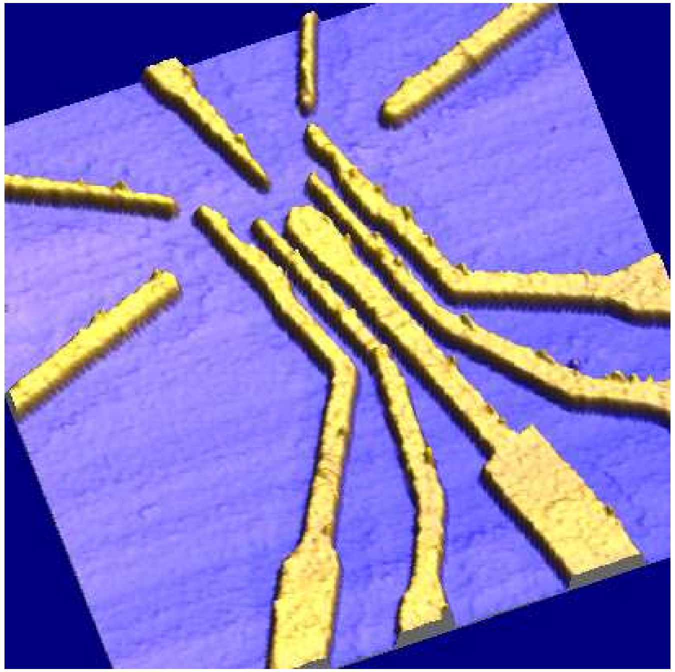
Control of electron and nuclear spins in GaAs quantum dots



KITP workshop on
Quantum Information Science
Santa Barbara, CA
1 Dec 2009

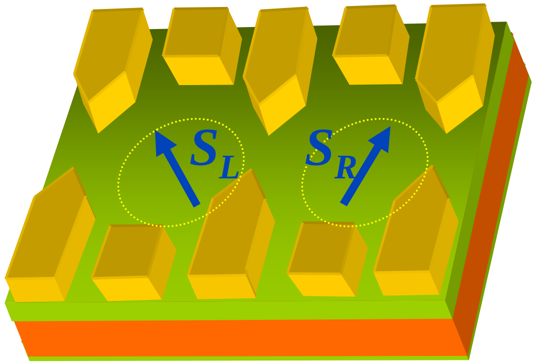
Lieven Vandersypen

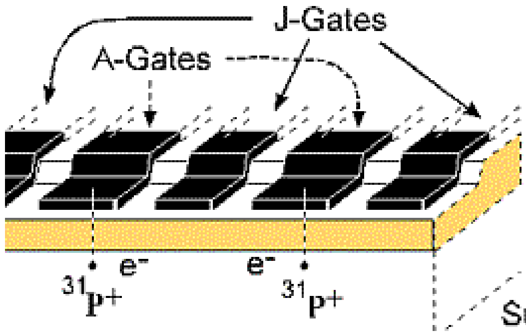
NWO FOM erc

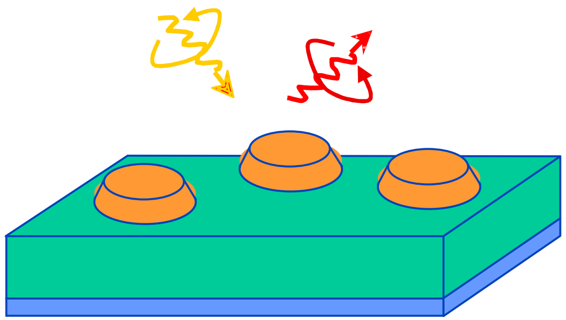
TU Delft
Delft University of Technology
Faculty Of Applied Sciences

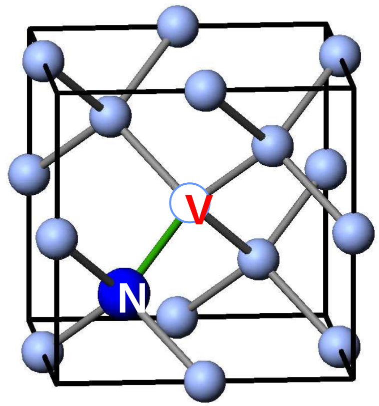
Kavli Institute of Nanoscience

Controlling *single* spins

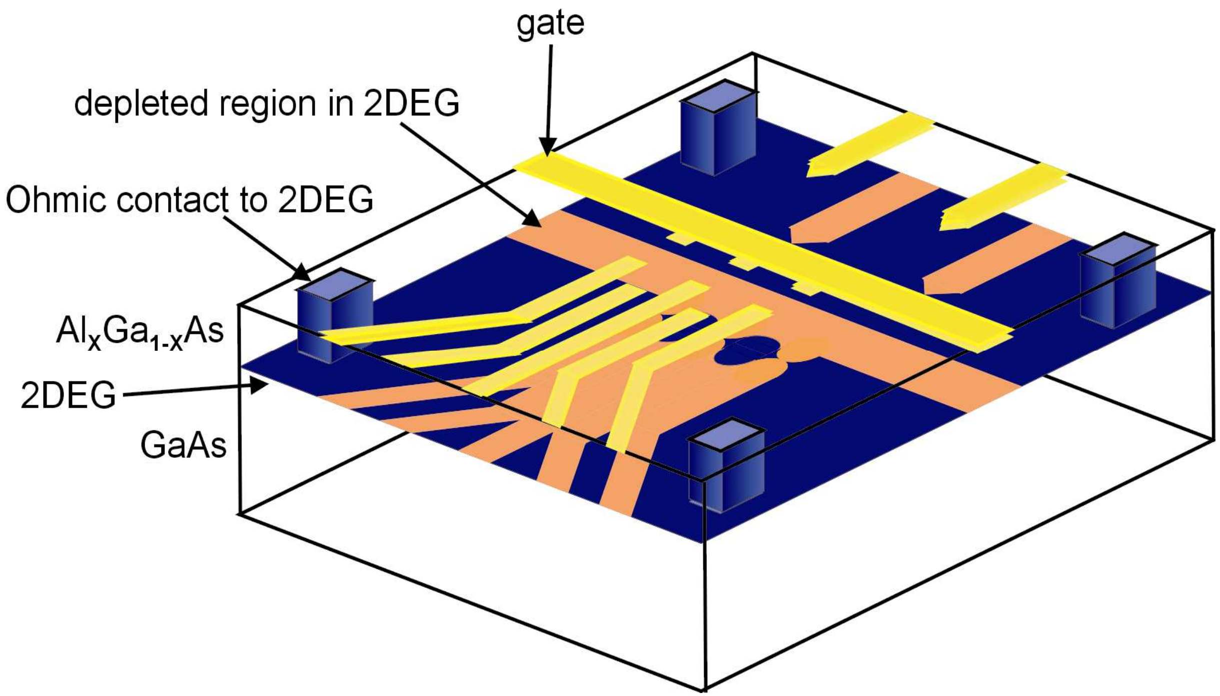






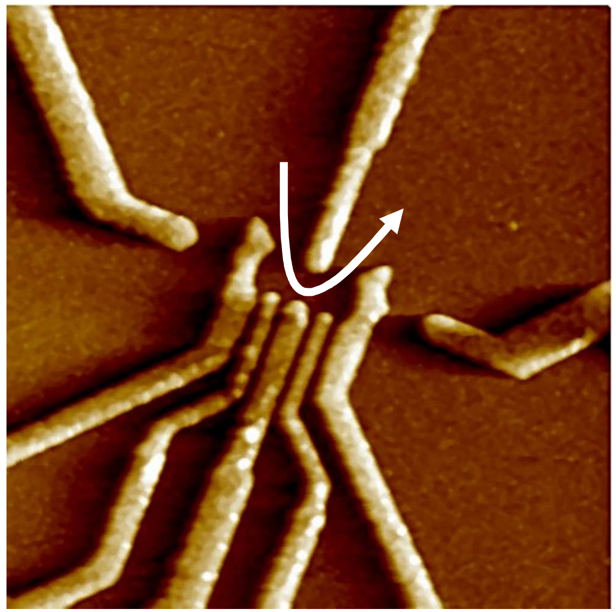


A well-controlled and fully tunable quantum dot system



Confinement

- Discrete # charges
- Quantized orbitals

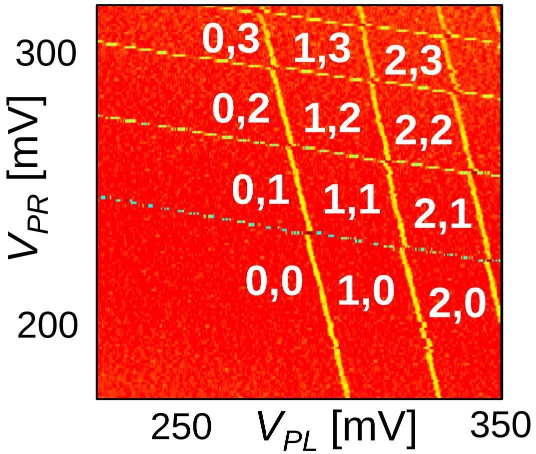


Electrical control and detection

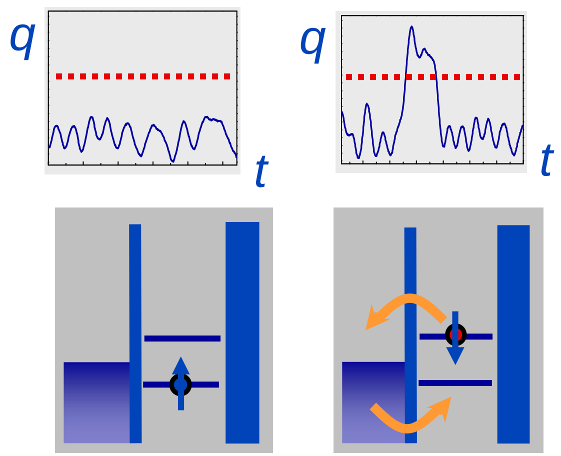
- Tunable # of electrons
- Tunable tunnel barriers
- Electrical contacts

Single-spin qubits in GaAs dots

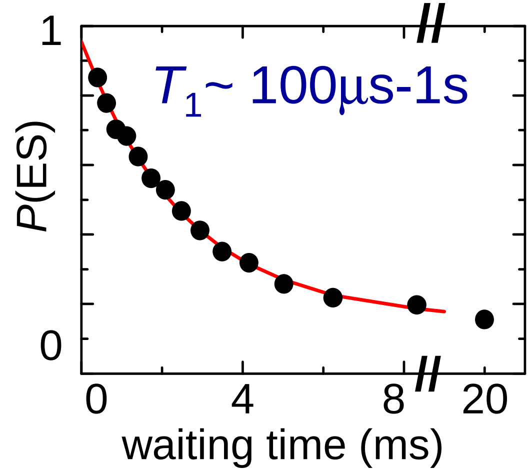
See also Hanson et al, Rev. Mod. Phys. 2007



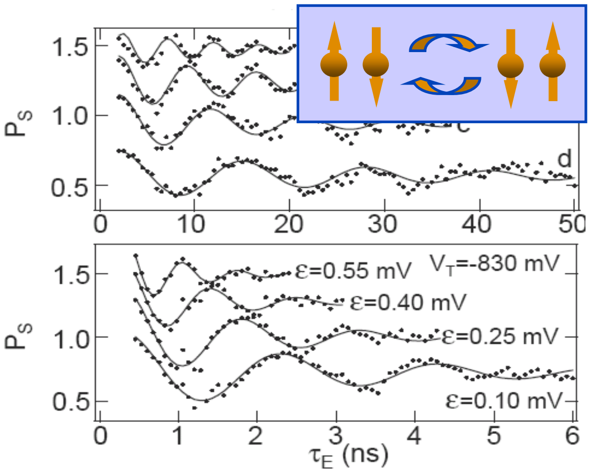
Ciorga et al, PRB 2000
Sprinzak et al., PRL 2002
Elzerman et al, PRB 2003



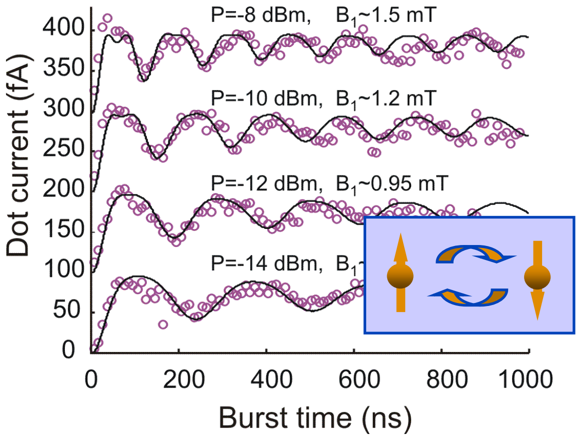
Elzerman et al., Nature 2004



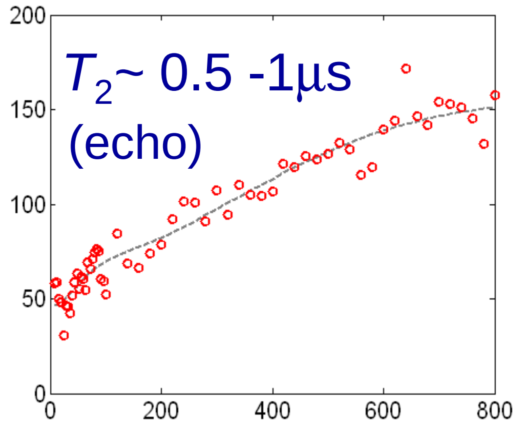
Fujisawa et al, Nature 2002
Amasha, PRL 2008



Petta et al., Science 2005



B(t) Koppens ea, Nature 2006
E(t) Nowack ea, Science 2007



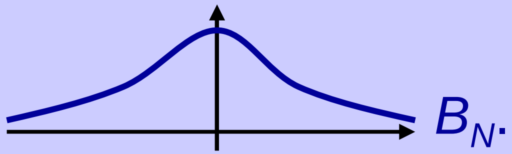
Petta et al., Science 2005
Koppens et al., PRL 2008

Electron spin dephasing in the random nuclear field

$$\mathcal{H} = g\mu_B \vec{S}\,\vec{B} + \vec{S}\sum_i A_i \vec{I}_i$$

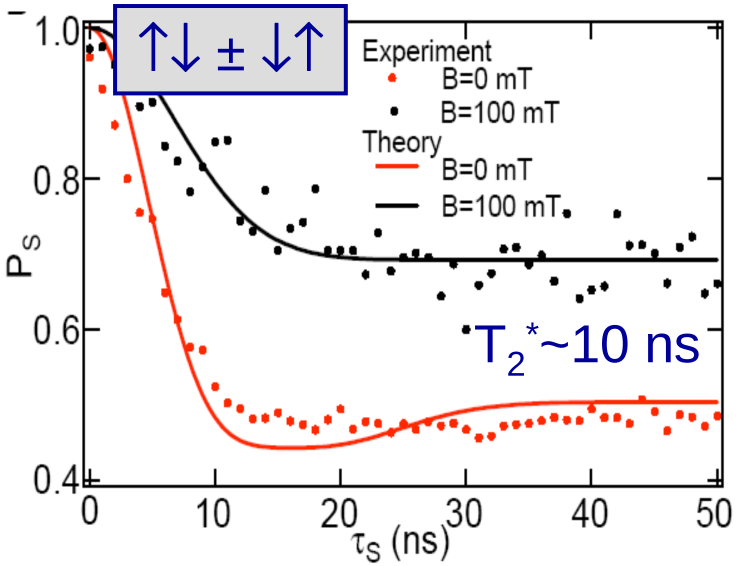
Overhauser field B_N

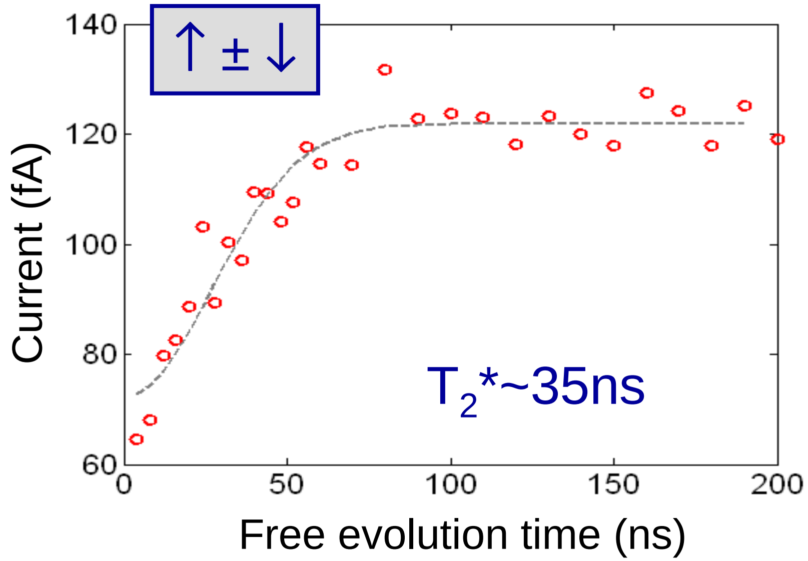
B_N is random and unknown



~ 20 ns dephasing time

Merkulov, Efros, Rosen, PRB 2002, Khaetskii, Loss, Glazman, PRL 2002



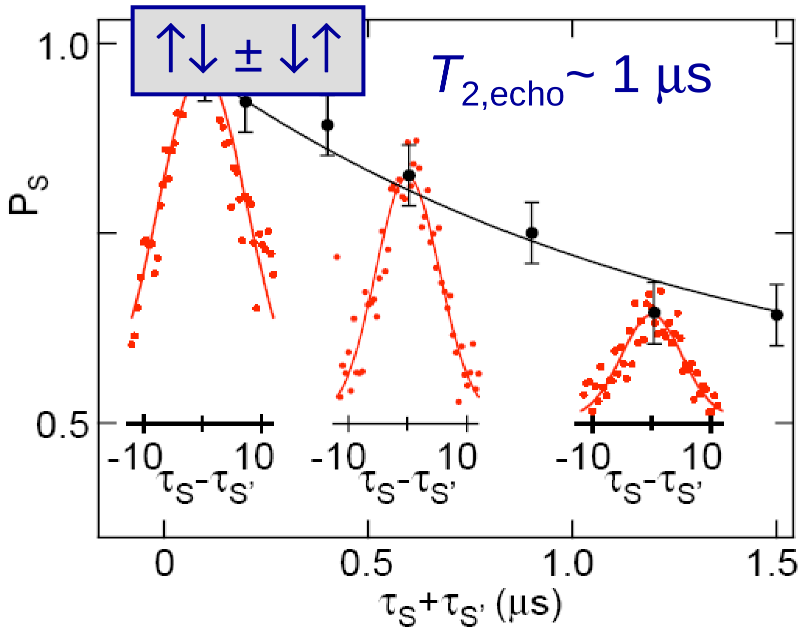


Electron spin decoherence due to random nuclear spin dynamics

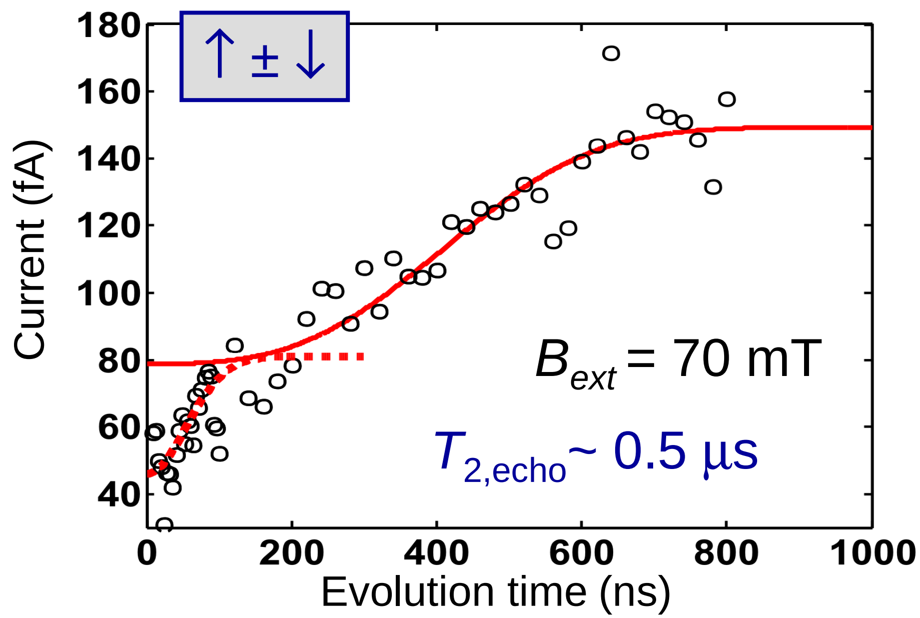
B_N fluctuates due to (1) dipole-dipole
(2) hyperfine-mediated

B_N evolves slowly on the timescale of the electron spin dynamics
$\Rightarrow T_{2,echo} \sim$ 1-100 μs

Coish & Loss PRB 2004, Witzel & Das Sarma PRB 2006, PRL 2007, Yao, Liu, Sham, PRB 2006, **…**

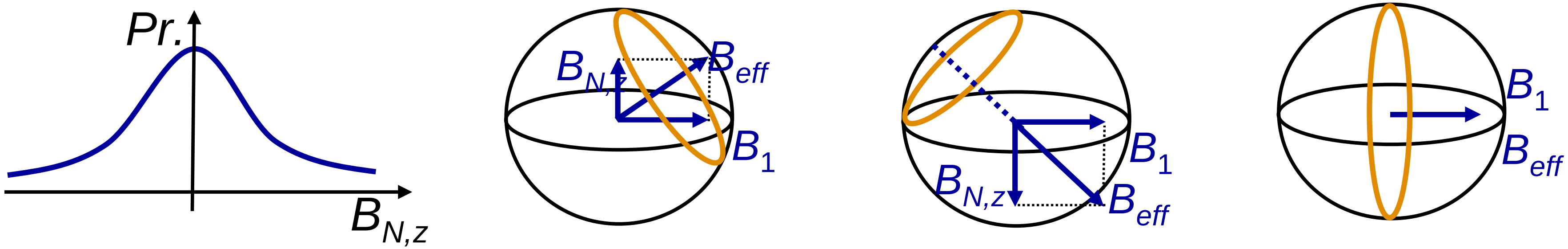


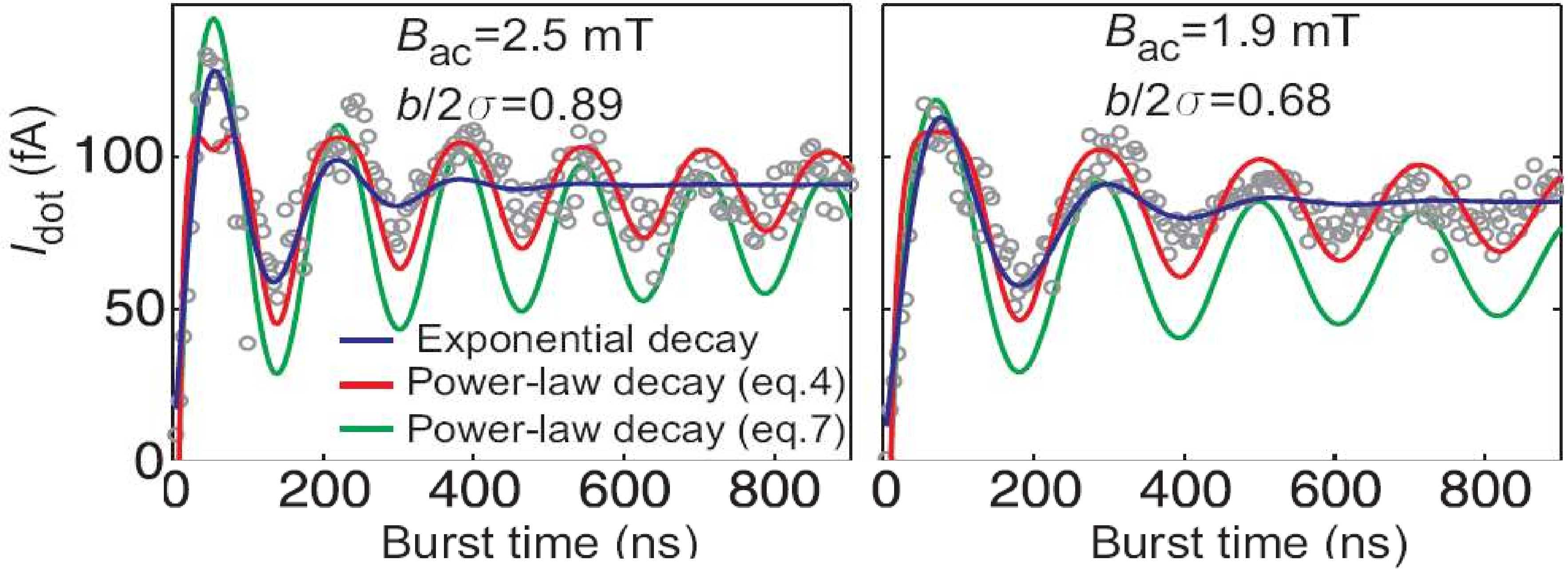
Petta *et al,* Science 2005



Koppens, Nowack, LMKV, PRL 2008

Decay of driven oscillations





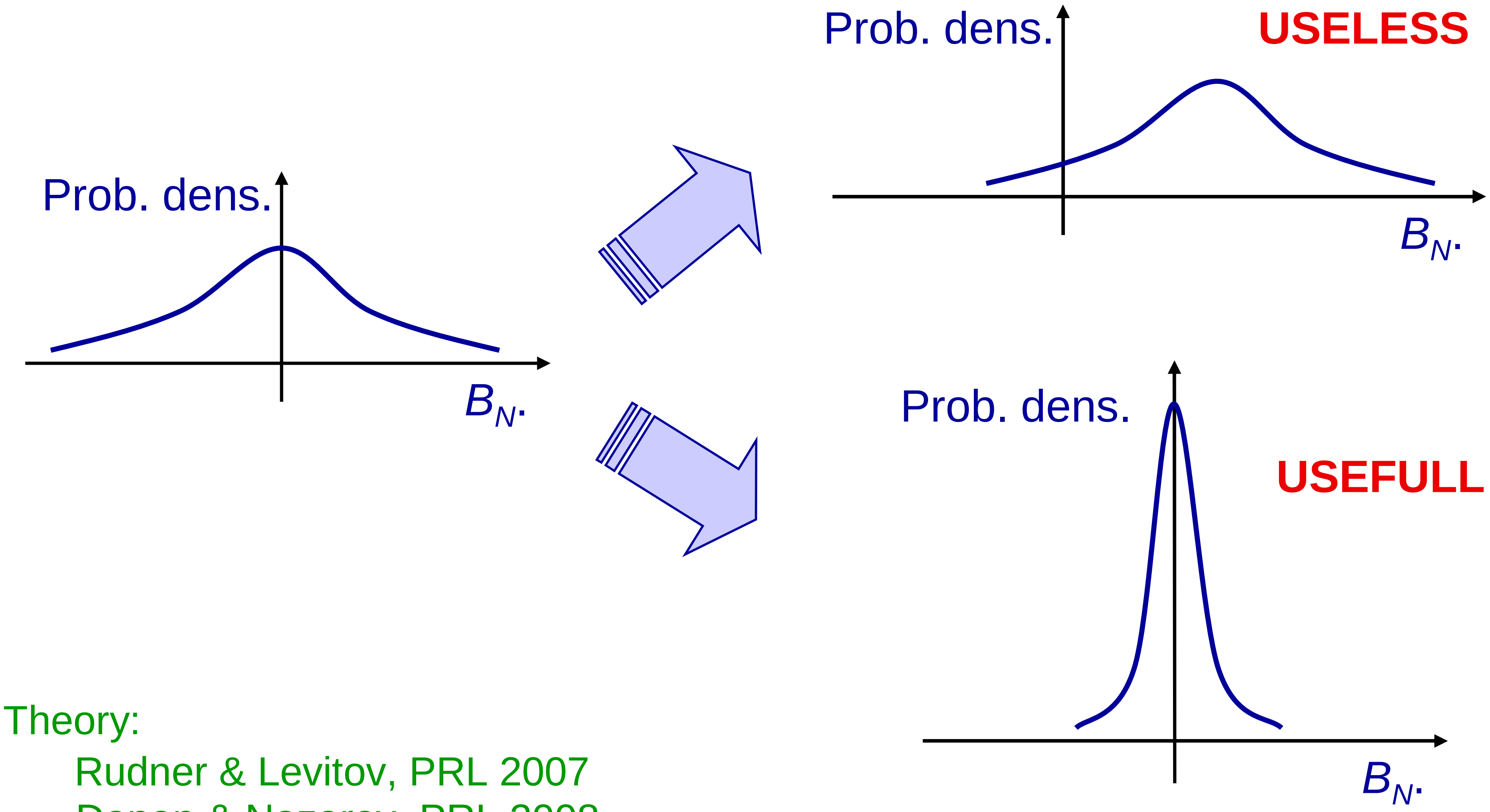
$$P_\uparrow(t) \sim \frac{1}{2} + C + \sqrt{\frac{b}{8\sigma^2 t}} \cos\left(\frac{b}{2}t + \frac{\pi}{4}\right) + \mathcal{O}\left(\frac{1}{t^{3/2}}\right)$$

Power-law decay

Phase shift

Koppens, Klauser, Coish, Nowack, Kouwenhoven, Loss, LMKV, PRL 2007

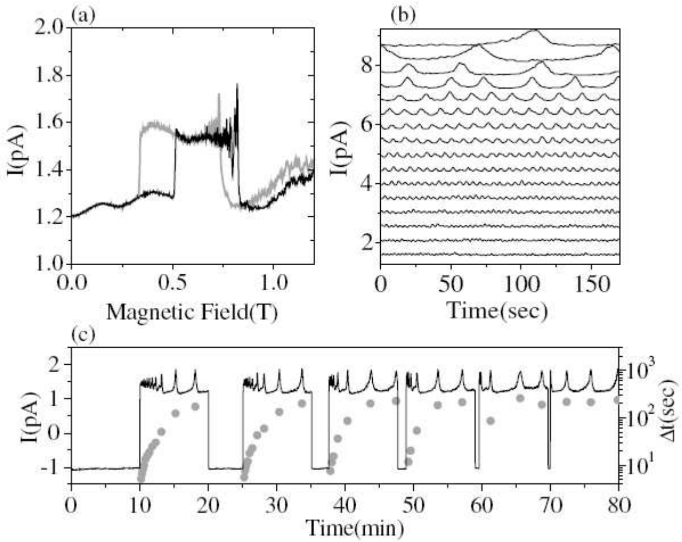
Can we reduce dephasing by nuclear spins?



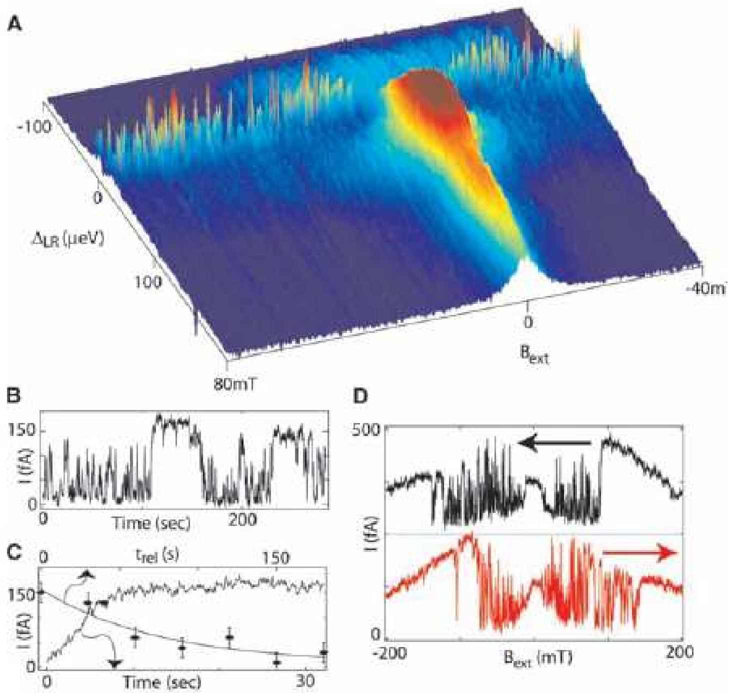
Theory:

Rudner & Levitov, PRL 2007
Danon & Nazarov, PRL 2008

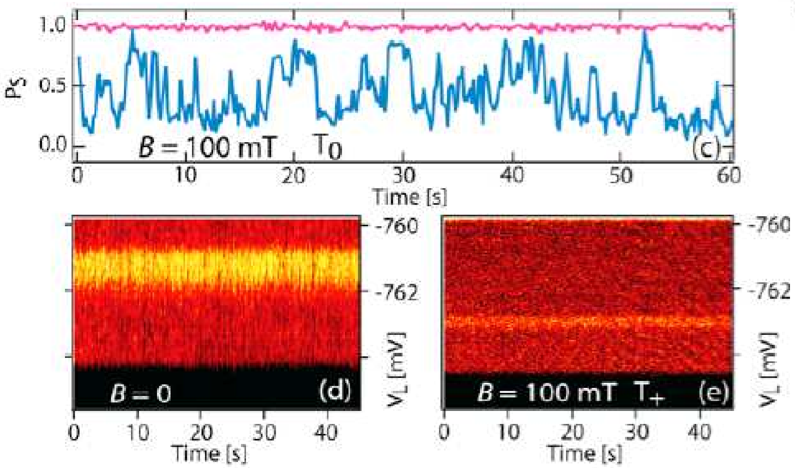
Dynamic nuclear spin polarization from electron-nuclear feedback



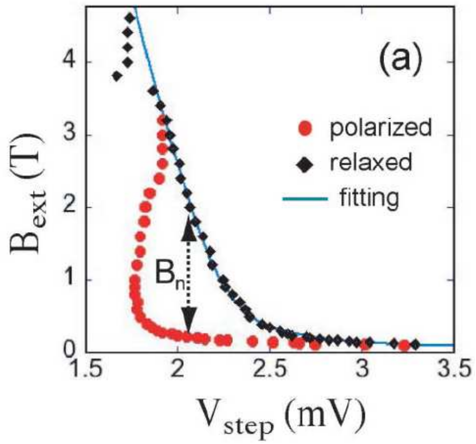
Ono & Tarucha, PRL 2004



Koppens, Folk et al, Science 2005

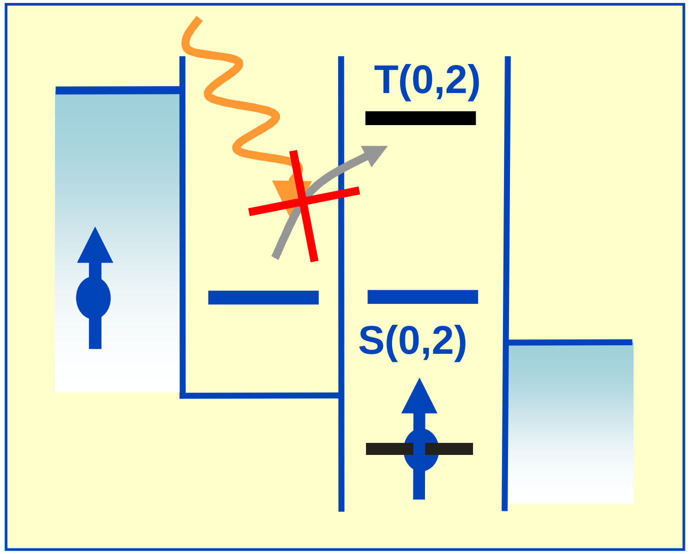


Reilly et al, PRL 2007



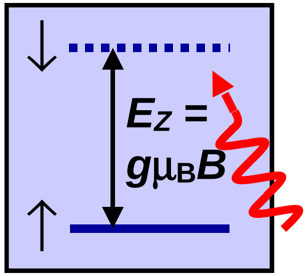
Baugh et al, PRL 2007

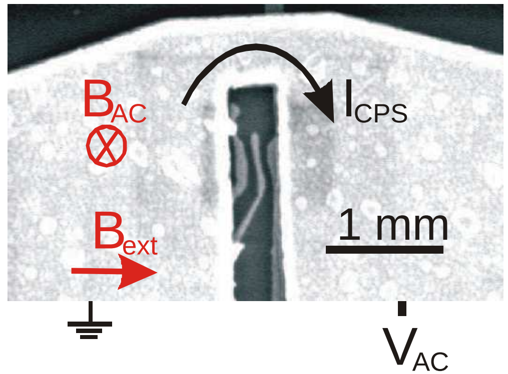
Single-electron spin resonance

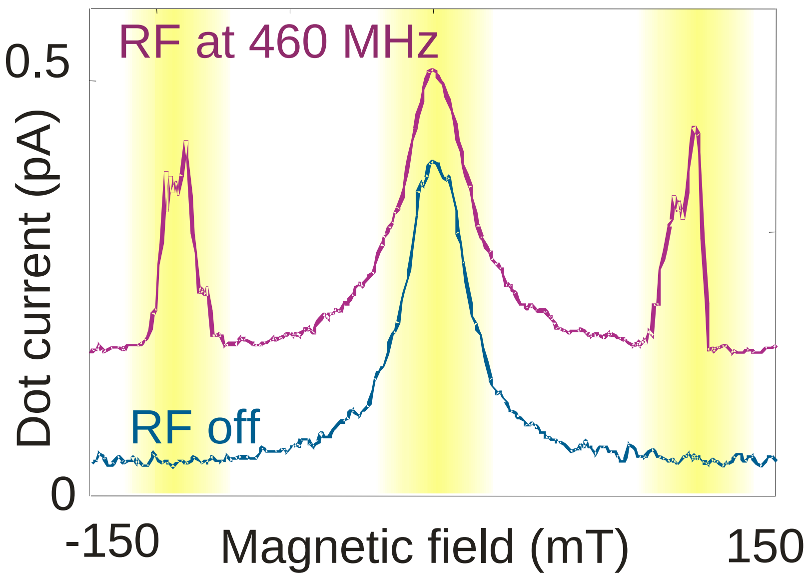


Inspiration: Engel & Loss PRL 2001

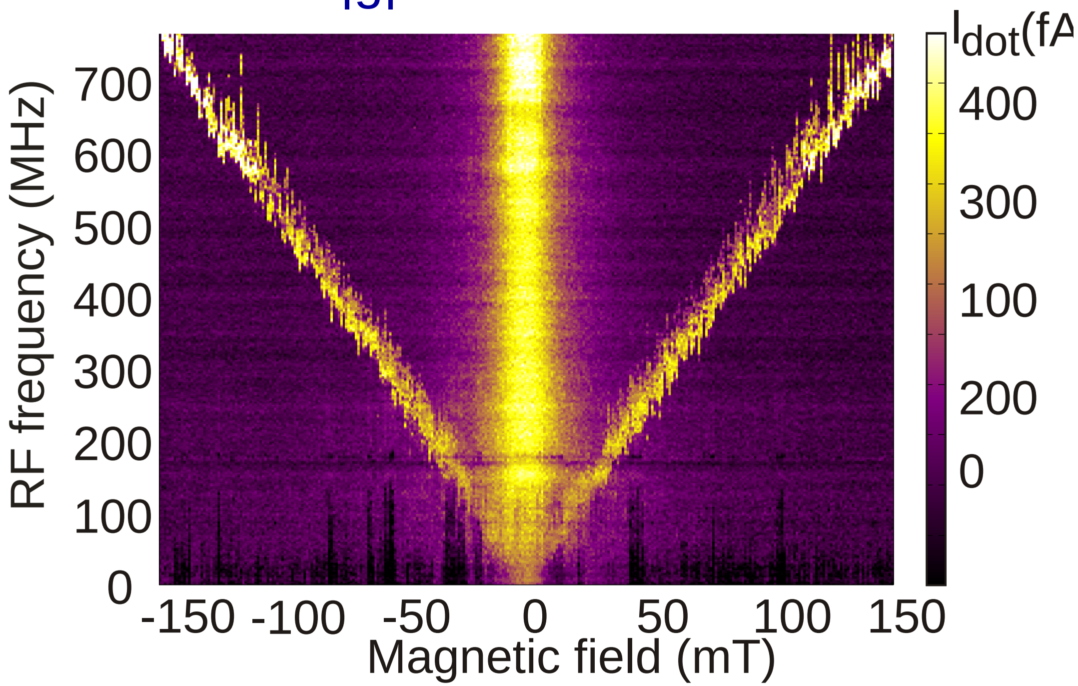
F. Koppens *et al.*, Nature 2006



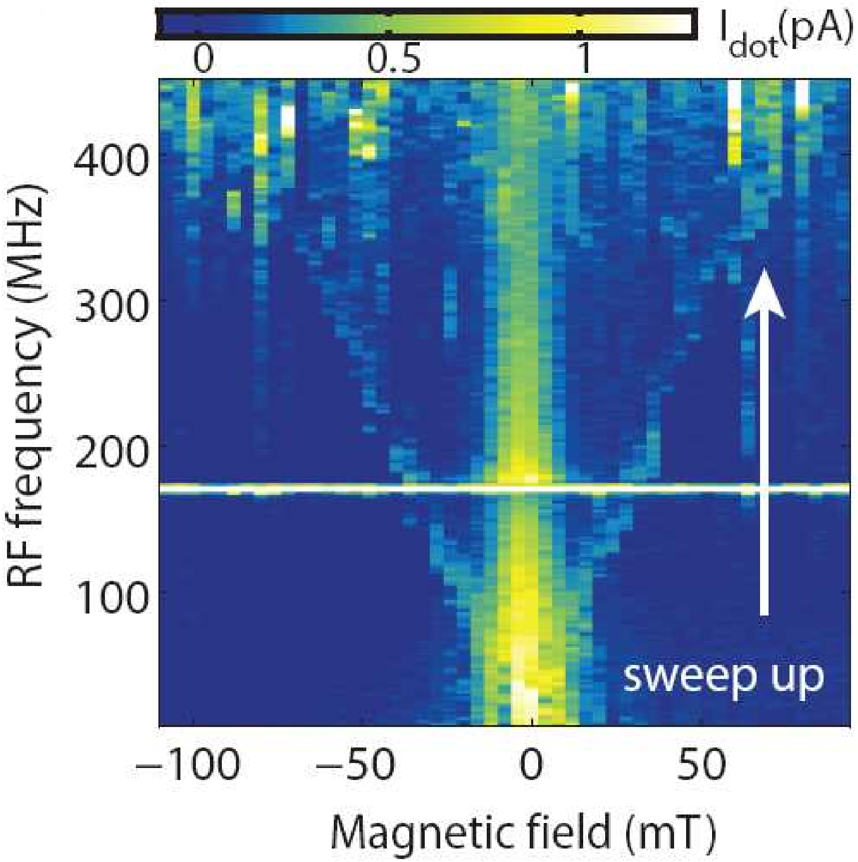


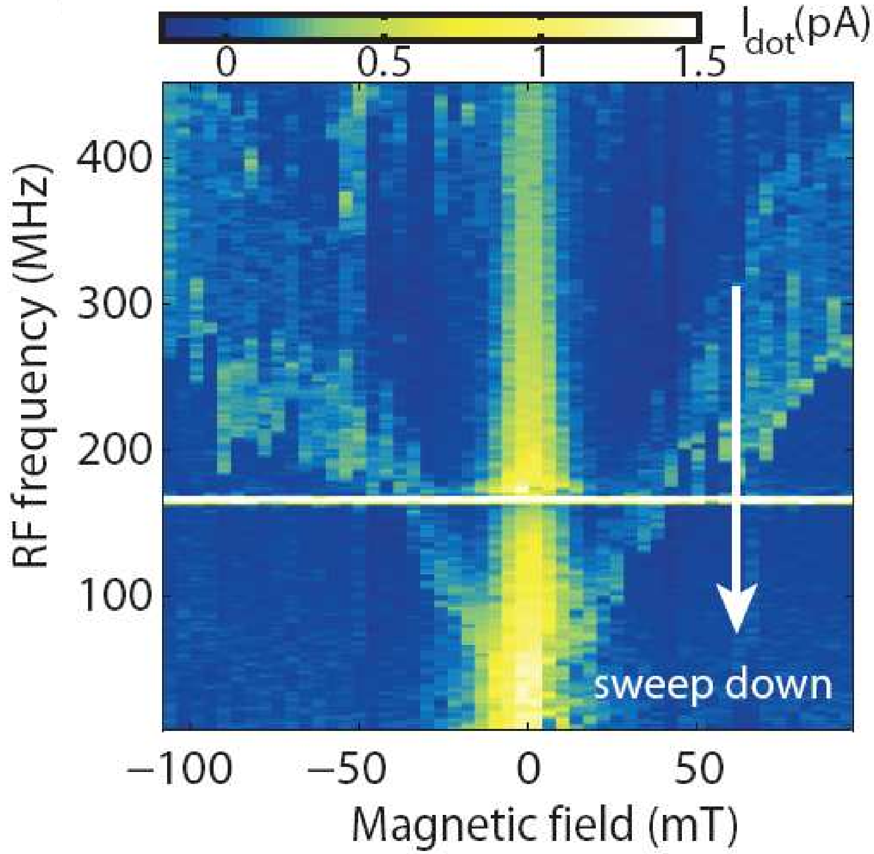


|g|-factor ~ 0.35



A surprising observation



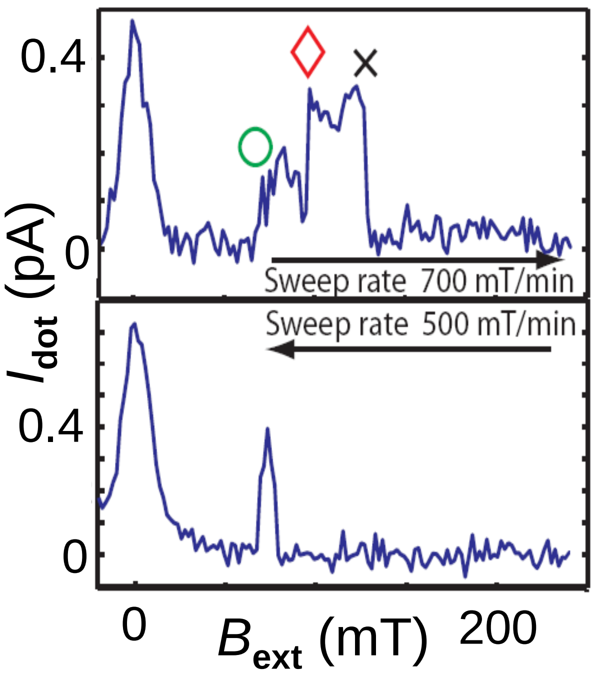


Difference with earlier data:

Larger interdot tunnel coupling
Stronger tunnel coupling to leads
Negative alignment of dot potentials

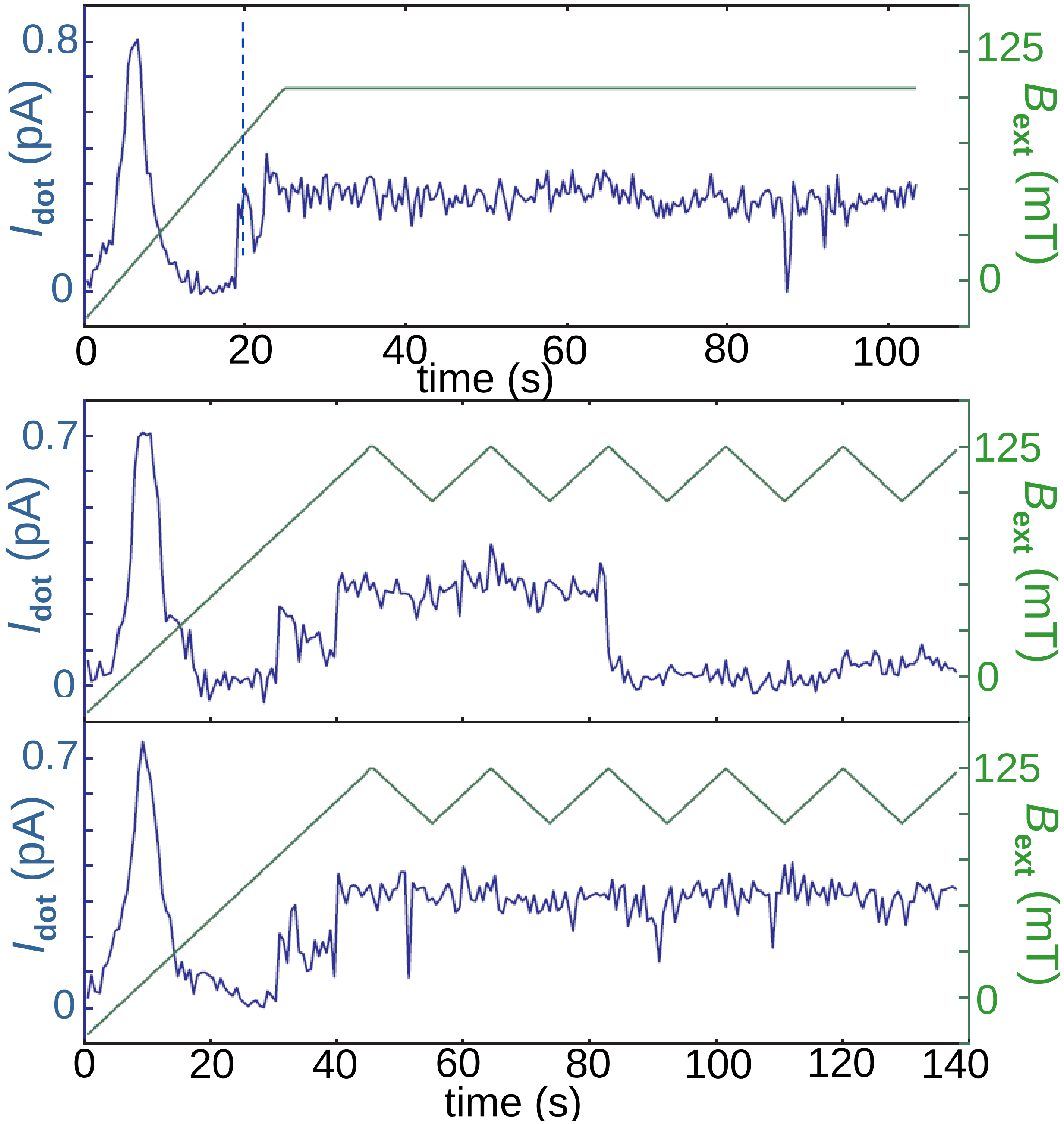
Feedback in B_N locks electron spin on resonance

Vink, Nowack, Koppens, Danon, Nazarov, LMKV, Nature Phys. 2009

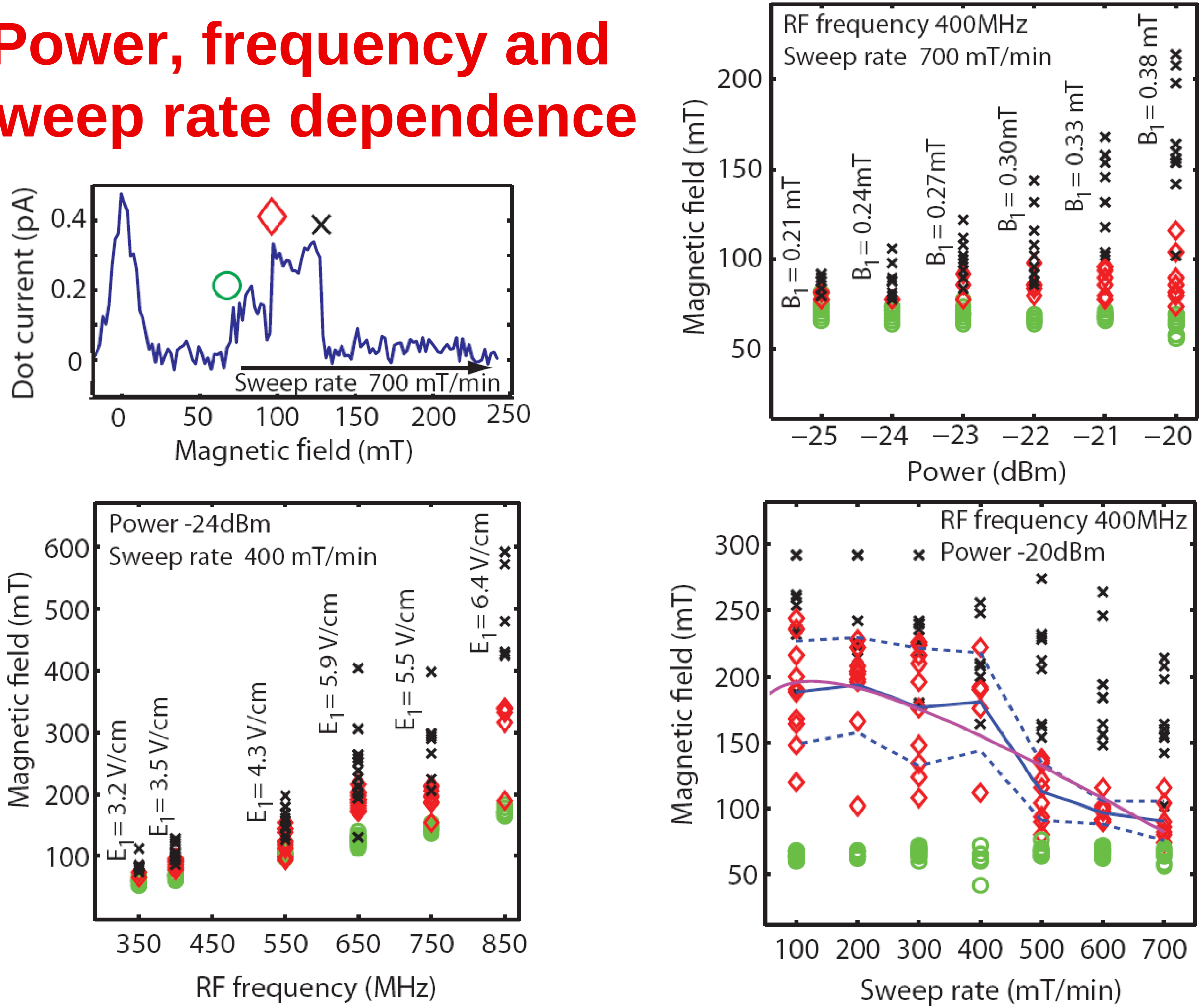


ESR condition:

$$hf = g\mu_B(B_{ext}+B_N)$$

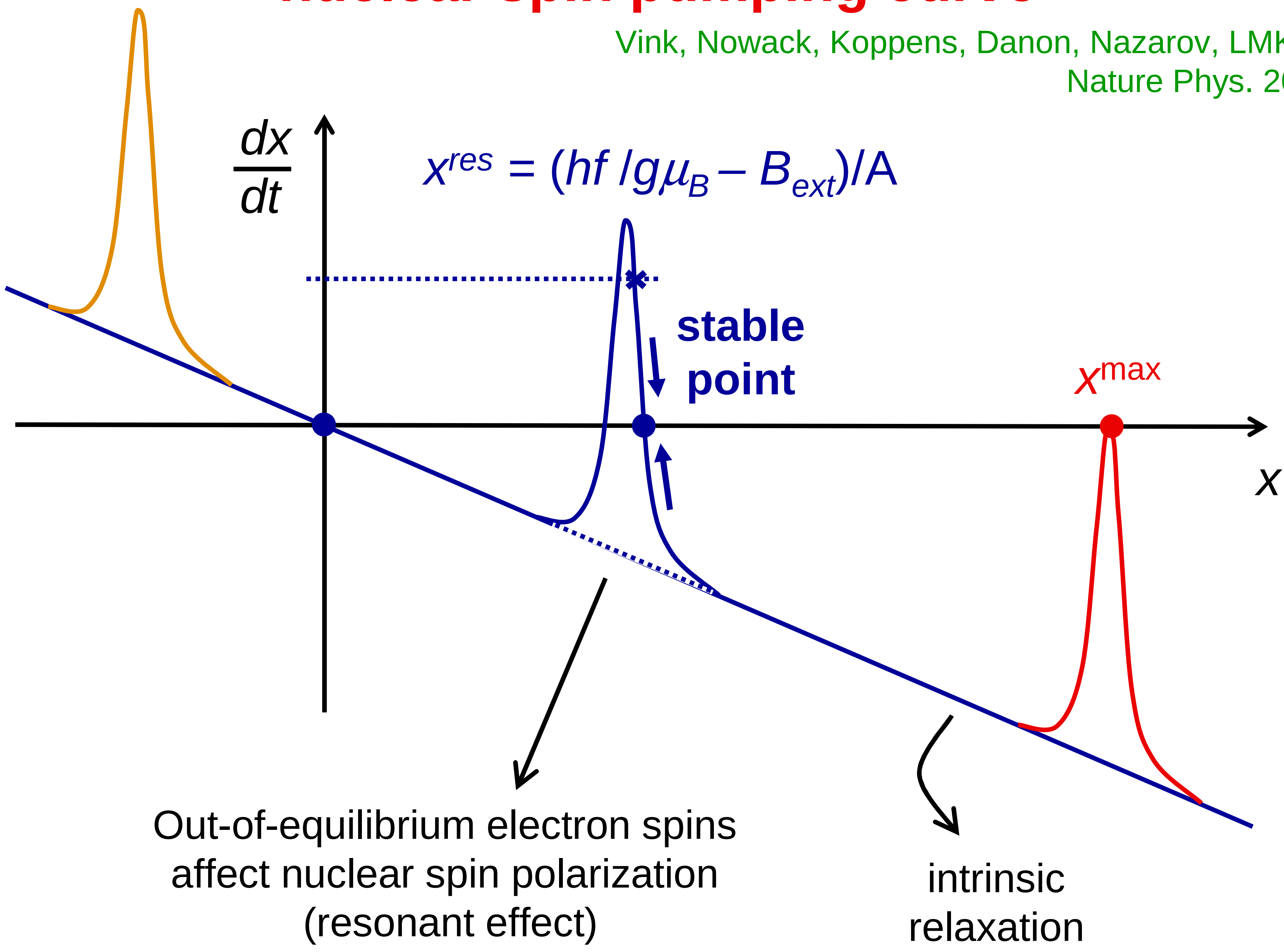


Power, frequency and sweep rate dependence

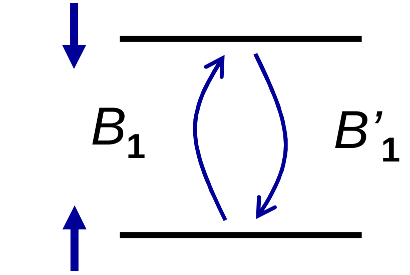


Origin of spin resonance locking – nuclear spin pumping curve

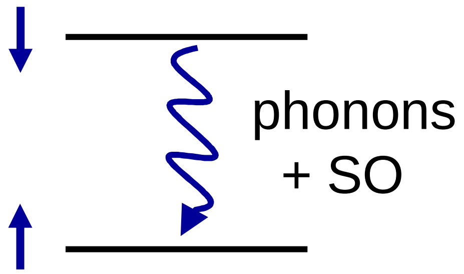
Vink, Nowack, Koppens, Danon, Nazarov, LMKV, Nature Phys. 2009

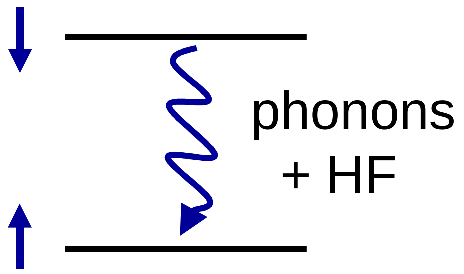


Microscopic pumping mechanism

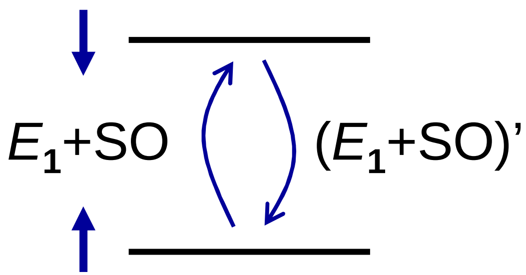


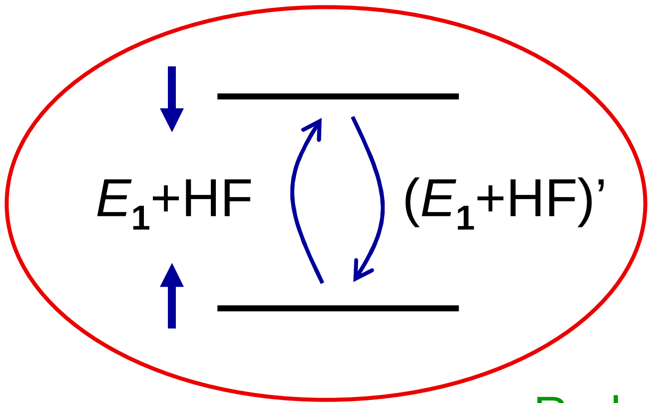
Observations:
B_N points against B_{ext}
B_N^{max} increases with B_{ac}, E_{ac}





Overhauser
B_N adds to B_{ext}

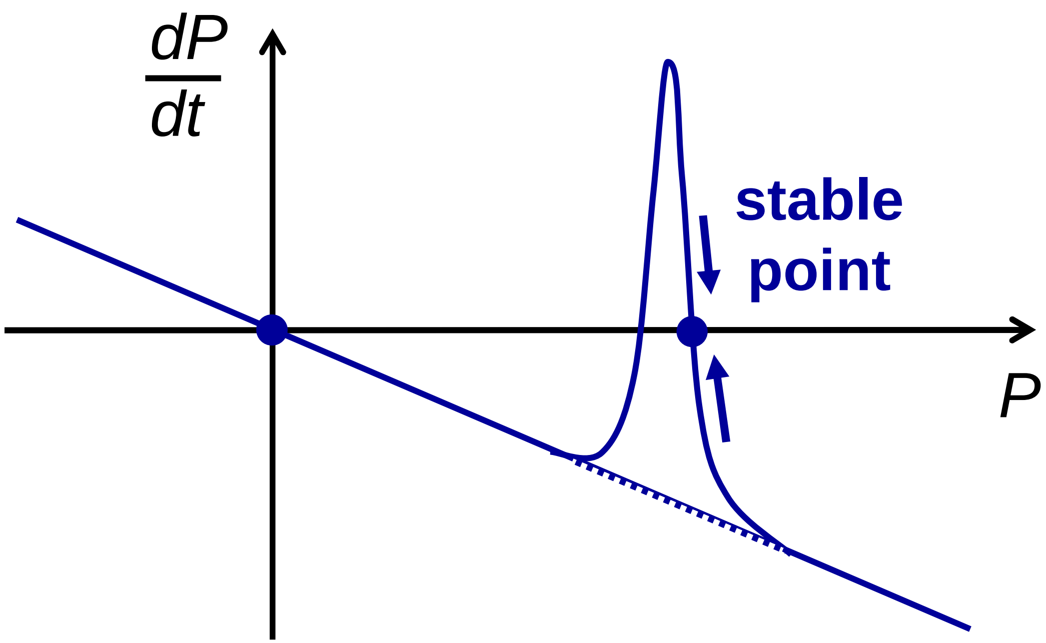




Sign B_N depends on
- electron spin polar.
- nuclear spin polar.
- matrix elements

Rudner & Levitov, PRL 2007

Suppression of nuclear spin fluctuations



Feedback keeps P pinned around stable point
slope sets “feedback strength”

no feedback

$$\sigma = \frac{A}{\sqrt{N}}$$

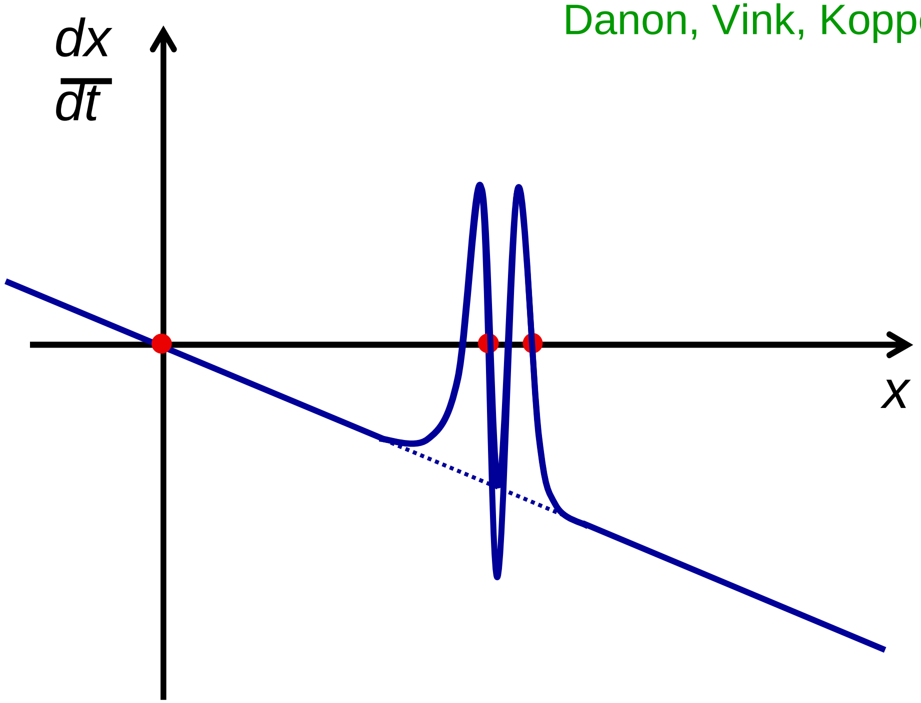
with feedback

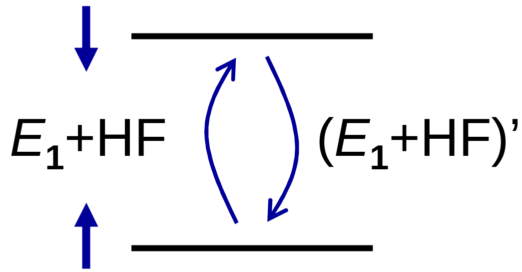
$$\sigma \approx \frac{A}{\sqrt{N}} \sqrt{\frac{B_1}{B_N^{max}}}$$

>10x narrower

Still richer physics for strong driving: multiple stable points

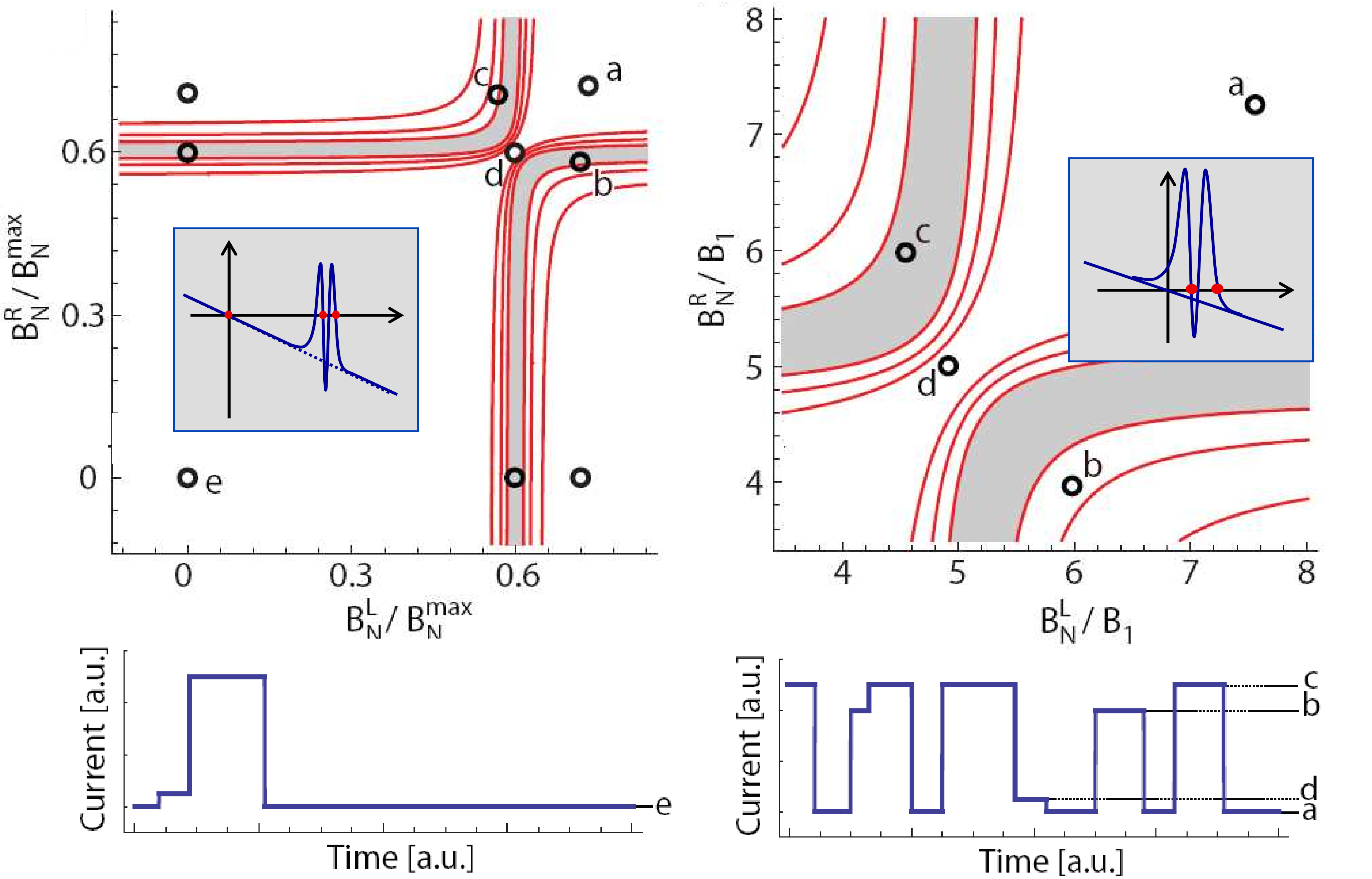
Danon, Vink, Koppens, Nowack, LMKV, Nazarov, PRL 2009



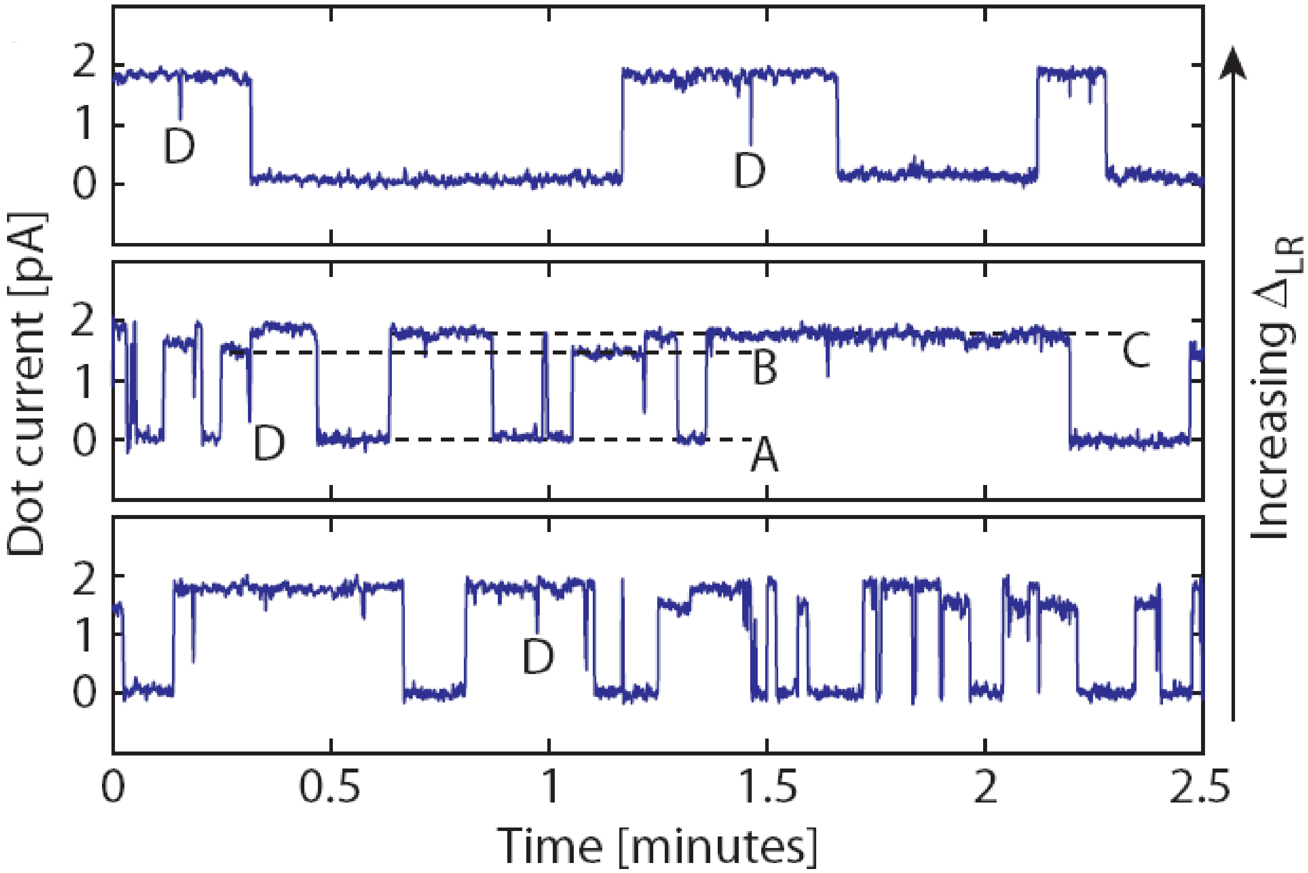


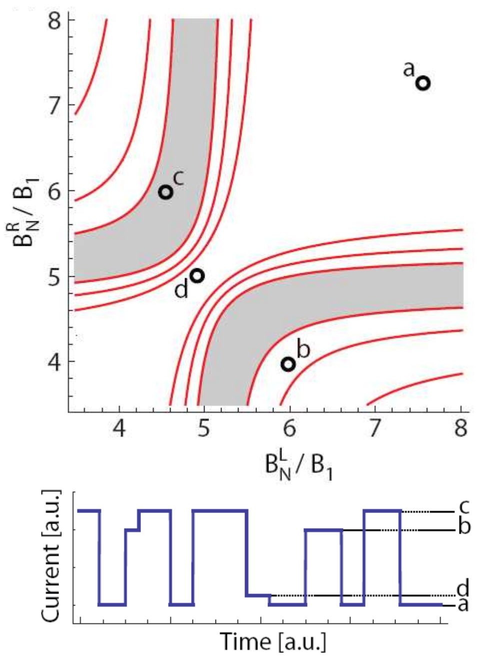
1) Equal ↑ and ↓ populations, hence no net nuclear spin pumping
2) Resonantly enhanced nuclear spin relaxation
   (nuclear spins flipped both ways)

Switching between stable points



Switching between stable points





Danon, Vink, Koppens, Nowack, LMKV, Nazarov, PRL 2009

Other work on suppression of nuclear field randomness

C. Latta et al (Imamoglu group) Nature Phys. 2009

single self-assembled dot
CW resonant trion excitation

X. Xu et al (Steel/Gammon group) Nature 2009

single self-assembled dot
coherent dark state spectroscopy (Raman resonance)

A. Greilich et al. (Bayer group), Science 2007, PRL 2008

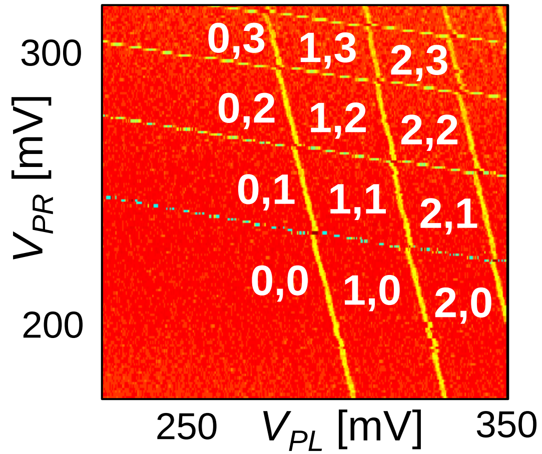
ensemble of self-assembled dots
laser pulse train resonant with trion transition

D. Reilly et al (Marcus group), Science 2008

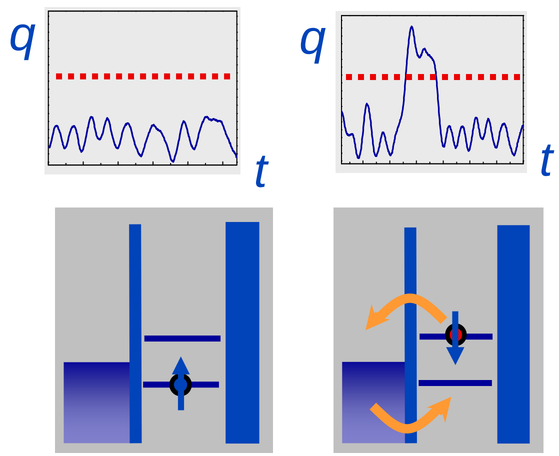
gate voltage pulse protocol
suppression of *difference* in B_N between two dots

Single-spin qubits in GaAs dots

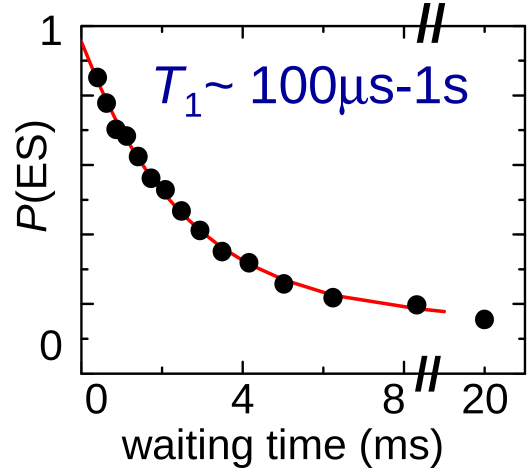
See also Hanson et al, Rev. Mod. Phys. 2007



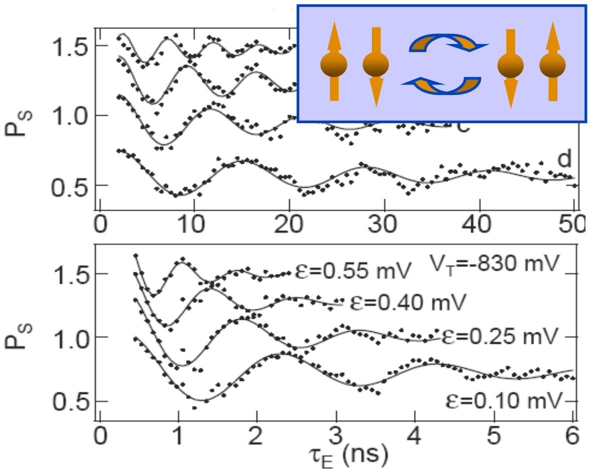
Ciorga et al, PRB 2000
Sprinzak et al., PRL 2002
Elzerman et al, PRB 2003



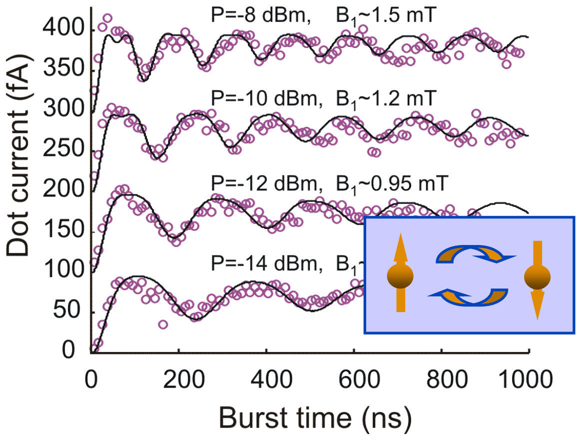
Elzerman et al., Nature 2004



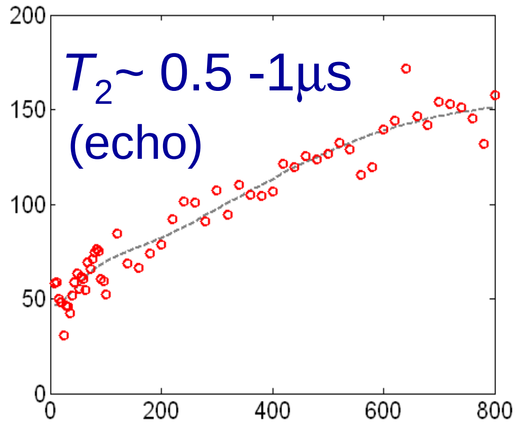
Fujisawa et al, Nature 2002
Amasha, PRL 2008



Petta et al., Science 2005

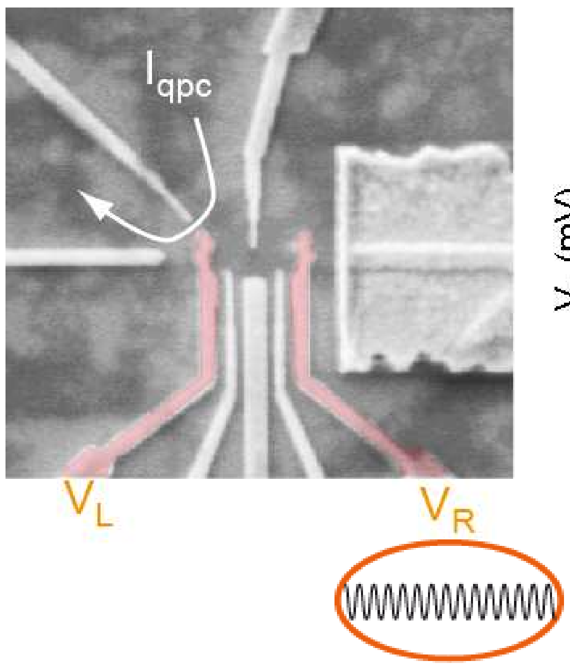


B(t) Koppens ea, Nature 2006
E(t) Nowack ea, Science 2007

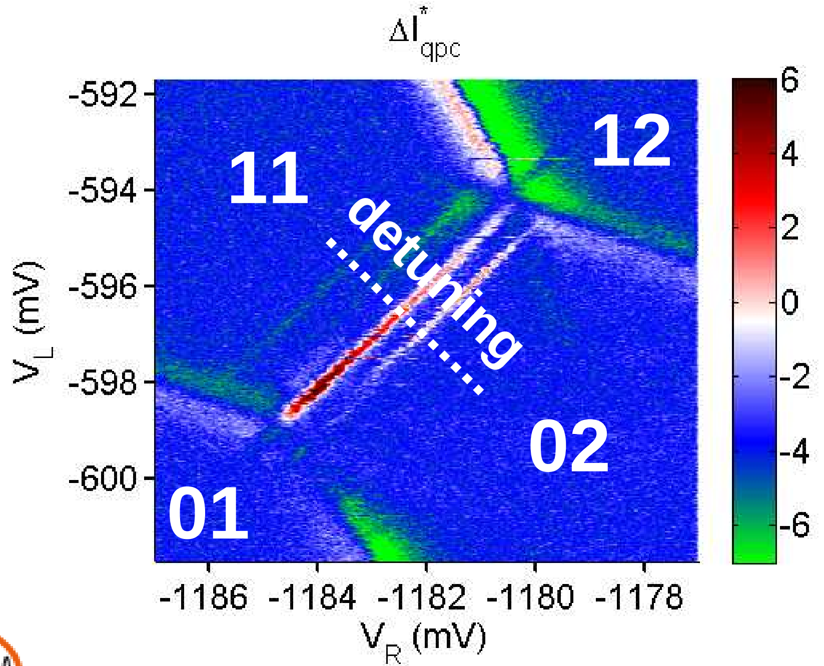


Petta et al., Science 2005
Koppens et al., PRL 2008

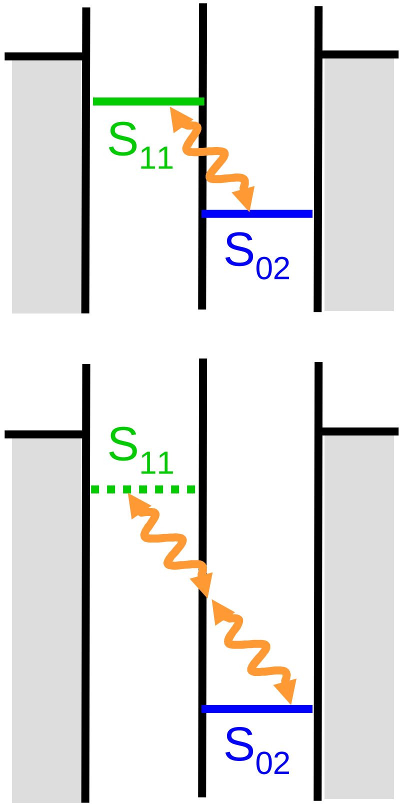
Photon-assisted tunneling (spin-conserving)



Sample fabrication
by T. Meunier



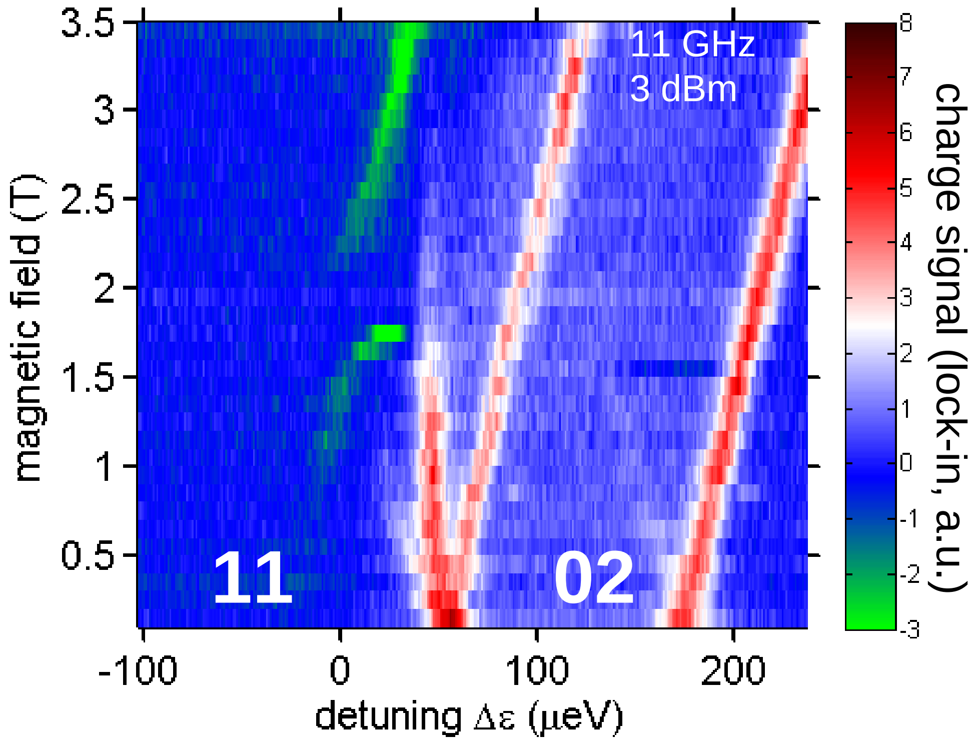
Lock-in charge measurement
with RF on/off modulation
(10 GHz, 2 dBm, 1.5 T)

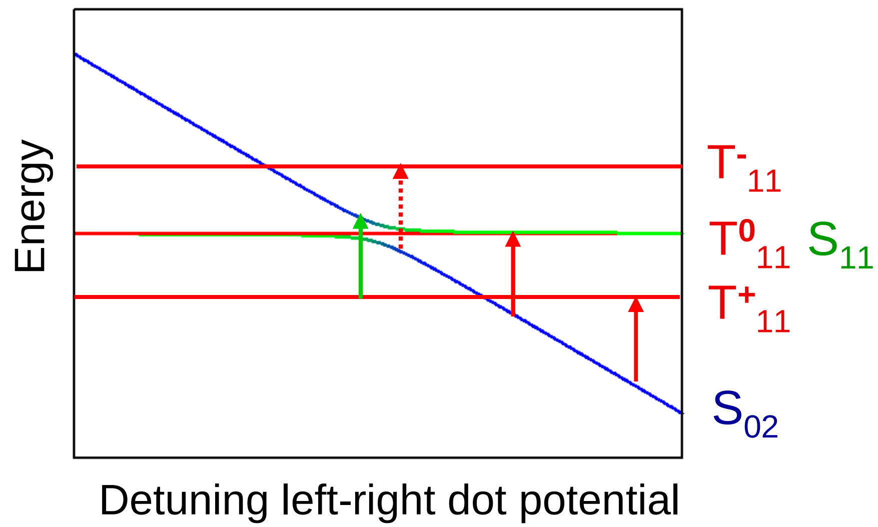


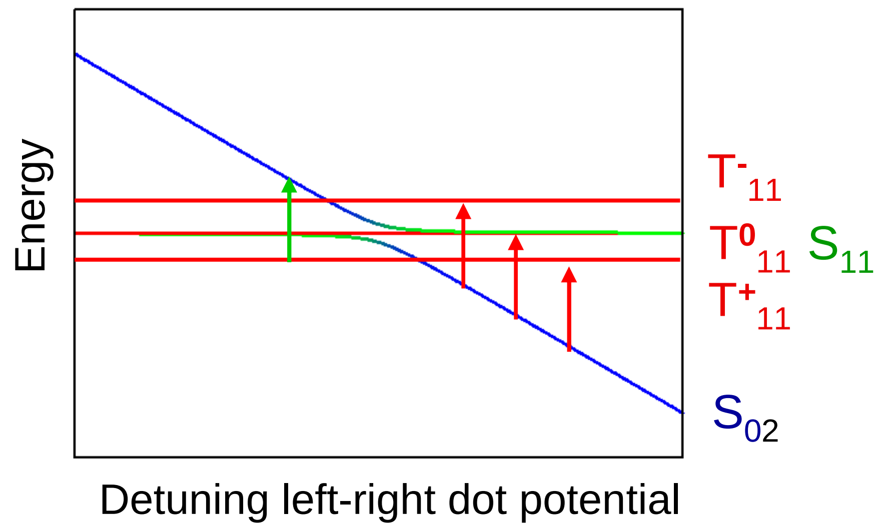
just the well-known photon-assisted tunneling sidebands?

Two-electron spin transitions

L. Schreiber, F. Braakman et al, unpublished

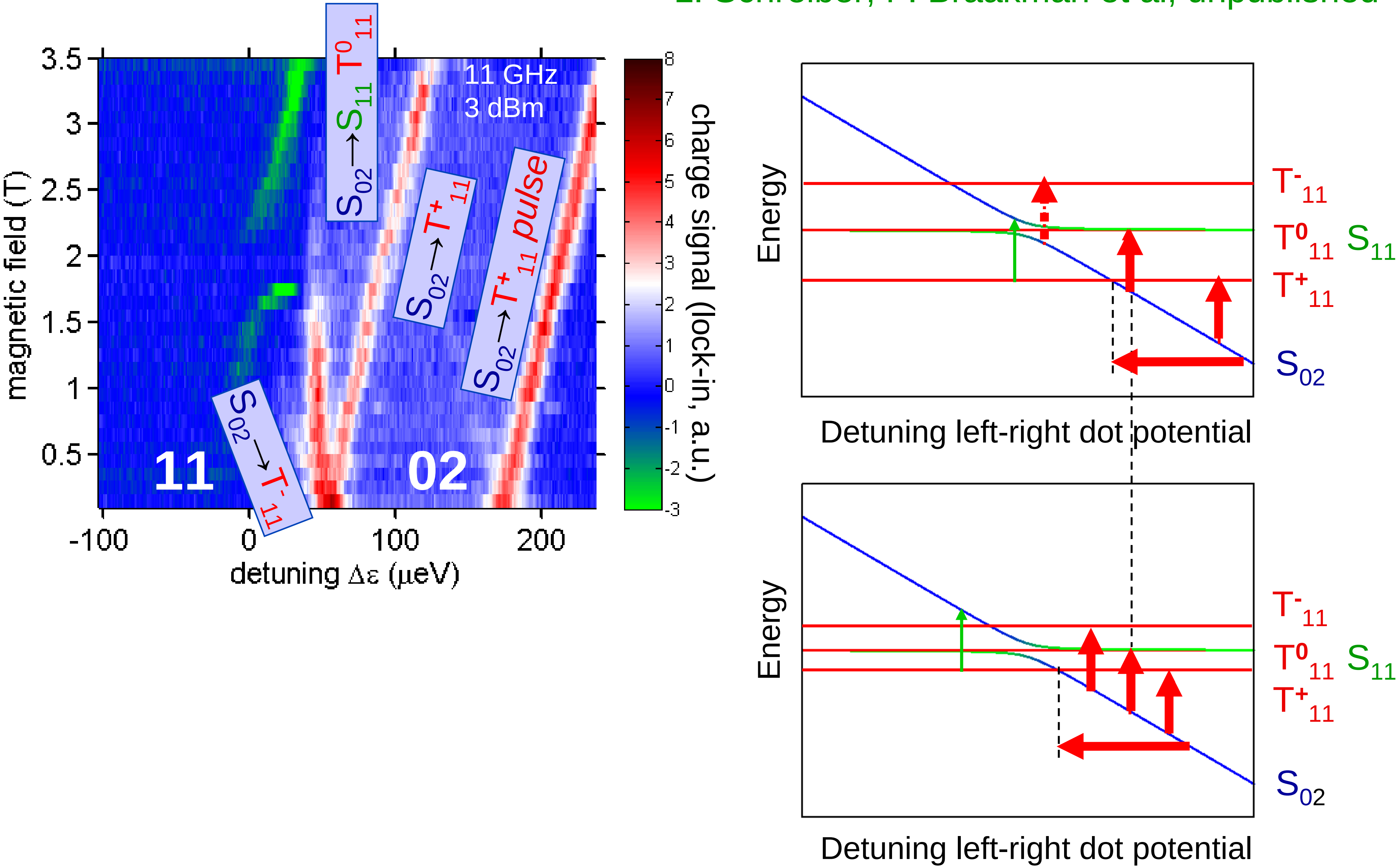






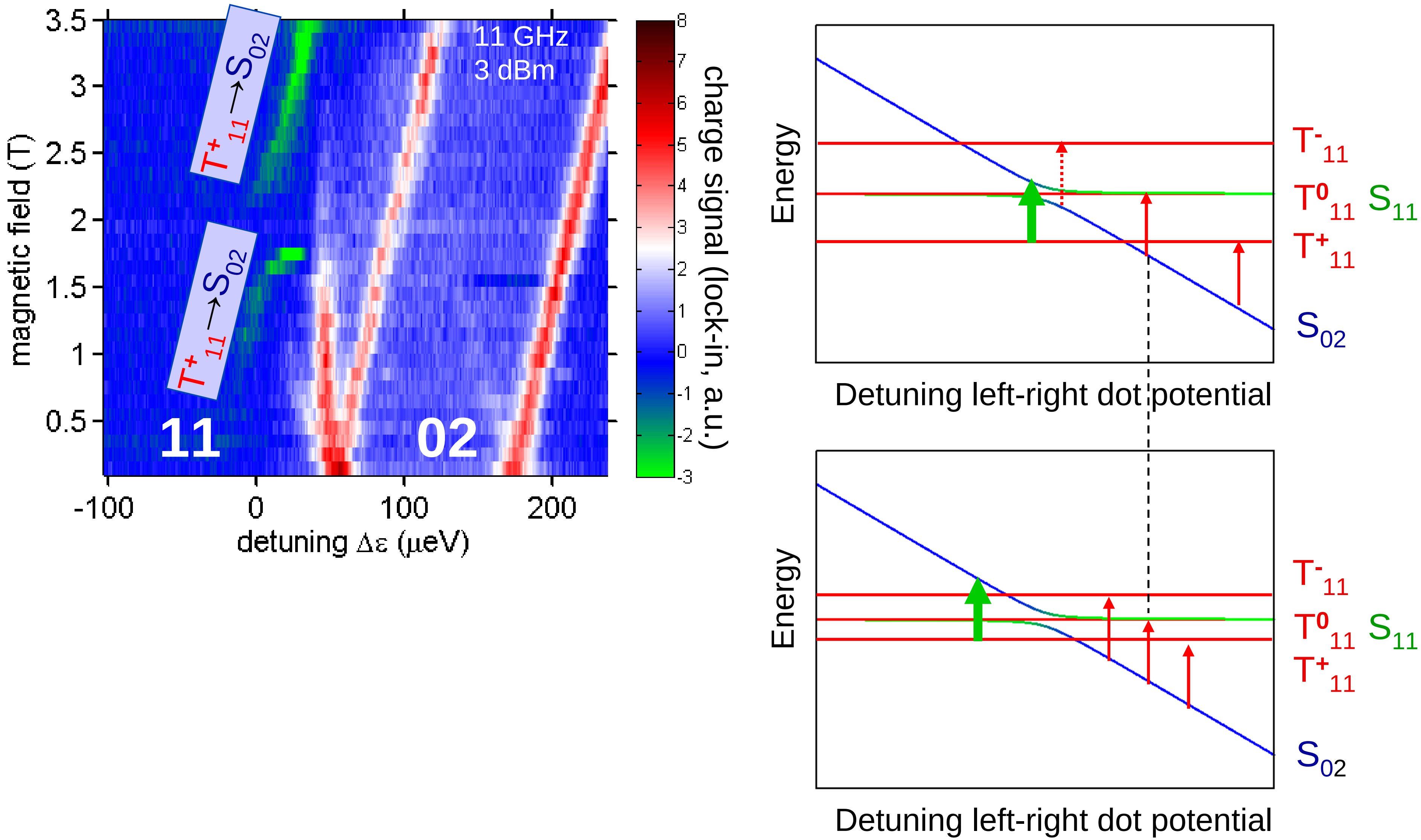
Two-electron spin transitions

L. Schreiber, F. Braakman et al, unpublished

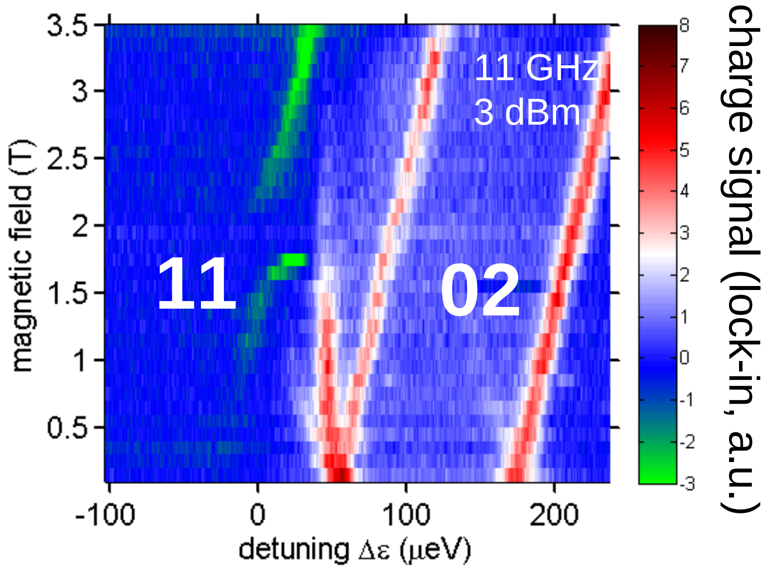


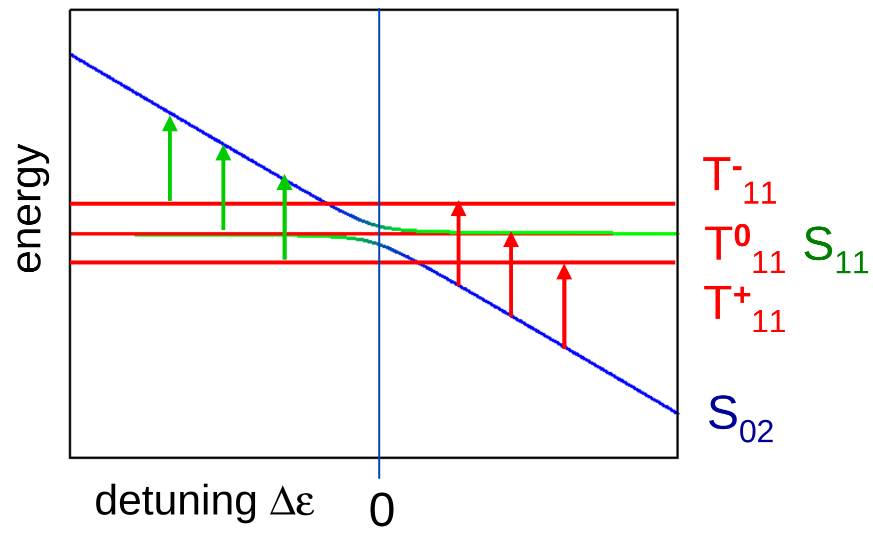
Two-electron spin transitions

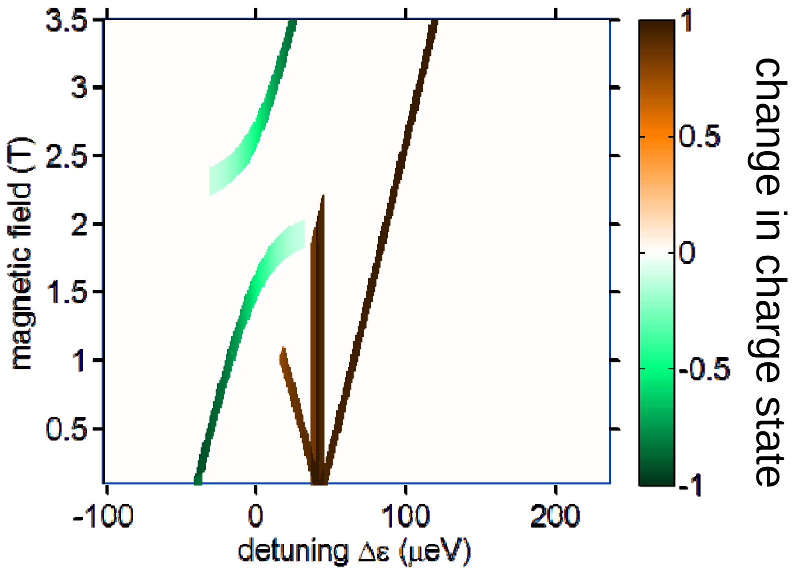
L. Schreiber, F. Braakman et al, unpublished



spin-PAT simulation





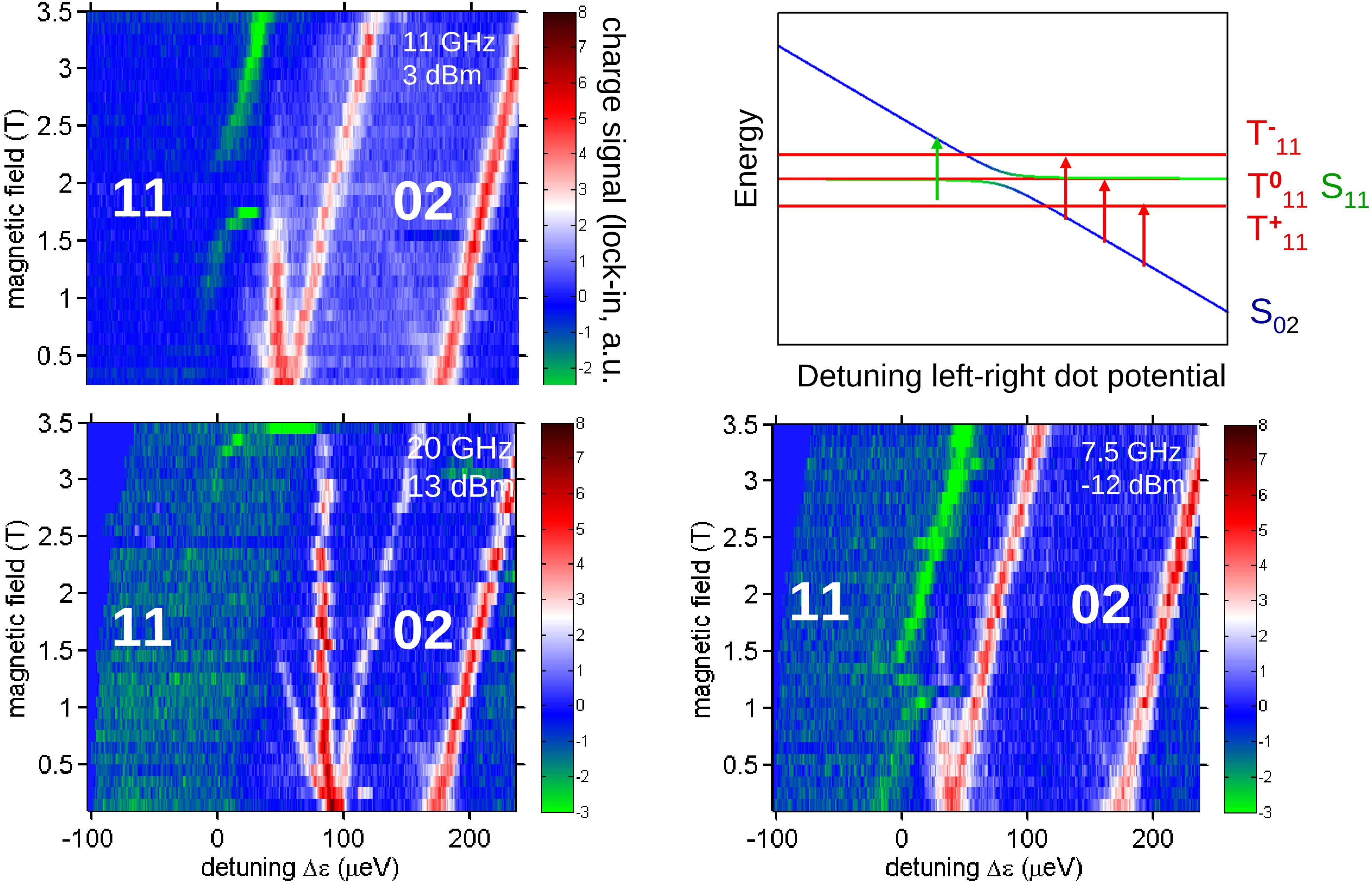


Extracted from comparison with data:

tunnel coupling t_c = 12 μeV
|g|-factor = 0.37
(given frequency 11 GHz)

Spin-flip-PAT Spectroscopy

L. Schreiber, F. Braakman et al, unpublished



Spin-orbit mechanism

Spin-orbit Hamiltonian

Dresselhaus (bulk property) $$\mathcal{H}_D^{2D,(001)} = \beta[-p_x\sigma_x + p_y\sigma_y]$$

Rashba (heterostructure property) $$\mathcal{H}_R = \alpha(-p_y\sigma_x + p_x\sigma_y)$$

For bound states (quantum numbers *n,l*)

$$\langle p_x \rangle = \langle p_y \rangle = 0$$

$$\langle nl \downarrow | H_{SO} | nl \uparrow \rangle \propto \langle nl | p_{x,y} | nl \rangle \langle \downarrow | \sigma_{x,y} | \uparrow \rangle = 0$$

Spin-orbit Hamiltonian directly couples states with different spin **&** orbital

$$\langle n'l' \uparrow | H_{SO} | nl \downarrow \rangle \cancel{=} 0$$

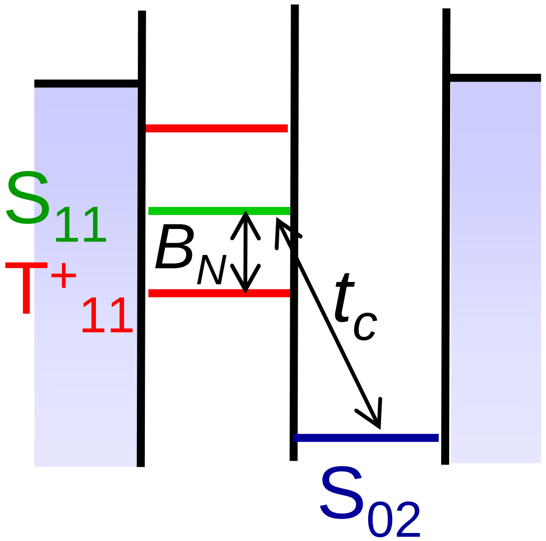
direct SO matrix element between S_{02} and T_{11}

Matrix element S_{02} to $T^{+,-}_{11} \sim t_c\, l_{ddot} / l_{SO} \sim 0.01\, t_c$

Hyperfine mechanism

Resonant transition from S_{02} to T^{+}_{11} via two-step process involving virtual transition to S_{11}:

(1) t_c couples S_{02} to S_{11}
(2) nuclei couple S_{11} to $T_{11}^{+,-}$ (suppressed with B)

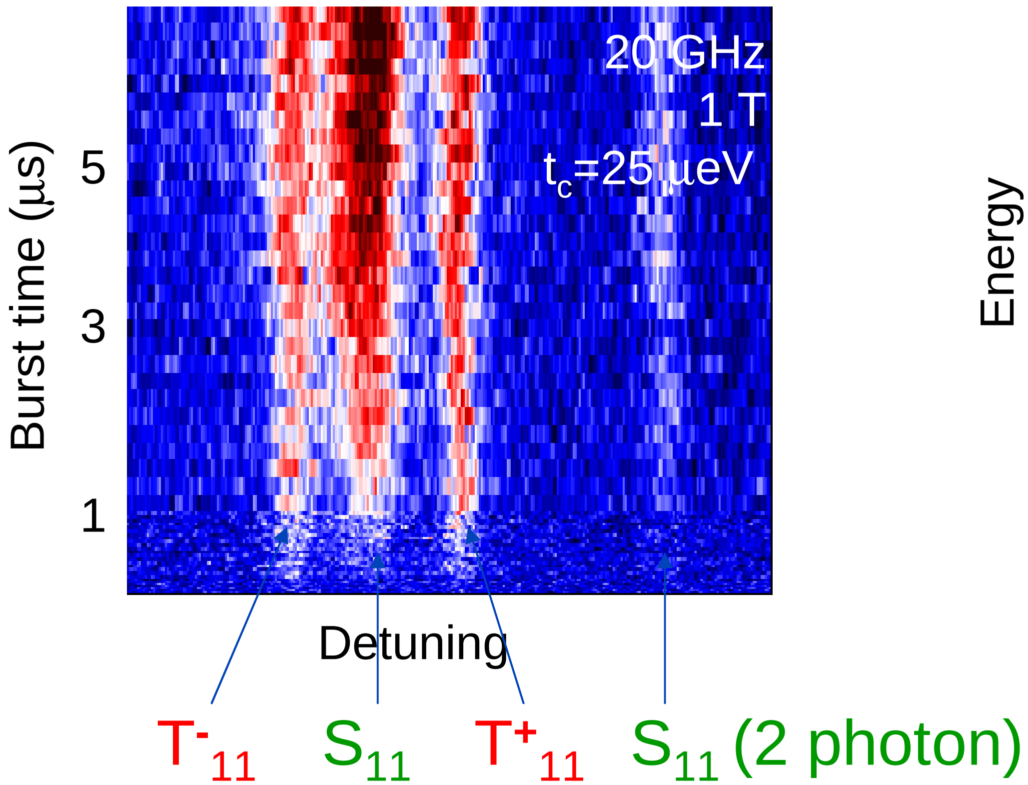


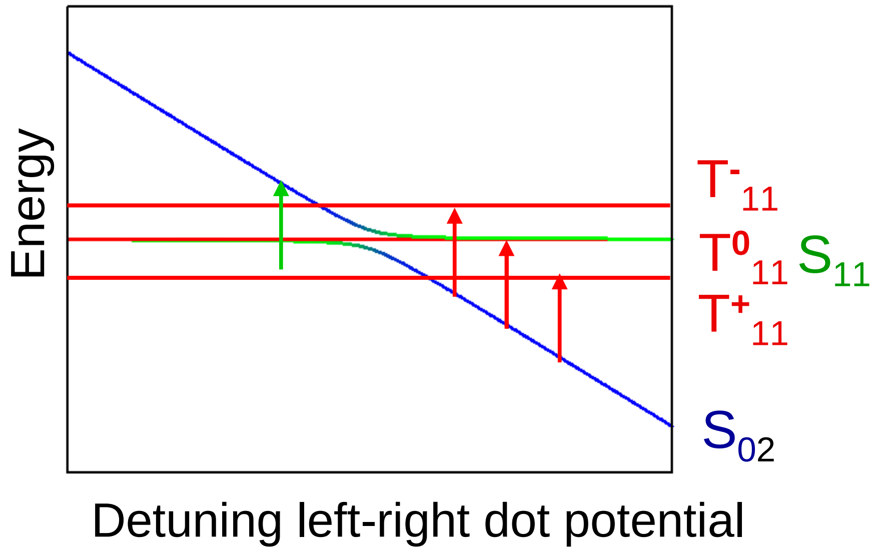
Matrix element S_{02} to $T^{+,-}_{11}$
$\sim t_c \, B_{\text{nuc}} / B_{\text{ext}} \sim 0.001 \, t_c$

Excitation by microwave bursts

microwave burst + 7 μs free relaxation (no initialization):

Raw data

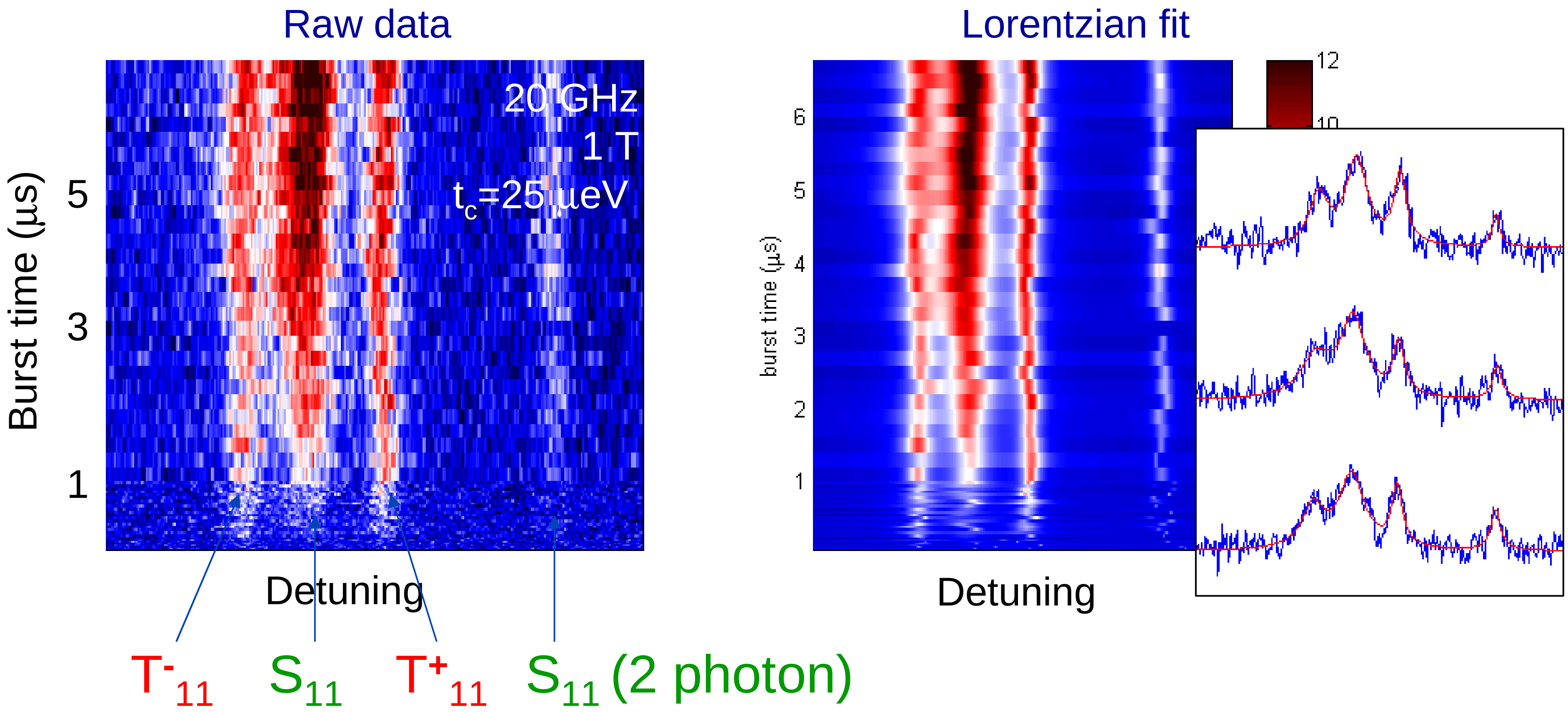




Signal increases with burst time and power
Transition to T^+_{11} and T^-_{11} show same behavior
Transition to S_{11}/T^0_{11} gives stronger signal

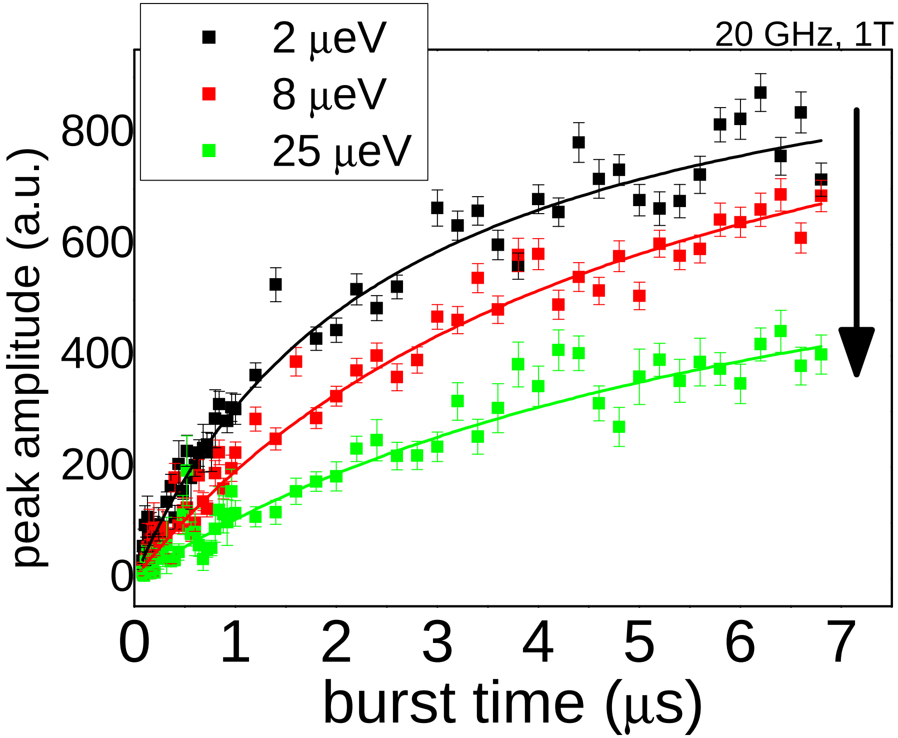
Excitation by microwave bursts

microwave burst + 7 μs free relaxation (no initialization):

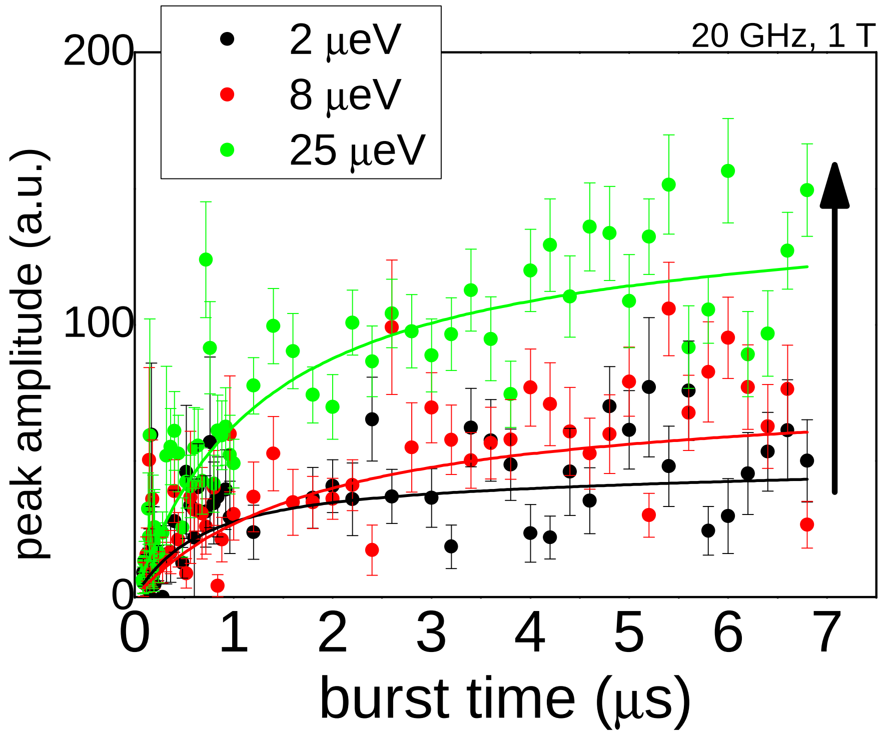


Dependence on interdot tunnel coupling

$S_{02} \rightarrow S_{11}$



$S_{02} \rightarrow T^{+}_{11}$



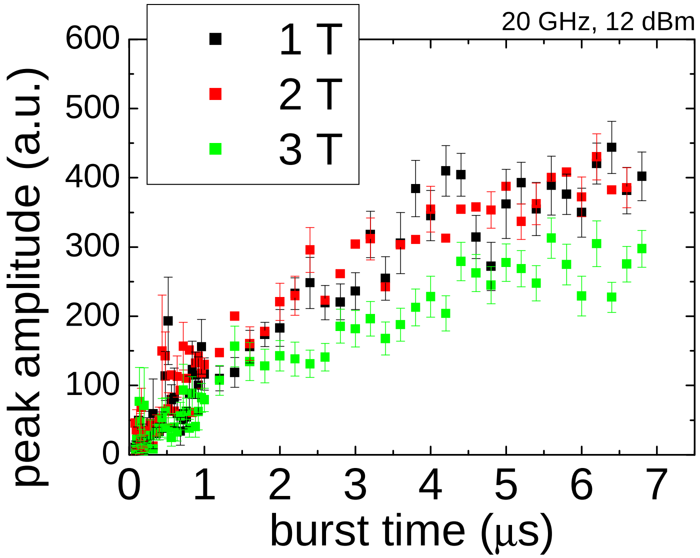
Preliminary data – datapoints represent peak area

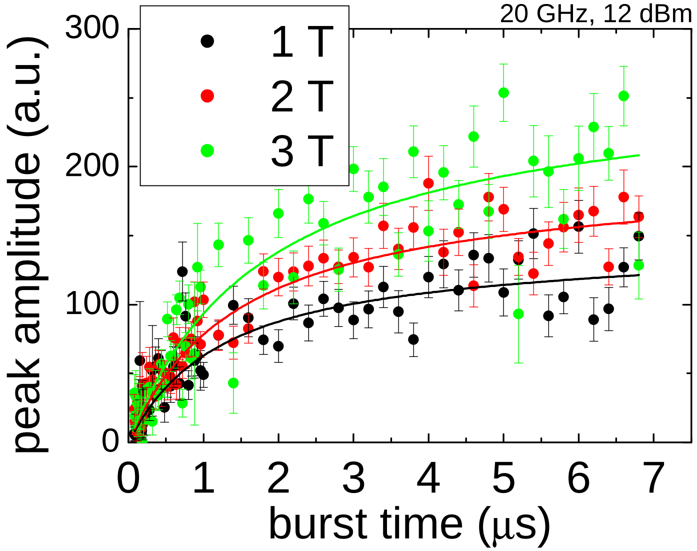
Signal is sensitive to both relaxation and excitation rates

Dependence on magnetic field

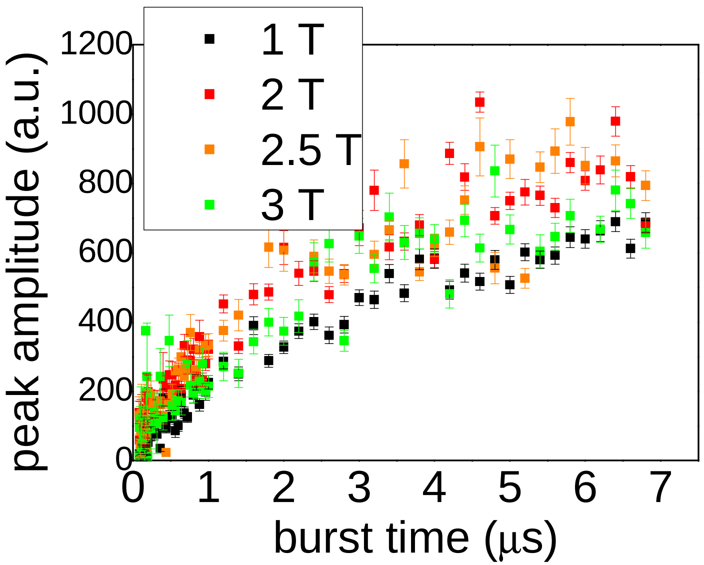
$S_{02} \rightarrow S_{11}$

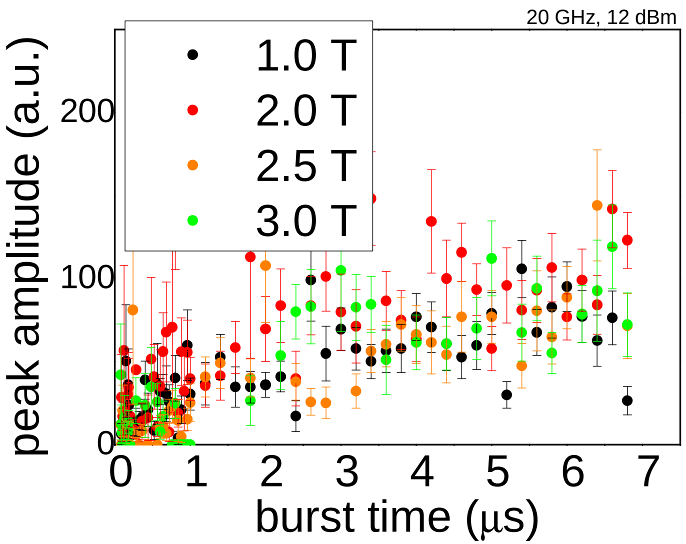
$S_{02} \rightarrow T^{+}_{11}$





t_c= 25µeV

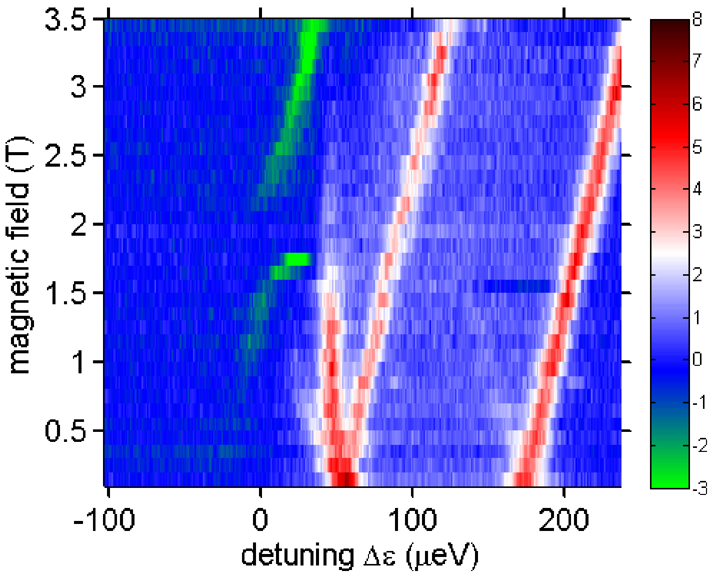


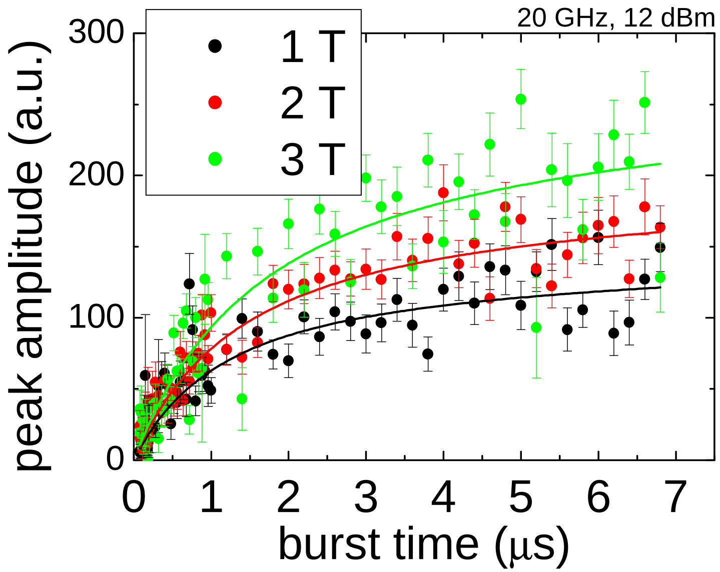


t_c= 8µeV

Summary part II

- Electrically-induced spin-flip tunneling transitions
- Implications for electron spin shuttling
- Likely mediated by spin-orbit interaction
- Permits double-dot spectroscopy – all transitions identified
- Incoherent process (spins entangled with orbitals)





People and collaborations

GaAs spin qubits

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Oostinga & Morpurgo (Geneva)

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