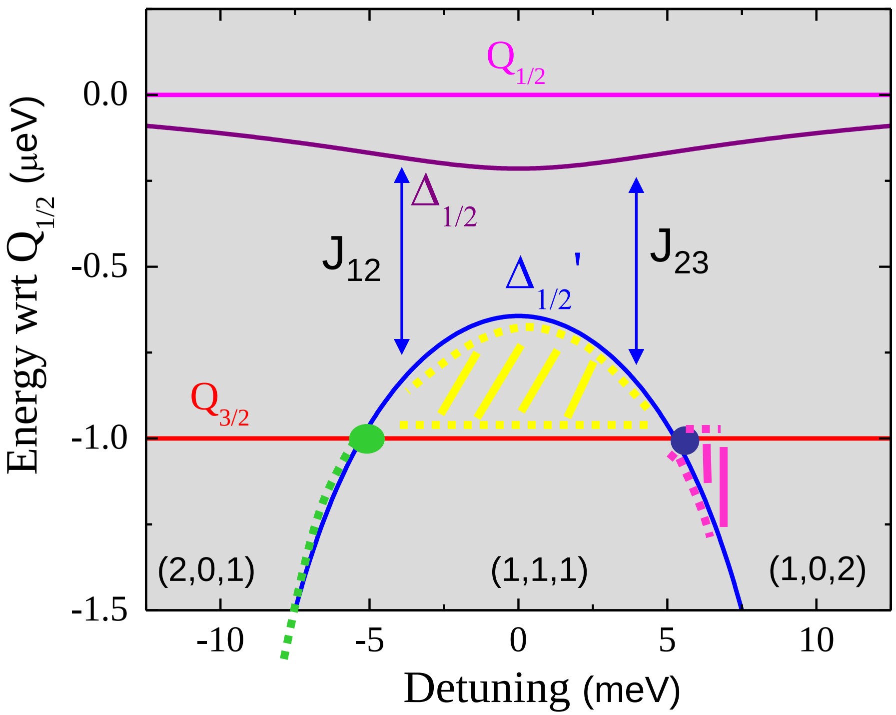
Three-Spin State Interferometer using LZS - 'Pairwise exchange control'

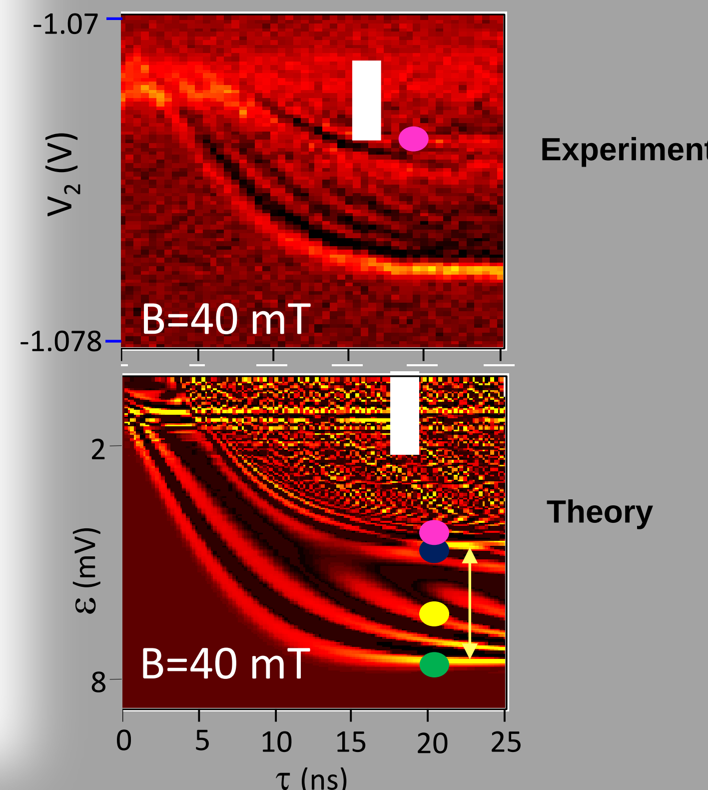
$$\Delta'_{+1/2} = \left((-J_{12} + J_{23} + \Omega)|\uparrow\uparrow\downarrow\rangle - (J_{23} + \Omega)|\uparrow\downarrow\uparrow\rangle + J_{12}|\downarrow\uparrow\uparrow\rangle \right) \;/\; [4\Omega^2 + 2\Omega(2J_{23} - J_{12})]^{1/2}$$

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

$\Omega = [J_{12}^2 + J_{23}^2 - J_{12}J_{23}]^{1/2}$

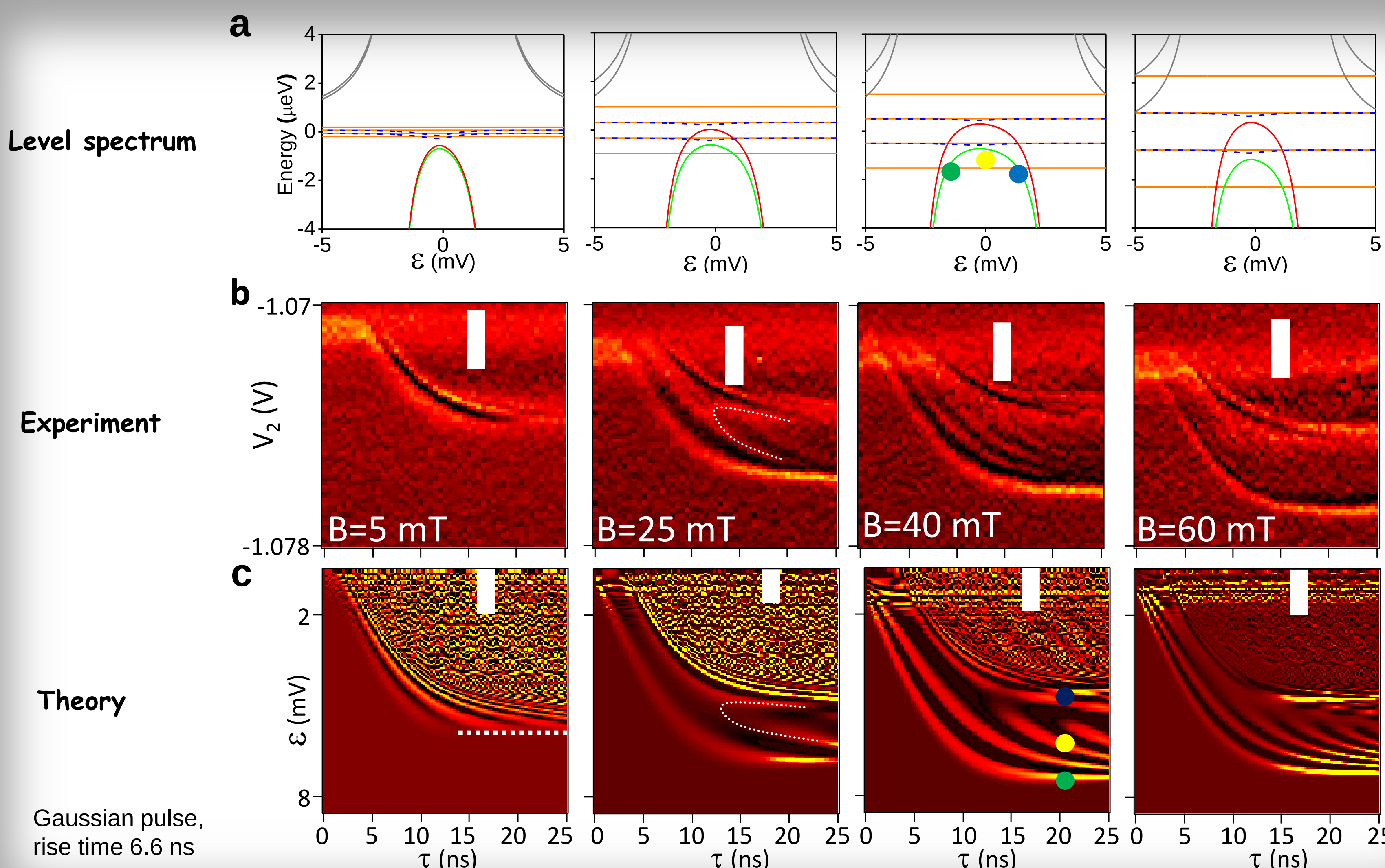
J_{12}, J_{23} interdot couplings





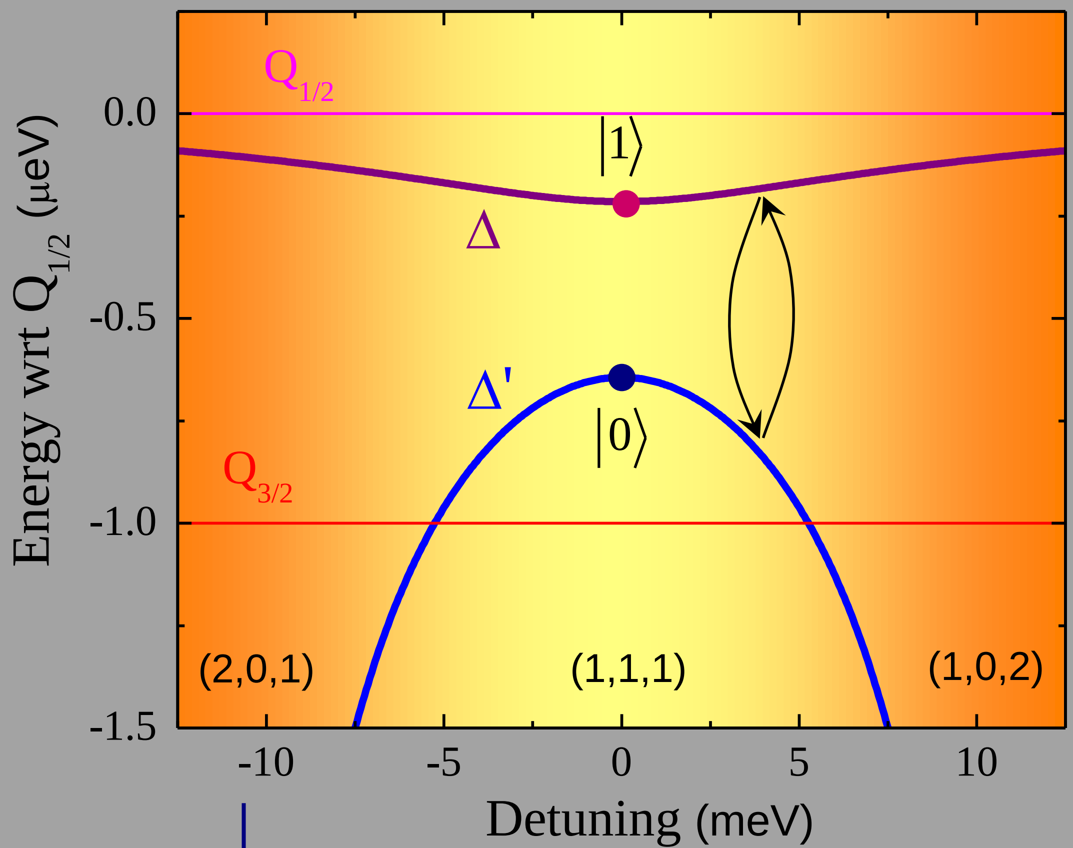
Gaudreau et al. Nature Physics **8**, 54 (2012)

Magnetic field dependence of coherent three-spin states oscillations

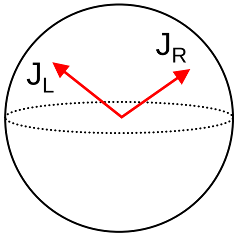


Gaudreau et al. Nature Physics 8, 54–58 (2012)

The All-Exchange Coherent Oscillations



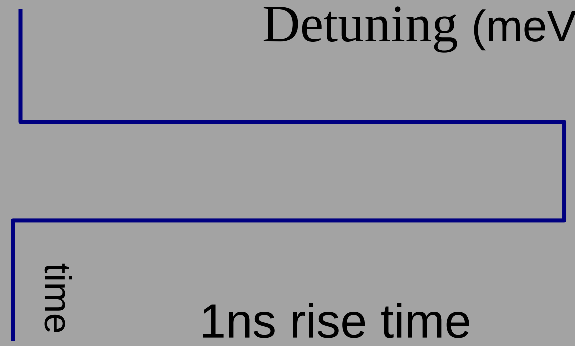
$$|1\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\uparrow\downarrow\rangle - |\downarrow\uparrow\uparrow\rangle\right)$$



$$|0\rangle = \frac{1}{\sqrt{6}}\left(|\uparrow\uparrow\downarrow\rangle + |\downarrow\uparrow\uparrow\rangle - 2|\uparrow\downarrow\uparrow\rangle\right)$$

DiVincenzo et al. Nature **408**, 339 (2000)

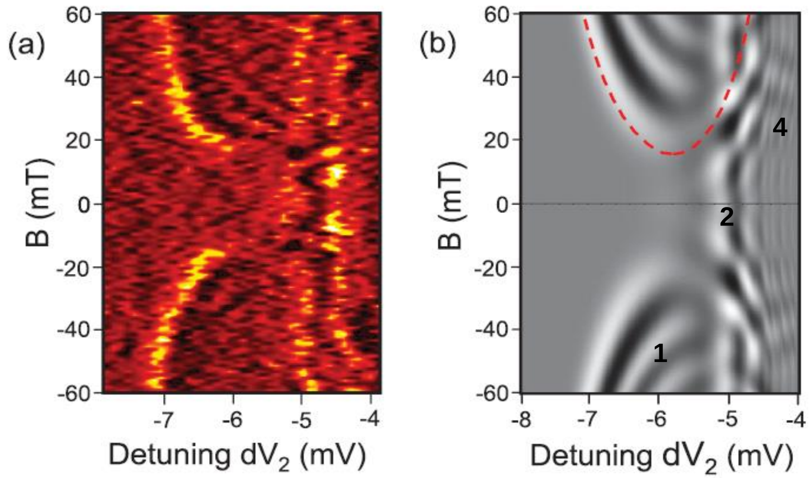
Medford et al. arXiv:1304.3413 (2013)

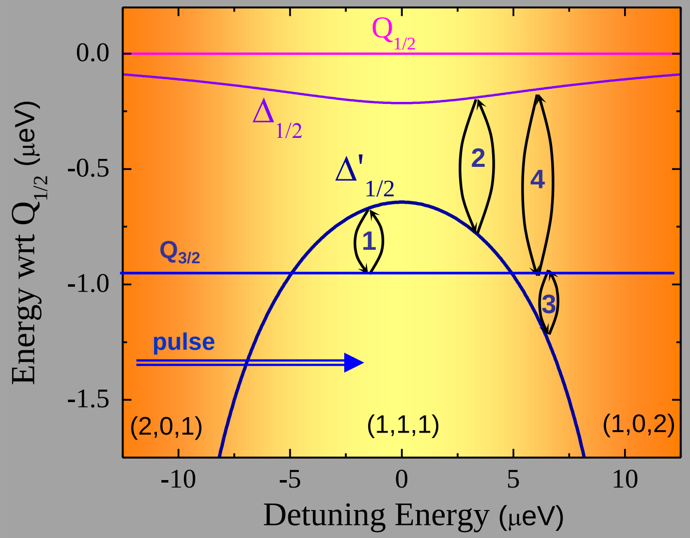


1ns rise time

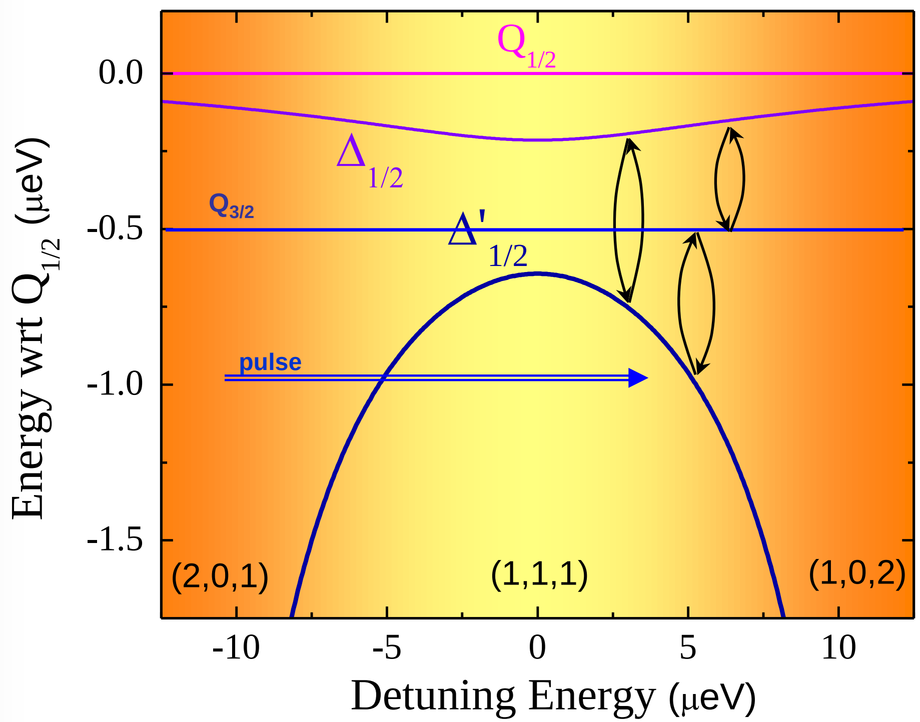
All-exchange and LZS fringes in one plot

Aers et al. PRB **2012**





Interplay between the all-exchange and far-side LZS



Summary

(1) Three-spins localised in a triple dot constitutes a versatile system offering new phenomena and new capabilities L. Gaudreau et al. Nature Physics **8**, 154–58 (2012)

(2) Bipolar spin blockade and leakage via coherent state superpositions
M. Busl et al Nature Nanotechnology **8**, 261 (2013)

(3) Rich coherent behaviours with 3-spin states
S. S. et al. Phys. Rev. Lett. **108**, 226802 (2012)
G.C. Aers et al. Phys. Rev. B **86**, 45316 (2012)

Acknowledgements

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Zbig Wasilewski

Nanofabrication:
Alicia Kam

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(McGill University)

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(Instituto de Ciencia de Materiales de Madrid)

Spin manipulation
Michel Pioro-Ladrière
(Sherbrook Unnversity)

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