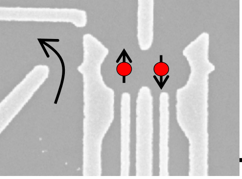
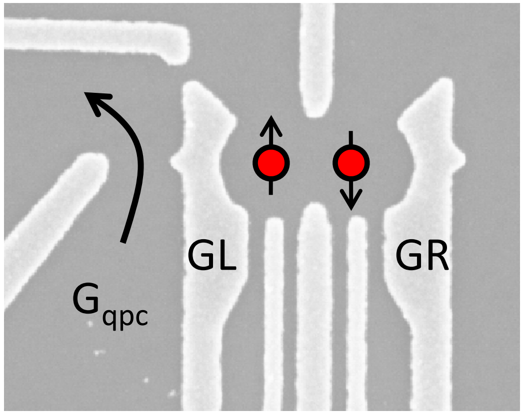


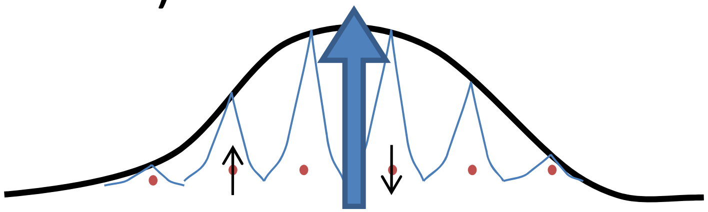
Probing and Controlling the Nuclear Spin Bath of GaAs Electron Spin Qubits

Hendrik Bluhm



Experiments (Harvard)

HB, Sandra Foletti,
Amir Yacoby



Theory

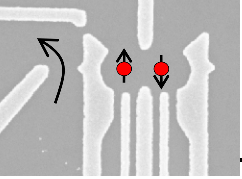
Izhar Neder, Mark Rudner, HB, AY
(Harvard)

MBE growth and e-beam writes:

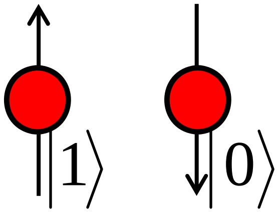
V. Umansky, D. Mahalu
(Weizmann Institute)

Funding

ARO
DoD



Motivation



GaAs based electron spin qubits

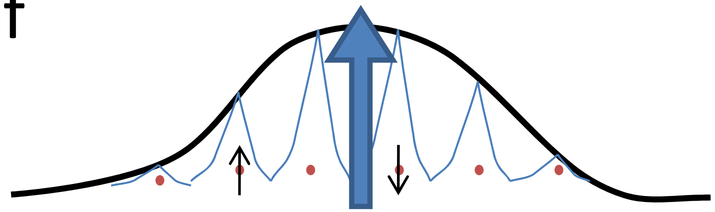
+ Properties favorable for scaleup.

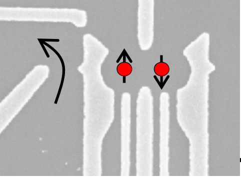
+ Individual qubits demonstrated (Harvard, Delft, Tokyo).

- Dephasing dominated by fluctuating nuclear hyperfine field.

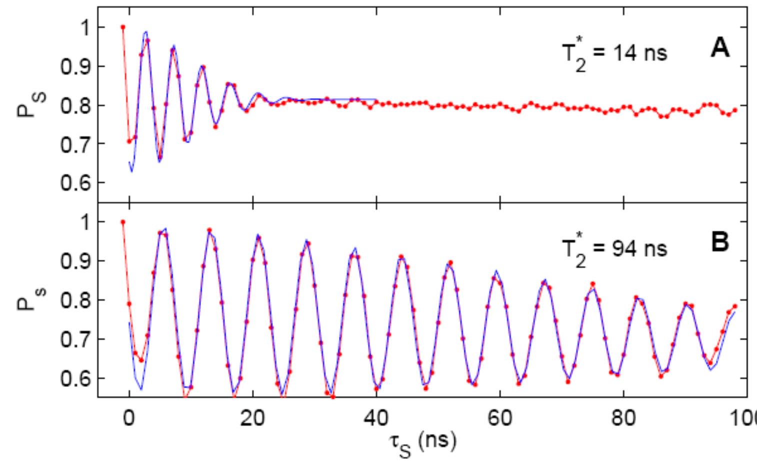
Fundamental interest

Understand quantum dynamics of an electron spin coupled to a mesoscopic bath of nuclear spins.



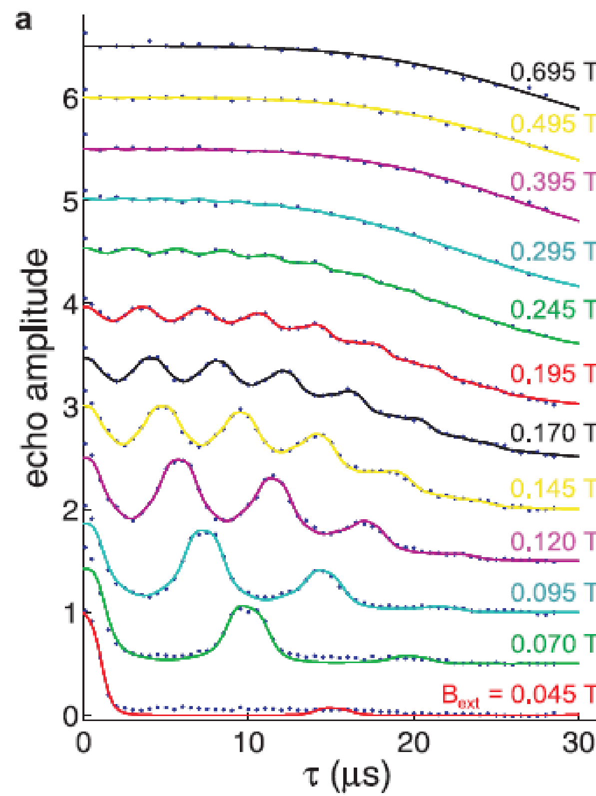


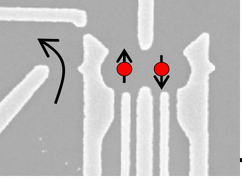
Main results



Spin physics
- Use qubit to probe and suppress fluctuations of nuclear bath.
- Detailed picture of nuclear decoherence.

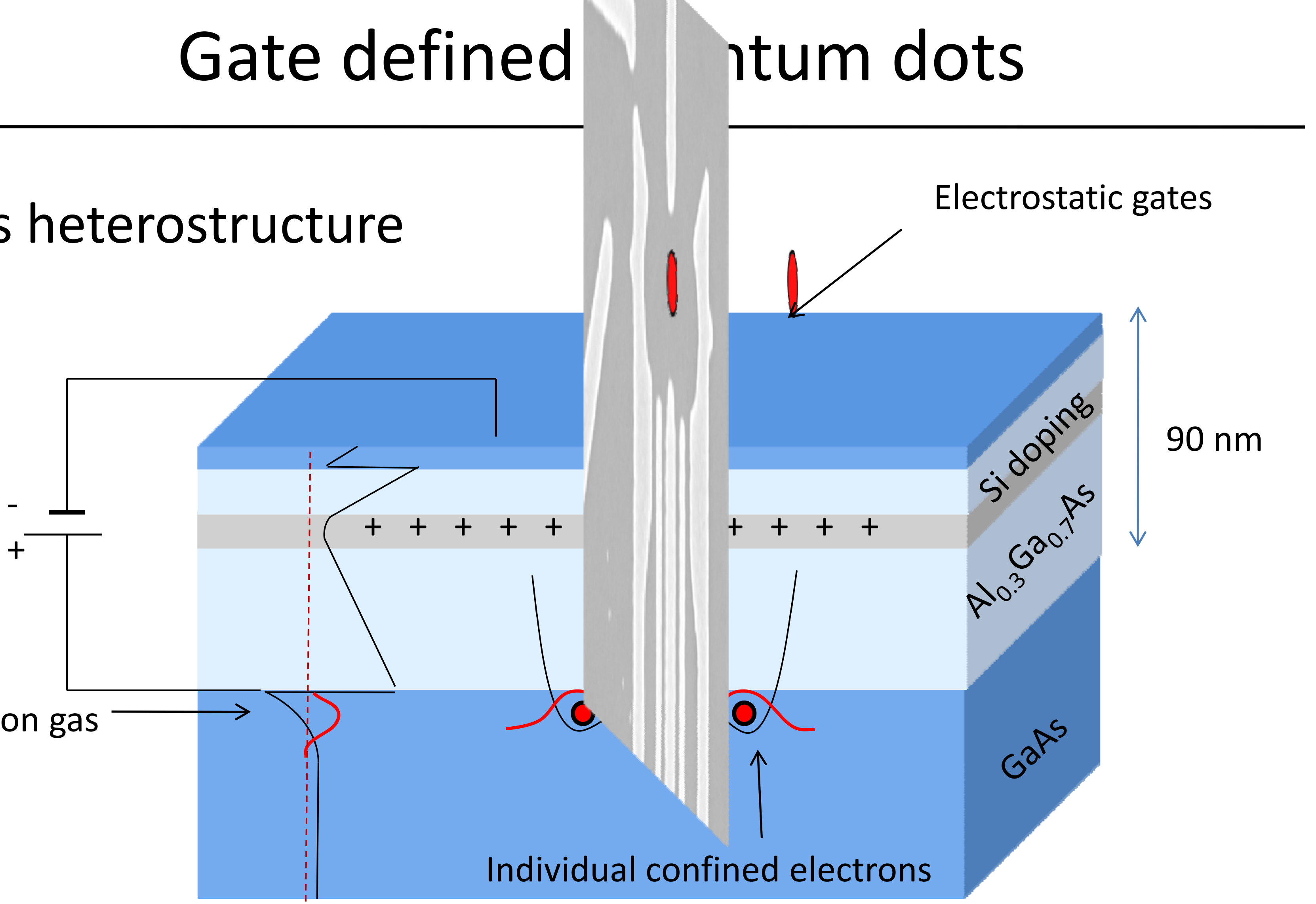
Qubit improvement
- Fast universal control.
- T_2 extended by a factor 100.



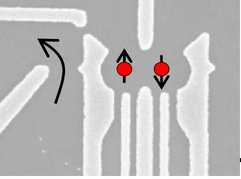


Gate defined ntum dots

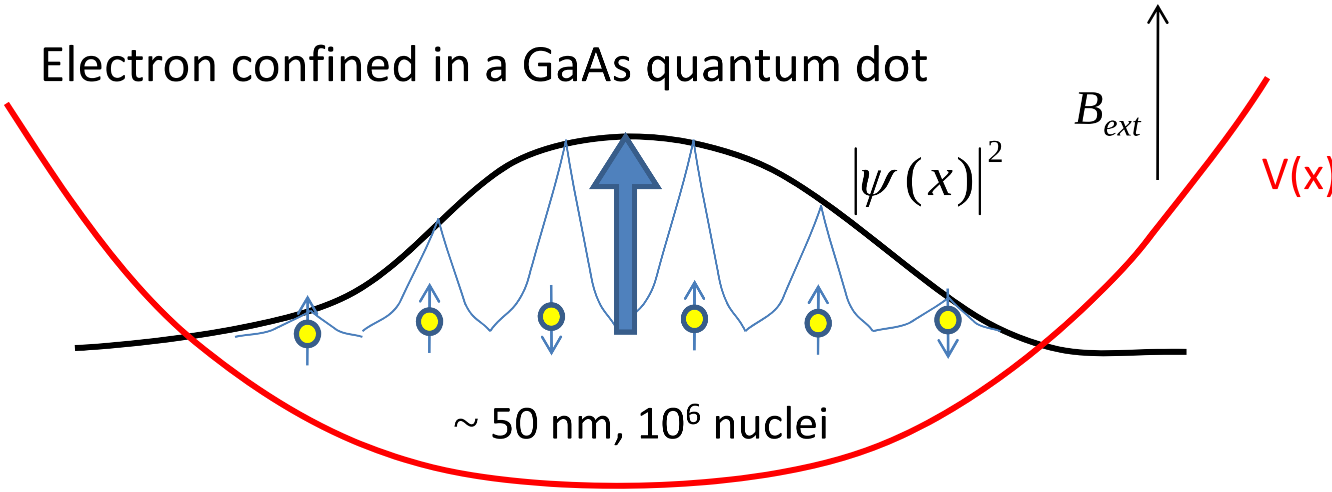
GaAs heterostructure



- Fully electrical control.
- Controlled fabrication.
- Time scale well-matched to classical Si hardware.



Hyperfine interaction



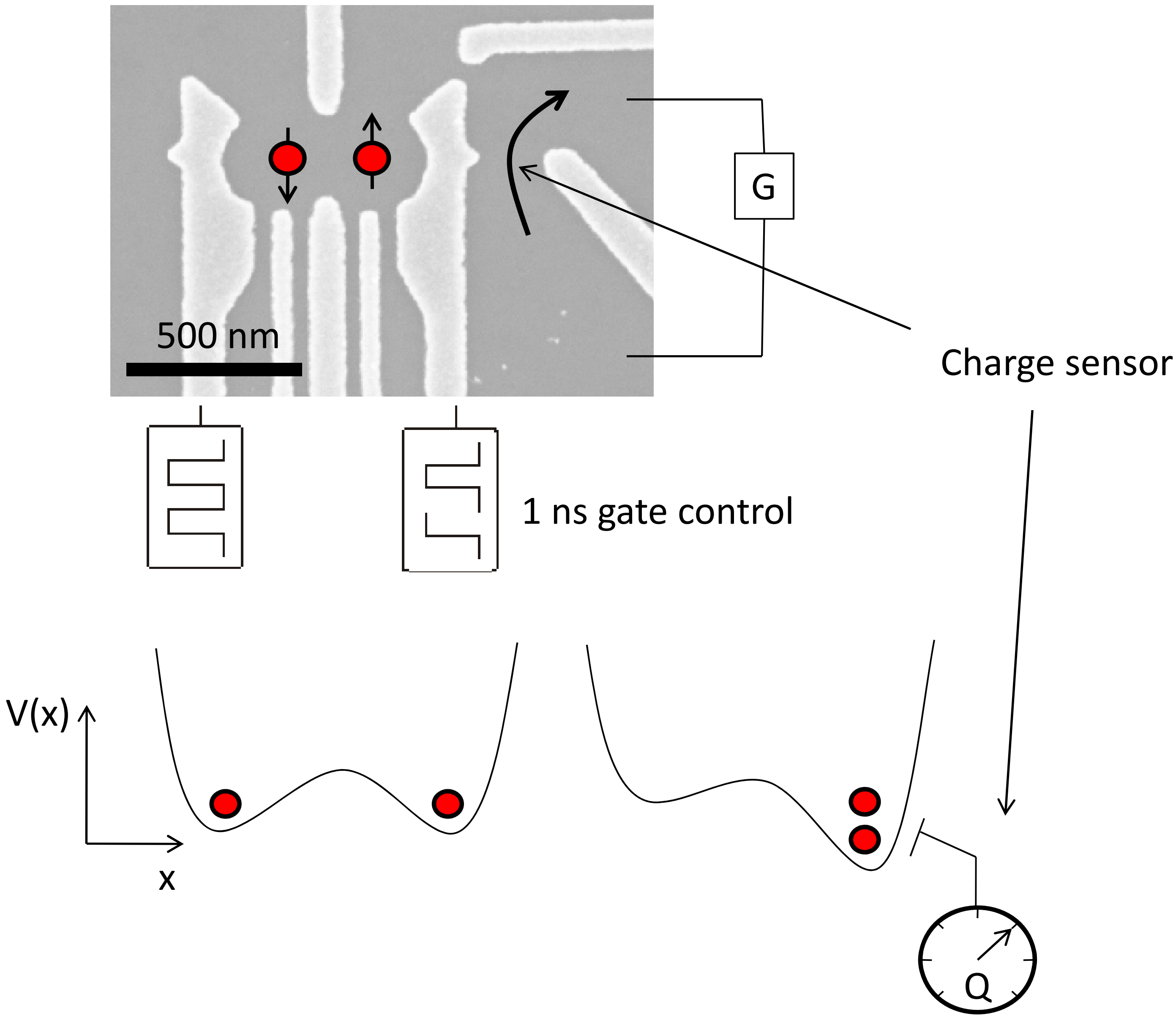
Hyperfine contact interaction

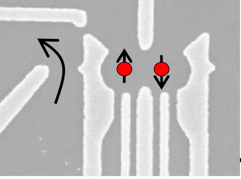
$$H = A \sum_j \vec{I}_j \cdot \vec{S} \left|\psi(x_j)\right|^2$$

Typical hyperfine field:
$A / N^{1/2}$ ~ 2 mT -> T_2^*

Interactions and Larmor precession of nuclei
$\Rightarrow$ Hyperfine field fluctuates
$\Rightarrow$ Decoherence of electron spin

Two-electron double quantum dots





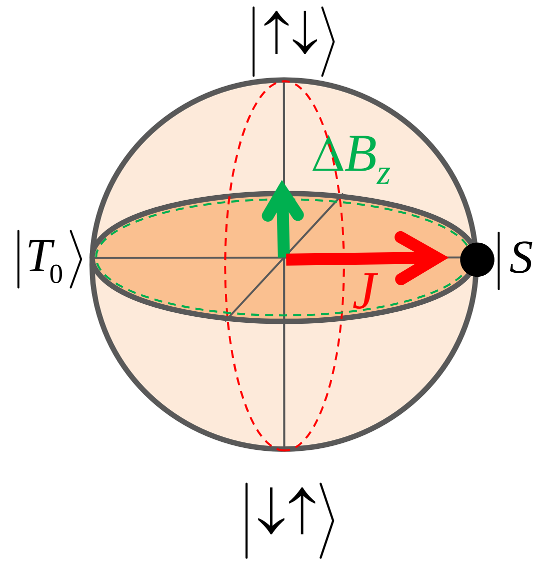
Qubit manipulation

Spin states

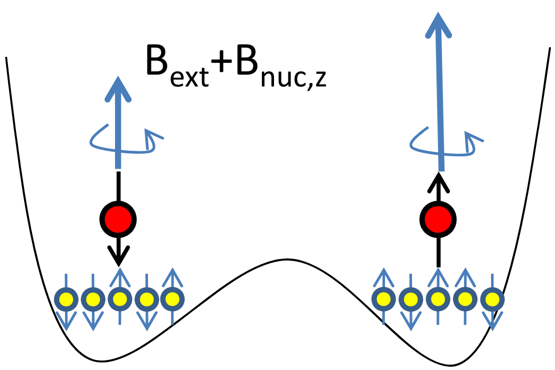
$$|S\rangle = \frac{1}{\sqrt{2}}\left(|\downarrow\uparrow\rangle - |\uparrow\downarrow\rangle\right)$$

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

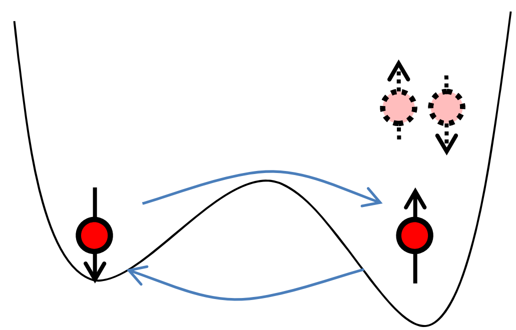
$$|T_+\rangle = |\uparrow\uparrow\rangle, |T_-\rangle = |\downarrow\downarrow\rangle$$

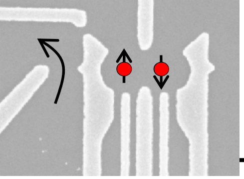


Free precession



Coherent exchange





Outline

Background

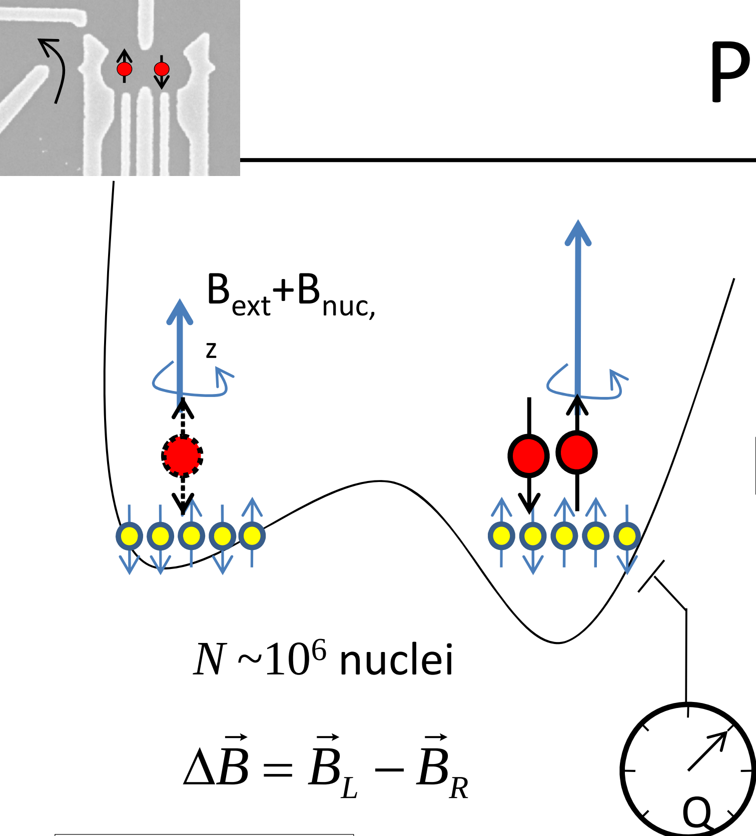
Experiments

- Principles of qubit operation
- Measuring and manipulating the nuclear hyperfine field

Suppressing fluctuations with 1-qubit feedback loop

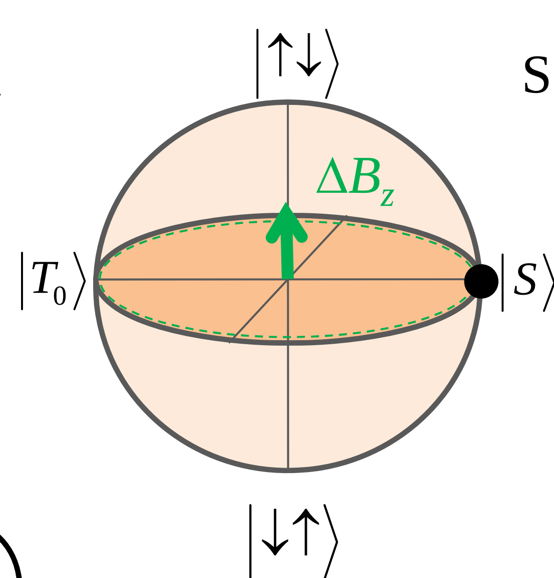
Hahn echo and CPMG

Probing ΔB_z



$N \sim 10^6$ nuclei

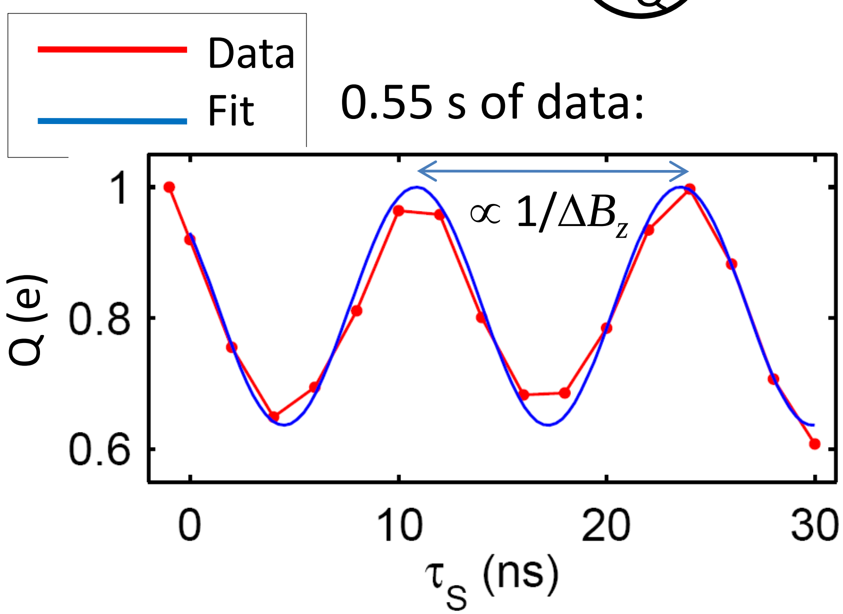
$$\Delta\vec{B} = \vec{B}_L - \vec{B}_R$$



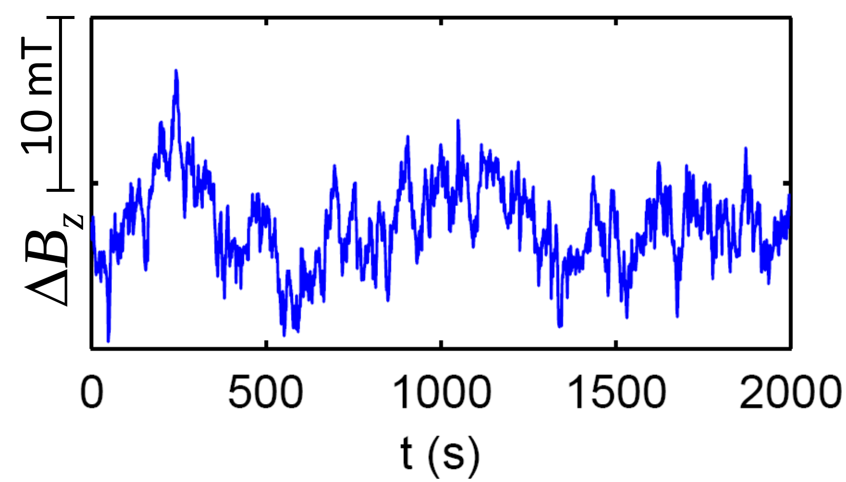
$$\text{Sensor signal} \propto \cos^2\left(\frac{\omega\tau_S}{2}\right)$$

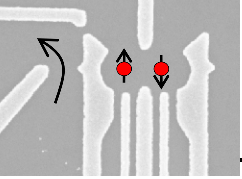
$$\omega = g^* \mu_B \Delta B_z / \hbar$$

0.55 s of data:

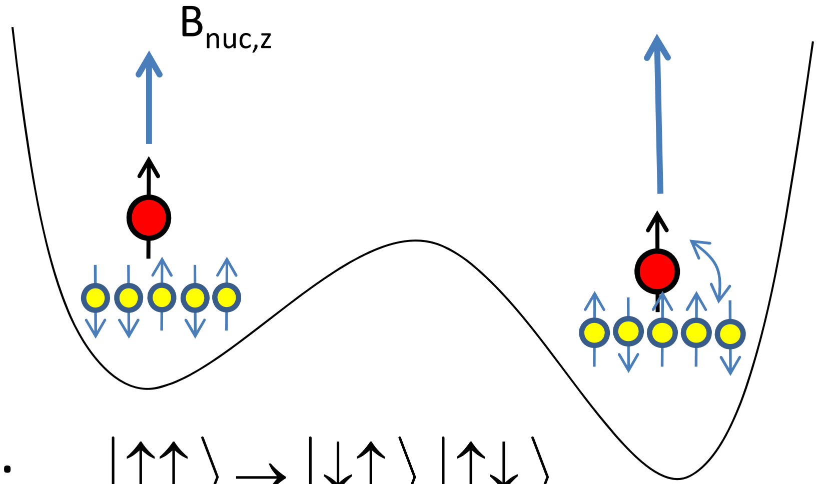


Typical time trace of hyperfine gradient





Manipulating B_{nuc}



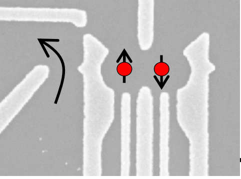
Repeated spin transfer from electrons to nuclei => Dynamic nuclear polarization

T_+-pump: $|\uparrow\uparrow\rangle \rightarrow |\downarrow\uparrow\rangle, |\uparrow\downarrow\rangle$

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

Previous work: average polarization, relaxation.
(Harvard, Petta et al., Reilly et al.)

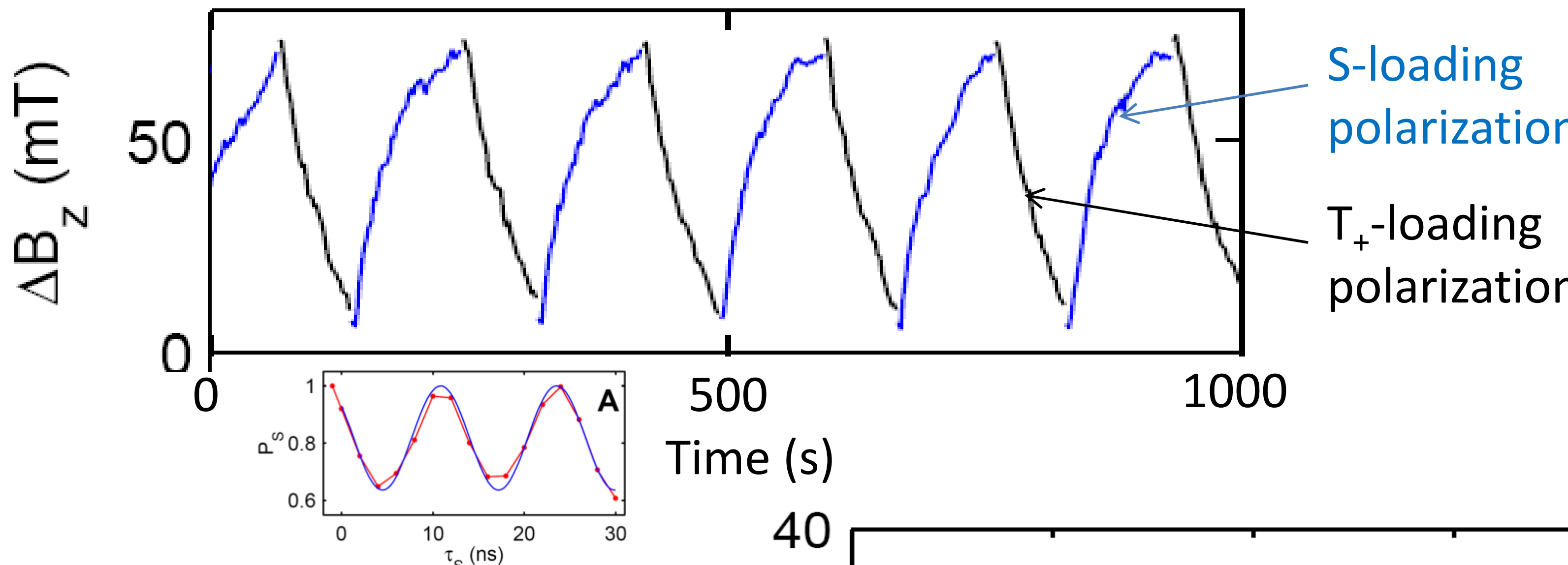
Here: Bi-directional real time control of gradient.



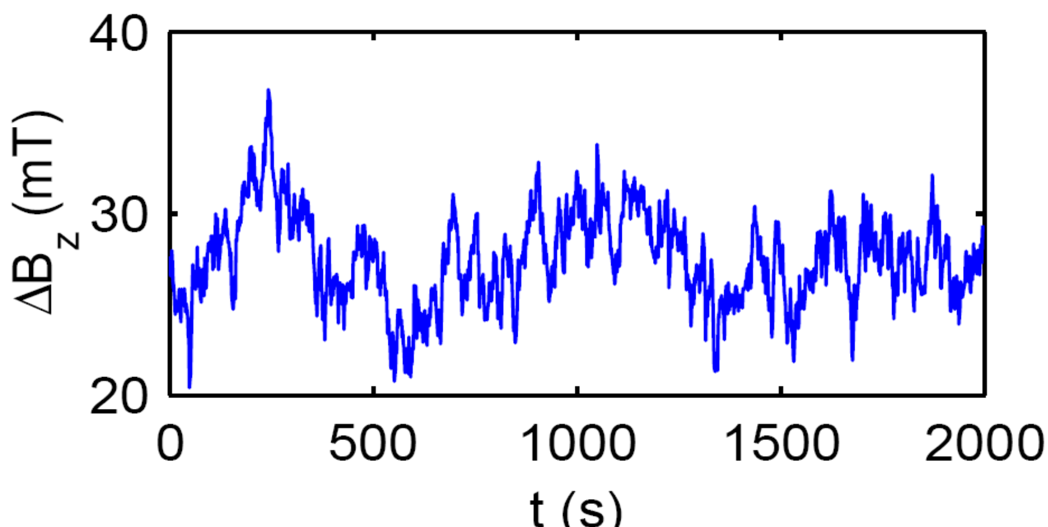
Effect of polarization on ΔB_z

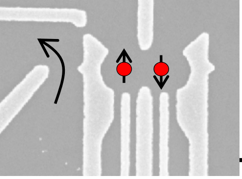
Polarize between measurements (typically ~10^6 cycles)

Real time control of ΔB_z

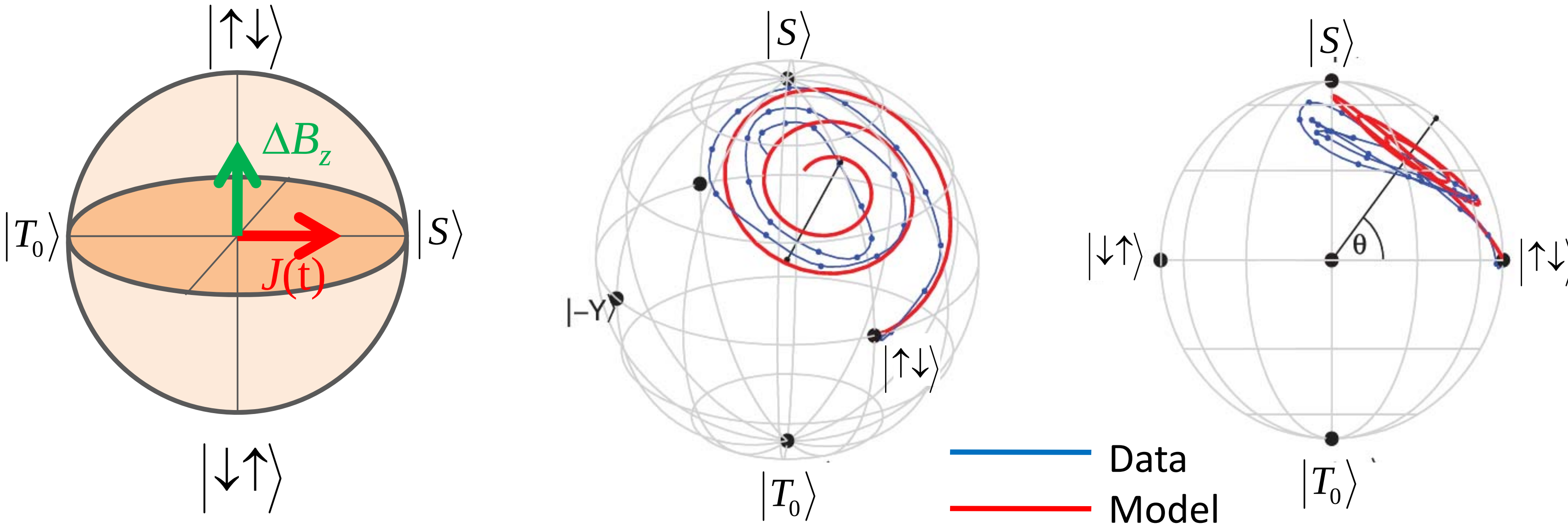


Steady state when relaxation compensates polarization.



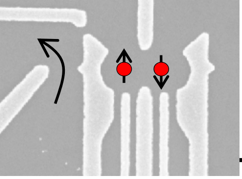


Universal single qubit control



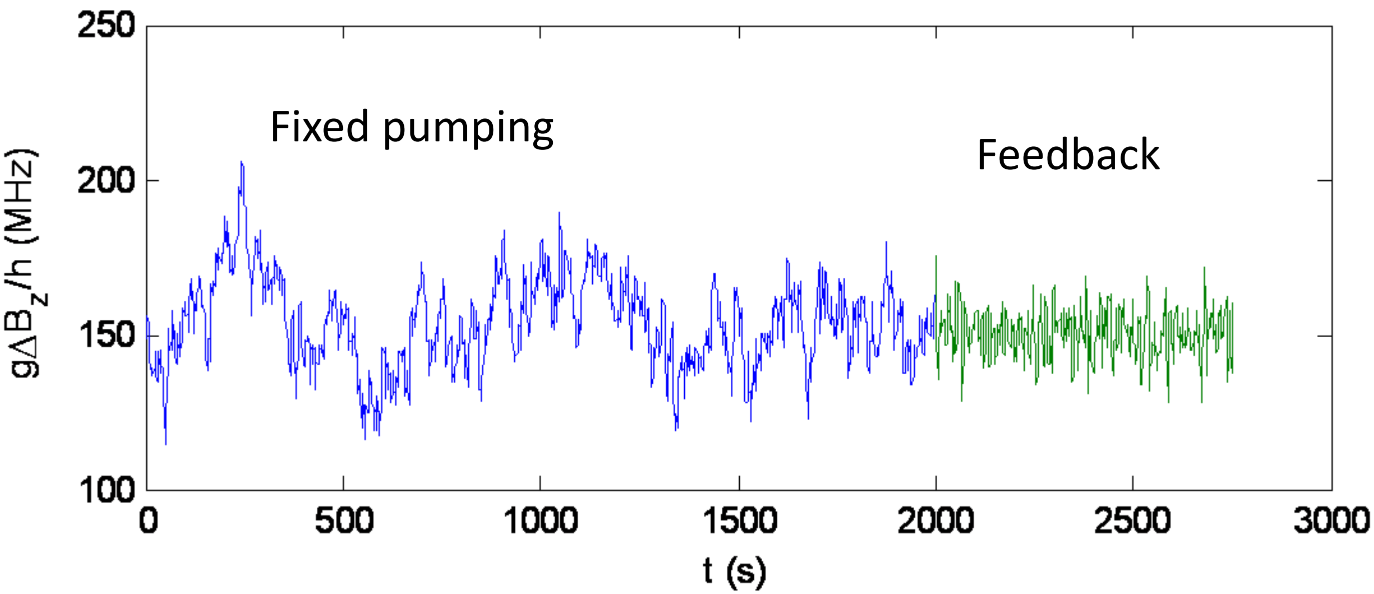
- Nuclei turned into resource
- Fast (ns gate times)
- Fully electrical
- Extrapolated fidelity of 99.99 %.

Nature Physics 2009.



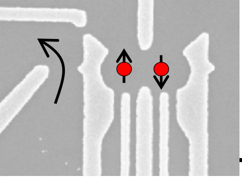
Preparing the bath via feedback

Control and measurement faster than bath dynamics
=> Software feedback – adjust polarization rate to keep ΔB_z stable.



- Qubit measures the nuclear bath
- Qubit manipulates bath

=> let it do all the feedback!



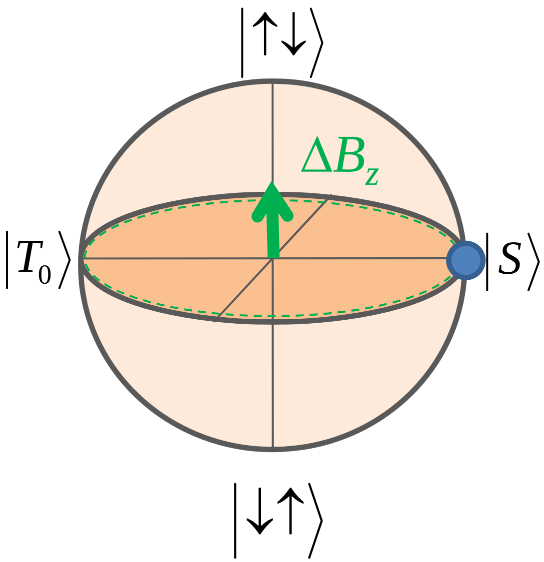
Pulses with built-in feedback

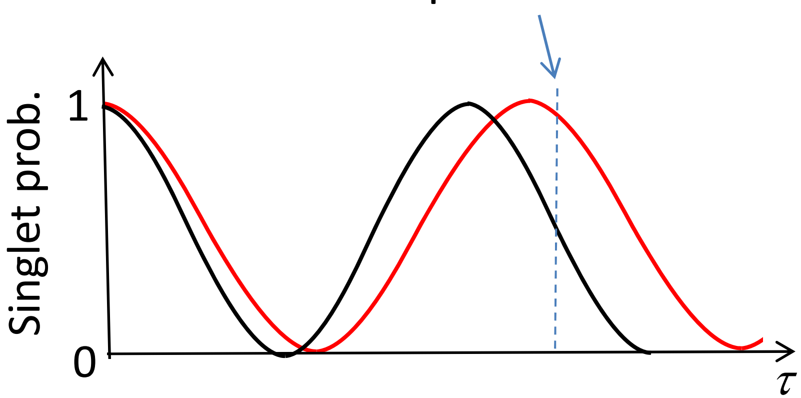
1. Initialise S
2. Evolve qubit for 15-30 ns
3. Polarize nuclei conditional on final state:
   S -> spin transfer possible
   T_0 -> spin transfer suppressed

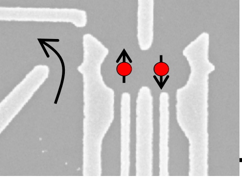
small ΔB_z => strong pumping
=> ΔB_z increases

large ΔB_z => weak pumping
=> ΔB_z decreases

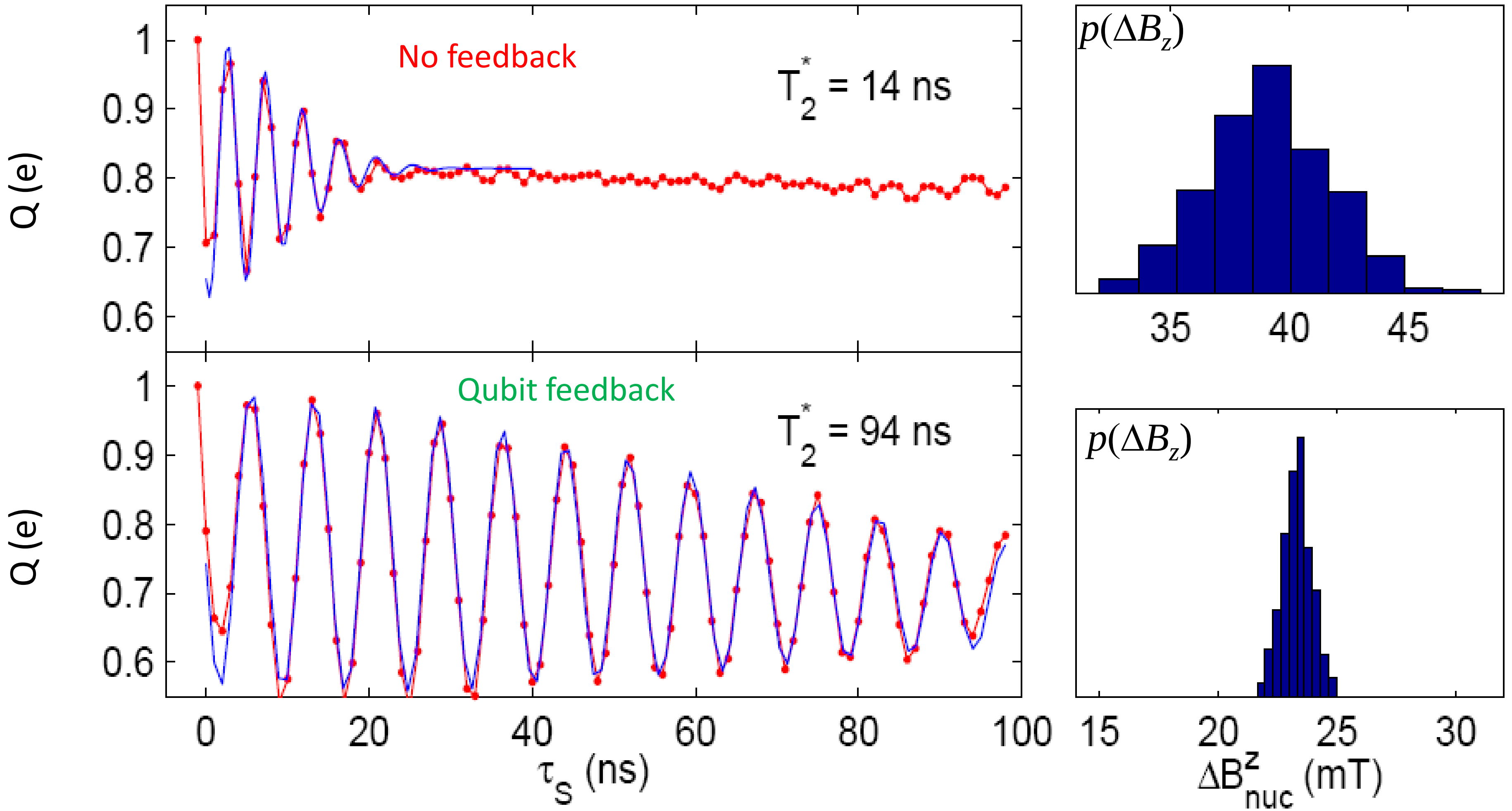
intermediate ΔB_z
=> stable fixpoint



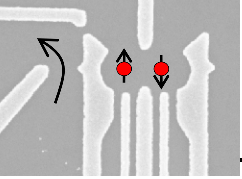




T_2* enhancement and narrowing



arXiv:1003.4031



Outline

Background

Experiments

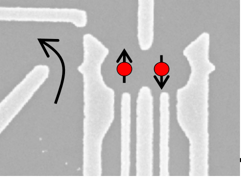
Device principles and operation

So far: bath control and slow dynamics (T_2^*)

Controlling the qubit:

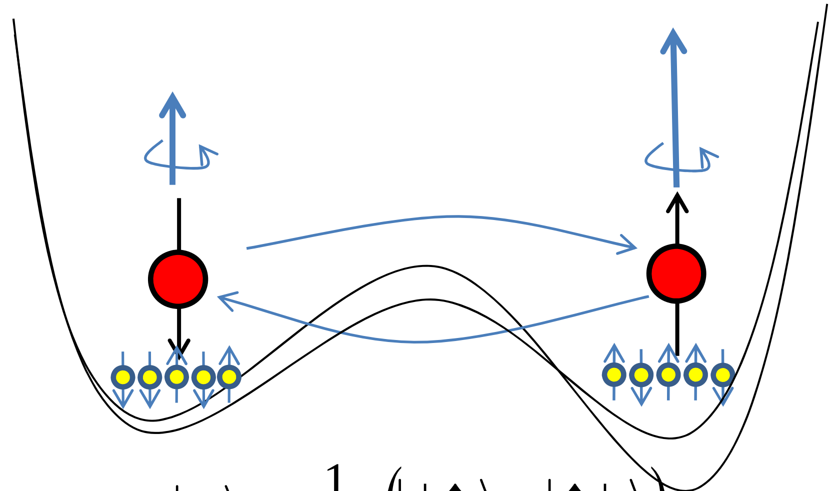
Coherence time and short time dynamics (T_2)

- Hahn echo and nuclear dynamics
- 200 μs coherence time with dynamic decoupling

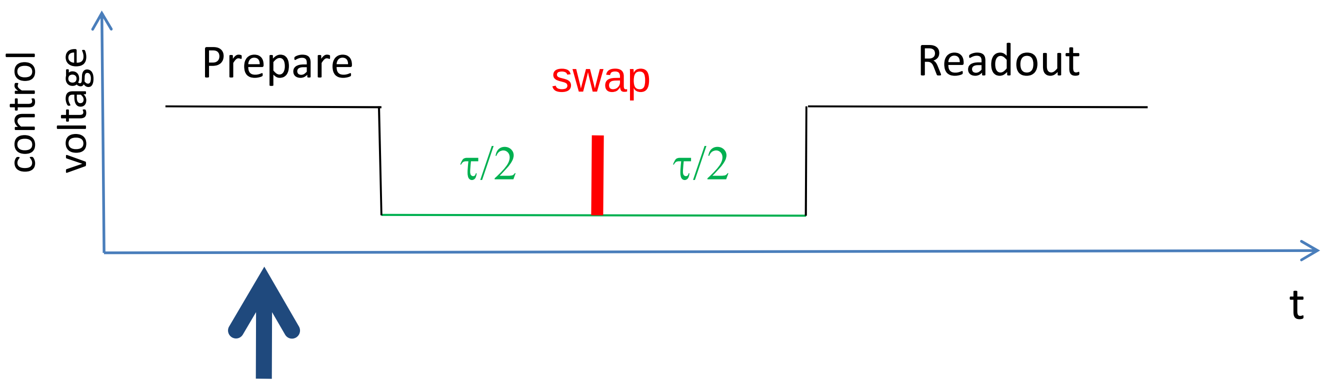


Hahn echo experiment

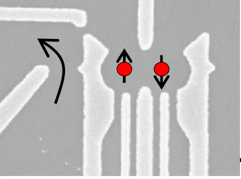
1. Prepare superposition state
2. Dephasing in random ΔB_z
3. Coherently swap electrons
4. Refocusing
5. Measure probability to return to initial state



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



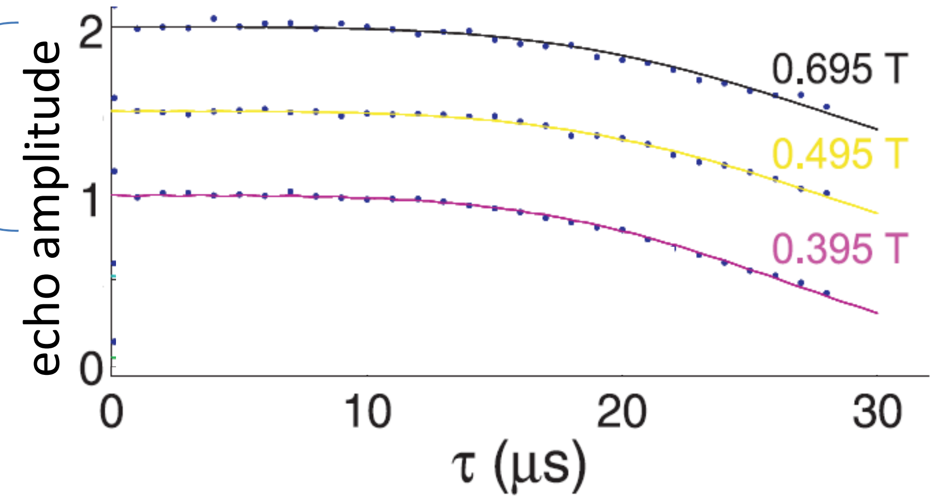
- Perfect refocusing for static ΔB_z
- Decoherence reveals bath dynamics.



Experiment

$B_{ext} \geq 400$ mT:

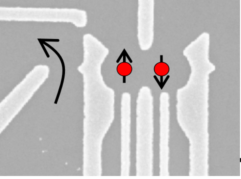
$$\text{Echo} \propto \exp\left(-(\tau / 30\,\mu s)^4\right)$$



Normalization:

1: complete refocussing, no decoherence

0: fully dephased, mixed state



Experiment

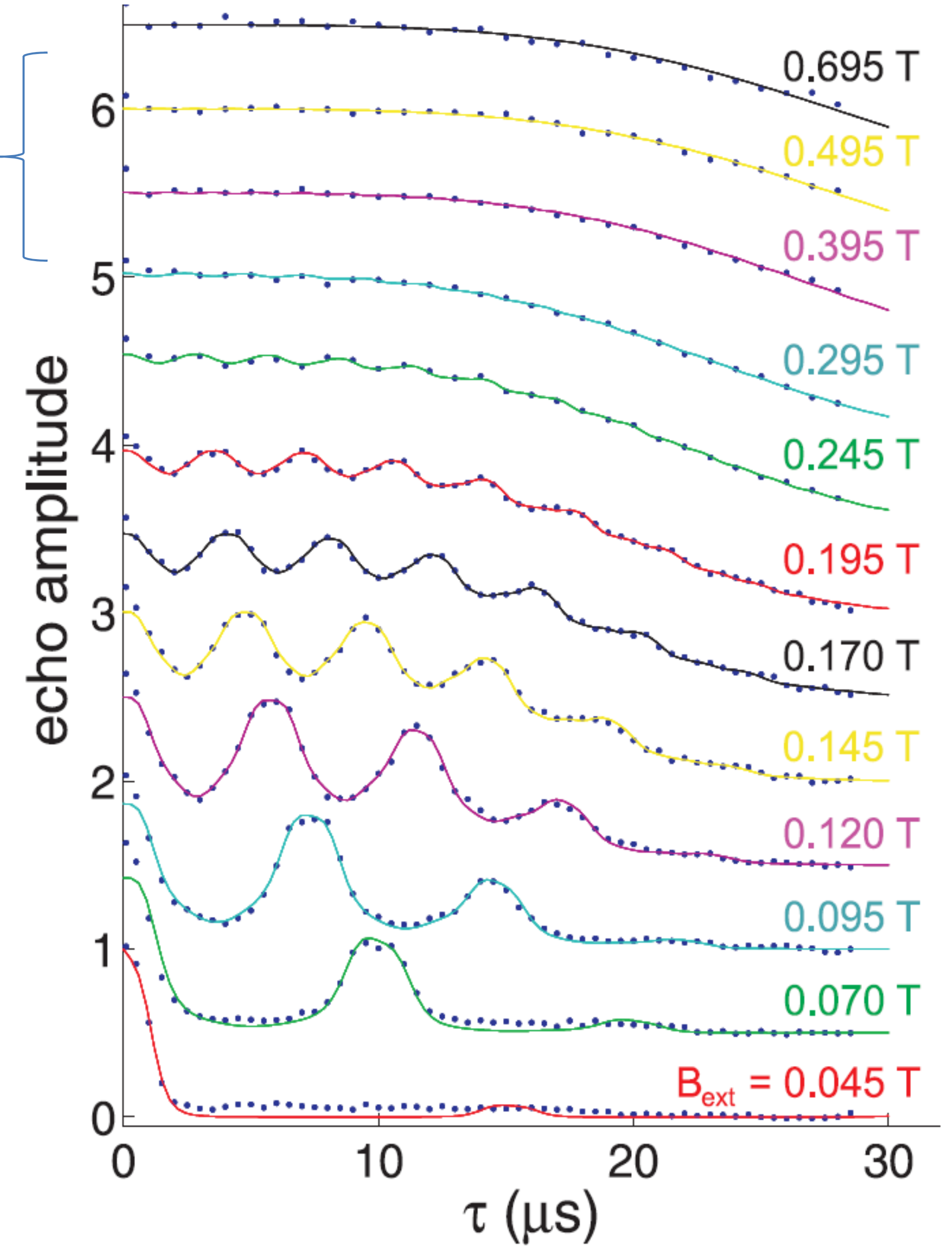
$B_{ext} \geq$ 400 mT:

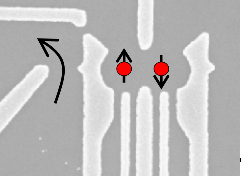
$$\text{Echo} \propto \exp\left(-(\tau / 30\,\mu s)^4\right)$$

Lower fields:

Periodic collapses and revivals

due to Larmor precession.

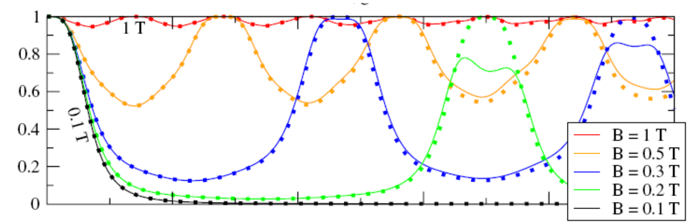


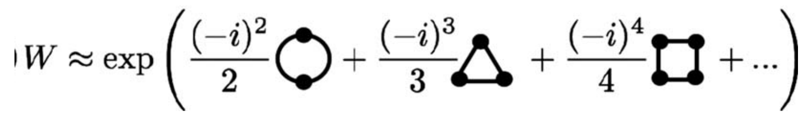


Decoherence model

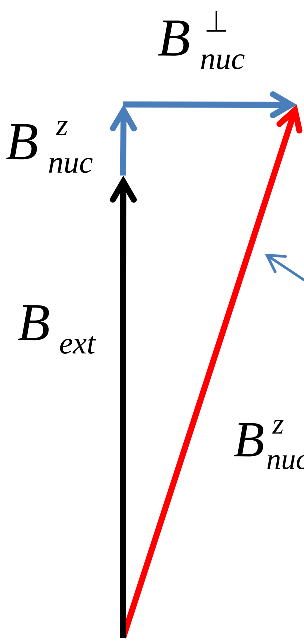
Predicted by Cywiński, Das Sarma et al., (PRL,PRB 2009) based on quantum treatment.

Intuitive picture: Yao et al., PRB 2006, PRL 2007

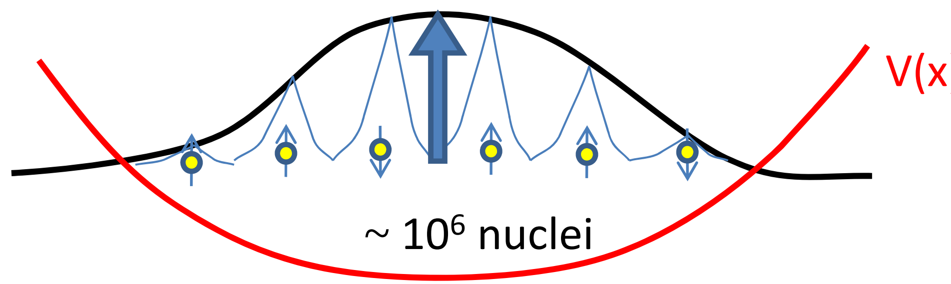


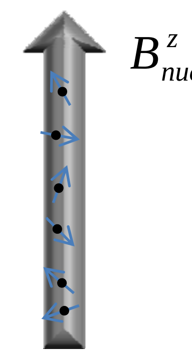


Semi-classical model



$$B_{tot} \approx B^{z}_{nuc} + B_{ext} + \frac{{B^{\perp}_{nuc}}^{2}}{2B_{ext}}$$

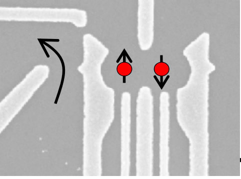




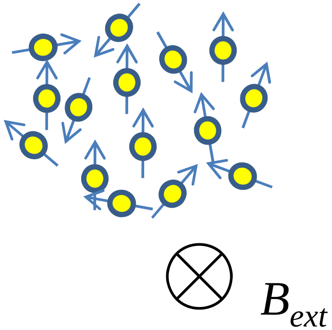
Spectral diffusion :
field independent decay

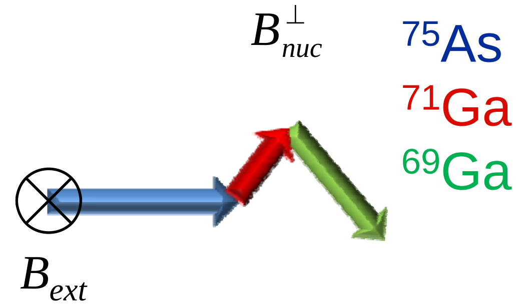
$$\exp\left(-(\tau / 37\,\mu s)^4\right)$$

(e.g. Witzel et al. PRB 2006)

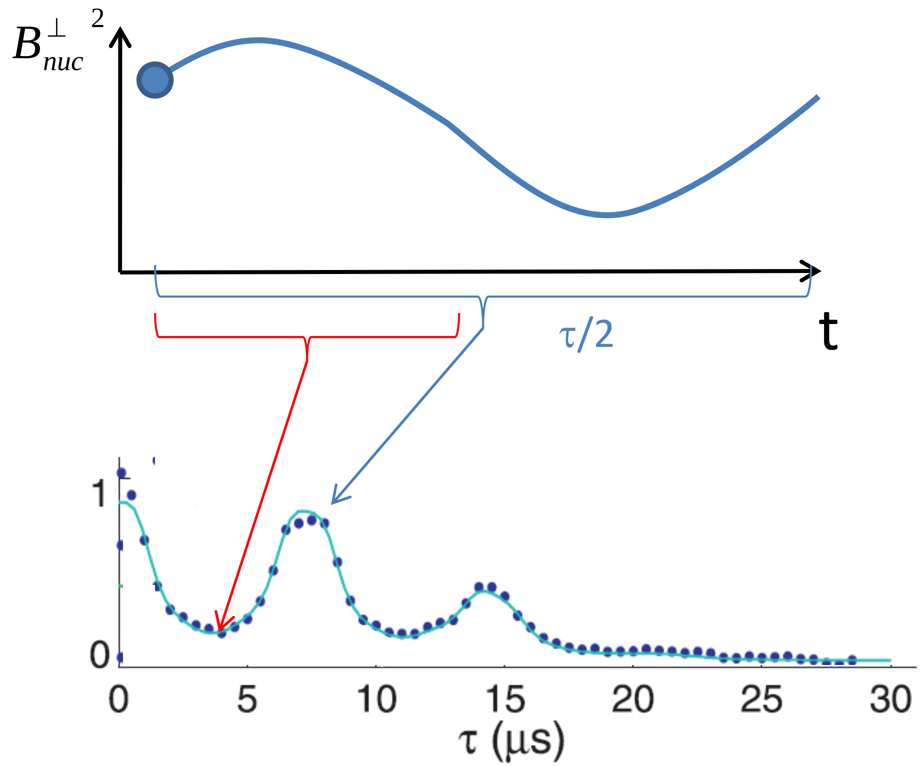


Origin of revivals





${B_{nuc}^{\perp}}^2$ oscillates due to relative Larmor precession.



Total phase = 0 when evolving over whole period

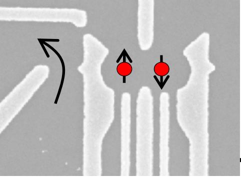
⇒Revivals

Random phase otherwise

⇒Collapses

Spread of precession rate

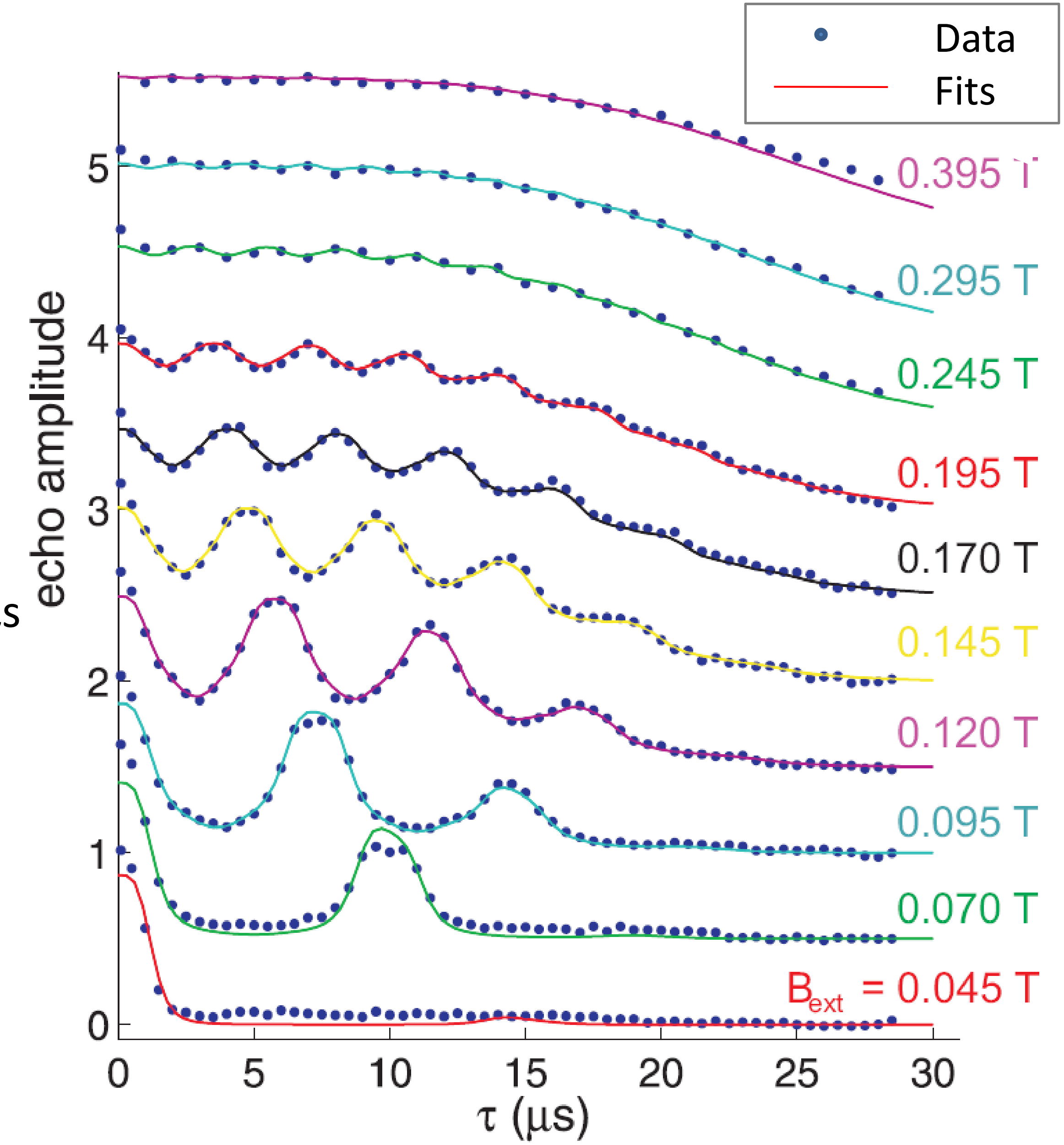
⇒Envelope decay

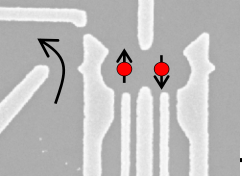


Echo revivals

Fit model: average over initial conditions. Exactly reproduces quantum results.

Field independent fit parameters:
#nuclei = 4.4 x 10^6
Spread of Larmor fields = 3 G
Spin diffusion decay time = 37 μs





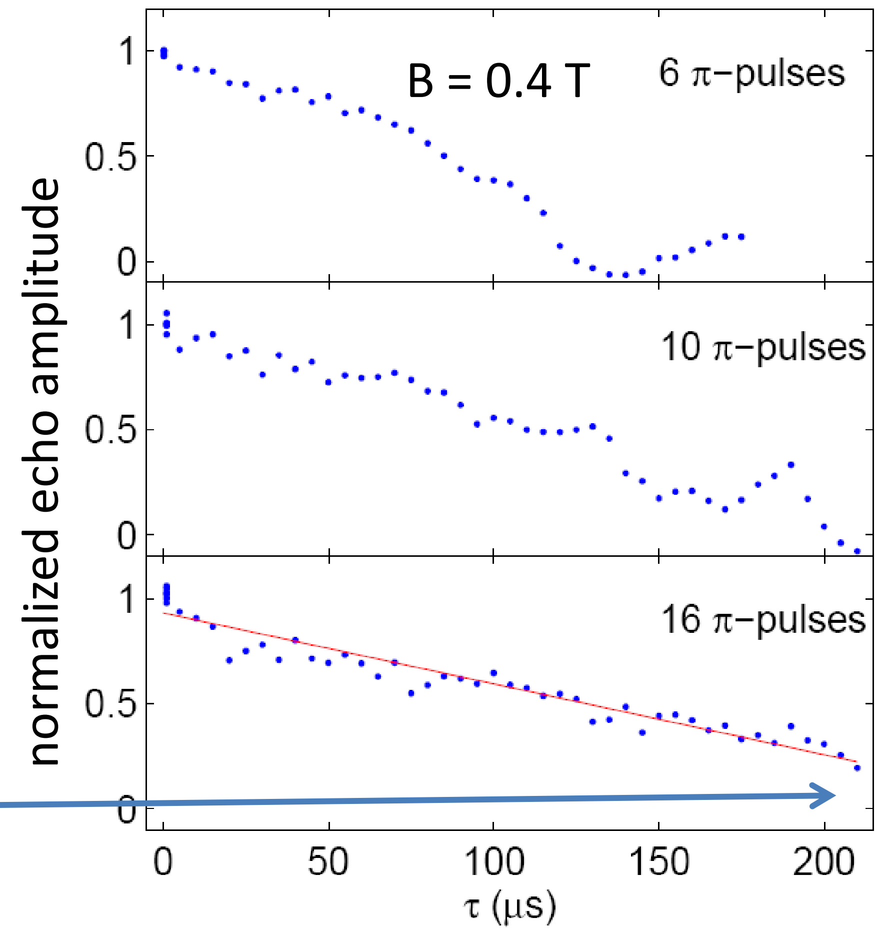
Carr-Purcell-Meiboom-Gill (CPMG)

Hahn echo

CPMG

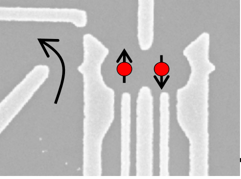
= concatenation of Hahn echo sequences.

Expect dramatically enhanced coherence time (Witzel et al., PRL 2007)



Linear fit extrapolates to

τ = 276 μs.

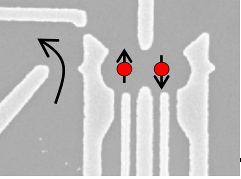


Summary

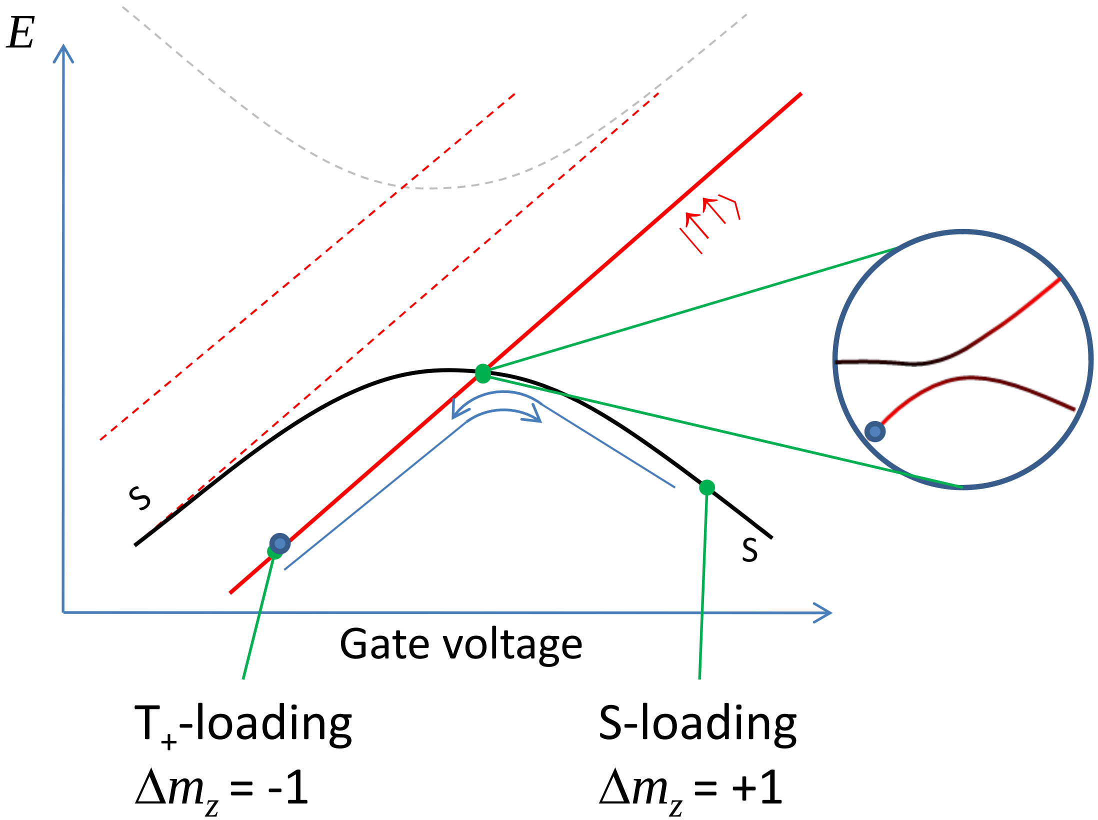
- Used qubit to probe **and control** fluctuations of nuclear bath.
- Semiclassical model provides detailed understanding of Hahn echo decay.
- Dynamic decoupling highly effective.

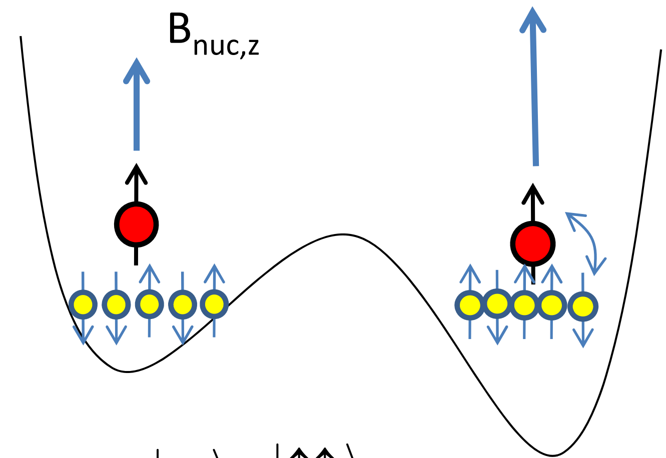
Figures of merit for qubit

- Memory time $T_2 \geq 200$ μs, sub-ns gates .
  => Exceeding 10^5 operations within T_2.
- Extrapolated gate error from nuclear fluctuations $\sim 10^{-4}$.



Manipulating B_{nuc}



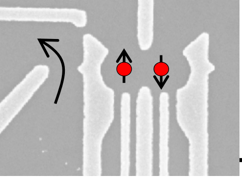


$$|T_+\rangle = |\uparrow\uparrow\rangle$$

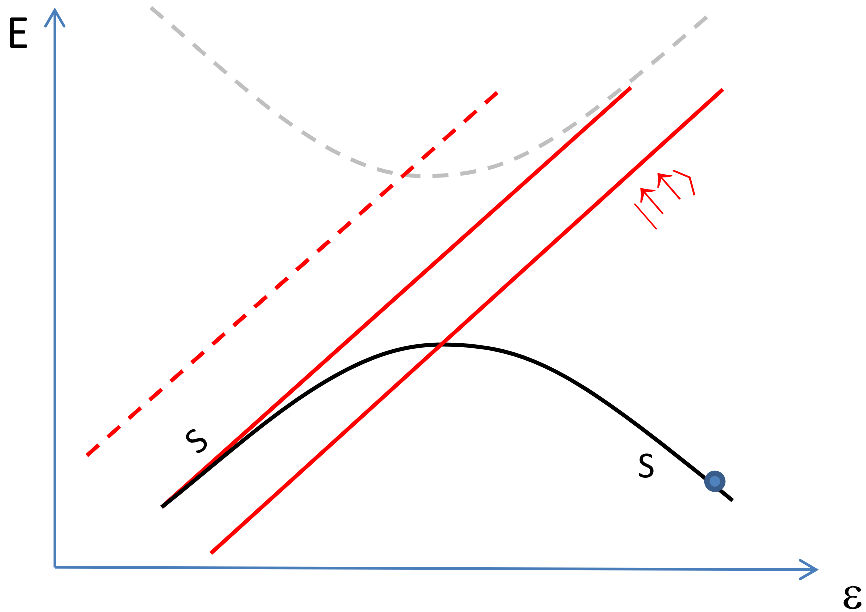
$$\rightarrow |S\rangle = \frac{1}{\sqrt{2}}\left(|\downarrow\uparrow\rangle - |\uparrow\downarrow\rangle\right)$$

Previous work: average polarization, relaxation.
(Harvard, Petta et al., Reilly et al.)

Here: Bi-directional real time control of gradient.



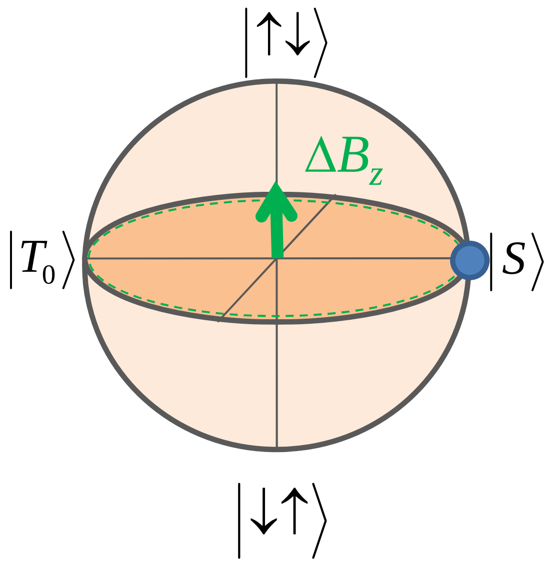
Pulses with built-in feedback

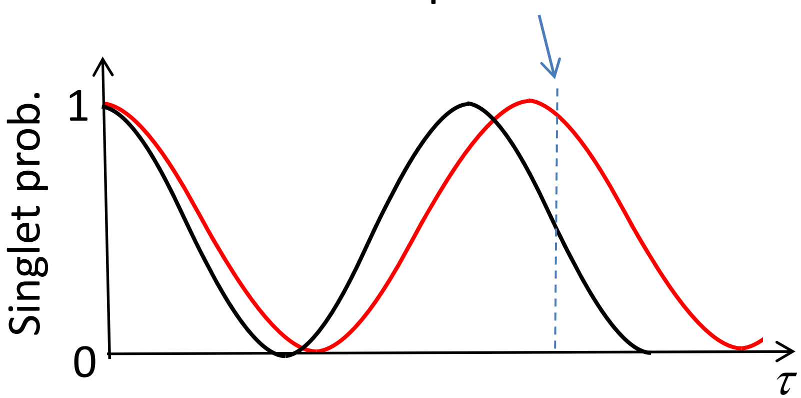


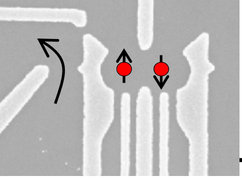
small ΔB_z => strong pumping
=> ΔB_z increases

large ΔB_z => weak pumping
=> ΔB_z decreases

intermediate ΔB_z
=> stable fixpoint







CPMG - data

Mixed-state reference (omitted π-pulses)

Linear fits intersect at

τ = 276 μs