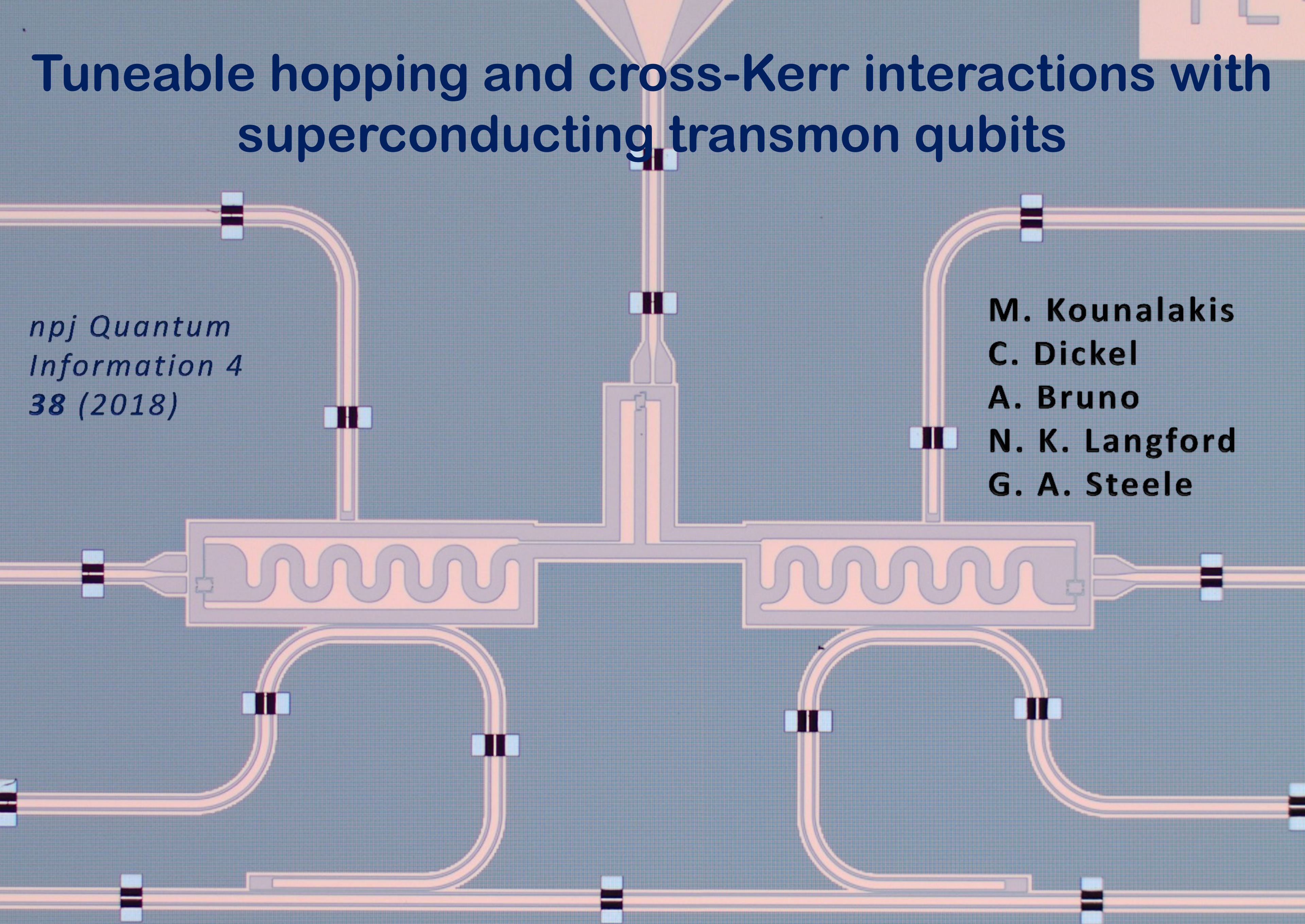
Tuneable hopping and cross-Kerr interactions with superconducting transmon qubits



*npj Quantum Information **4** 38 (2018)*

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Acknowledgements: **DiCarlo lab**

Motivation

Implementing on-chip interaction regimes for many-body quantum simulations

Strongly correlated systems

➢ **Many interesting (unsolved) quantum many-body problems in lattice structures:**

- High Tc superconductors → pairing mechanism?
- Topological properties of fractional QH states?
- Color confinement in QCD
- ….

➢ **Large Hilbert spaces: theory gets difficult**

Analytical/Numerical methods:

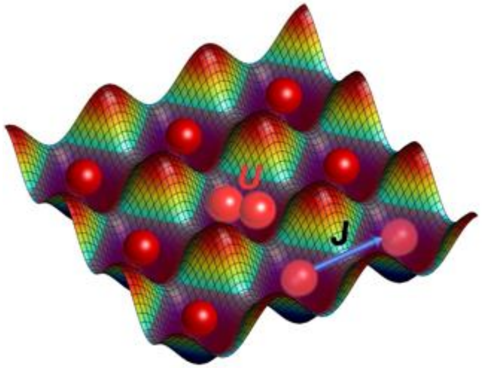
- Mean-field theory (limited at low dimensions)
- DMRG (limitations above 1D)
- Matrix product states
- Keldysh path integral formalism
- …….

➢ **Quantum simulation**

Use well-controlled engineered quantum mechanical systems to study these models

Start "simple" → ***Increase complexity: particles & interactions***

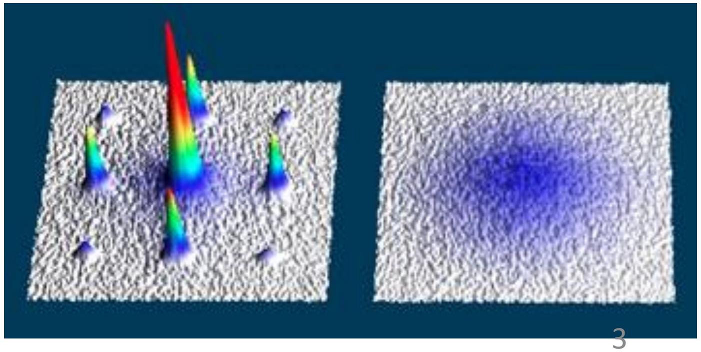
➢ **A paradigmatic many-body system: *"Bose – Hubbard model"***



http://photon.physnet.uni-hamburg.de

Phase transition at the interplay of hopping vs on-site interactions (J vs U)

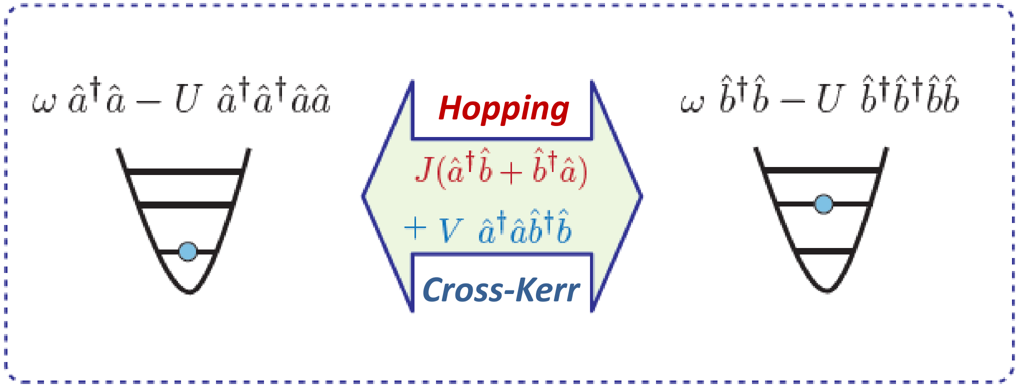
Superfluid to Mott-Insulator Transition:

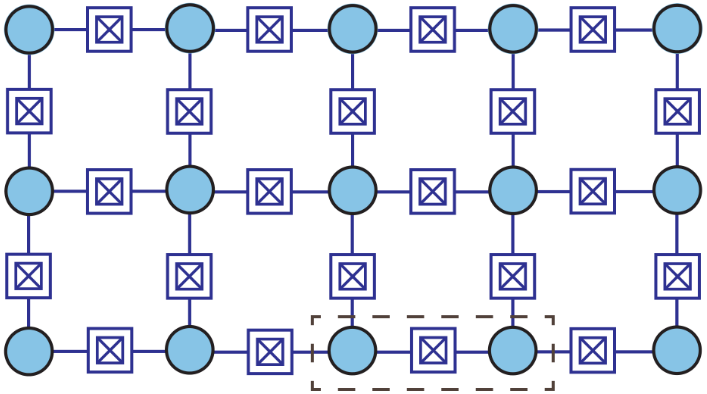


Nature ***415****, 39-44 (2002)*

Extended Bose-Hubbard models

Adding new interaction terms: "*cross-Kerr*"





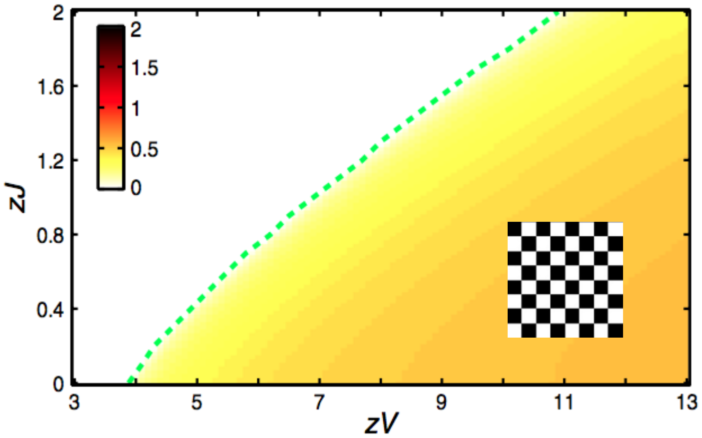
Competing interactions leading to richer quantum phase transitions

- ***Photon crystalline-supersolid phases?***

(Mean-field theory predictions)

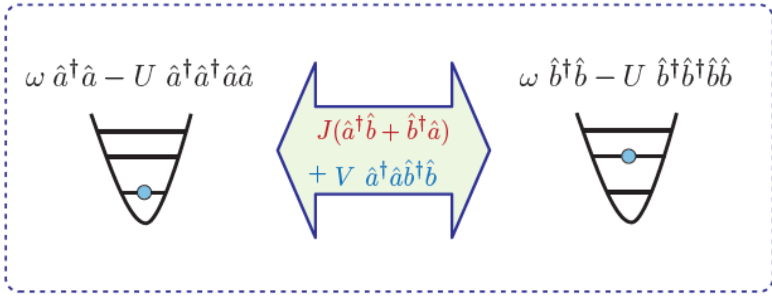
Jin et al, Phys. Rev. Lett. (2013)

Exploring different J/V regimes could lead to exotic phases of light

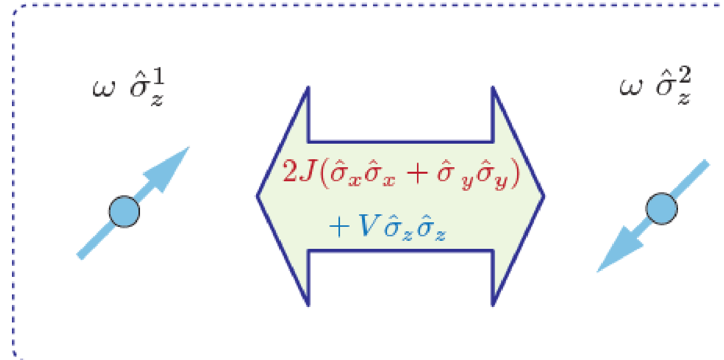


Emulating spin systems

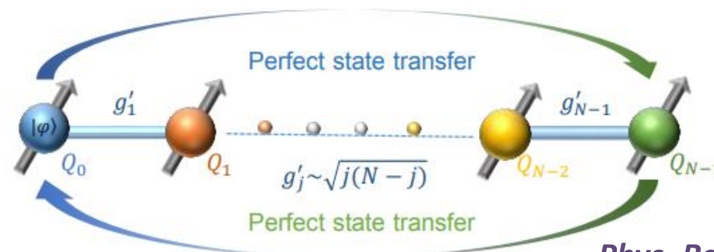
Restricting to qubit manifold:



Heisenberg XXZ model

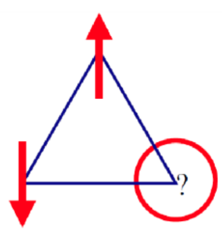


- State transfer protocols in spin chains



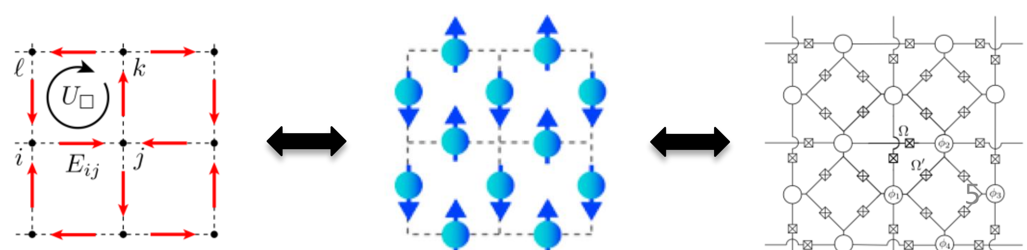
Phys. Rev. Lett. 92 (2004)
Phys. Rev. Applied 10 (2018)

- Frustration



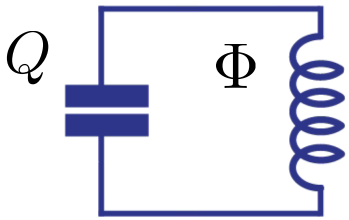
- Simulating lattice gauge fields

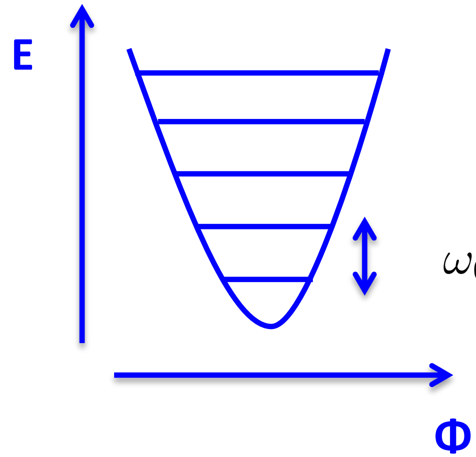
Marcos et al,
Ann. Phys. (2014)



Superconducting transmon qubits

LC circuit



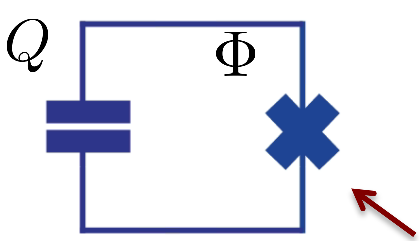


$$H = \frac{Q^2}{2C} + \frac{\Phi^2}{2L}$$

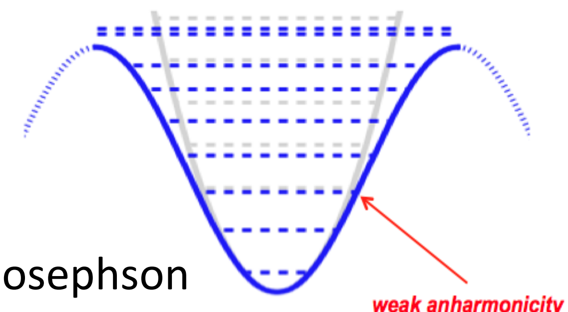
$$\omega_{01} = \frac{1}{\sqrt{LC}} \sim 5 - 10\ \mathrm{GHz}$$

Operating above the energy scale of thermal effects

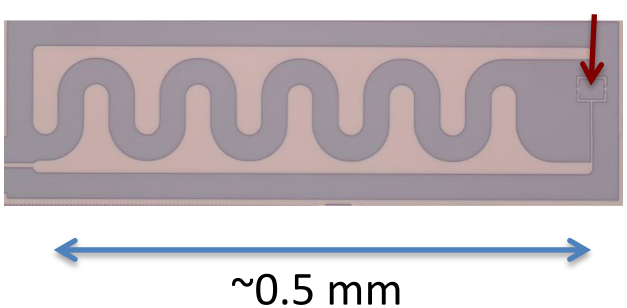
Transmon qubit



SIS Josephson junction



- Non-dissipative (superconducting)
- Flexible in design and engineering
- Nonlinearity provided by Josephson junctions

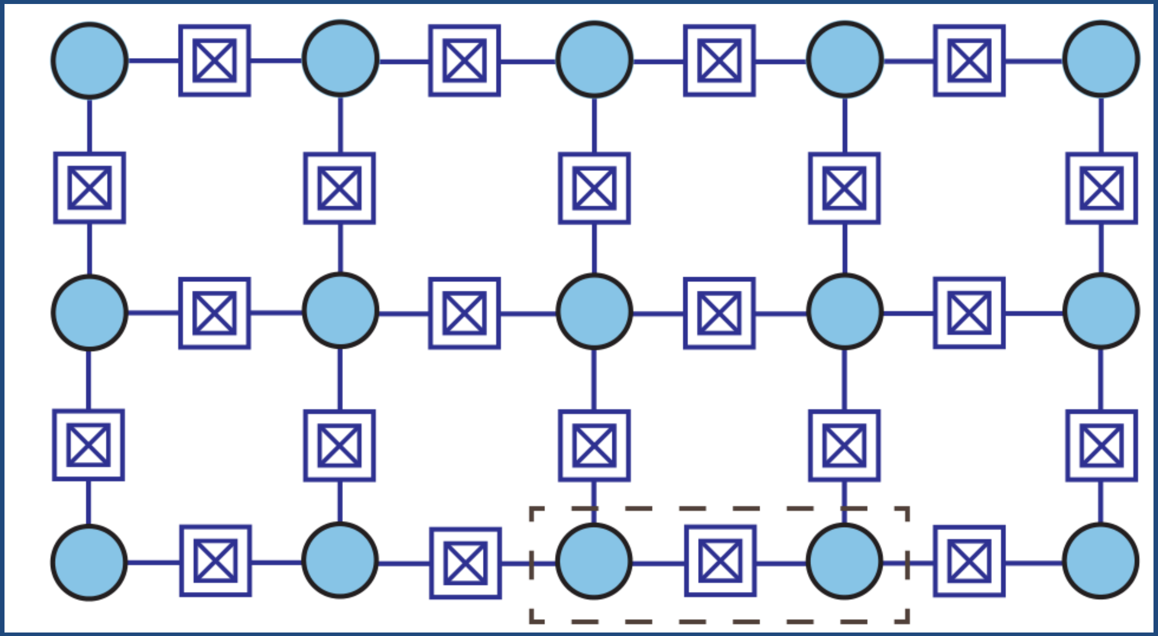


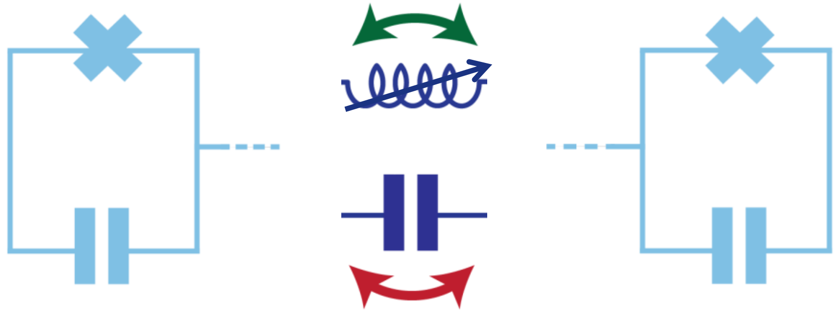
$$H = \frac{Q^2}{2C} - E_{\mathrm{J}} \cos\Phi \quad = \quad \omega_A\ \hat{a}^\dagger \hat{a} - \frac{E_{C_A}}{2}\ \hat{a}^\dagger \hat{a}^\dagger \hat{a}\hat{a}$$

Koch et al. PRA (2007)

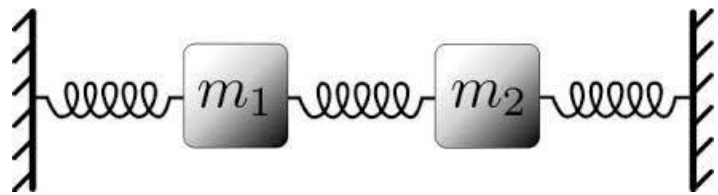
Anharmonicity / On-site interaction

Coupling transmons

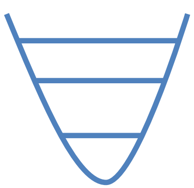




Same as coupled mass-spring system:

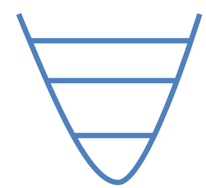


Dipole coupling / hopping interaction



$$-J_{\mathrm{L}}(\hat{a}^\dagger\hat{b} + \hat{b}^\dagger\hat{a})$$

$$J_{\mathrm{C}}(\hat{a}^\dagger\hat{b} + \hat{b}^\dagger\hat{a})$$

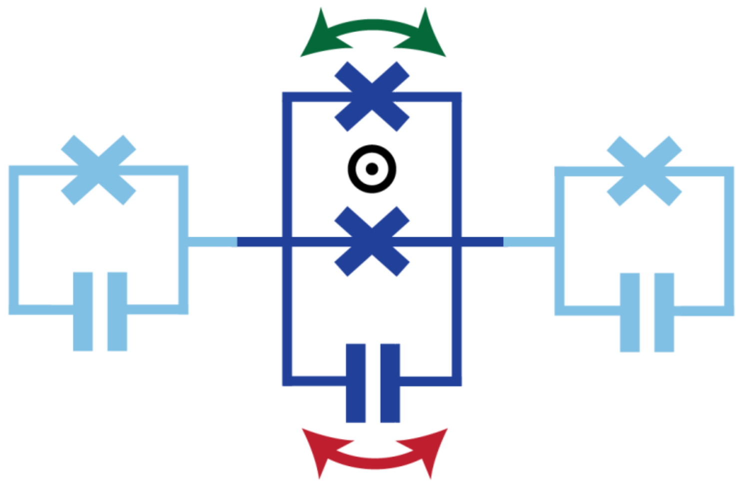


$$\omega_A\ \hat{a}^\dagger\hat{a} - \frac{E_{C_A}}{2}\ \hat{a}^\dagger\hat{a}^\dagger\hat{a}\hat{a}$$

$$\omega_B\ \hat{b}^\dagger\hat{b} - \frac{E_{C_B}}{2}\ \hat{b}^\dagger\hat{b}^\dagger\hat{b}\hat{b}$$

A capacitor in parallel to a tuneable inductor can be used to turn coupling on/off

Our coupling scheme: A SQUID and a capacitor

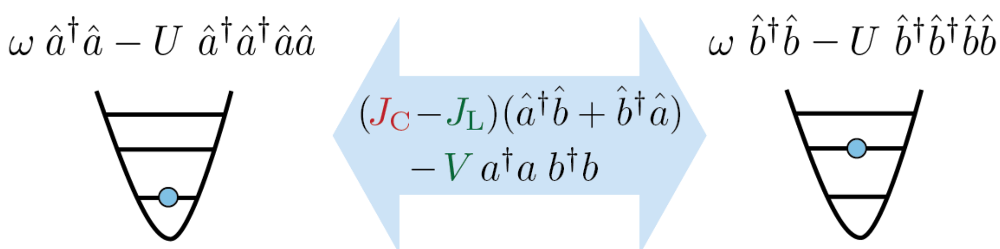


SQUID: flux-tuneable nonlinear inductor

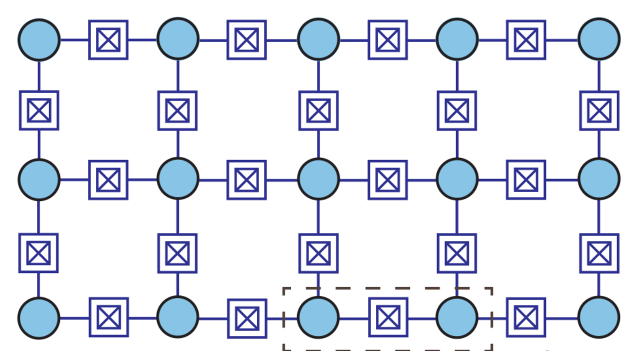
$$-J_{\mathrm{L}}(\hat{a}^\dagger\hat{b} + \hat{b}^\dagger\hat{a}) - V\, a^\dagger a\, b^\dagger b + \ldots$$

Nonlinearity in the coupling results in cross-Kerr interaction

Combined with a capacitor:



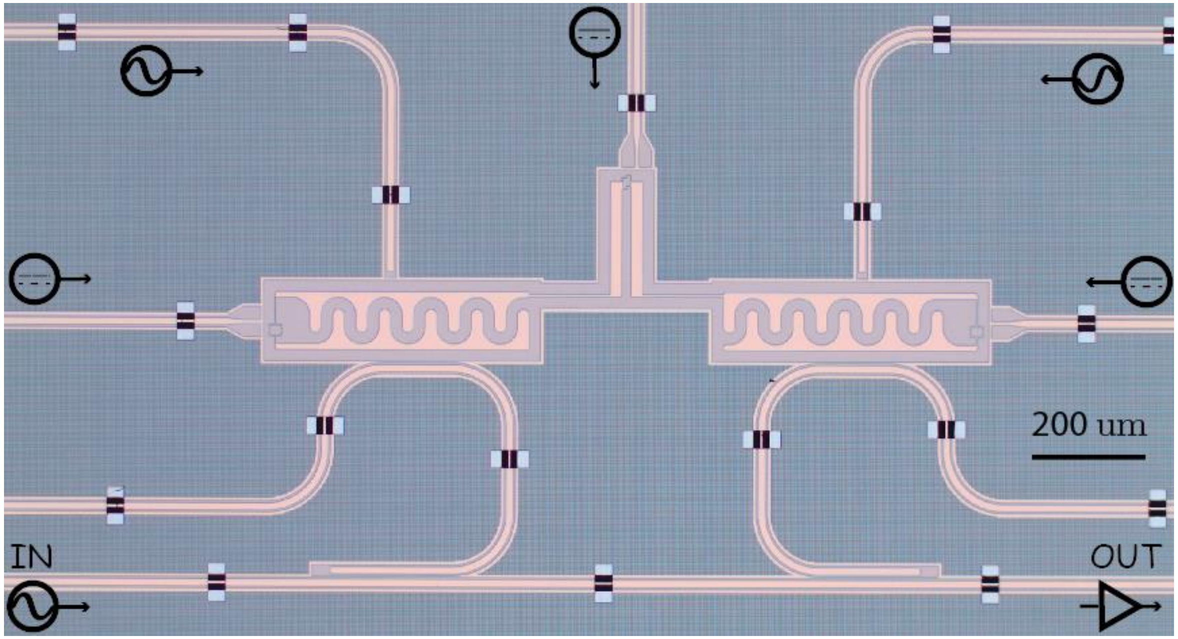
Tuneable J/V coupling regimes

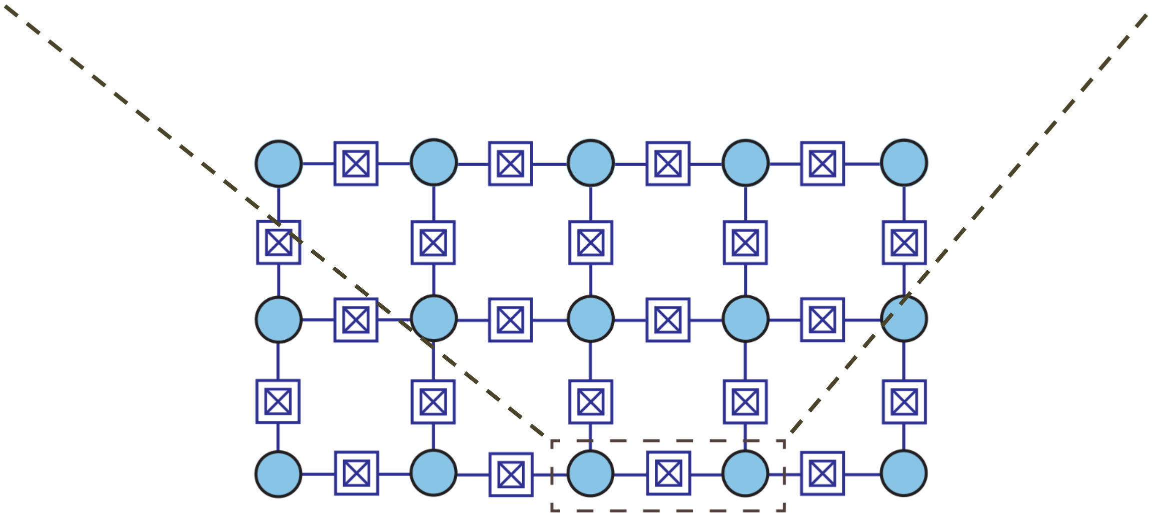


Implementation

Implementation

NbTiN chip:



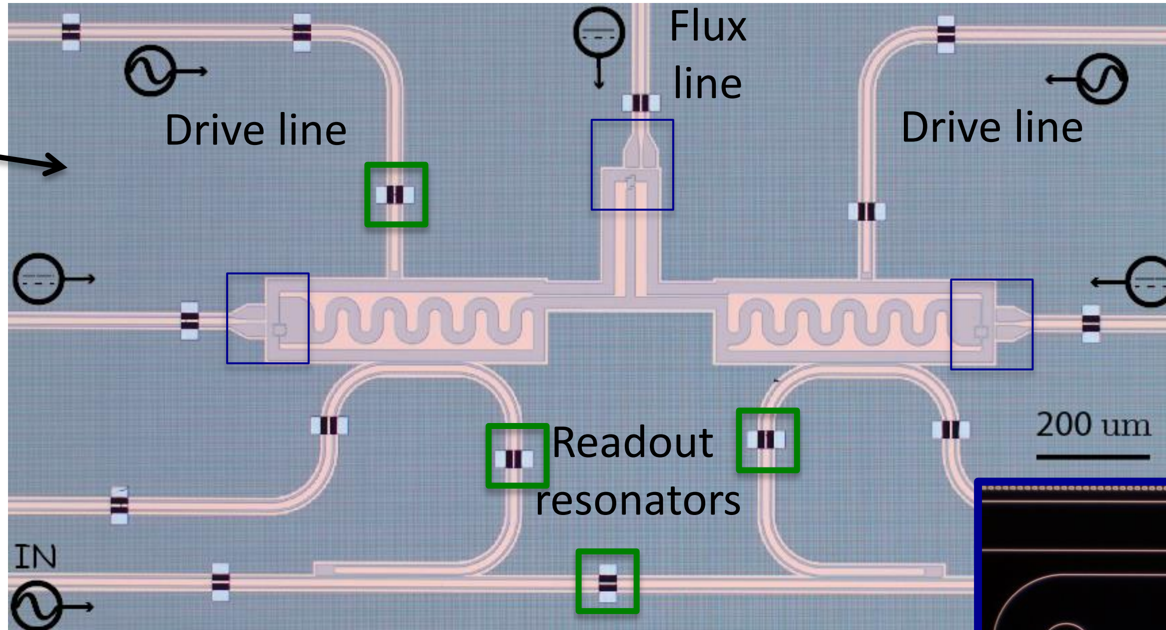


Implementation

NbTiN chip:

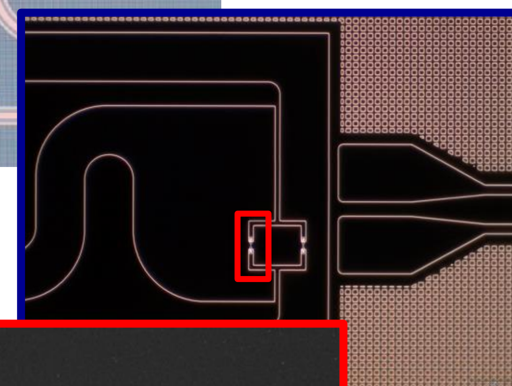
Ground plane

Flux line

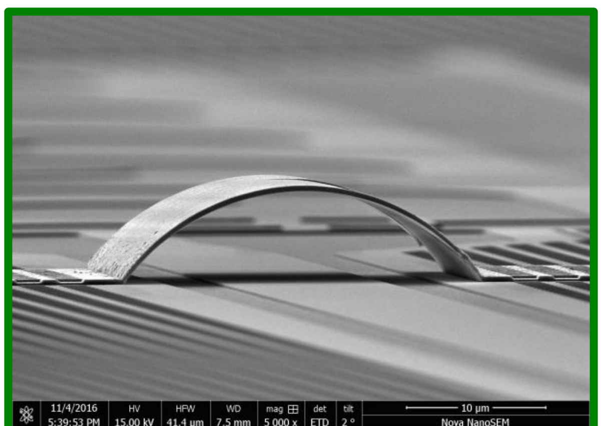


Flux line

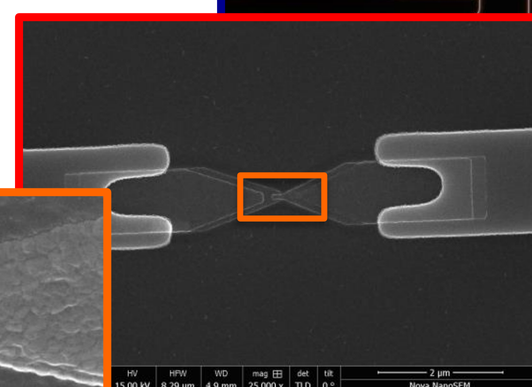
SQUID loop

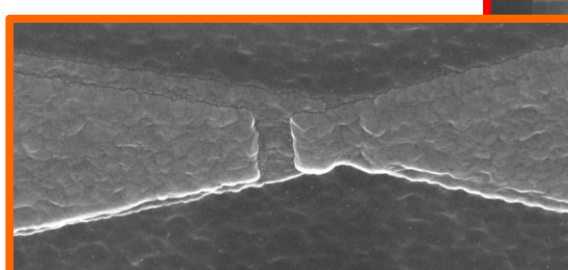


Air-bridges



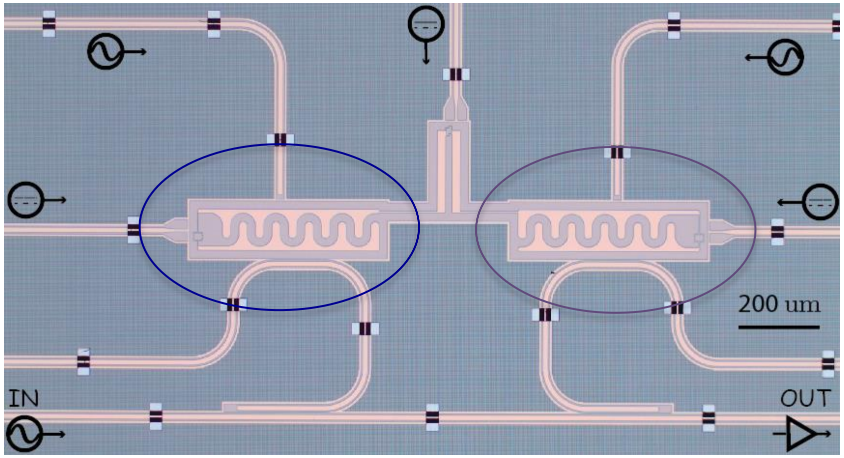
Al/AlOx/Al junctions



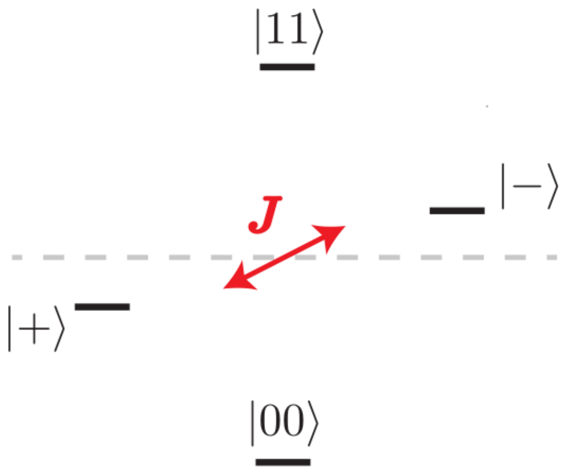


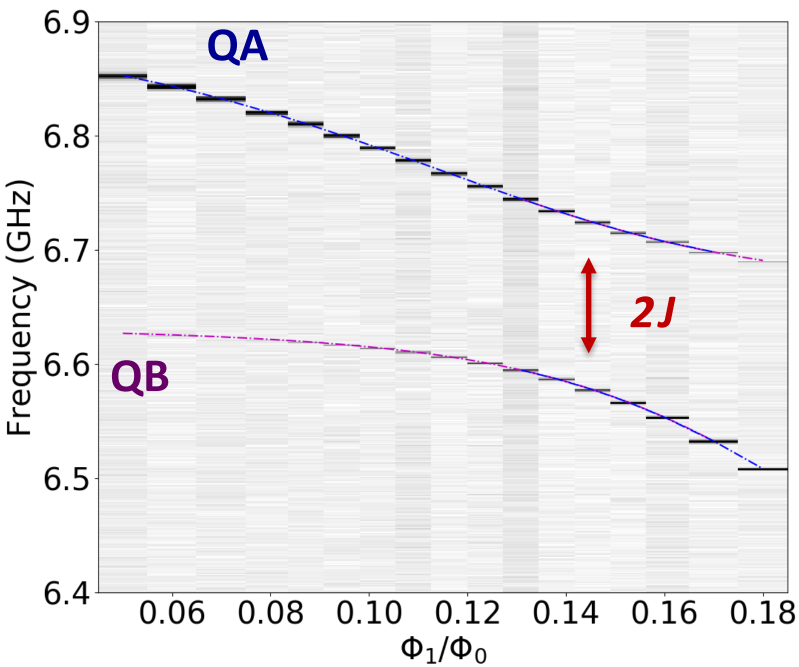
Measuring the normal mode splitting

- “Cross” **QA** into resonance with **QB**
- Normal mode splitting determines the linear qubit-qubit coupling

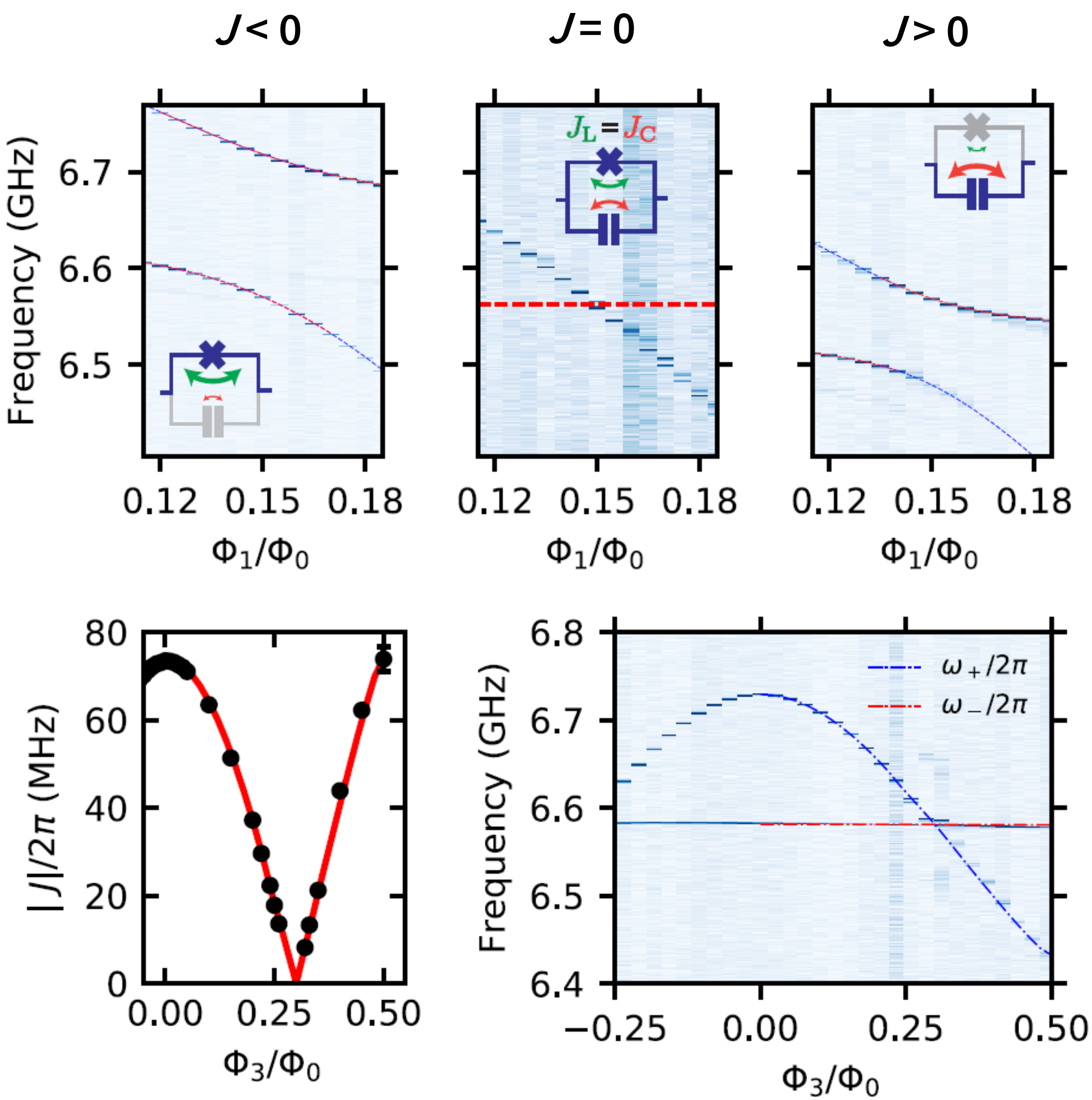


Avoided crossing

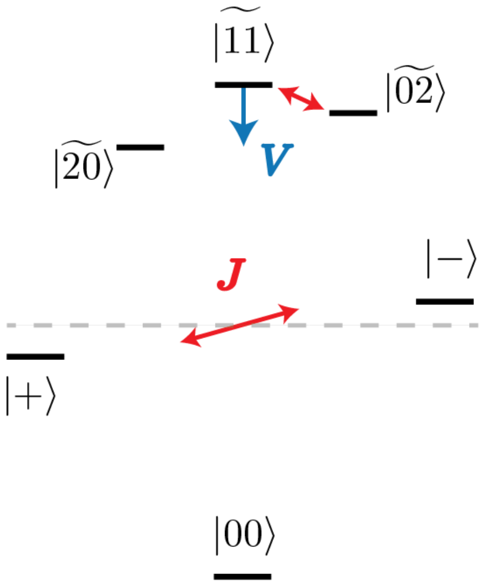




Tuning the linear coupling through zero



Measuring the cross-Kerr coupling



Cross-Kerr: the energy of one qubit depends on the other being populated

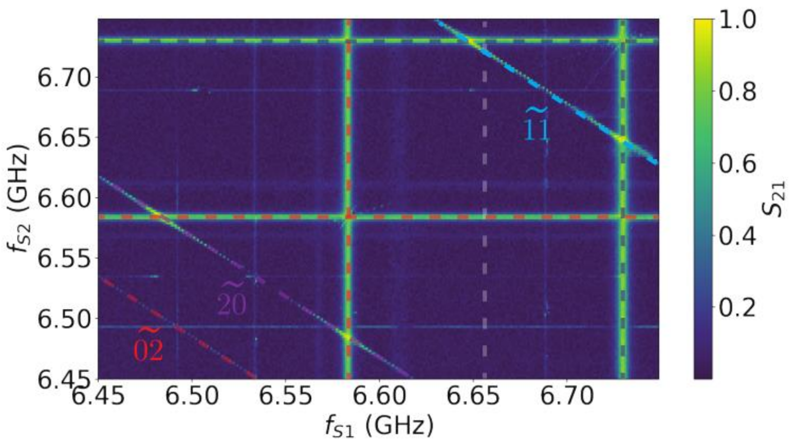
$-V\, a^\dagger a\, b^\dagger b$ ➡ ***Negative shift of 11 level***

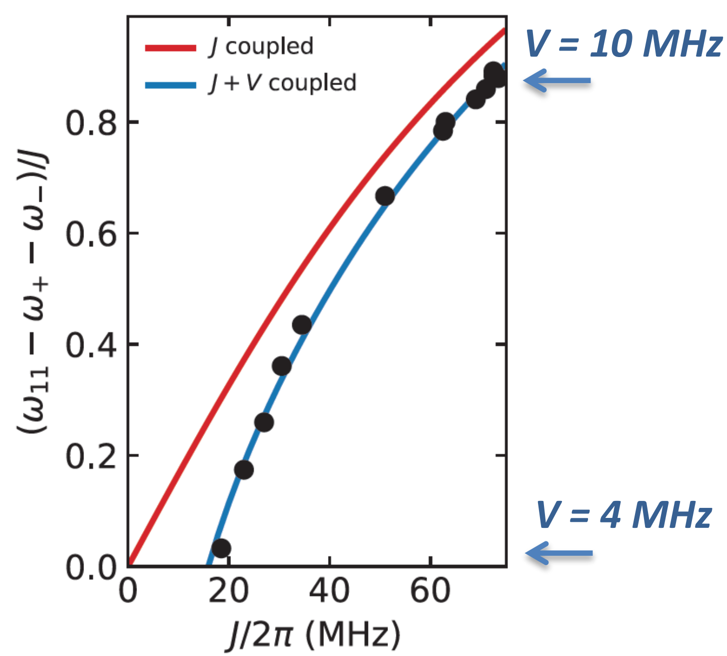
$$\omega_{11} - \omega_+ - \omega_- < 0$$

BUT: transmons are weakly anharmonic

➡ ***Repulsion of 11 due to higher levels***

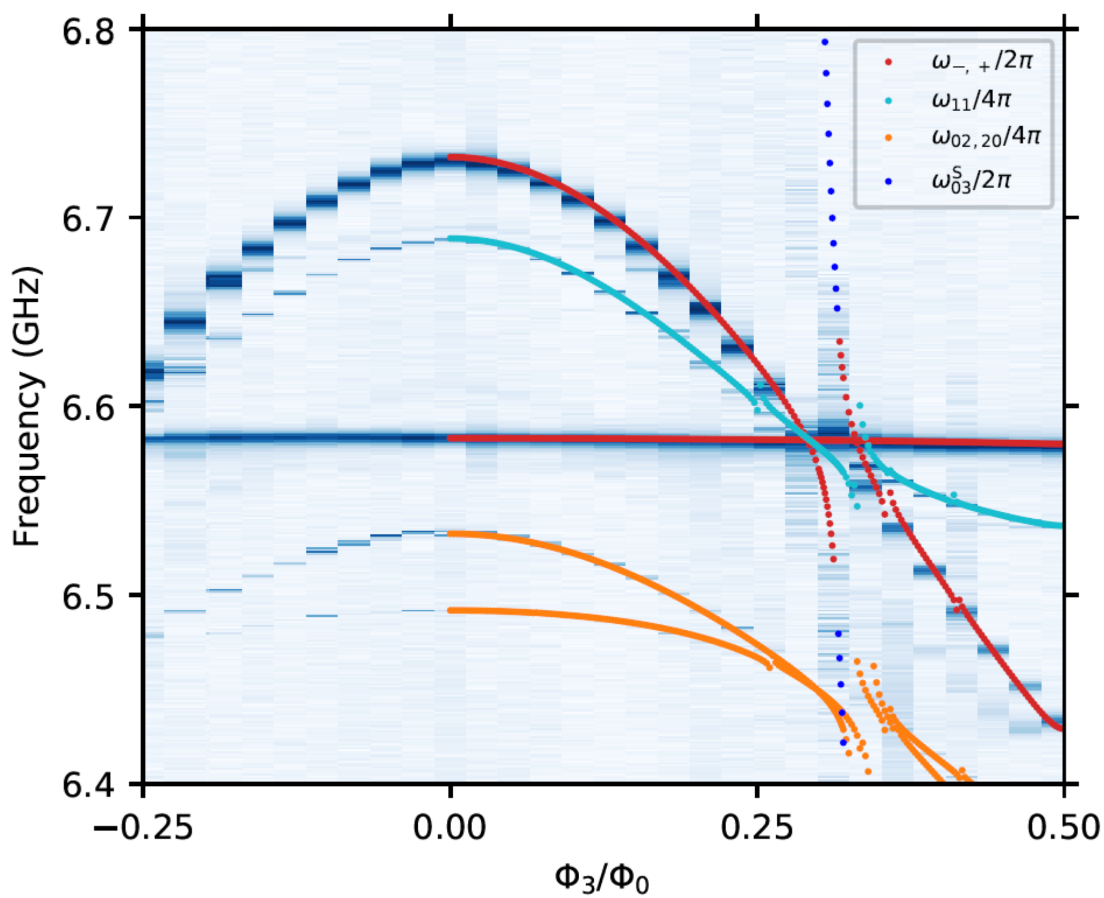
3-tone spectroscopy

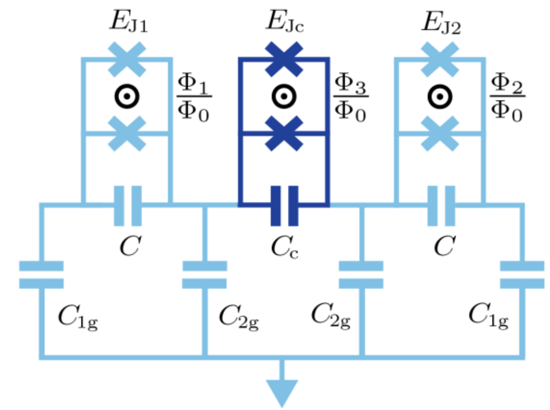




Full circuit model

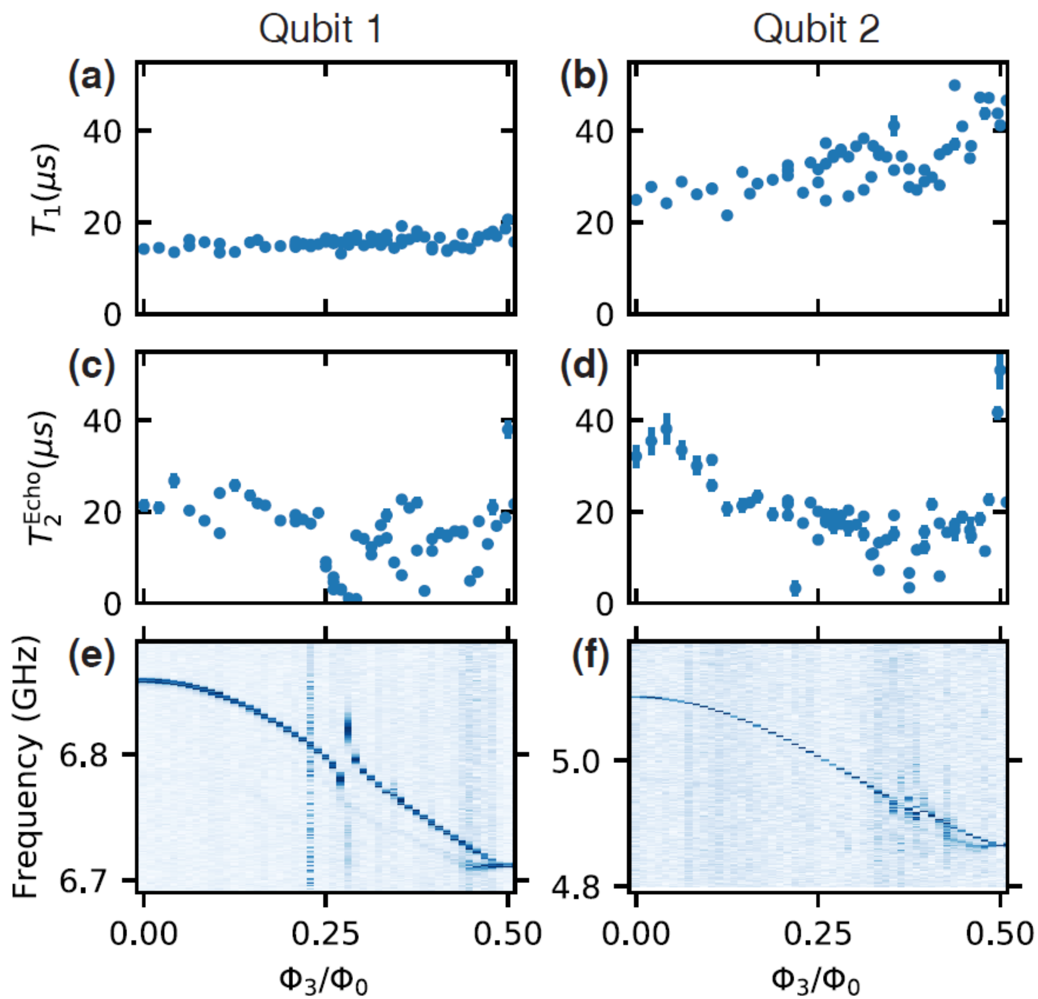
Higher excitation manifold of the coupled system:





- All transitions well-understood including interfering “coupler mode”
- Crucial for scaling up to more complicated circuits

High coherence vs coupler tuning

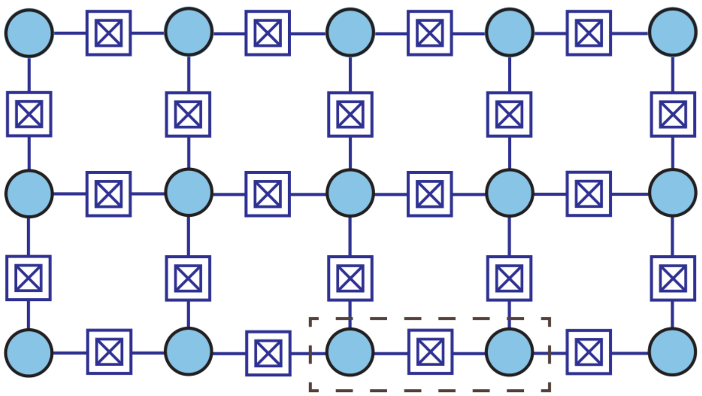


- High coherence compared to interaction timescales (2-3 orders of magnitude)
- Relaxation times unaffected by the coupler

Outlook to new experiments

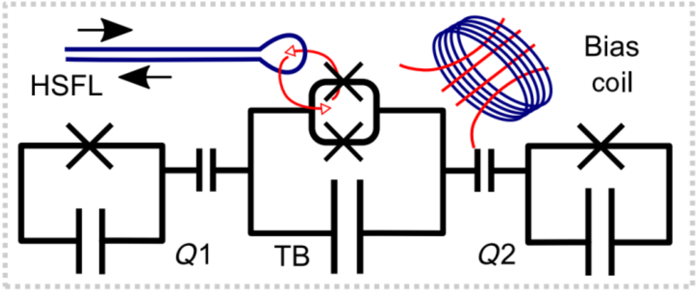
Spin models with off-resonant qubits

Scaling up leads to complexity…



- ***Circuitry gets more complicated***
- ***Frequency crowding***
- ***Flux cross-talk***

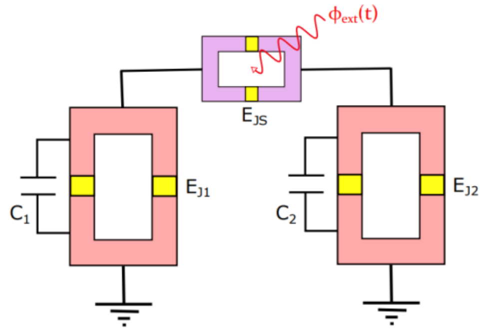
Making off-resonant qubits interact



D. McKay et al., Phys. Rev. Applied 6 (2016)
M. Ganzhorn et al., arXiv:1809.05057

Difference frequency: **XY** coupling (hopping)
Sum frequency: **pure XX** coupling (squeezing)
Cross-Kerr: **ZZ** coupling

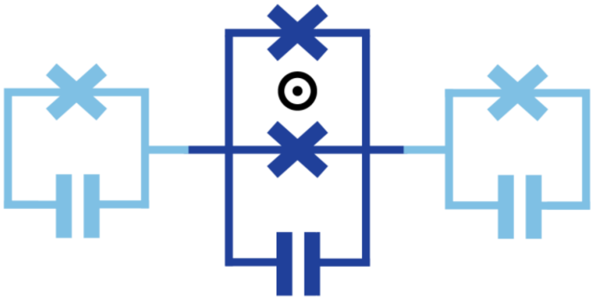
Smart choice of flux modulation of our coupler can implement arbitrary spin model interactions between two detuned qubits

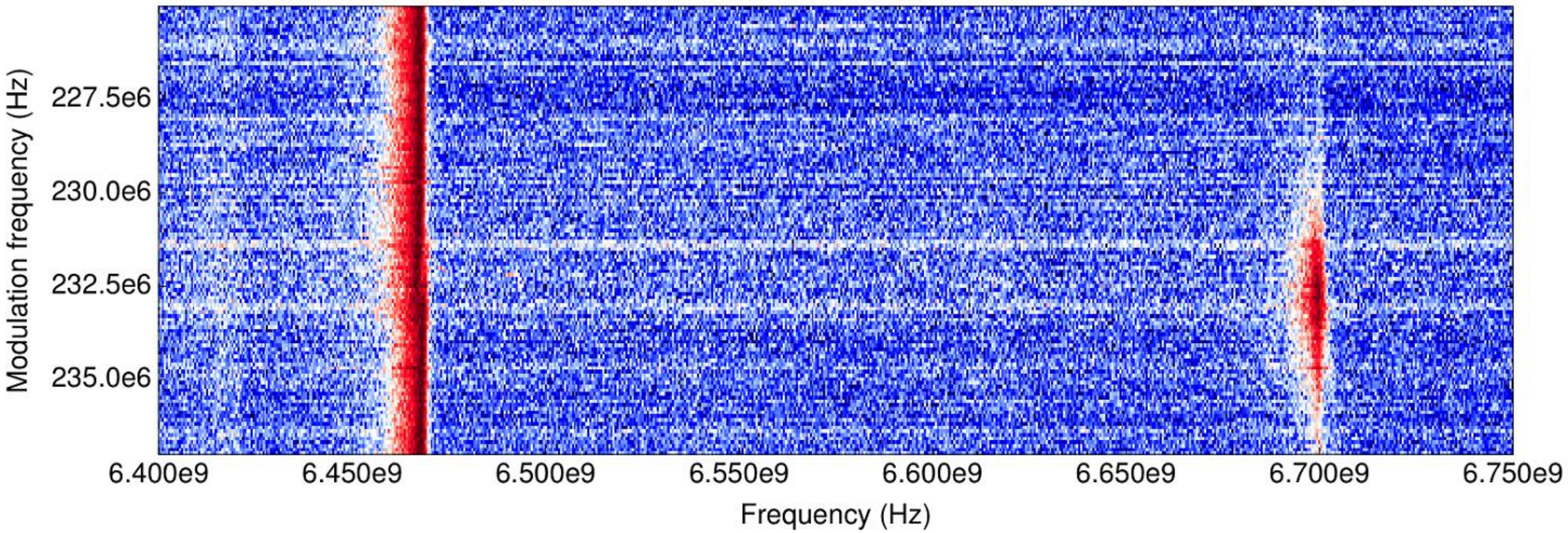


M. Sameti & M. J. Hartmann arXiv:1808.03176
Collodo et al., arXiv:1808.00889

Towards dynamic flux pumping in our device

Sweeping the coupler flux modulation around the frequency difference





Work in progress..

Summary

- A scalable building block for analog quantum simulation of many-body systems
- Tuning and suppressing hopping terms
- Tuning the strength of nonlinear (cross-Kerr) interactions relative to hopping
- High relaxation times unaffected by the coupler
- Towards parametrically activated spin model interactions in off-resonant qubits

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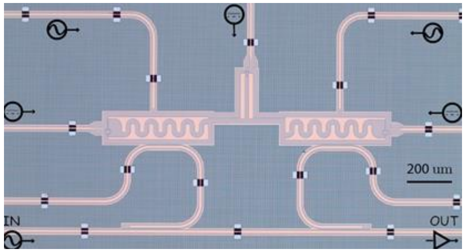

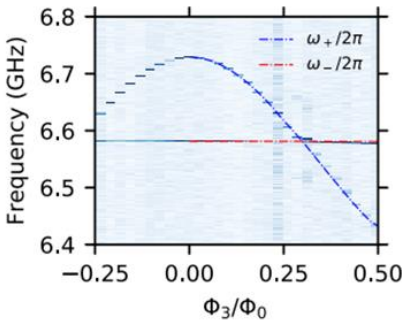

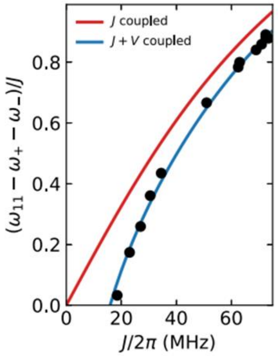

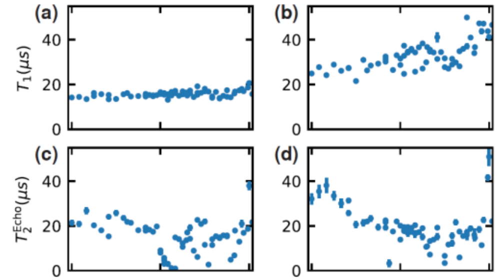

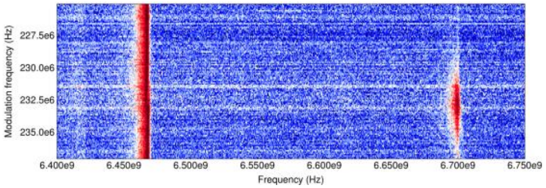

Acknowledgements: **DiCarlo lab**

   

C. Dickel A. Bruno N. Langford G. Steele

  

F. Luthi R. Sagastizabal L. DiCarlo

Thank you for your attention!