Few Electron Spin Q-bits and Nuclear Polarization with a Single Electron

Amir Yacoby
Harvard University

Two Electron Spin Q-bit

Experiments in collaboration with:
Jason Petta, Princeton U.
Alex Johnson,
Jake Taylor
C. M. Marcus,
M. D. Lukin
} Harvard U.

Nuclear Polarization

Experiments in collaboration with:
Sandra Foletti,
Diana Mahalu,
Vladimir Umanski
} Weizmann Institute

Useful discussions with:
Hans Andreas Engel Harvard U.
Bert Halperin
Leonid Levitov MIT
Daniel Loss Basel
Peter Zoller Innsbruck

- Two Electron Spin qubit $\alpha|S\rangle + \beta|T_0\rangle$

  T2* = 10ns Nuclear field gradients
  T2 = 1 μs Nuclear flip flop processes

- Nuclear Spins – Problem or Resource

-Electron Nuclear Hyperfine Interaction –
  -Exp: Awschalom, Imamoglu, Kopens, Marcus, Tarucha, Yusa, A…
  -Theory: Dobravitski, Glazman, Hu, Loss, Taylor, …

- Double dot devices as a tool to probe the coupling between the electron and Nuclear spin bath

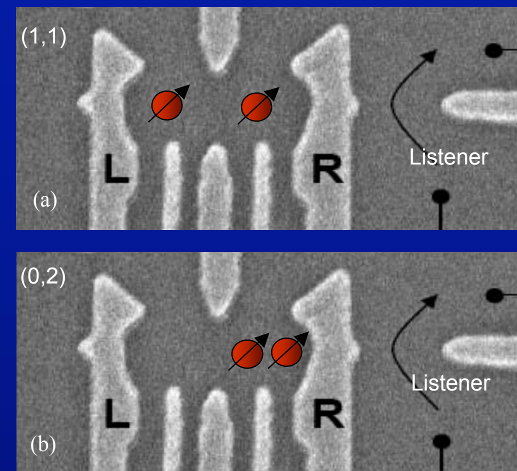
- Adiabatic pumping of nuclei

- Dynamic pumping of nuclei

Funding: ARO

Few electron spin subspaces – Logical Qbits

Single electron spin – RF magnetic field (Loss and Di Vincezo '98)



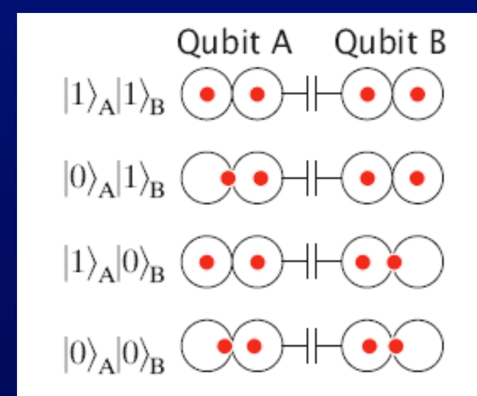
Subspaces of few electron spins:

Two electrons – Magnetic field gradient and electric field (J. Levy '02)

$$\left.\begin{array}{l} |\uparrow\uparrow\rangle \\ |\downarrow\downarrow\rangle \\ |\uparrow\downarrow\rangle+|\downarrow\uparrow\rangle \end{array}\right\} \text{ Triplet } (m_z=1,-1,0)$$

$$|\uparrow\downarrow\rangle-|\downarrow\uparrow\rangle \quad \text{Singlet } (m_z=0)$$

Capacitive coupling between Qbits



$|0_L\rangle = |S\rangle \quad |1_L\rangle = |T_0\rangle$

Absence of overlap:
identical wave functions
Immune to charge fluctuations - DFS

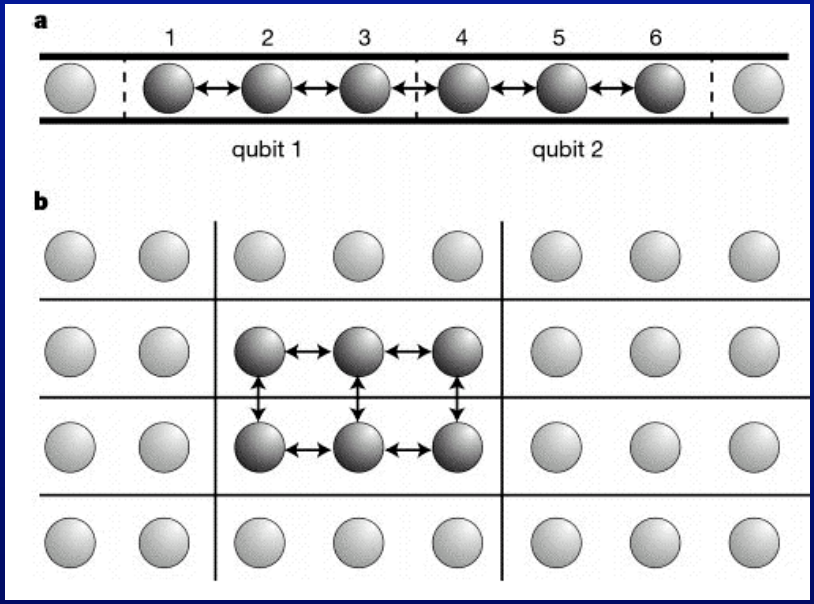
$|0_L\rangle = |S\rangle \quad |1_L\rangle = |T_+\rangle$

Control of nuclear subsystem

J. M. Taylor et al, Nature Physics 1, 177 (2005).

Few electron spin subspaces – Logical Qbits

Three electrons – Universal operations only with exchange interaction

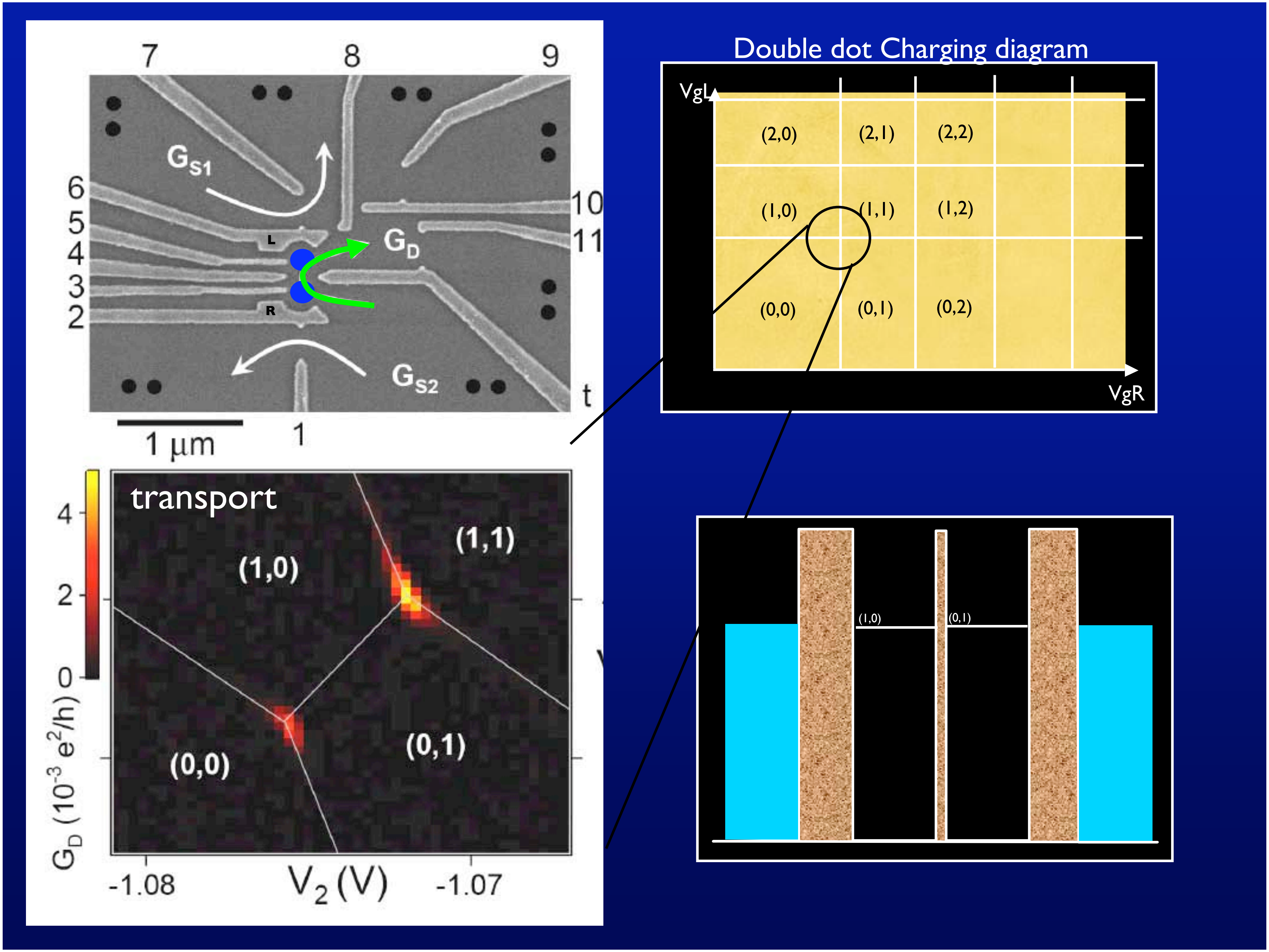


exchange interaction can be turned on simultaneously.

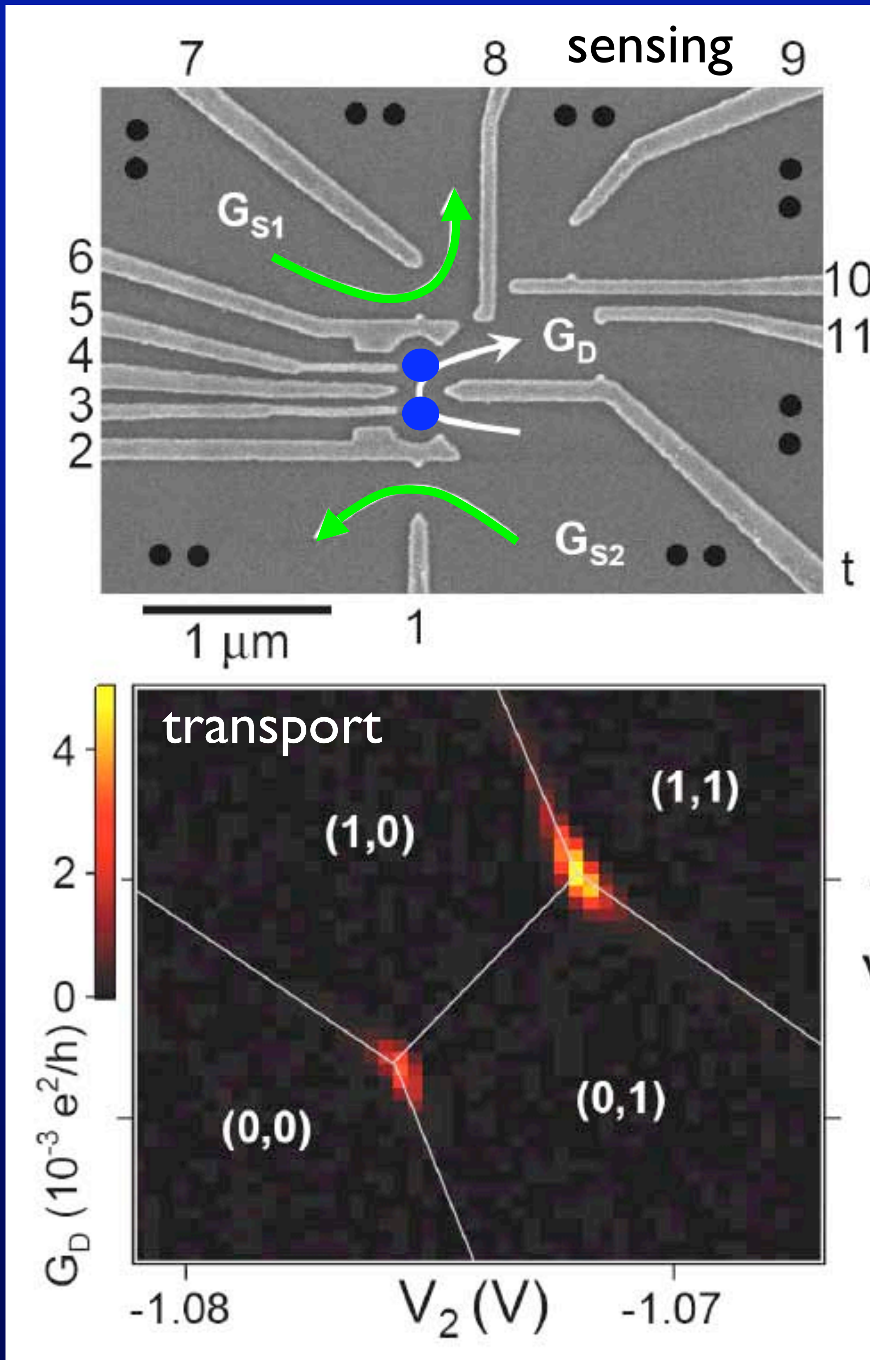
$$\left|0_L\right\rangle = \left|S\right\rangle\left|\uparrow\right\rangle$$

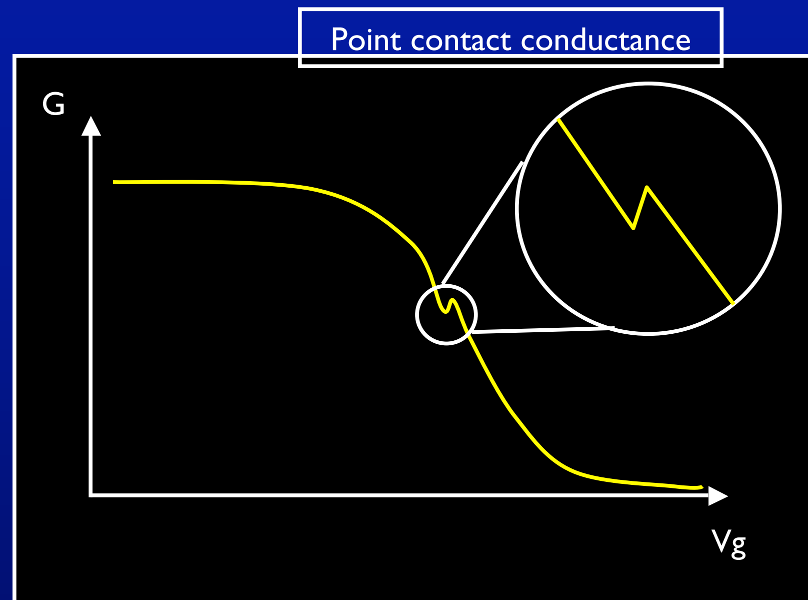
$$\left|1_L\right\rangle = \left(\frac{2}{3}\right)^{1/2}\left|T_+\right\rangle\left|\downarrow\right\rangle - \left(\frac{1}{3}\right)^{1/2}\left|T_-\right\rangle\left|\uparrow\right\rangle$$

Di. Vincenzo et al, *Nature* **408**, 339 (2000).

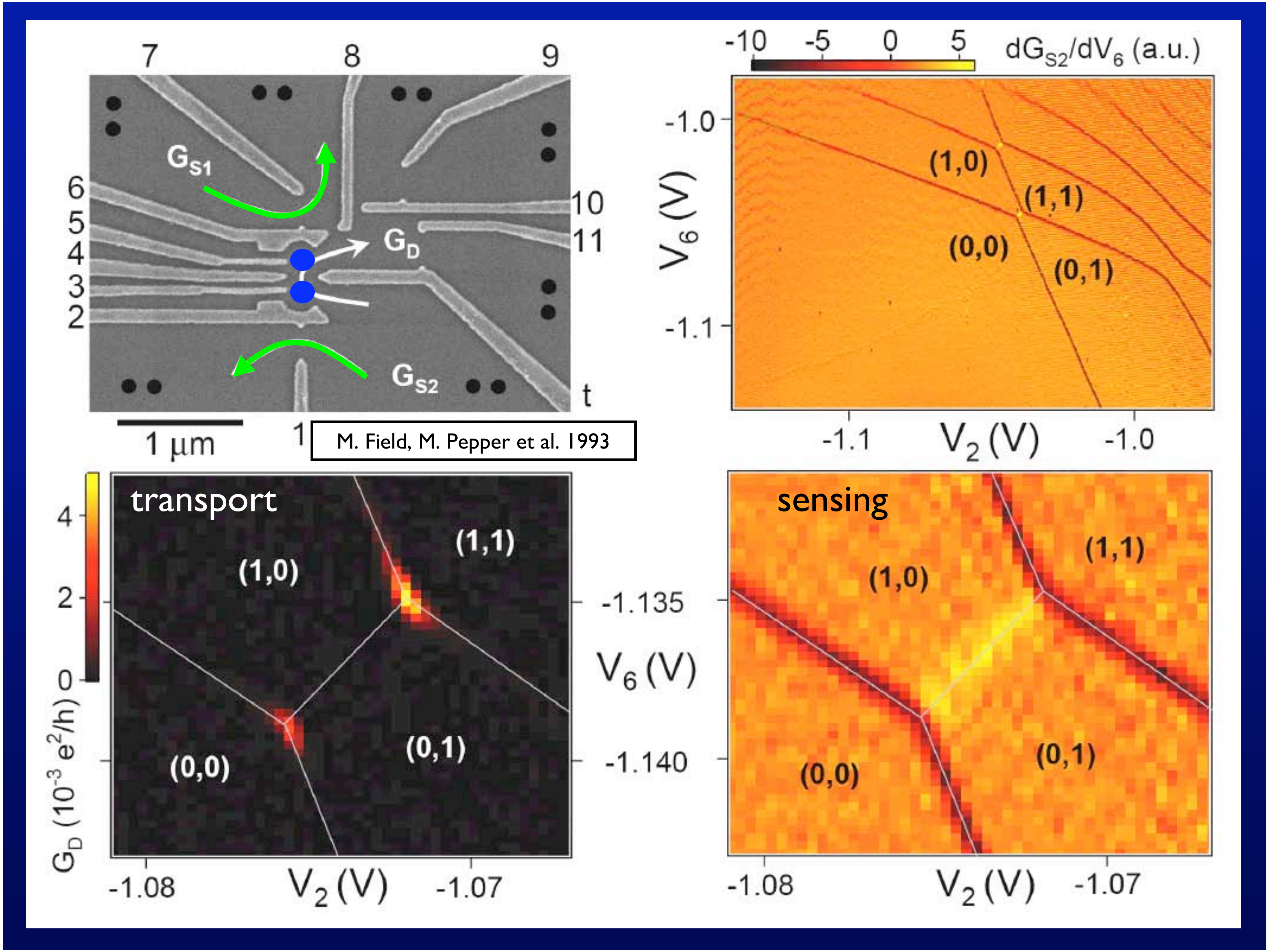


Double dot Charging diagram
VgL
VgR
(2,0)
(2,1)
(2,2)
(1,0)
(1,1)
(1,2)
(0,0)
(0,1)
(0,2)
7
8
9
6
5
4
3
2
10
11
t
1
L
R
G_{S1}
G_D
G_{S2}
1 μm
transport
(1,0)
(1,1)
(0,0)
(0,1)
G_D (10^{-3} e^2/h)
4
2
0
-1.08
V_2 (V)
-1.07
(1,0)
(0,1)



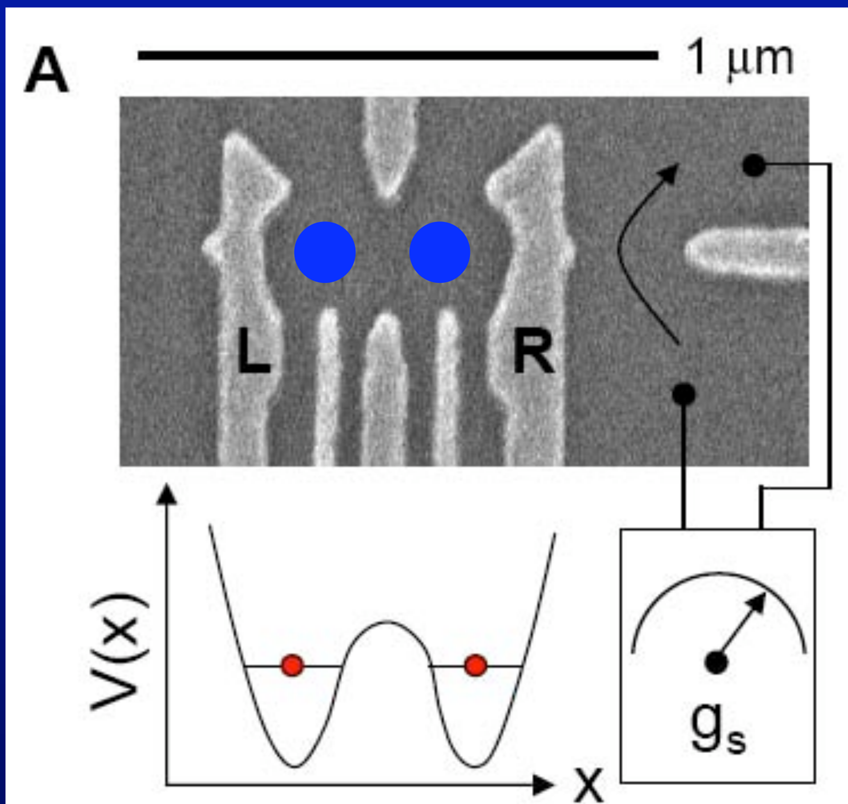


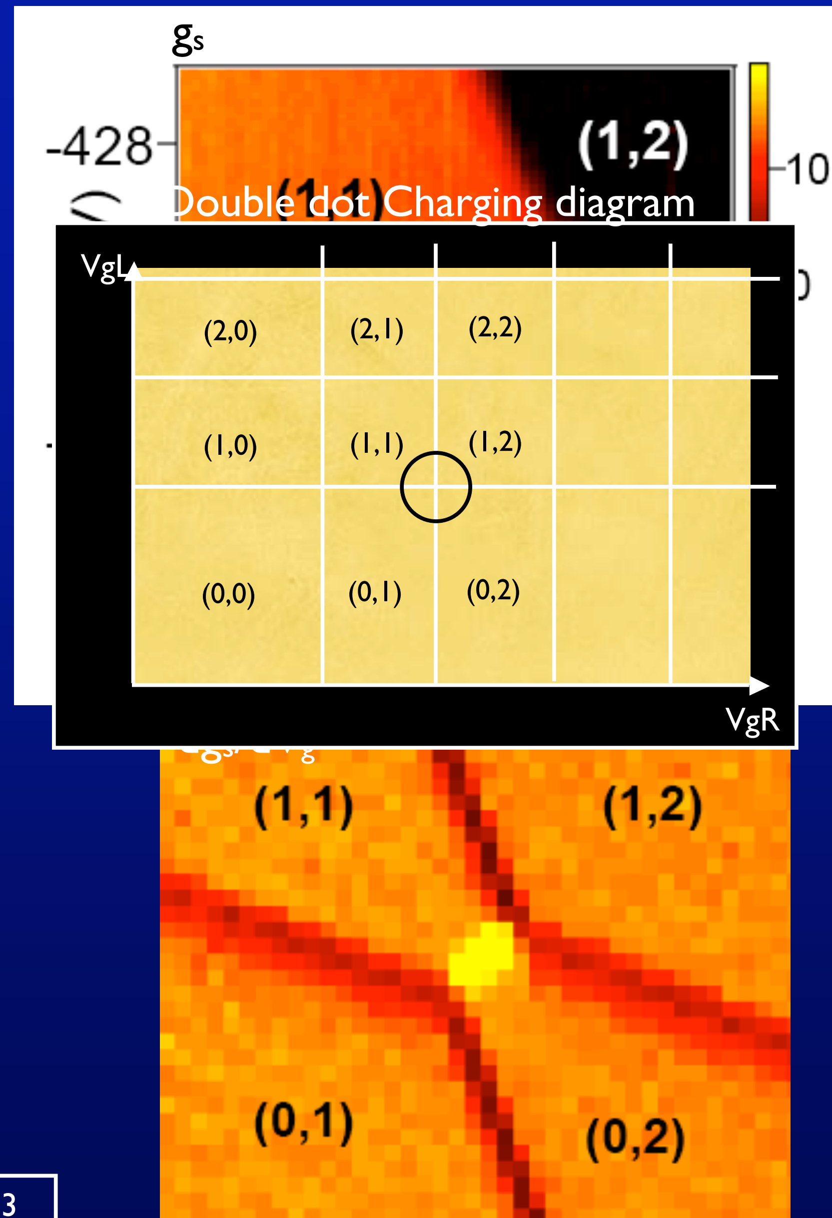
M. Field, M. Pepper et al. 1993



7
8
9
G_{S1}
6
5
4
3
2
10
11
G_D
G_{S2}
t
1 μm
1
M. Field, M. Pepper et al. 1993
-10 -5 0 5
dG_{S2}/dV_6 (a.u.)
-1.0
-1.1
V_6 (V)
(1,0)
(1,1)
(0,0)
(0,1)
-1.1
V_2 (V)
-1.0
transport
4
2
0
G_D (10^{-3} e^2/h)
(1,0)
(1,1)
(0,0)
(0,1)
-1.08
V_2 (V)
-1.07
-1.135
V_6 (V)
-1.140
sensing
(1,0)
(1,1)
(0,0)
(0,1)
-1.08
V_2 (V)
-1.07

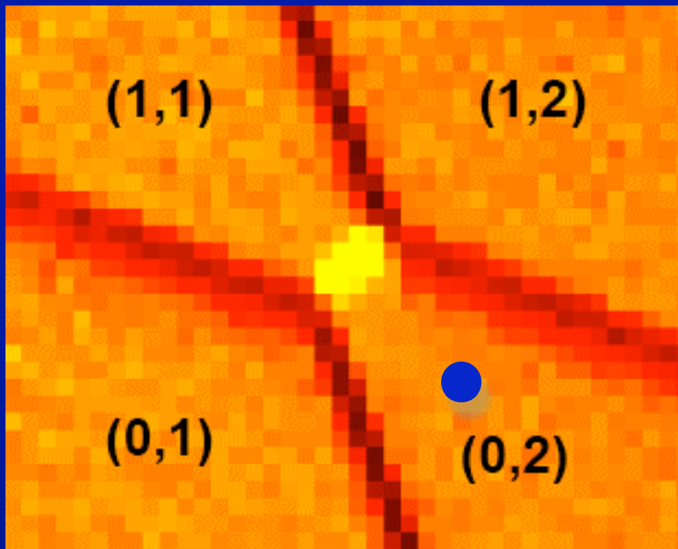
Spin Relaxation and Dephasing: The Two-Electron System

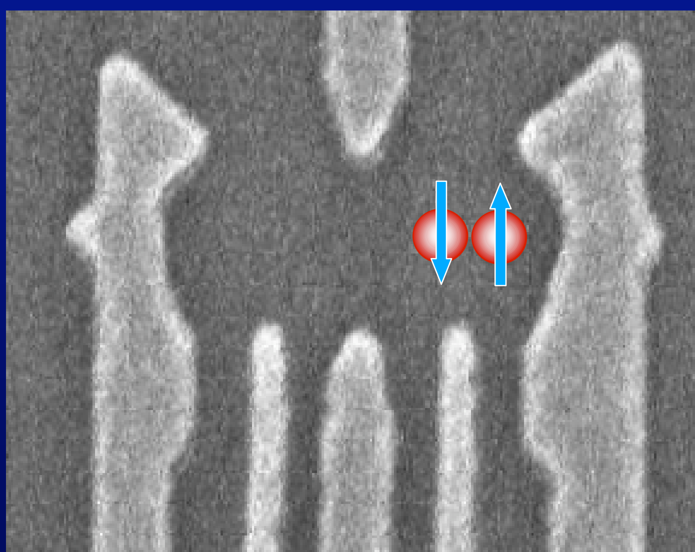




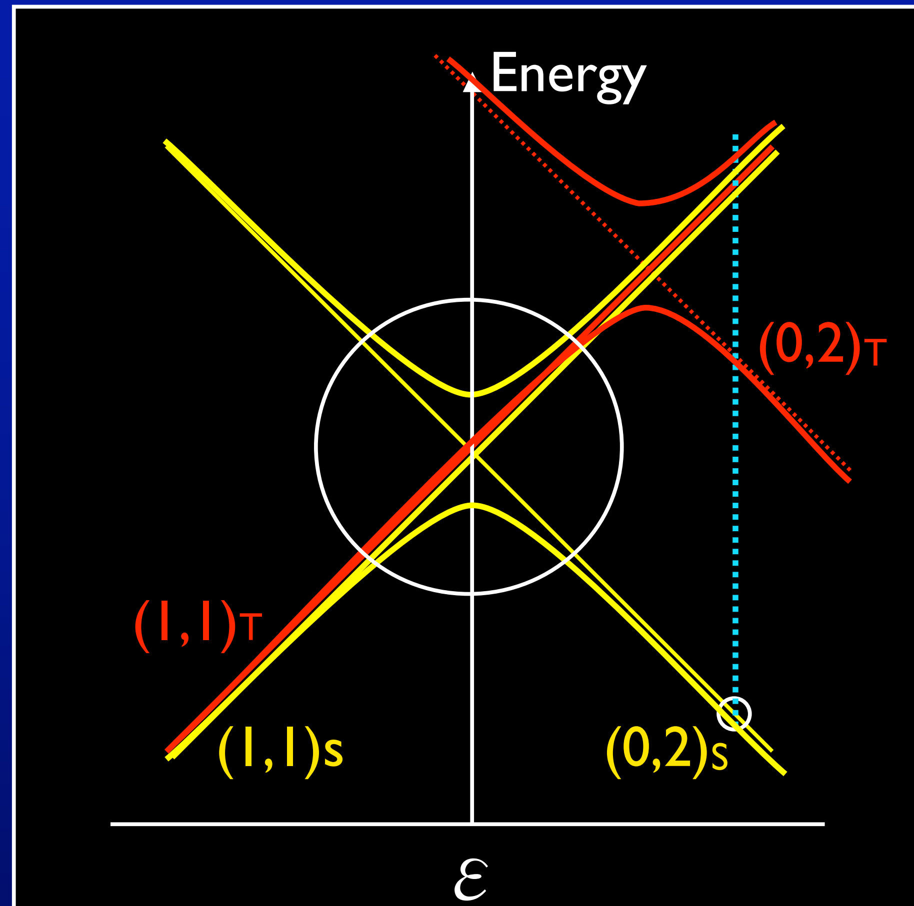
M. Field, M. Pepper et al. 1993

Controllable Energy Diagram





$$|\uparrow\uparrow\rangle ; |\downarrow\downarrow\rangle ; |\uparrow\downarrow\rangle ; |\downarrow\uparrow\rangle$$



Ground state configurations

Tunnel coupling

$|\uparrow\uparrow\rangle$

$|\downarrow\downarrow\rangle$

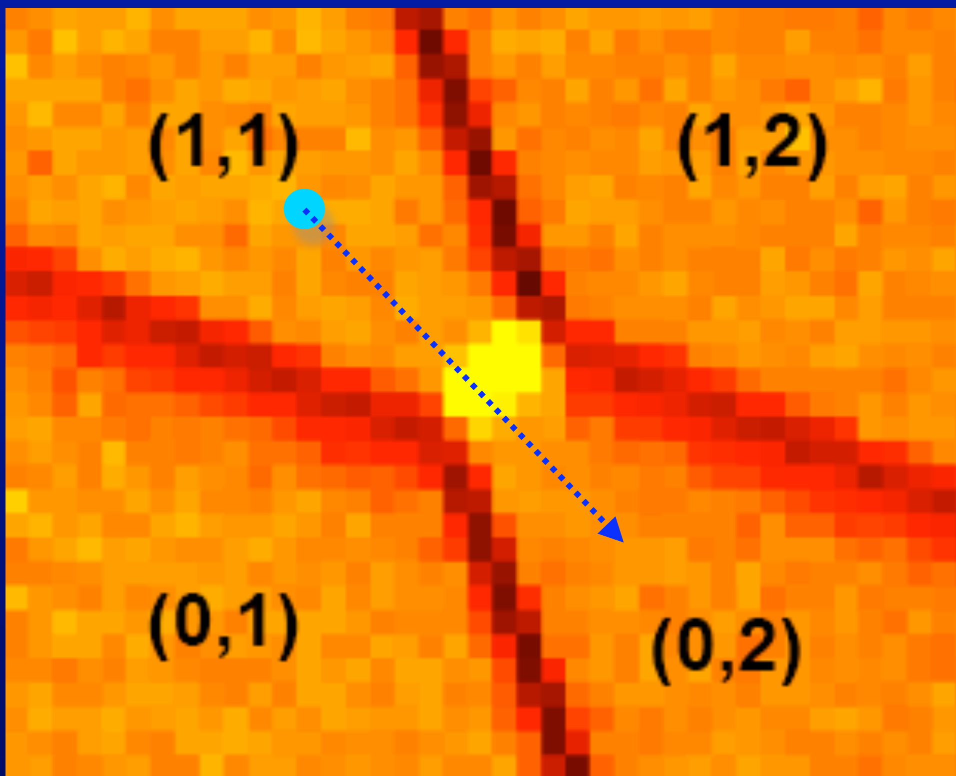
$|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle$

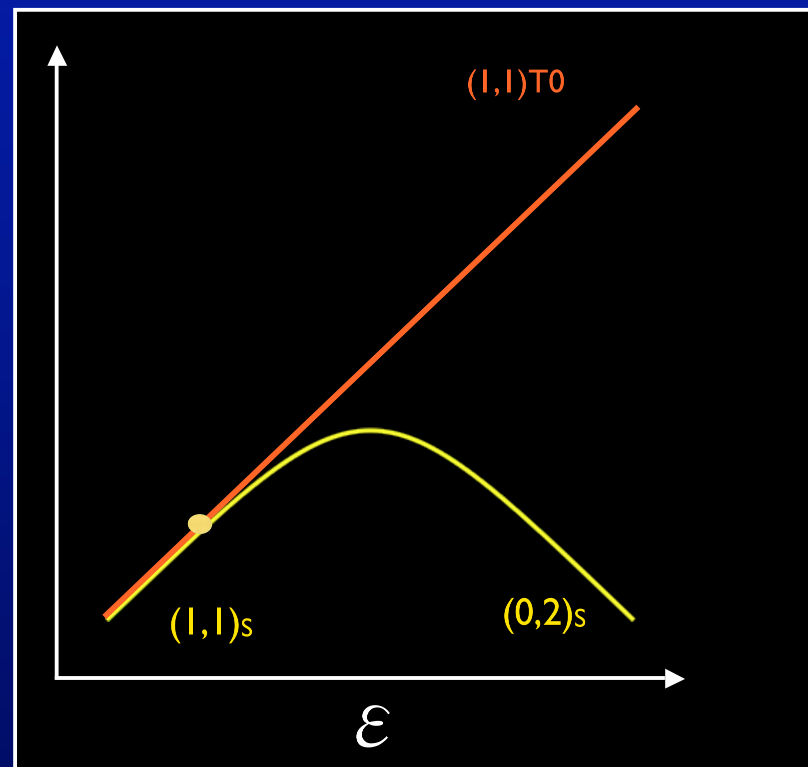
Triplet (m_z=1,-1,0)

$|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

Singlet (m_z=0)

Conversion of Spin to Charge

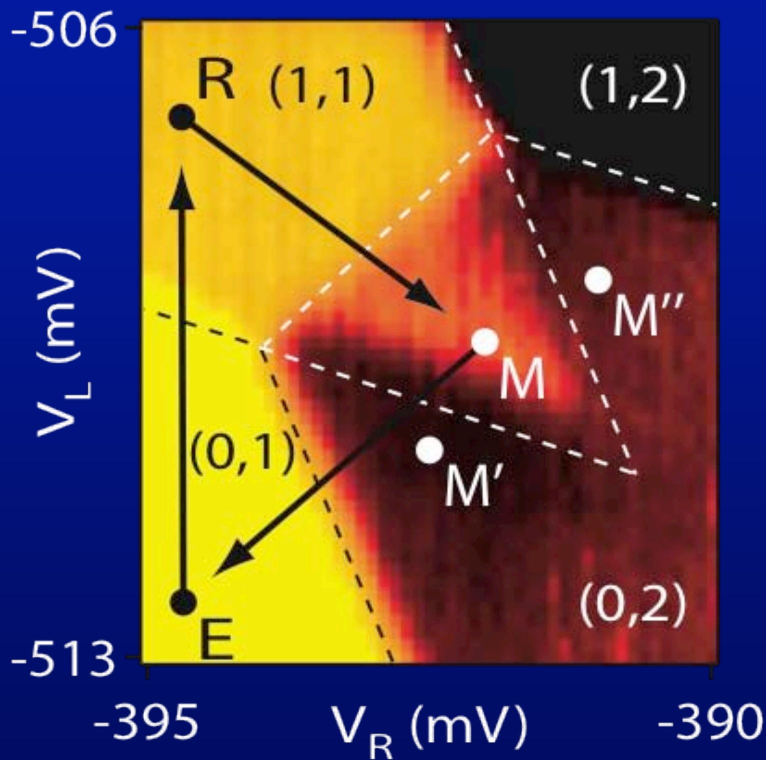


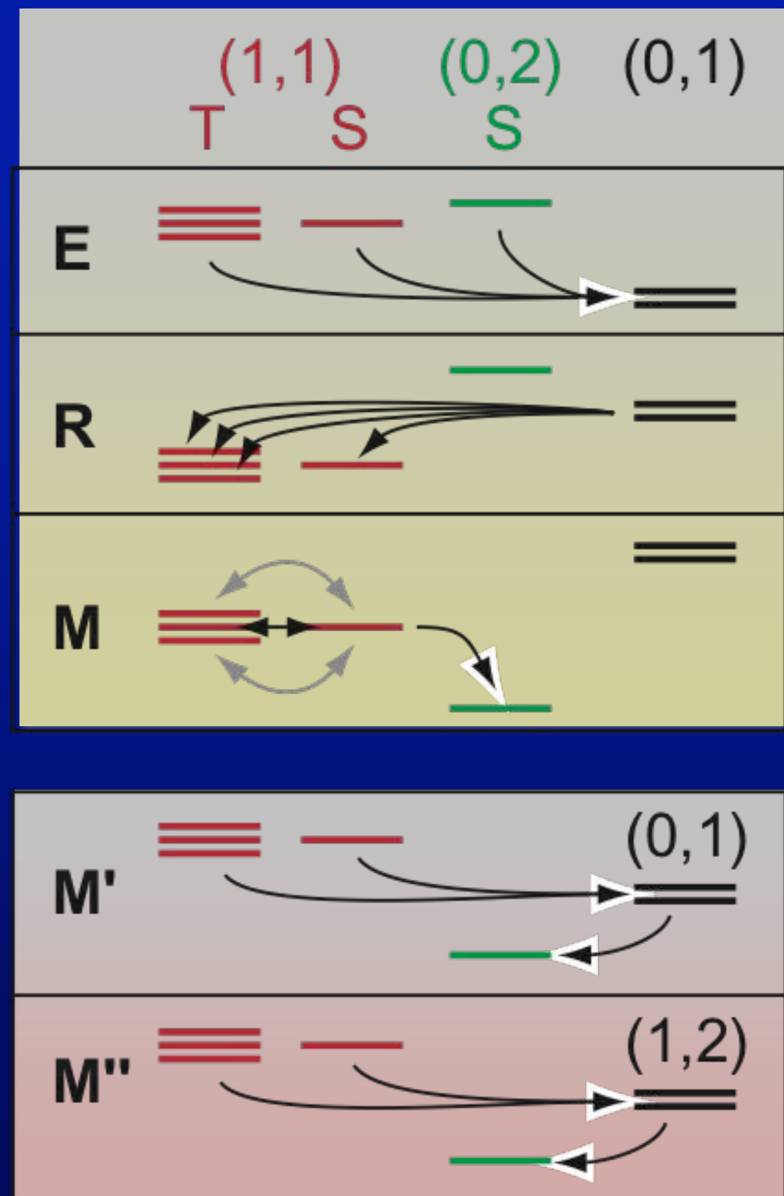


Relies on long spin relaxation times ~100 ms

S. Amasha et al, condmat 2007,
A. Johnson, et al, Nature '04,
Kroutvar et al, Nature '04,
Fujisawa et al, Nature '02.

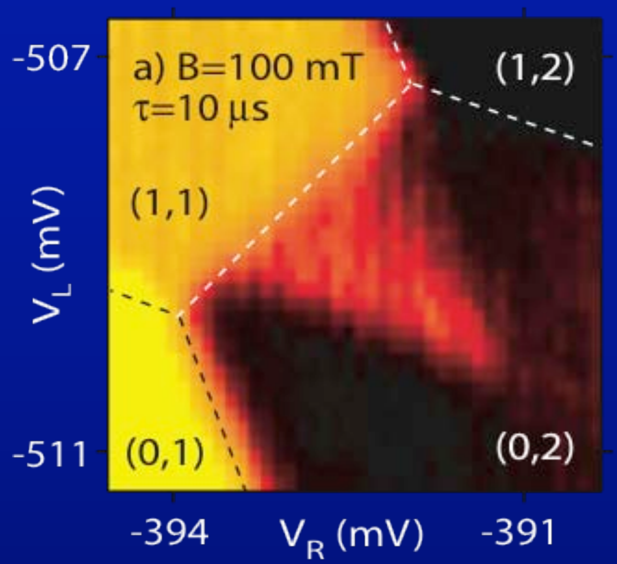
Spin relaxation: Getting Stuck in (1,1)

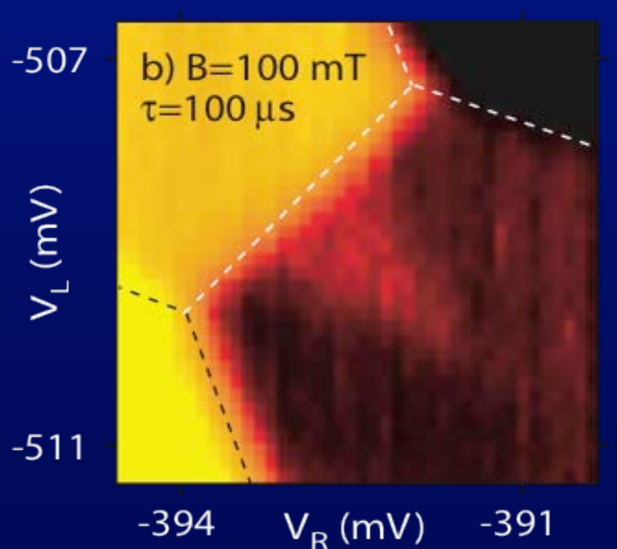


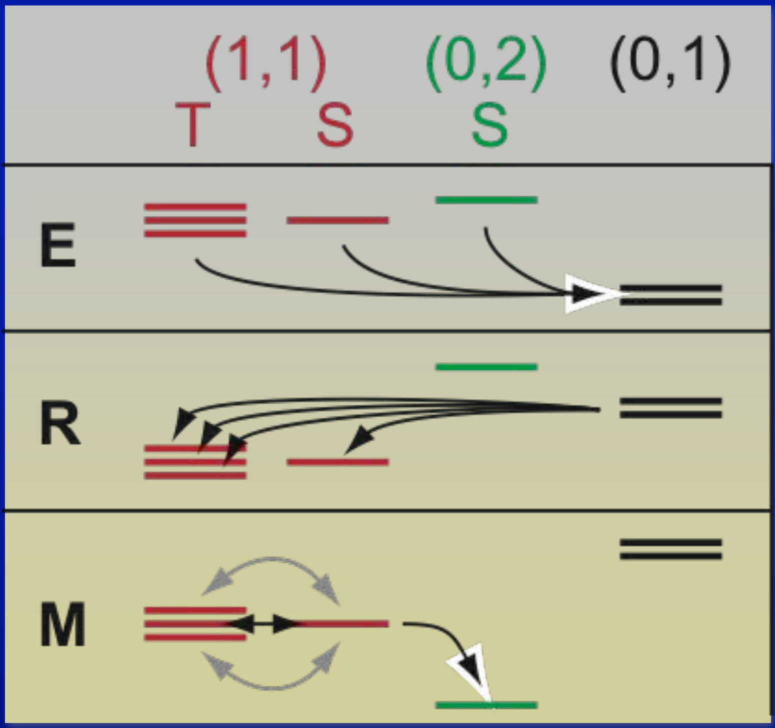


In "measurement triangle"
dark: transition to (0,2) occurs
light: transition to (0,2) blockaded

Spin relaxation: Getting Stuck in (1,1)







In a Uniform External Magnetic Field

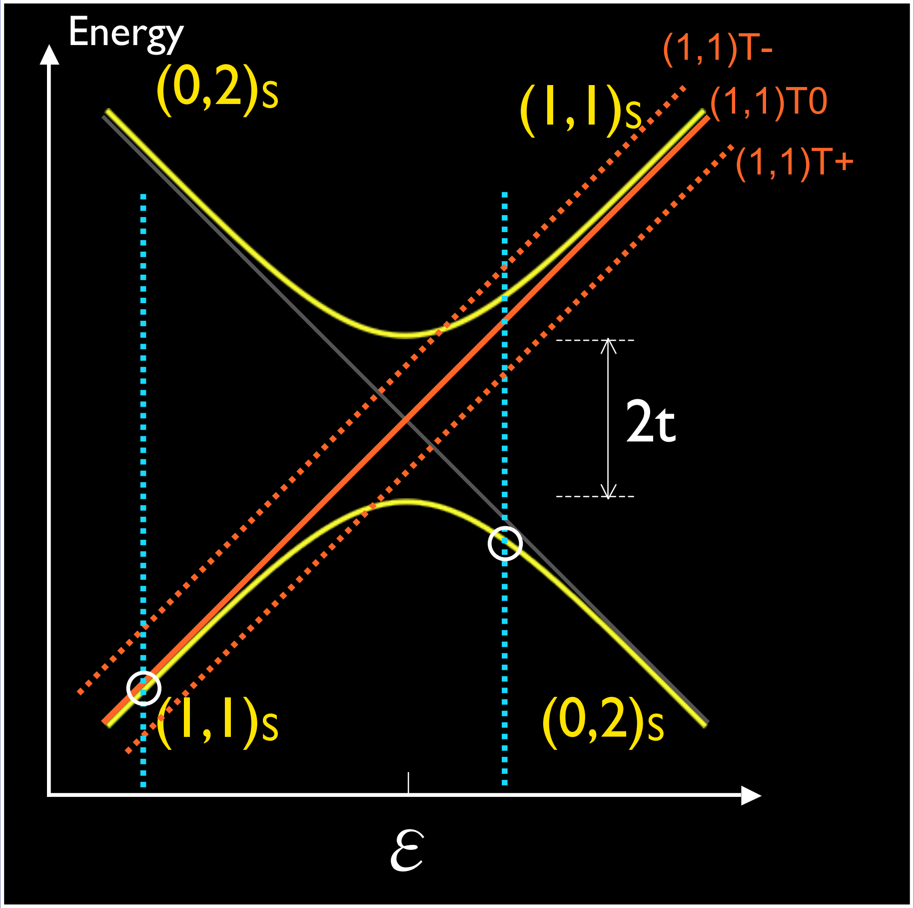
Ignore T+ and T-

Logical q-bit (J. Levy, PRL 89, 147902, 02')

$$|0\rangle_L = |S\rangle \qquad |1\rangle_L = |T_0\rangle$$

In (1,1) – $|0\rangle_L$, $|1\rangle_L$

Immune to charge fluctuations and uniform magnetic filed

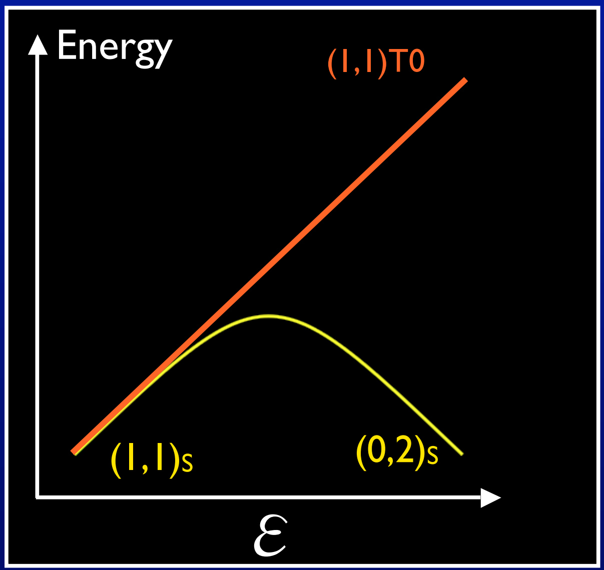


Comparison with Spin 1/2

$|0\rangle_L = |S\rangle$ $|1\rangle_L = |T_0\rangle$

$\alpha|S\rangle + \beta|T_0\rangle$

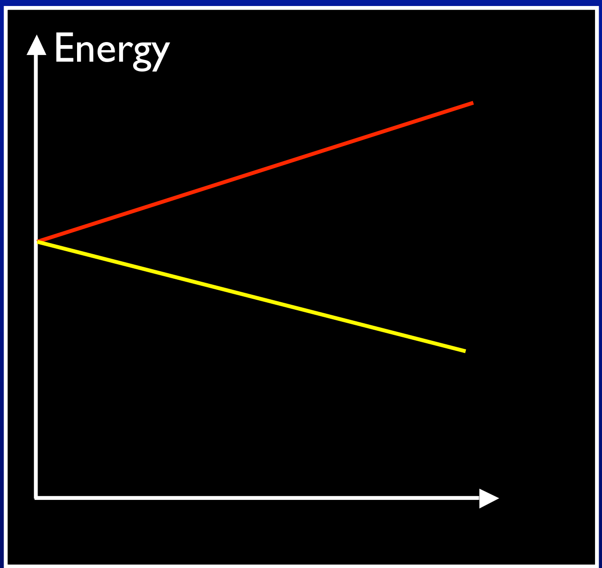
Exchange $\mathcal{E}$: $E_{ex}(\varepsilon)\cdot\hat{\sigma}_Z$



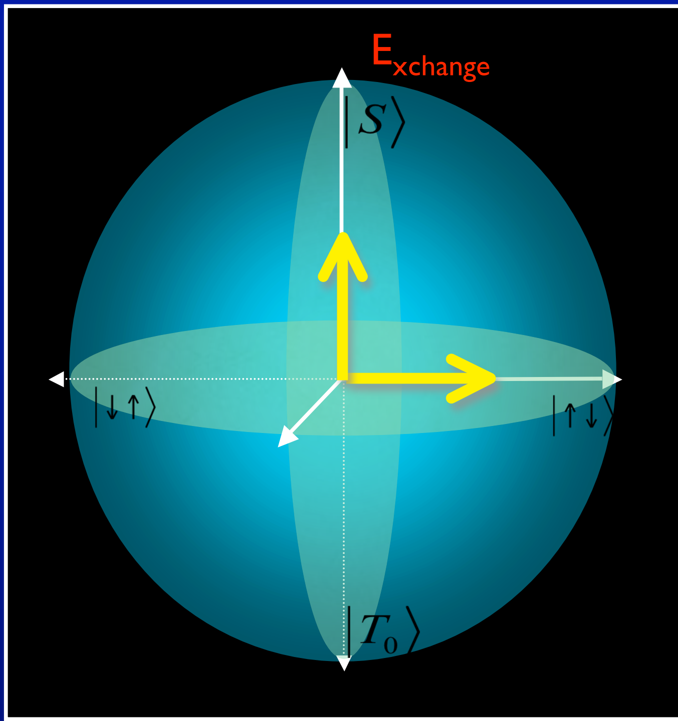
$|0\rangle_L = |\uparrow\rangle$ $|1\rangle_L = |\downarrow\rangle$

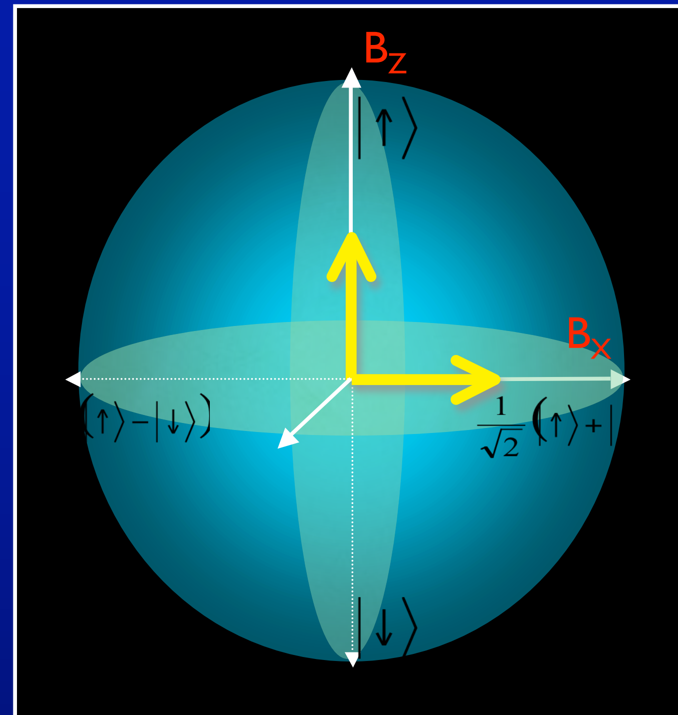
$\alpha|\uparrow\rangle + \beta|\downarrow\rangle$

External field : $g\mu_B B_Z \cdot\hat{\sigma}_Z$



Comparison with Spin 1/2





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

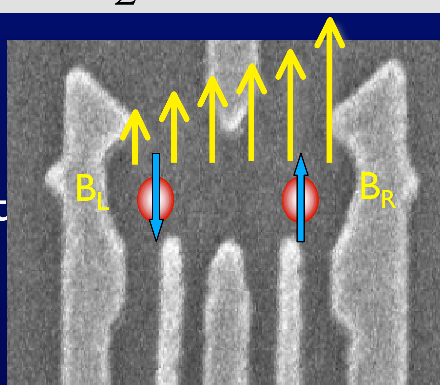
$$\frac{1}{2}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right) + \frac{1}{2}\left(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle\right) = |\uparrow\downarrow\rangle$$

$$g\mu_B B_X \cdot \hat{\sigma}_X$$

Eigenstates:

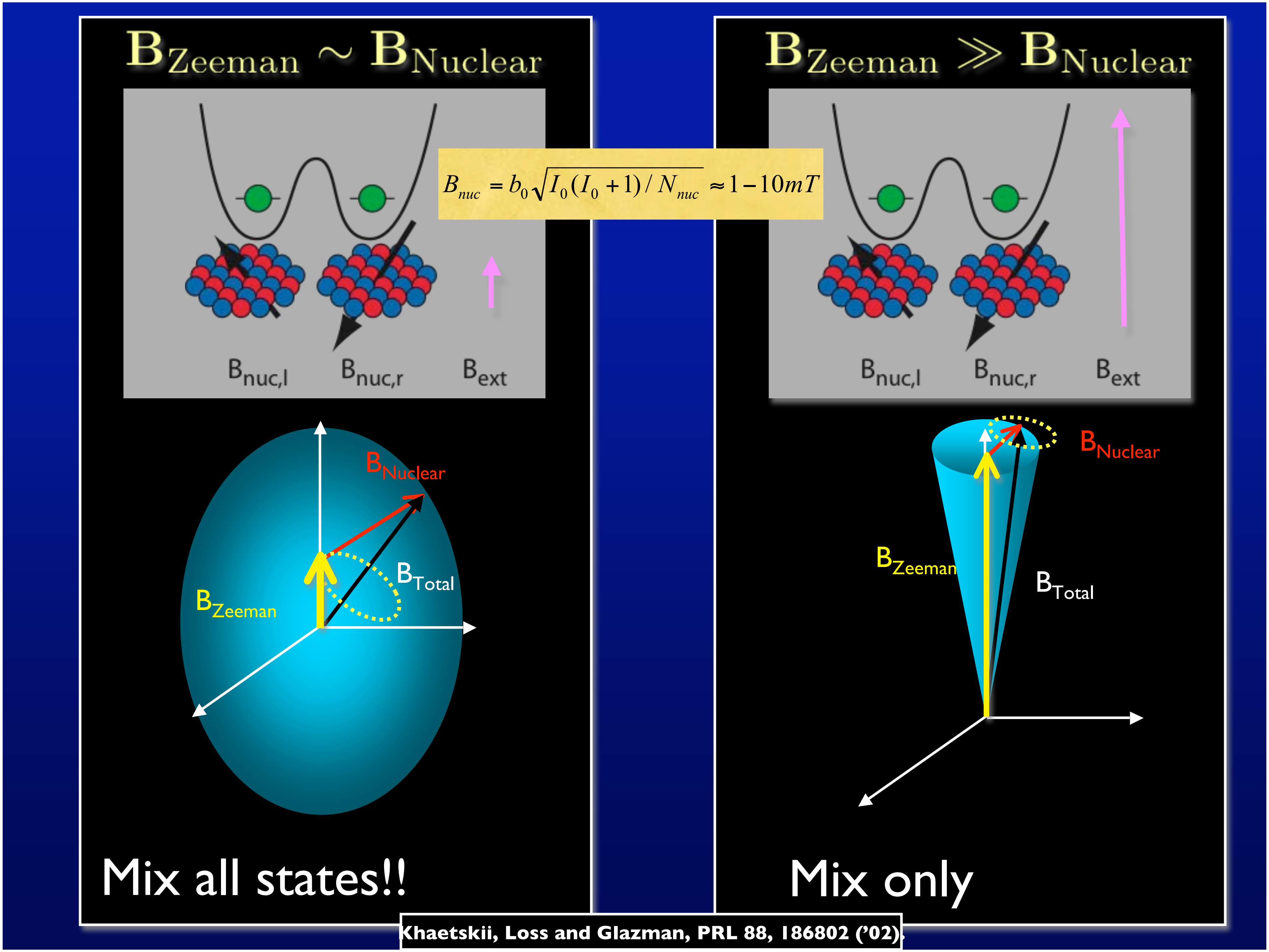
$$|X\pm\rangle \frac{1}{\sqrt{2}}\left(|\uparrow\rangle \pm |\downarrow\rangle\right)$$

Magnetic field gradient



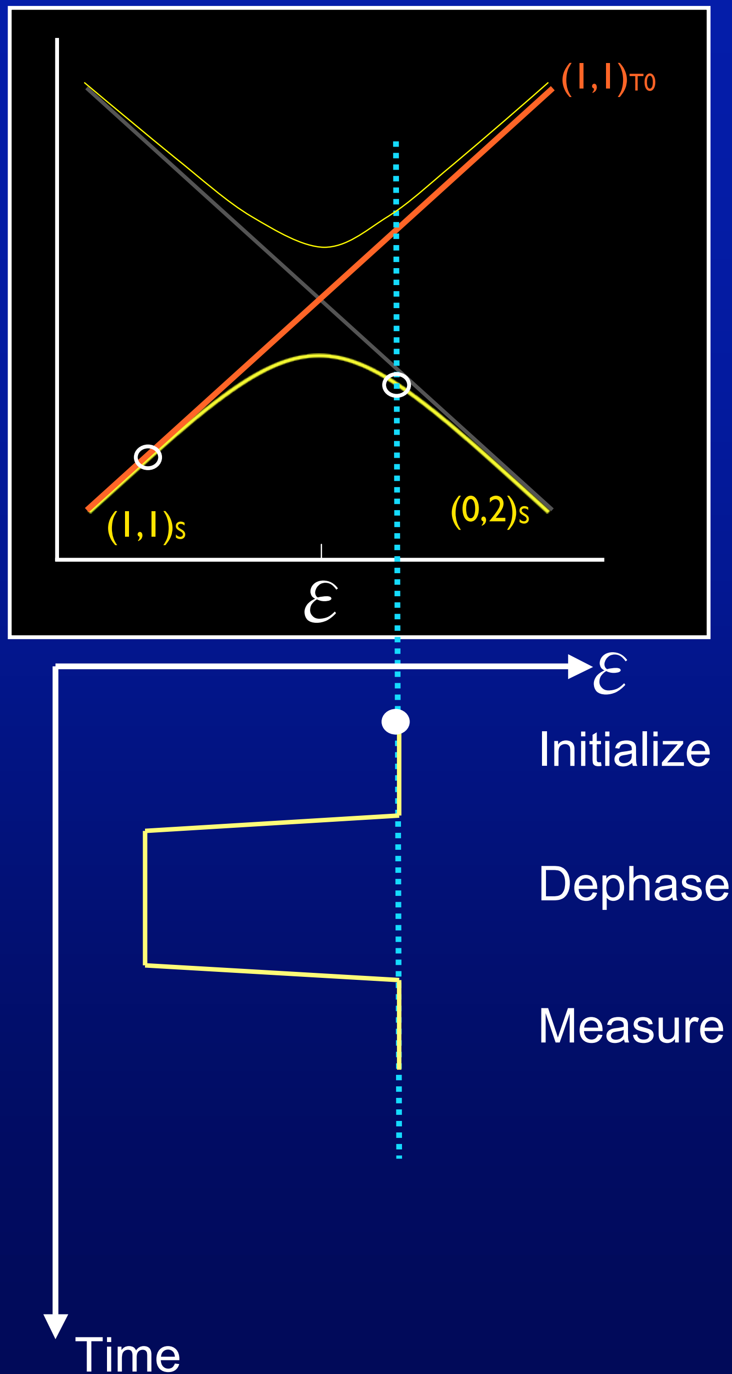
$$|\psi(t)\rangle = e^{iB_Lt}|\uparrow\rangle e^{-iB_Rt}|\downarrow\rangle - e^{-iB_Lt}|\downarrow\rangle e^{iB_Rt}|\uparrow\rangle =$$

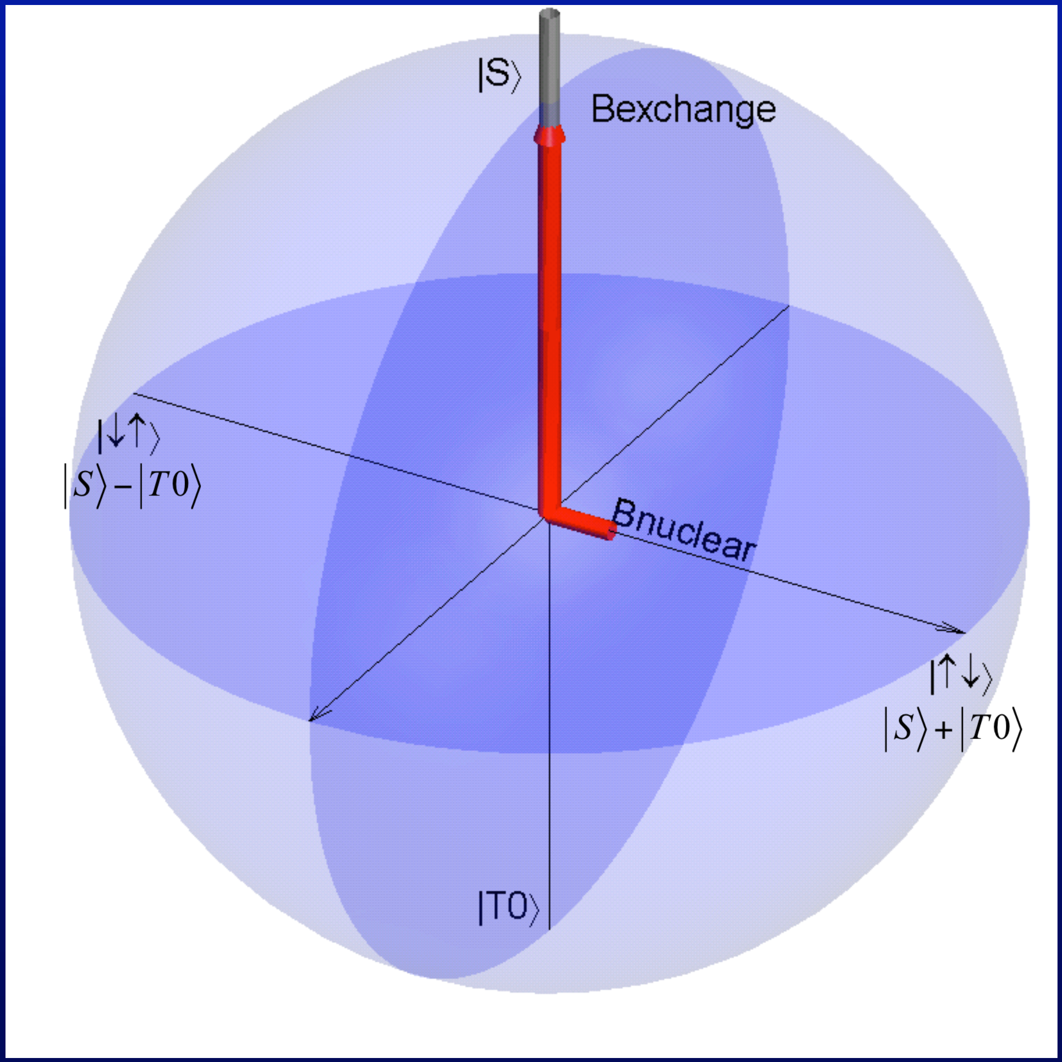
Random nuclear hyperfine field produces a slow varying field gradient


$B_{Zeeman} \sim B_{Nuclear}$
$B_{nuc,l}$
$B_{nuc,r}$
B_{ext}
$B_{nuc} = b_0\sqrt{I_0(I_0+1)/N_{nuc}} \approx 1-10mT$
$B_{Nuclear}$
B_{Total}
B_{Zeeman}
Mix all states!!
$B_{Zeeman} \gg B_{Nuclear}$
$B_{nuc,l}$
$B_{nuc,r}$
B_{ext}
$B_{Nuclear}$
B_{Zeeman}
B_{Total}
Mix only
Khaetskii, Loss and Glazman, PRL 88, 186802 ('02).

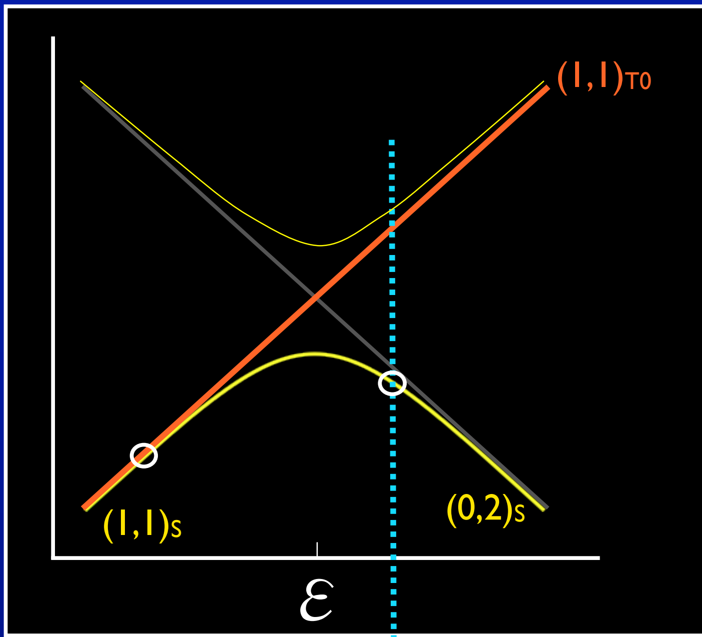
Measuring T2*

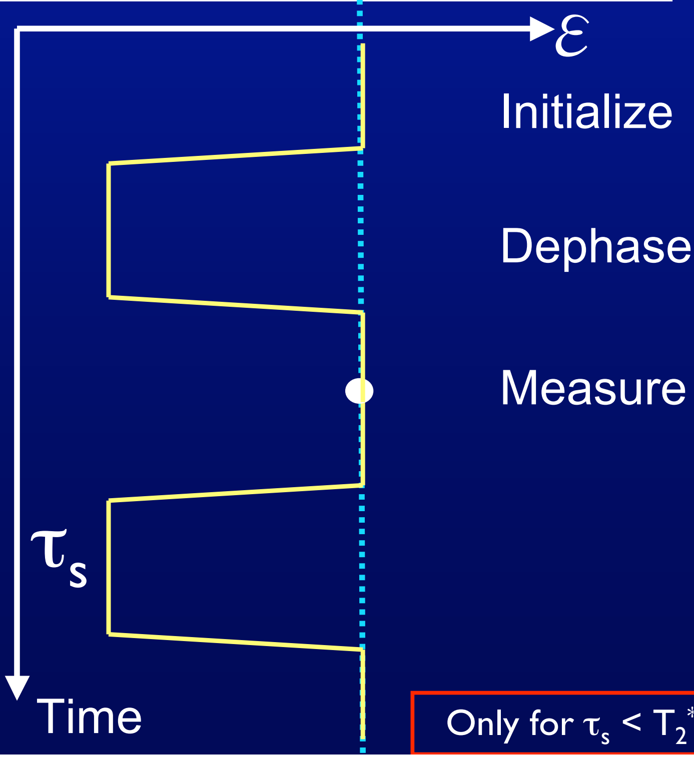
Re-define the q-bit

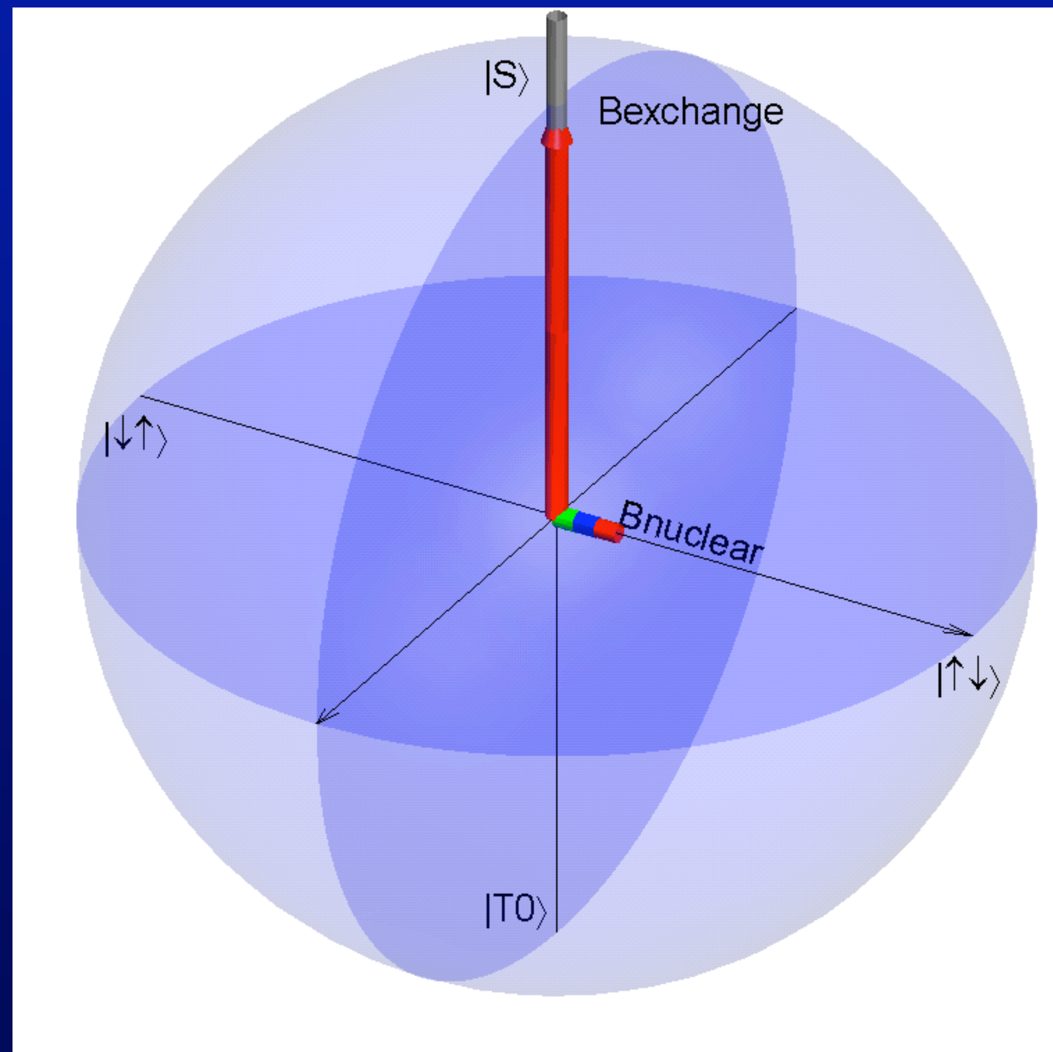




Measuring T2*

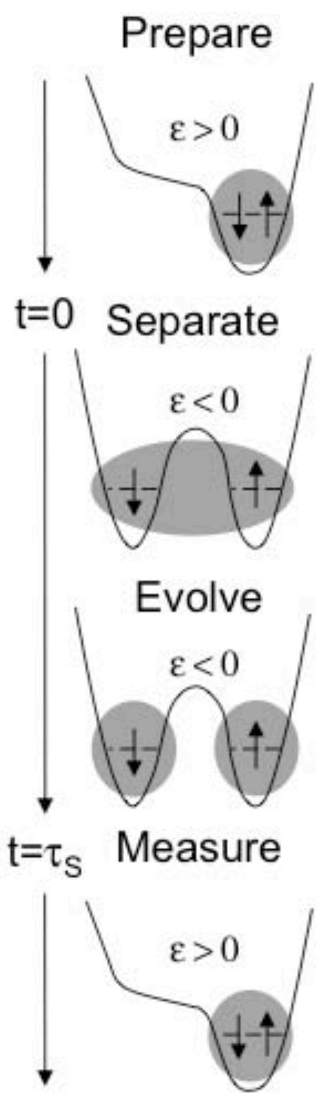


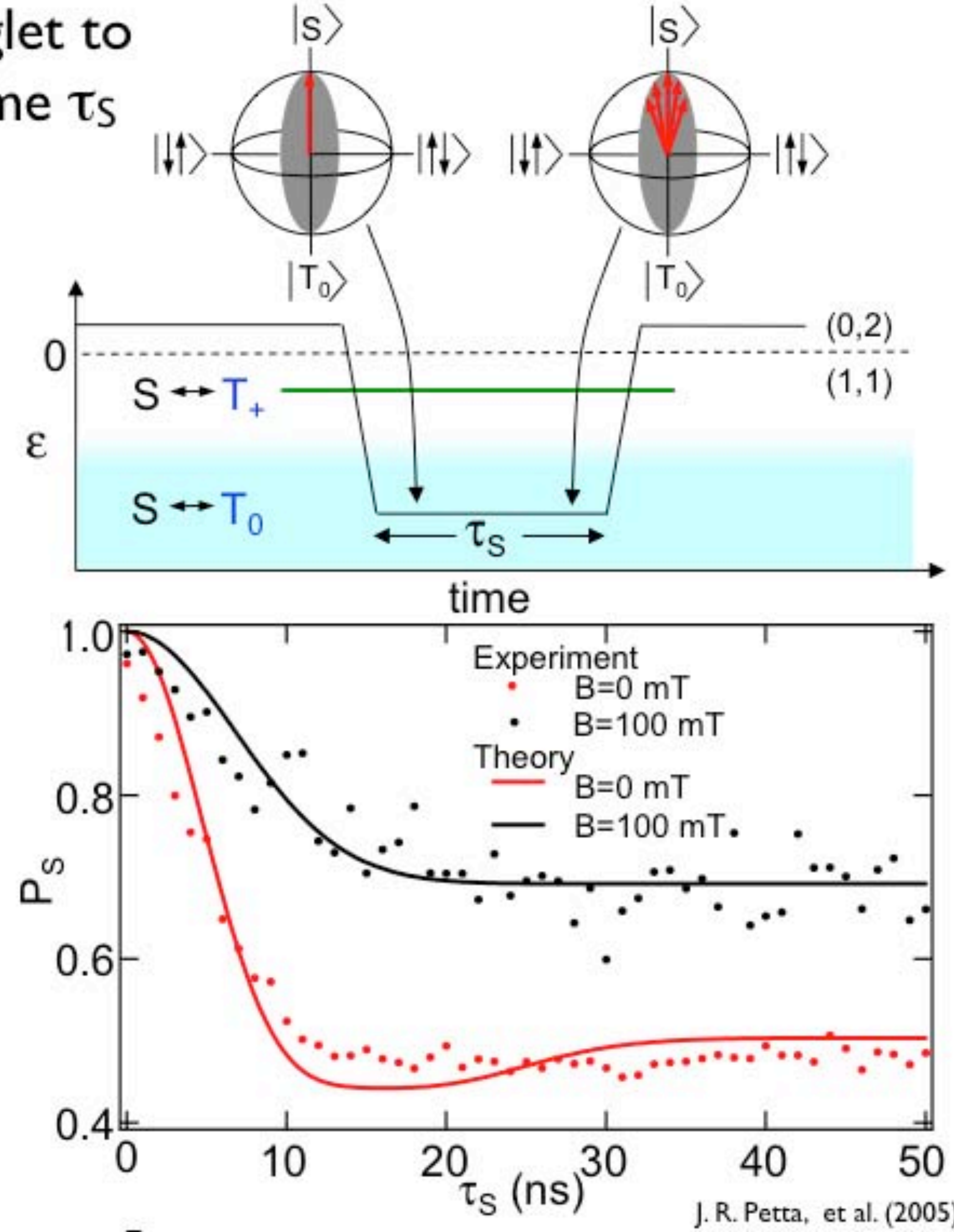




Only for $\tau_s < T_2^*$ have high return probability

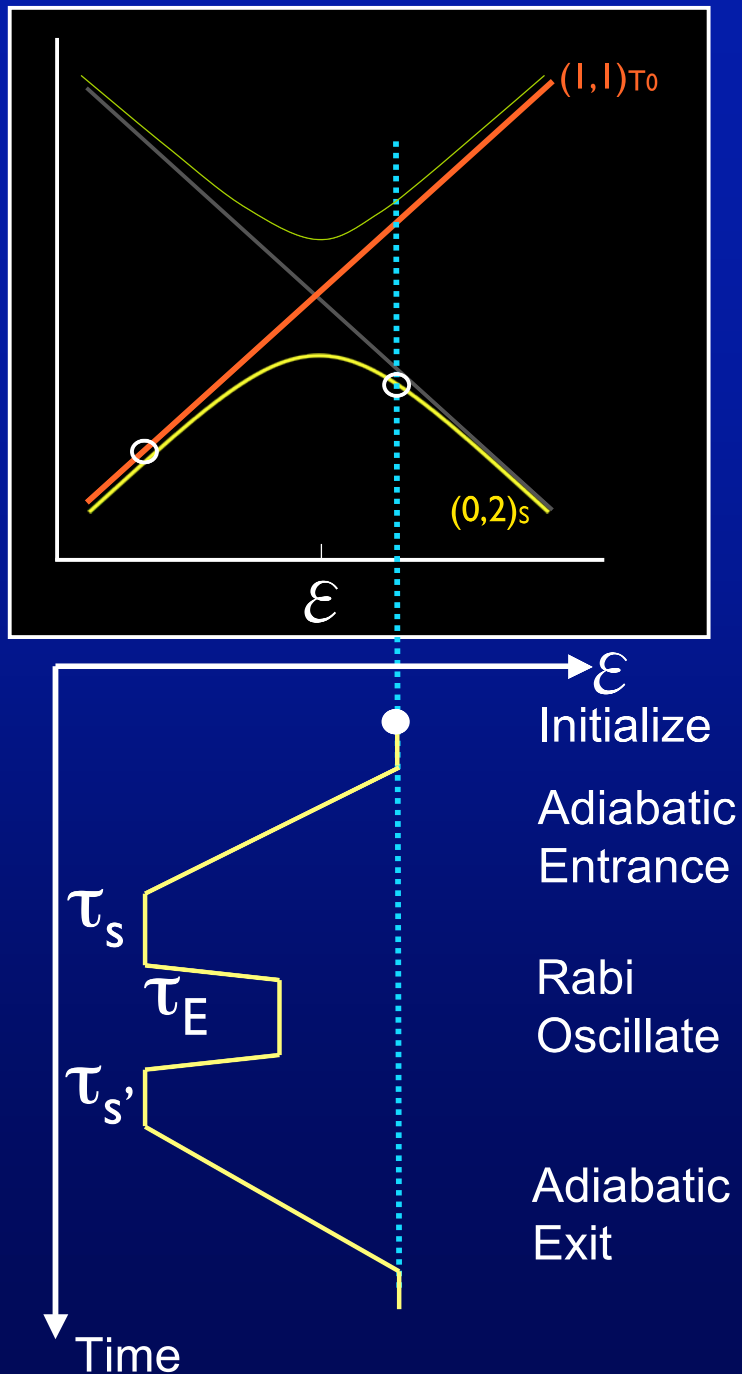
Probability for separated singlet to be found in a singlet after time τ_S

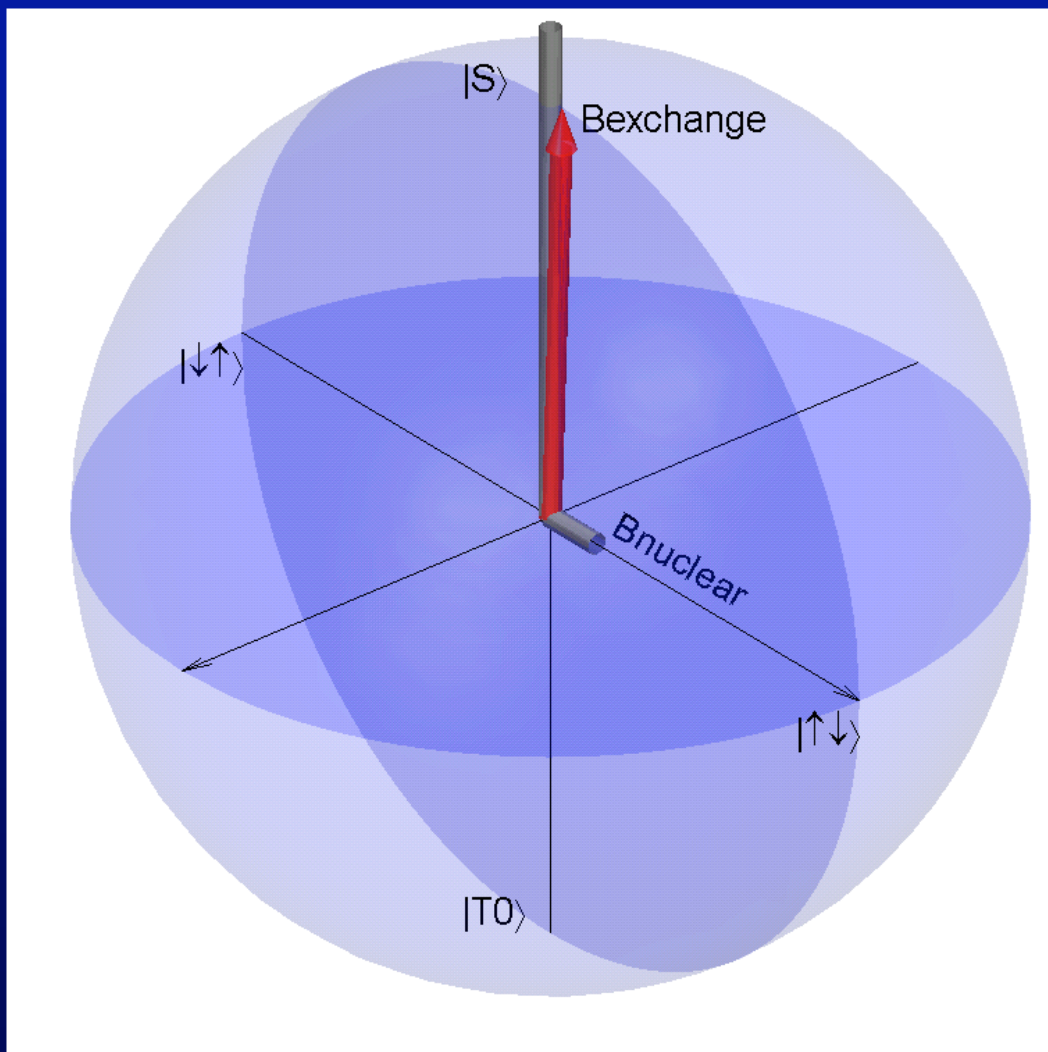




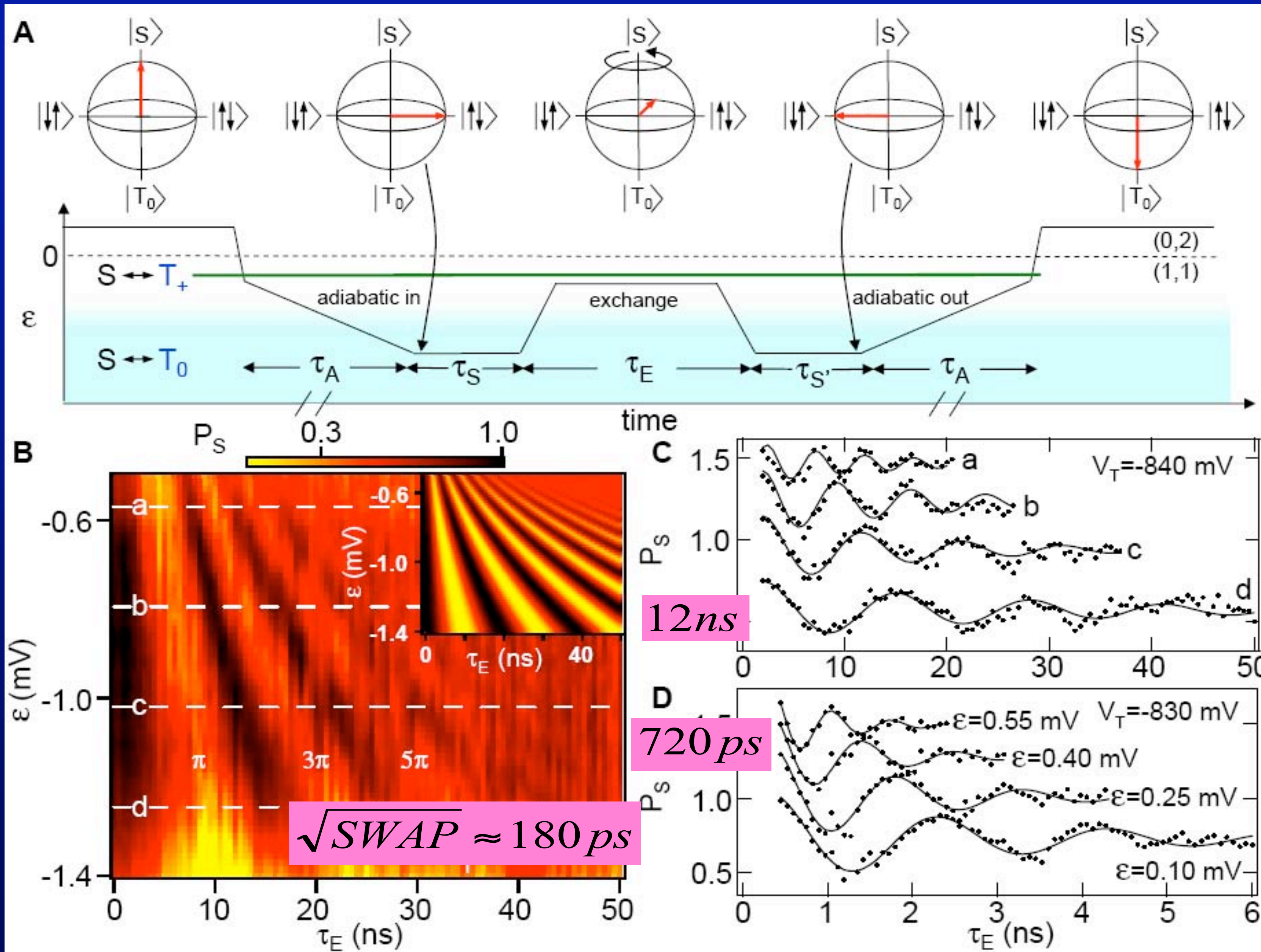
Coherent Spin Control

Rabi Oscillations



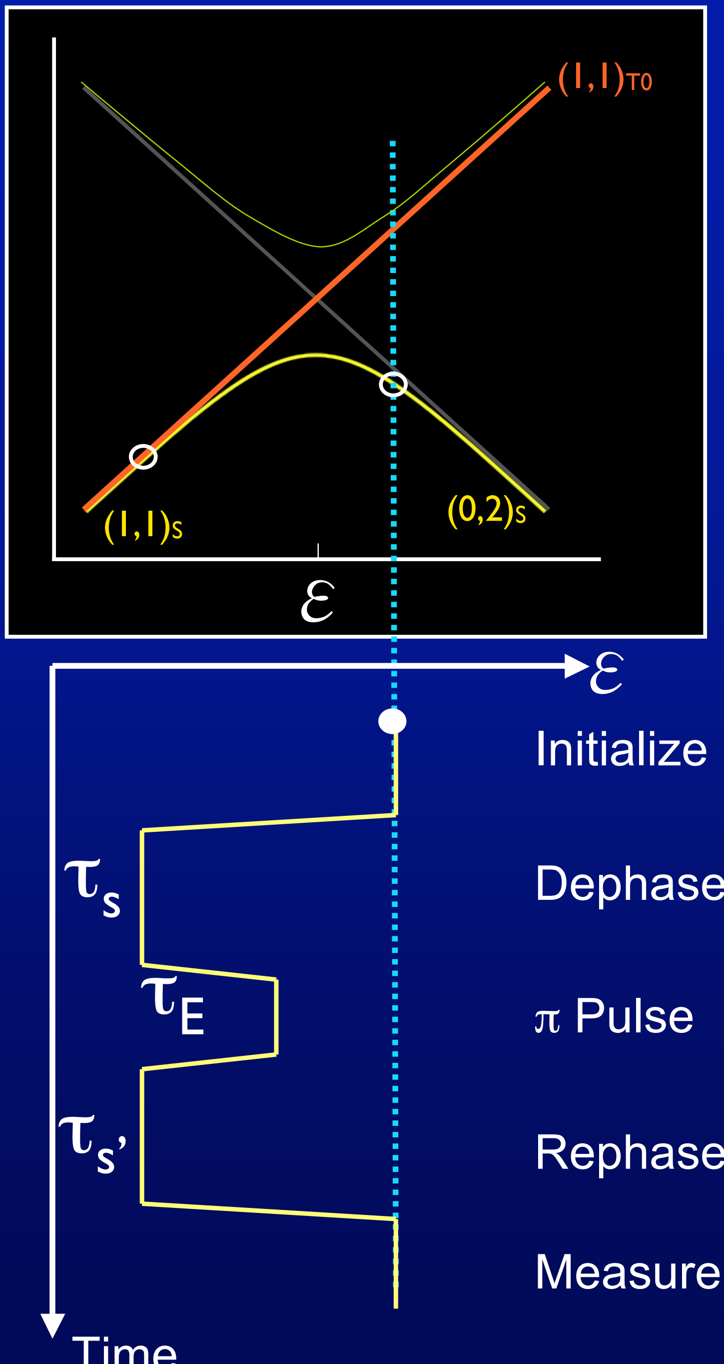


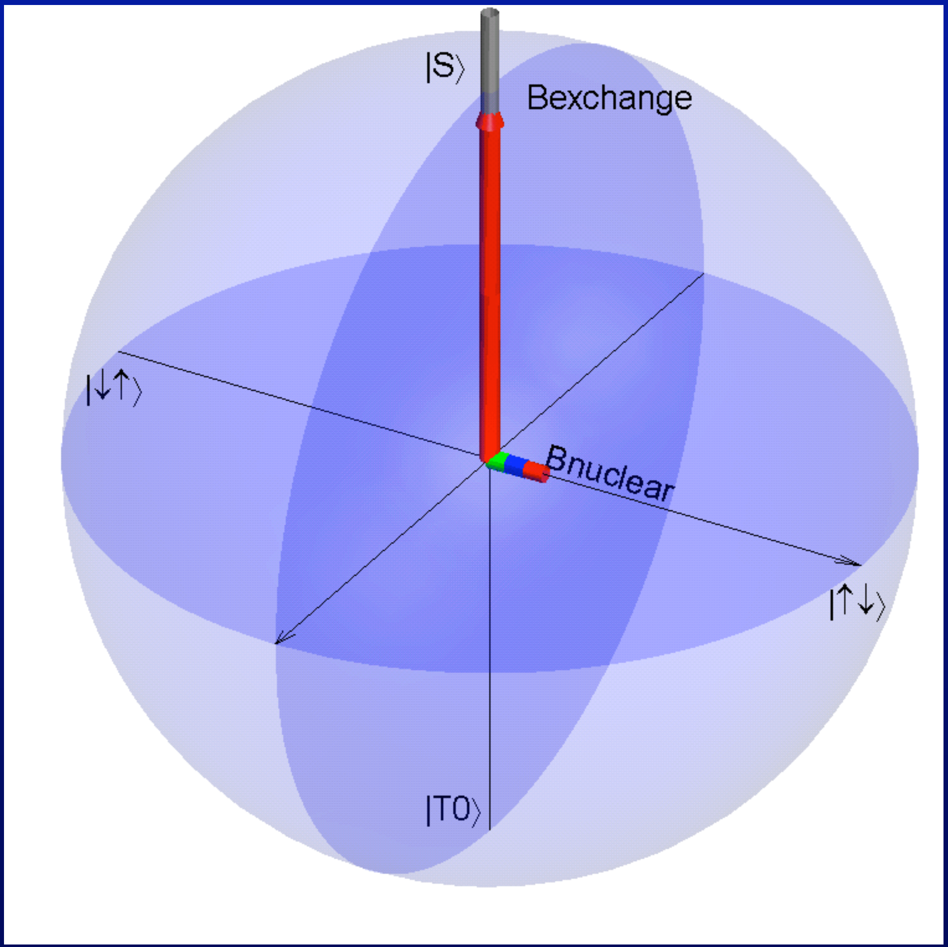
Rabi Oscillations



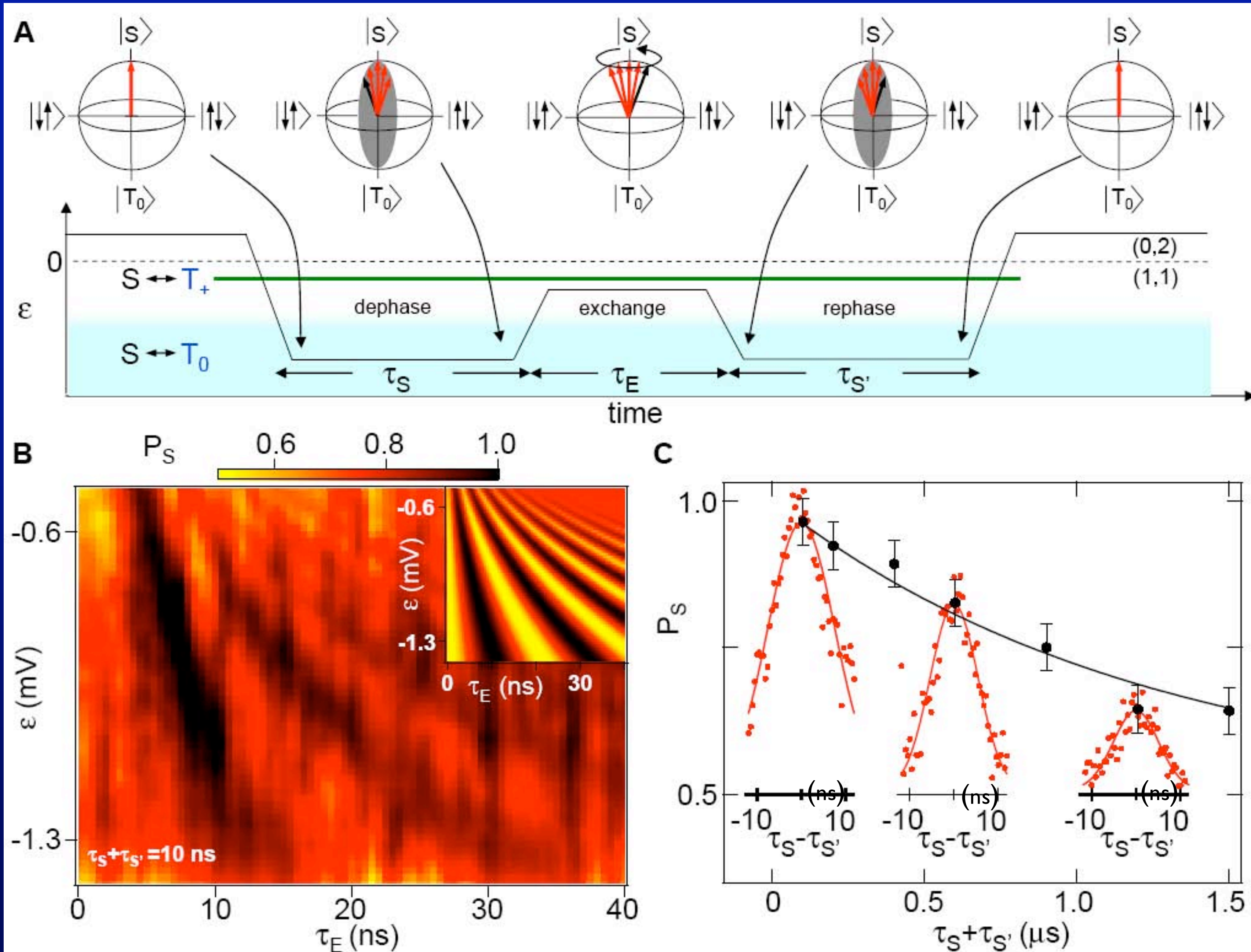
J. R. Petta, A. C. Johnson, J. Taylor, A. Yacoby, M.D. Lukin, C. M. Marcus, Science

Refocusing-Spin Echo





Qunatum treatment of the nuclear spin operator,
Coish and Loss, condmat 0506090 and Phys. Rev. B70, 195340 ('0



J. R. Petta, A. C. Johnson, J. Taylor, A. Yacoby, M.D. Lukin, C. M. Marcus, Science (2005)

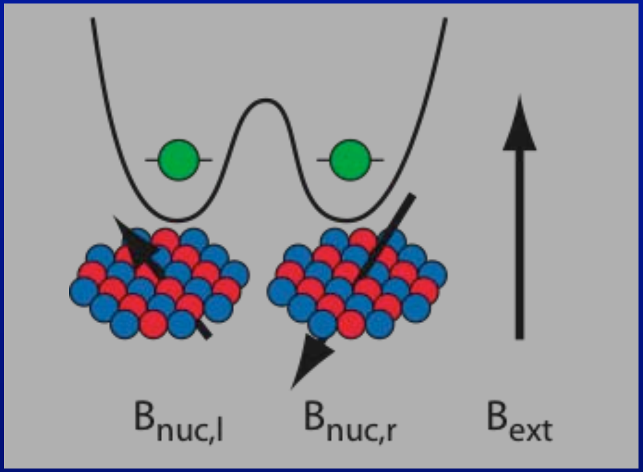
Nuclear Environment

Control nuclear environment:

controlled X rotations

Increase T2* and T2

Quantum state narrowing of nuclear ensemble –
D. Klauser, W. A. Coish, D. Loss



Store information in nuclei:

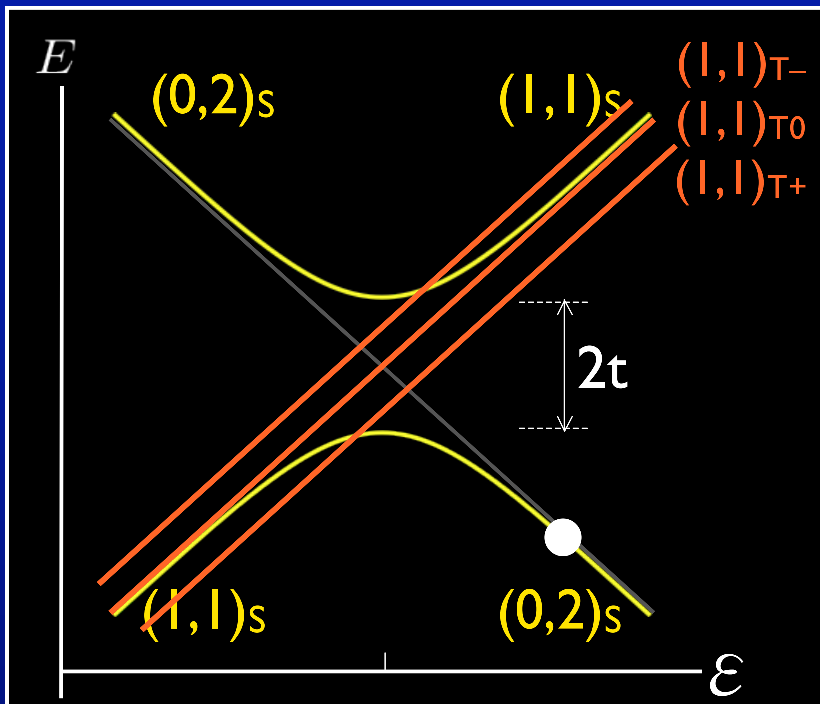
P in Si

NV centers in diamond

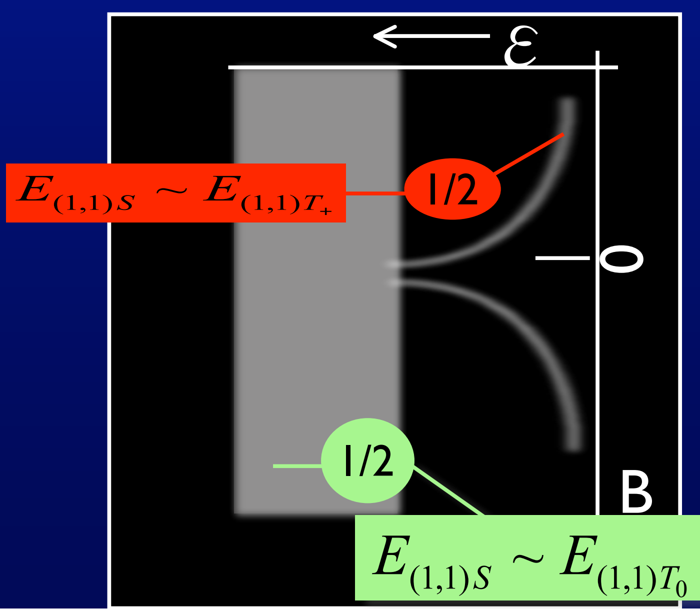
Nuclear spin ensemble in GaAs

Si nanowires (Si 29) and carbon nanotubes (C 13)

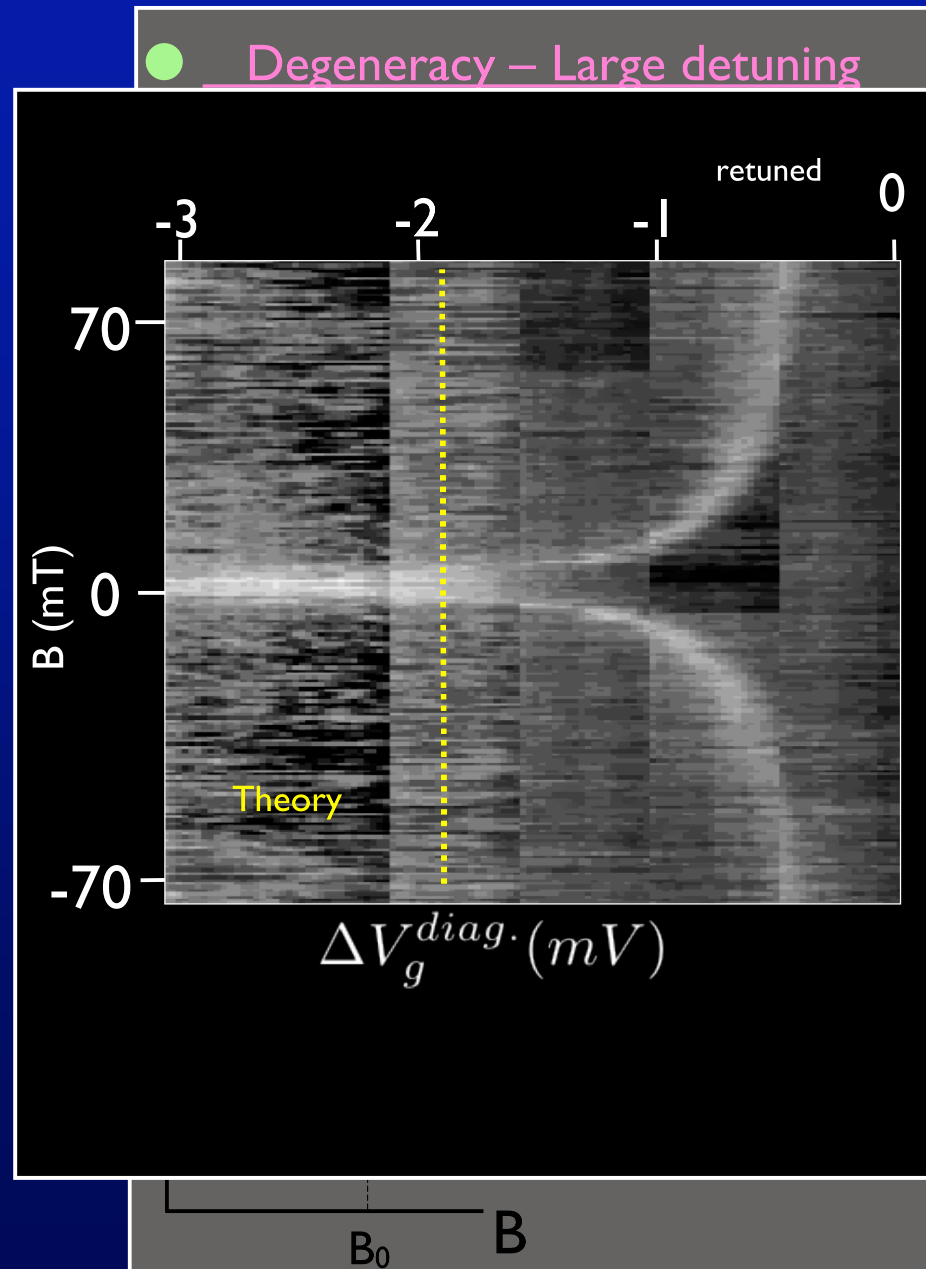
S – T+ Subspace



E
(0,2)S
(1,1)S
(1,1)T–
(1,1)T0
(1,1)T+
2t
(1,1)S
(0,2)S
ε



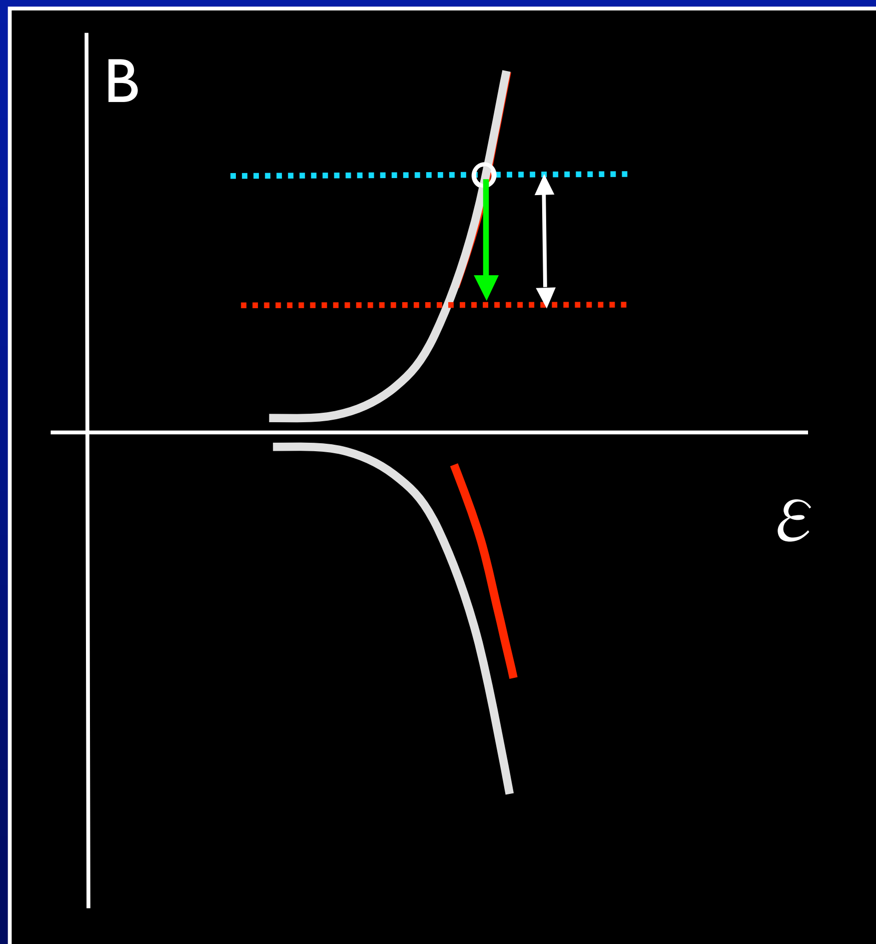
ε
$E_{(1,1)S} \sim E_{(1,1)T_+}$
1/2
0
1/2
B
$E_{(1,1)S} \sim E_{(1,1)T_0}$



Degeneracy – Large detuning
retuned
-3
-2
-1
0
70
0
-70
B (mT)
Theory
$\Delta V_g^{diag.}(mV)$
B0
B

Nuclear Programming

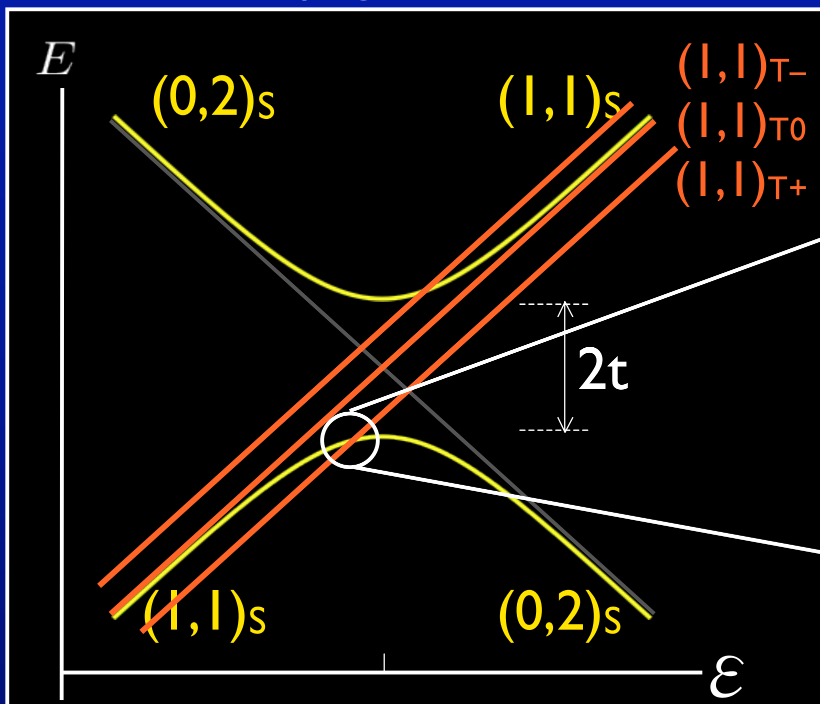
$$J(\varepsilon) = g\mu_B\left(B + \langle B_{Nuc}\rangle\right)$$

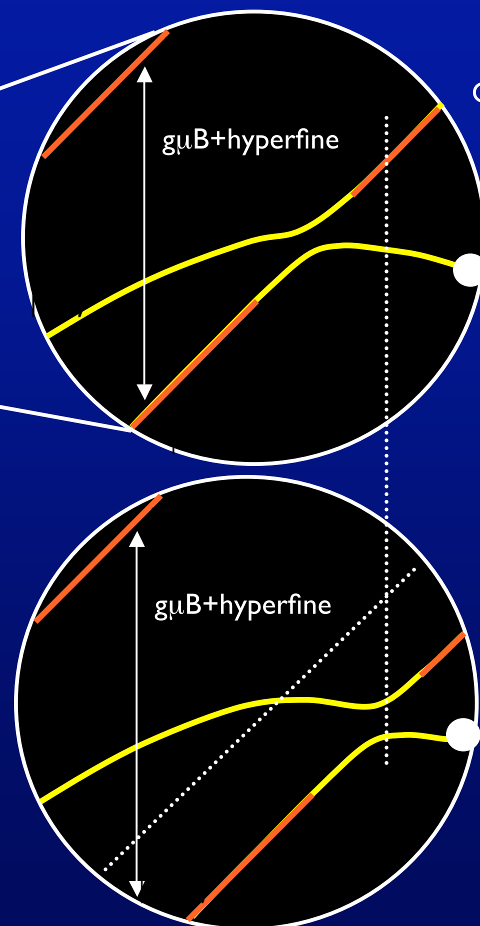


With Nuclear polarization

Nuclear Programming

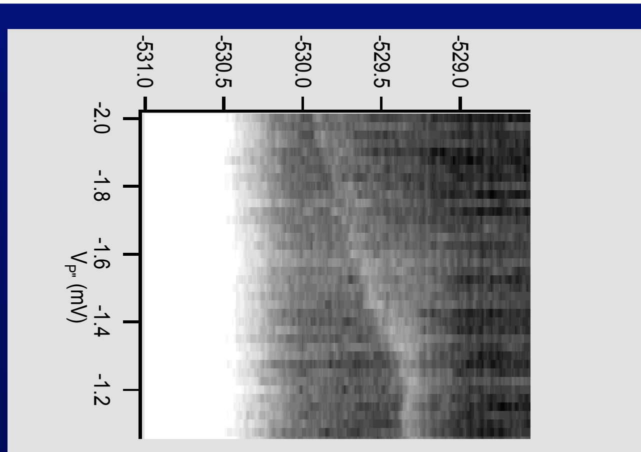
Adiabatic Pumping of Nuclei

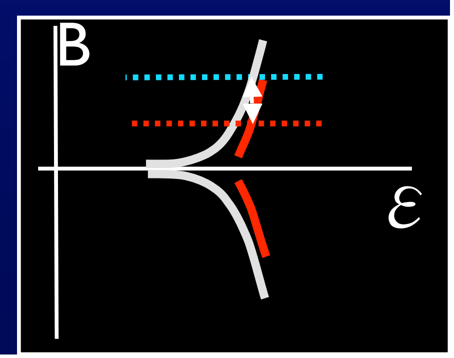




One nuclear spin is flipped per cycle

Self limiting Hyperfine field

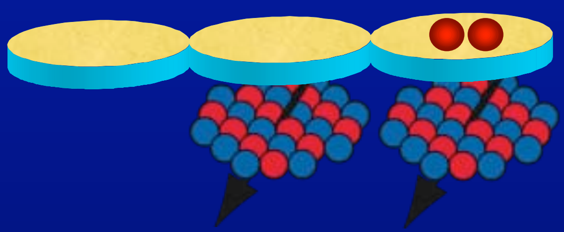




Is polarization built equally in both dots?

Controlled X Rotations

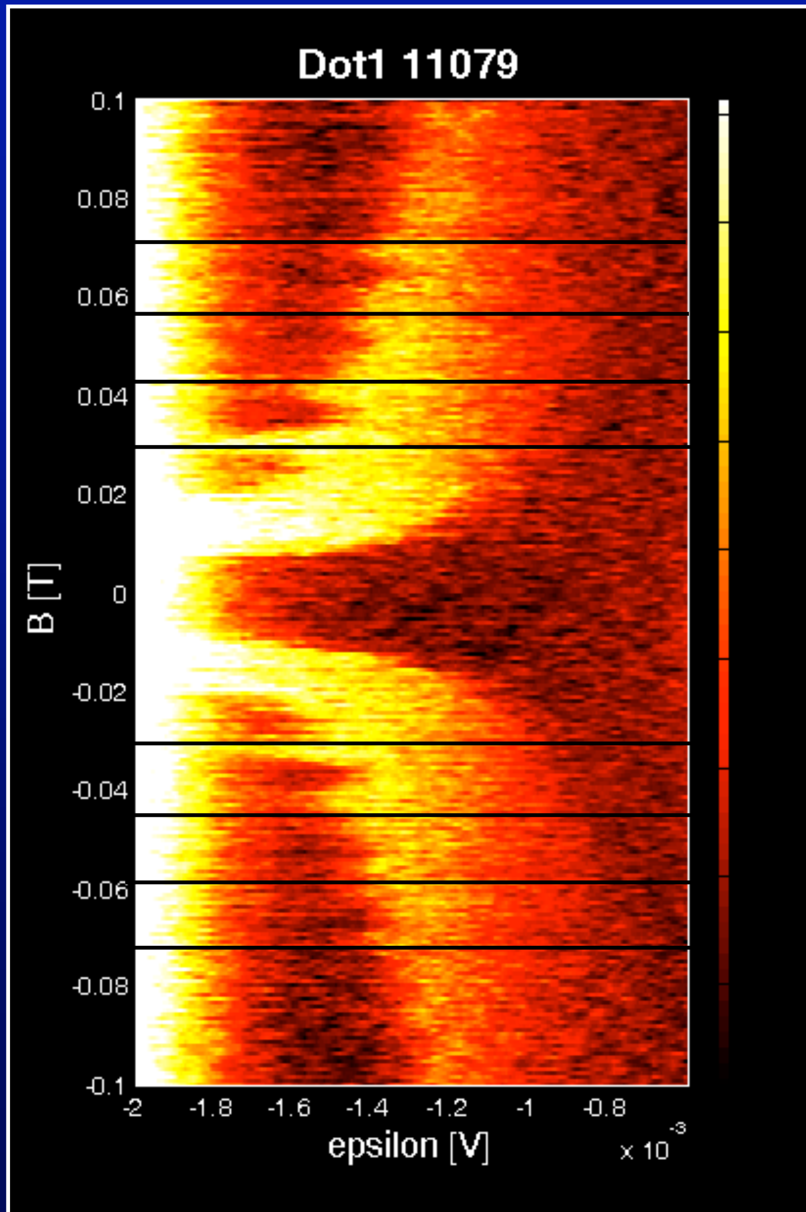
Adiabatic pumping

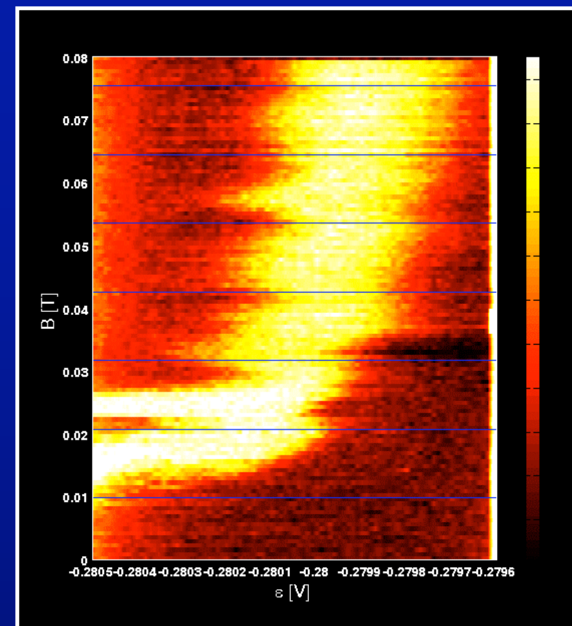


Desired Field Gradient
For X Rotations

Transfer

Careful look – no reload





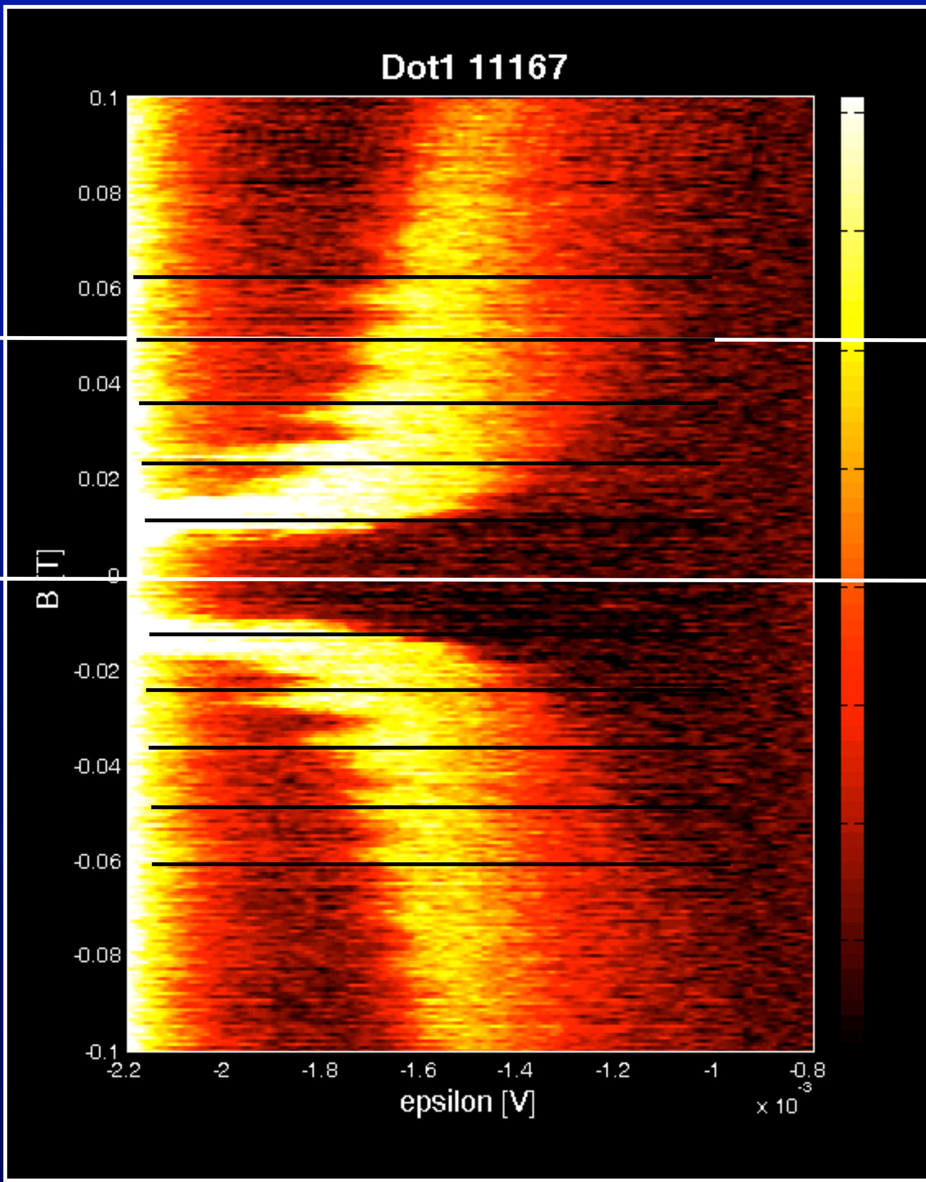
Slow data acquisition

Nuclear polarization changes with magnetic field

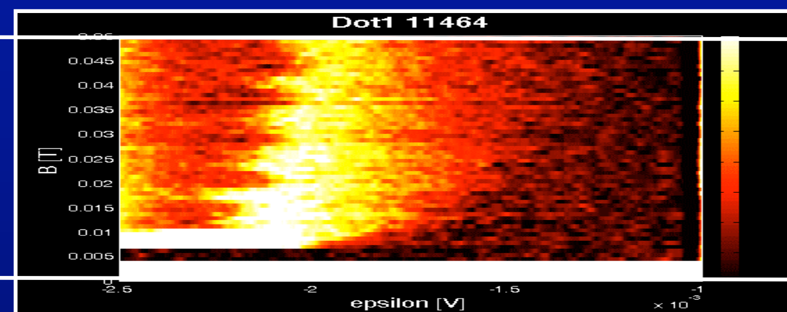
200ns

Pulse cycle 12μs

Dependence on Duty Cycle



Total time = 12 us

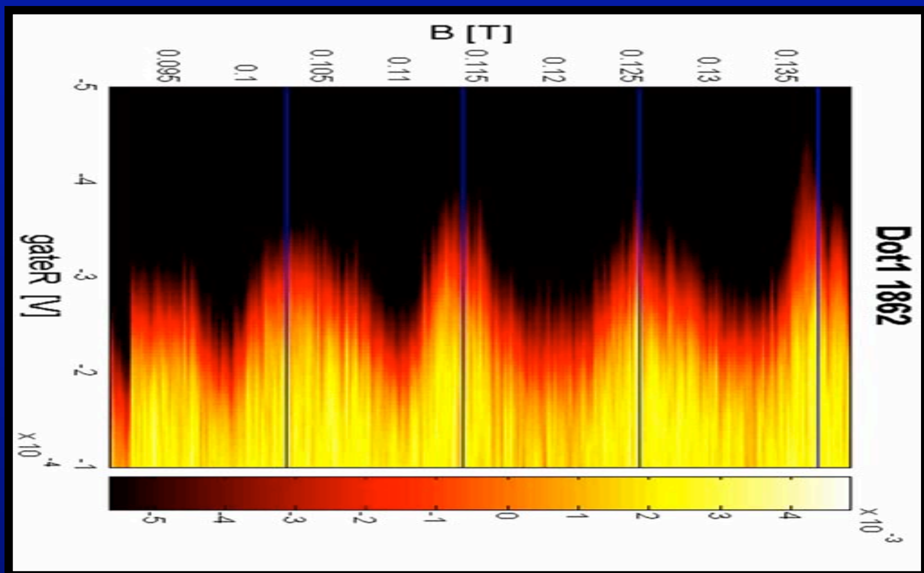


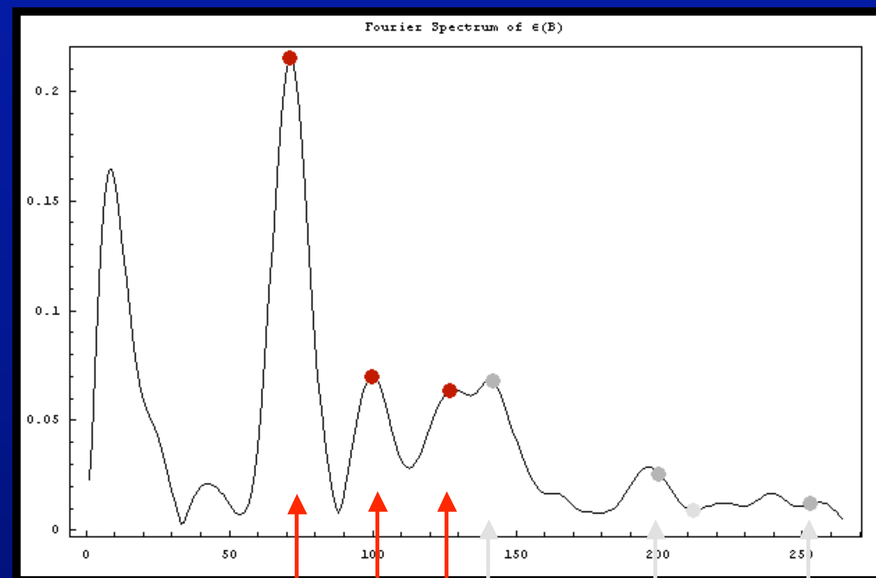
Total time = 17 us

time	Ga69	Ga71	As75	Measured
10us	9.7 mT	7.6mT	13.6mT	12.7mT
12us	8.1 mT	6.4mT	11.4mT	10.8mT
15 us	6.5 mT	5.1mT	9.1mT	8.3mT
17 us	5.7 mT	4.5mT	8mT	7.4mT

Obtain correct ratios

All Nuclei Contribute





As 75

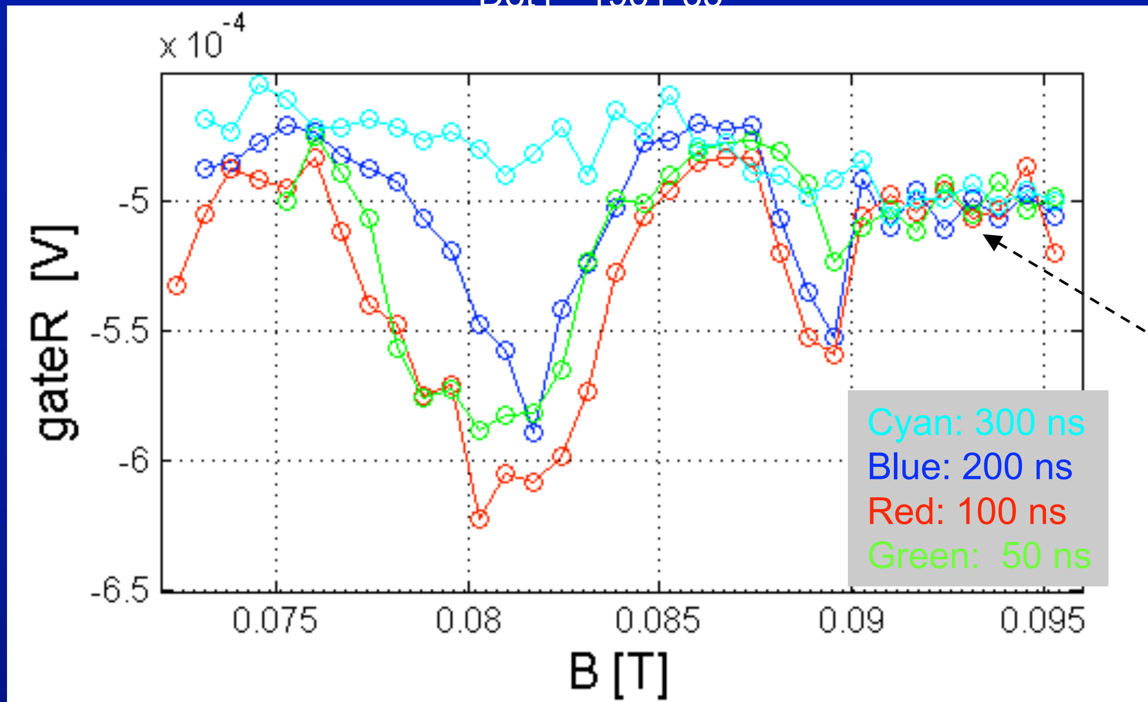
Ga 69

Ga 71

200 ns mixing time, 12 μs total time

Weights according to abundance
50% As 75
30% Ga 69
20% Ga 71

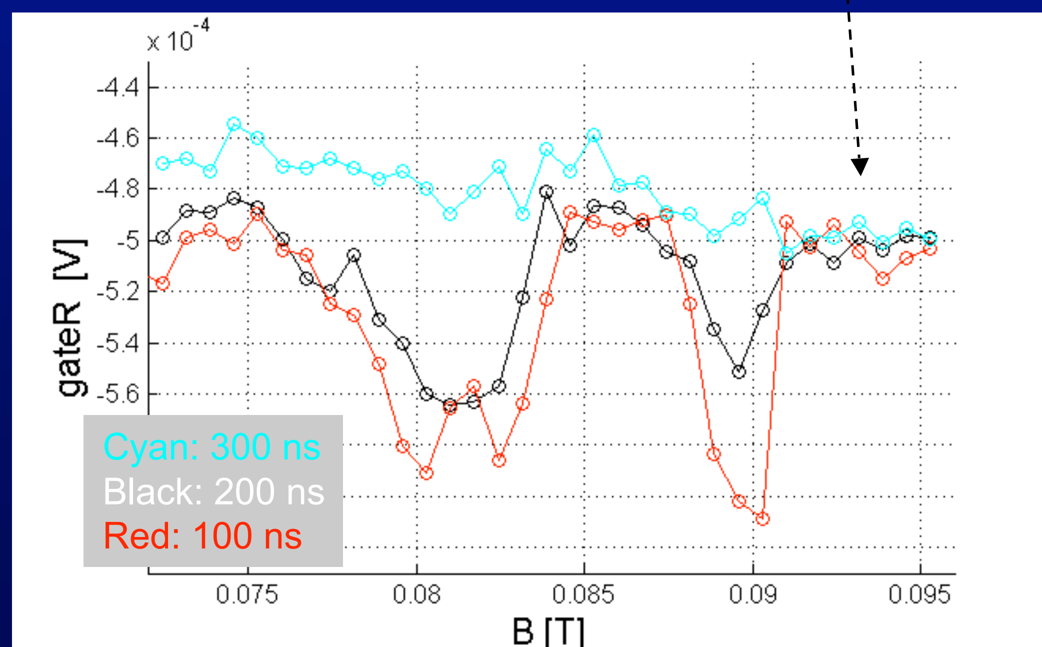
Dot1_ 1931-35



This first point are taken with no pulses during the “pumping time”.

The measurments are all taken with the 300 ns-pulse and the pumping pulse is changing.

Dot1_ 1935-37

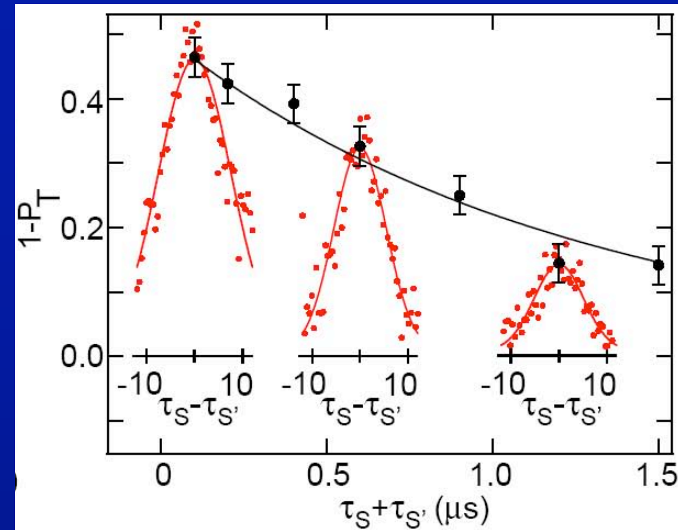


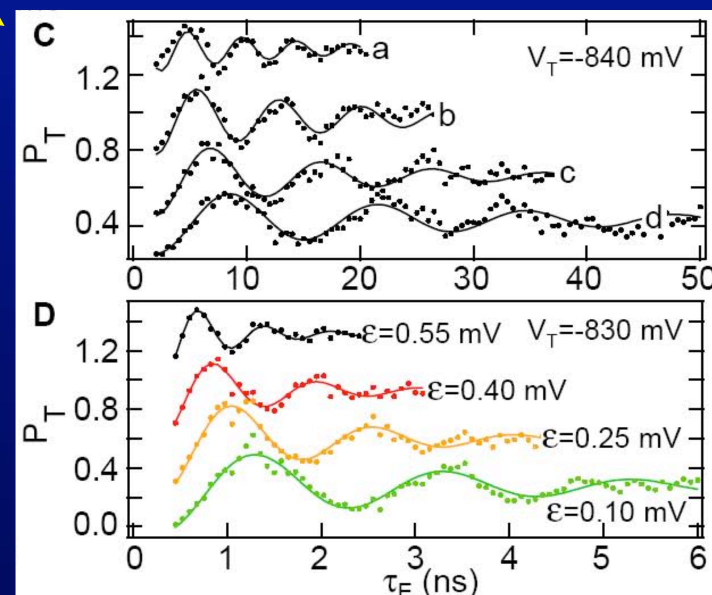
Summary

Coherent control of two electron states

Spin Echo – Measurement of T2

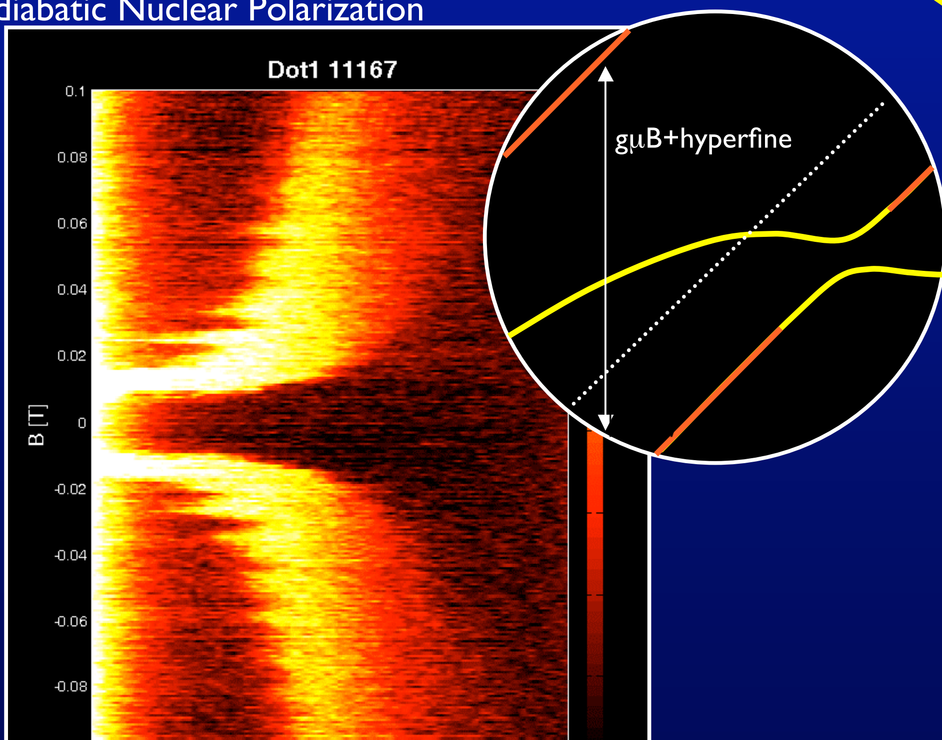
Controlled spin Manipulation





Cotroling the environment

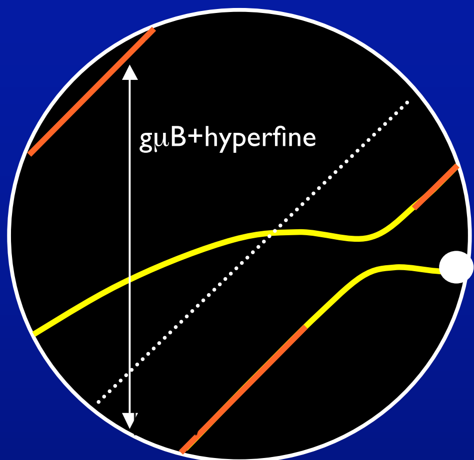
Adiabatic Nuclear Polarization



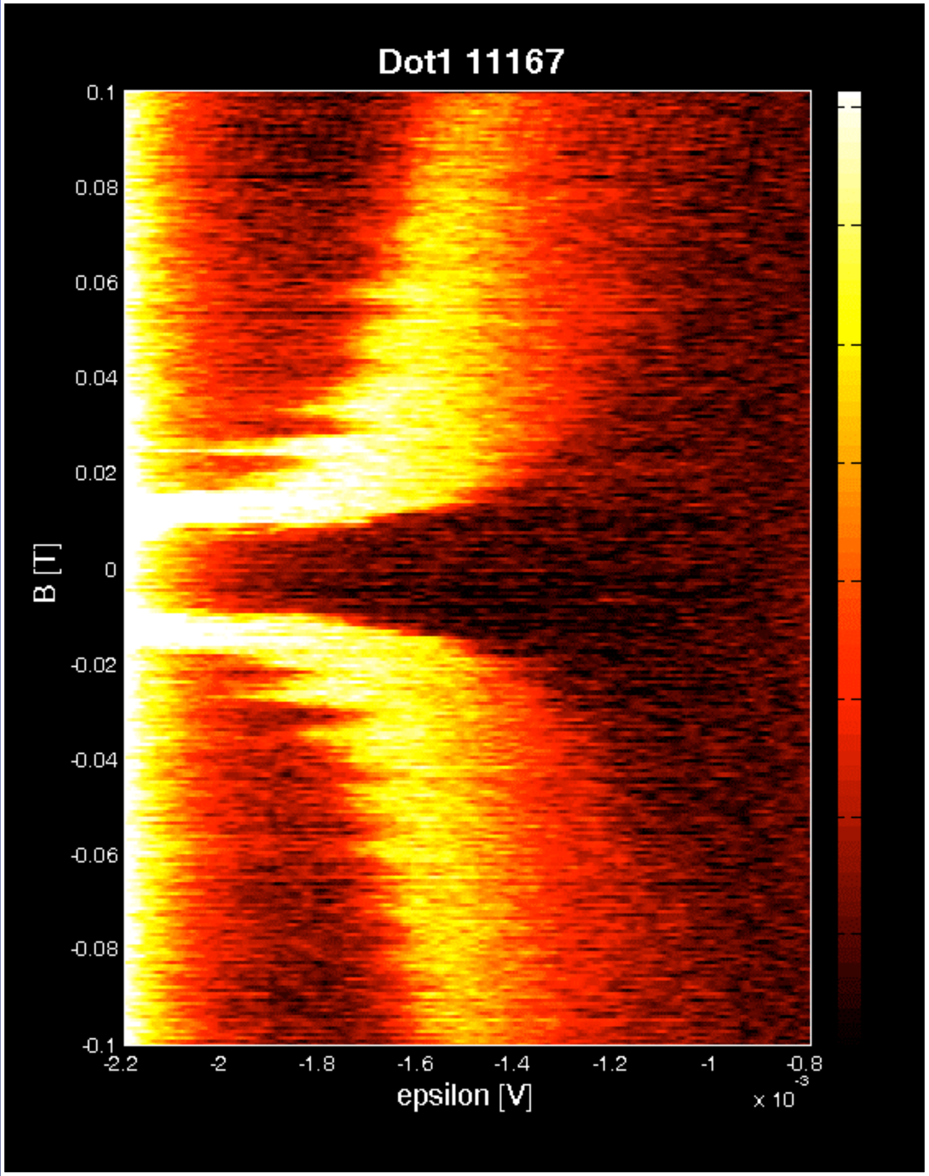
Dynamic nuclear polarization
commensurate with nuclear Larmor

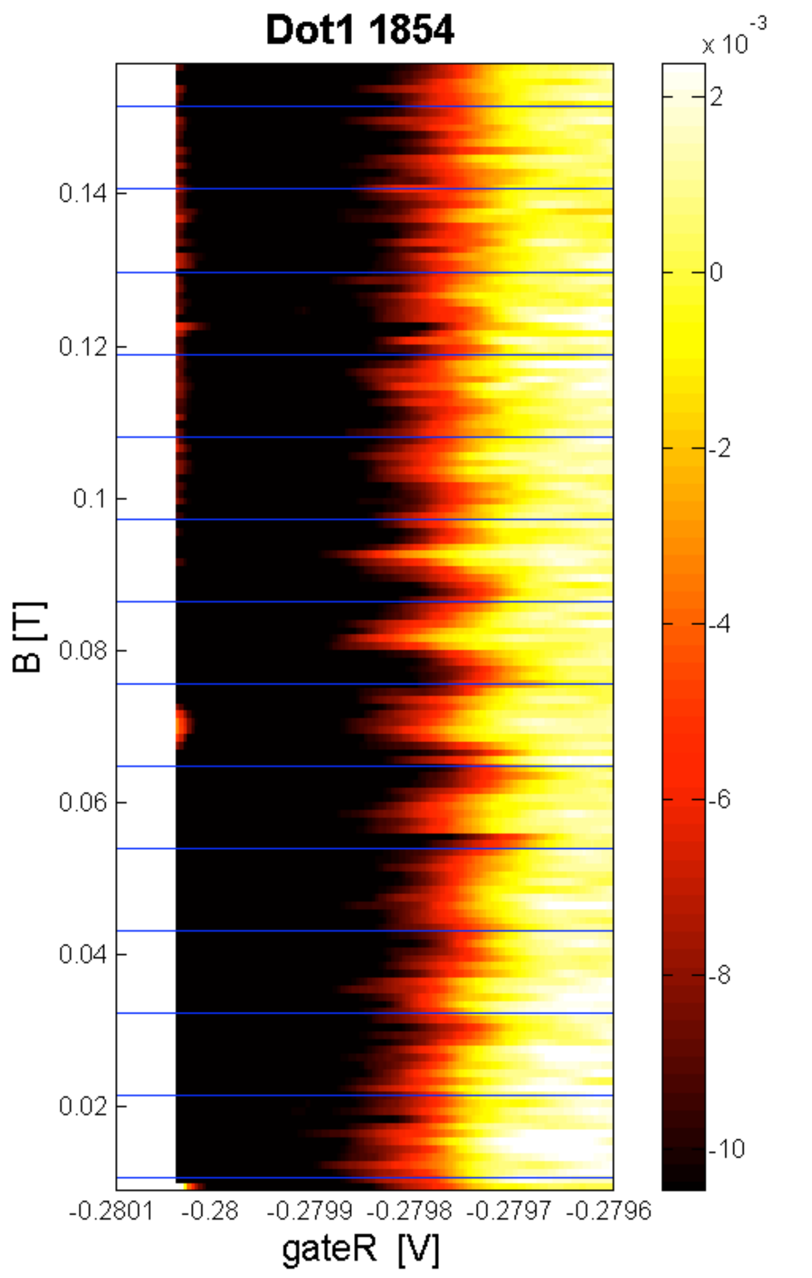
Summary

Adiabatic Nuclear Polarization

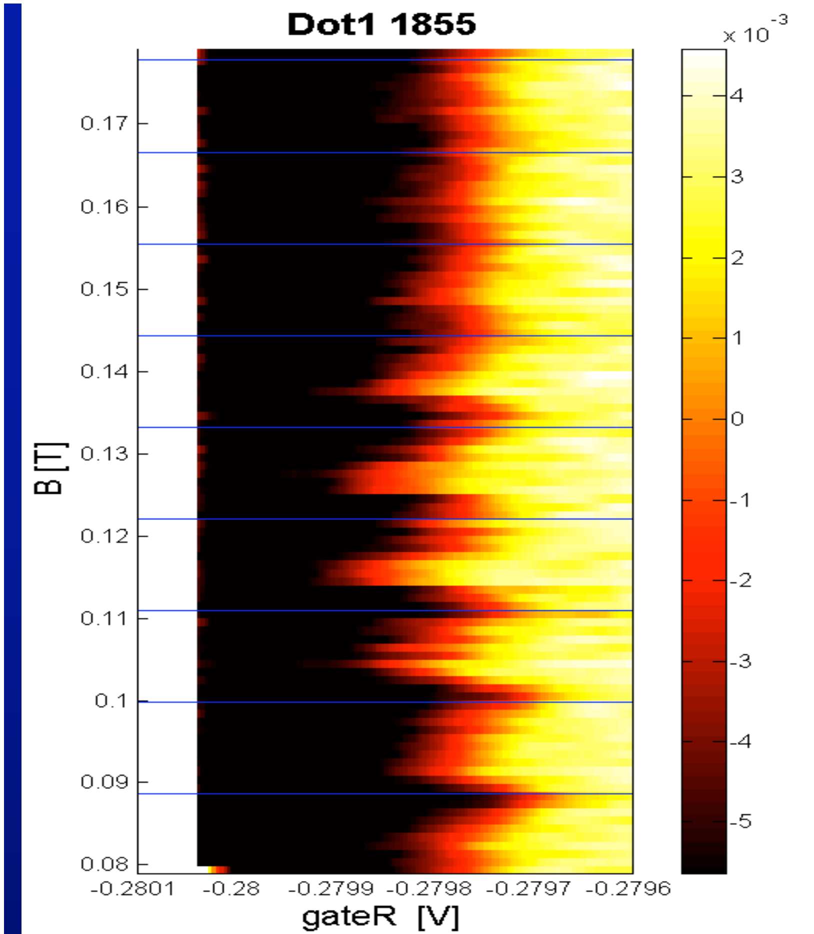


Dynamic nuclear polarization commensurate with nuclear Larmor





Measurement@ 69 mT, gateR @ -280.05 mV
Pump @ -279.8 m



Measurement@ 69 mT, gateR @ -280.05 mV
Pump @ -279.7 m