Microsecond-lived quantum states in a carbon-based circuit in cQED

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Hybrid Quantum Circuits

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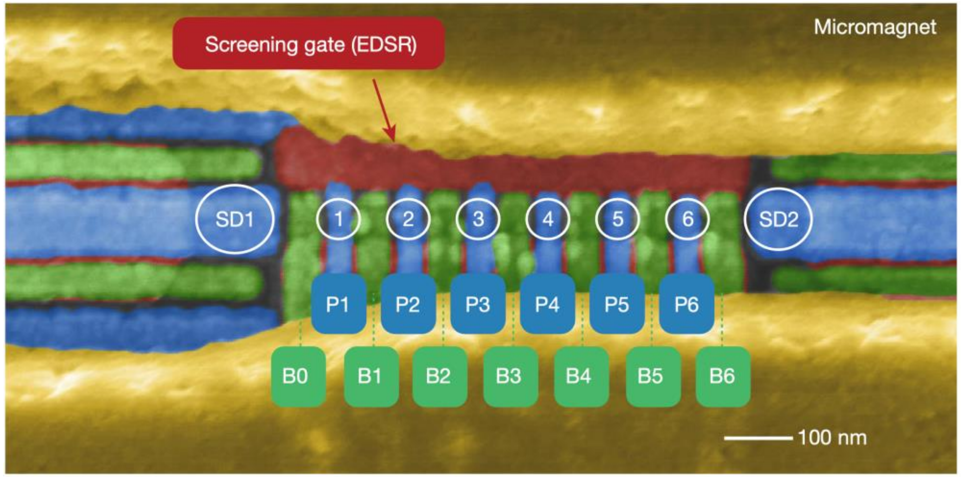
France 2030

Large-scale control of individual quantum systems: the quantum computing challenge

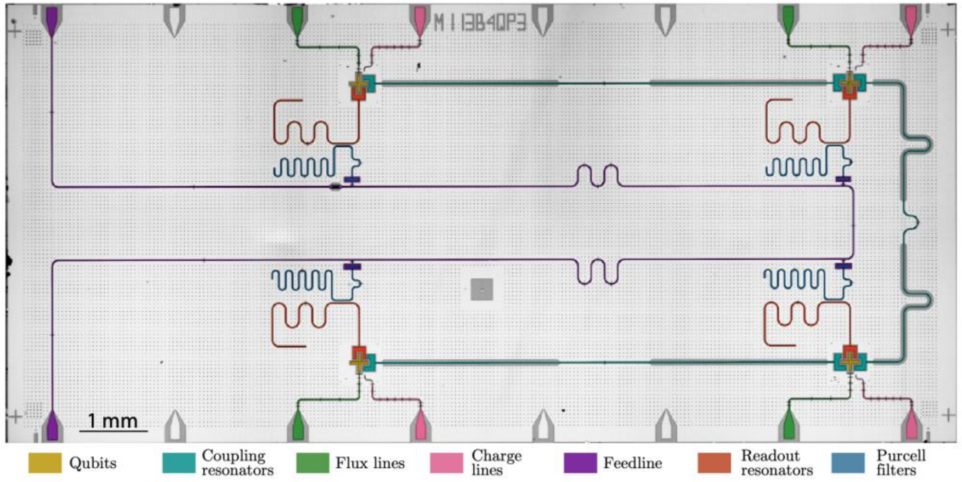
Semiconductor spin qubits in quantum dots



*Philips et al., Nature, **609** (2022)*

- ✓ Ultra-pure materials
- ✓ Long coherence times

Superconducting qubits in the cQED architecture



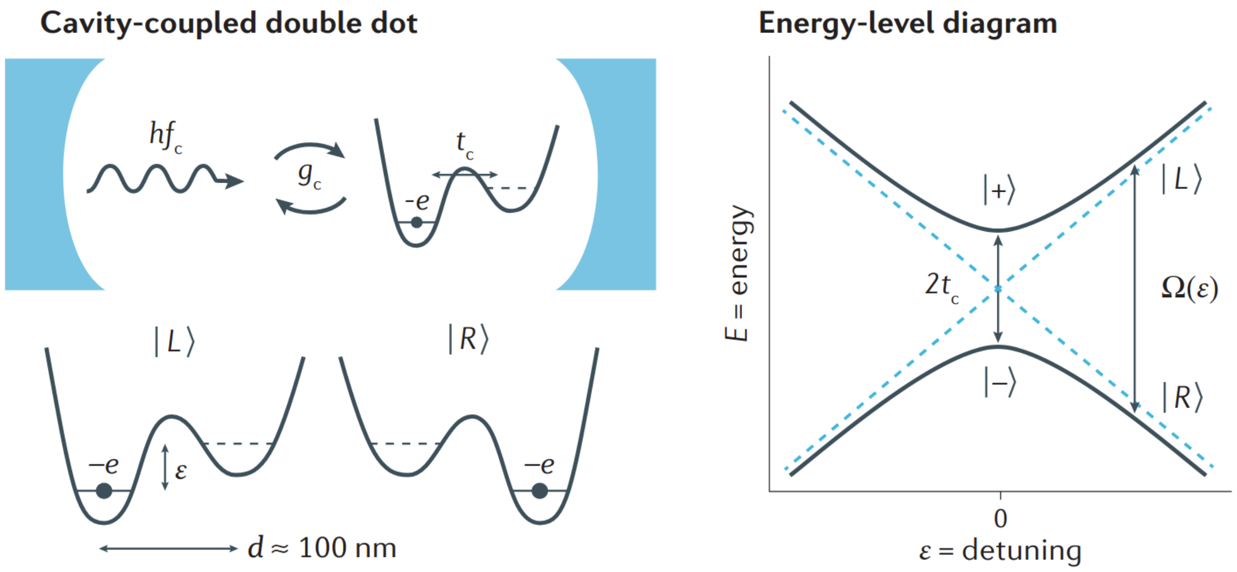
*Blais et al., RMP, **93** (2021)*

- ✓ Long-range coupling between qubits
- ✓ Interesting read-out schemes (dispersive, QND, multiplexed…)

Decrease of spin coherence in cQED

Coherence times of Si spin qubit in drop below 100 ns in cavities

J. Dijkema *et al.*, Nat. Phys. **21**, 168 (2025).



G. Burkard *et al.*, Nature Reviews Physics (2020).

Possible reasons :

- Spin-electric conversion via electric dipole
  → Charge noise channel

Dipole coupling + Non-collinear $\vec{B}$

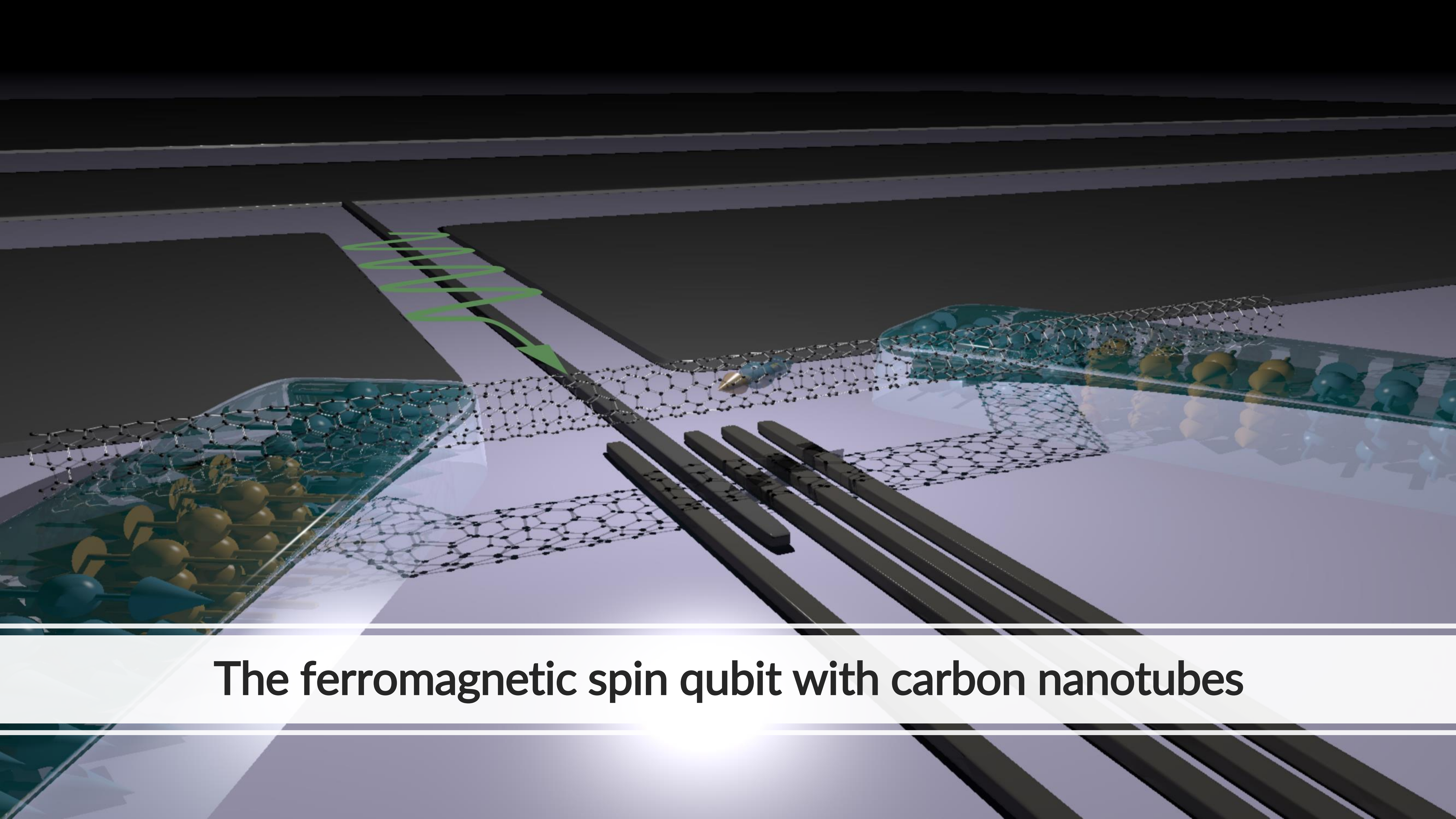
$|n,\sigma\rangle \leftrightarrow |\bar{n},\sigma\rangle$ $|n,\sigma\rangle \leftrightarrow |\bar{n},\bar{\sigma}\rangle$

Two-sites discrete SOI
$|n,\sigma\rangle \leftrightarrow |n,\bar{\sigma}\rangle$

- Purcell relaxation

Léo Noirot *et al.*, arXiv:2503.10788 (2025)

The ferromagnetic spin qubit with carbon nanotubes



Nuclear spins induced dephasing

$$T_2^* = \frac{\hbar}{2\boldsymbol{pA}}\sqrt{\frac{3}{I(I+1)}N}$$

p : part of nuclear spins
A : average hyperfine interaction
I : nuclear spin value
N : total number of nuclei

➡ **Use materials with low percentage of nuclear spins**

	GaAs	Si	^{28}Si	CNT	^{12}C CNT
p	1	0.047	8×10^{-4}	0.011	8×10^{-4}
N	$\sim 2 \times 10^6$	$\sim 10^5$		$\sim 5 \times 10^4$	
A	$44\ \mu\text{eV}$	$-2.52\ \mu\text{eV}$		$\mathbf{0.1 - 0.5\ \mu eV}$	
$T_2^*\ (\mu\text{s})$	~ 0.01	~ 2	~ 120	$\sim \mathbf{25}$	$\sim \mathbf{350}$

➡ **Hyperfine coupling matters significantly too**

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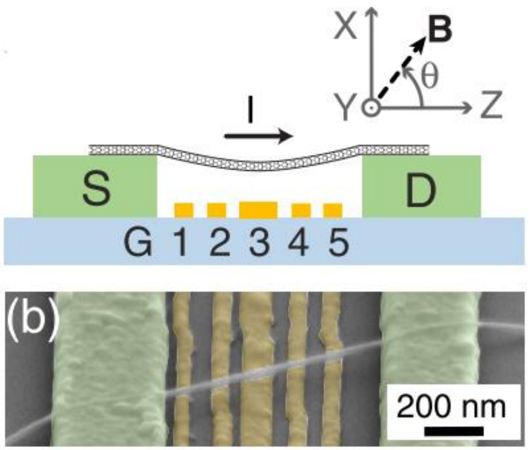
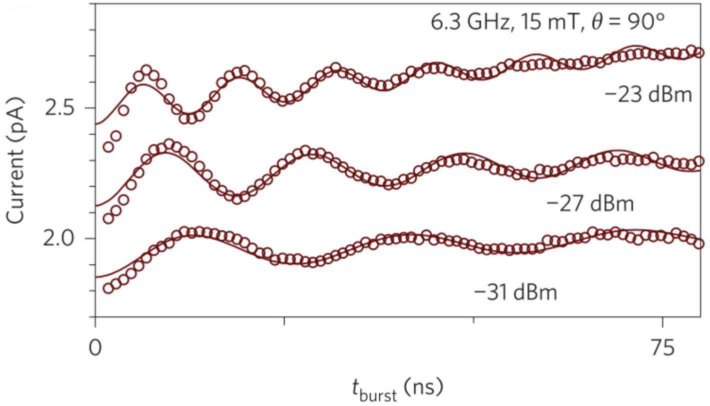
Valley-spin qubit in CNT



E.A. Laird *et al.*, Nat. Nanotechnol. **8**, 565 (2013).
T. Pei *et al.*, Phys. Rev. Lett. **118**, 177701 (2017).

$$T_2^* \sim 0.01\ \mu\text{s}$$



The ferromagnetic spin qubit

Carbon nanotube:

- Longest predicted T_2^* if grown with ^{12}C
- Suspended to avoid stray charges

✓ Long coherence times

Double quantum dot:

- Trap a single electron

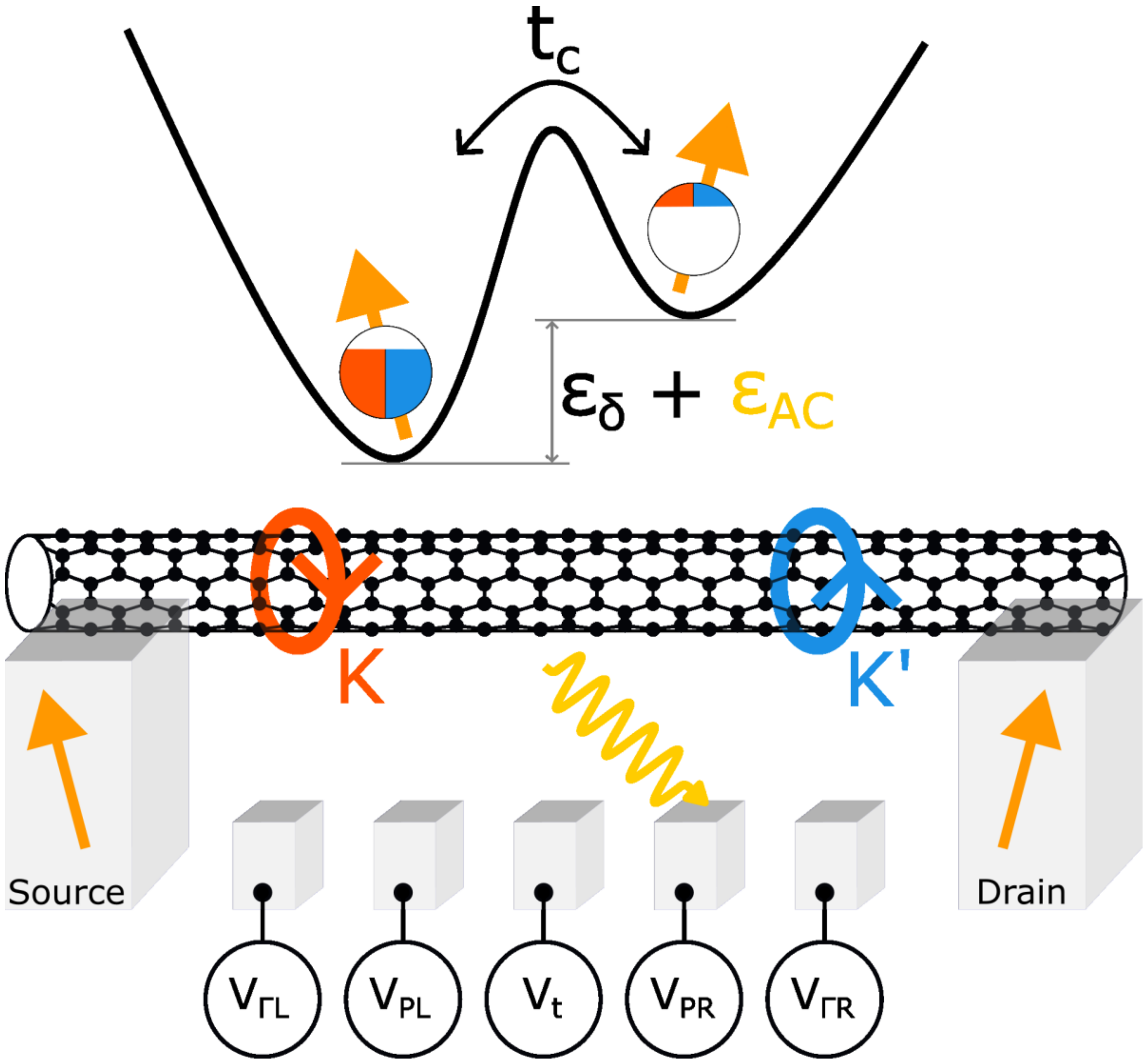
✓ Charge dipole

Non colinear ferromagnetic contacts:

- Lifts spin degeneracy

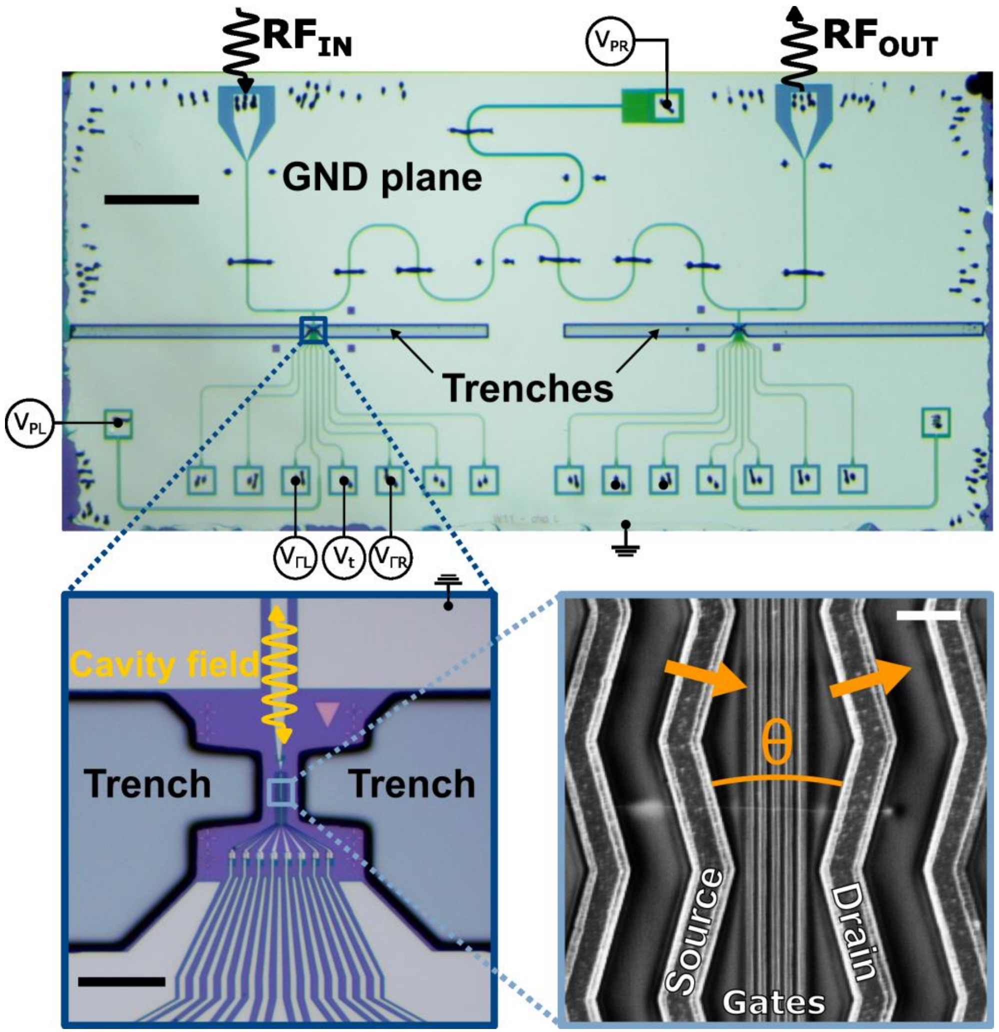
✓ Spin-charge hybridization

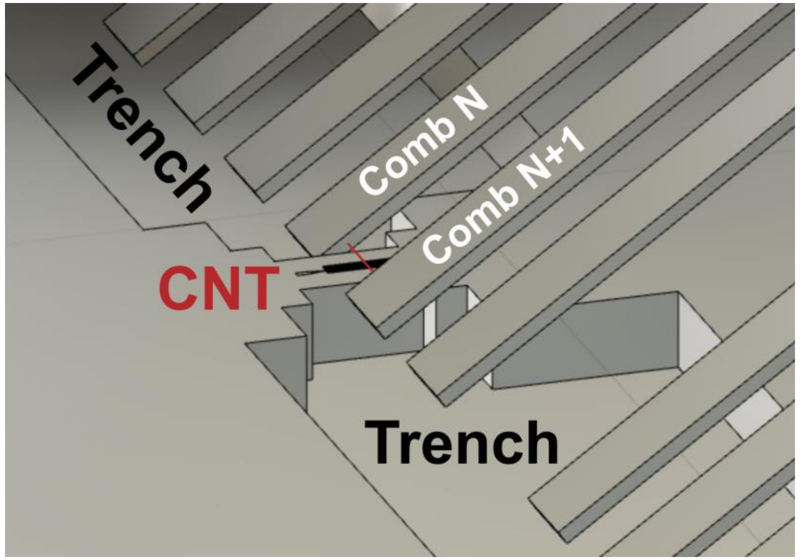
Spin-photon coupling



S. Sahoo et al., Nature Physics ***1****, 99 (2005)*
Cottet & Kontos, PRL (2010)

Overview of the device

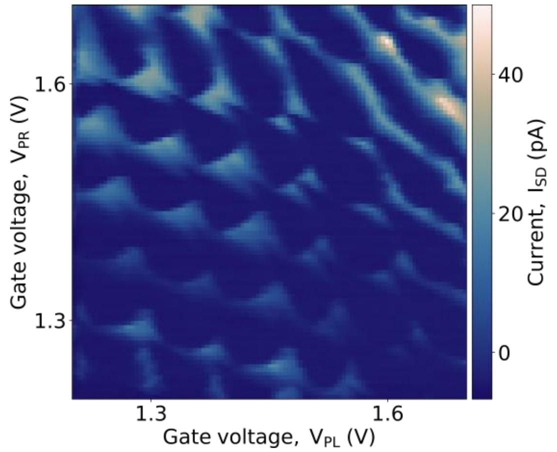




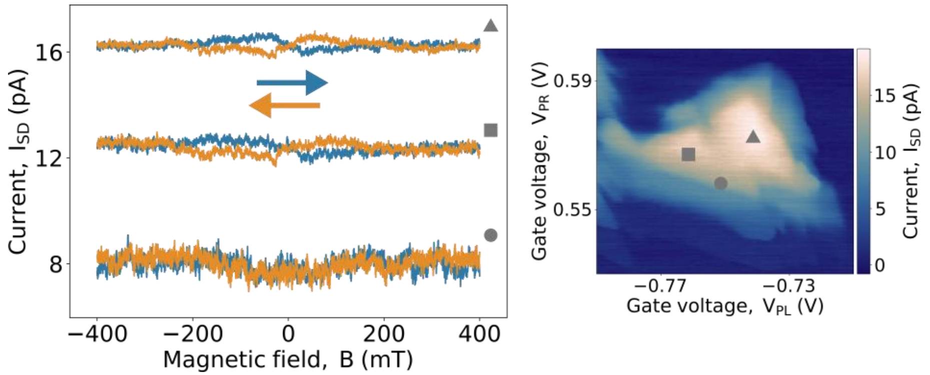
- ✓ cQED: Niobium microwave cavity
- ✓ Spin-photon coupling: non-colinear ferromagnetic contacts + double quantum dot
- ✓ Ultra-clean material: suspended carbon nanotube integrated under vacuum after the cleanroom process

Tuning the system

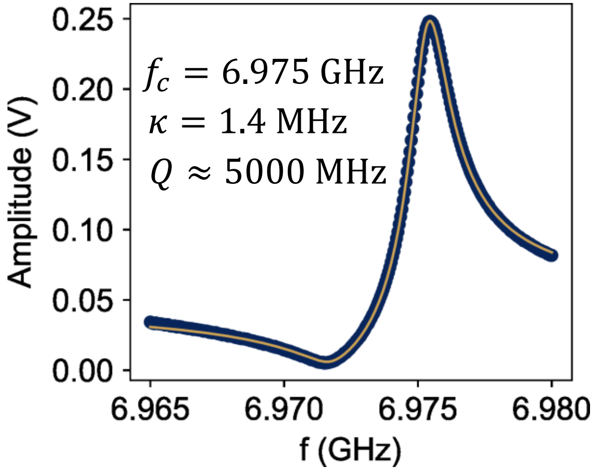
✓ Double quantum dot



✓ Ferromagnetic contacts



✓ Cavity resonance



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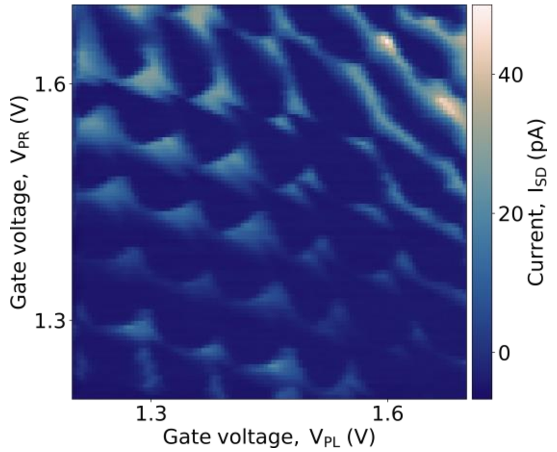

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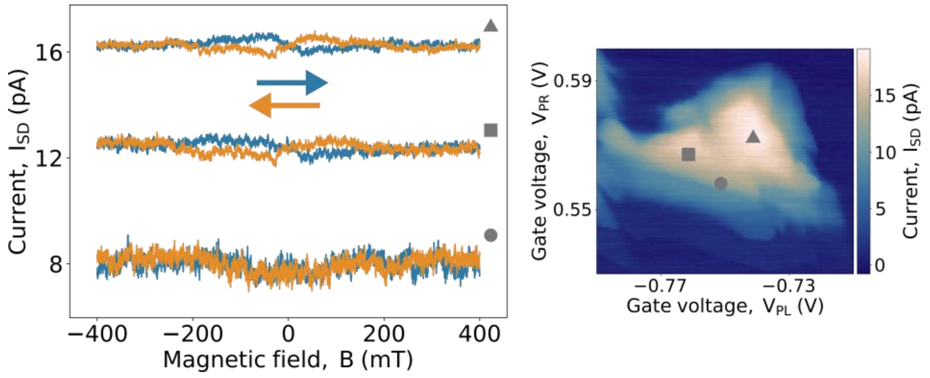

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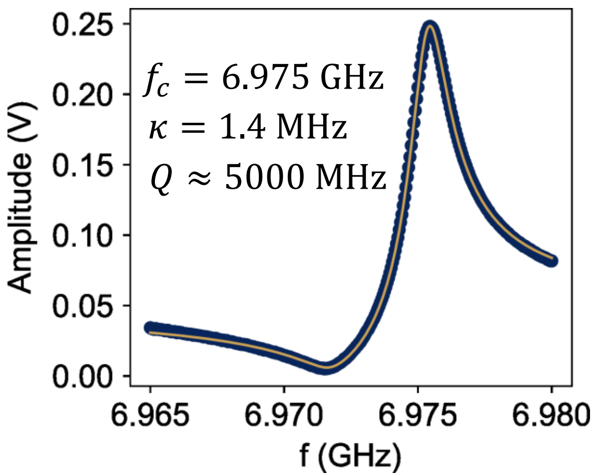
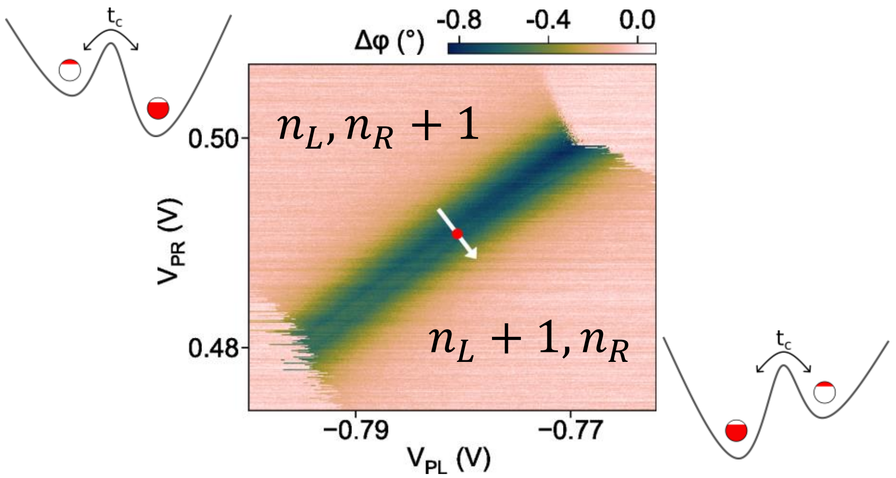
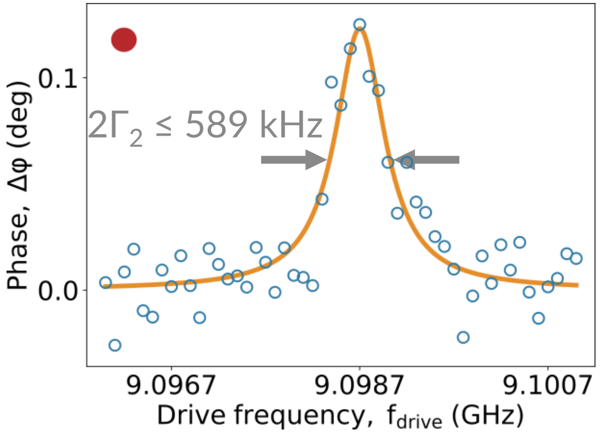


✓ Charge-photon coupling



✓ 2-tone spectroscopy

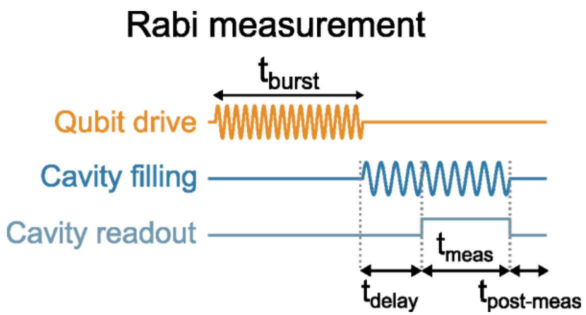


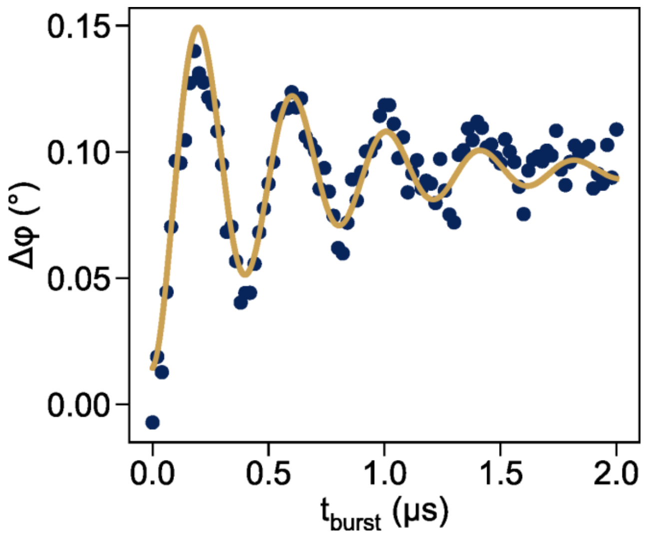
$$\Delta\varphi = \frac{Re(\chi)}{\kappa/2}\langle\hat{\sigma}_z\rangle$$

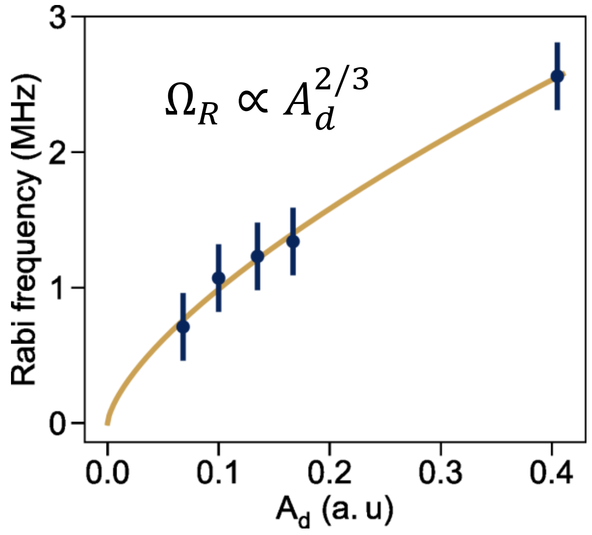
χ : charge susceptibility

κ : cavity decay rate

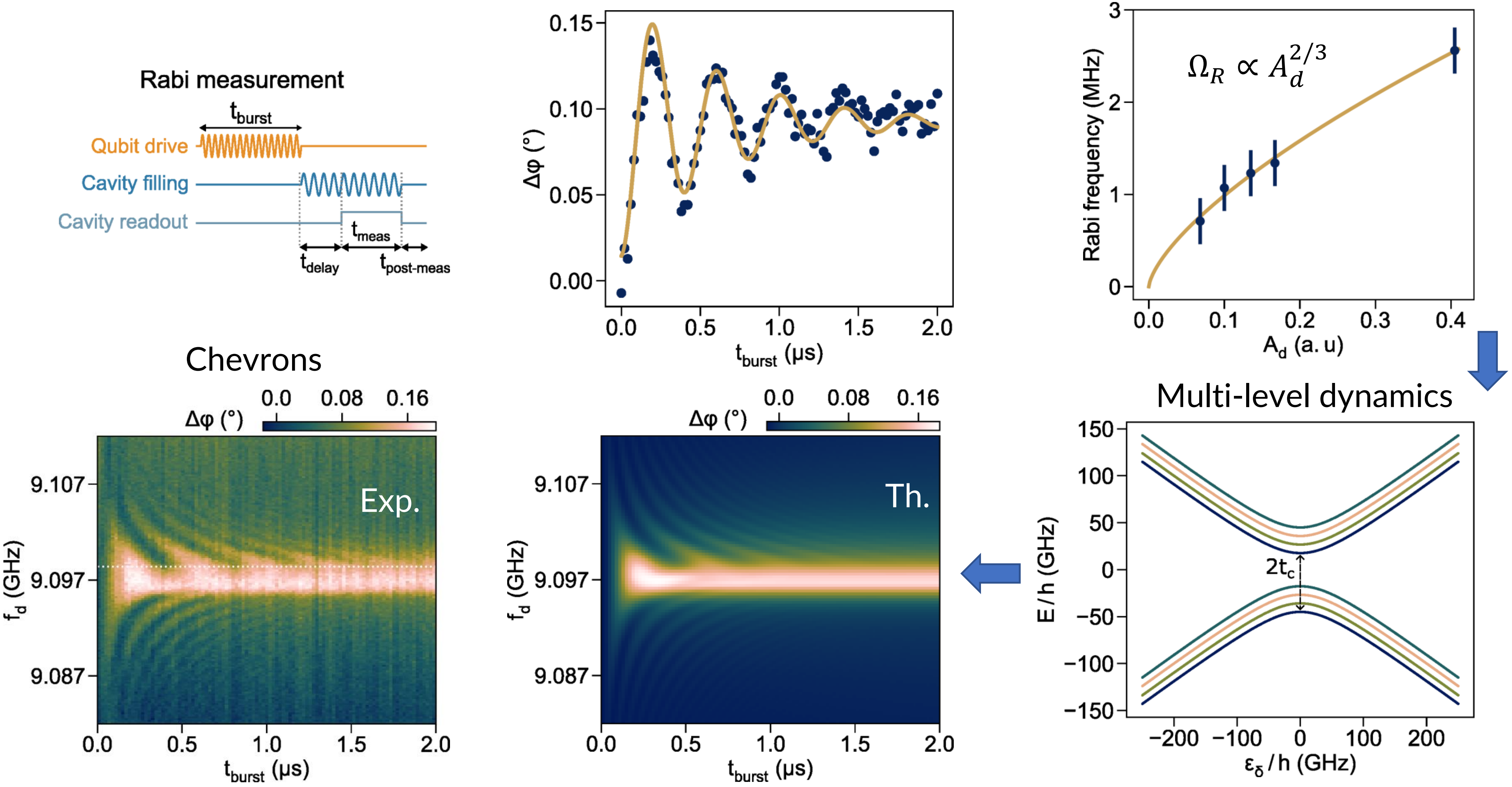
Rabi oscillations





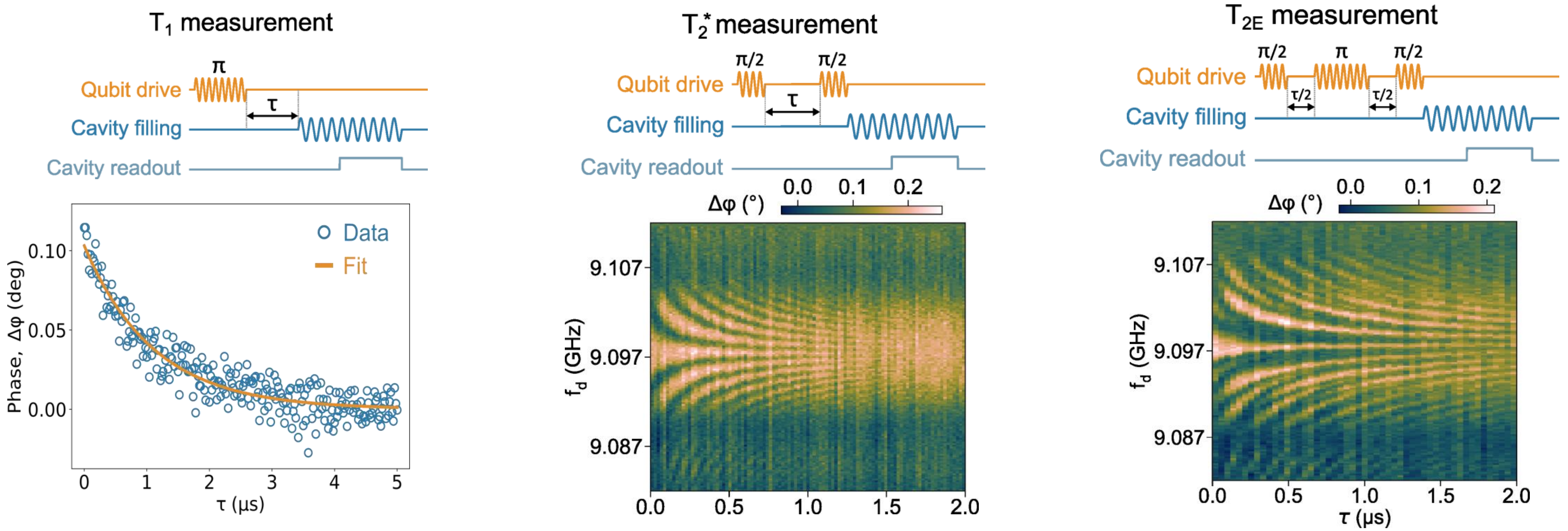


Rabi oscillations



A. Théry *et al.*, PRB **109**, 064505 (2024)

Microsecond-lived quantum state in carbon



T = 300 mK
B = 0 mT

Figures of merit:

$T_1 = 1.12\ \mu s$

$T_2^* = 1.27\ \mu s$

$\} \ T_\varphi = 2.9\ \mu s$

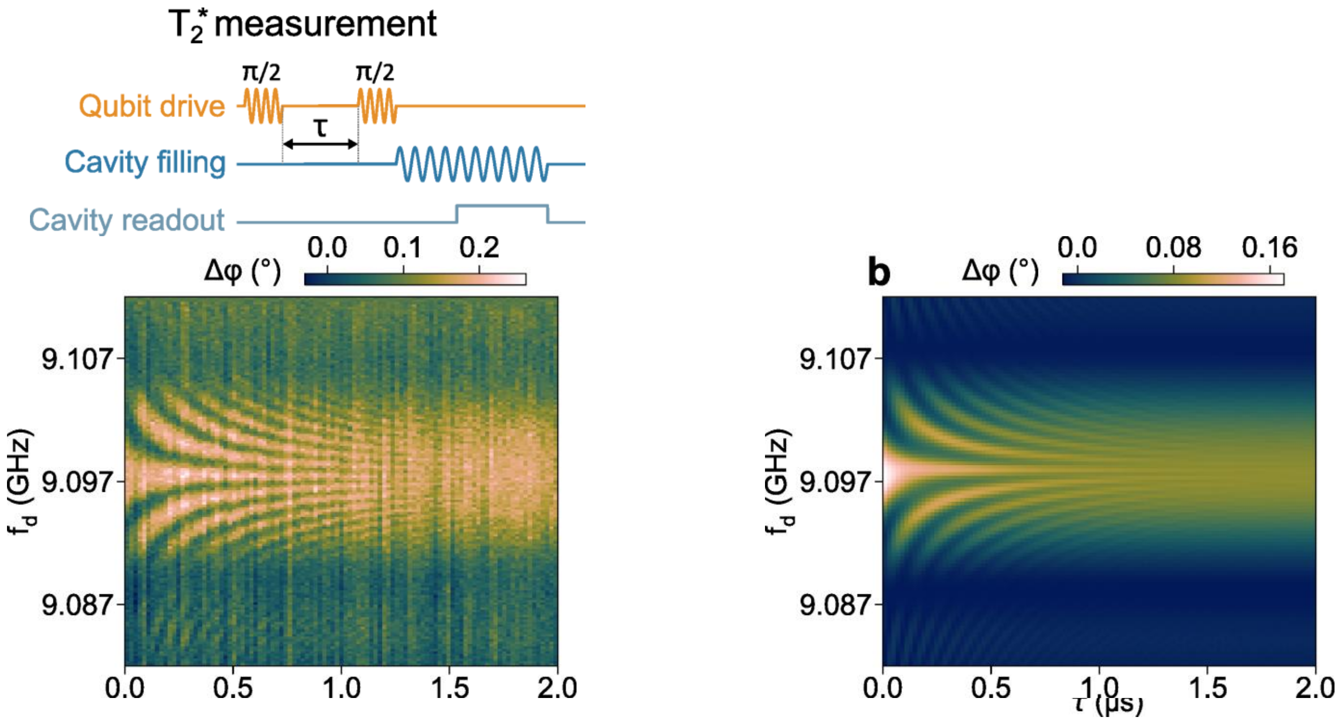
$T_{2E} = 2.02\ \mu s \lesssim 2\ T_1$

Putting coherence times in perspective:

- ✓ 2 orders of magnitude larger than previous carbon-based devices (E. A. Laird, et al., Nat. Nano. 8, 565 (2013))
- ✓ 1 order of magnitude larger than Si-based devices in cQED (J. Dijkema *et al.*, Nat. Phys. **21**, 168 (2025))

Microsecond-lived quantum state in carbon

Ramsey simulation with same parameters as for the Rabi



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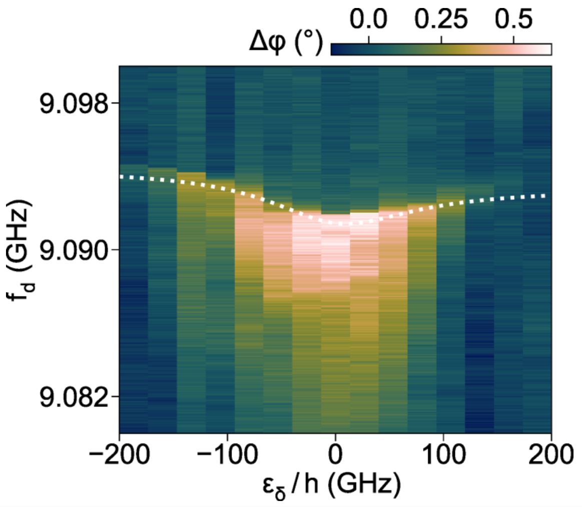
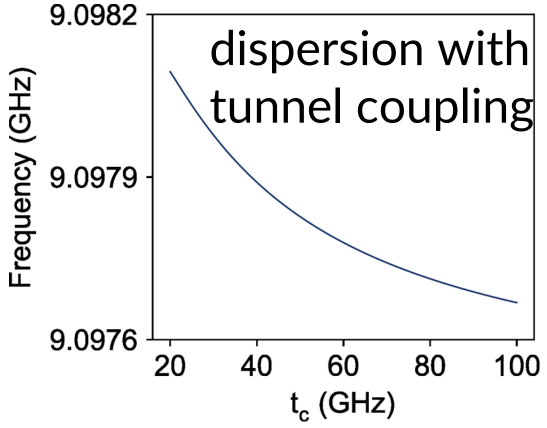
Decoherence investigation

Resilience to charge noise



Weak dispersion in detuning reproduced by the model



- Charge noise $\boldsymbol{\Gamma_{\varphi,c}} \sim \mathbf{40\ kHz}$ with $\sqrt{\langle\sigma_\epsilon\rangle^2} \sim 10\ \mu\mathrm{eV}$
- Nuclear spin noise from ^{13}C $\boldsymbol{\Gamma_{\varphi,hf}} \sim \mathbf{40\ kHz}$ with hyperfine coupling $A = 0.5\ \mu\mathrm{eV}$
- Purcell relaxation with cavity mode $\boldsymbol{\Gamma_{cav}} = \frac{\kappa g^2}{(\omega_c - \omega_q)^2} \sim \mathbf{2\ Hz}$
- Relaxation from phonons stretching modes do not account for both Rabi/Ramsey and T_1 measurements

  Mariani & von Oppen, PRB 80, 155411 (2009)
- **Cotunneling** is predicted to contribute equally to T_2^* and T_1 in the same way as Γ_{lead}/U. Compatible with $\mathrm{T}_2^* \approx \mathrm{T}_1$

  Hartmann & Wilhelm, physica status solidi (b) 233, 385–390 (2002)

Conclusion and perspectives

→Carbon nanotube based qubit in cQED architecture with **coherence times above 1 μs**

→Close to natural Si spin qubit without cavity

→Decoherence likely **limited by cotunneling**

B. Neukelmance, B. Hue *et al.*, arXiv:2410.19477 (2024)
Accepted at Nature Communications

→High kinetic inductance resonators to boost the coupling

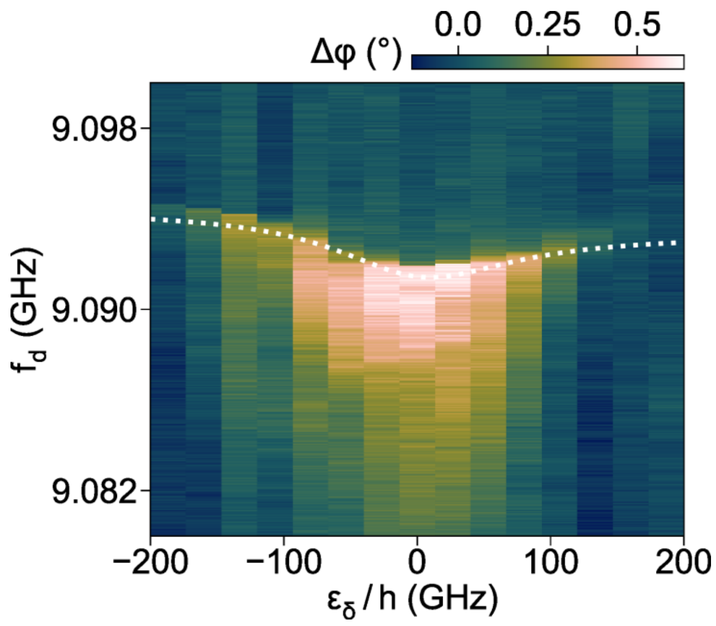
→Increased chips and CNT quality from C12 startup for better tunability of Γ_{leads} and DQD parameters

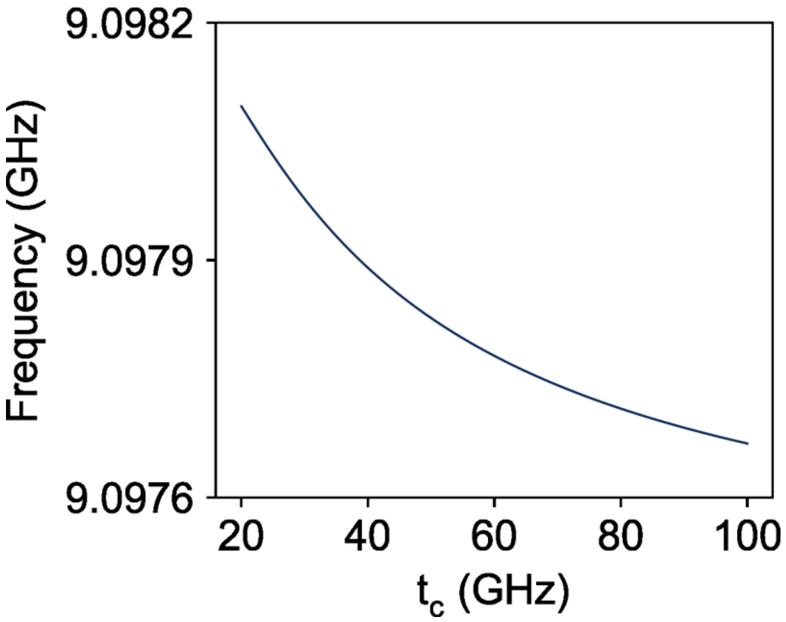
→Two spin qubits in a cavity

→Isotopically purified ^{12}C CNT

Resilience to dephasing

Resilience to charge noise





Observed weak dispersion in detuning

Confirmed by the model with same parameters

Predicted very weak dispersion with tunnel coupling

Resilience to magnetic noise