# High-fidelity entangling gate for double-quantum-dot spin qubits

John M. Nichol, Lucas A. Orona, Shannon P. Harvey, Saeed Fallahi, Geoffrey C. Gardner, Michael J. Manfra and Amir Yacoby

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Florian Froning

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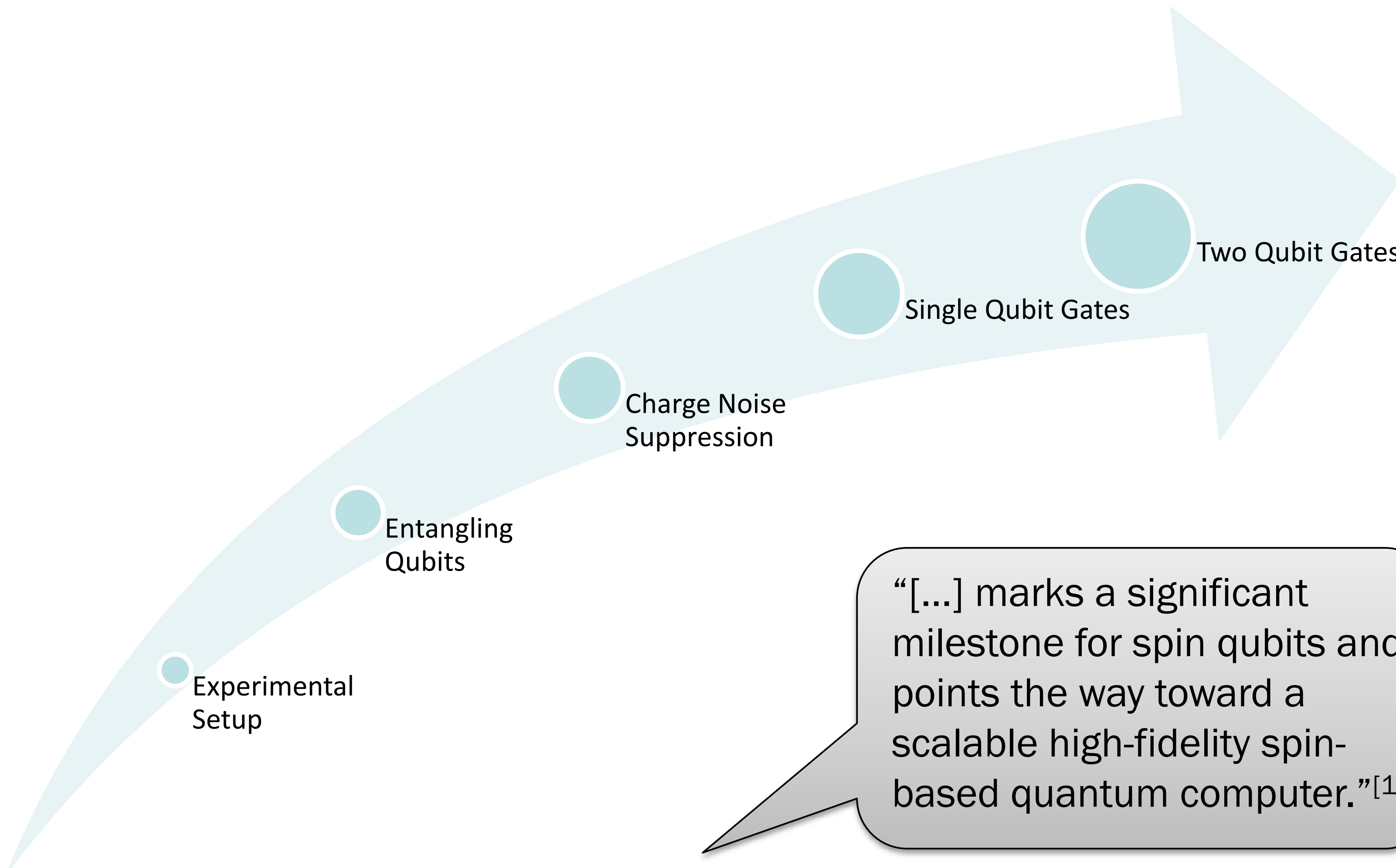
# Outline




"[...] marks a significant milestone for spin qubits and points the way toward a scalable high-fidelity spin-based quantum computer."[1]

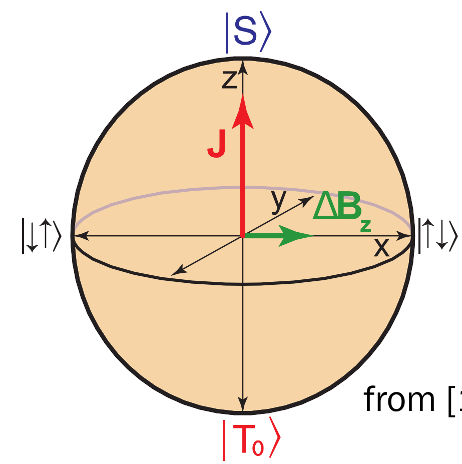
[1] from Editorial Summary, npj Quantum Information

# Experimental Setup

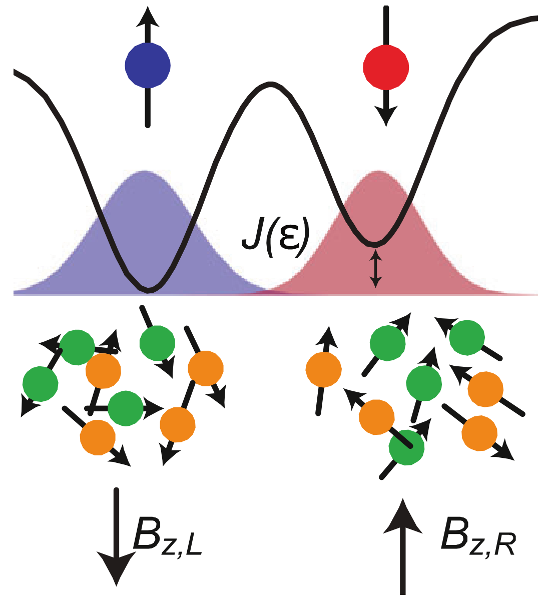
- Singlet-Triplet Qubit with basis states

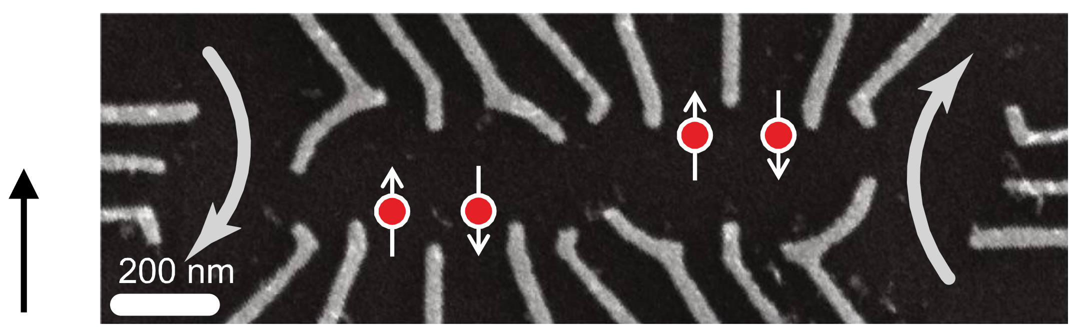
$$|S\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right) \quad |T_0\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle\right)$$

- exchange splitting $J(\varepsilon)$
  - lifts degeneracy of $|S\rangle, |T_0\rangle$
- magnetic field gradient $\Delta B_z$
  - lifts degeneracy of $|\uparrow\downarrow\rangle, |\downarrow\uparrow\rangle$
  - dynamic nuclear polarization




from [1]



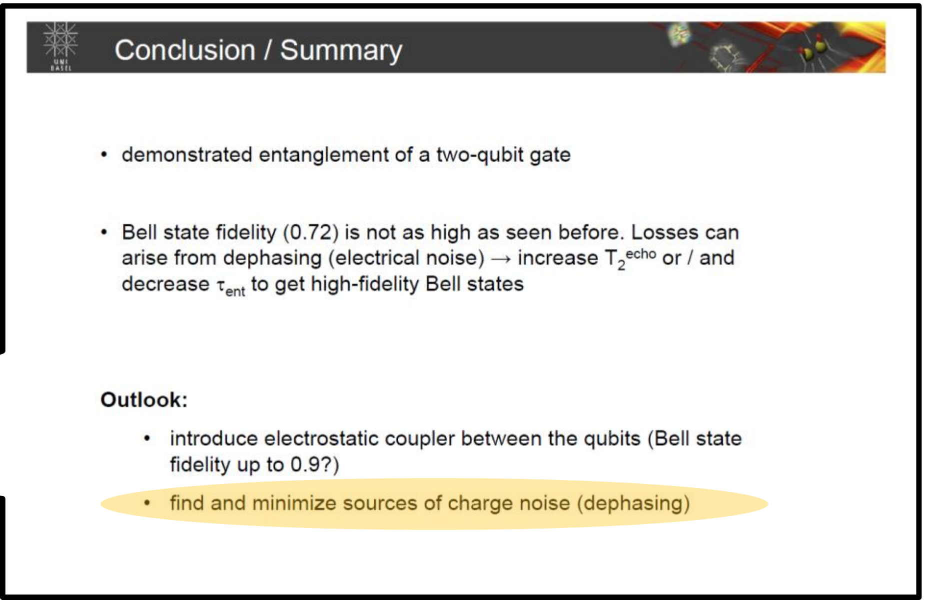




$B_{\mathrm{ext}} = 700\,\mathrm{mT}$

[1] Shulman et al., Science 336, 202 (2012)

# Entangling qubits

- capacitively mediated, dipole-dipole coupling between two qubits can generate entangled state
- previous gate fidelity not very high[1]
  - Bell state fidelity 0.72
- susceptible to charge noise





[1] Shulman et al., Science 336, 202 (2012)
[2] D. Maradan, FMM talk, 04.05.2012

# Charge Noise Suppression

- operate in regime where $\Delta B_z \gg J(\varepsilon)$
- qubit sensitivity to charge noise is reduced

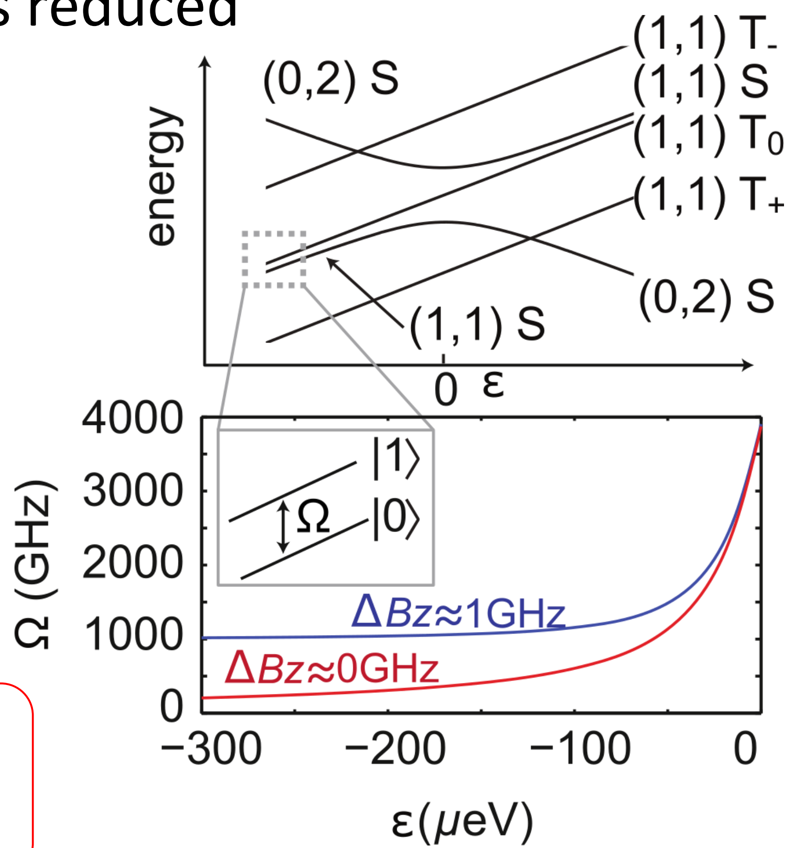
$$\Omega(\varepsilon) = \sqrt{\Delta B_z^2 + J(\varepsilon)^2}$$

$$\approx \Delta B_z + \frac{J(\varepsilon)^2}{2\Delta B_z}$$

$$\Omega'(\varepsilon) = \left(\frac{J(\varepsilon)}{\Delta B_z}\right) J'(\varepsilon)$$

$\Delta B_z \approx 1\,\mathrm{GHz}$

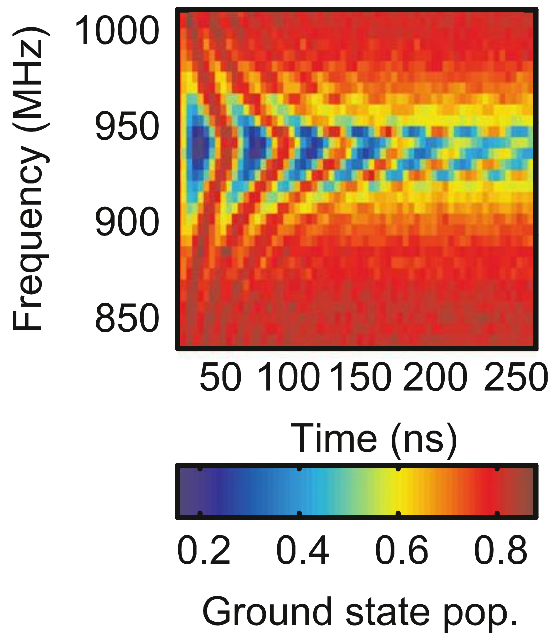
$100\,\mathrm{MHz} < J(\varepsilon)/2\pi < 300\,\mathrm{MHz}$

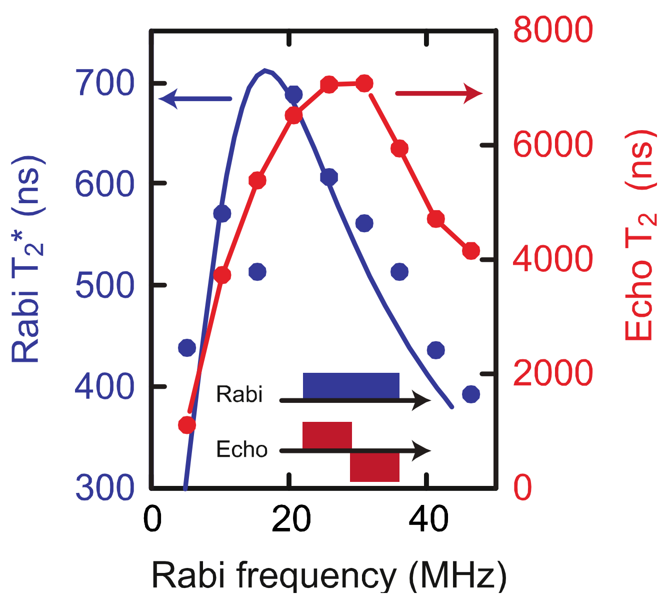


# Single Qubit Gates

- drive Rabi oscillations: coherence time is longer due to insensitivity to magnetic gradient fluctuations
- average gate fidelity: 98.6 %
- π-gate fidelity: 99 %

static exchange splitting: $T^*_2 \approx 80$ ns



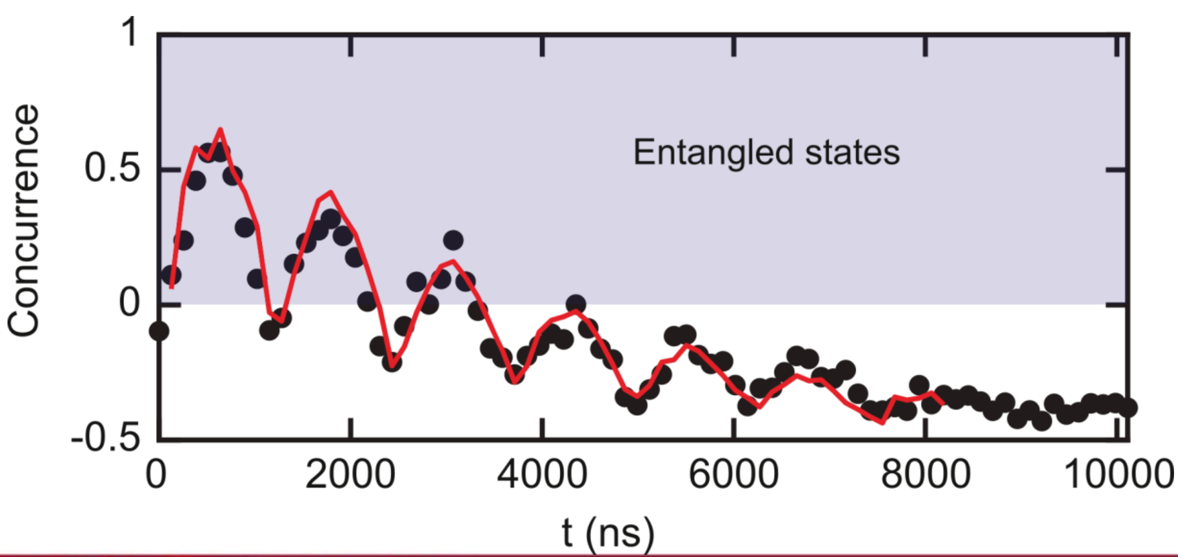
# Two Qubit Entangling Gate

- interaction Hamiltonian: $H_{\text{int}} \approx \frac{J_{12}}{2}\sigma_z \otimes \sigma_z \cos(\phi_1 - \phi_2)$
- constructive interference of qubit rotations: CPhase gate

**Def.: Concurrence**

$$C = \lambda_4 - \lambda_3 - \lambda_2 - \lambda_1$$

$\lambda_i$: eigenvalues of two-qubit matrix
0: no entanglement
1: maximal entanglement

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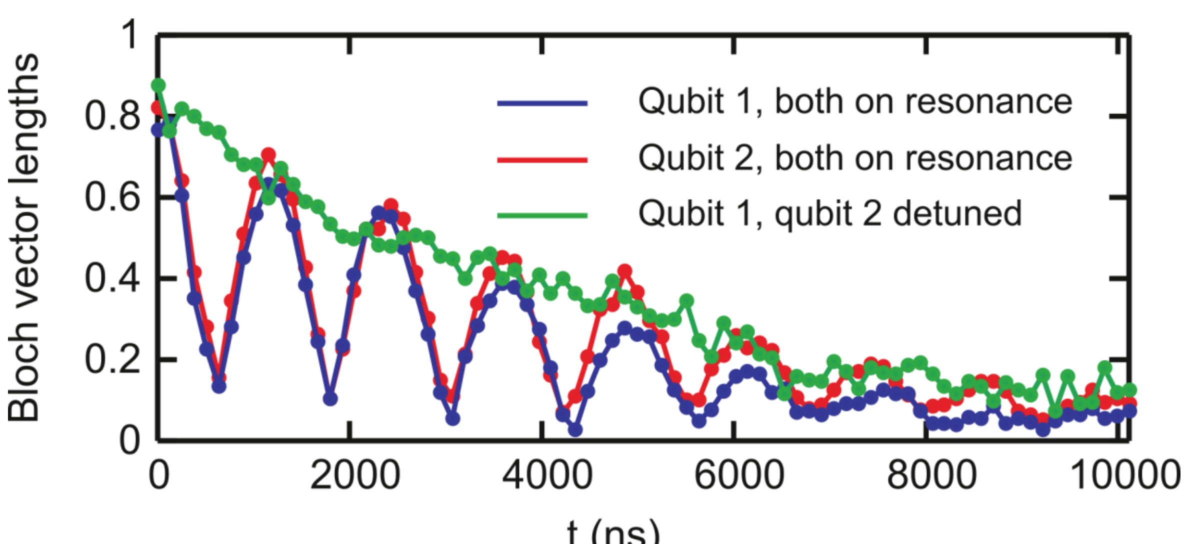
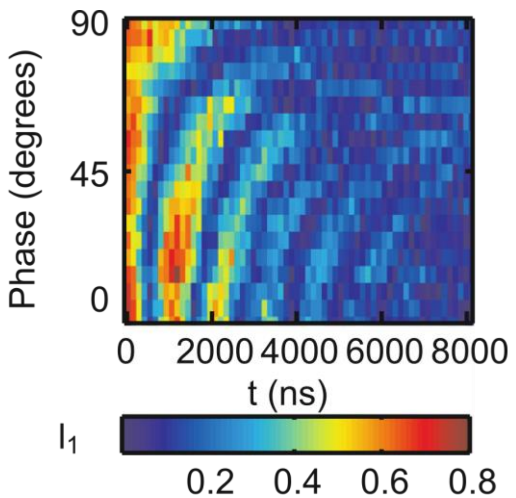
**Def.: Bloch vector length**

$$l = \sqrt{\langle\sigma_{\mathrm{x}}\rangle^2 + \langle\sigma_{\mathrm{y}}\rangle^2 + \langle\sigma_{\mathrm{z}}\rangle^2}$$

$\langle\sigma_i\rangle$: single qubit expectation value



# Summary + Outlook

- suppress charge noise by setting $\Delta B_{\mathrm{z}} \gg J(\varepsilon)$
- single qubit gate fidelity close to unity
- two qubit gate fidelity of 87 %
  - Bell state fidelity improved from 0.72 to 0.93
- higher gate fidelities could be possible in nuclear spin free materials (e.g. Si)
  - magnetic field gradient with micromagnets
- faul-tolerant quantum computation with spins in reach