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ARTICLES

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A dressed spin qubit in silicon

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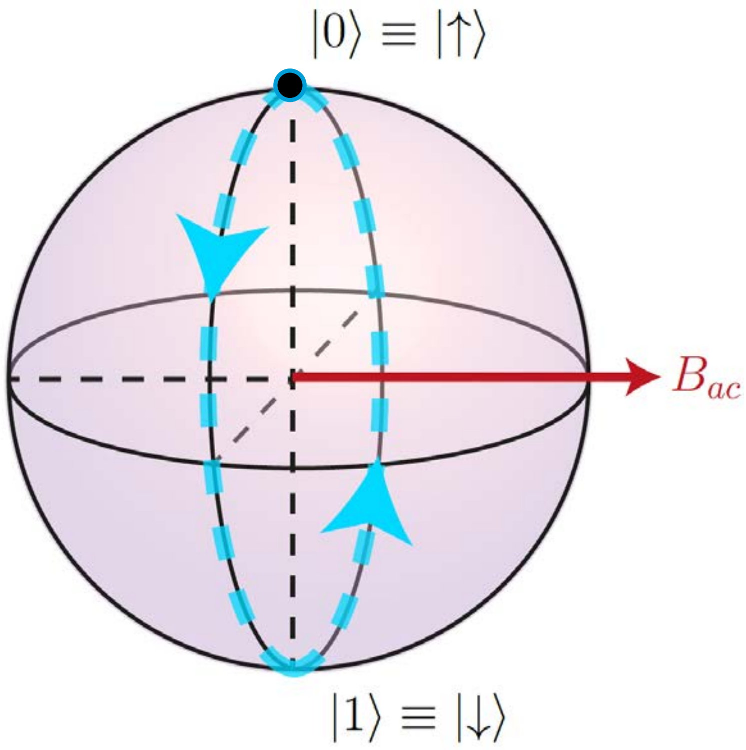
Coherent dressing of a quantum two-level system provides access to a new quantum system with improved properties—a different and easily tunable level splitting, faster control and longer coherence times. In our work we investigate the properties of the dressed, donor-bound electron spin in silicon, and assess its potential as a quantum bit in scalable architectures. The two dressed spin-polariton levels constitute a quantum bit that can be coherently driven with an oscillating magnetic field, an oscillating electric field, frequency modulation of the driving field or a simple detuning pulse. We measure coherence times of $T_{2\rho}^{*} = 2.4$ ms and $T_{2\rho}^{\mathrm{Hahn}} = 9$ ms, one order of magnitude longer than those of the undressed spin. Furthermore, the use of the dressed states enables coherent coupling of the solid-state spins to electric fields and mechanical oscillations.

“… ‘dressing’ means that an electromagnetic driving field coherently interacts with the quantum system, so that the eigenstates of the driven system are the entangled states of the photons and the quantum system.”

“For the case of a single spin in a static magnetic field B_0 that is driven with an oscillating magnetic field B_1, this means that the eigenstates are no longer the spin-up and spin-down states, but the symmetric and antisymmetric superpositions of these states with the driving field.”

“Normal” spin qubit



- *Driving on resonance:*

$$\nu_{Larmor} = g\mu_B B$$

$$B_{ac} \sim \cos(2\pi\nu_{Larmor}t)$$

- *Rabi frequency:*

$$\Omega_R = \frac{1}{2} g\mu_B B_{ac}$$

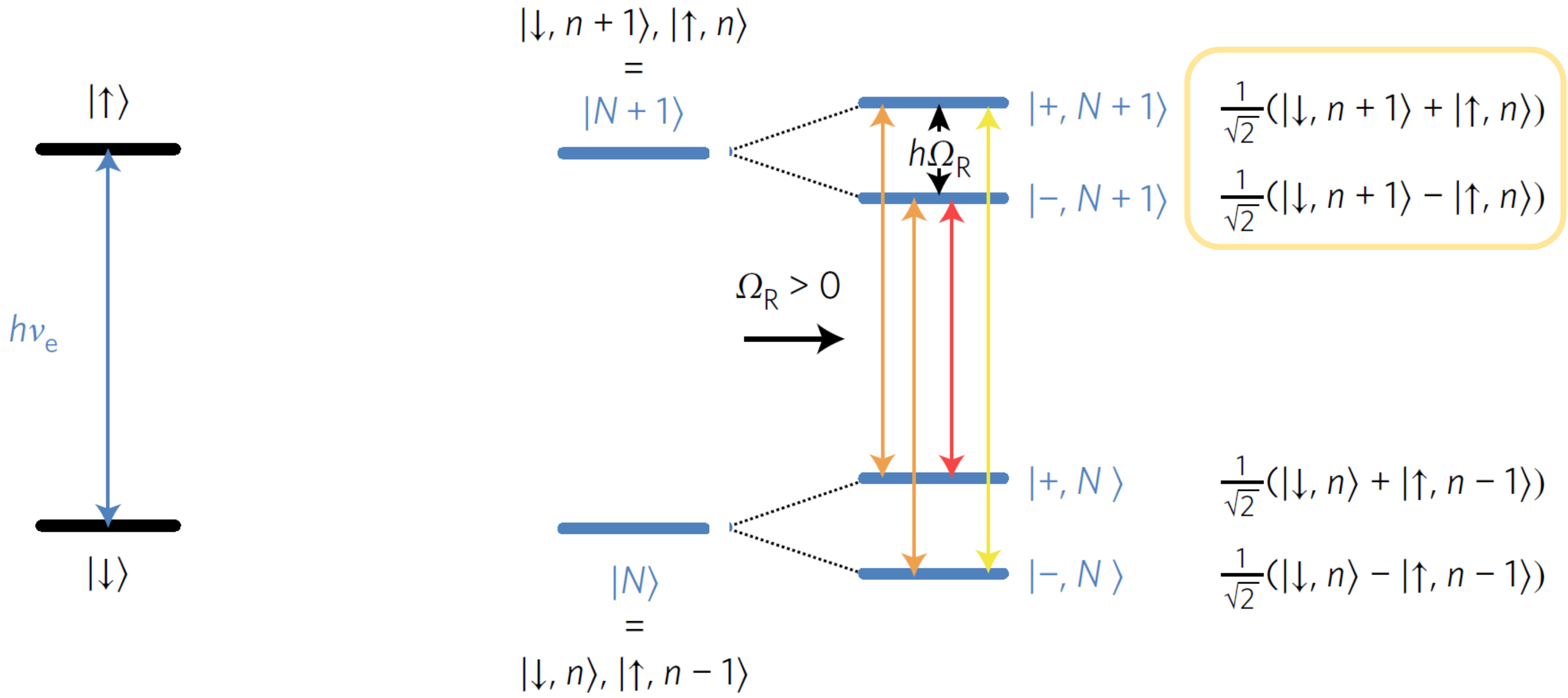
- *Hamiltonian in rotating frame:*

$$H = \frac{1}{2} h(\Delta\nu\sigma_z + \Omega_R\sigma_x)$$

$$\Delta\nu = g\mu_B B - \nu_{MW}$$

Level diagrams

- *Original basis*
- *Dressed basis (no driving)*
- *Dressed basis (with driving)*



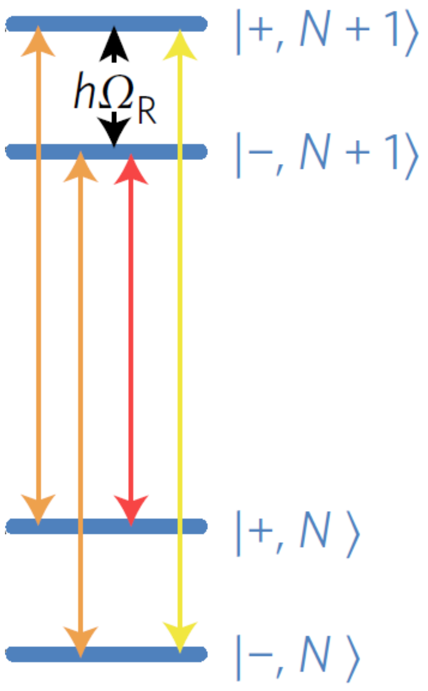
- *For classical driving: number of photons is very large and not exact ➔ omit N, but driving power still determines* Ω_R

Dressed qubit

- *Hamiltonian:*

$$H = \tfrac{1}{2}h(\Delta\nu\sigma_z + \Omega_R\sigma_x) \rightarrow \boxed{H^\rho = \tfrac{1}{2}h(\Omega_R\sigma_z + \Delta\nu\sigma_x)}$$

$$\Delta\nu = g\mu_B B - \nu_{MW}$$



$$\frac{1}{\sqrt{2}}(|\downarrow, n+1\rangle + |\uparrow, n\rangle)$$

$$\frac{1}{\sqrt{2}}(|\downarrow, n+1\rangle - |\uparrow, n\rangle)$$

- *Driving on resonance:*

$$\Delta\nu(t) = \Delta\nu_{FM}\cos(2\pi\nu_{FM}t + \phi)$$

- *Rabi frequency:*

$$\Omega_R = \tfrac{1}{2}g\mu_B B_{ac} \rightarrow \boxed{\Omega_{R\rho} = \tfrac{1}{2}\Delta\nu_{FM}}$$

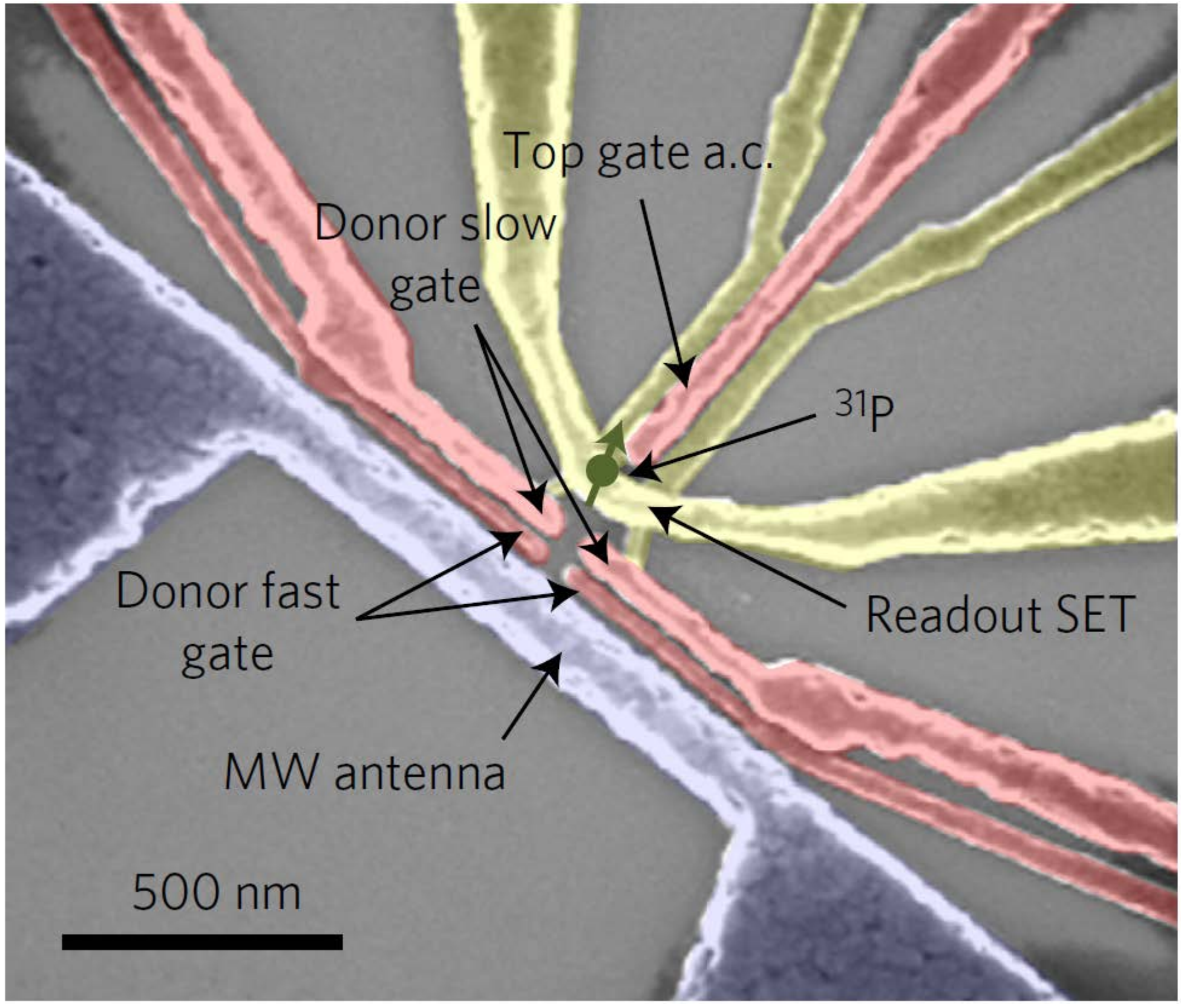
Advantages of using dressed qubits

- *Dynamically tunable level splitting*
  - *Coupling to various quantum systems*
  - *Strong driving*

- *Increased coherence times*

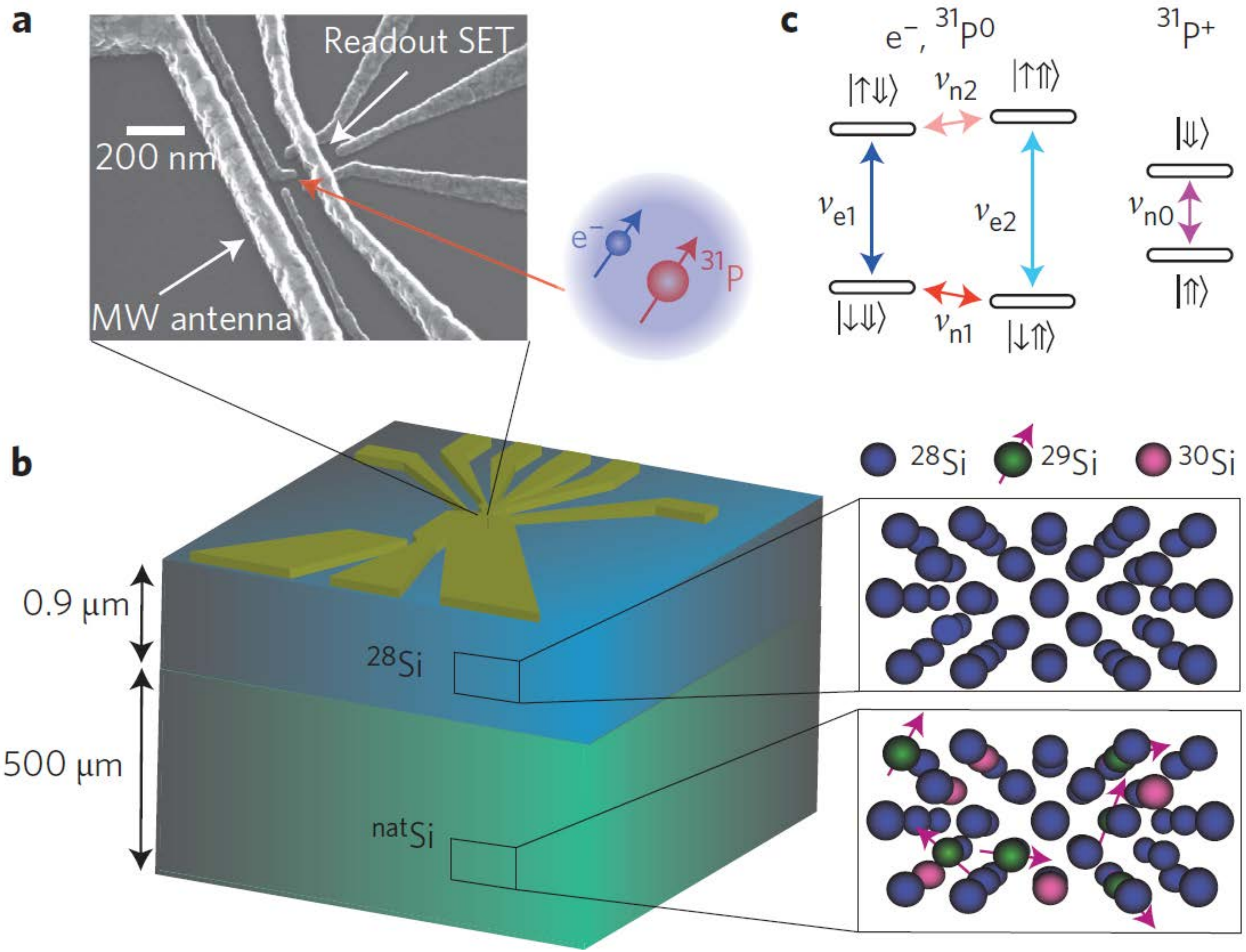
- *Different ways of coherent driving*

Sample



- P donor in isotopically purified silicon (red gates)
- SET charge sensor (yellow gates)
  - Single-shot readout
- MW antenna (blue stripline)
- B = 1.55 T
- $T_{electron}$ = 100 mK

Sample details



*Muhonen et al., Nature Nanotechnology **9**, (2014)*

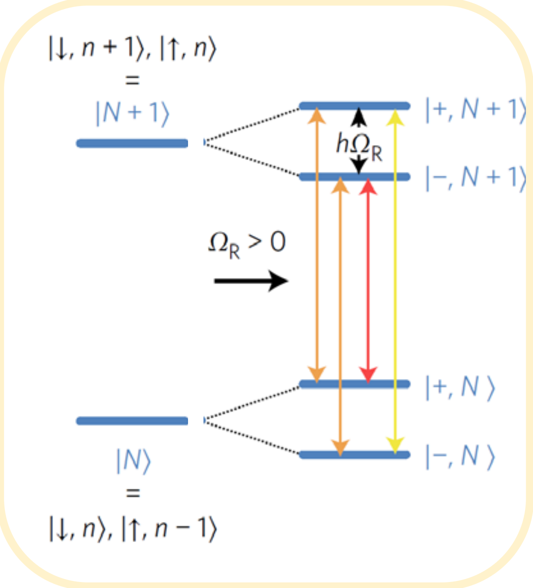
Mollow triplet spectrum

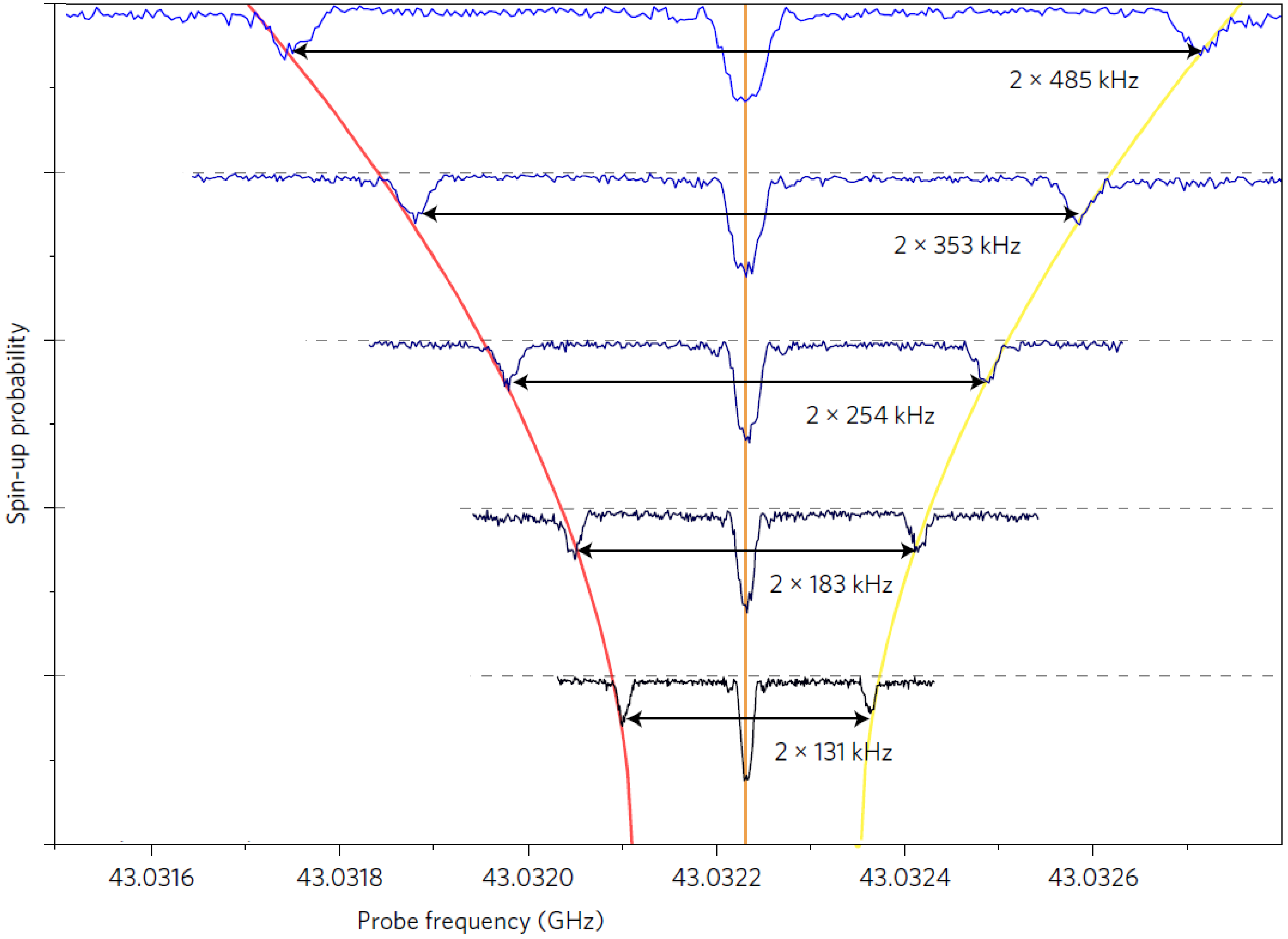
- *Pump freq. =* ν_{Larmor}
- *Probe freq. swept across* ν_{Larmor}
- *Pump and probe powers and duration such that both induce* $m\pi$ *rotation*

Pump to create dressed qubit + probe to measure spectrum of dressed qubit

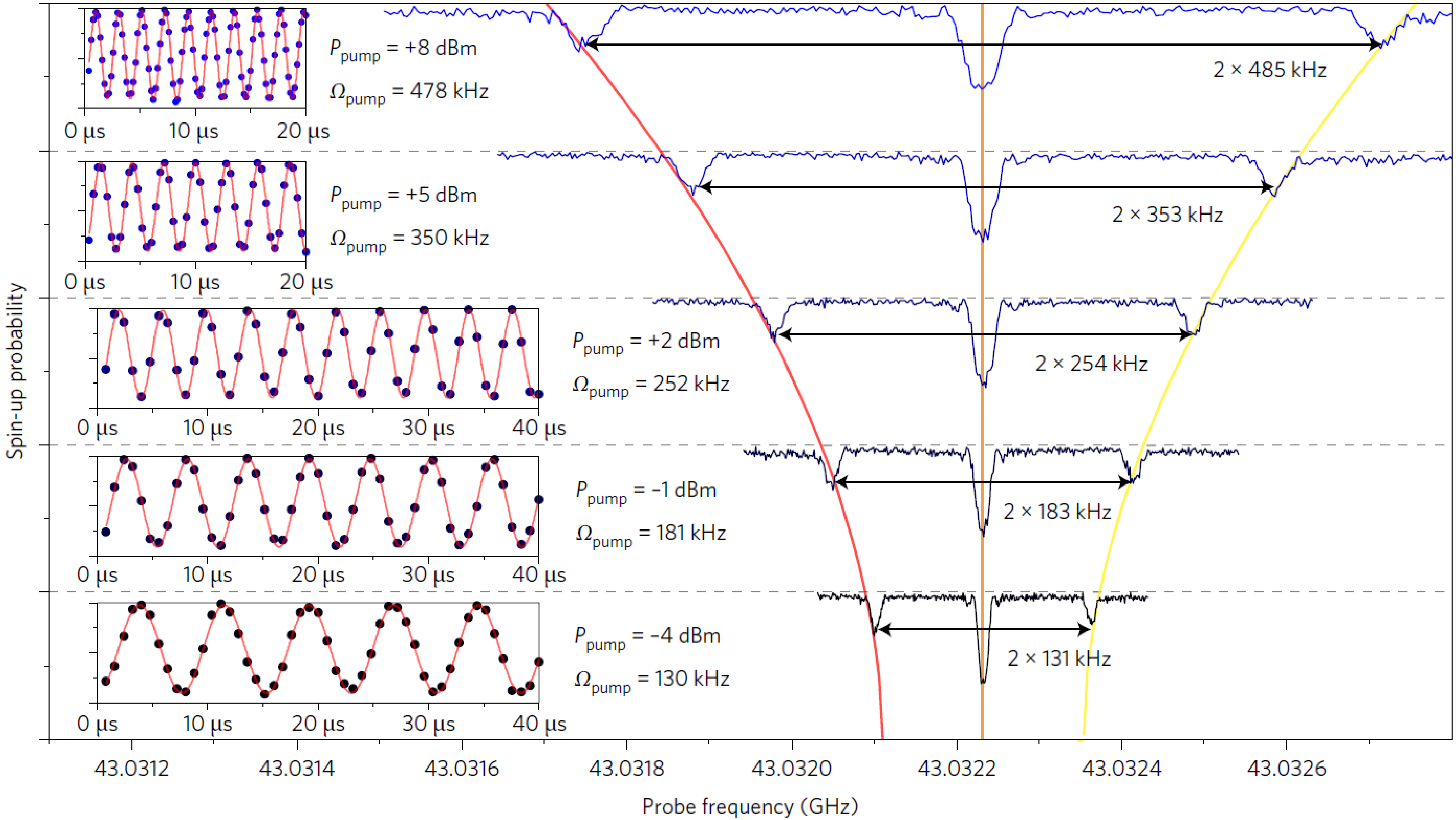
Mollow triplet spectrum

- *Pump freq.* = ν_{Larmor}
- *Probe freq. swept across* ν_{Larmor}
- *Pump and probe powers and duration such that both induce* $m\pi$ *rotation*





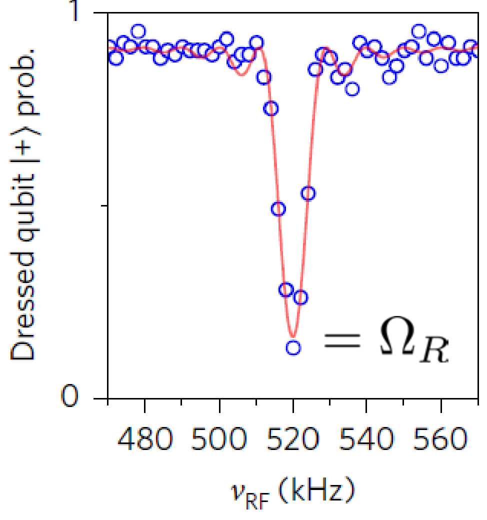
Mollow triplet spectrum



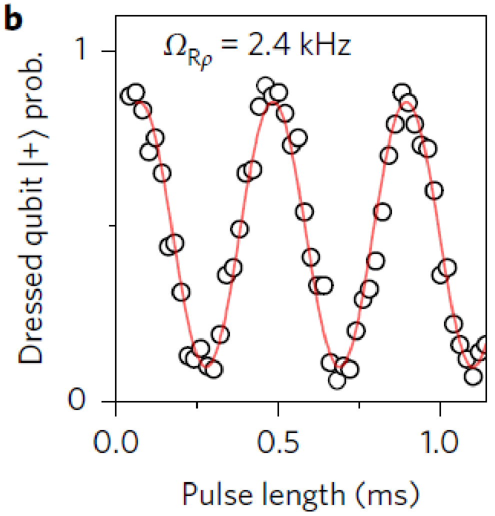
Four ways to perform Rabi oscillations of the dressed qubit

$$H^{\rho} = \frac{1}{2}h(\Omega_R \sigma_z + \Delta\nu \sigma_x)$$

a



b



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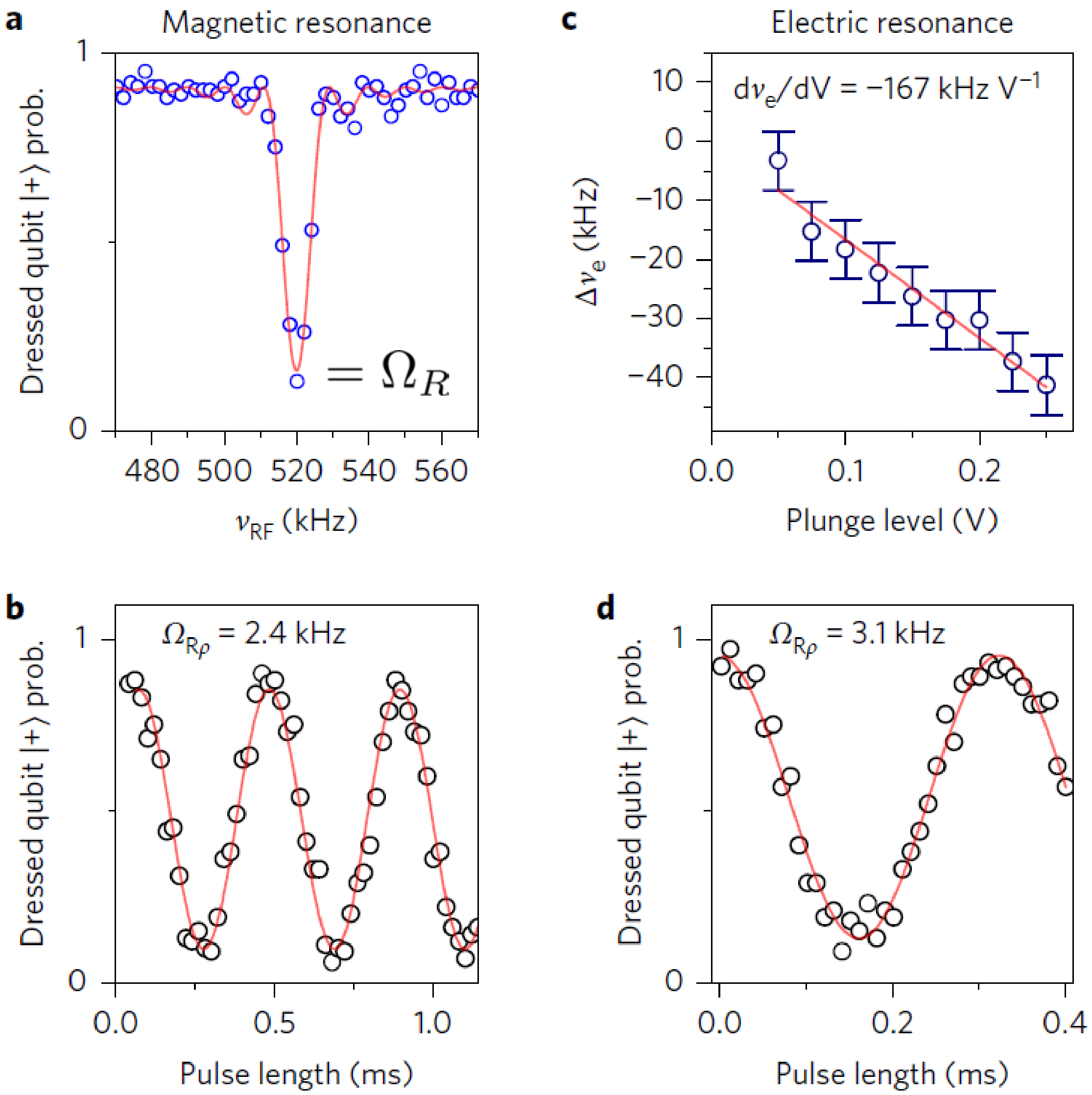

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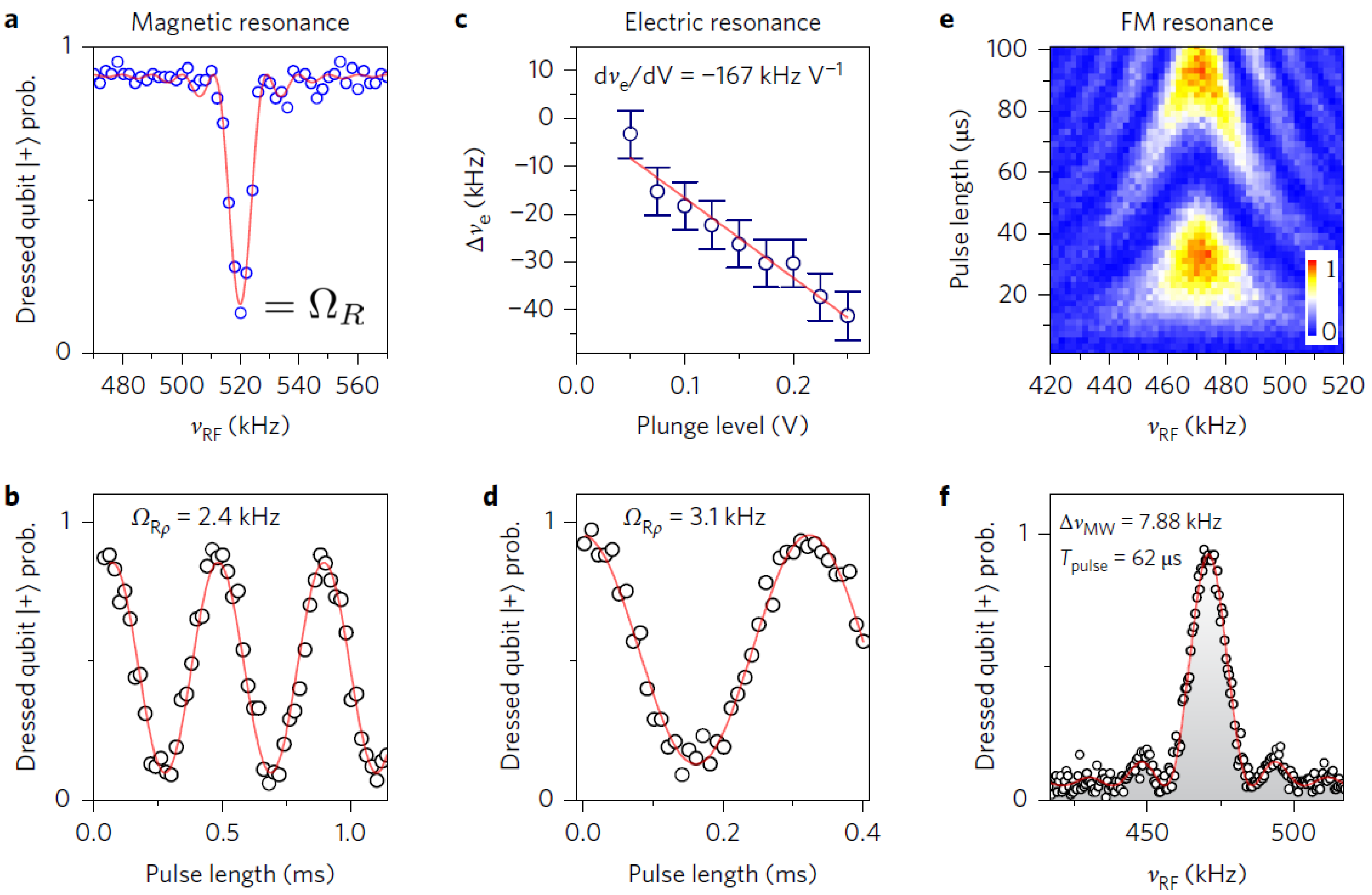

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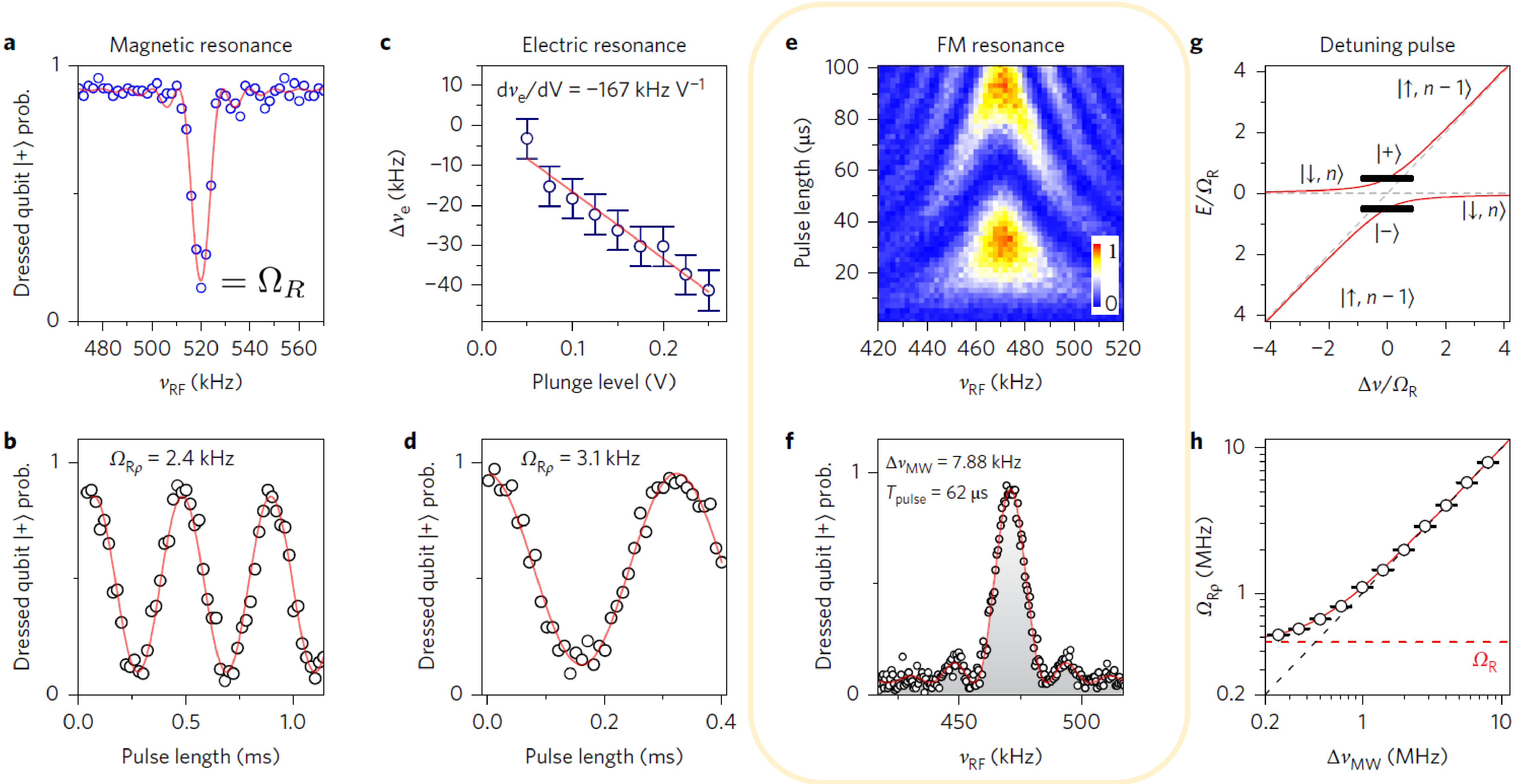
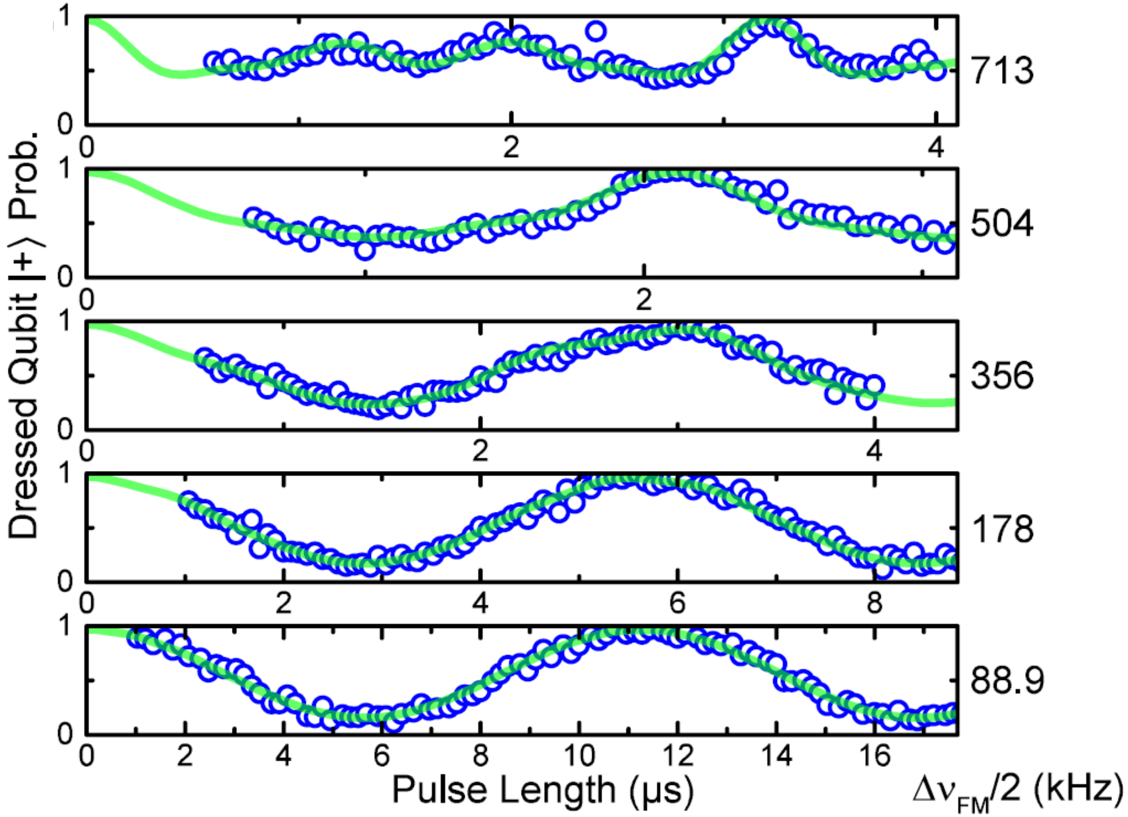


Strong driving regime

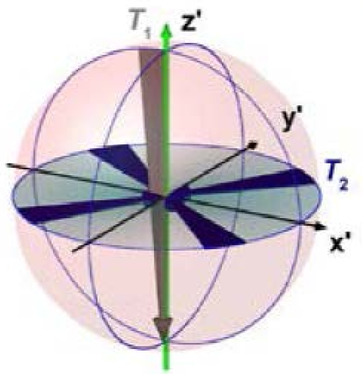


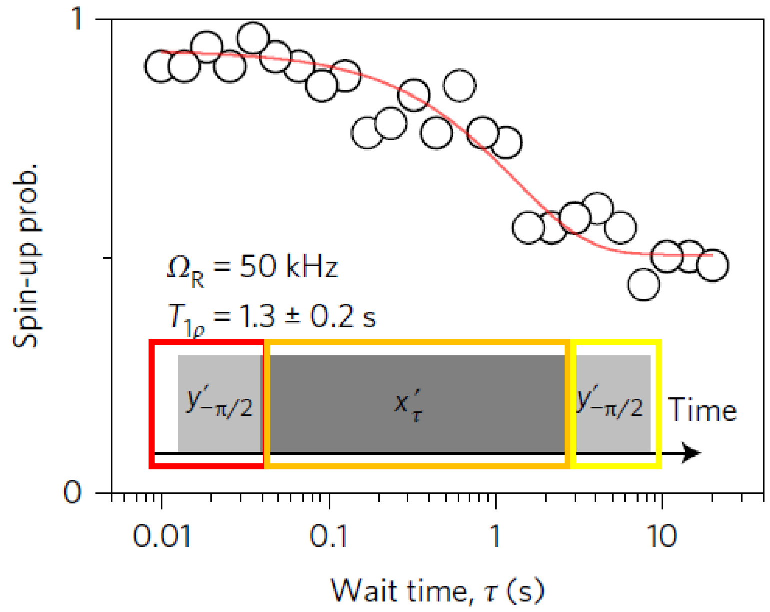
$$\Omega_{R\rho} \equiv \Delta\nu_{FM}/2 \approx \Omega_R$$

*Laucht et al., Phys. Rev. B **94**, (2016)*

Dressed qubit relaxation time

- *Rotating frame*



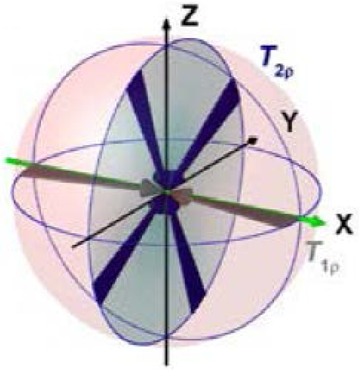


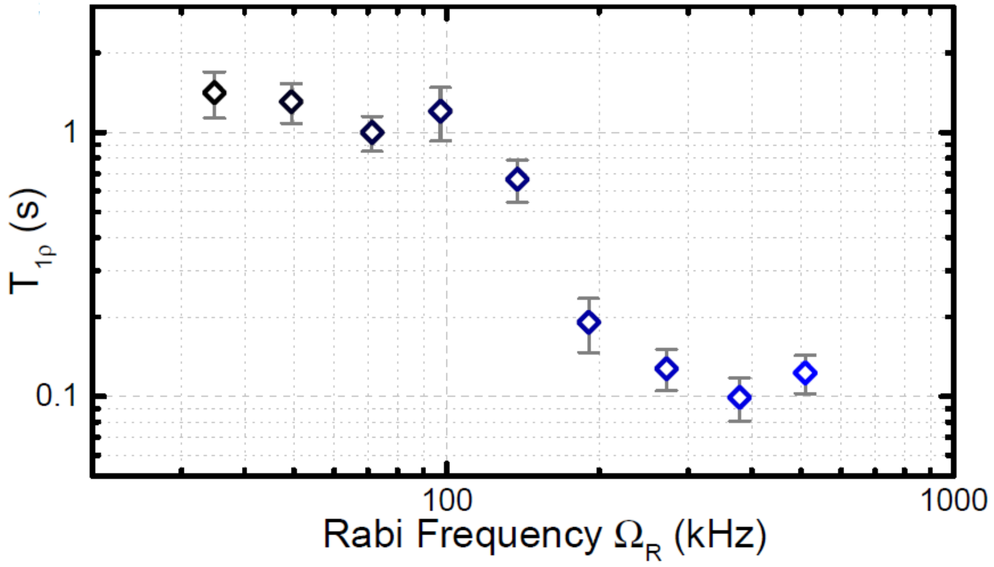
Initialize dressed qubit

Idle dressed qubit

Read-out dressed qubit

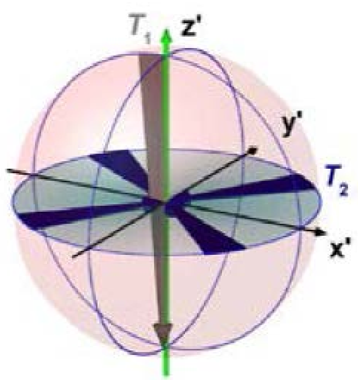
- *Double rotating frame*



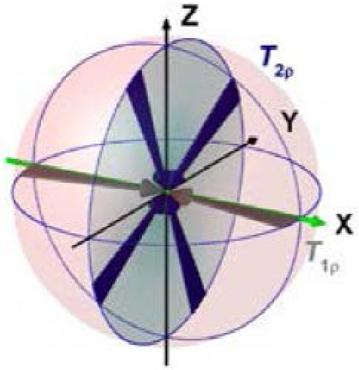


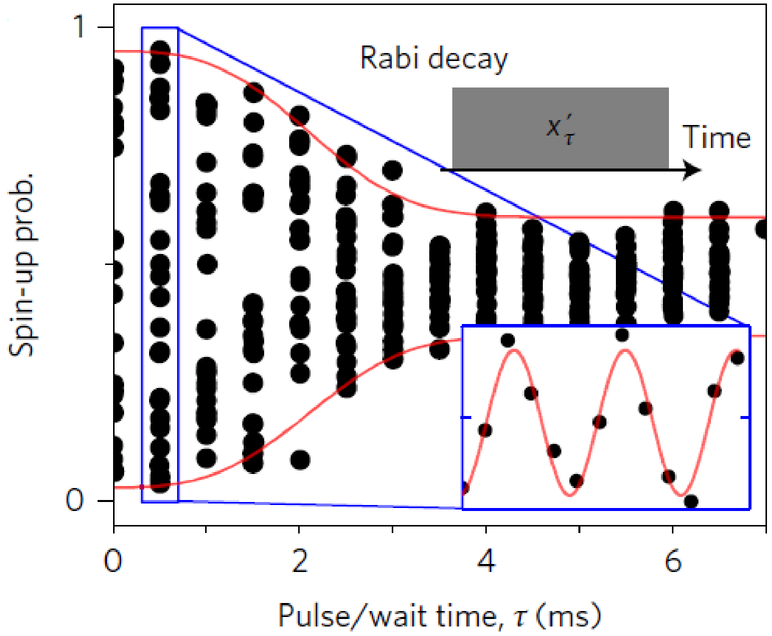
Dressed qubit dephasing time

- *Rotating frame*



- *Double rotating frame*



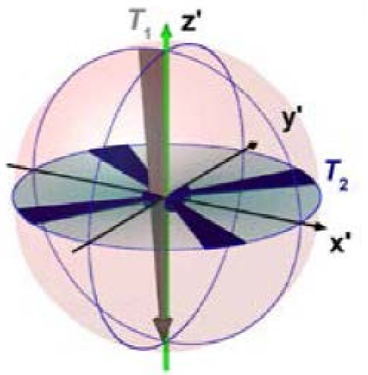


Decay of "original" Rabi oscillations
=
Free induction decay Dressed qubit

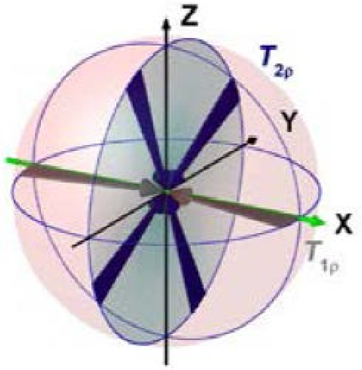
$$T_{2\rho}^* = 2.4 \text{ ms}$$

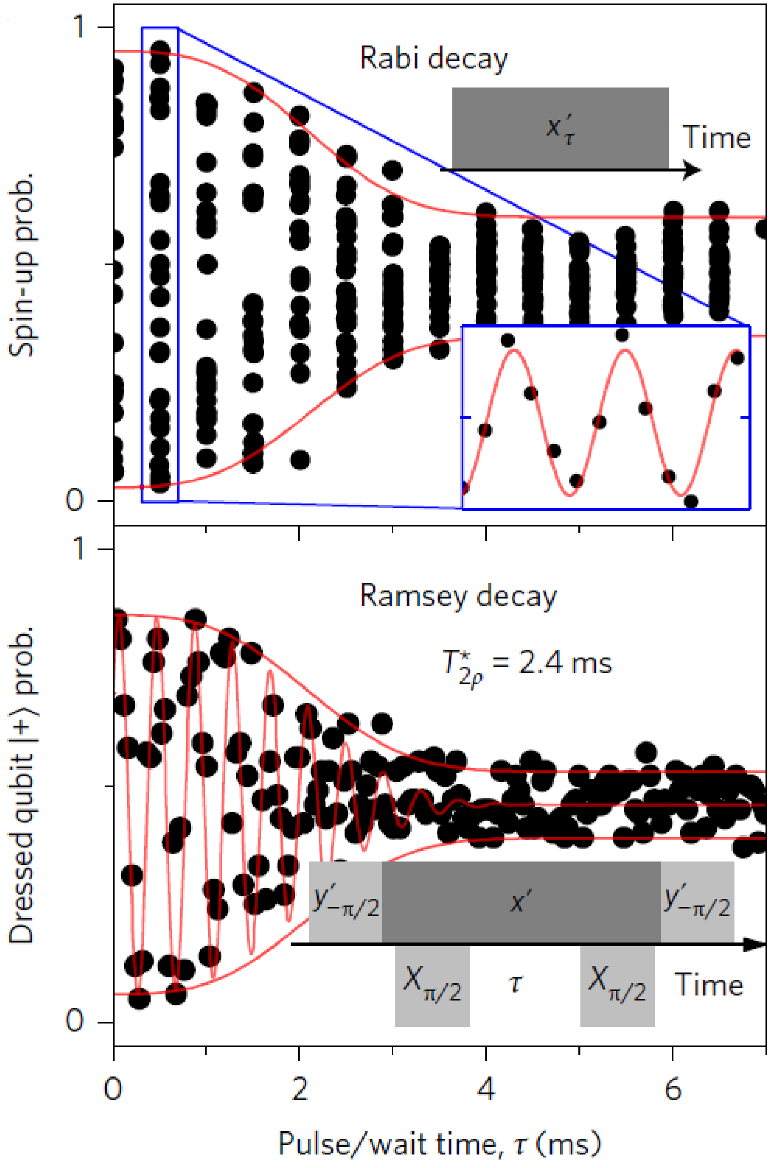
Dressed qubit dephasing time

- ❑ *Rotating frame*



- ❑ *Double rotating frame*





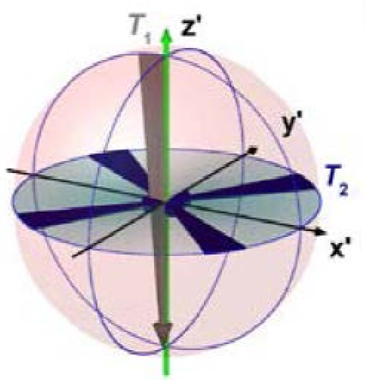
Decay of “original” Rabi oscillations
=
Free induction decay Dressed qubit

$$T^*_{2\rho} = 2.4 \text{ ms}$$

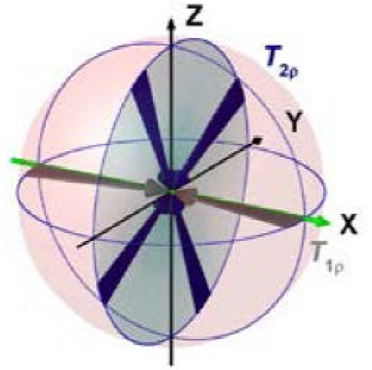
Ramsey in the dressed qubit frame

Refocusing sequences on the dressed qubit

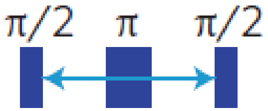
- *Rotating frame*



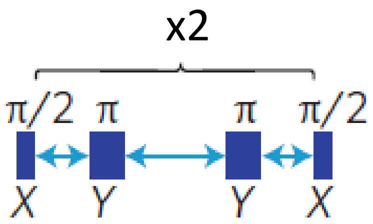
- *Double rotating frame*



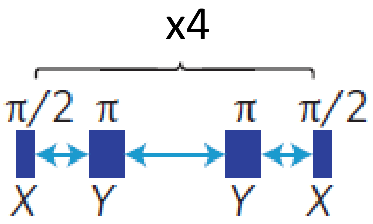
Hahn echo:

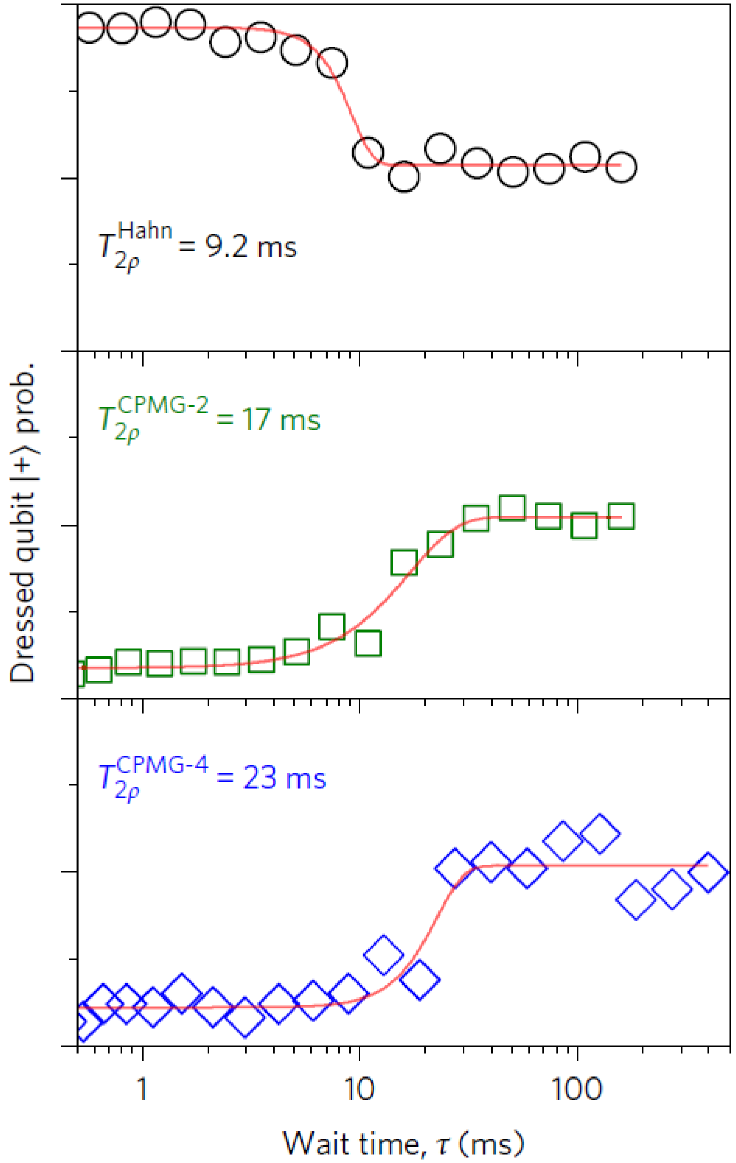


CPMG-2:



CPMG-4:





Comparison coherence times "normal" vs dressed spin qubit

- *"Normal" spin qubit*

$$T_2^* = 268\ \mu\text{s}$$

$$T_2^{Hahn} = 0.95\ \text{ms}$$

$$T_2^{CPMG-4} = 3\ \text{ms}$$

- *Dressed spin qubit*

$$T_{2\rho}^* = 2.4\ \text{ms}$$

$$T_{2\rho}^{Hahn} = 9.2\ \text{ms}$$

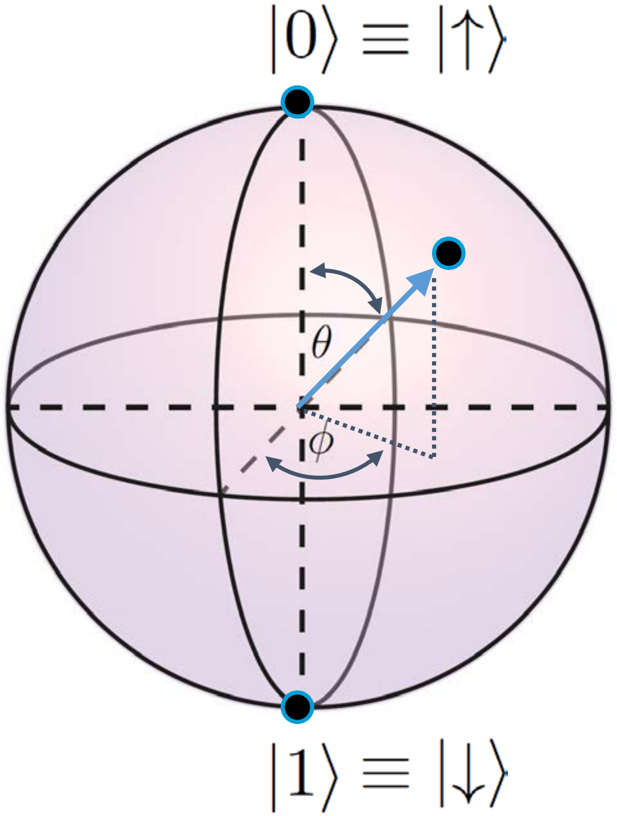
$$T_{2\rho}^{CPMG-4} = 23\ \text{ms}$$

→ Coherence times are improved by order of magnitude!

Muhonen et al., Nature Nanotechnology ***9****, (2014)*

Supplementary slides

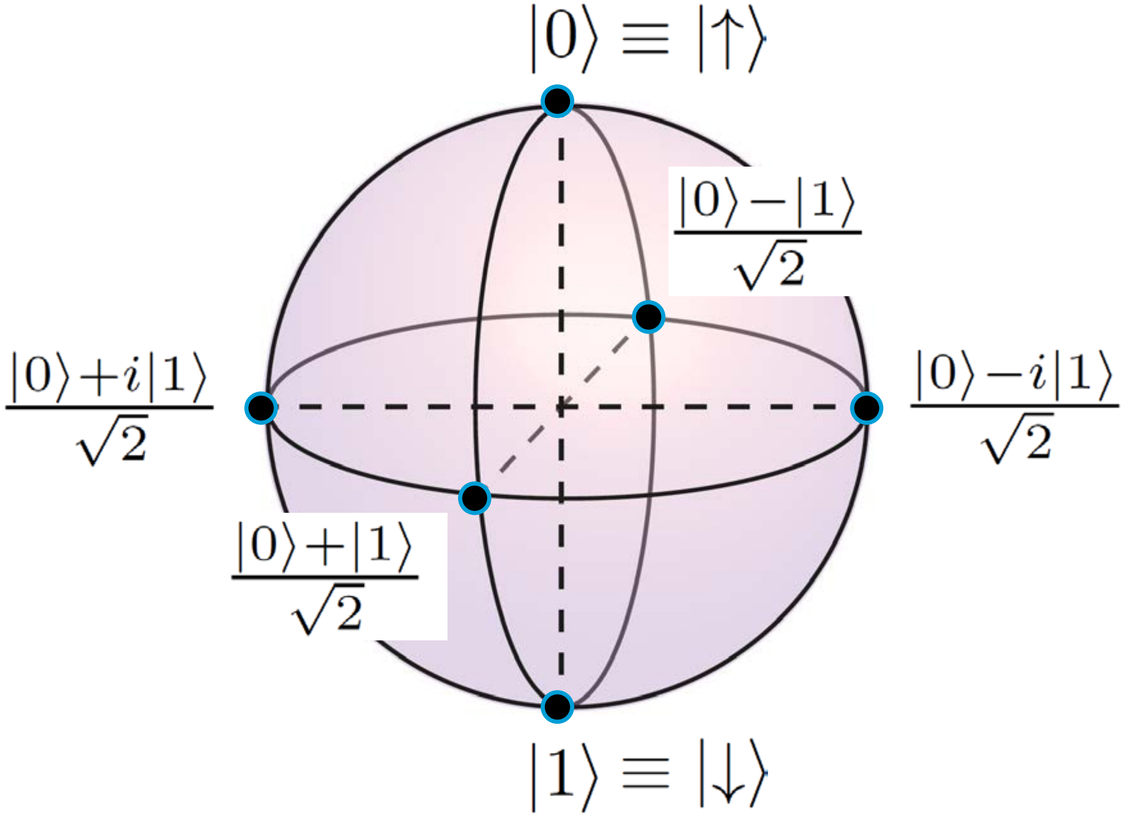
"Normal" spin qubit



$$|\psi\rangle = \alpha\,|0\rangle + \beta\,|1\rangle$$

$$|\psi\rangle = \cos\left(\frac{\theta}{2}\right)|0\rangle + e^{i\phi}\sin\left(\frac{\theta}{2}\right)|1\rangle$$

“Normal” spin qubit



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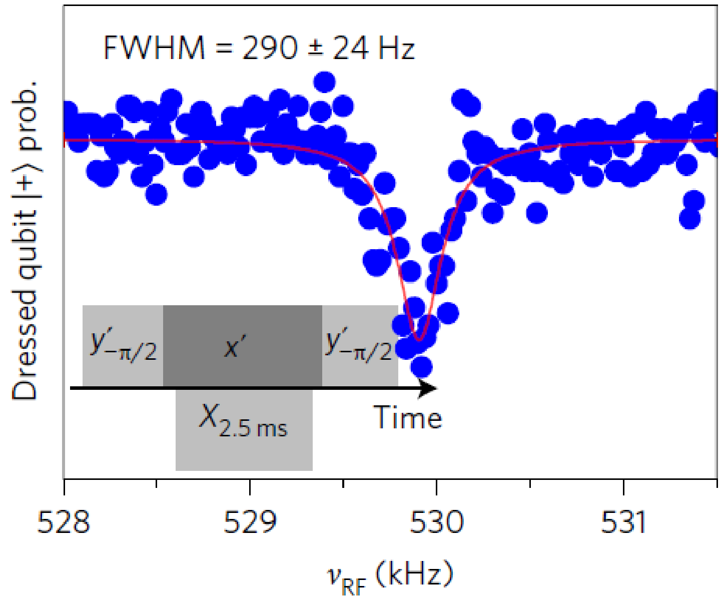
Dressed qubit linewidth



More Mollow triplet measurements

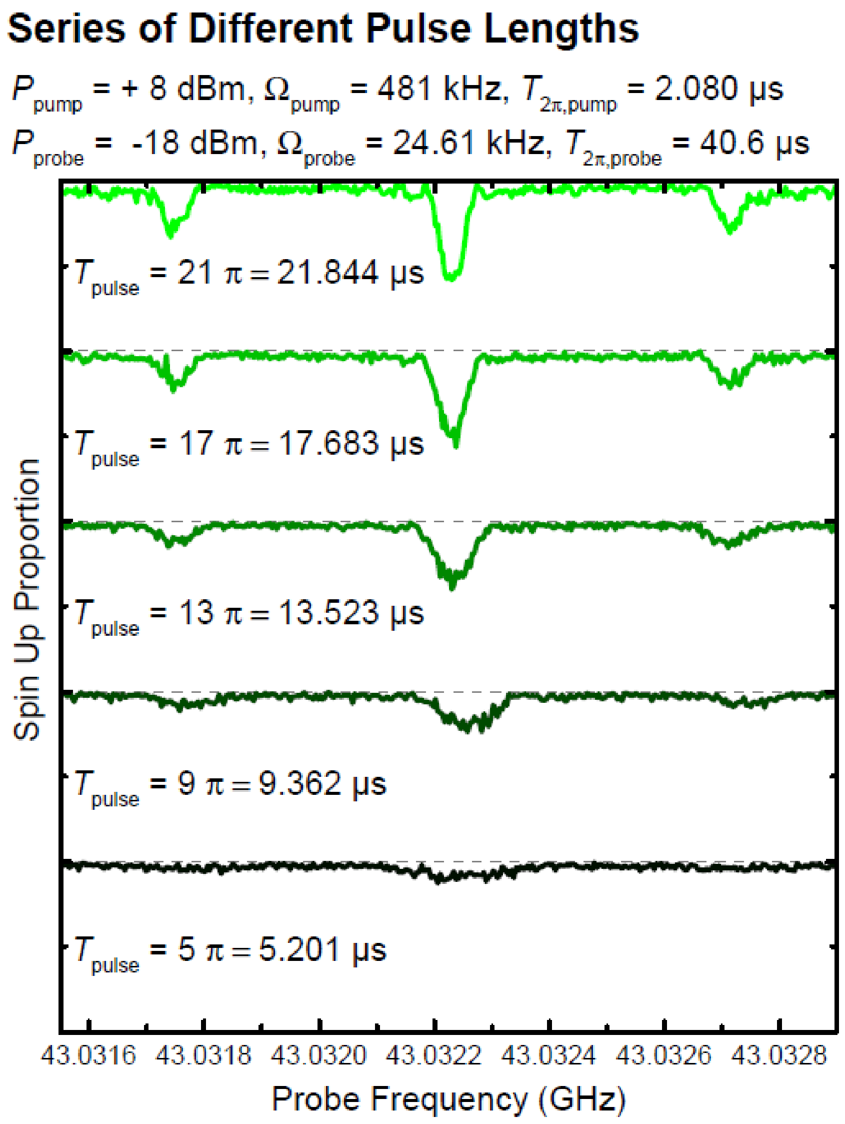
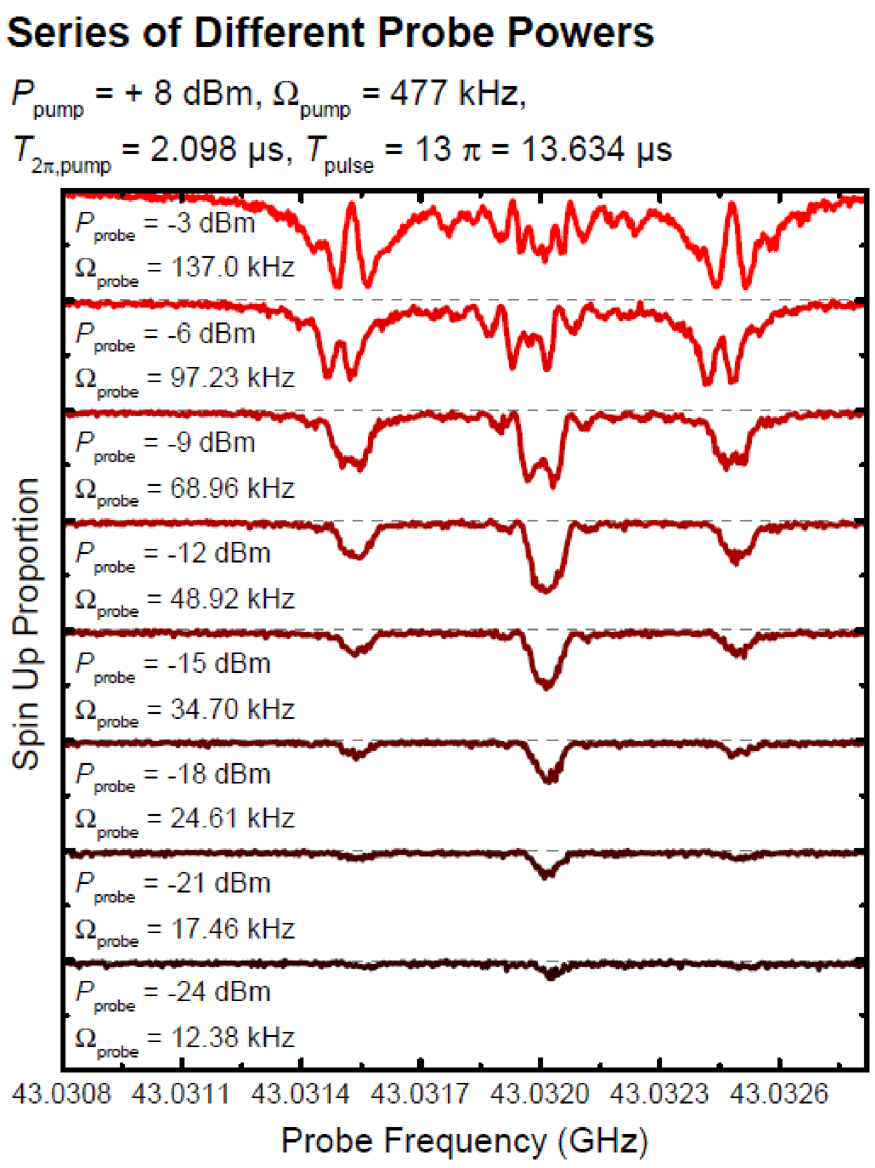


Figure S1: **Dressing the electron spin.** Mollow spectra of the dressed electron spin for different microwave pulse lengths. Here, a strong, resonant driving field $P_{\rm pump}$ was used to dress the spin state, while a weaker probe field $P_{\rm probe} = P_{\rm pump} - 26$ dB was scanned over the Mollow triplet to record the spectra.

More Mollow triplet measurements



Dressed qubit control by detuning pulse

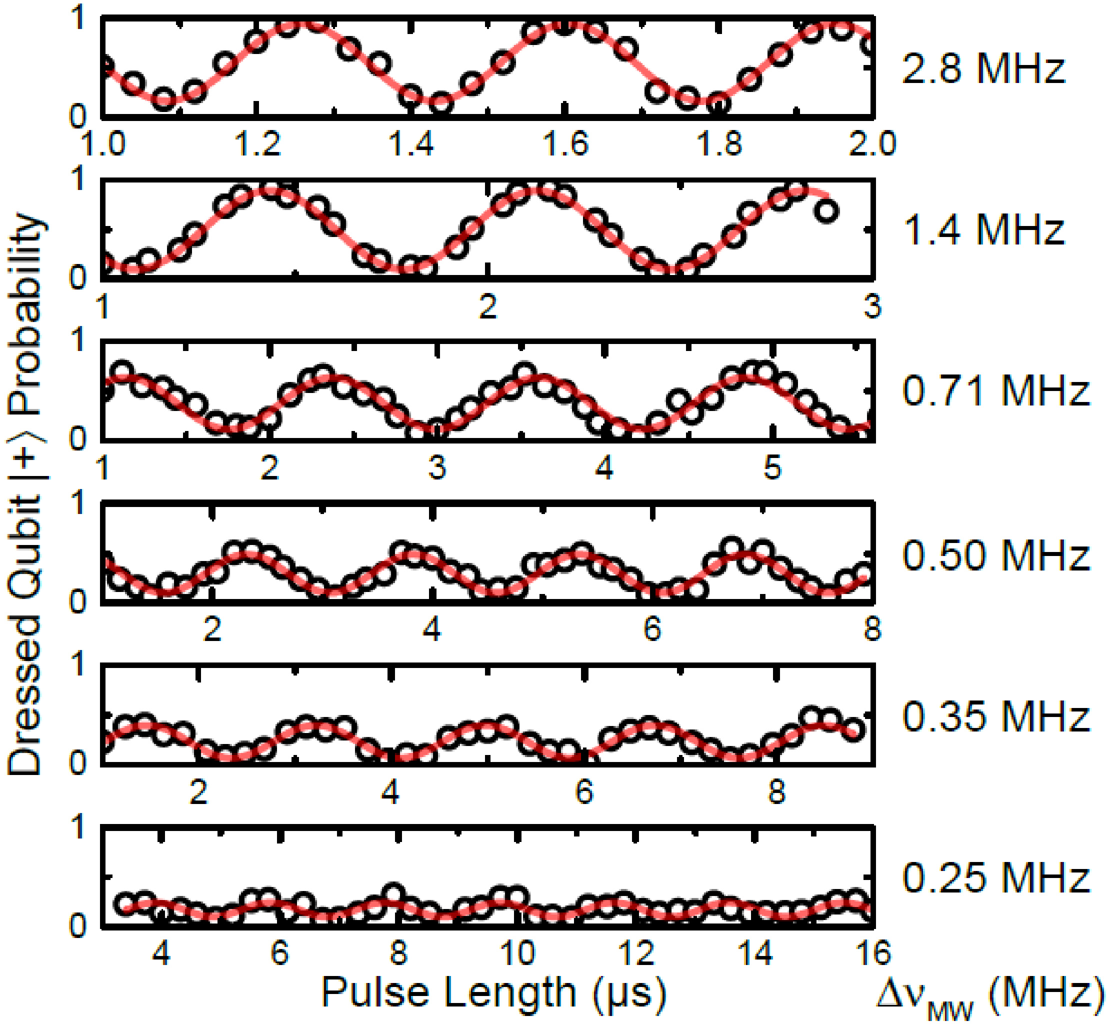


Figure S3: **Dressed qubit control by detuning pulse.** Rabi oscillations of the dressed qubit for different detuning amplitudes $\Delta\nu_{\mathrm{MW}}$ during the detuning pulse. Once $\Delta\nu_{\mathrm{MW}} \leqslant \Omega_R$ the amplitude of the Rabi oscillations decreases.