IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January 2016.
KRYO 2015 oral presentation. Not submitted for publication.

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[1]Karlsruhe Institute of Technology (KIT)
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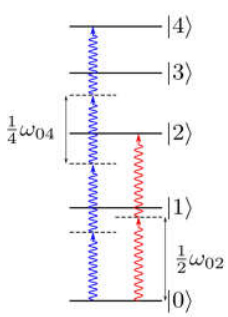
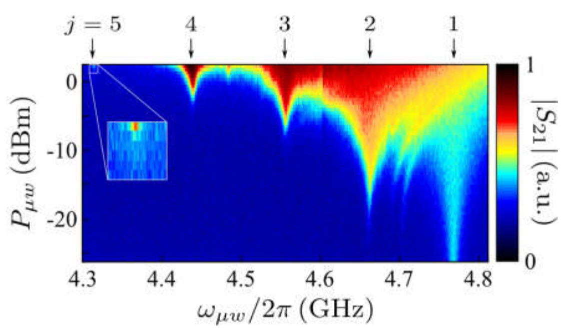
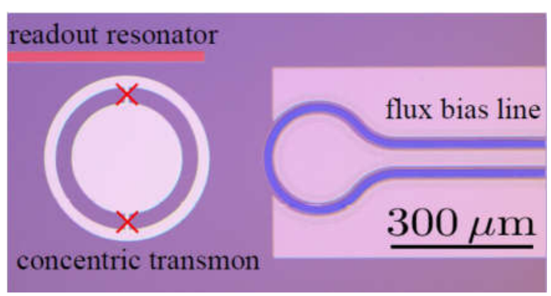
September 29th 2015, Burg Warberg, Kryo 2015

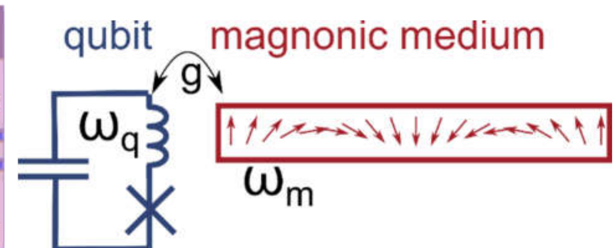
Experiments with superconducting qubits

multi-photon dressing, qubits with magnetic coupling









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Introduction

- Anharmonic many-level quantum circuit
  - Dispersive shifts, power spectroscopy, Rabi sidebands
- Concentric transmons
  - Gradiometric, fast tunable, site-selective σ_z coupling
- Ongoing
  - QuantumMagnonics:
    quantum limited detection of dynamics in ferromagnets

Bits and Quantum Bits

Today's chips

1st transistor 1947

Integrated circuit
1-4 GHz clock rate
Multi-core processsor

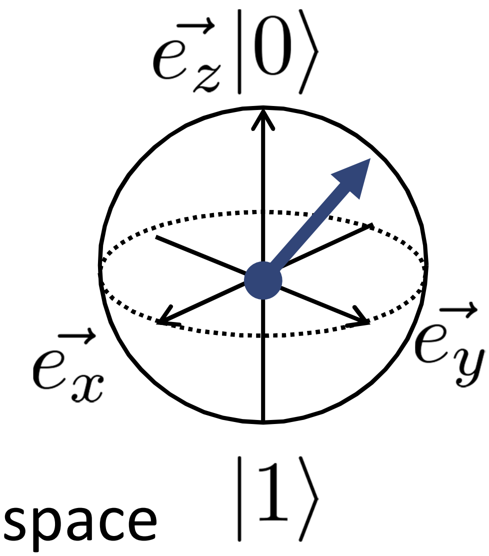
Classical bit

1 1 0 1 1 0

Quantum bit (qubit)

S = 1/2

$$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

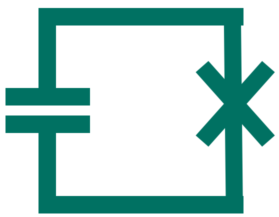


Superposition & entanglement: 2^N- dim. Hilbert space

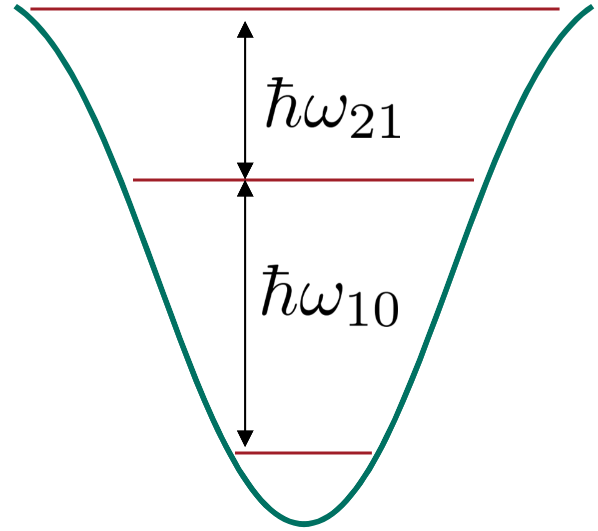
$$|\Psi\rangle = \sum_{j=0}^{2^N-1} \alpha_j |\phi_{j,1}\rangle \otimes |\phi_{j,2}\rangle \otimes \ldots \otimes |\phi_{j,N}\rangle$$

→ Parallel processing (Shor factoring, Grover search, Q-simulation)

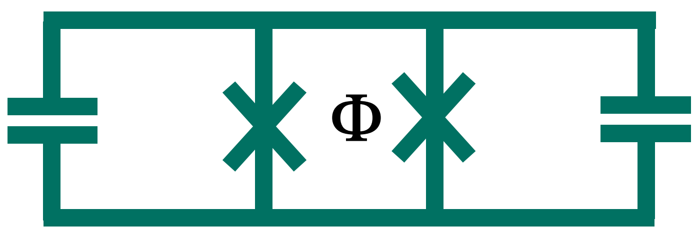
Transmons: capacitively shunted Josephson junction → Anharmonic oscillator



$$L_J(\phi) \propto \frac{1}{I_c \cos\phi}$$



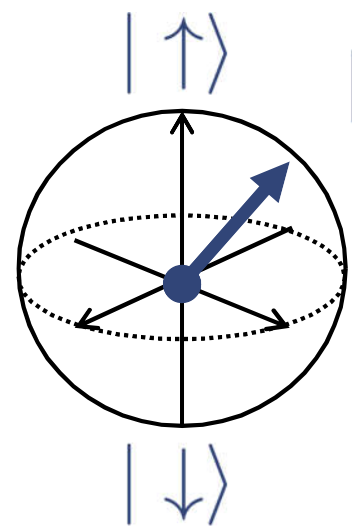
Non-linear, tunable LC oscillator



Magnetic flux Φ changes $L_J(\phi)$

$$\omega_{10}(\Phi) \approx \frac{1}{\sqrt{L_J(\Phi)C}}$$

Two lowest levels → **Bloch sphere**



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

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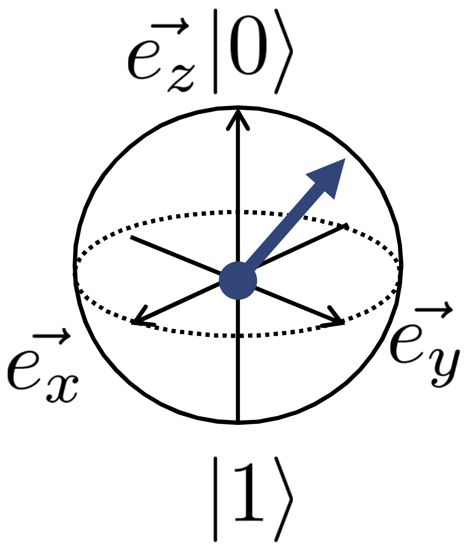
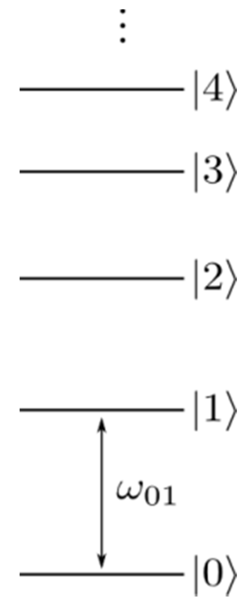
Anharmonic many-level quantum circuit



$$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

transmon qubit:
weak anharmonicity



Consider higher quantum levels

efficient & robust quantum gates

enhanced security of key distribution in quantum cryptography

quantum simulation

spin-½ ↔ two levels

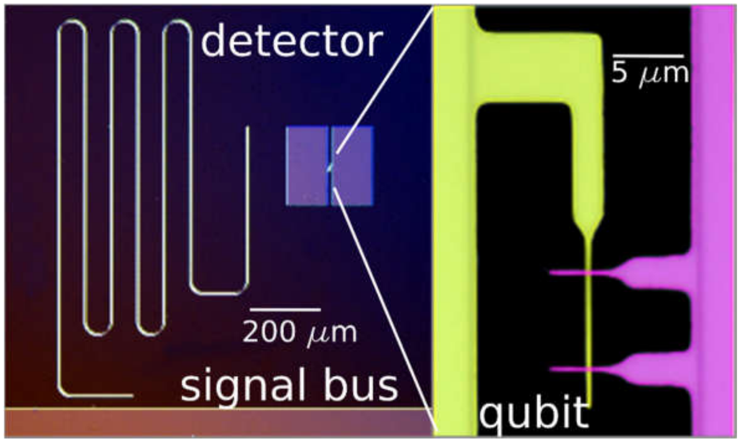
spin-1 ↔ three levels

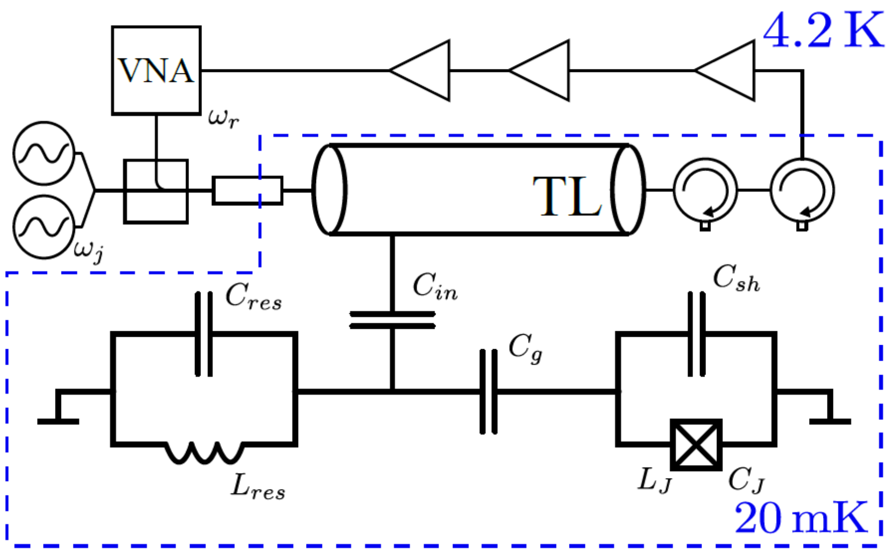
Neeley Nat. Phys. **4,** 523 (2008)
Fedorov Nat. **481,** 170 (2011)

Bruß PRL **88**, 127901 (2002)
Cerf PRL **88**, 127902 (2002)

Paraoanu JLTP **175,** 633 (2014)

Experiment





$$\hat{H} = \hbar \sum_j \omega_j |j\rangle\langle j| + \hbar\omega_r \hat{a}^\dagger \hat{a} + \hbar \sum_{i,j} g_{ij} |i\rangle\langle j| \left(\hat{a}^\dagger + \hat{a}\right)$$

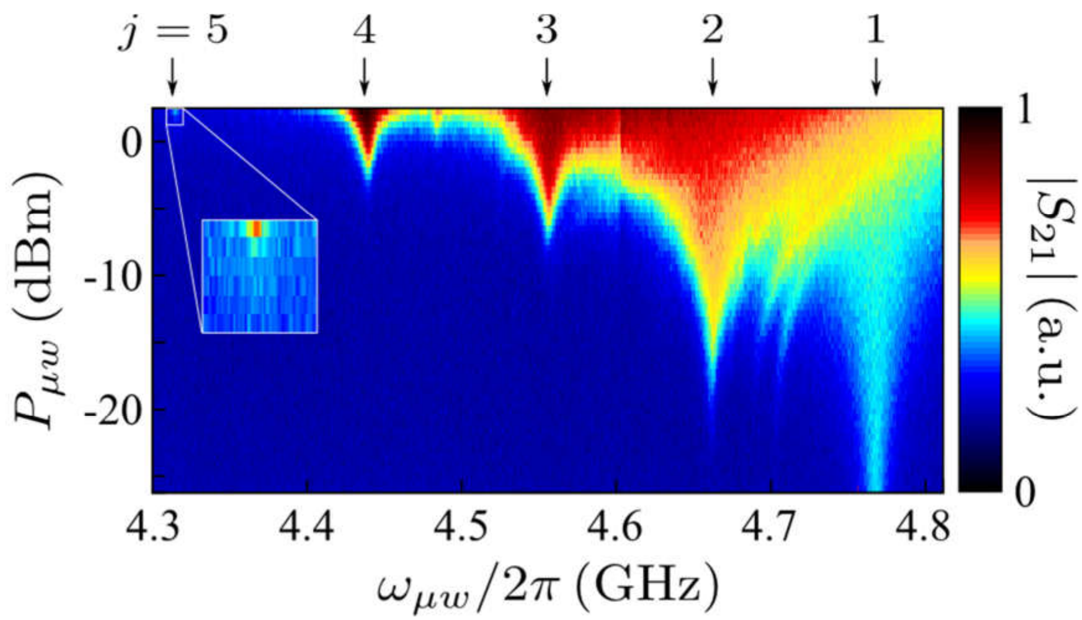
- microstrip geometry Sandberg *et al.* APL **102,** 072601 (2013)
- overlap Josephson junction
- transmon regime: $E_J \gg E_C \Rightarrow \alpha_r \sim 0.05$
- spectroscopic measurements
  - VNA readout tone
  - microwave drive/probe tone

Koch *et al.* PRA **76**, 042319 (2007)

Blais *et al.* PRA **69**, 062320 (2004)

Braumüller *et al.*,PRB **91**, 054523 (2015)

Power spectroscopy – multiphoton transitions



Braumüller *et al.*,PRB **91**, 054523 (2015)

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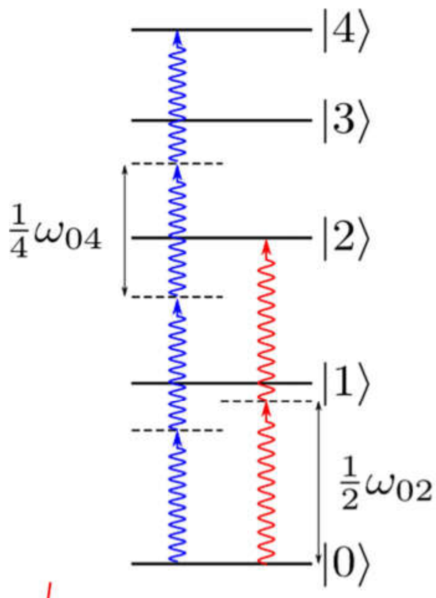
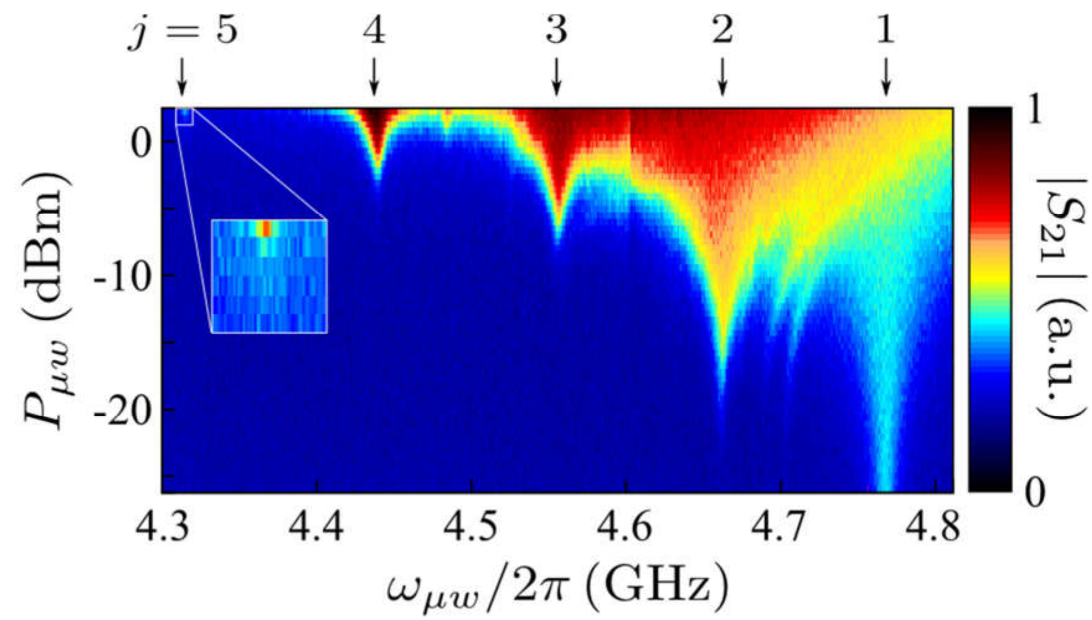
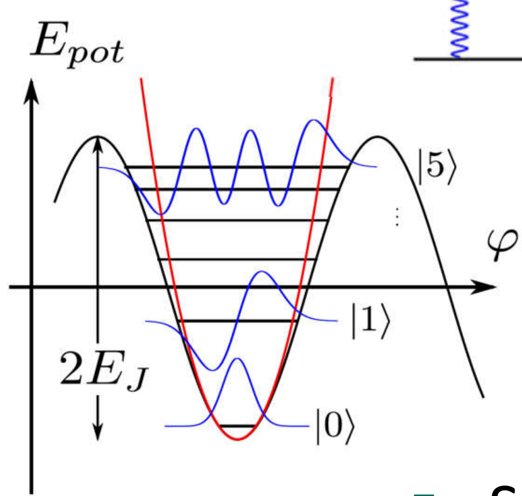






Multi-photon transitions $1/j \ (|0\rangle \leftrightarrow |j\rangle)$

- Six bound states in Josephson potential
- Dispersive shift scales with excitation number ‹n›

Braumüller *et al.*,PRB **91**, 054523 (2015)

Dispersive shift by higher levels

effective Hamiltonian

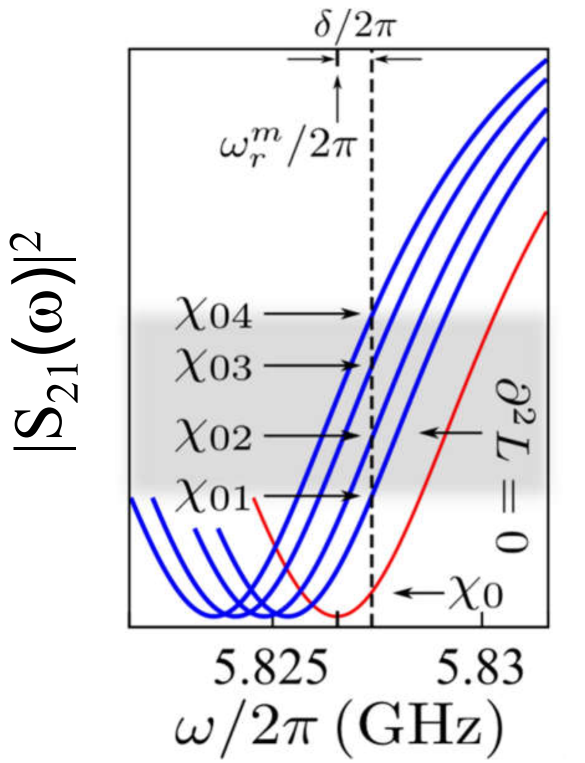
$$\hat{H}' = \hbar \sum_j \omega_j |j\rangle\langle j| + \underbrace{\hbar \sum_{j=1} \chi_{j-1,j} |j\rangle\langle j|}_{\text{Induced by resonator}} + \hbar \hat{a}^\dagger \hat{a} \left(\omega_r \underbrace{- \chi_{01} |0\rangle\langle 0| + \sum_{j=1} (\chi_{j-1,j} - \chi_{j,j+1}) |j\rangle\langle j|}_{\text{Induced by qubit}} \right)$$

Braumüller *et al.*,PRB **91**, 054523 (2015)

Dispersive shift by higher levels

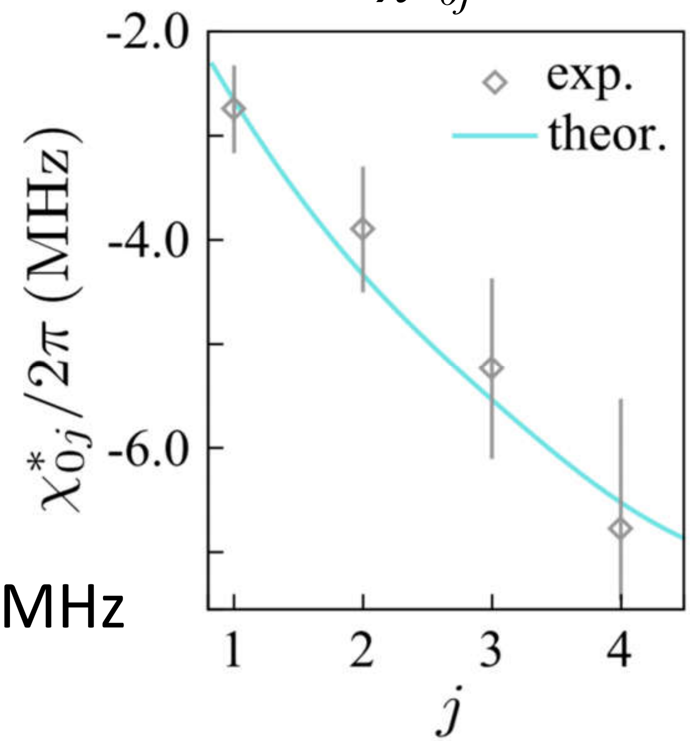
Rotating-wave Hamiltonian

$$\hat{H}' = \hbar \sum_j \omega_j |j\rangle\langle j| + \underbrace{\hbar \sum_{j=1} \chi_{j-1,j} |j\rangle\langle j|}_{\text{Induced by resonator}} + \hbar \hat{a}^\dagger \hat{a}\left(\omega_r - \underbrace{\chi_{01}|0\rangle\langle 0| + \sum_{j=1}(\chi_{j-1,j} - \chi_{j,j+1})|j\rangle\langle j|}_{\text{Induced by qubit}}\right)$$



Spectroscopy: equal population of $|0\rangle, |j\rangle$

Relative resonator shift χ^*_{0j}



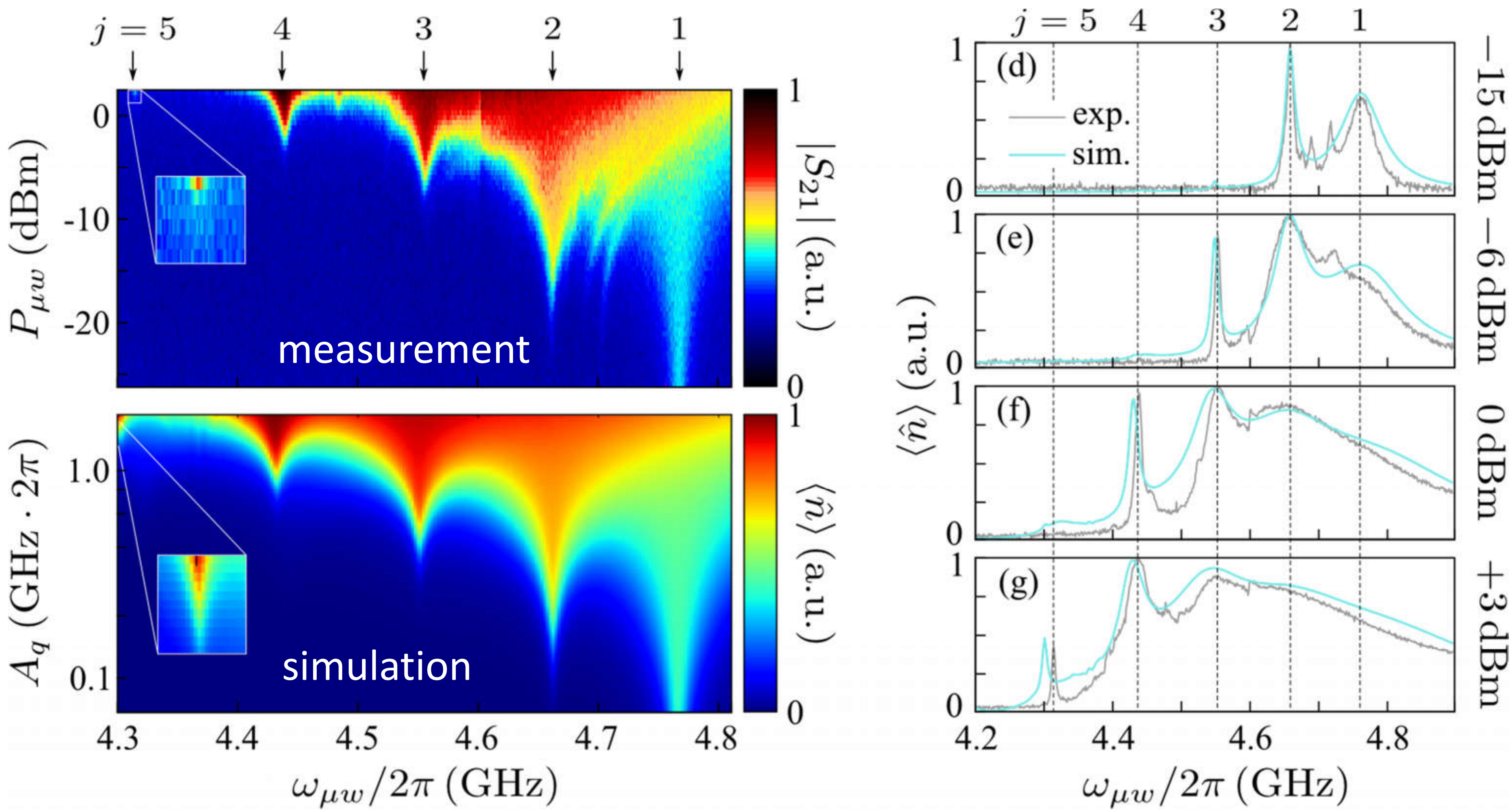
g_{01} = 115 MHz

$\Delta \approx$1 GHz

Braumüller *et al.*,PRB **91**, 054523 (2015)

Power spectroscopy – data & simulation

$$\hat{H}^{sim} = \hat{H} + \hbar A_q \sum_{i,j} \frac{g_{ij}}{g_{01}} |i\rangle\langle j| \cos \omega_{\mu w} t$$



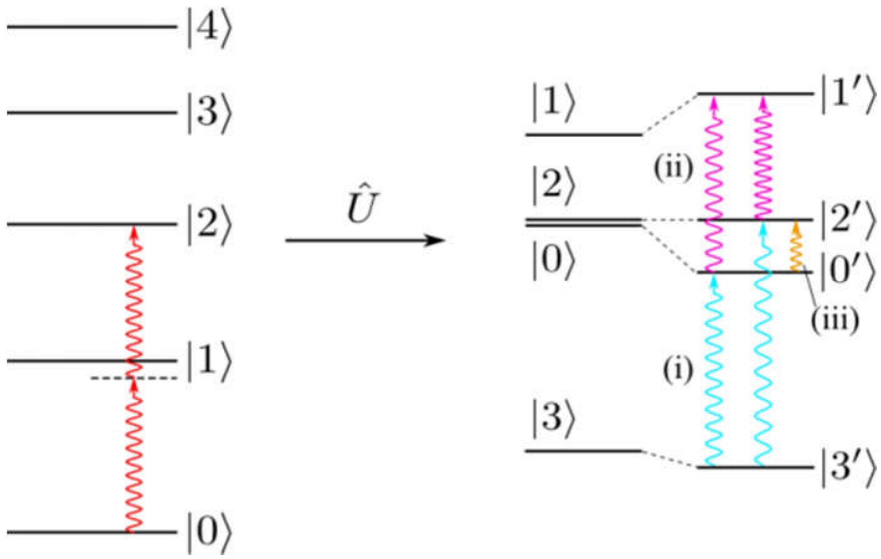
 Martin Weides KIT & JGU Mainz

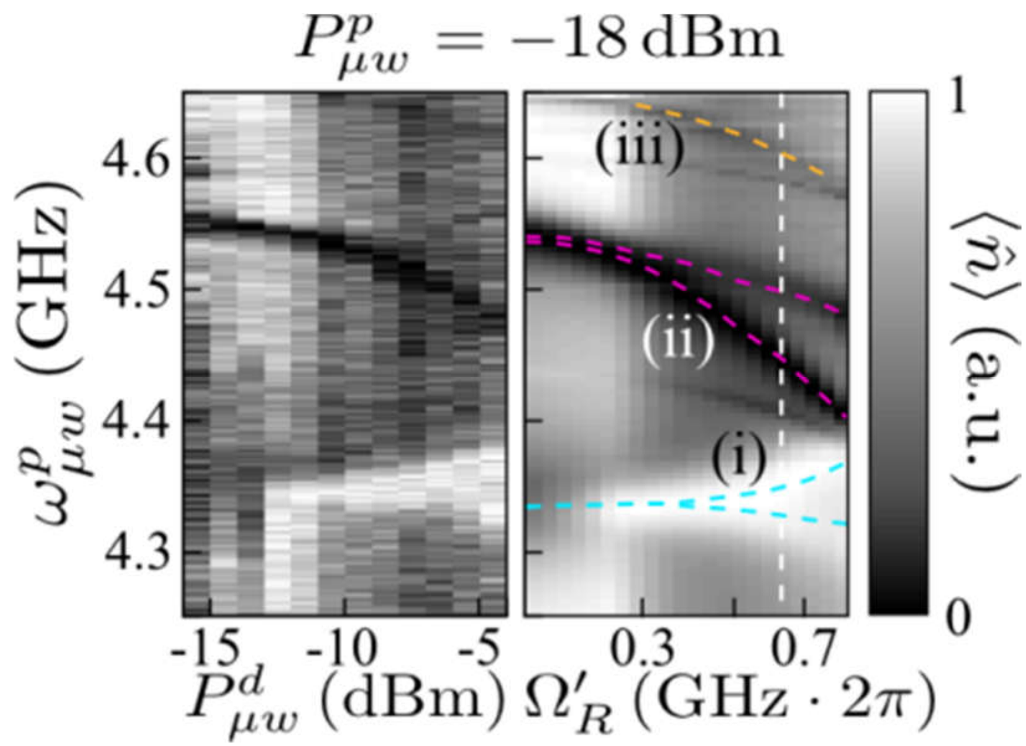
Braumüller *et al.*,PRB **91**, 054523 (2015)

Multiphoton dressing $|0\rangle - |2\rangle$, Rabi sidebands

Strong drive

Sweep drive amp, probe freq.





- $|0\rangle, |2\rangle$ degenerate in rotating frame → dressing
- Probing level structure (in rotating frame) with weak probe tone

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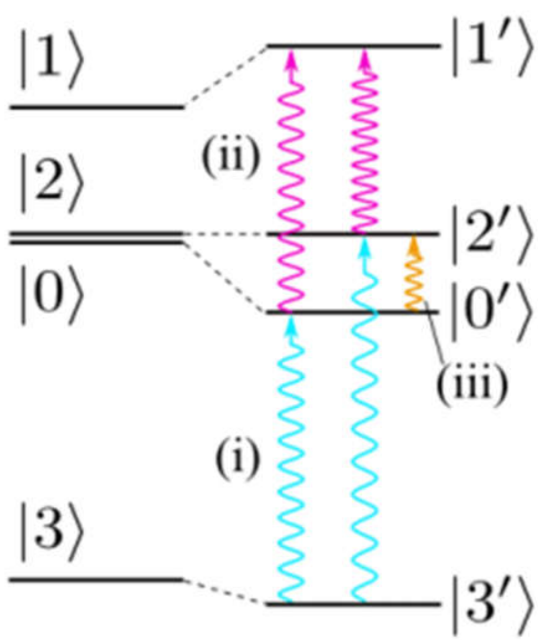
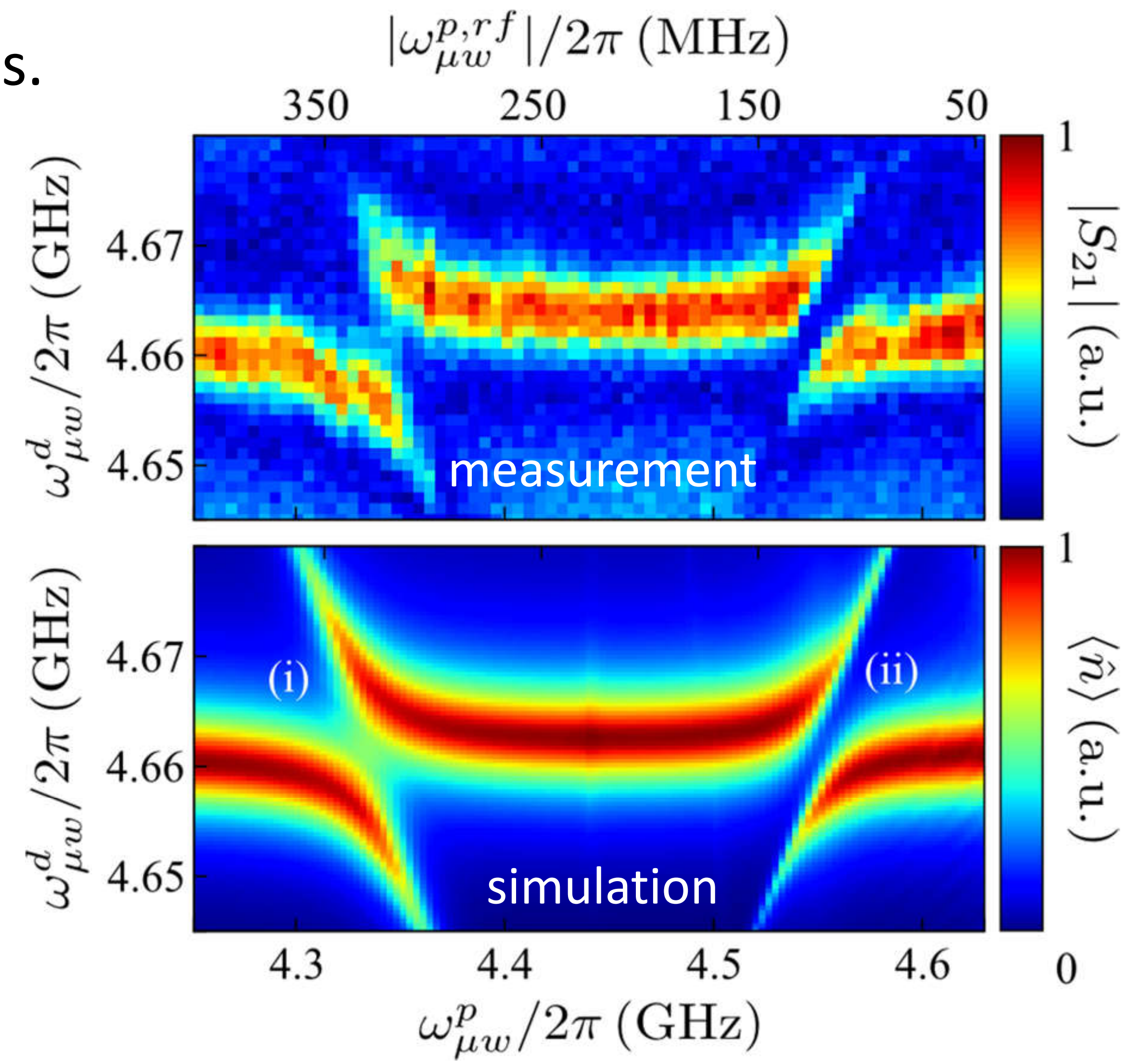
Braumüller *et al.*,PRB **91**, 054523 (2015)

Multiphoton dressing – pumping the |2⟩-level

Sweep drive & probe freqs.



$$\omega_3^{rf}/2\pi = (-)330\,\mathrm{MHz} \quad (i)$$
$$\omega_1^{rf}/2\pi = 104\,\mathrm{MHz} \quad (ii)$$



Dynamical coupling of levels by probe tone
→ avoided crossing, Autler-Townes doublet

Braumüller *et al.*,PRB **91**, 054523 (2015)

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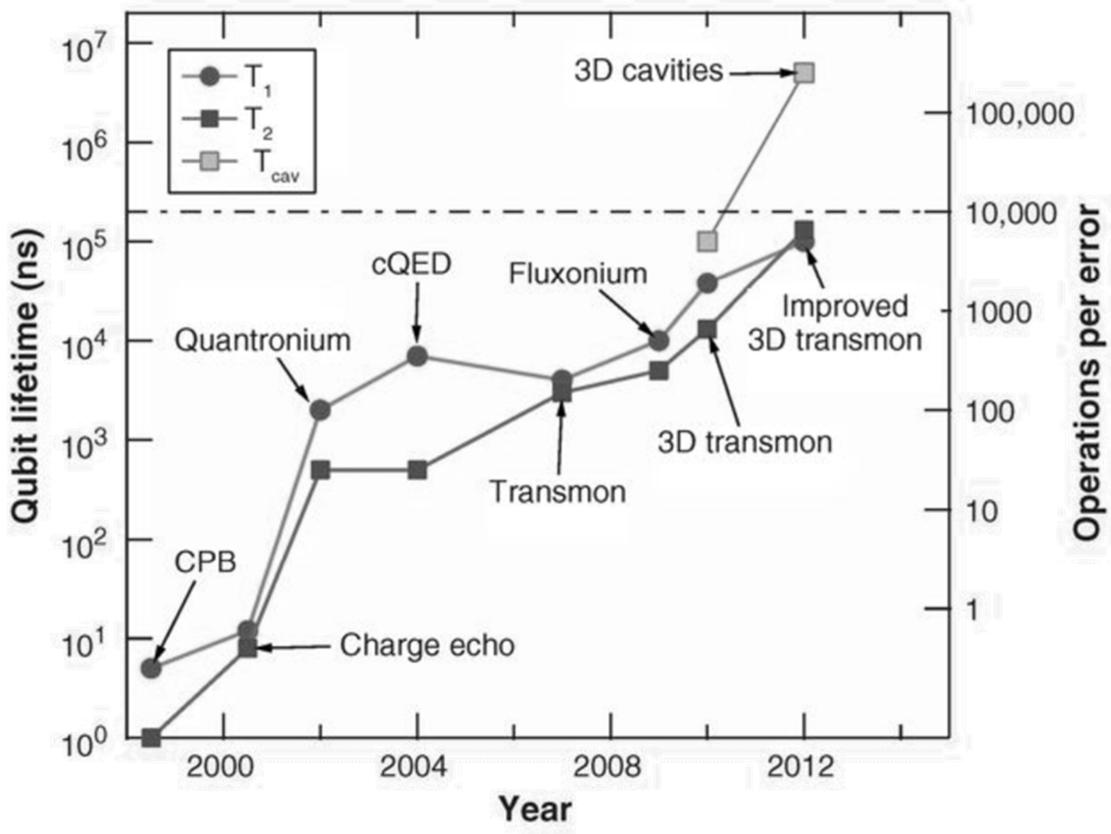
Advancing coherence in superconducting qubits



Devoret, Schoelkopf Science **339**, 116 (2013)

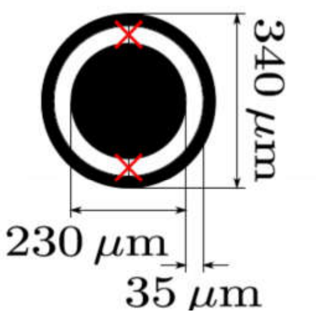
- Long coherence: scalable quantum computation, error correction
- Useful: high experimental flexibility by fast flux tuning of levels

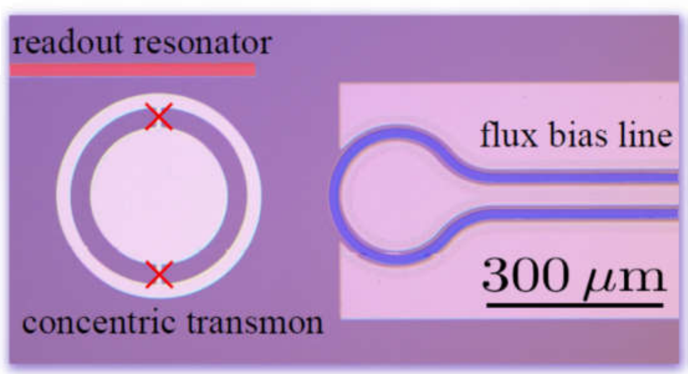
Karlsruhe Institute of Technology

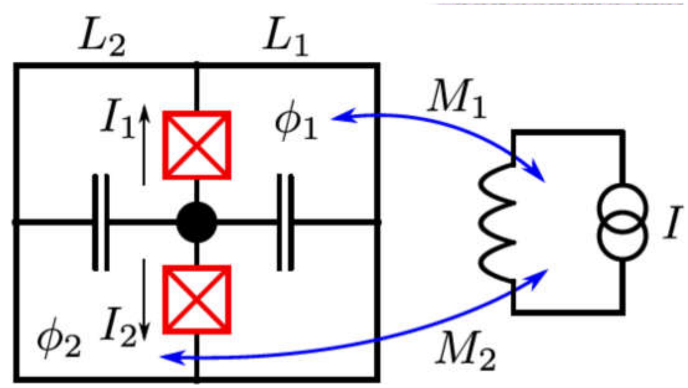
Novel design: Tunable, concentric transmon qubit (2d)

Coherence T_2 limited by energy relaxation $T_2^{-1} = \frac{1}{2}T_1^{-1} + \tau_\phi^{-1}$

- Minimize surface/interface TLS loss → microstrip design
- radiative decay → reduce qubit‘s dipole moment (symmetry)



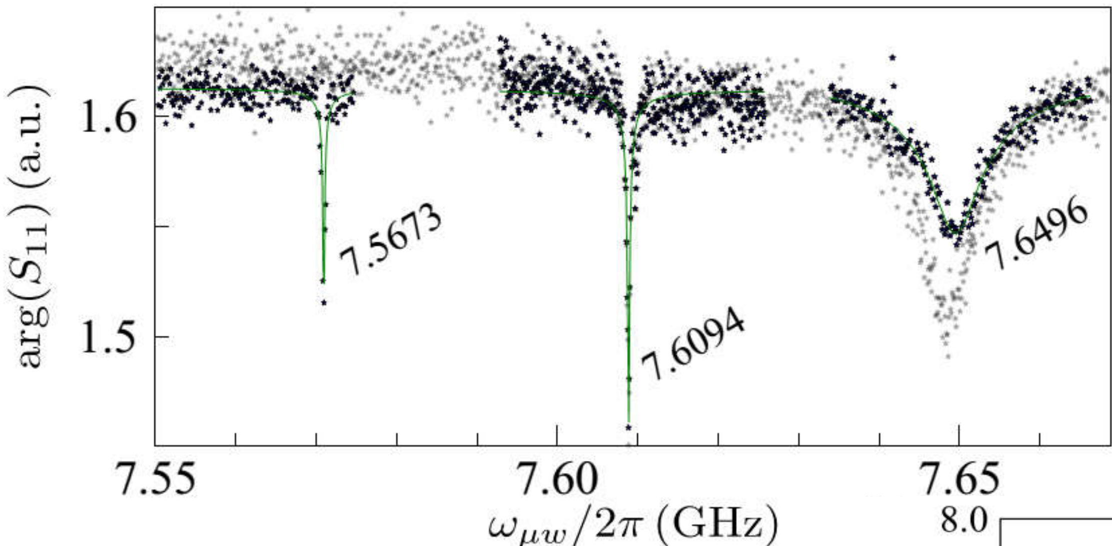


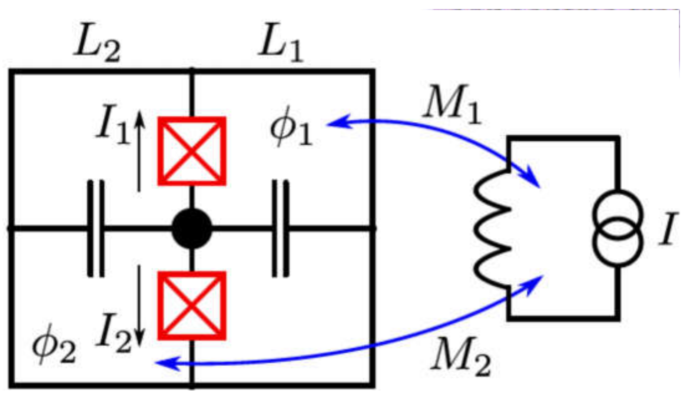


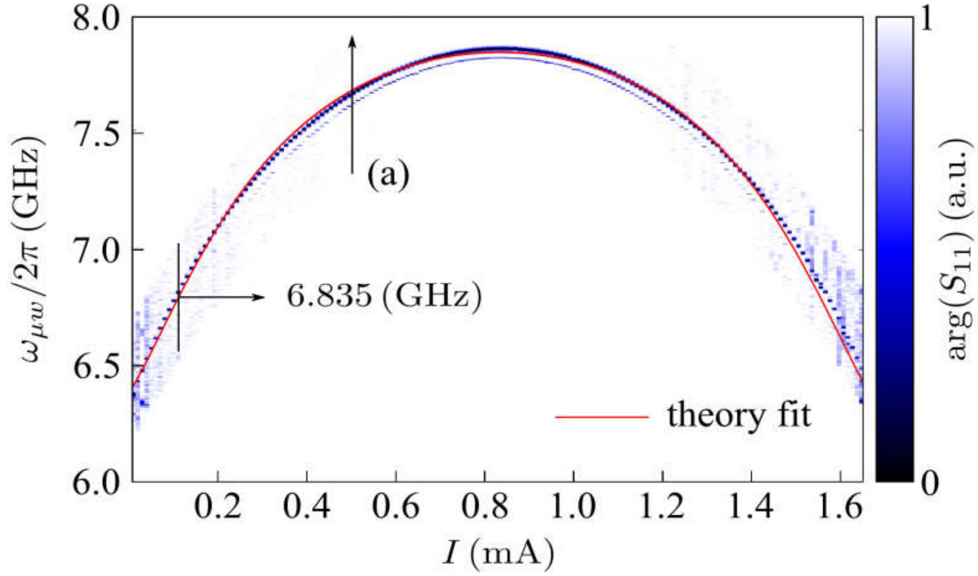
- Fast (ns) tunability
- Side-selective σ_z **and** σ_x couplings

Braumüller *et al.*, arXiv:1509.08014

Concentric transmon qubit – flux spectroscopy





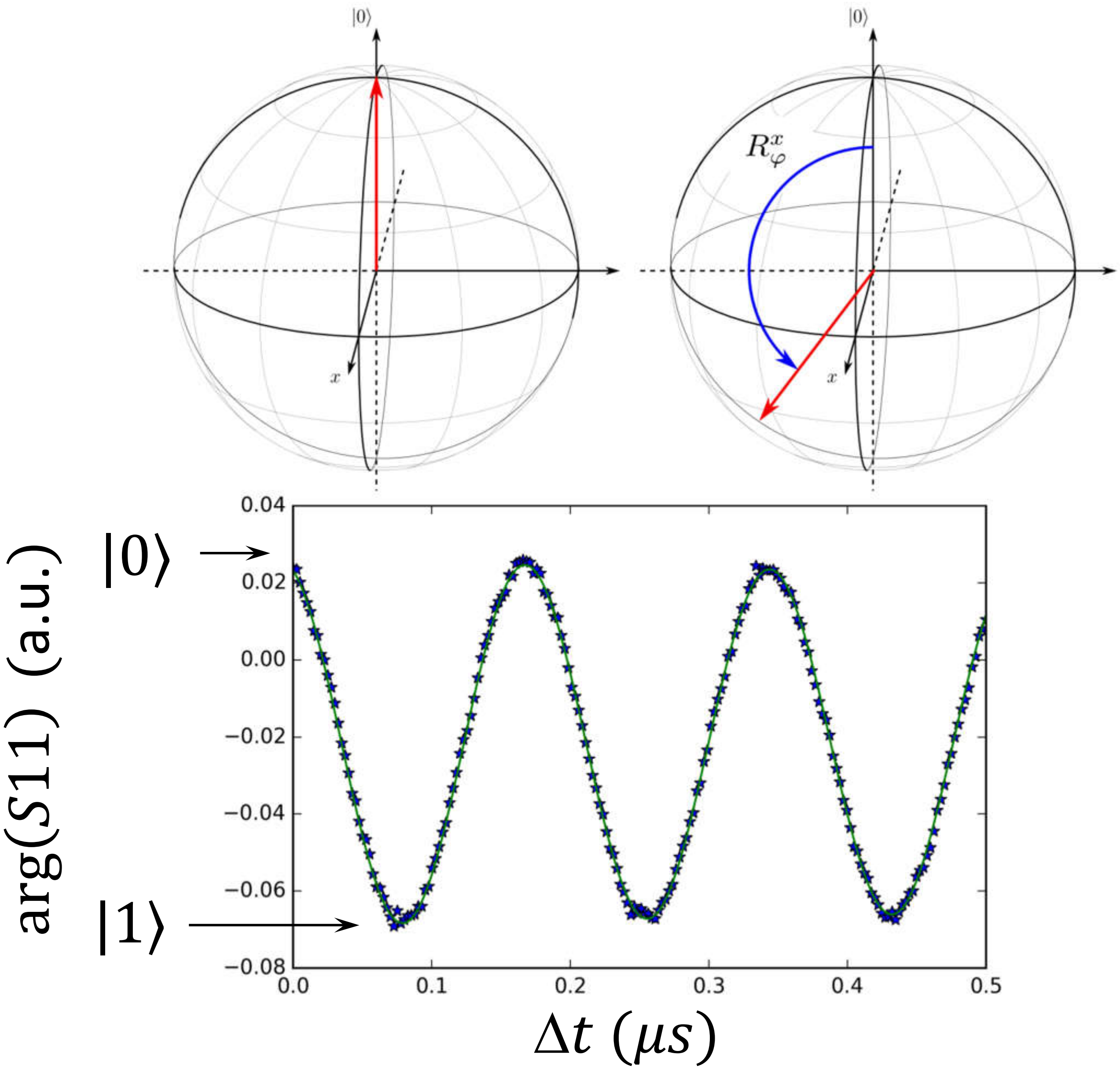


E_{J}, E_{C} do not match conventional transmon theory Koch *et al.* PRA **76**, 042319 (2007)

→ Modified Hamiltonian considering geometric inductance

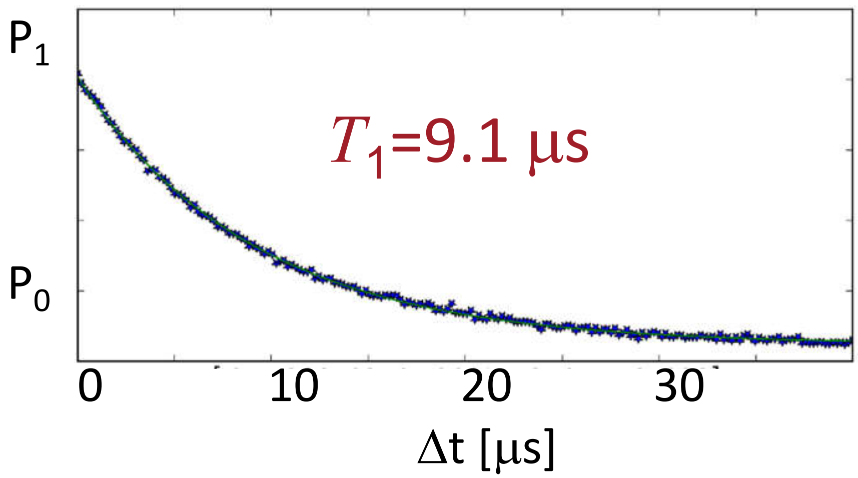
 Martin Weides KIT & JGU Mainz Braumüller *et al.*, arXiv:1509.08014

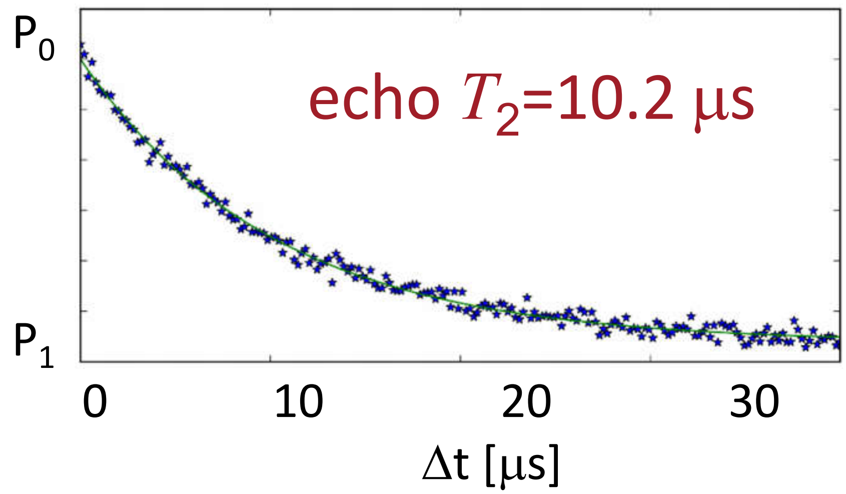
Pulsed measurements – Rabi oscillations

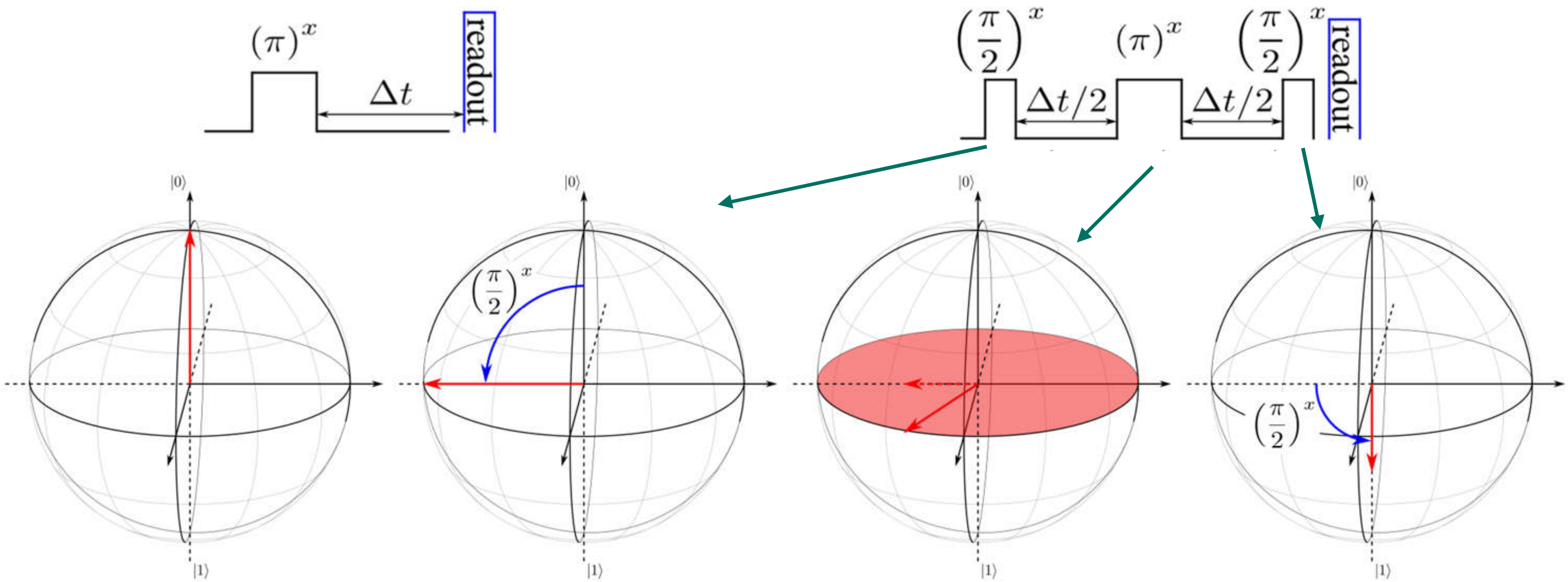


Braumüller *et al.*, arXiv:1509.08014

Pulsed measurements – Lifetime and coherence







 Braumüller *et al.*, arXiv:1509.08014

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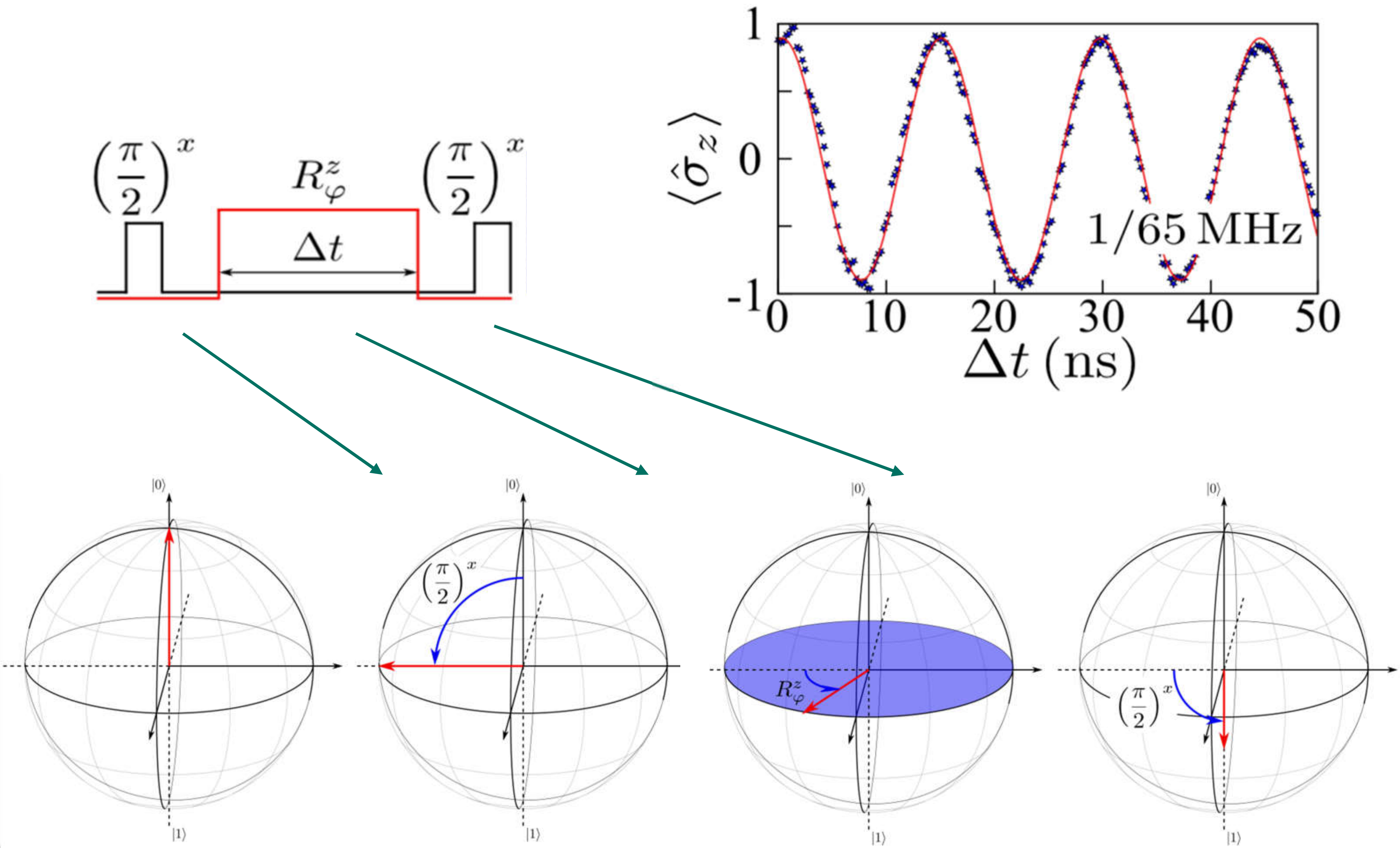
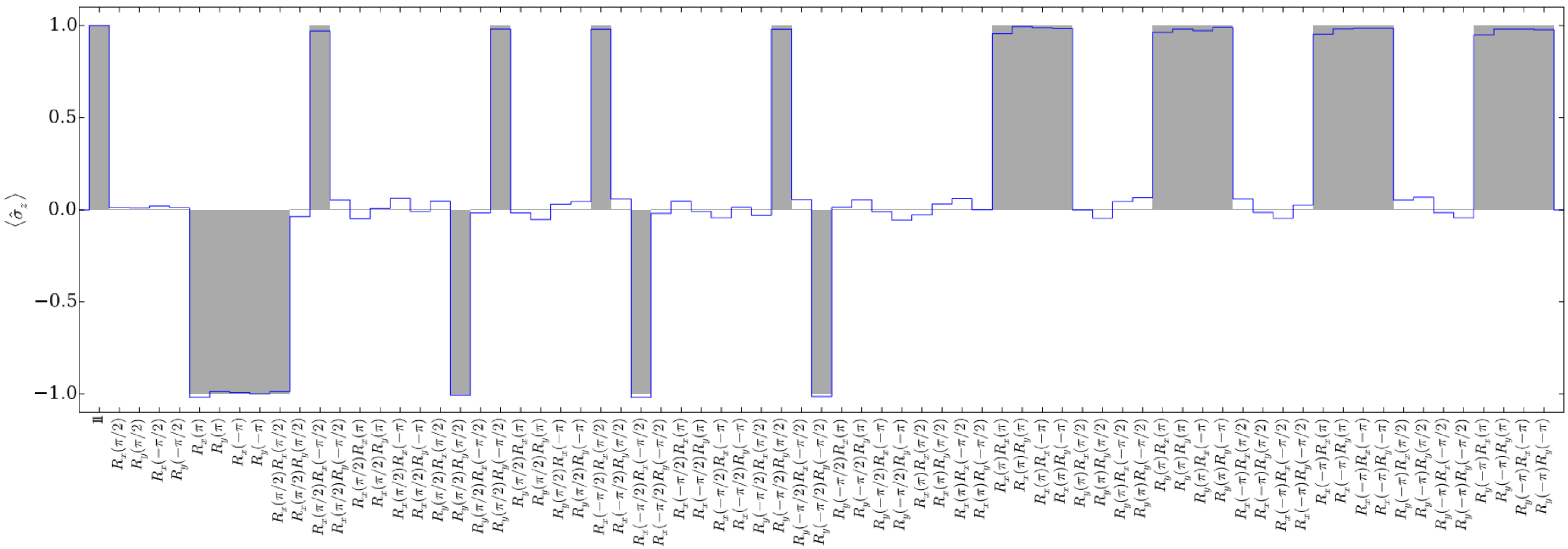
Pulsed measurements – fast z (energy splitting)-control



Braumüller *et al.*, arXiv:1509.08014

XYZ-tomography, benchmarking, state control



Full σ_x,σ_y,σ_z control, SSB-mixing, shaped pulses (DRAG)

→ **Gate benchmarking (99.54%)**

→ Precise qubit state control

→ Monitor decay $|\psi_i\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$ (x-axis)

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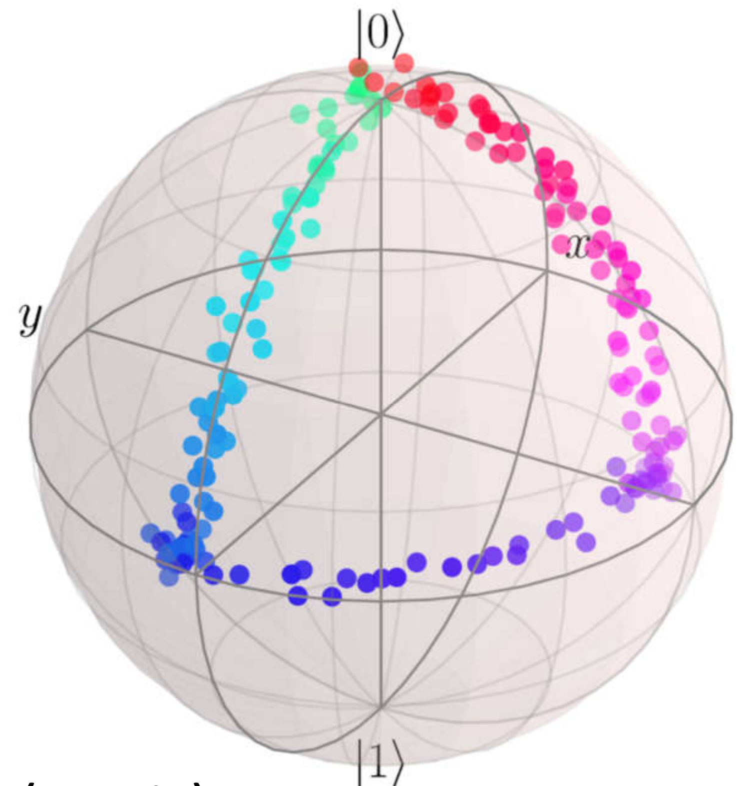
Schneider MA thesis (2015)

XYZ-tomography, benchmarking, state control



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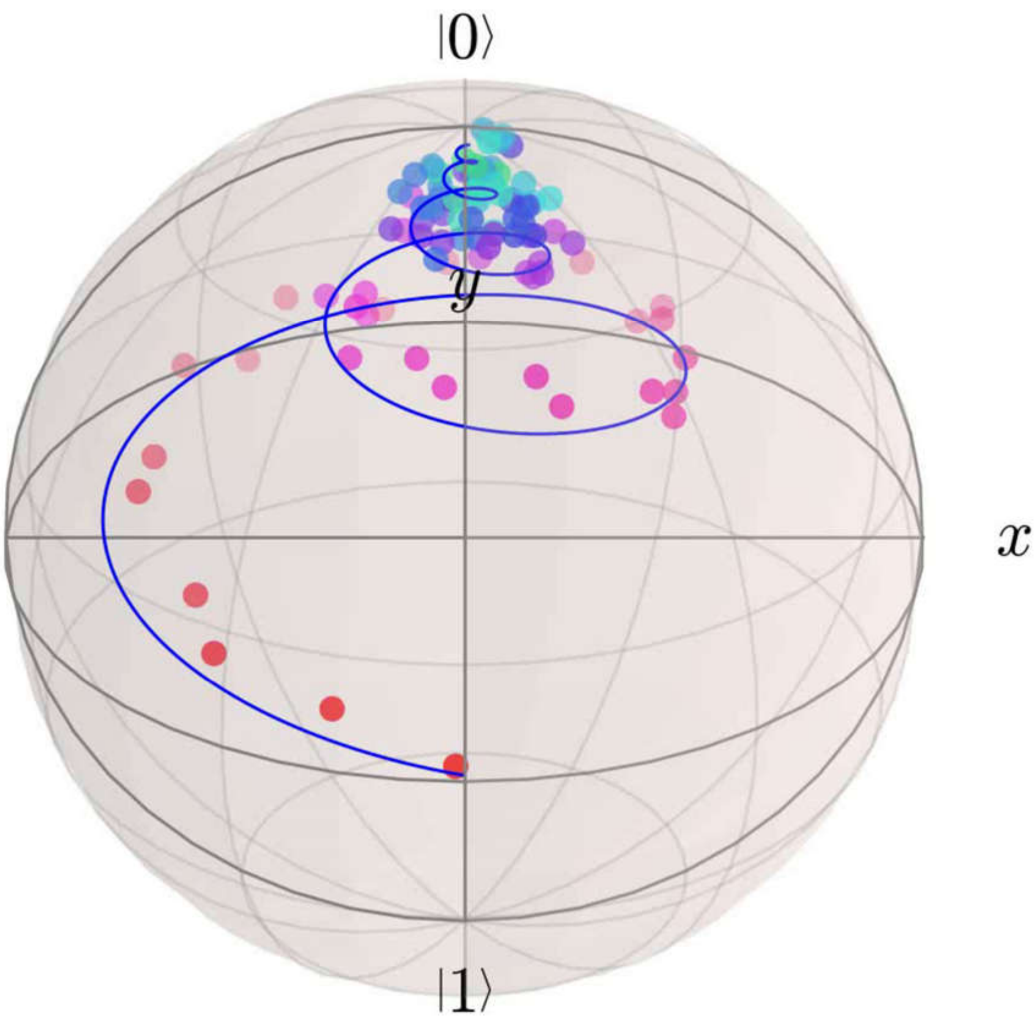

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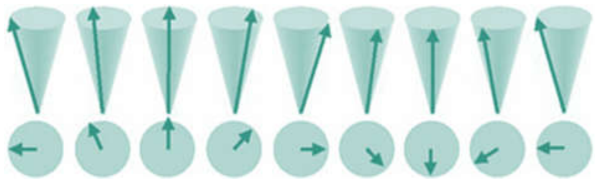
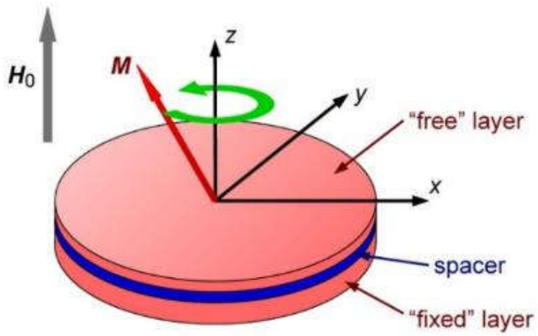
Magnonics: spin waves in nanostructures

Magnon: quantized spin wave excitation



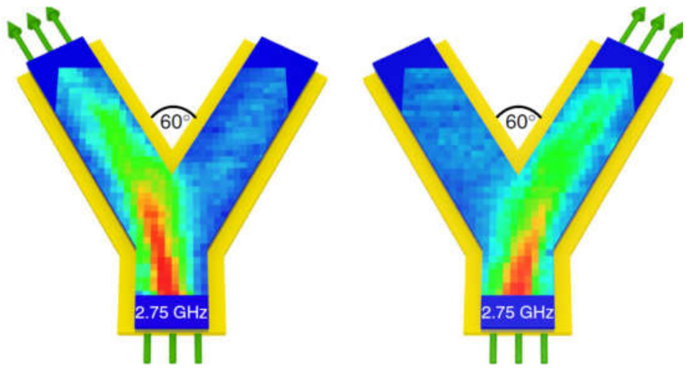
Future information technology

(e.g. spin-torque oscillator, spin-wave propagation control for logic)



Slavin *et al*., Nat. Nanotech. 4, 479 (2009)

Linewidth Δf > 1 MHz



Vogt *et al*., Nat. Commun. 5, 3727 (2014)

Attenuation length ~10 um

Strong magnon damping: magnon/phonon/electron scattering

Grand challenge:

To understand physics, single magnon information needed!

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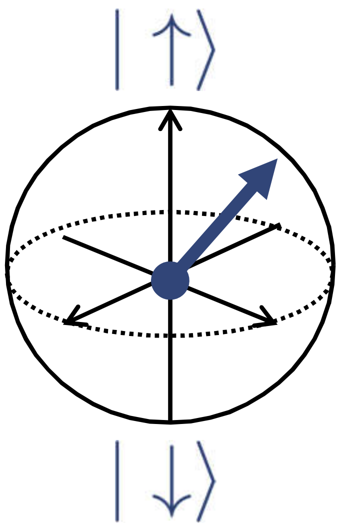
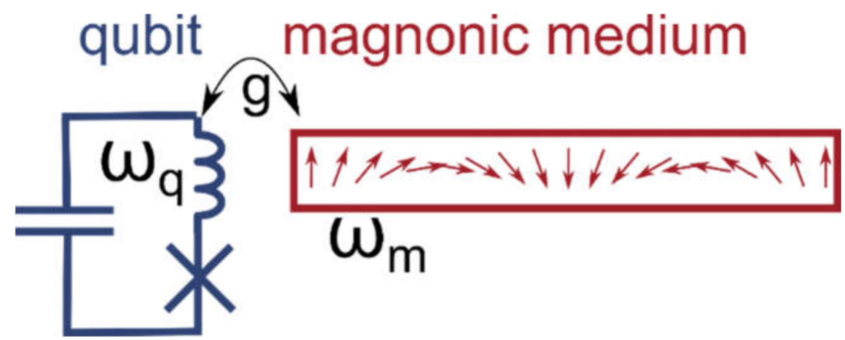
How to probe a single magnon?

- Quantum ground state (T=10 mK) $\hbar\omega_m \gg k_B T$
- Ultra-low power spectroscopy, coherent coupling
- **How to achieve?**

Extend magnon to artificial spin!



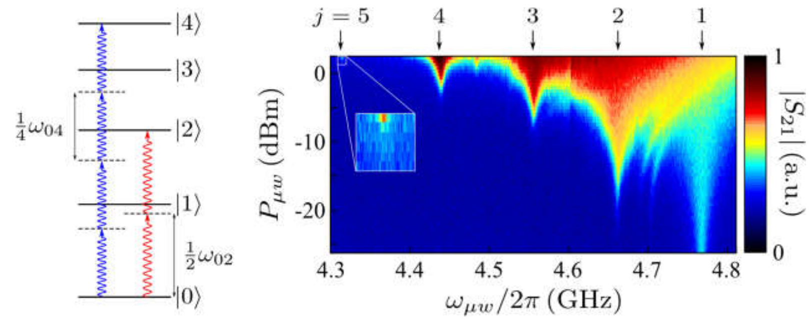
$$|\Psi\rangle = \alpha|\uparrow\rangle + \beta|\downarrow\rangle$$



Access magnon lifetime and coherence via coherent coupling

Use concentric transmon with σ_z coupling

Summary



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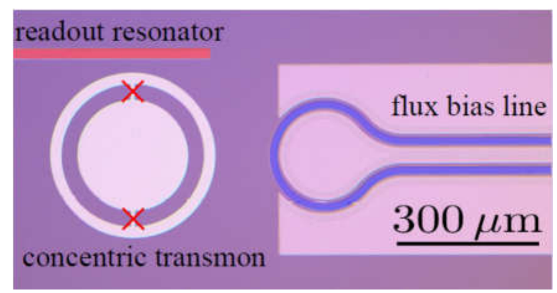

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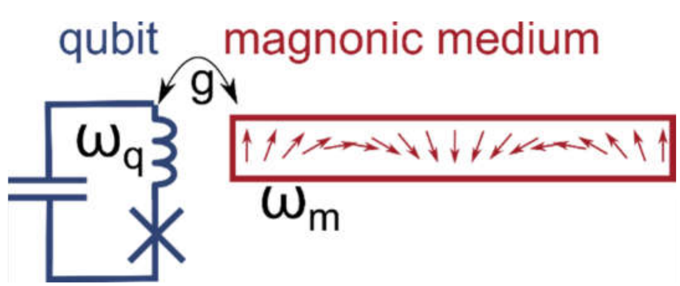

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Max Zanner

PhD
Jochen Braumüller
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Steffen Schlör
Ping Yang

Technician
Lucas Radtke

Scientists
Hannes Rotzinger
Sasha Lukashenko
Alexey Ustinov
Martin Weides

Thank you for your attention

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