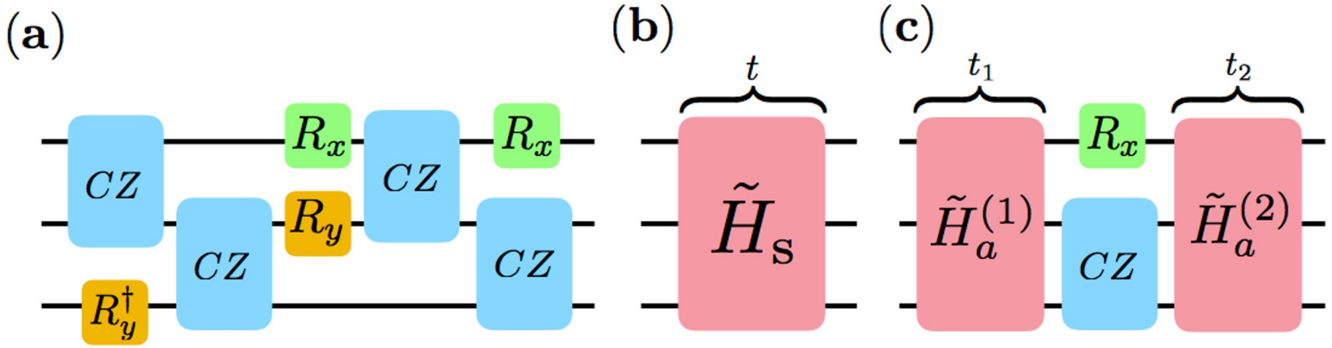
Quantum Architectures for Analogues and Theory Applications

Outline

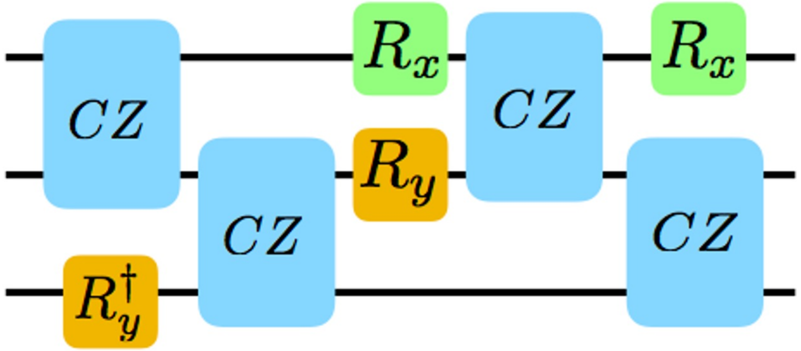


- Digital Simulations
  - Spin Systems (PRL 112, 200501 (2014), Phys Rev X 5 021027 (2015))
  - Fermionic Systems (10.1038/ncomms8654)
  - QG (PRL 119, 040501 (2017), Nature volume 612, pages 51–55 (2022))
- Analog Simulations
  - GAAH Model (arXiv:2206.13107)
  - Hawking Radiation (Nature Communications | (2023) 14:3263)
  - Dirac Equation (New Journal of Physics 15 (2013) 055008)
- Digital Analog Simulations
  - Fermion Fermion scattering (PRL 114, 070502 (2015))
- Optimal Control (PHYSICAL REVIEW A 101, 062307 (2020))
- Analog Circuits (REVIEWS OF MODERN PHYSICS 84 2012, EPL 128, 24002 (2020))

Digital-Analog Quantum Simulations with Superconducting Circuits arxiv:1711.09810

Digital Simulations

(a)



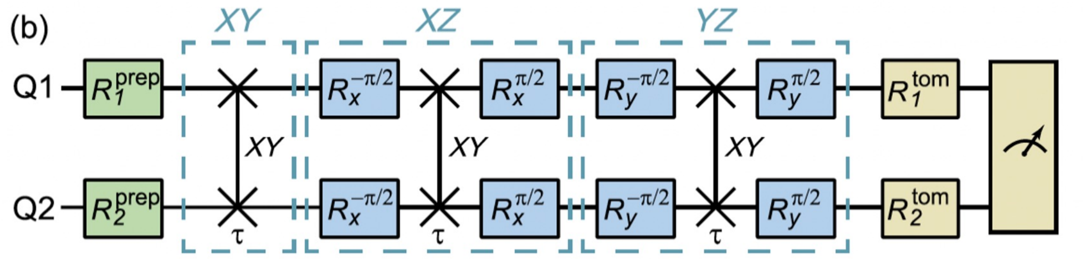
Spin Systems

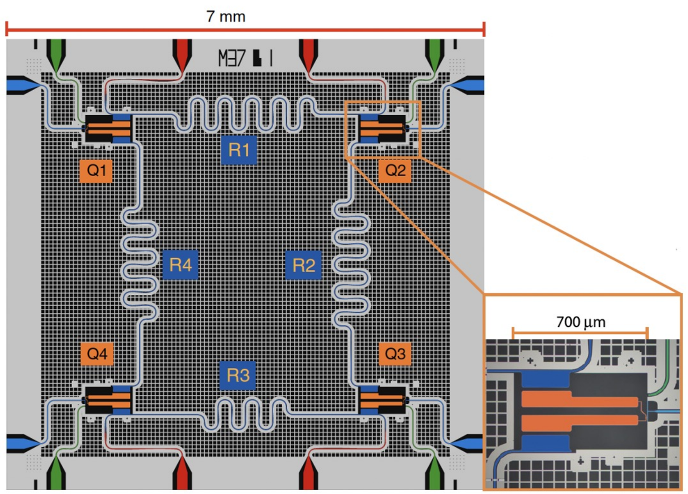
Heisenberg Model

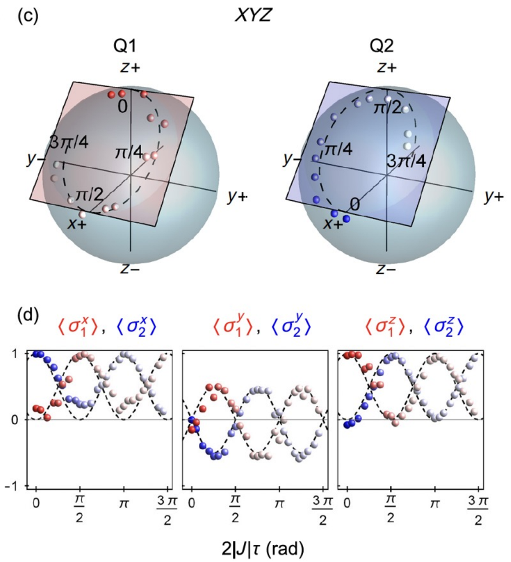
$$H_{xyz} = \sum_{(i,j)} (J_x \sigma_i^x \sigma_j^x + J_y \sigma_i^y \sigma_j^y + J_z \sigma_i^z \sigma_j^z)$$

Suzuki-Lie-Trotter expansion

$$e^{-iHt} \simeq \left(e^{-iH_1 t/l} \cdots e^{-iH_M t/l}\right)^l + \sum_{i<j} \frac{[H_i, H_j]t^2}{2l}$$







Phys Rev X 5 021027 (2015)

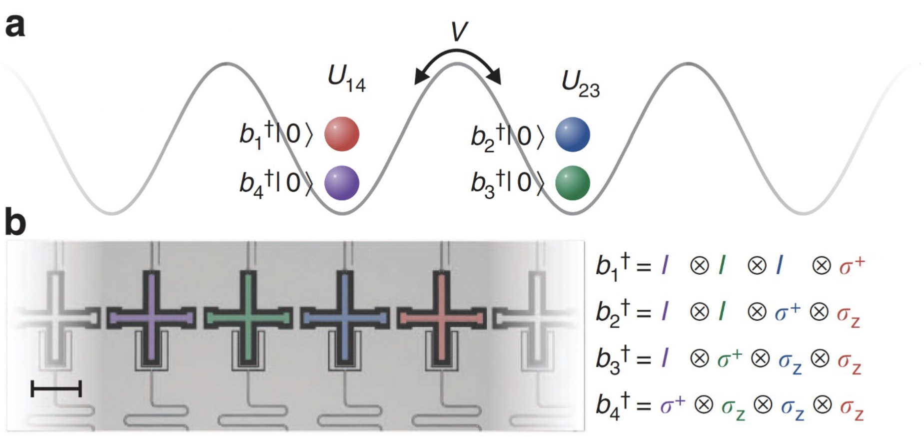
Fermionic Systems

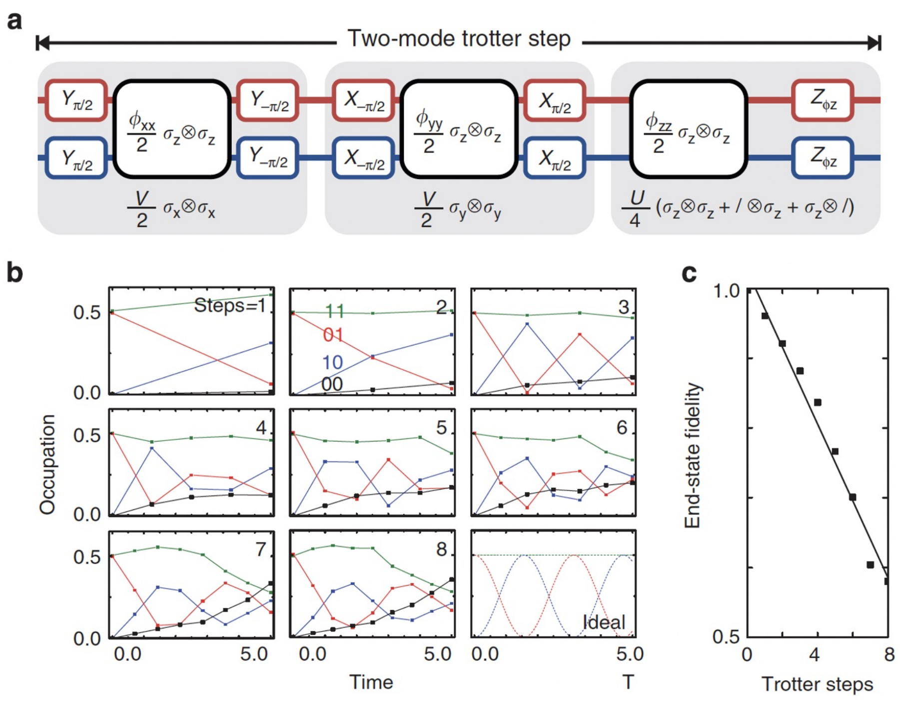
Fermi-Hubbard model

$$H = -V\left(b_1^\dagger b_2 + b_2^\dagger b_1\right) + U b_1^\dagger b_1 b_2^\dagger b_2$$

Jordan-Wigner mapping

$$\begin{aligned} b_1^\dagger &= \mathbb{I} \otimes \mathbb{I} \otimes \sigma^+, \\ b_2^\dagger &= \mathbb{I} \otimes \sigma^+ \otimes \sigma^z, \\ b_3^\dagger &= \sigma^+ \otimes \sigma^z \otimes \sigma^z. \end{aligned}$$





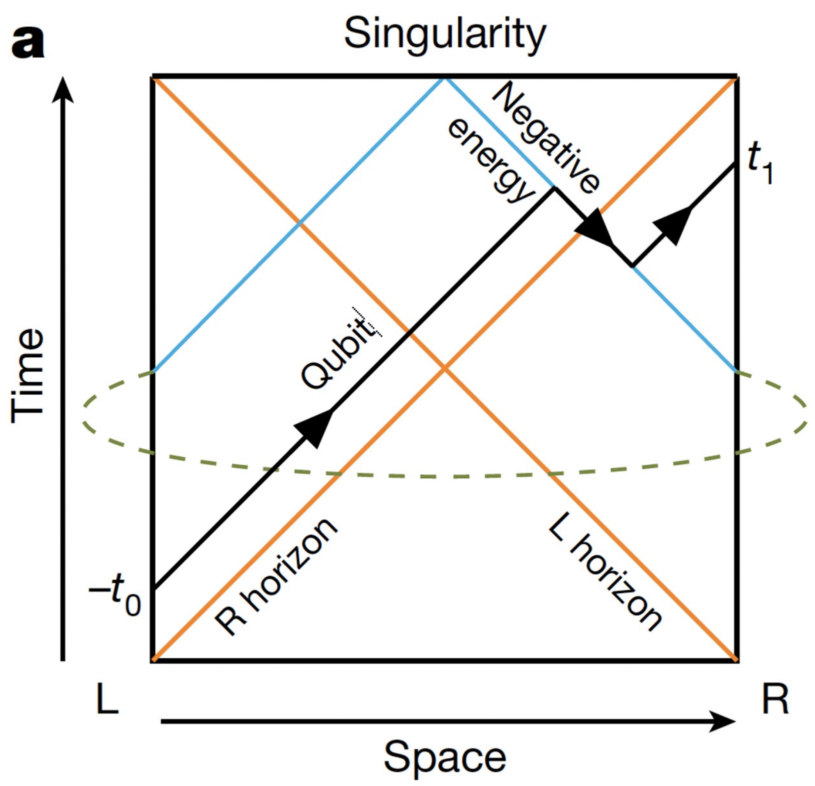
DOI: 10.1038/ncomms8654

Quantum Gravity

Sachdev-Ye-Kitaev (SYK) model

$$H = \frac{1}{4 \times 4!} \sum_{i,j,k,l=1}^{N} J_{ijkl} \chi_i \chi_j \chi_k \chi_l$$

Majorana fermionic operators are codified as $\chi_{2n-1} = (\prod_{j=1}^{n-1} \sigma_j^z)\sigma_n^x$ and $\chi_{2n} = (\prod_{j=1}^{n-1} \sigma_j^z)\sigma_n^y$, with $\{\chi_i, \chi_j\} = 2\delta_{ij}$.

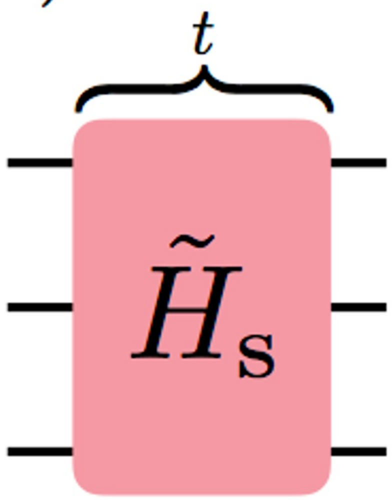


Simulation on the Google Sycamore superconducting qubit array with a nine-qubit circuit of 164 controlled-Z gates and 295 single-qubit gates

PRL 119, 040501 (2017), Nature volume 612, pages 51–55 (2022)

Analog Simulations

(b)

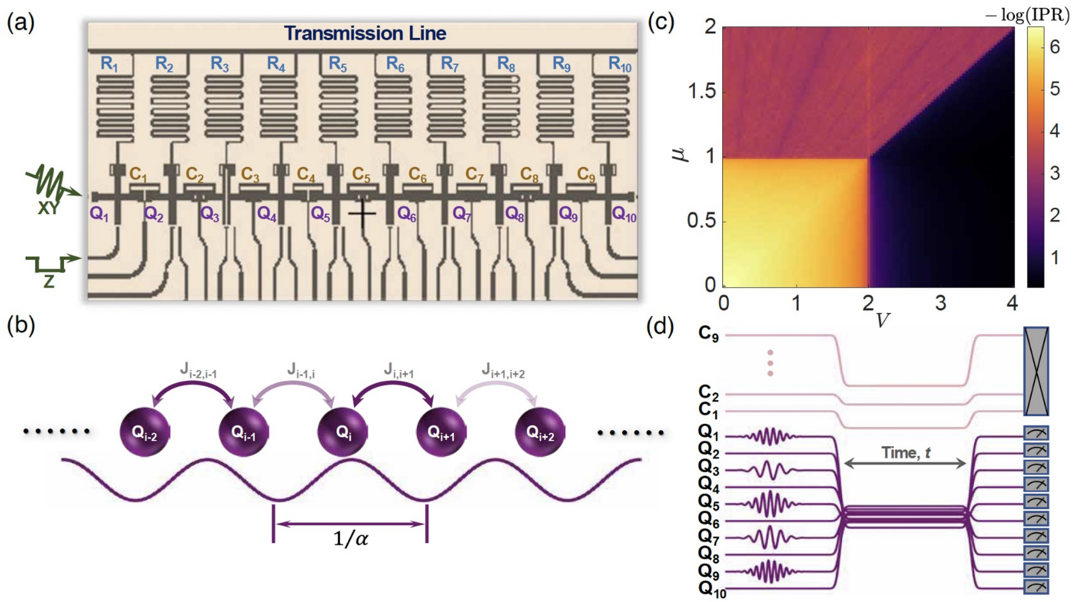


GAAH model

Generalized Aubry André Harper model

$$\frac{\hat{H}}{\hbar} = \lambda \sum_{j=1}^{9} \left(1 + \mu \cos\left[2\pi \left(j + \frac{1}{2}\right)\alpha + \delta\right]\right) \hat{a}_j^{\dagger}\hat{a}_{j+1} + \mathrm{H.c.}$$
$$+ \lambda \sum_{j=1}^{10} V \cos(2\pi j \alpha + \delta)\hat{a}_j^{\dagger}\hat{a}_j. \quad (2)$$

We initially excite the leftmost qubit Q_1, i.e., the system is initialized as $|\psi(0)\rangle = |1000000000\rangle$, where $|0\rangle$ ($|1\rangle$) denotes the ground (excited) state of a qubit. Then we apply the fast Z pulse on each qubit and coupler, and the system will evolve under the Hamiltonian Eq.(2), satisfying Schrödinger equation $|\psi(t)\rangle = e^{-i\hat{H}t}|\psi(0)\rangle$. We monitor its dynamics from $t = 0$ to 500 ns, by measuring the photon occupancy probabilities of each qubit $P_j(t) = \langle\psi(t)|\hat{a}_j^{\dagger}\hat{a}_j|\psi(t)\rangle$. For each time point, we perform 5000 repeated single-shot measurements.



10 qubits with tunable couplers

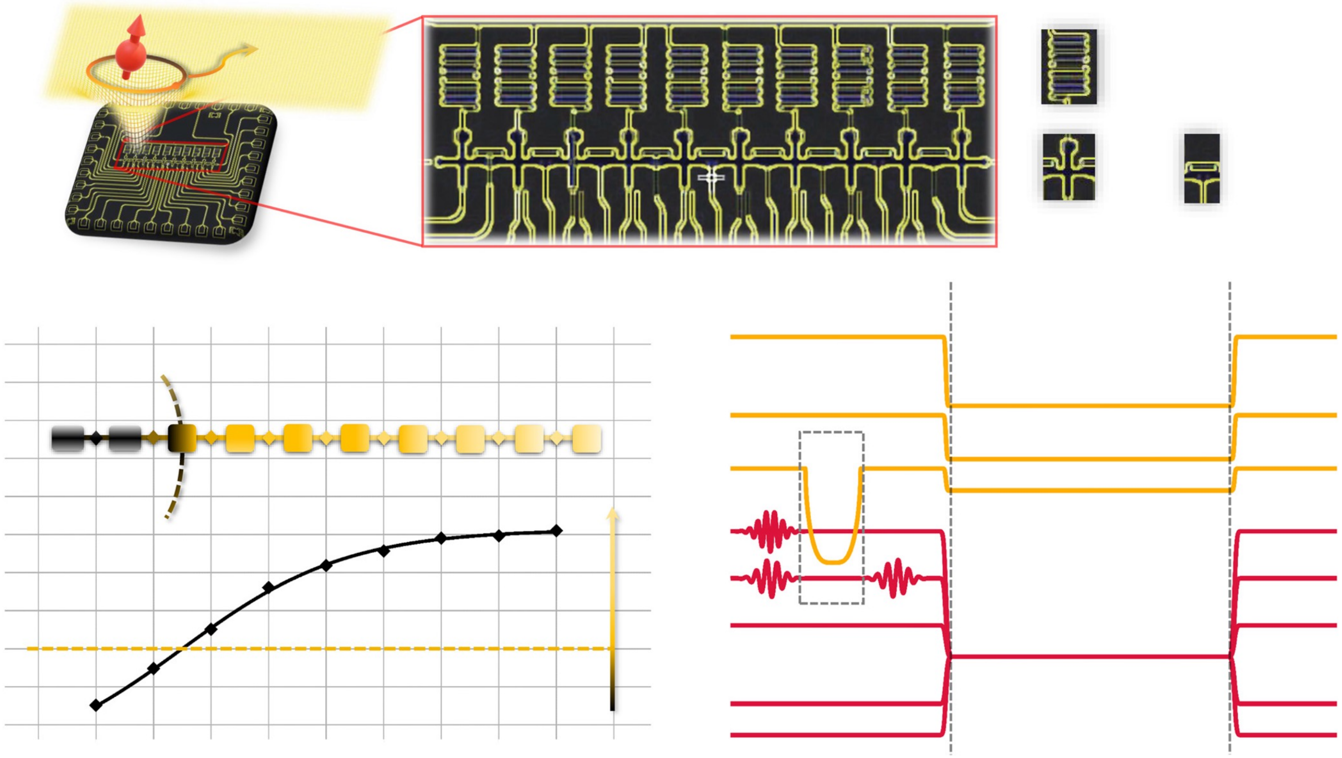
arXiv:2206.13107

Hawking Radiation

(1+1) Dira field on curved space

$$i\gamma^a e^{\mu}_{(a)}\partial_\mu \psi + \frac{i}{2}\gamma^a \frac{1}{\sqrt{-g}}\partial_\mu\left(\sqrt{-g}e^{\mu}_{(a)}\right)\psi - m\psi = 0,$$

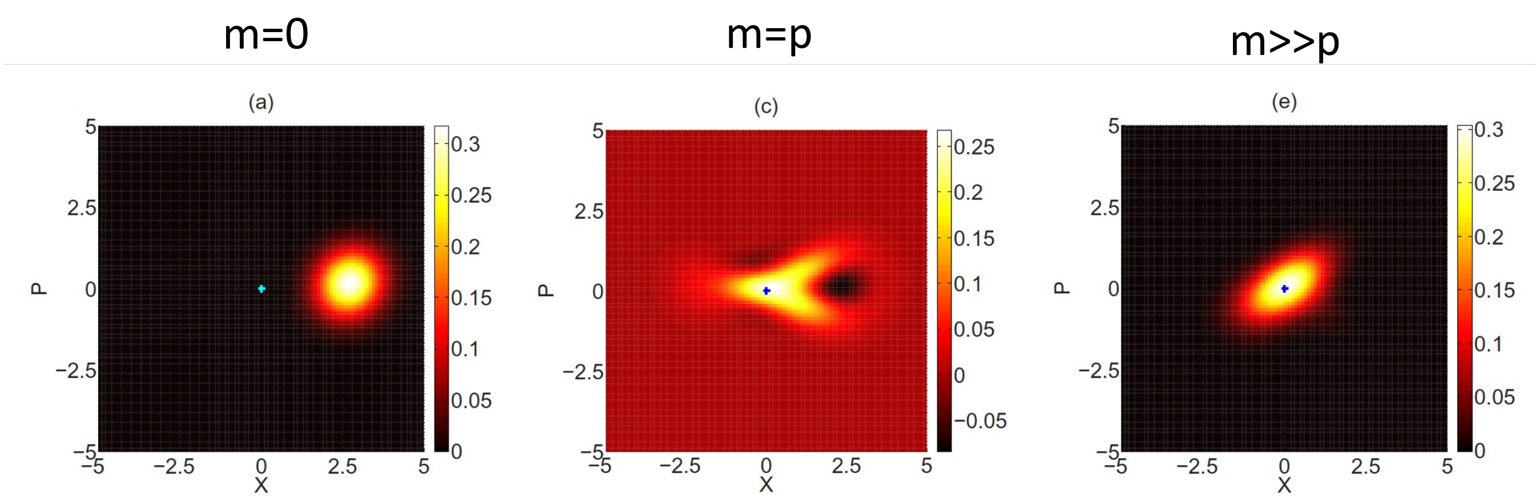
$$\hat{H} = -\sum_j \kappa_j\left(\hat{\sigma}_j^+\hat{\sigma}_{j+1}^- + \hat{\sigma}_j^-\hat{\sigma}_{j+1}^+\right) - \sum_j \mu_j \hat{\sigma}_j^+\hat{\sigma}_j^-$$



Nature Communications | (2023) 14:3263

Dirac Equation

By using three classical microwave drives, superconducting qubit strongly coupled to a resonator field mode can be used to simulate the dynamics of the 1+1 Dirac equation:



Wigner function W(x, p) of the field mode state inside the resonator

$$\mathcal{H} = \frac{\hbar\omega_q}{2}\sigma_z + \hbar\omega a^\dagger a - \hbar g\left(\sigma^\dagger a + \sigma a^\dagger\right) - \hbar\Omega\left(e^{i(\omega t+\varphi)}\sigma + e^{-i(\omega t+\varphi)}\sigma^\dagger\right)$$
$$-\hbar\lambda\left(e^{i(\nu t+\varphi)}\sigma + e^{-i(\nu t+\varphi)}\sigma^\dagger\right) + \hbar\xi\left(e^{i\omega t}a + e^{-i\omega t}a^\dagger\right),$$

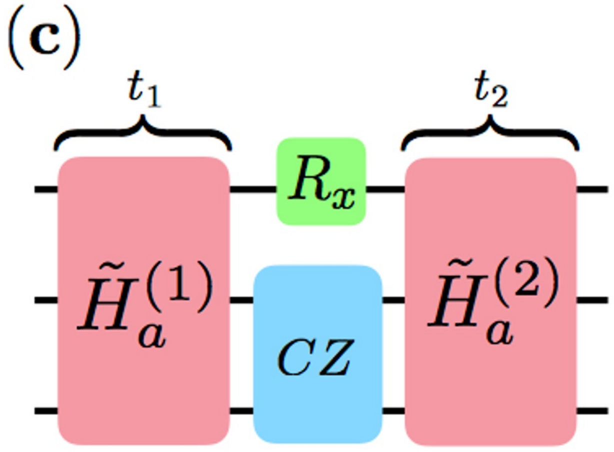
$$\mathcal{H}_{\rm eff} = \frac{\hbar\lambda}{2}\sigma_z + \frac{\hbar g}{\sqrt{2}}\sigma_y\hat{p} + \hbar\xi\sqrt{2}\,\hat{x},$$

mass kinetic potential

$$\hat{x} = (a + a^\dagger)/\sqrt{2},\ \hat{p} = -i(a - a^\dagger)/\sqrt{2}$$

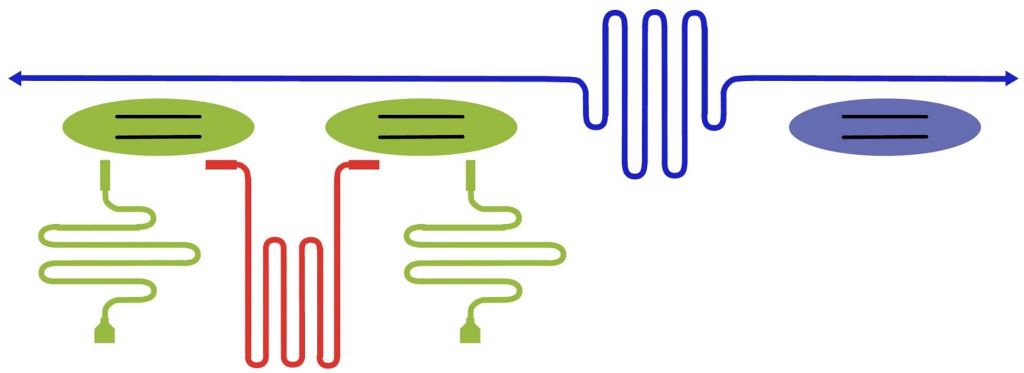
New Journal of Physics 15 (2013) 055008

Digital-Analog Simulations



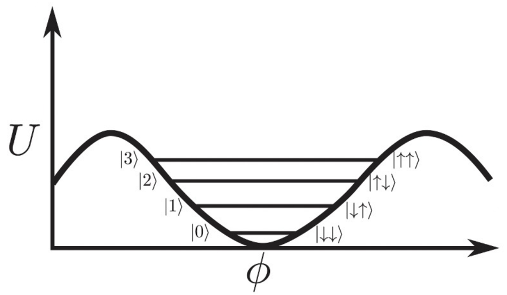
Fermion Fermion Scattering

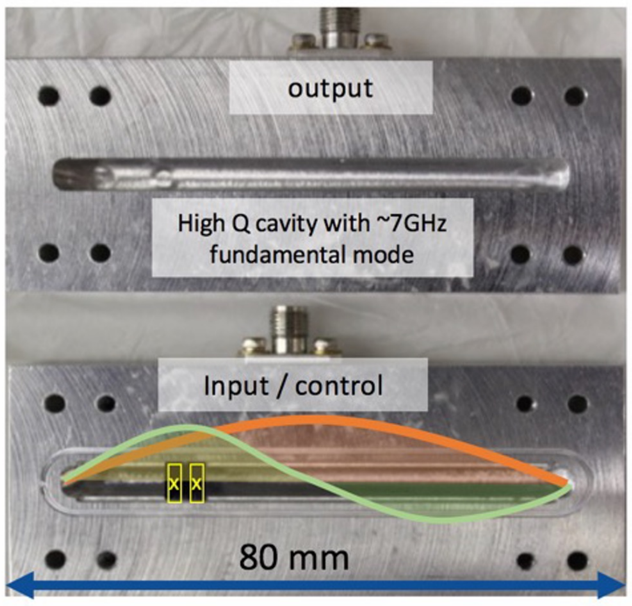
Analog-digital quantum simulation of fermion-fermion scattering mediated by a continuum of bosonic modes. Qubits simulate fermionic modes via digital techniques, while the continuum of an open transmission line simulates bosonic modes in quantum field theory.

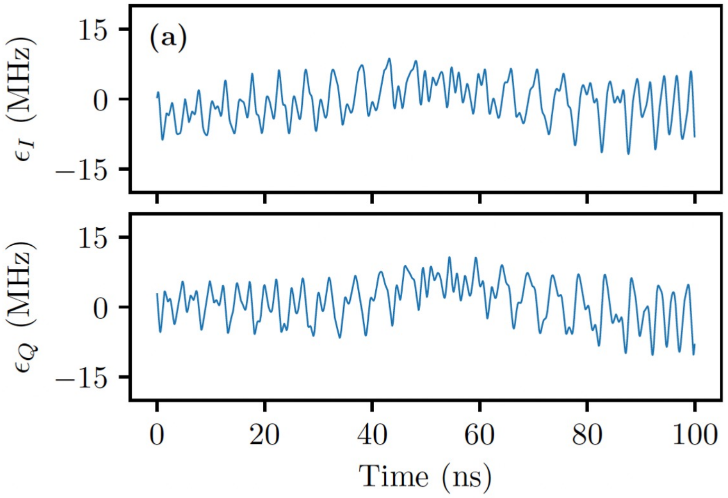


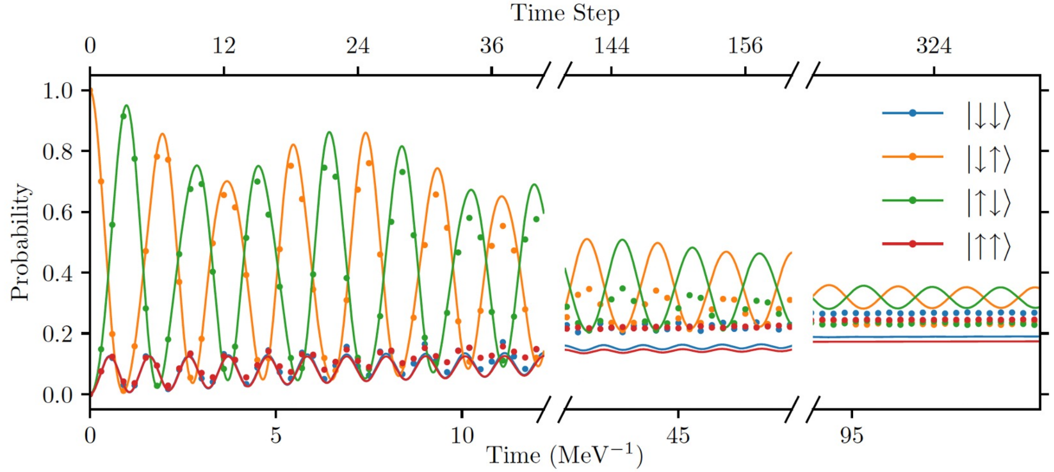
PRL 114, 070502 (2015)

Optimal Control on a qudit



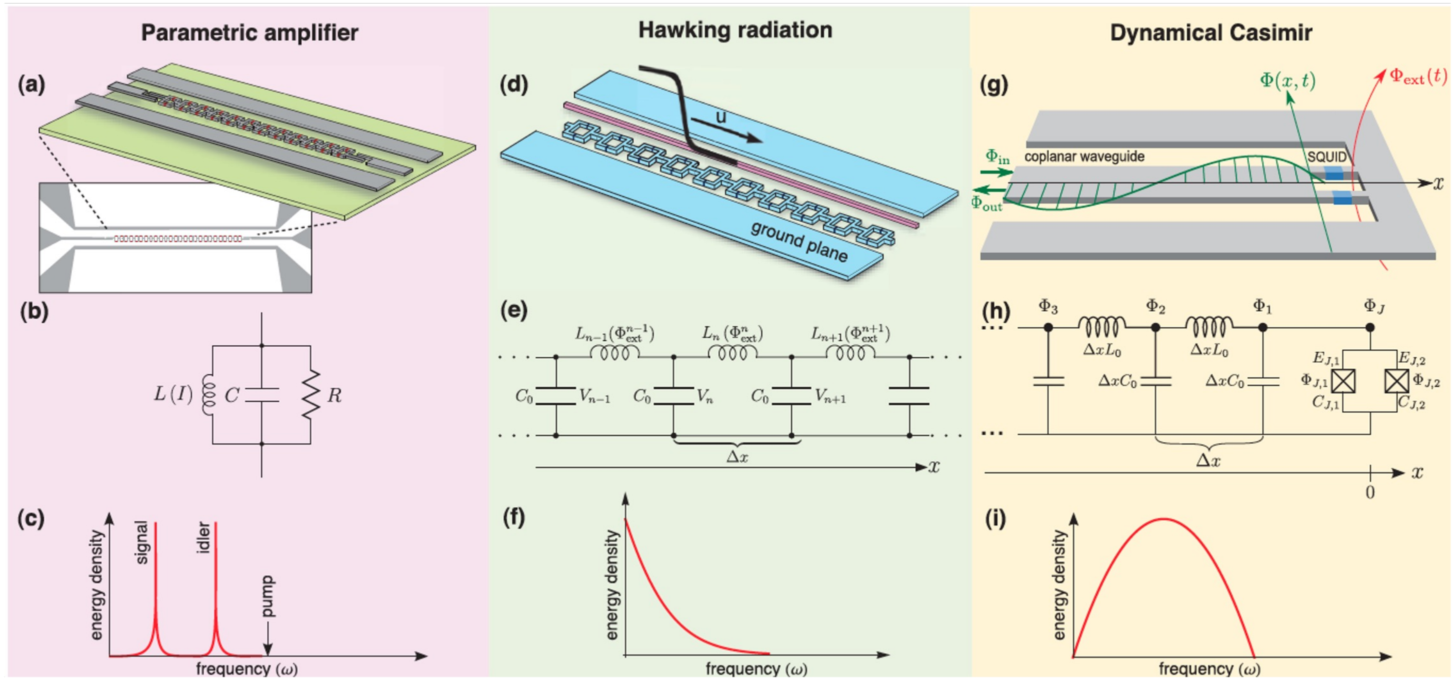






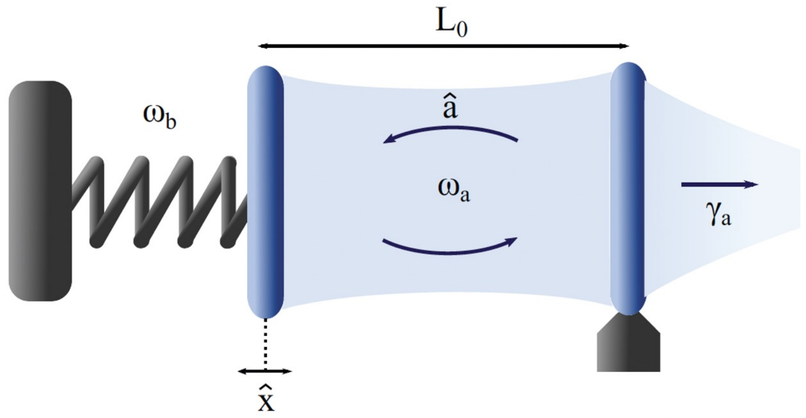
Pederiva et al. PHYSICAL REVIEW A 101, 062307 (2020)

Analog Circuits

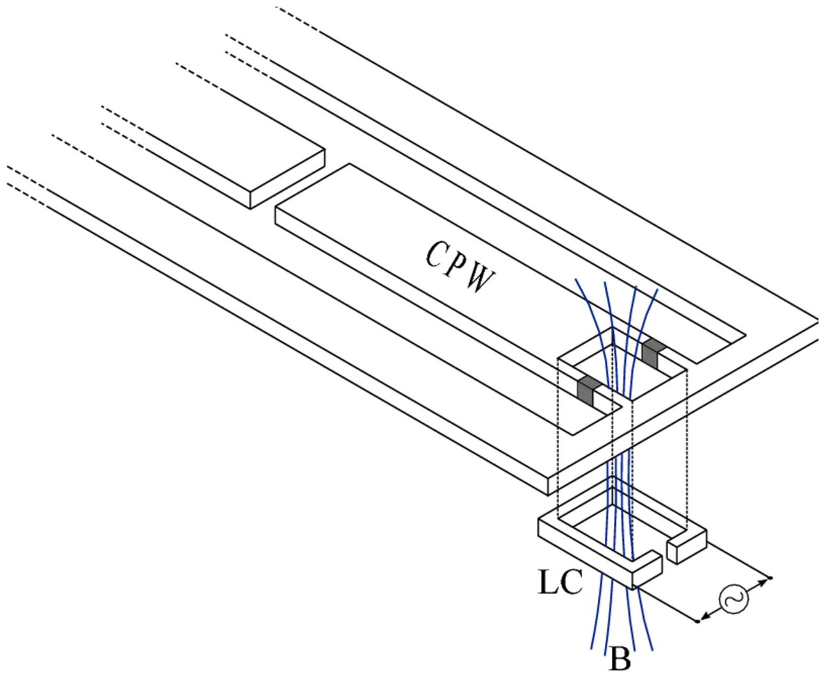


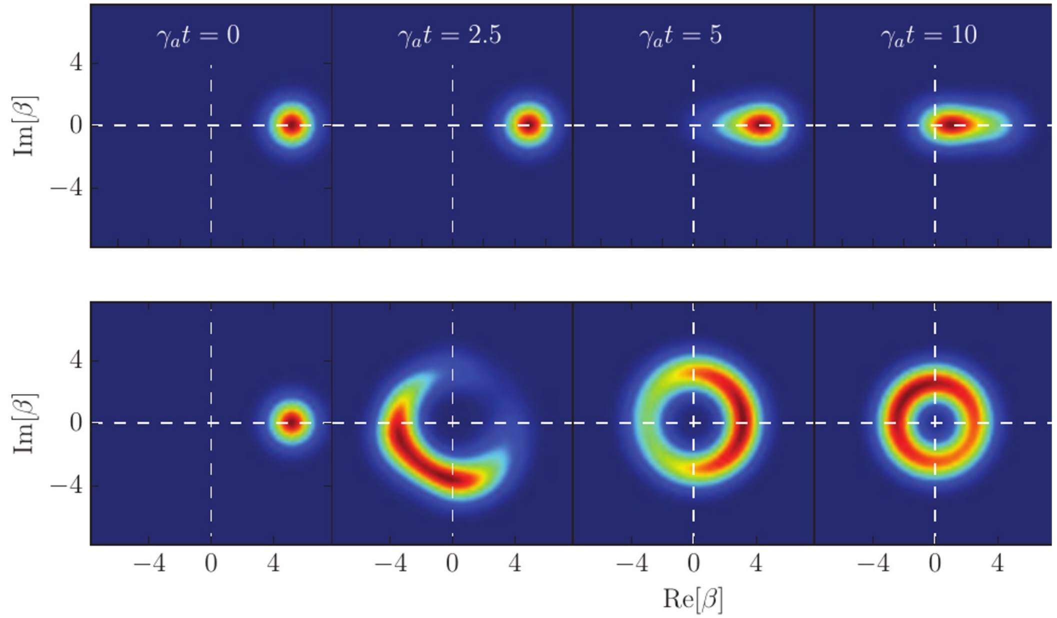
REVIEWS OF MODERN PHYSICS, VOLUME 84, JANUARY–MARCH 2012

Possibility of transforming the virtual photons corresponding to the zero-point fluctuations into an observable quantum vacuum radiation when the background on which the quantum field lives is modulated in either space or time



Baby toy model: friction force on dynamical Casimir emission





S. G. Butera & IC, *Quantum fluctuations of the friction force induced by the dynamical Casimir emission,* EPL 128, 24002 (2020).

Superconducting Devices at INFN

Qub-IT

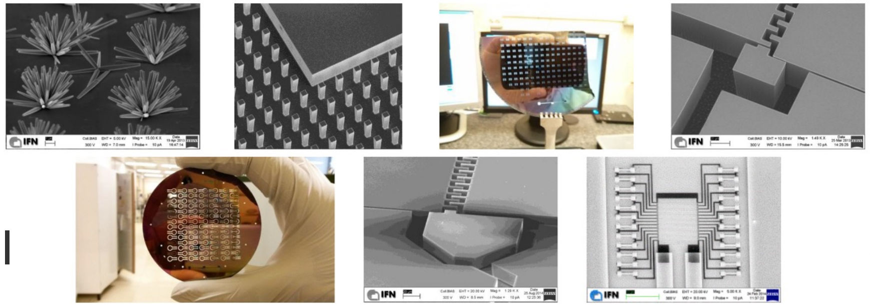
DARTWARS

Detector Array Readout with Traveling Wave AmplifieRS

Consiglio Nazionale
delle Ricerche

NANOMICROFAB
ADVANCED LAB

CNR, National Research Council



INRiM
ISTITUTO NAZIONALE
DI RICERCA METROLOGICA

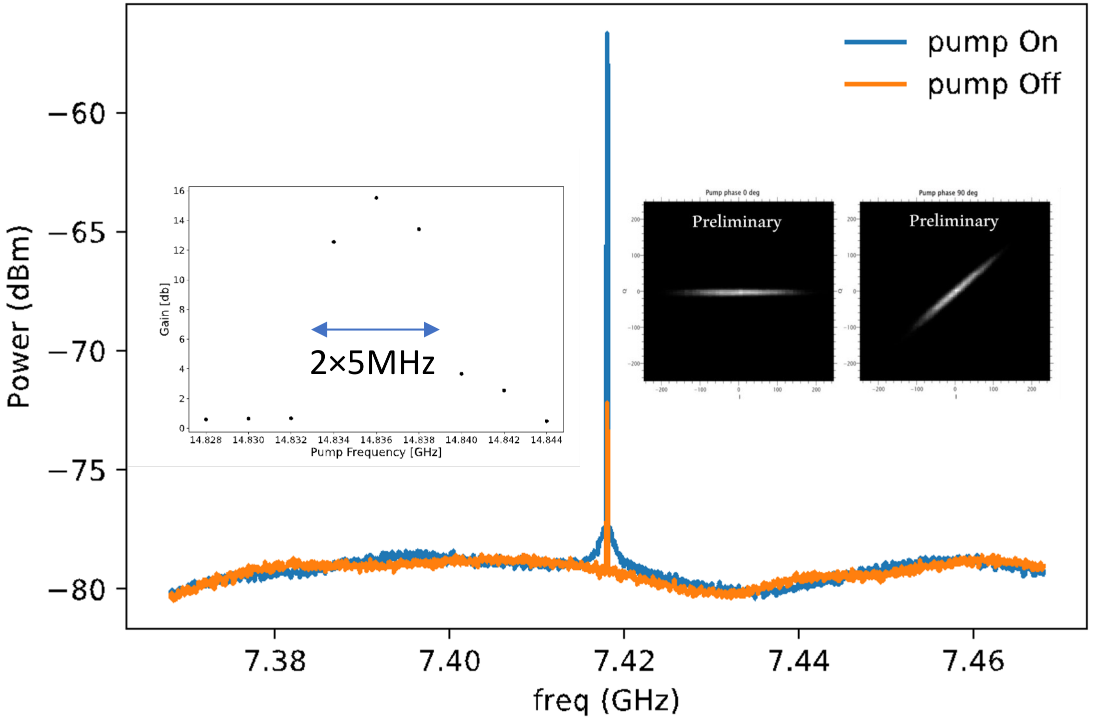
PIQuET
PIEMONTE QUANTUM ENABLING TECHNOLOGY

INRiM, Italian Metrology Institute

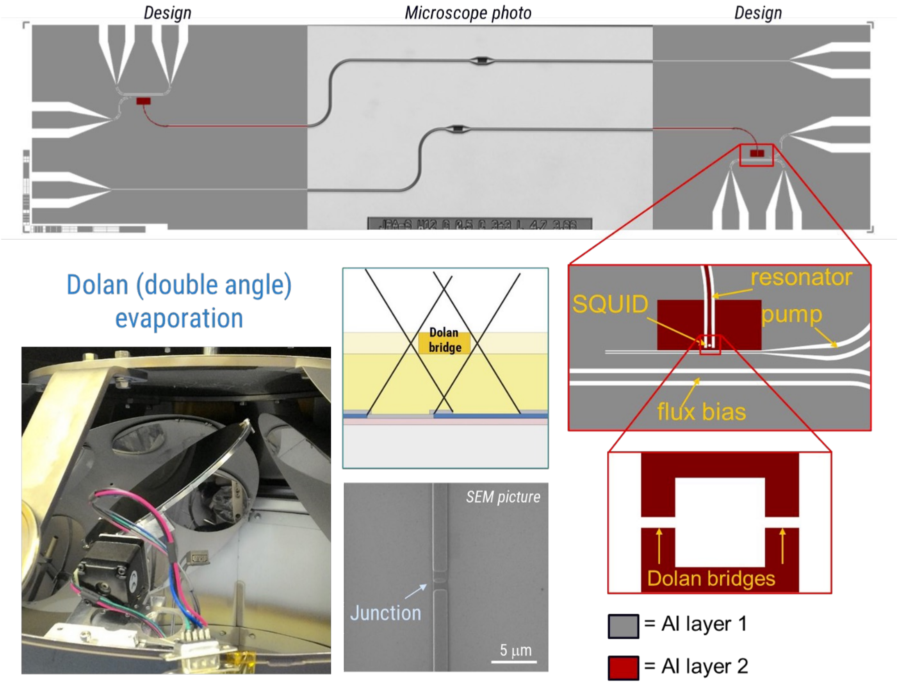
FBK, Fondazione Bruno Kessler

FONDAZIONE
BRUNO KESSLER

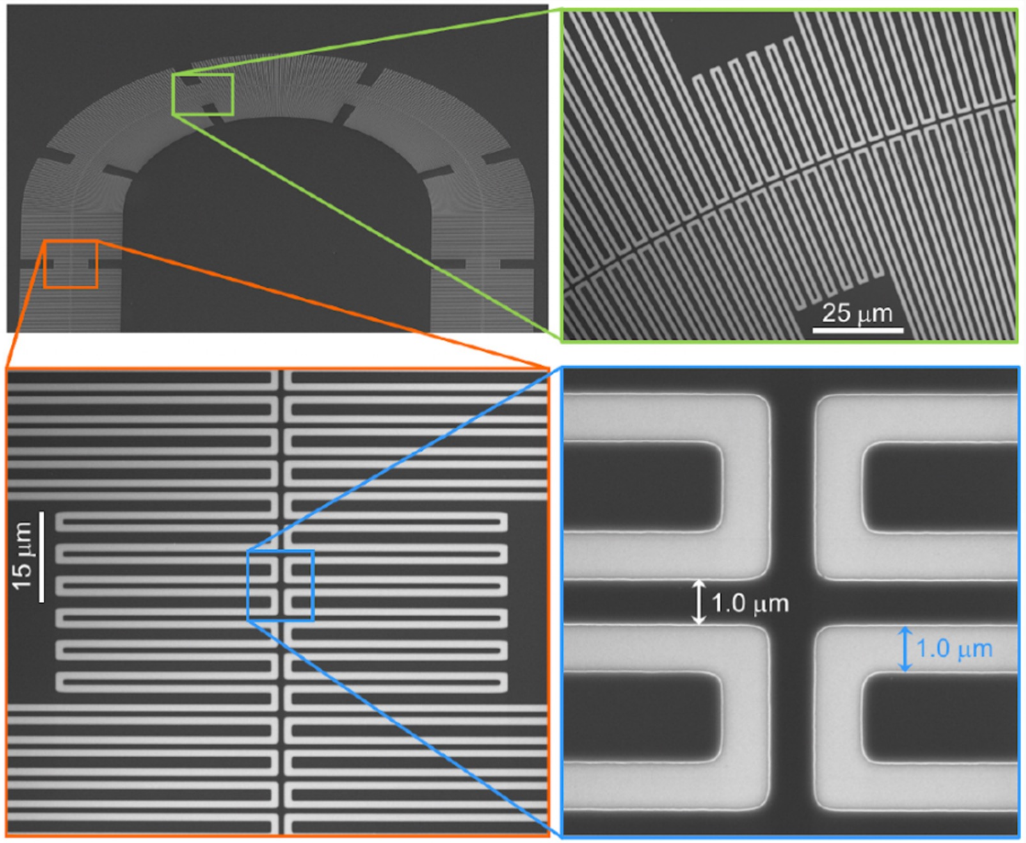
Realization of a Flux JPA

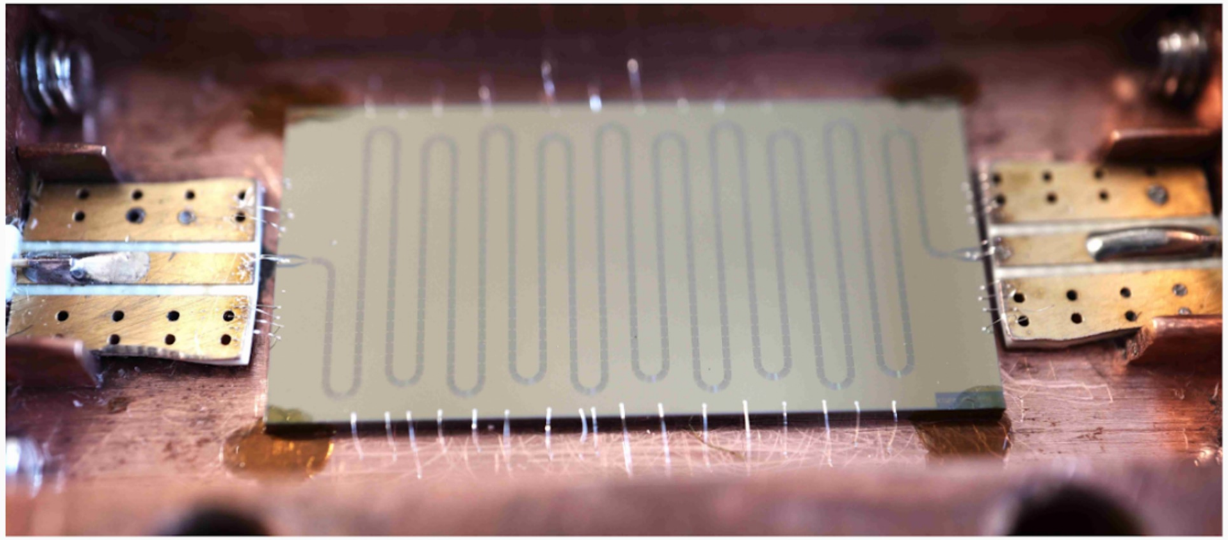


$$T_n^{JPA} = \frac{P_n}{k_B\, \Delta\nu \left(G5 + G_{JPA}\right)} = \left(0.130 \pm^{0.075}_{0.049}\right) K$$



FONDAZIONE BRUNO KESSLER





KITWPA in the copper box

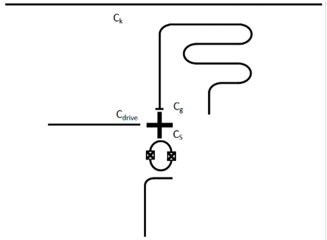
SEM pictures of the fabricated KI-TWPA.

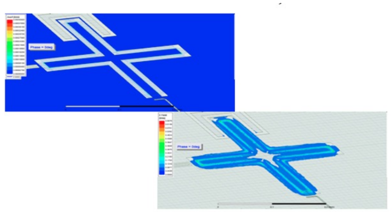
- The first KI-TWPA prototype based on the preliminary *half-size* layout L1 has been produced early in 2023;
- Device composed of 523 *super-cells* with a length of about 17 cm. Gain expected in the (7–11) dB range;
- Characterization results from these preliminary amplifiers are be crucial in refining the final design;

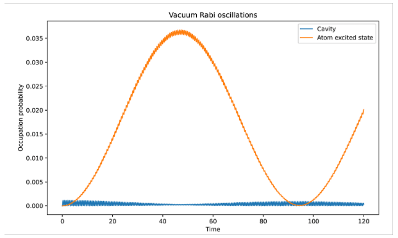
Design of 2D and 3D Superconducting Qubits

2D Qubits

$$\mathcal{L} = \frac{\dot{\vec{\Phi}} \cdot C \dot{\vec{\Phi}}}{2} - \frac{\vec{\Phi} \cdot L^{-1} \vec{\Phi}}{2} + E_j \cos\left(\frac{2\pi}{\Phi_0}\phi\right)$$







Circuit Modeling → Circuit Design → Electromagnetic Simulations → Quantum Simulation

1) Connect physical elements (C, L, Ic, Z0) to quantum-circuit properties (lifetime, frequency, couplings)

2) Design of circuit with first estimate of circuit element values

3) Layout realization, E.M. simulation and design optimization.

4) Evolution of quantum Hamiltonian based on circuit parameters

3D Qubits

From HFSS simulation

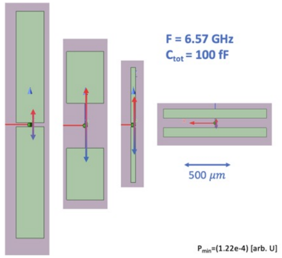
$$g_{01} = \frac{2e \cdot d_{eff}}{\hbar} E_0 \frac{1}{\sqrt{2}} \left(\frac{Ej}{8Ec}\right)^{1/4}$$

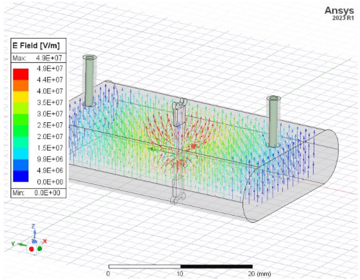
$$\hbar w_q = \sqrt{8\,Ec\,Ej} - Ec$$

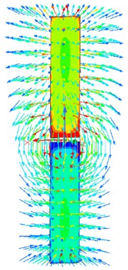
$$Ec = \frac{e^2}{2C}$$

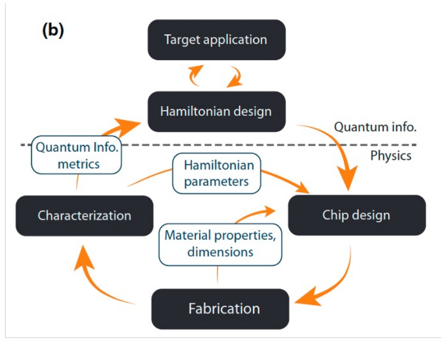
$$E_0 = \sqrt{\frac{\hbar w_r}{2\varepsilon_0 V}} \qquad V = \frac{\int \varepsilon_r(\vec{r}) \|\vec{E}(\vec{r})\|^2 d\vec{r}}{\max(\|\vec{E}(\vec{r})\|^2)} \approx \frac{1}{4} V_{cavity}$$

For TE_{110} mode



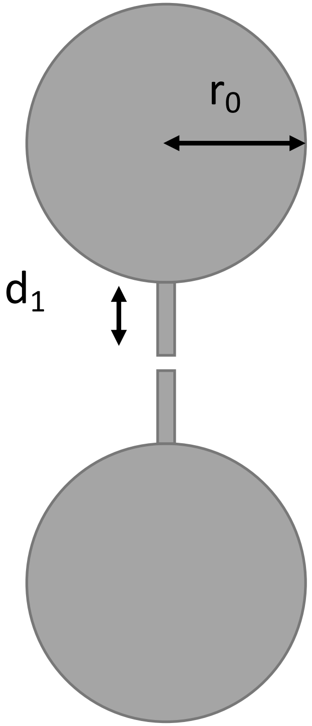


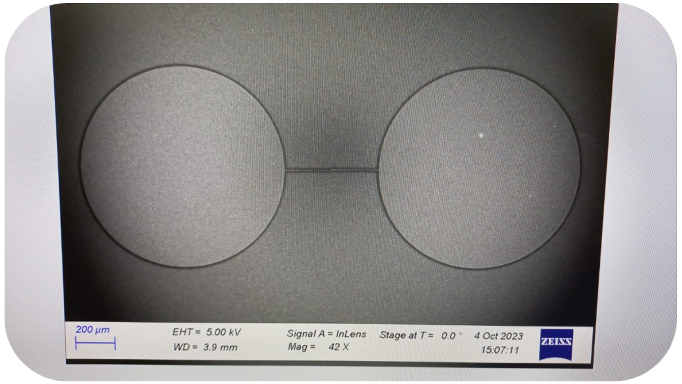


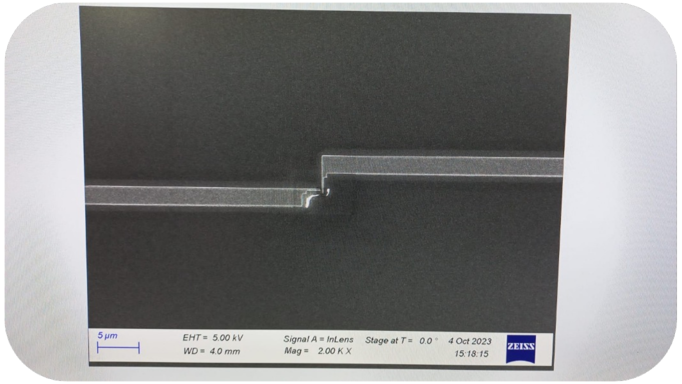


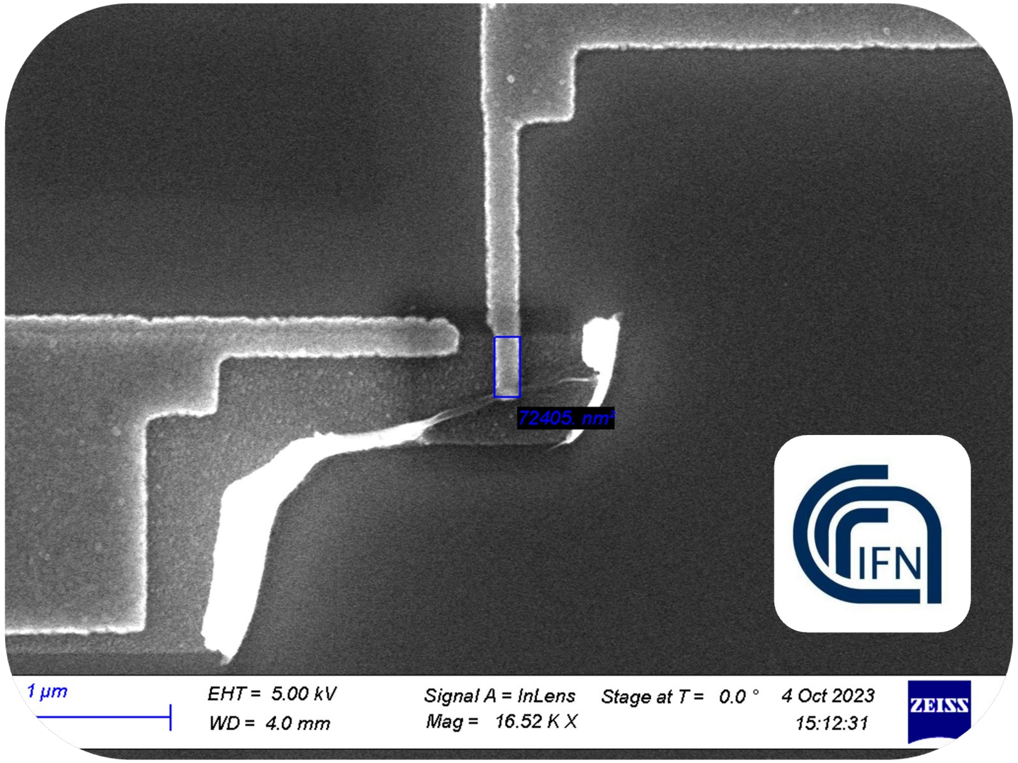
Y. Gao, PRX QUANTUM 2, 040202 (2021)

Manufactoring of 3D qubits with circular pads at CNR





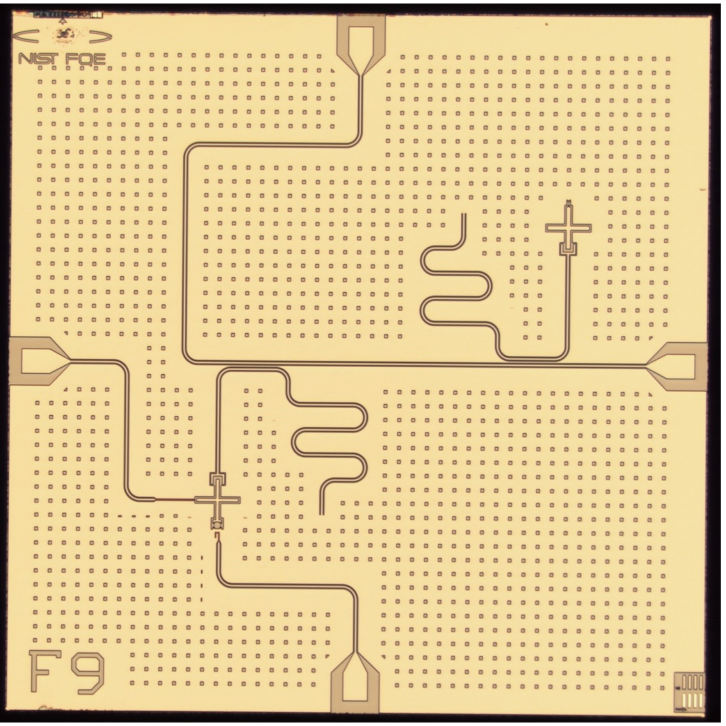


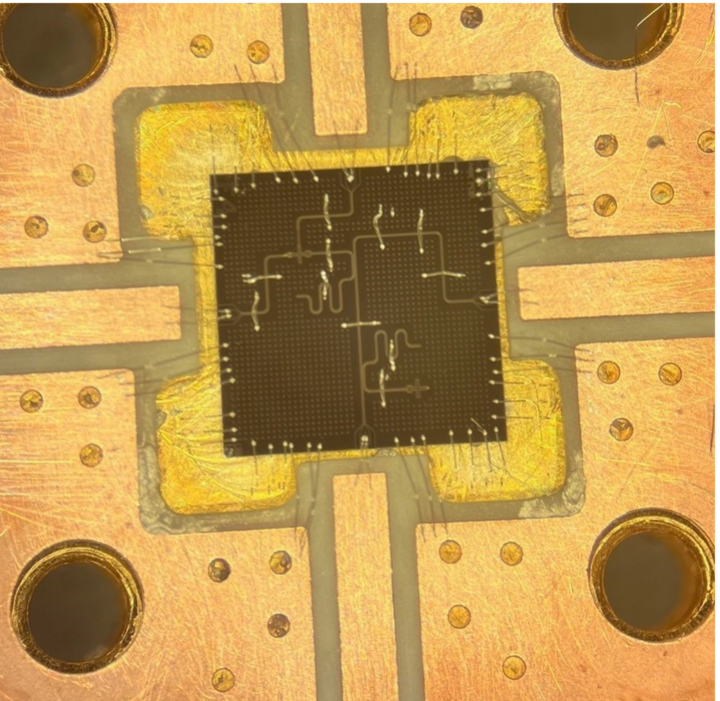


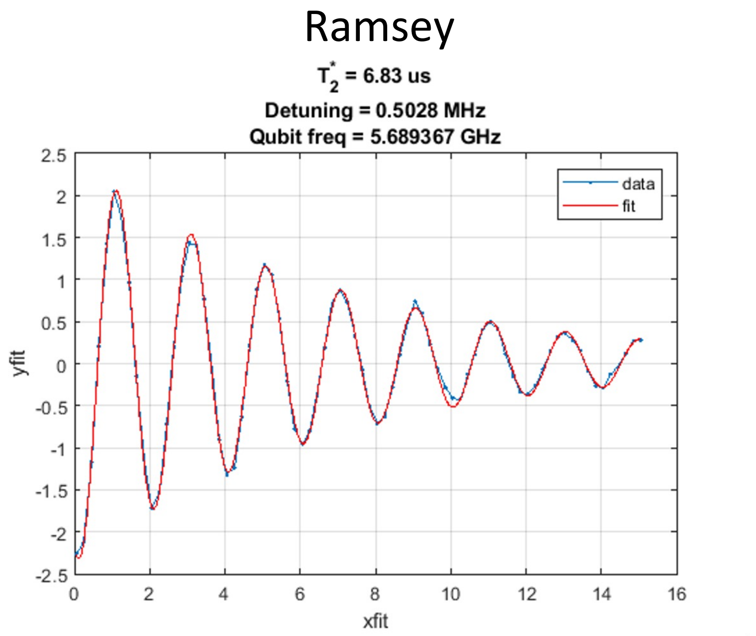
Aluminum JJ with area approx. 200 x 350 nm

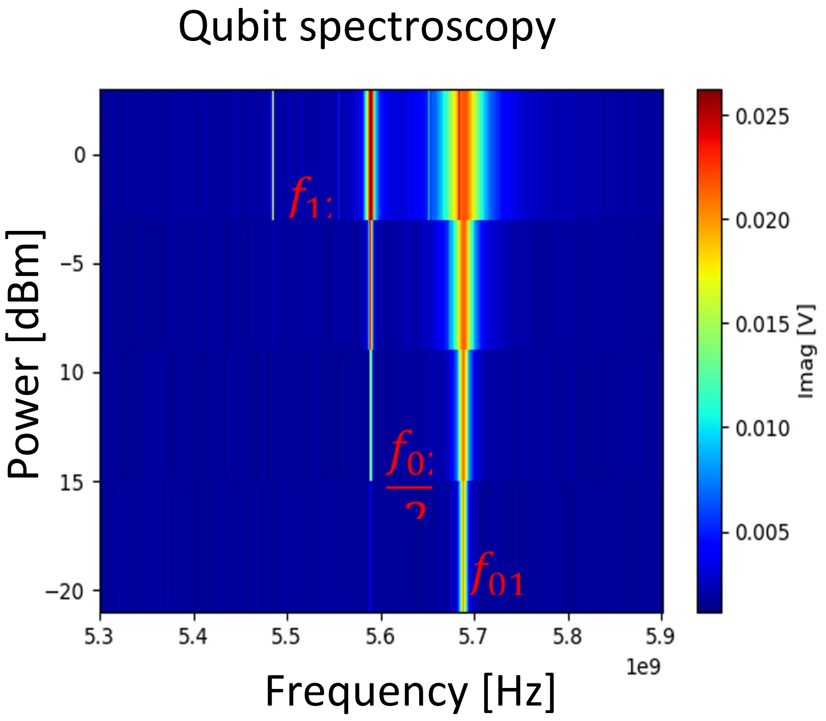
2d qubits

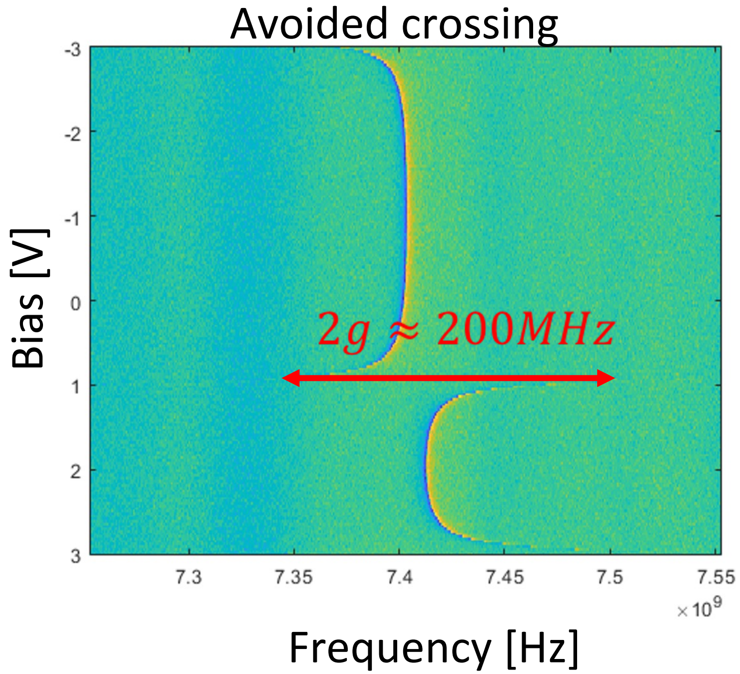
First version fabricated @ NIST
Second Fab @ NIST currently under characterization
Next fab @ FBK



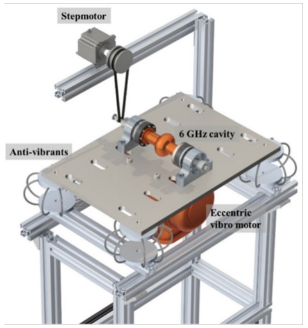


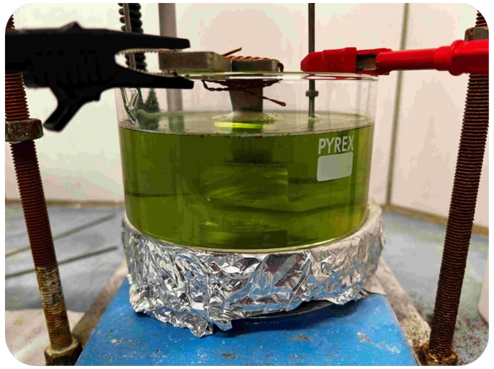






3D Cavity Fabrication

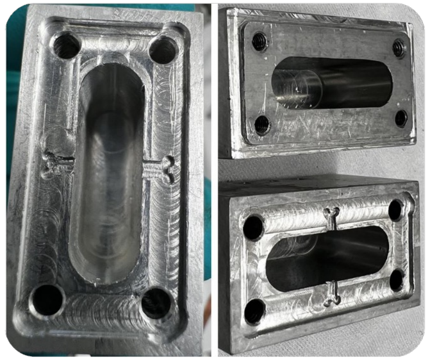




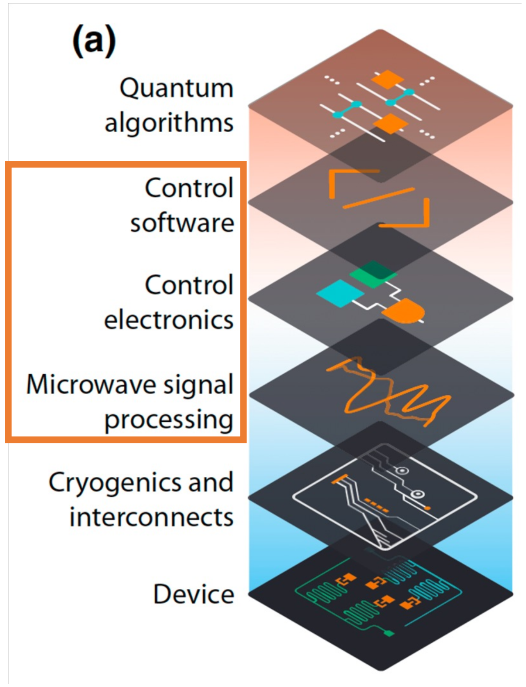
Mechanical
machining

▸ Vibro-tumbling

▸ Electropolishing



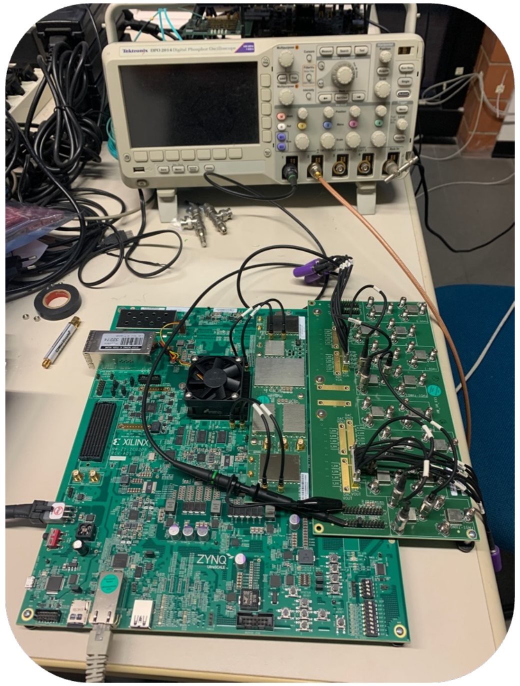
Qubit control with RFSoC hardware

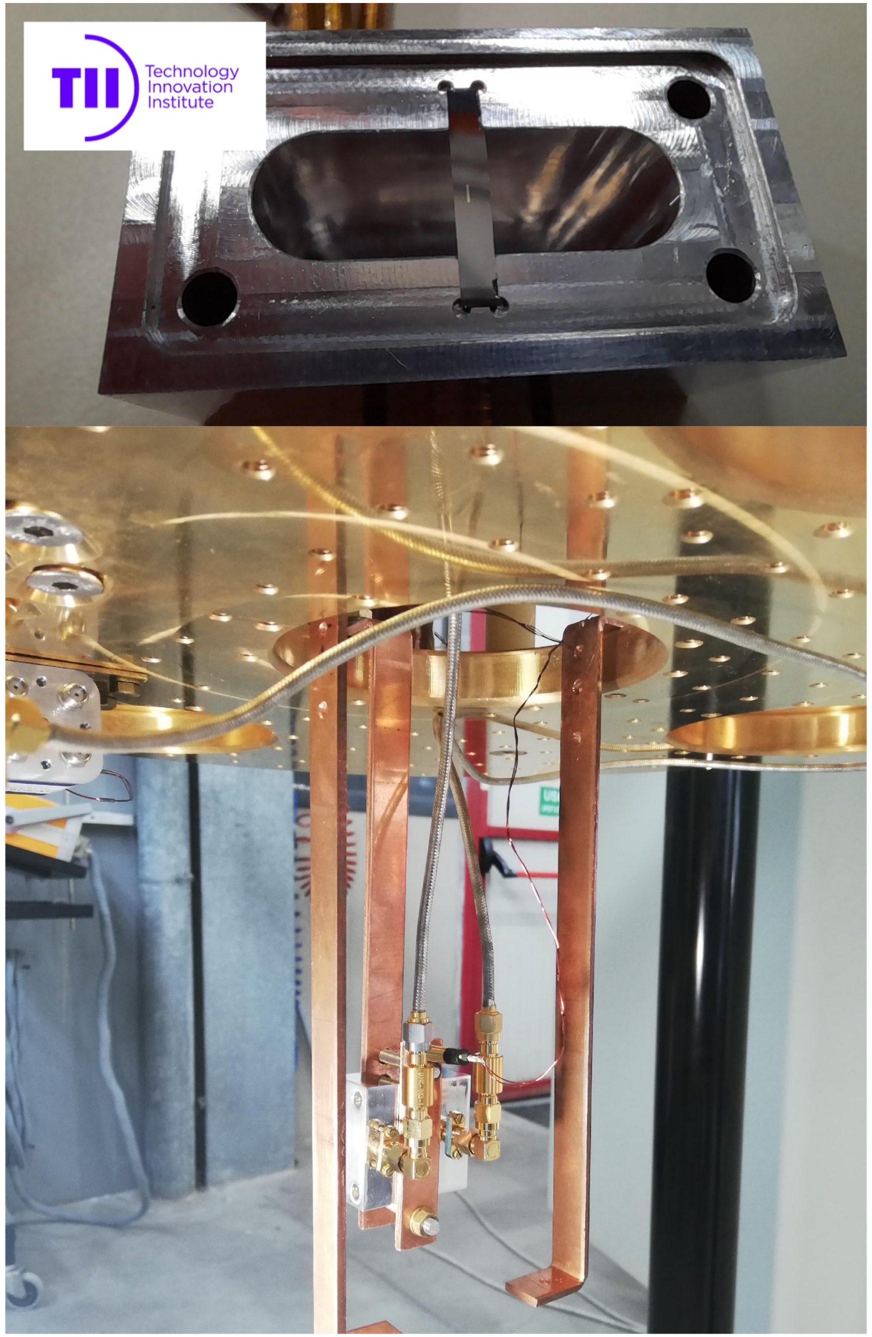


QICK is a kit of firmware and software done to use the Xilinx RFSoC to control quantum systems.

Firmware exists for the ZCU111, ZCU216, and RFSoC4x2 evaluation boards.

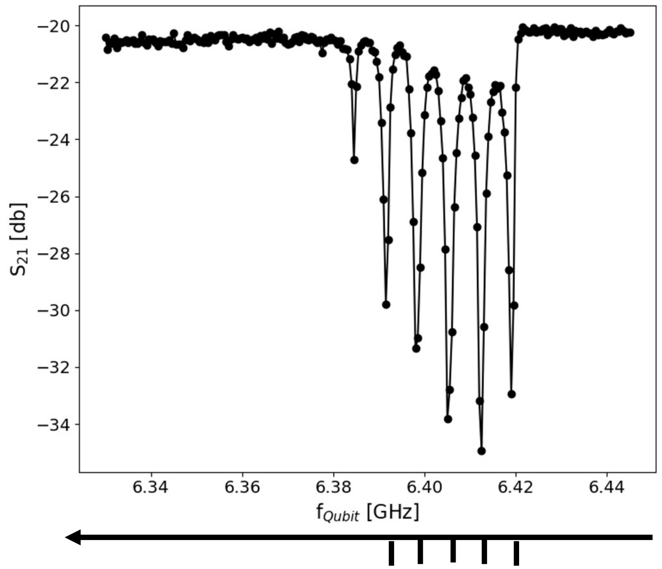
Extending use of QICK also to the ZCU208 board.





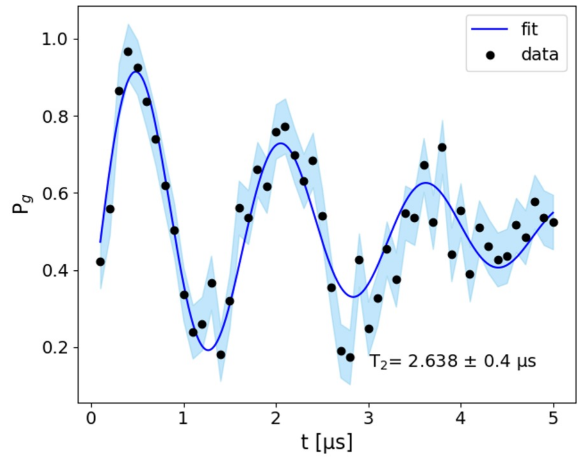
3D Resonator Coupled to a Superconducting Qubit

Photon Counting

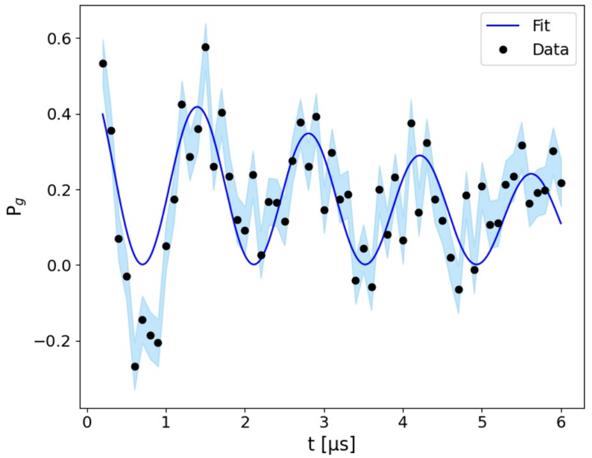


Number of photons in cavity 4 3 2 1 0

Ramsey Spectroscopy



Rabi Oscillations



3D qubit manufactured at the Technology Innovation Institute of Abu Dhabi