Journal Club, 25-10-2019

# Long-Range Microwave Mediated Interactions Between Electron Spins

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(Dated: May 3, 2019)

Entangling gates for electron spins in semiconductor quantum dots are generally based on exchange, a short-ranged interaction that requires wavefunction overlap. Coherent spin-photon coupling raises the prospect of using photons as long-distance interconnects for spin qubits. Realizing a key milestone for spin-based quantum information processing, we demonstrate microwave-mediated spin-spin interactions between two electrons that are physically separated by more than 4 mm. Coherent spin-photon coupling is demonstrated for each individual spin using microwave transmission spectroscopy. An enhanced vacuum Rabi splitting is observed when both spins are tuned into resonance with the cavity, indicative of a coherent spin-spin interaction. Our results demonstrate that microwave-frequency photons can be used as a resource to generate long-range two-qubit gates between spatially separated spins.

arXiv:1905.00776

in continuation to …

# ARTICLE

doi:10.1038/nature25769

# A coherent spin–photon interface in silicon

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**Electron spins in silicon quantum dots are attractive systems for quantum computing owing to their long coherence times and the promise of rapid scaling of the number of dots in a system using semiconductor fabrication techniques. Although nearest-neighbour exchange coupling of two spins has been demonstrated, the interaction of spins via microwave-frequency photons could enable long-distance spin–spin coupling and connections between arbitrary pairs of qubits ('all-to-all' connectivity) in a spin-based quantum processor. Realizing coherent spin–photon coupling is challenging because of the small magnetic-dipole moment of a single spin, which limits magnetic-dipole coupling rates to less than 1 kilohertz. Here we demonstrate strong coupling between a single spin in silicon and a single microwave-frequency photon, with spin–photon coupling rates of more than 10 megahertz. The mechanism that enables the coherent spin–photon interactions is based on spin–charge hybridization in the presence of a magnetic-field gradient. In addition to spin–photon coupling, we demonstrate coherent control and dispersive readout of a single spin. These results open up a direct path to entangling single spins using microwave-frequency photons.**

[1]X. Mi et al., Nature **555**, 599 (2018), [2]N. Samkharadze et al., Science **359**, 1123 (2018), [3]A. J. Landig et al., Nature **560**, 179 (2018)

# Google's quantum supremacy !?

## Quantum supremacy using a programmable superconducting processor

Google AI Quantum and collaborators†

The tantalizing promise of quantum computers is that certain computational tasks might be executed exponentially faster on a quantum processor than on a classical processor. A fundamental challenge is to build a high-fidelity processor capable of running quantum algorithms in an exponentially large computational space. Here, we report using a processor with programmable superconducting qubits to create quantum states on 53 qubits, occupying a state space $2^{53} \sim 10^{16}$. Measurements from repeated experiments sample the corresponding probability distribution, which we verify using classical simulations. While our processor takes about 200 seconds to sample one instance of the quantum circuit 1 million times, a state-of-the-art supercomputer would require approximately 10,000 years to perform the equivalent task. This dramatic speedup relative to all known classical algorithms provides an experimental realization of quantum supremacy on a computational task and heralds the advent of a much-anticipated computing paradigm.

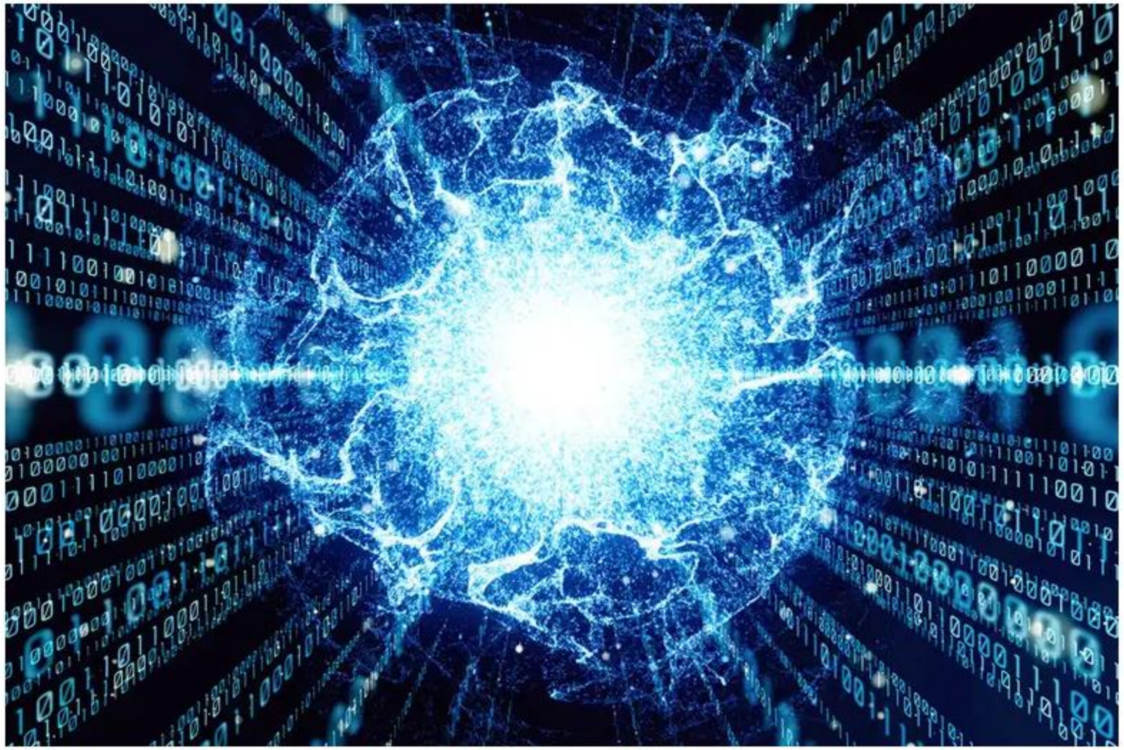
leaked preprint from Google

# Google's quantum supremacy !?

## Google claims it has finally reached quantum supremacy

PHYSICS 23 September 2019

By Chelsea Whyte



Google's demonstration reportedly involved checking a series of binary numbers were truly random
iStock / Getty Images Plus

"The paper describes how Google's quantum processor tackled a ***random sampling problem*** – that is, checking that a set of numbers has a truly random distribution. This is very difficult for a traditional computer when there are a lot of numbers involved."

"The paper calculates the task would have taken ***Summit***, the world's best supercomputer, ***10000 years*** – but ***Sycamore*** did it in ***3 minutes and 20 seconds***."

https://www.newscientist.com/article/2217347-google-claims-it-has-finally-reached-quantum-supremacy/

# Google's quantum supremacy !?

## IBM says Google may not have reached quantum supremacy after all

PHYSICS 22 October 2019

By Leah Crane

IBM is in a race with Google to develop quantum computers
CONNIE ZHOU/IBM

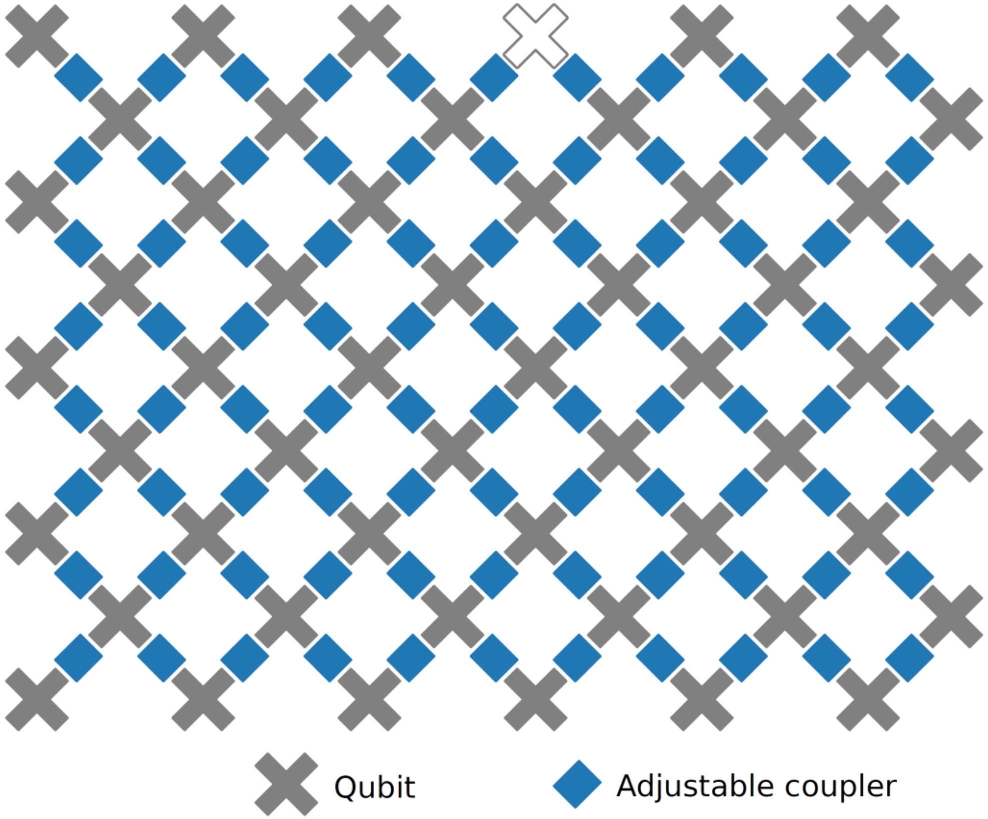
"In this case, the IBM researchers say that Google did not fully take advantage of the ***supercomputer's storage potential***. Taking that into account, they calculated that it actually would be reasonable for a classical supercomputer to do this calculation"[1]

"An ideal simulation of the same task can be performed on a ***classical system in 2.5 days and with far greater fidelity***"[2]

[1]https://www.newscientist.com/article/2220813-ibm-says-google-may-not-have-reached-quantum-supremacy-after-all/
[2]arXiv:1910.09534

# Google's "Sycamore" quantum processor

Device uses *53 transmon qubits* and *86 adjustable couplers*, high-fidelity single- and two-qubit operations, each qubit coupled to four nearest neighbors




Spin-based quantum computing: **single-qubit gates** J. Yoneda et al., Nat. Nanotechnol. **13**, 102 (2018); **exchange-based two-qubit gates** M. Veldhorst et al., Nature **526**, 410 (2015), D. M. Zajac et al., Science **359**, 439 (2018), T. F. Watson et al., Nature **555**, 633 (2018)

# Spin-photon coupling

**Challenge**: weak magnetic moment of an electron, $\mu_B \approx 58\mu eV/T$, combined with the small magnetic field generated by the vacuum fluctuations of the cavity
→ ***intrinsic spin-photon coupling rate in kHz range***

**Solution** (for electron spin): combination of *electric-dipole interaction* and *spin-charge hybridization* gives rise to large effective spin-photon coupling rate

single electron spin

Hybridize through ***micromagnet, artificial SOI***

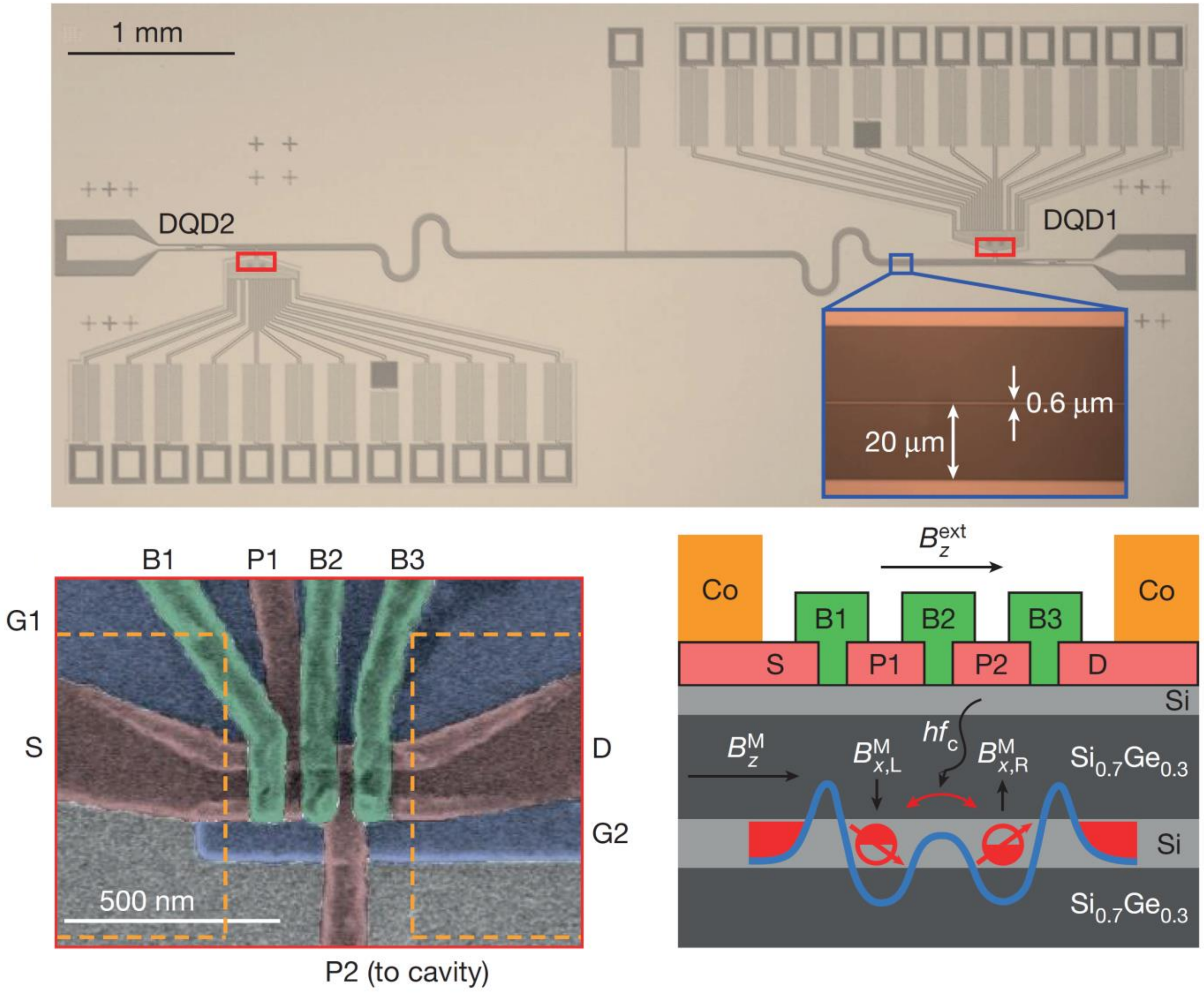
single electron charge state

Hybridize through ***electric-dipole interaction***

single photon in cavity

X. Mi et al., Nature **555**, 599 (2018)

# Strong spin-photon coupling




- **Microwave cavity**

  $\lambda/2$ Nb superconducting coplanar waveguide resonator

  $Z_r = 200 - 300\Omega \; (g_s \propto g_C \propto \sqrt{Z_r})$

  $f_c = 5.846$ GHz, $\frac{\kappa}{2\pi} =$1.3 MHz

- **Si/SiGe double QD**

  tuned to the single electron regime

  $|\uparrow\rangle$

  $|\downarrow\rangle$

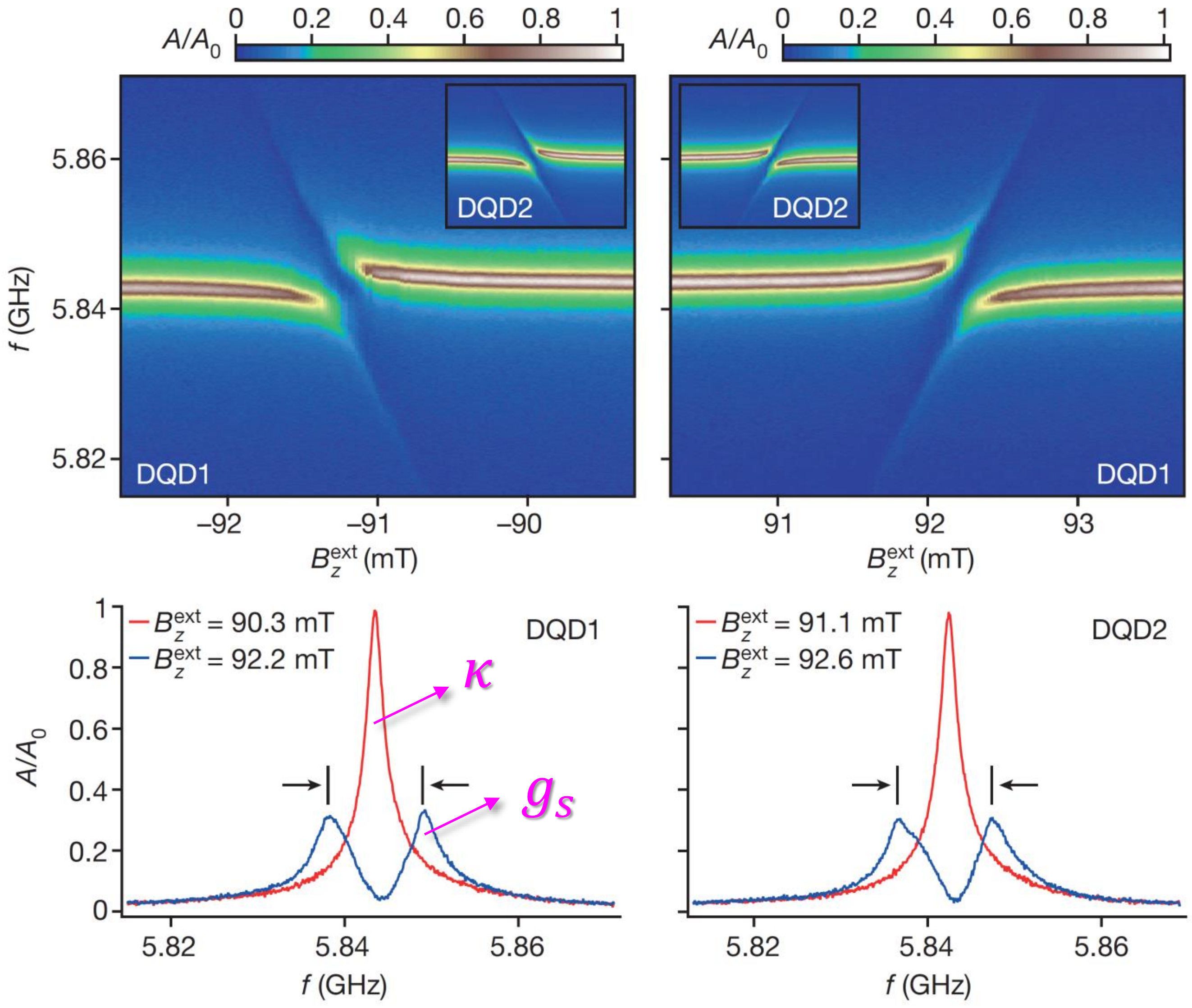
  $E_Z = g\mu_B B_{tot}$

- **Co micromagnet**

  $\vec{B}_{tot} = \vec{B}_{ext} + \vec{B}_M$

**Spin qubit**: [1]X. Mi et al., Nature **555**, 599 (2018), [2]N. Samkharadze et al., Science **359**, 1123 (2018), [3]A. J. Landig et al., Nature **560**, 179 (2018). **Superconducting qubit**: [4]A. Wallraff et al., Nature **431**, 162 (2004)

# Strong spin-photon coupling




Spin-photon coupling rate:

$$\frac{g_s}{2\pi} = 5.5 \text{ MHz}$$

Photon decay rate:

$$\frac{\kappa}{2\pi} = 1.8 \text{ MHz}$$

Spin decoherence rate:

$$\frac{\gamma_s}{2\pi} = 2.4 \text{ MHz}$$

Strong-coupling regime

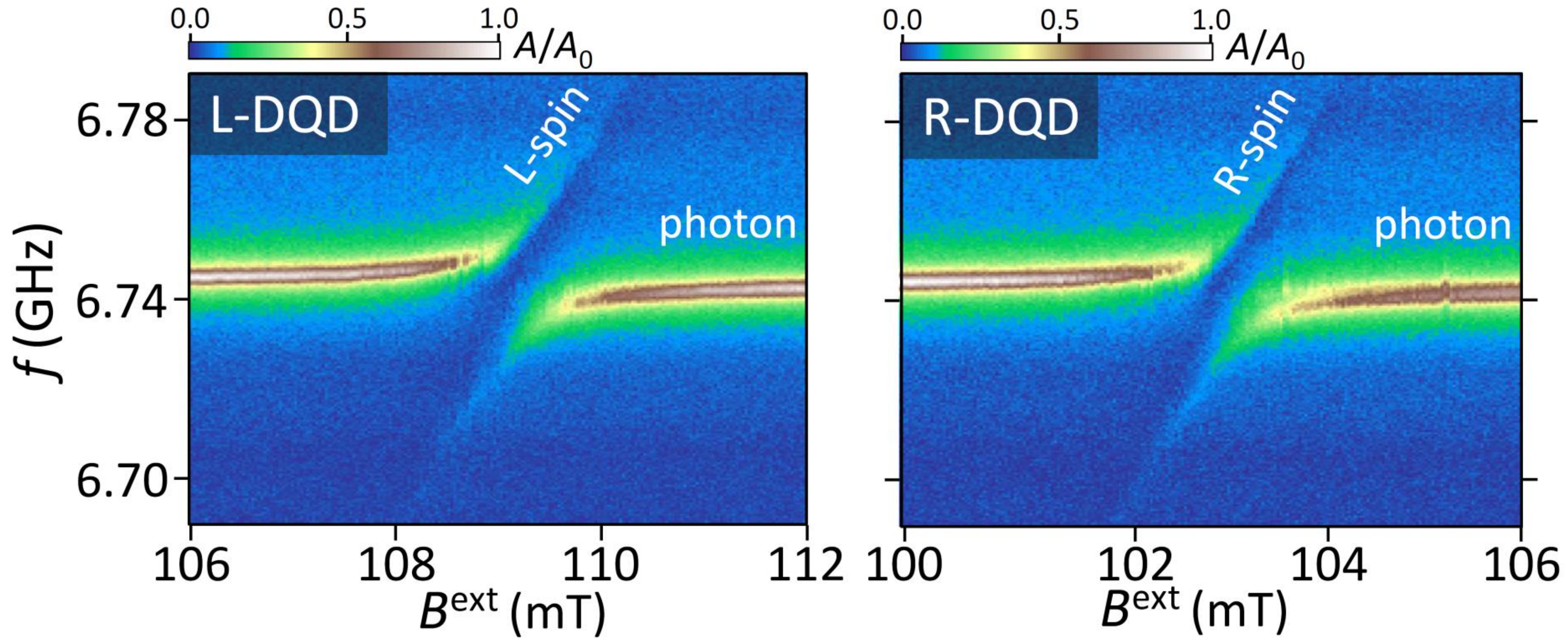
$$g_s > \gamma_s, \kappa$$

[1]X. Mi et al., Nature **555**, 599 (2018)

# Challenges towards spin-spin coupling

**Challenge**: Qubit Zeeman energies do not match because of *variations in micromagnet fabrication*, limited electrical control of (electron) spin qubits

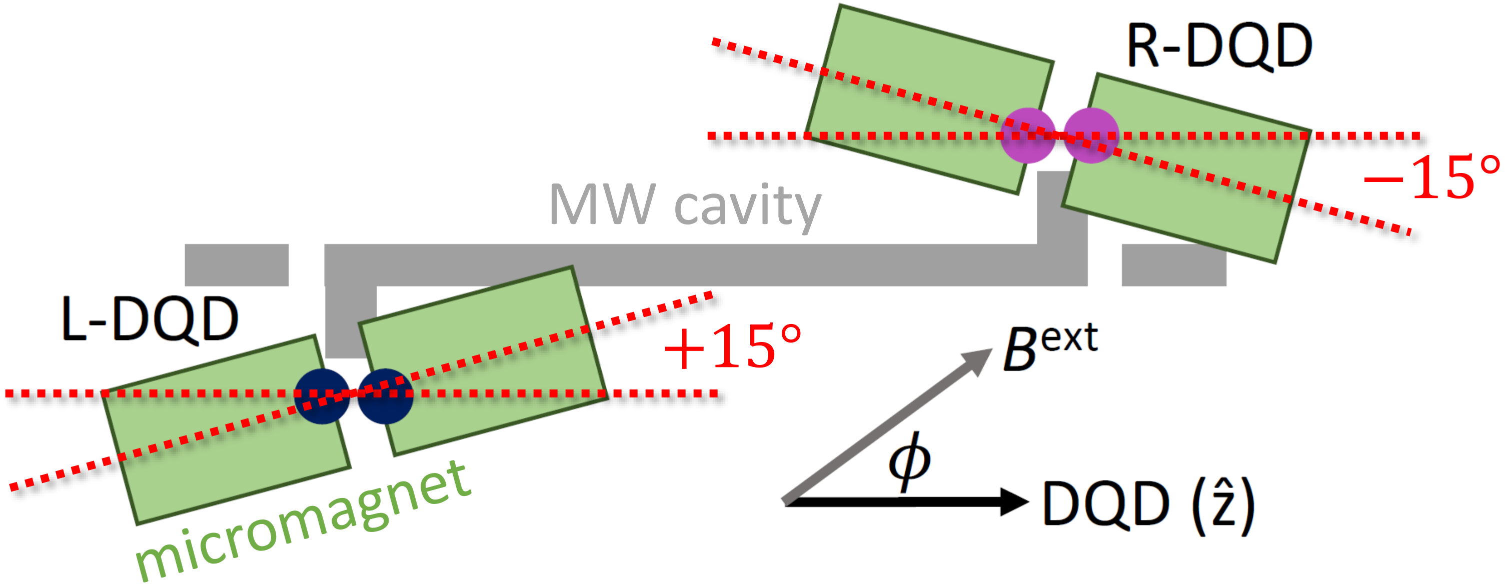
$$E_{Z,L} = g\mu_B B_{tot,L} \neq E_{Z,R} = g\mu_B B_{tot,R}$$




[1]F. Borjans et al., arXiv:1905.00776 (2019). **Superconducting qubit**: [2]J. Majer et al., Nature **449**, 443 (2007)

# Challenges towards spin-spin coupling

**Solution**: micromagnets intentionally tilted, adjusting the angle of $\vec{B}_{ext}$ provides a knob for simultaneous tuning of qubit frequencies.




[1]F. Borjans et al., arXiv:1905.00776 (2019). **Adapted from NV center community**: [2]T. Astner at al., Phys. Rev. Lett. **118**, 140502 (2017)

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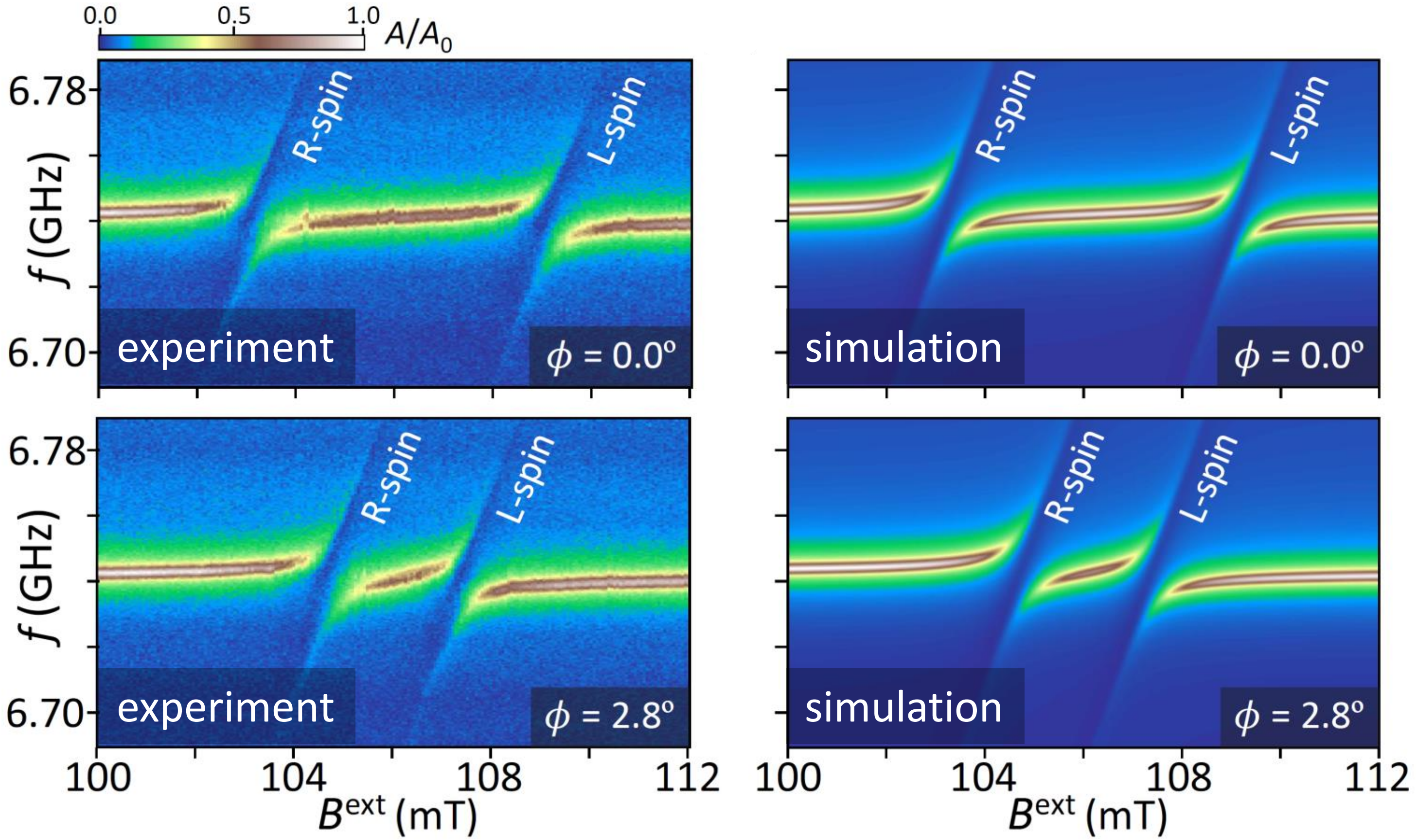
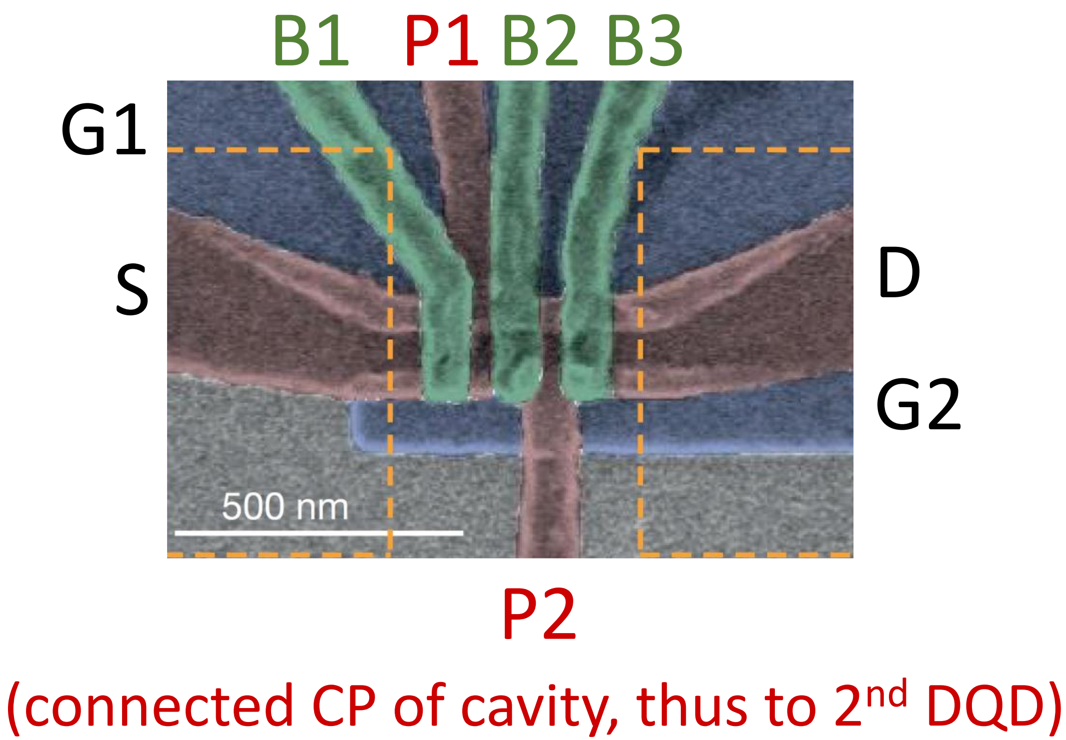



[1]F. Borjans et al., arXiv:1905.00776 (2019). **Adapted from NV center community**: [2]T. Astner at al., Phys. Rev. Lett. **118**, 140502 (2017)

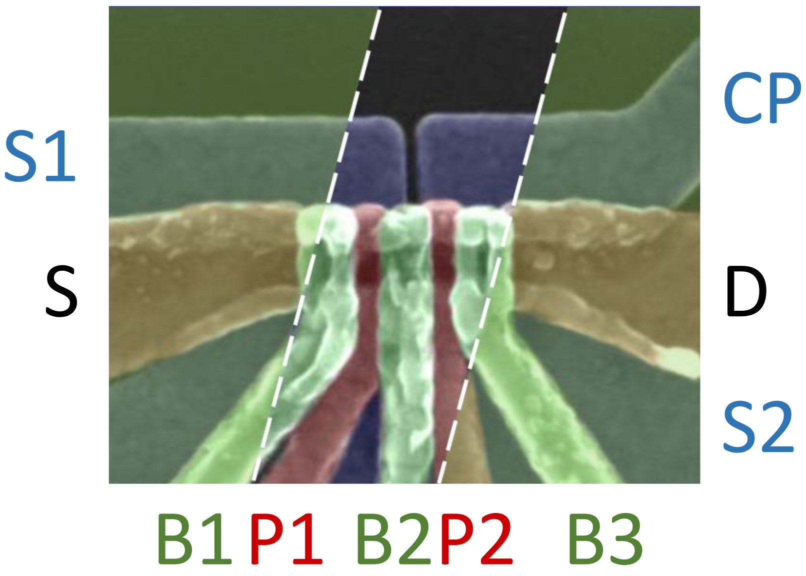
# Challenges towards spin-spin coupling

Independent tuning of DQDs to the one electron regime

Mi et al.[1]

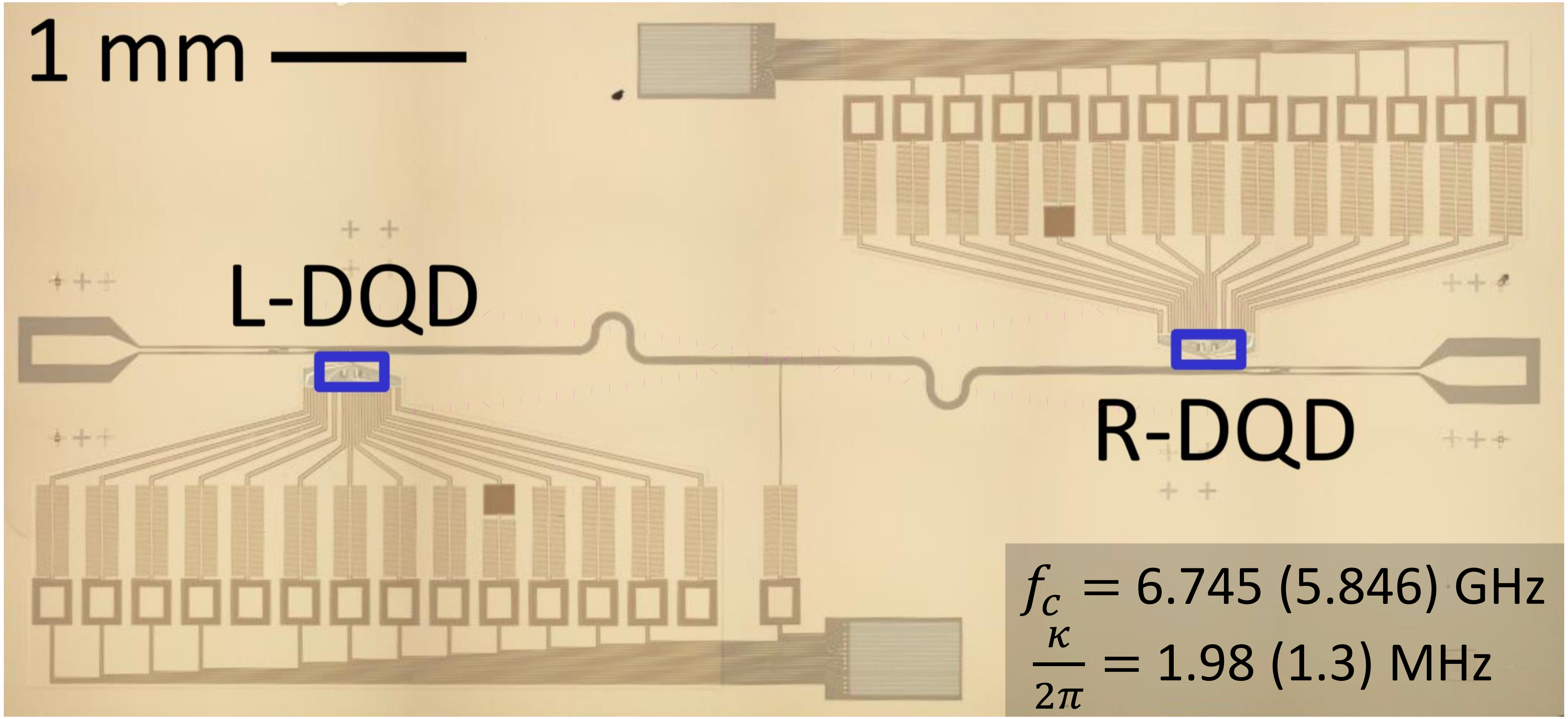



Borjans et al.[2]
(split-gate coupler)



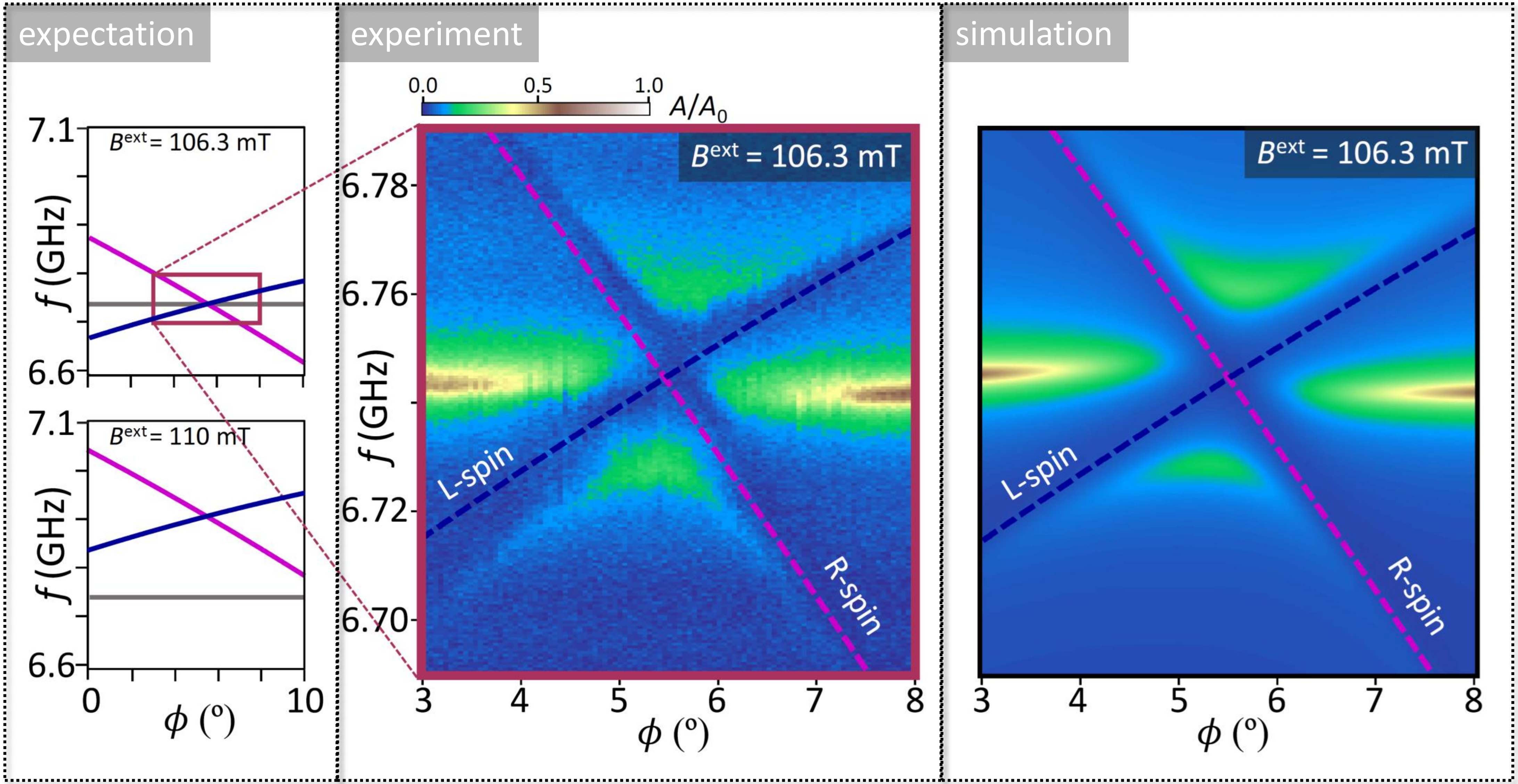

[1]X. Mi et al., Nature **555**, 599 (2018), [2]F. Borjans et al., arXiv:1905.00776 (2019)

# Spin-spin coupling device



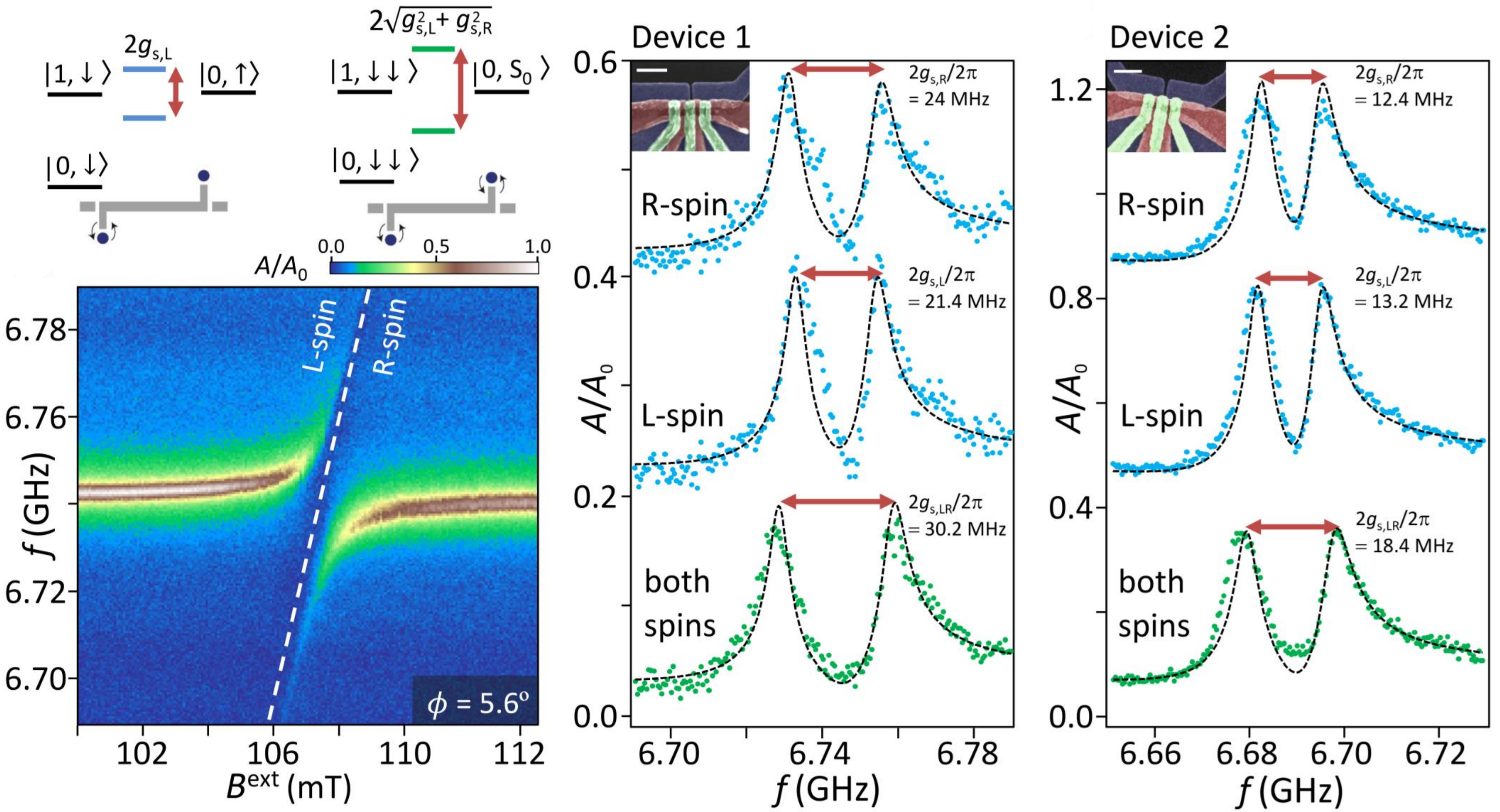

F. Borjans et al., arXiv:1905.00776 (2019)

# Tuning the spins in resonance with the cavity




F. Borjans et al., arXiv:1905.00776 (2019)

# Cavity-mediated spin-spin coupling

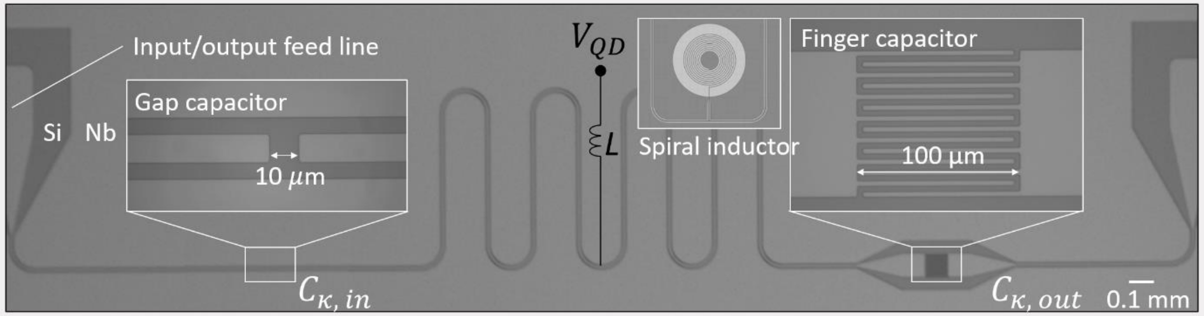



F. Borjans et al., arXiv:1905.00776 (2019)

# Outlook 2: hybrid Si superconducting devices

## Superconducting microwave resonators

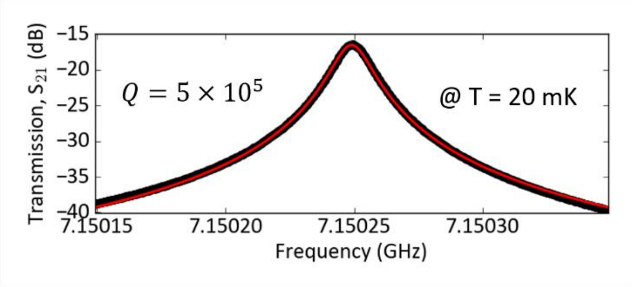
**λ/2 resonator in coplanar waveguide (CPW) geometry**



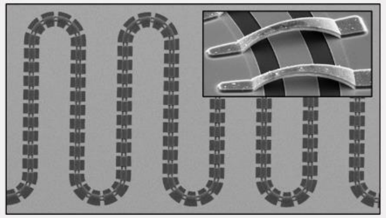

$f \sim$ 7GHz $\sim$ 29 $\mu$eV $\sim$ 330 mK, resonator length ~ 8.5 mm

CPW fabrication: optical lithography & dry etch (ICP)

Both 50 Ω (Nb, $Q<10^7$) and high impedance resonators (TiN, $Q<10^5$) for enhancement of the electric component of the vacuum fluctuations $\propto \sqrt{Z_r}$




Airbridges



Height 4 μm, length 25-100 μm, width 10-300μm

[1] M. Goeppl et al., J. Appl. Phys. **104**, 113904 (2008), [2] F. Chen et al., Appl. Phys. Lett. **98**, 132509 (2011), [3] T. Frey et al., PRL **108**, 046807 (2012), [4] N. Samkharadze et al., Phys. Rev. Appl. **5**, 044004 (2016)

- Fast charge sensing[1,2]

[1]A. Stockklauser *et al.*, Phys. Rev. X **7**, 011030 (2017)
[2]J. Stehlik et al., Phys. Rev. Appl. **4**, 014018 (2015)

- Long-range qubit coupling via microwave photons[3-5]

[3]X. Mi *et al.*, Nature **555**, 599 (2018)
[4]N. Samkharadze *et al.*, Science **359**, 1123 (2018)
[5]A. J. Landig *et al.*, Nature **560**, 179 (2018)