A few recent results on superconducting qubits: (1) one photon simultaneously exciting two qubits; (2) strong coupling between a single photon and a two-photon Fock state; and (3) Thouless pumping

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This talk will cover several experimental and theoretical results on superconducting qubits.

(1) We investigated a superconducting circuit composed of two flux qubits ultrastrongly coupled to a common *LC* resonator. Owing to the large anharmonicity of the flux qubits, the system can be described well by a generalized Dicke Hamiltonian containing spin-spin interaction terms. We observed an avoided level crossing providing evidence of the exotic interaction that allows the simultaneous excitation of two artificial atoms by absorbing one photon from the resonator. This multi-atom ultrastrongly coupled system opens the door to studying novel processes for quantum optics and quantum-information tasks on a chip.

A.F. Kockum et al., *Deterministic quantum nonlinear optics with single atoms and virtual photons,* Phys. Rev. A **95**, 063849 (2017). [PDF][Link][arXiv]; L. Garziano, V. Macri, R. Stassi, O. Di Stefano, F. Nori, S. Savasta, *One Photon Can Simultaneously Excite Two or More Atoms,* Phys. Rev. Lett. **117**, 043601 (2016). [PDF][Link][arXiv][Suppl. Info.]; A. Tomonaga, R. Stassi, H. Mukai, F. Nori, F. Yoshihara, J.S. Tsai, *Spectral properties of two superconducting artificial atoms coupled to a resonator in the ultrastrong coupling regime,* Nature Communications **16**, 5294 (2025). [PDF][Link][arXiv]

(2) We report an experimental observation of the strong coupling between a single-photon and a two-photon Fock state in an ultrastrongly-coupled circuit-QED system. The ultrastrong light-matter interaction breaks the excitation number conservation, and an external flux bias breaks the parity conservation. The combined effect of the two enables the strong one-two-photon coupling. Quantum Rabi-like avoided level-crossing is resolved when tuning the two-photon resonance frequency of the first mode across the single-photon resonance frequency of the second mode. Within this new photonic regime, we observe thresholdless 2nd-harmonic generation for a mean photon number in the resonator below one. These results represent a step towards a new regime of quantum nonlinear optics, where individual photons can deterministically and coherently interact with each other in the absence of any stimulating field.

S.P. Wang, A. Mercurio, A. Ridolfo, Y. Wang, M. Chen, W. Wang, Y. Liu, H. Sun, T. Li, F. Nori, S. Savasta, J.Q. You, *Strong coupling between a single-photon and a two-photon Fock state,* Nature Communications **16**, 8730 (2025). [PDF][Link][arXiv][Suppl. Info.]

(3) I will summarize experimental observations of the competition and interplay between Thouless pumping and disorder on a 41-qubit superconducting quantum processor. This highly controllable system provides a valuable quantum simulating platform for studying various aspects of topological physics in the presence of disorder.

Y. Liu, Y.R. Zhang, … , F. Nori, K. Xu, H. Fan, *Interplay between disorder and topology in Thouless pumping on a super-conducting quantum processor,* Nature Communications **16**, 108 (2025). [PDF][Link][arXiv][Suppl. Info.]