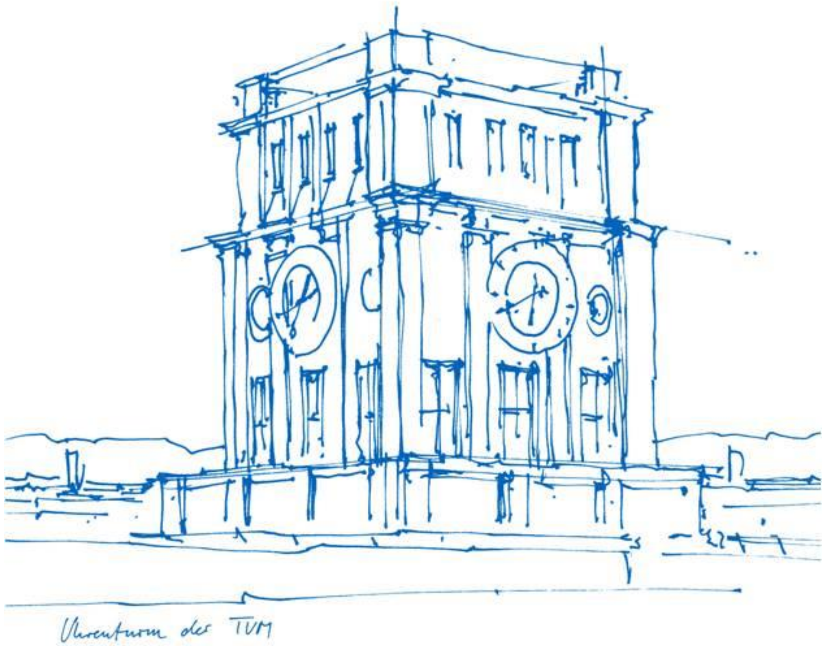
Seminar on Advances in Solid State Physics
SS 2021

Waveguide quantum electrodynamics with superconducting artificial giant atoms

Bharath Kannan, Max J. Ruckriegel, Daniel L. Campbell, Anton Frisk Kockum, Jochen Braumüller, David K. Kim, Morten Kjaergaard, Philip Krantz, Alexander Melville, Bethany M. Niedzielski, Antti Vepsäläinen, Roni Winik, Jonilyn L. Yoder, Franco Nori, Terry P. Orlando, Simon Gustavsson & William D. Oliver

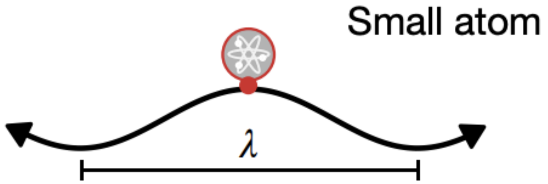
Published on Nature 583, 775–779 (2020)



Contents

1. Introduction

- Waveguide QED allows the investigation of exciting effects: resonance fluorescence, collective lamb shift,…
- so far: small atoms, dimensions much smaller than wavelength



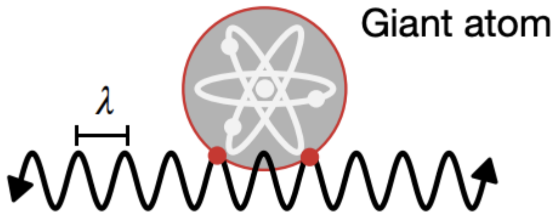
Kannan, B., Ruckriegel, M.J., Campbell, D.L. et al. Waveguide quantum electrodynamics with superconducting artificial giant atoms. Nature 583, 775–779 (2020)

- if you use artificial atoms like transmons one can explore new areas like coupling strength

1. Introduction

- Even more interesting: giant atoms

- Atoms so big that the dimensions are significantly larger than the wavelength → no more dipole approximation can be used



Kannan, B., Ruckriegel, M.J., Campbell, D.L. et al. Waveguide quantum electrodynamics with superconducting artificial giant atoms. Nature 583, 775–779 (2020)

- You can do that with superconducting systems

- Goal: nonlinear quantum circuit

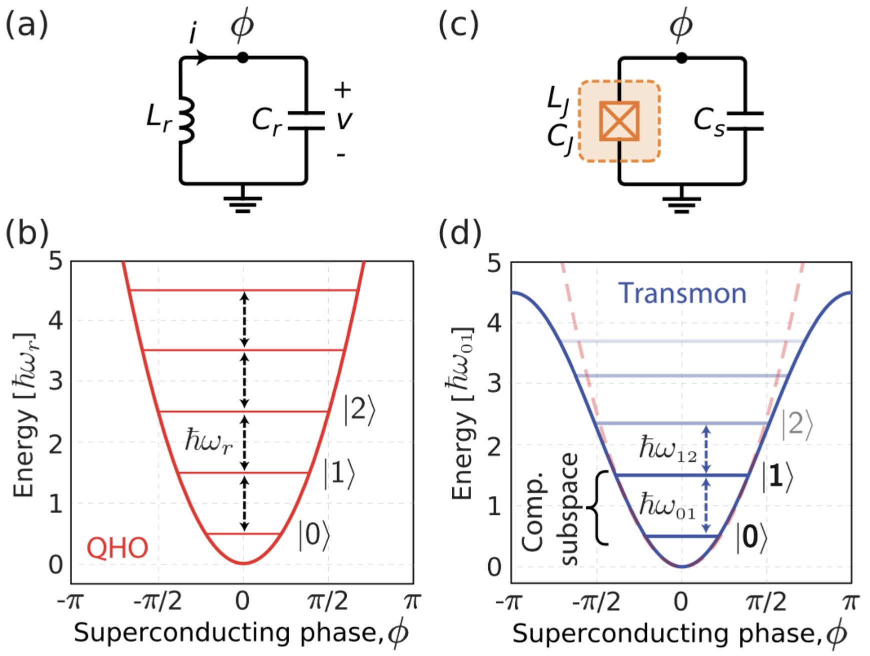
Quantum electrodynamics

- with superconductivity and Josephson junctions we can built superconducting quantum mechanical circuits

- Quantum states we are interested in have a frequency of ≈ 5 GHz
→ $T_{th} \approx 30\ \mathrm{mK}$
→ need T ≪ T_{th}
→ dilution refrigerators to cool circuit down

- Quantum circuits are constructed by combining linear inductors, capacitors and Josephson junctions

1. Introduction



P. Krantz, M. Kjaergaard, F. Yan, T. P. Orlando, S. Gustavsson, and W. D. Oliver, "A quantum engineer's guide to superconducting qubits", Applied Physics Reviews 6, 021318(2019)

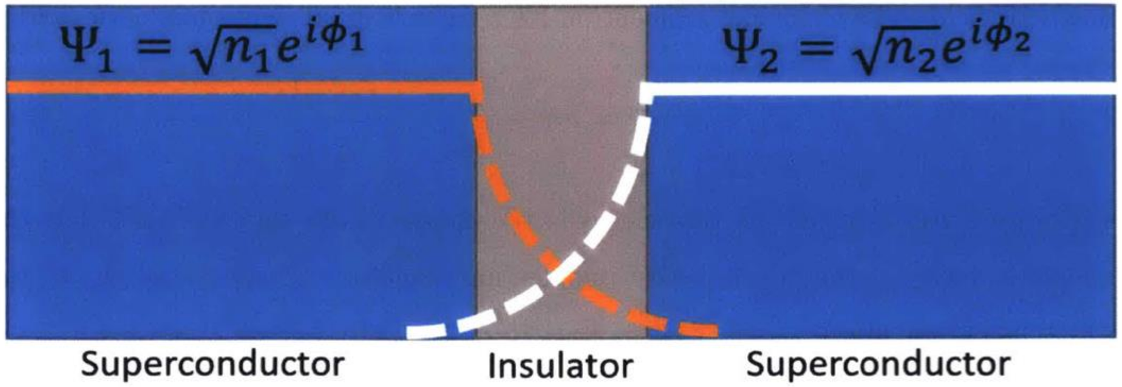
Start: linear LC resonant circuit

→ Energy oscillates between electrical energy in the capacitor C and the magnetic energy in the inductor L
→ Energy levels of potential are equidistantly spaced

But in an atom this isn‘t the case

→ use so called transmon qubits

Josephson junction



Josephson junctions: SC-I-SC tunnel junction

Josephson effect: tunneling of cooper pairs through insulating barrier

Coupling can be described by Hamiltonian (pair tunneling) $\hat{H} = \begin{bmatrix} 2eV_1 & -E_J \\ -E_J & 2eV_2 \end{bmatrix}$

→ Josephson equations via Schrödinger equations:

E_J barrier of constant energy due to insulator

$$\dot{\phi} = \frac{2eV}{\hbar} \qquad I = I_C \sin(\phi)$$

$$I_c = \frac{2eE_J}{\hbar}$$

DC-voltage across junction:

→ current through junction oscillate with frequency $\omega = 2eV/\hbar$

$$\phi = \phi_1 - \phi_2$$

→ $I = I_C \sin(\frac{2eV}{\hbar}t)$

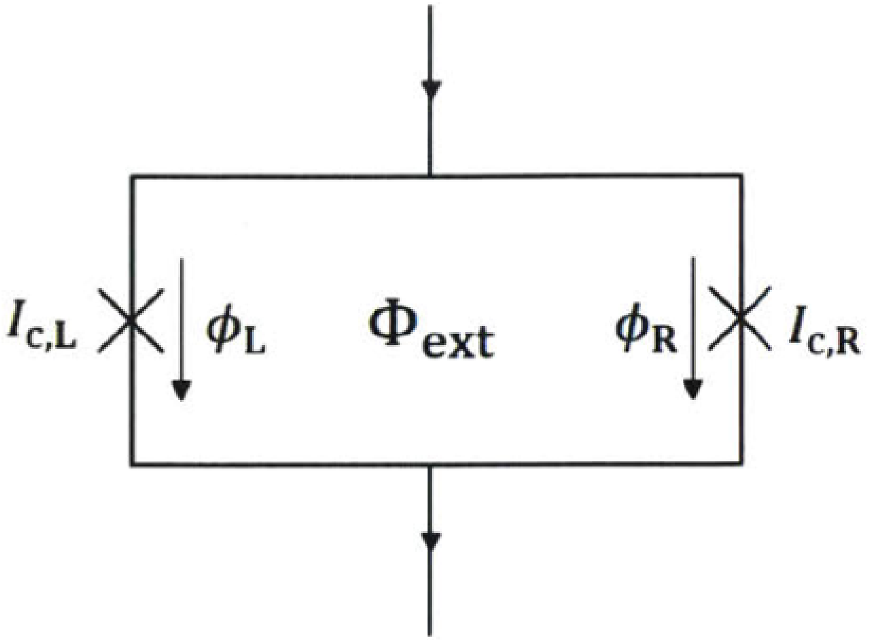
Waveguide Quantum Electrodynamics with Superconducting Qubits, Bharath Kannan, master thesis (2018)

SQUID's

DC-SQUID (superconducting quantum interference device):

- two Josephson junctions in parallel
- an external magnetic flux ϕ_{ext} threaded through the loop
  → can be used to tune the properties of the circuit
- current passing through (assuming SQUID is symmetric)

→ $I = 2I_C \left|\cos\left(\frac{\pi\phi_{ext}}{\phi_0}\right)\right| \sin(\phi_p)$ $\qquad \phi_p = \frac{\phi_R + \phi_L}{2}$



Waveguide Quantum Electrodynamics with Superconducting Qubits, Bharath Kannan, master thesis (2018)

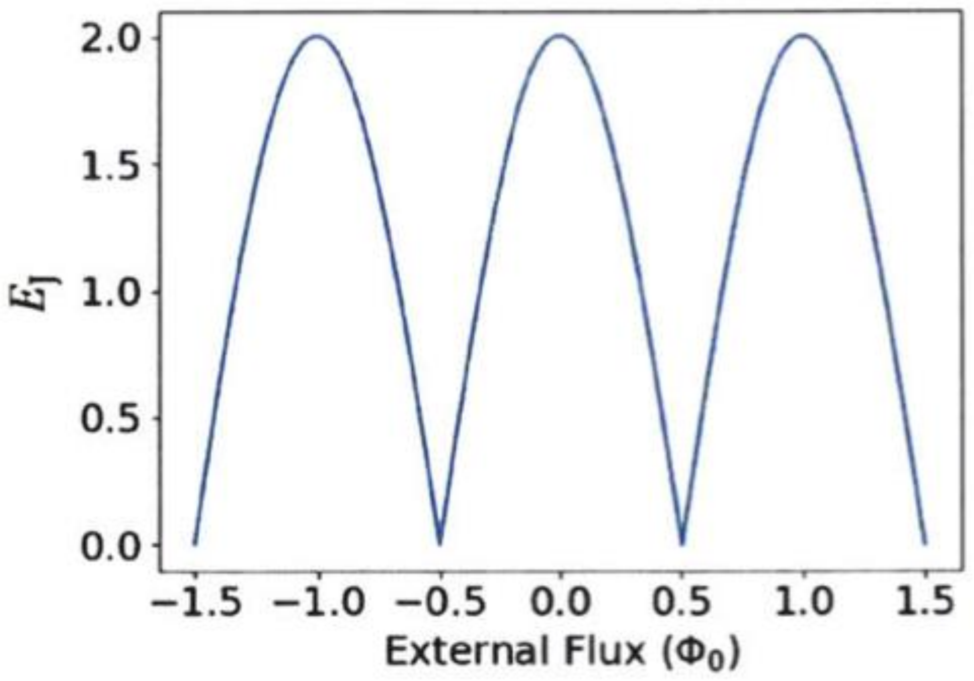
SQUID's

- the SQUID can be treated as tunable single junction

Josephson Energy E_J of SQUID:

$$E_J(\phi_{ext}) = 2E_J \left|\cos\left(\frac{\pi\phi_{ext}}{\phi_0}\right)\right|$$

→ this tunability enables the construction of artificial atoms tunable in frequency



Waveguide Quantum Electrodynamics with Superconducting Qubits, Bharath Kannan, master thesis (2018)

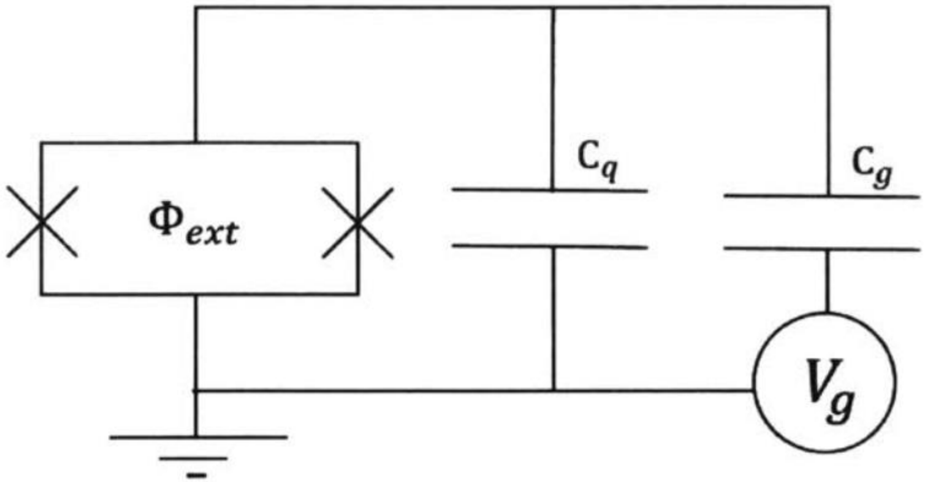
Transmon qubit

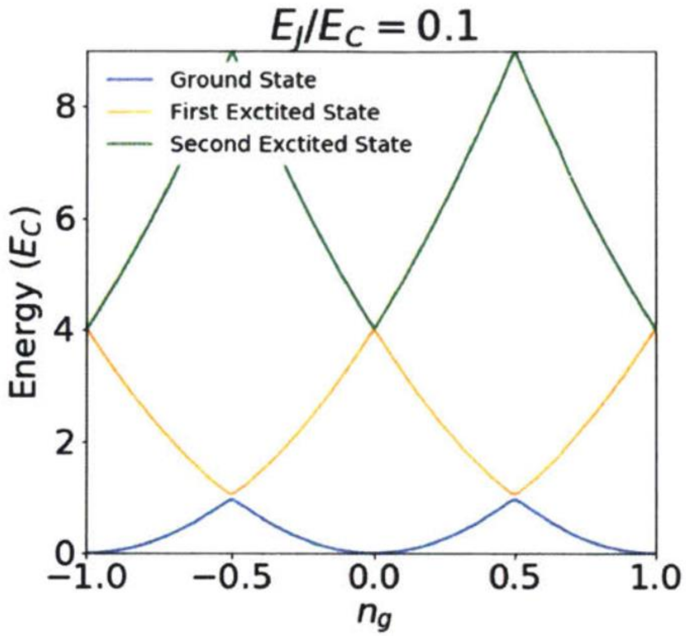
- Transmon qubit is the name for a charge qubit (also known as Cooper pair box) driven in a certain regime
- consists of a squid parallel to two capacitors (or one big capacitor)

$$E_C = \frac{e^2}{2(C_q + C_g)}$$

$$\hat{\mathcal{H}}_{\mathrm{CPB}} = 4E_{\mathrm{C}} \sum_n (n - n_{\mathrm{g}})^2 \left|n\right\rangle \left\langle n\right| - \frac{E_{\mathrm{J}}(\Phi_{\mathrm{ext}})}{2} \sum_n \left|n\right\rangle \left\langle n+1\right| + \left|n+1\right\rangle \left\langle n\right|$$

$$n_g = \frac{-C_g V_g}{2e}$$





Waveguide Quantum Electrodynamics with Superconducting
Bharath Kannan, master thesis (2018)

Transmon Qubit

Transmon Regime:

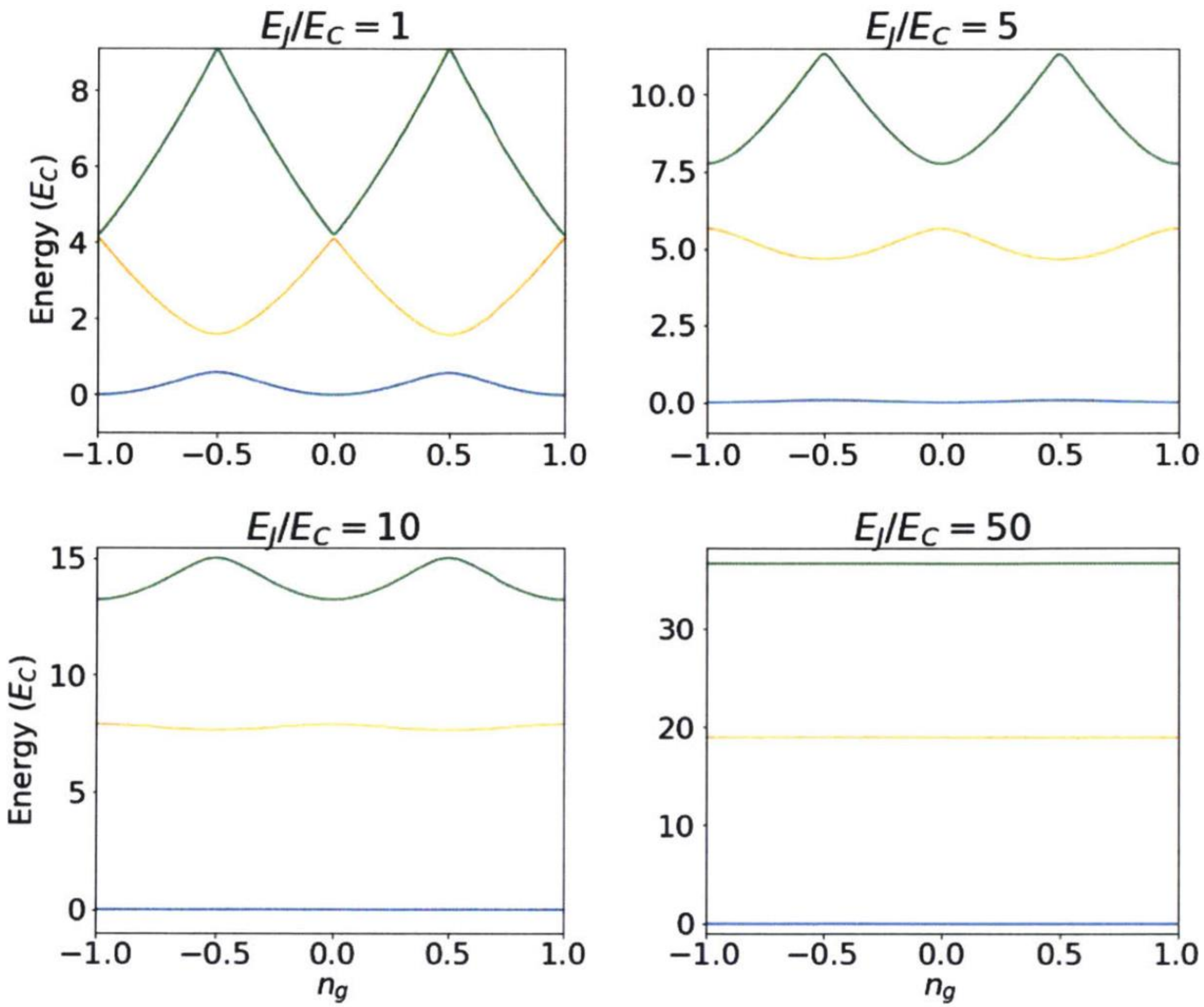
- Operating the qubit in a regime with $E_C \ll E_J$

→ flattening of the bands
→ bands represent eigenenergies

Applied external flux can now be used to tune the qubit frequency

$$E_{01} = \sqrt{8E_C E_J} - E_C$$

$$E_{12} = \sqrt{8E_C E_J} - 2E_C$$



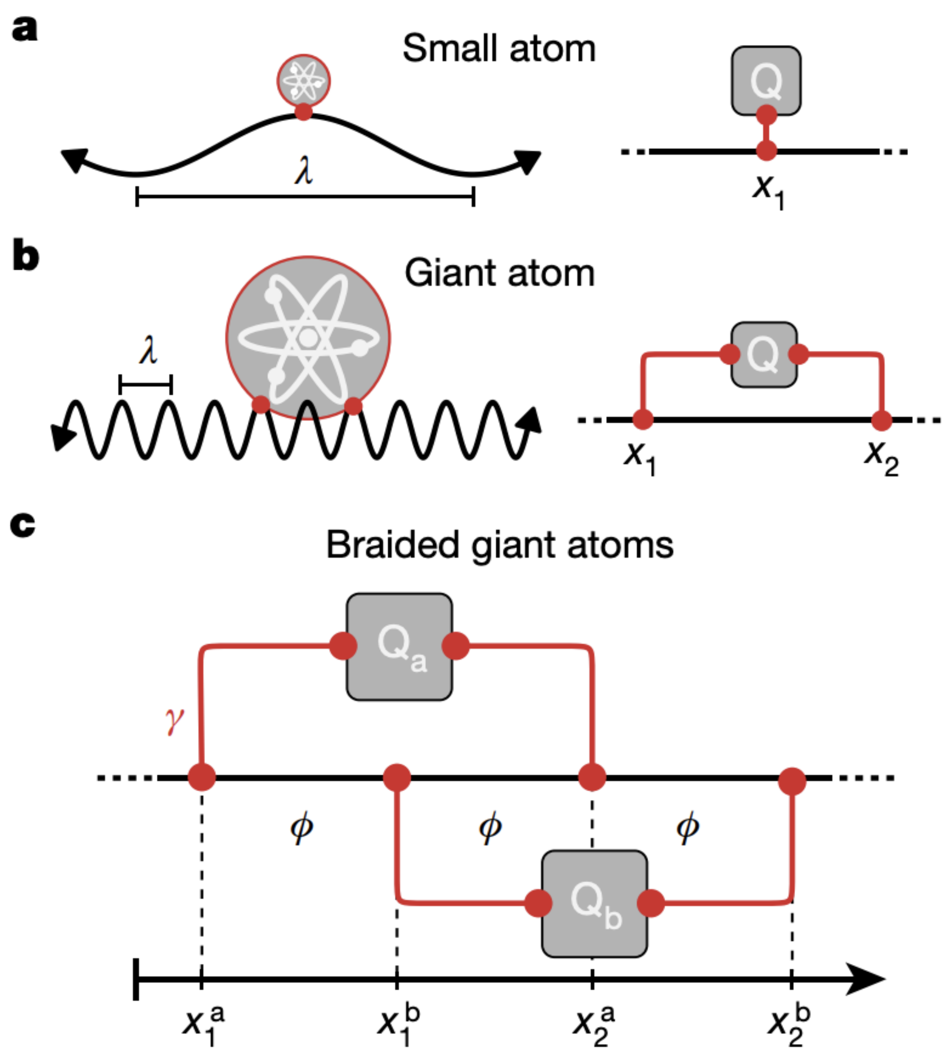
Waveguide Quantum Electrodynamics with Superconducting Qubits, Bharath Kannan, master thesis (2018)

Experimental setup

- To realize the giant atoms:
  Qubits are coupled two times to the waveguide

- Two frequency-tunable transmon qubits to measure interaction effects between two giant atoms

- Goal: demonstrate decoherence-free interactions between multiple giant atoms

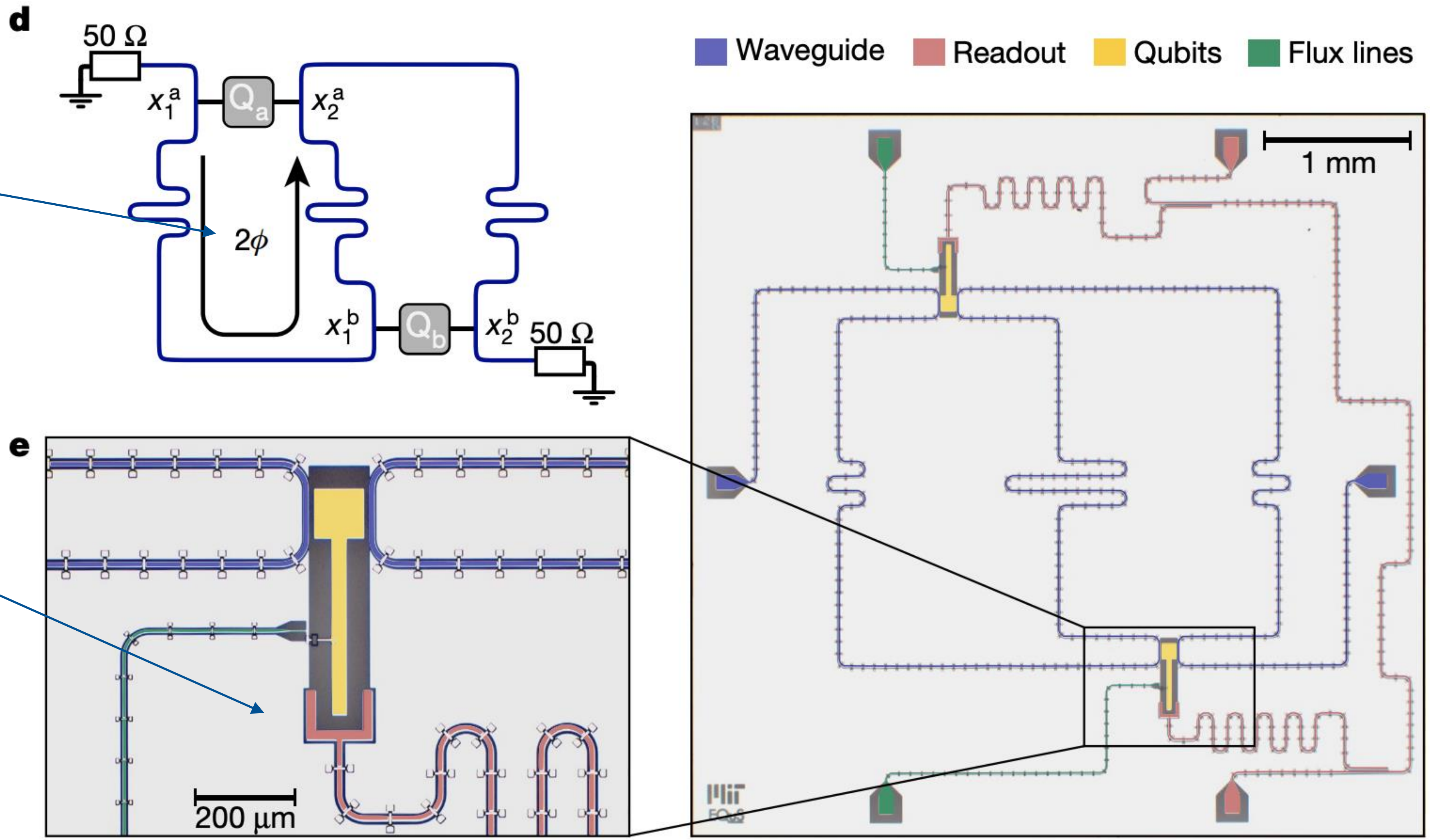


Kannan, B., Ruckriegel, M.J., Campbell, D.L. et al. Waveguide quantum electrodynamics with superconducting artificial giant atoms. Nature 583, 775–779 (2020)

Experimental setup

Photons will experience phase shift $\phi = 2\pi\Delta x/\lambda(\omega)$

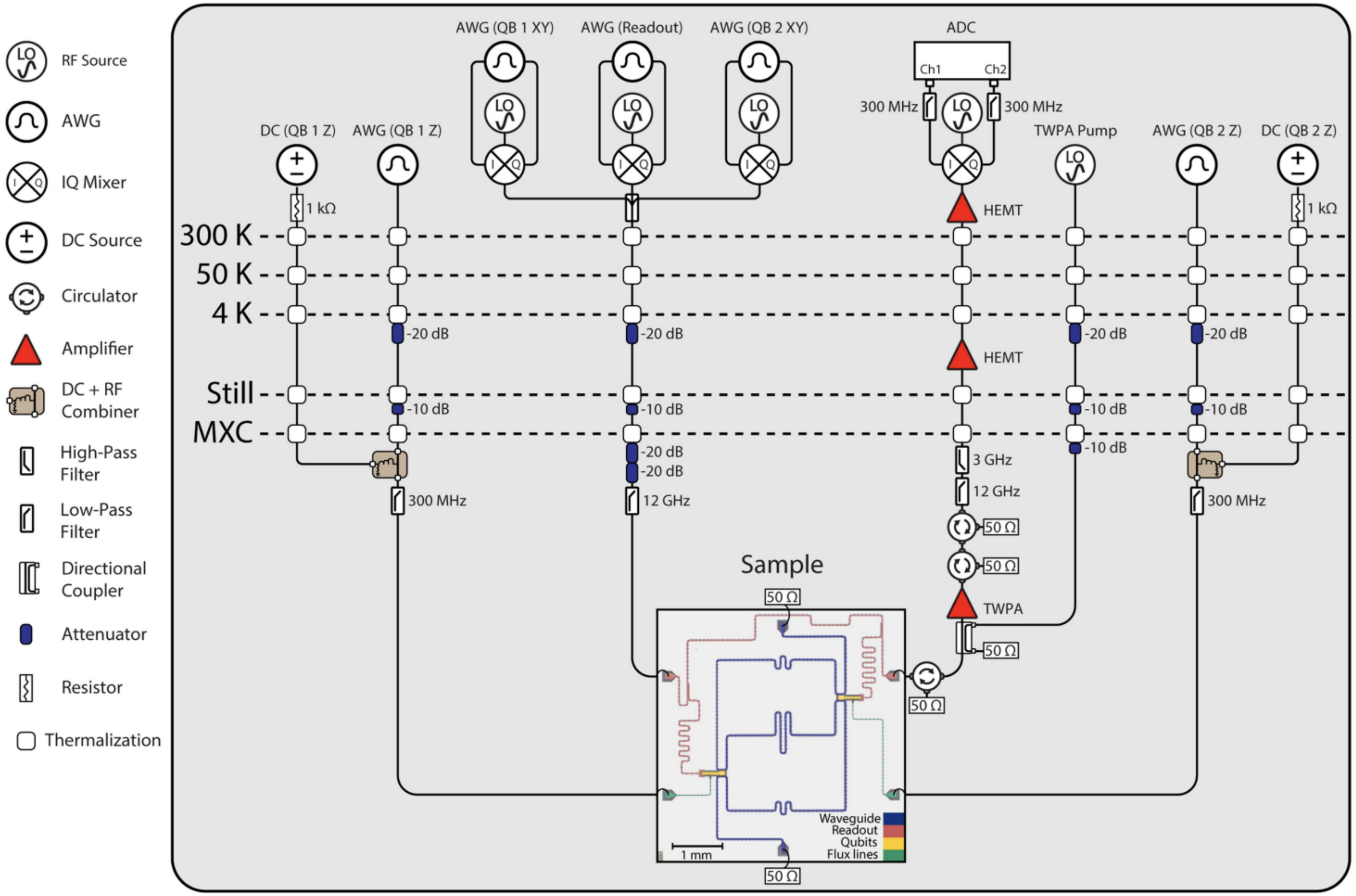
capacitive coupling to a superconducting resonator for readout



Kannan, B., Ruckriegel, M.J., Campbell, D.L. et al. Waveguide quantum electrodynamics with superconducting artificial giant atoms. Nature 583, 775–779 (2020)

Experimental setup

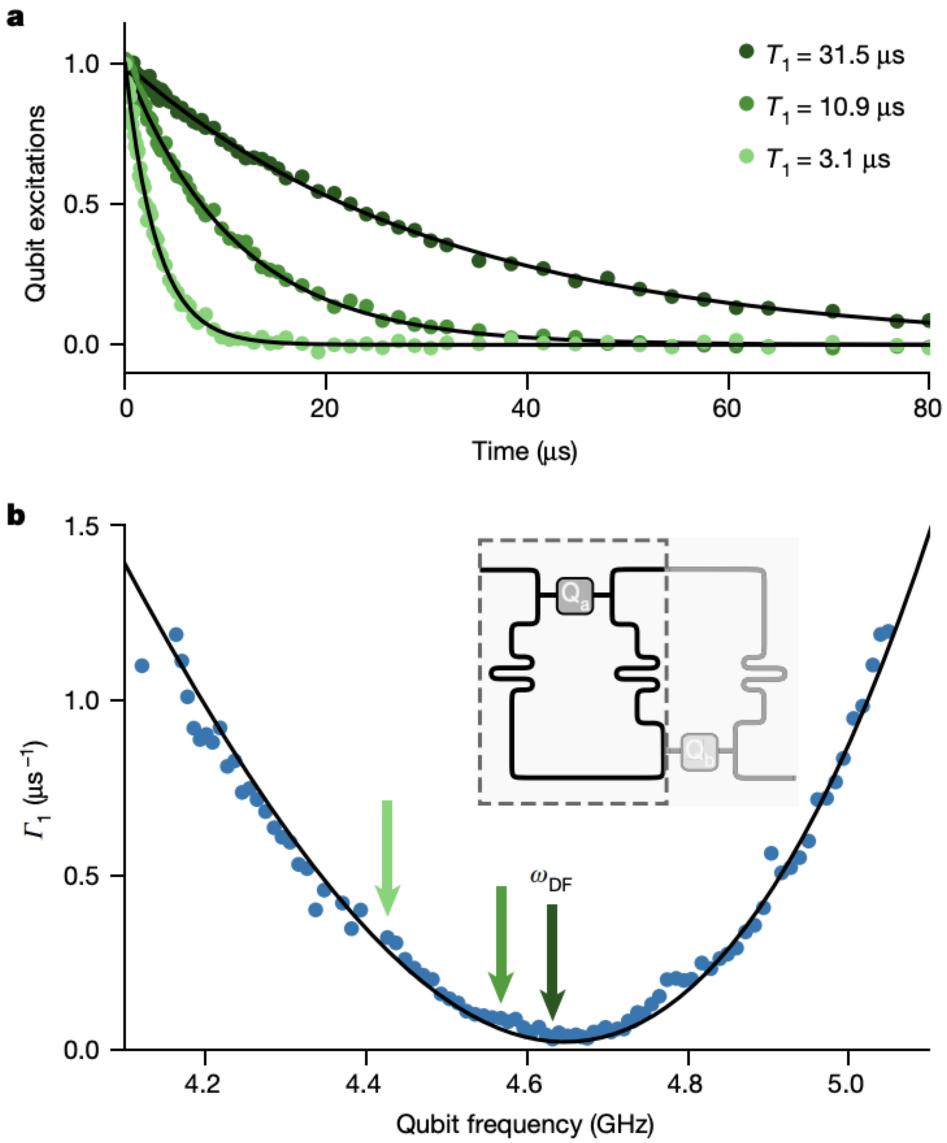
- Cooling via dilution refrigerator → T = 10 mK
- Samples are magnetically shielded
- 50 Ω resistors to minimize impedance mismatches from external devices (photons are not reflected)



Kannan, B., Ruckriegel, M.J., Campbell, D.L. et al. Waveguide quantum electrodynamics with superconducting artificial giant atoms. Nature 583, 775–779 (2020)

Characterization of the system

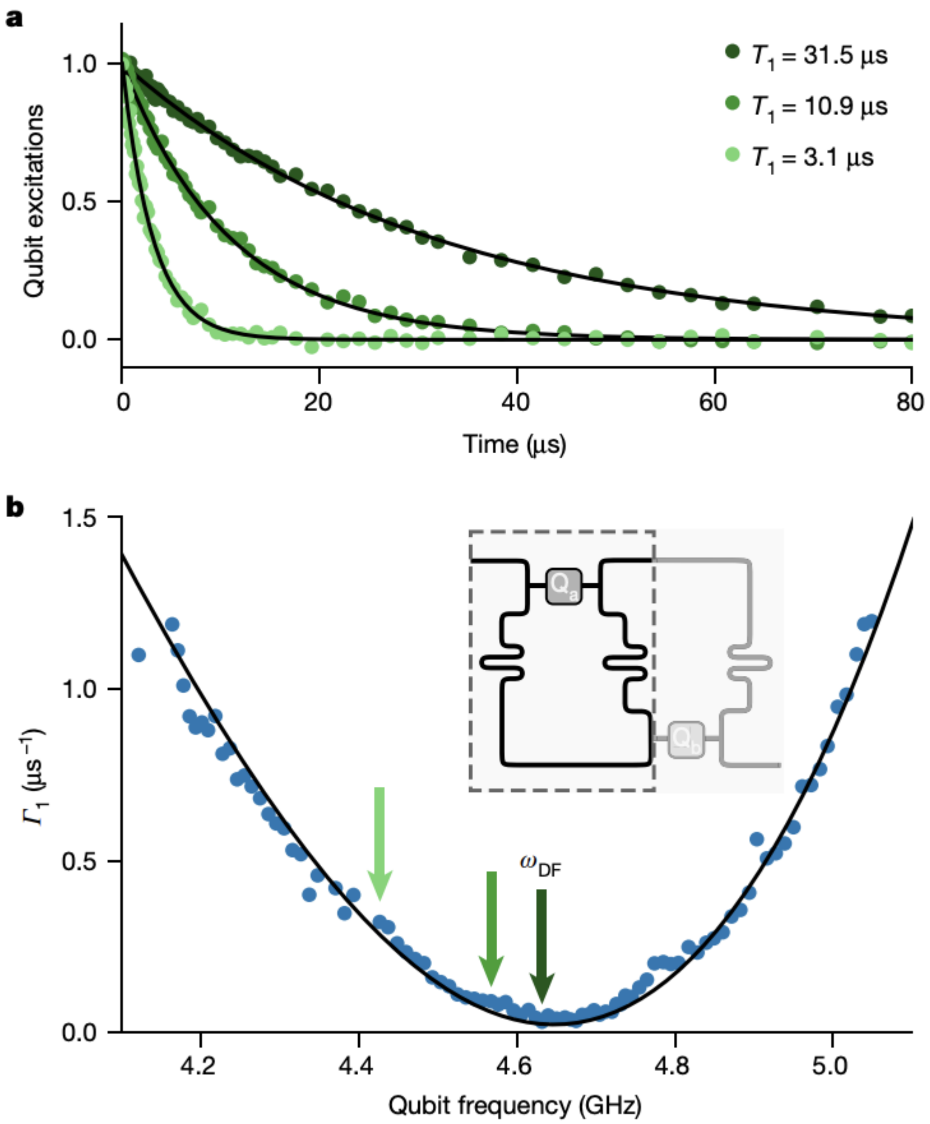
- detune the qubits away from each other
- excitation of the qubit from the state |0⟩ to |1⟩ with a so called Π – pulse
- measuring after certain time state of qubit
- From qubit energy relaxation time T_1 → relaxation rates $\Gamma_1 = T_1^{-1}$



Kannan, B., Ruckriegel, M.J., Campbell, D.L. et al. Waveguide quantum electrodynamics with superconducting artificial giant atoms. Nature 583, 775–779 (2020)

Characterization of the system

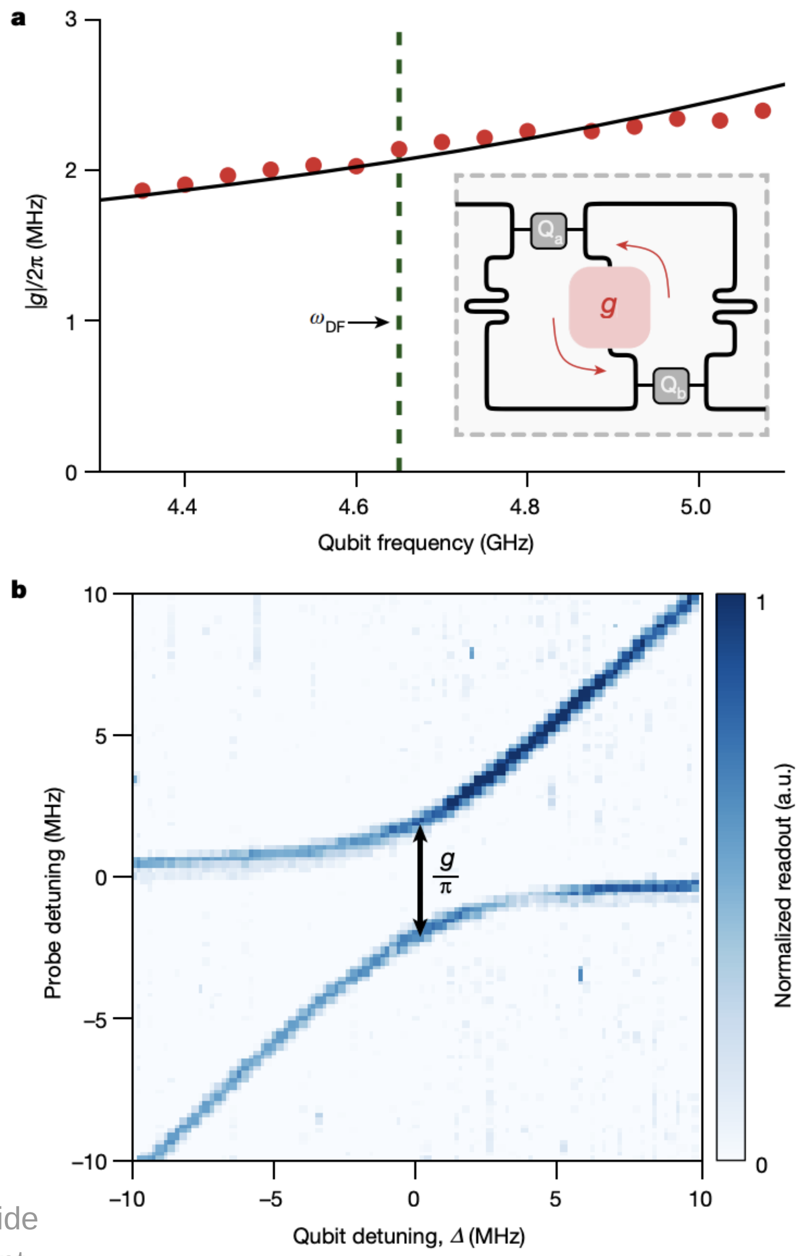
- relaxation rate depends on the qubit transition frequency
- qubit-waveguide decoupling at a decoherence-free frequency $\omega_{DF}/2\pi = 4.645\ \text{GHz}$ with lifetime of $T_1 = 31.5\ \mu\text{s}$
- Same measurement was done for qubit b → same result



Kannan, B., Ruckriegel, M.J., Campbell, D.L. et al. Waveguide quantum electrodynamics with superconducting artificial giant atoms. Nature 583, 775–779 (2020)

qubit–qubit interactions

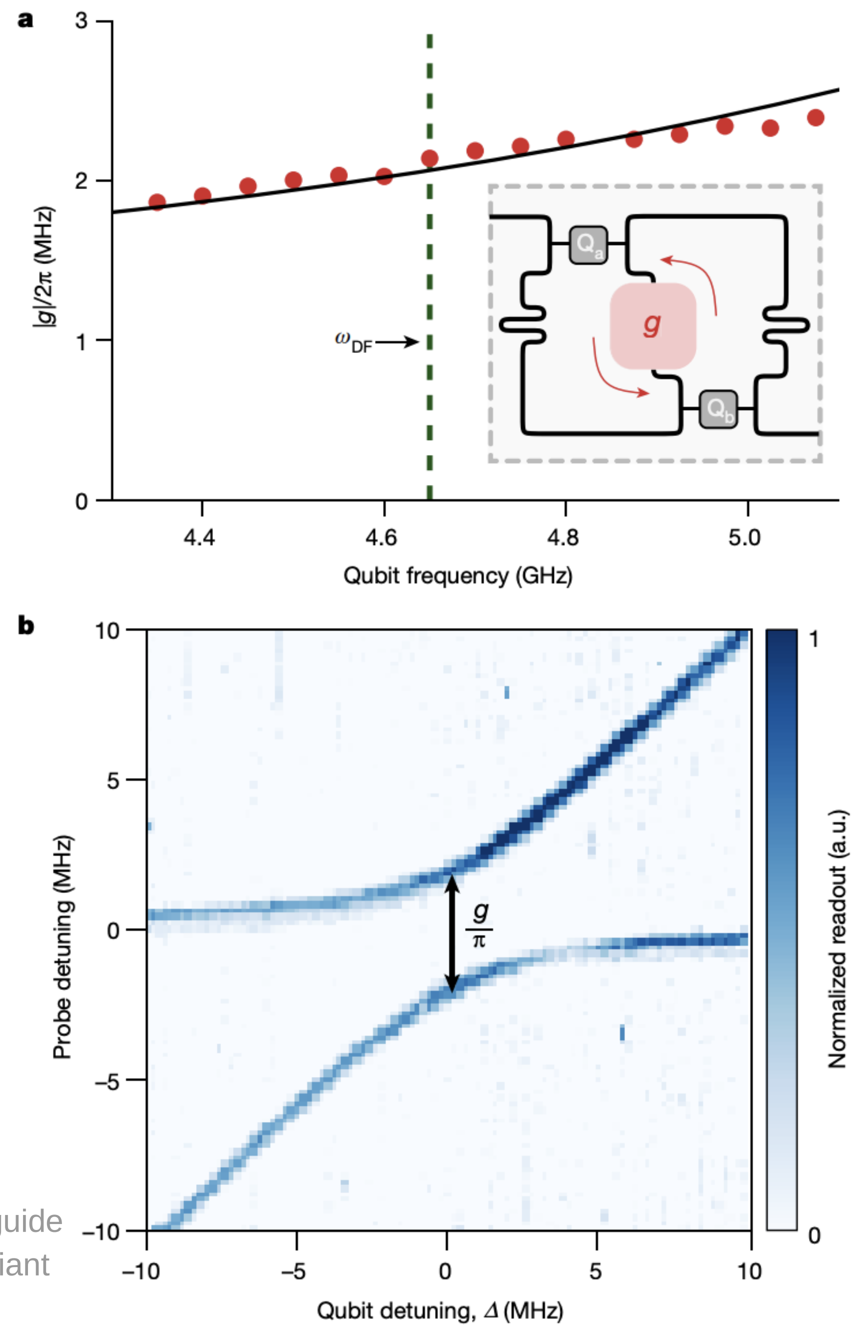
- measure the interaction strength between qubits at different qubit frequencies
- this is done via qubit spectroscopy
- plot the microwave signal to manipulate the qubit against qubit detuning
- Couped system of two qubits → expecting split peak behavior → two resonance curves



Kannan, B., Ruckriegel, M.J., Campbell, D.L. et al. Waveguide quantum electrodynamics with superconducting artificial giant atoms. Nature 583, 775–779 (2020)

qubit–qubit interactions

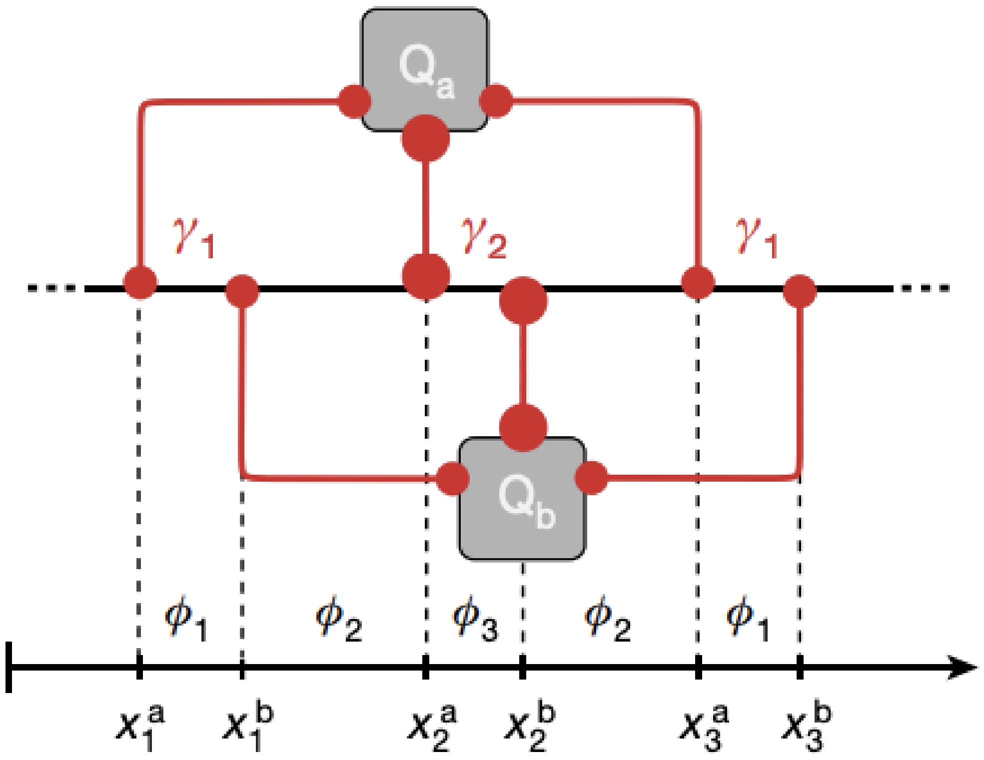
- From the difference of the resonance peaks → coupling strength
- In a: coupling strength for different qubit frequencies
- finite exchange interaction at the decoherence-free frequency $\omega_{DF} = \omega_a = \omega_b$
- qubits are decoupled from spontaneous emission into the waveguide → still qubit exchange interaction



Kannan, B., Ruckriegel, M.J., Campbell, D.L. et al. Waveguide quantum electrodynamics with superconducting artificial giant atoms. Nature 583, 775–779 (2020)

Geometry dependence

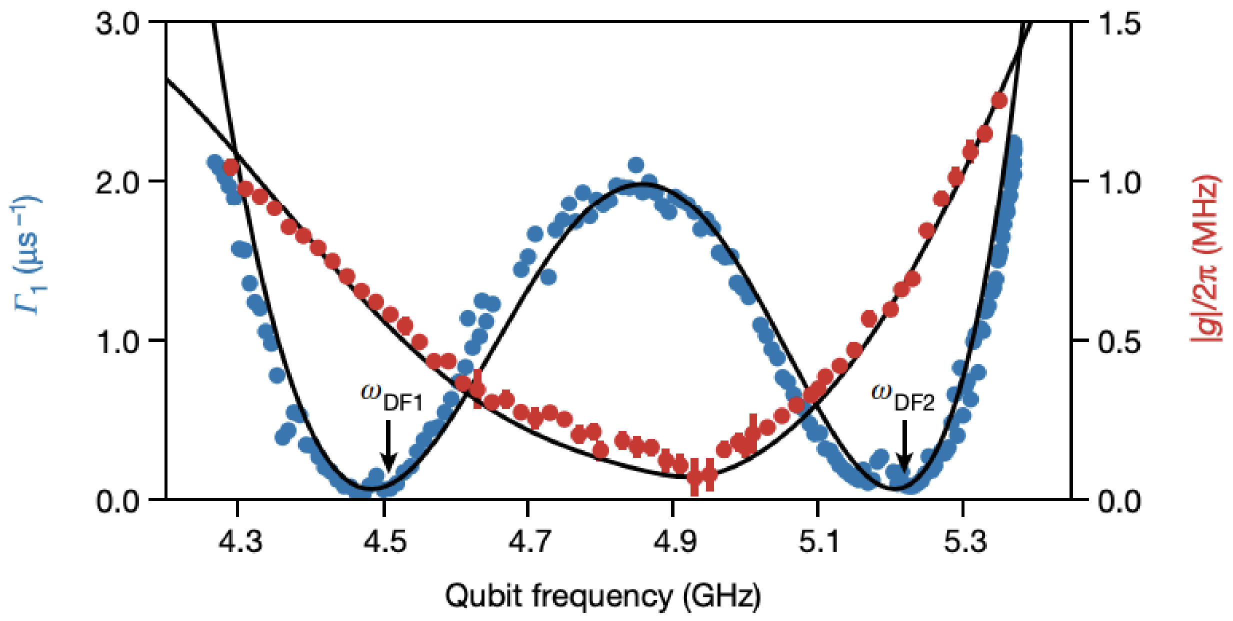
- Data of measurements strongly depend on geometry
- chose geometry such that qubit relaxation and exchange can be simultaneously suppressed
- perform entangling gates between the qubits
- two qubits, each coupled to a waveguide at three locations
- first and last coupling points are equal in strength and the central coupling point is larger



Kannan, B., Ruckriegel, M.J., Campbell, D.L. et al. Waveguide quantum electrodynamics with superconducting artificial giant atoms. Nature 583, 775–779 (2020)

Two decoherence free frequencies

- Geometry chosen:
  relaxation spectra for both qubits have two decoherence-free frequencies
- Thus, each qubit can be placed at a unique decoherence-free frequency and suppress exchange interactions between them
- asymmetry due to the frequency dependence of the coupling strengths



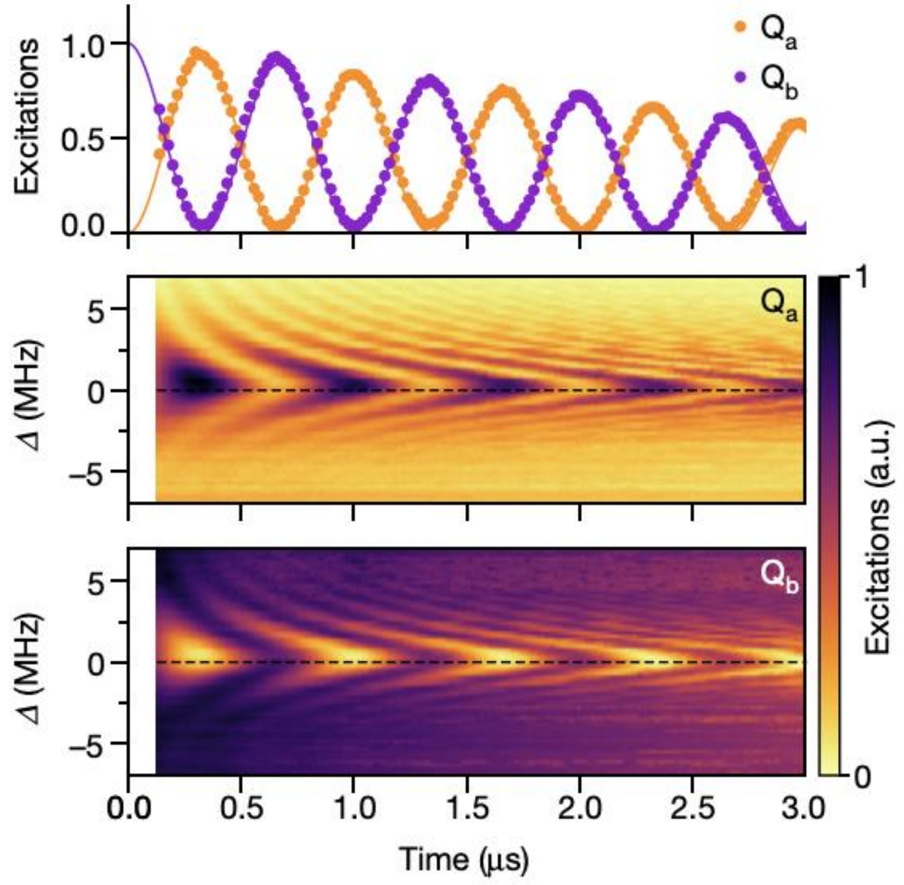
Kannan, B., Ruckriegel, M.J., Campbell, D.L. et al. Waveguide quantum electrodynamics with superconducting artificial giant atoms. Nature 583, 775–779 (2020)

Entanglement generation

- demonstrate that giant atoms can be used to prepare entangled states in waveguide QED devices

- When placed on resonance at ω_{DF2}, the qubits exchange excitations at a rate $g/2\pi = 735\ kHz$

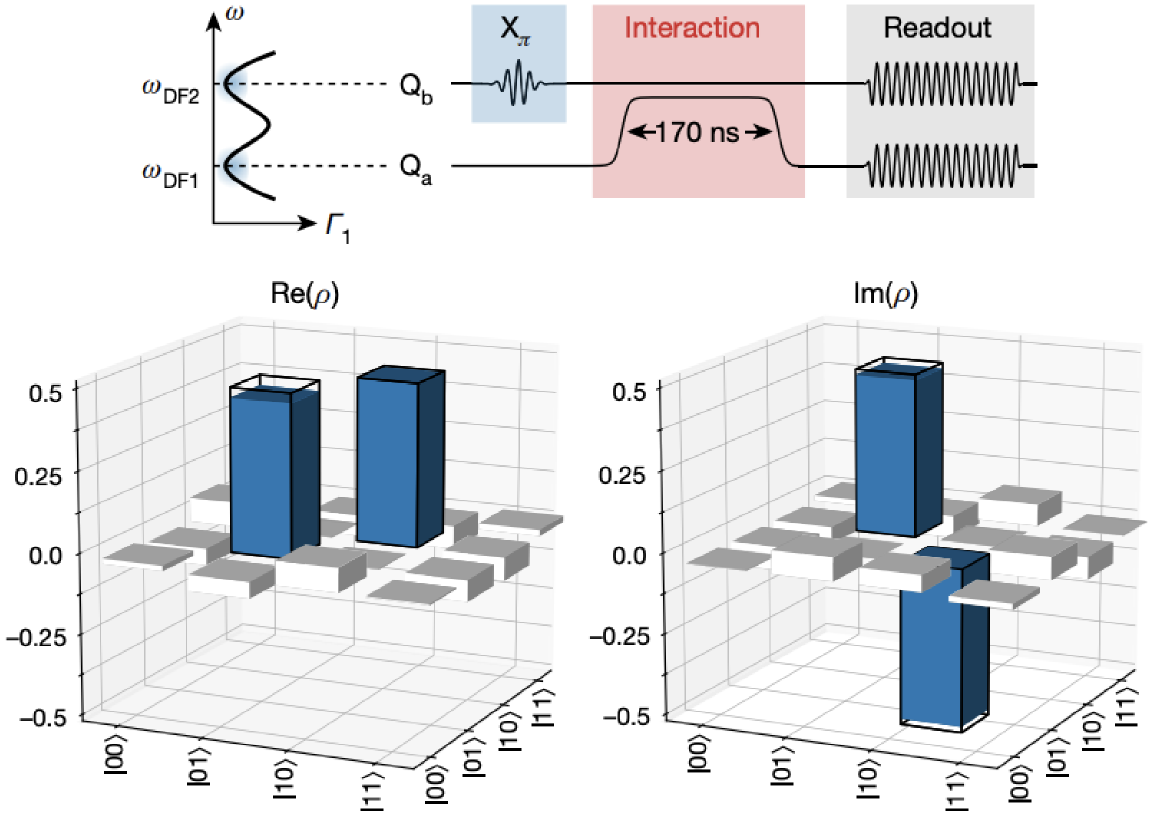
- confirm this by observing the chevron pattern formed by this excitation swap as a function of the interaction time and qubit–qubit detuning Δ



Kannan, B., Ruckriegel, M.J., Campbell, D.L. et al. Waveguide quantum electrodynamics with superconducting artificial giant atoms. Nature 583, 775–779 (2020)

Entanglement generation

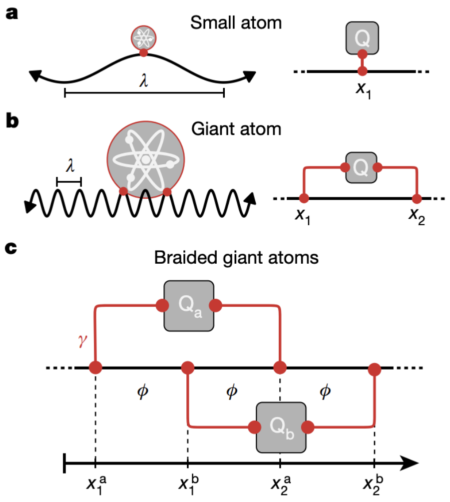
- Using the pulse sequence to prepare the state: $(|01\rangle - i|10\rangle)/\sqrt{2}$
- Starting with no interaction between both qubit and excite one qubit with a π - Pulse
- Let them interact by changing the frequency of qubit a for a certain time
- experimentally determine the state of the qubit
- The state-preparation fidelity is 94%

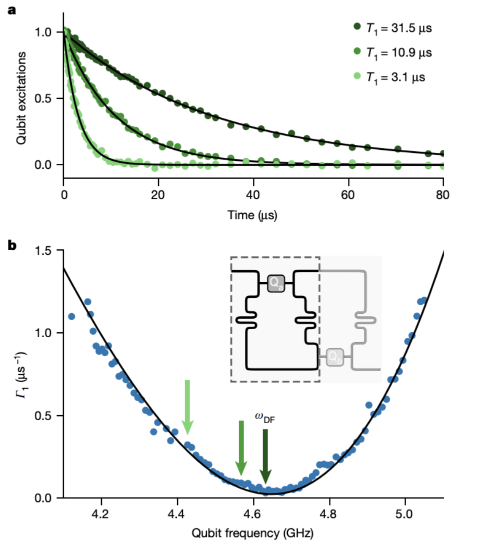


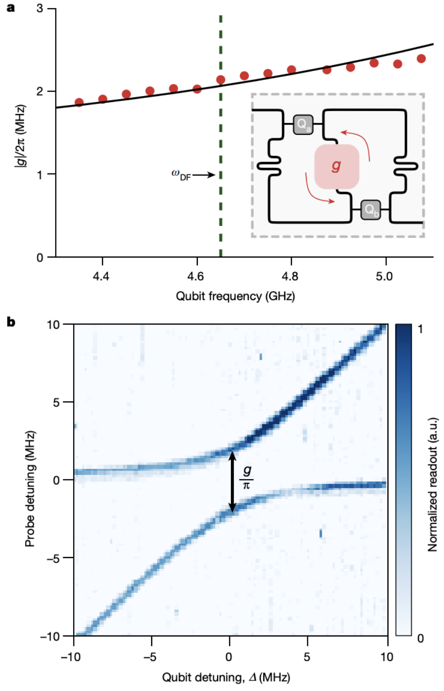
Kannan, B., Ruckriegel, M.J., Campbell, D.L. et al. Waveguide quantum electrodynamics with superconducting artificial giant atoms. Nature 583, 775–779 (2020)

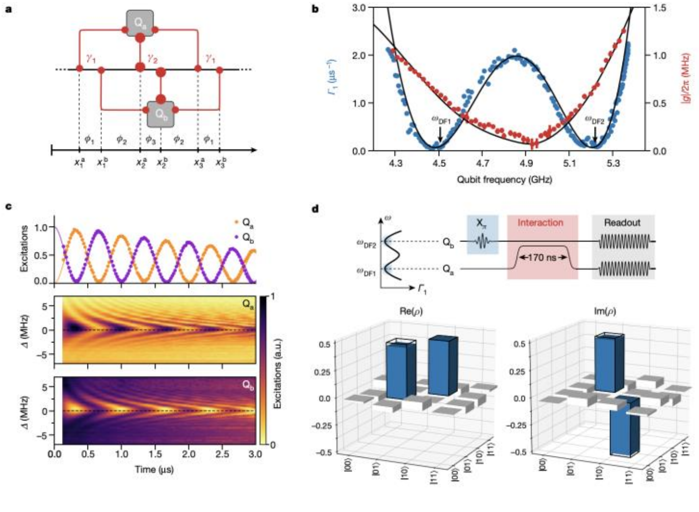
4. Conclusion

- introduced giant atoms consisting of transmons touch waveguides several times
- decoupling of qubit-waveguide at decoherence free frequencies was studied
- qubit-qubit interaction were examined
- generation of entanglement was investigated









Kannan, B., Ruckriegel, M.J., Campbell, D.L. et al. Waveguide quantum electrodynamics with superconducting artificial giant atoms. Nature 583, 775–779 (2020)

Thank you for listening