Superconducting qubits for analogue quantum simulation

Gerhard Kirchmair

Workshop on Quantum Science and Quantum Technologies
ICTP Trieste

September 13th 2017

universität innsbruck
CIFAR AZRIELI Global Scholars
Atoms, Light, and Molecules
Innsbruck Physics Research Center
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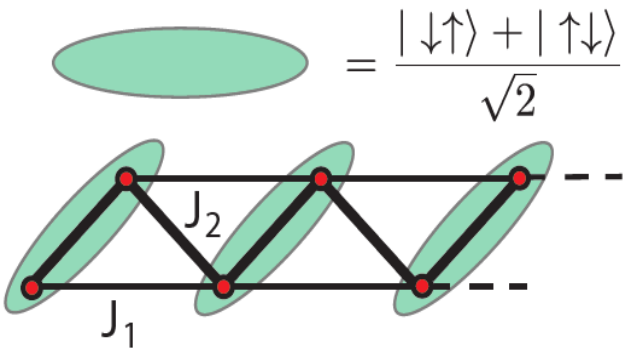
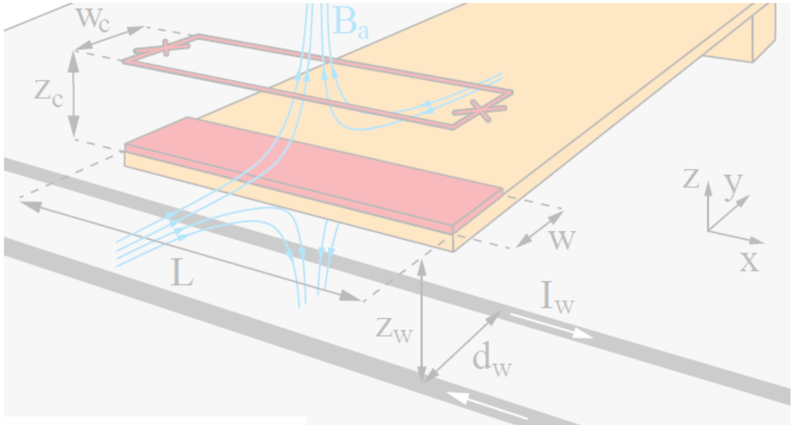
IQI
FWF
Der Wissenschaftsfonds.
ÖAW
ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN

Experiments in Innsbruck on cQED

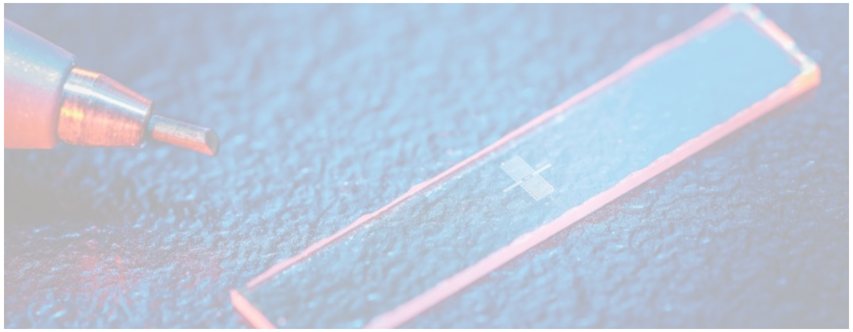
Quantum Simulation using cQED



Quantum Magnetomechanic



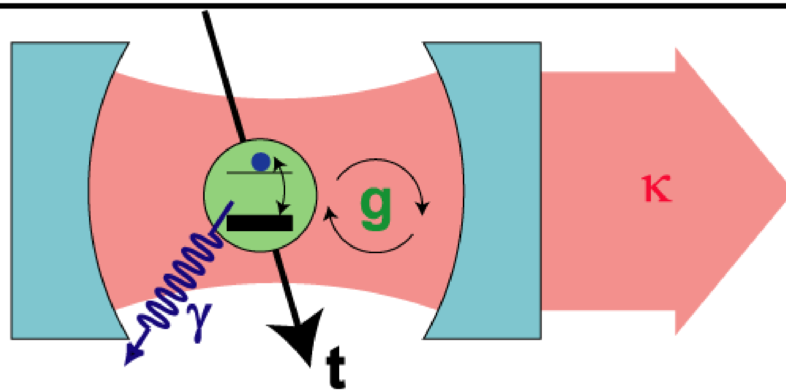
Josephson Junction array resonators



Outline

- Introduction to Circuit QED
  - Cavities
  - Qubits
  - Coupling
- Analog quantum simulation of spin models
  - 3D Transmons as Spins
  - Simulating dipolar quantum magnetism
  - First experiments

cavity QED → circuit QED



optical photons
⇓
microwave photons

optical resonators
⇓
microwave resonators

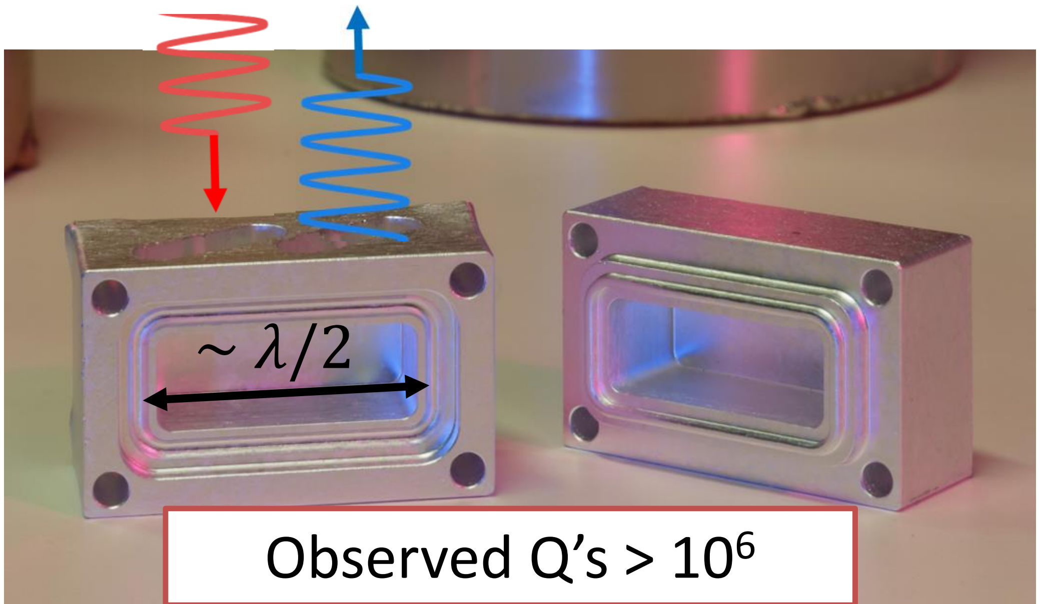
atoms as two level systems
⇓
nonlinear quantum circuits

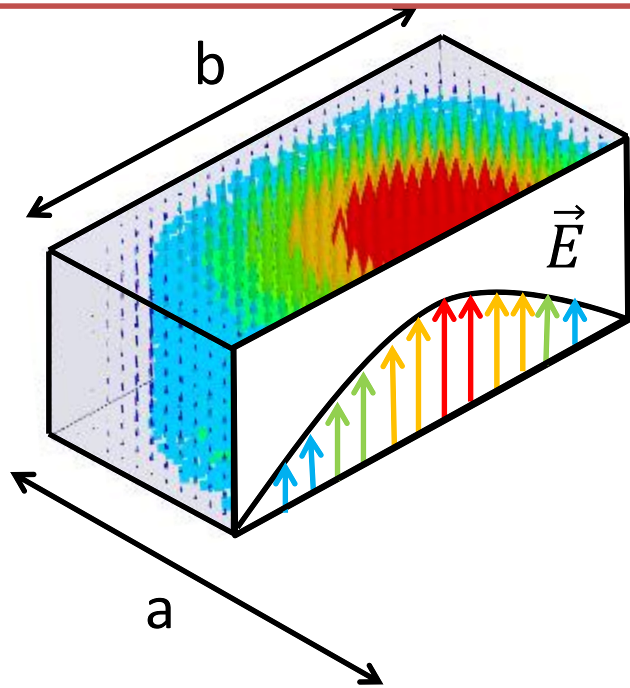
QIP, quantum optics, quantum measurement…

Many groups around the world:
Yale University, UC Santa Barbara, ETH Zurich, TU Delft, Princeton, University of Chicago, Chalmers, Saclay, KIT Karlsruhe …

Cavities

Waveguide microwave resonator

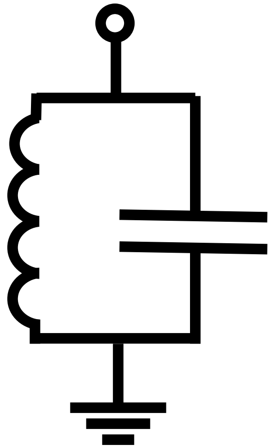




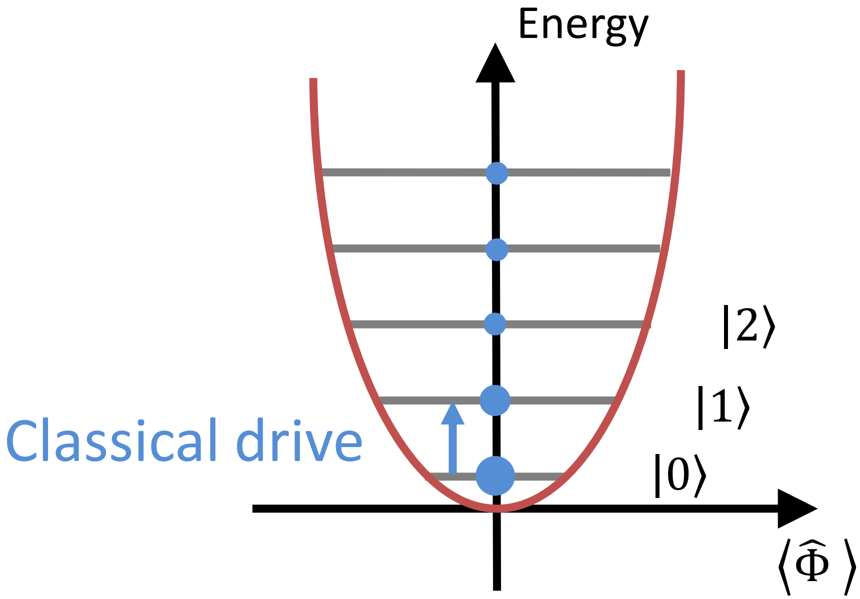
Reagor et.al. Appl. Phys. Lett. 102, 192604 (2013)

Quantum Circuits

Around a resonance:



$\hat{\Phi} \leftarrow L$ $\quad C \rightarrow \hat{Q}$



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

$$\hat{Q} = \sqrt{\frac{\hbar}{2\,Z_0}}\left(a + a^\dagger\right) \quad \hat{\Phi} = i\sqrt{\frac{\hbar\,Z_0}{2}}\left(a - a^\dagger\right)$$

$$H = \hbar\omega_0\left(a^\dagger a + \frac{1}{2}\right)$$

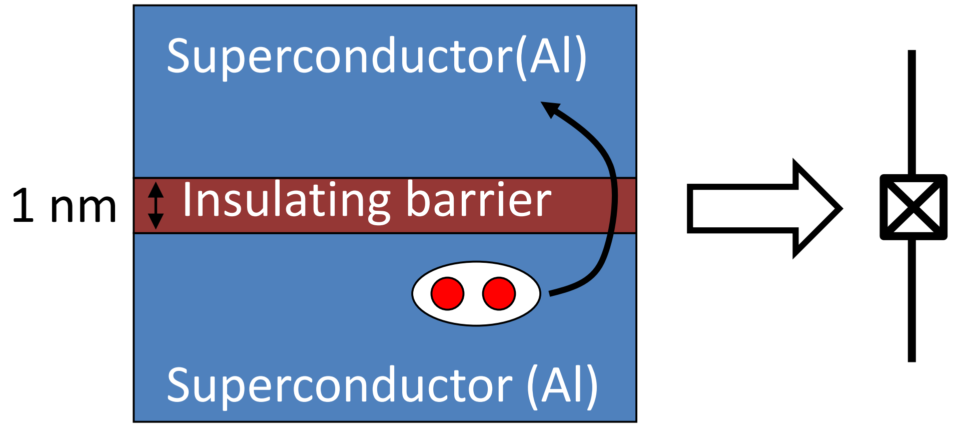
Quantum Harmonic Oscillator

$$Z_0 = \sqrt{\frac{L}{C}} \longrightarrow 1 \ldots 100\ \Omega$$

$$\omega_0 = \sqrt{\frac{1}{LC}} \longrightarrow 4 \ldots 10\ GHz$$

Qubits – 3D Transmon

Josephson Junction

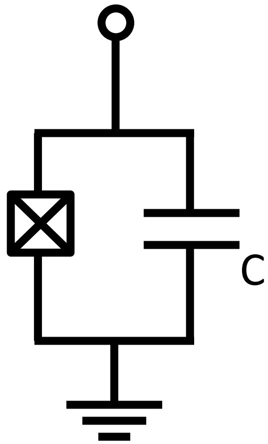


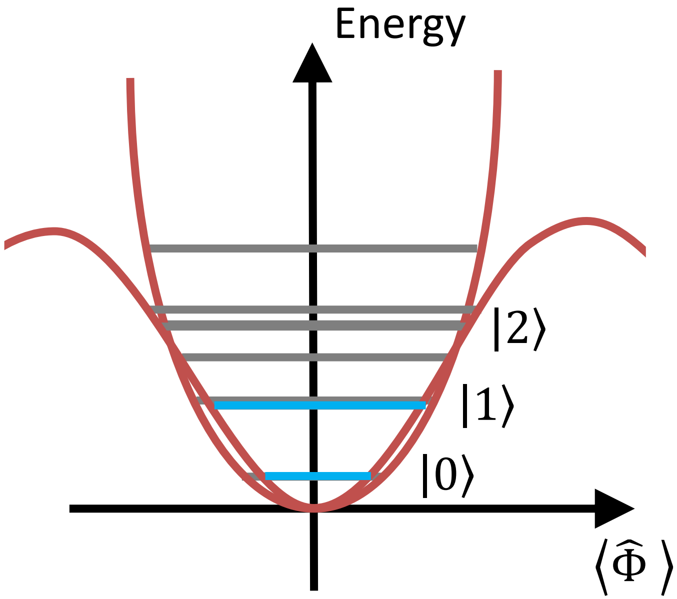
$$\hat{H} = -E_j \cos\hat{\varphi}$$

$$\hat{H} = -E_j \cos\hat{\varphi} + \frac{\hat{Q}^2}{2C}$$

Superconducting Qubits - Transmon

Transmon





$$\hat{H} = -E_j \cos\hat{\varphi} + \frac{\hat{Q}^2}{2\,C_\Sigma}$$

$$\varphi = \frac{2e}{\hbar}\Phi$$

Using the same replacement rules as for the Harmonic Oscillator

$$H = \hbar\omega_0\, b^\dagger b - \frac{E_c}{2}\left(b^\dagger b\right)^2$$

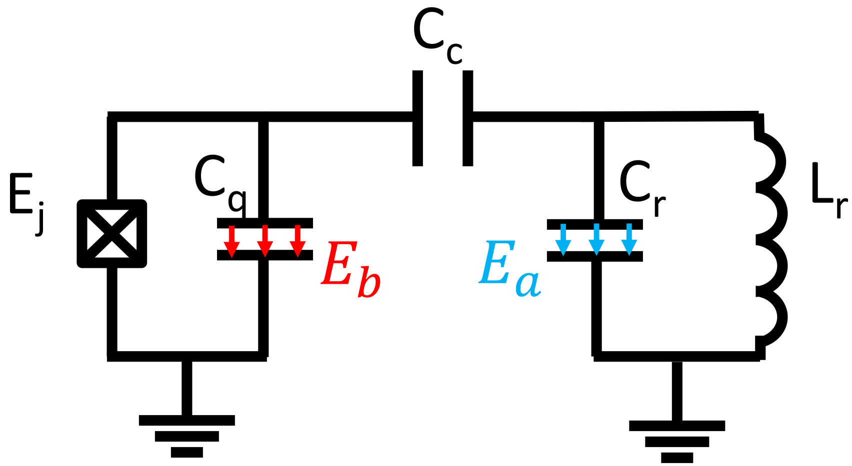
$$H = \hbar\frac{\omega_0}{2}\sigma_z$$

$$\omega_0 = 5 - 10\ GHz$$

$$E_c = 300\ MHz = \alpha$$

Koch et.al. Phys. Rev. A 76, 042319

Transmon coupled to a Resonators



$$H = \hbar \frac{\omega_q}{2} \sigma_z + \hbar \omega_r \, a^\dagger a$$

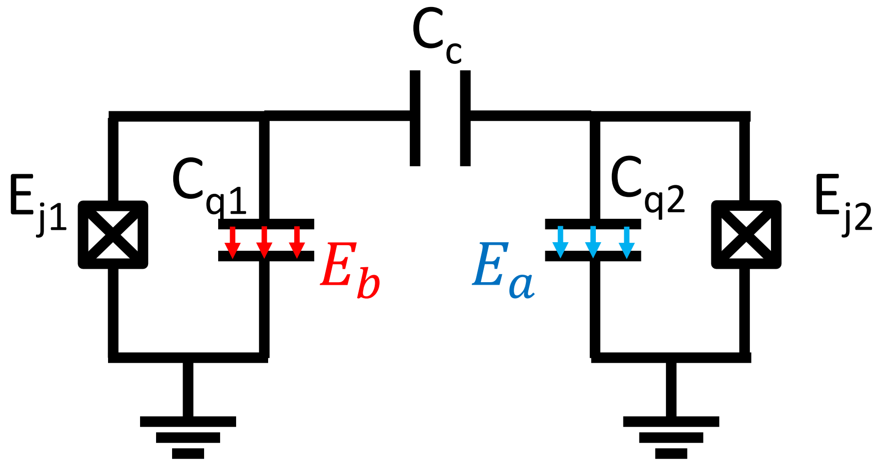
$$H_{int} = \hbar g (a^\dagger \sigma^- + a \sigma^+) \qquad g = 50 - 250 \text{ MHz}$$

Jaynes Cummings Hamiltonian

⇩

driving, readout, interactions

Transmon - Transmon coupling

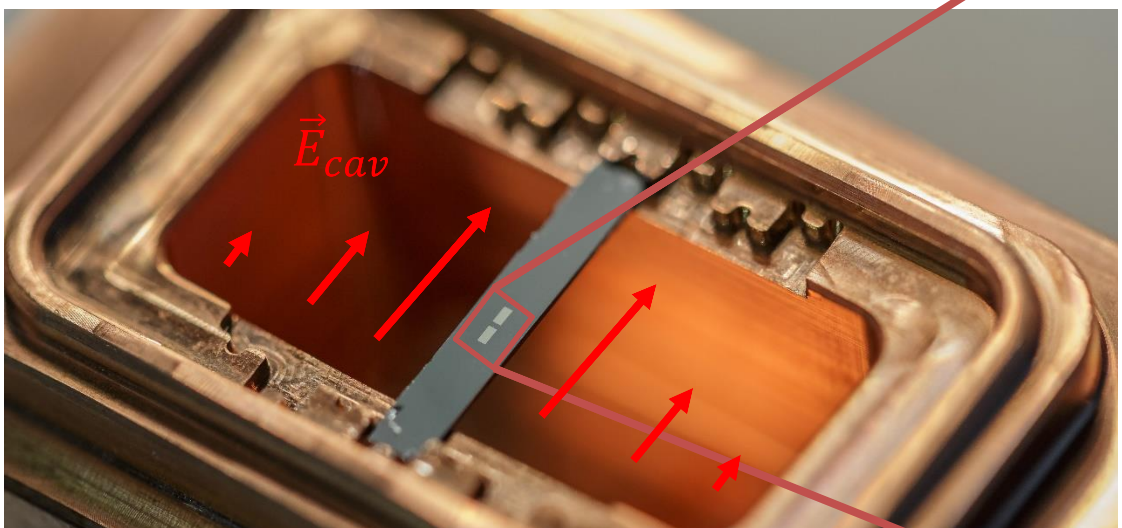


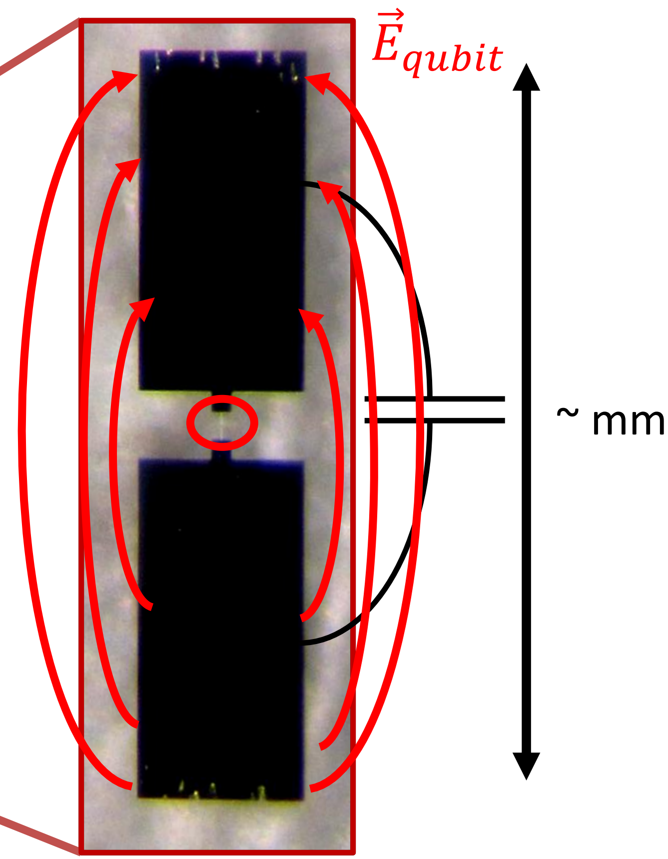
Direct capacitive qubit-qubit interaction

$$H_{int} = \hbar J(\sigma^+\sigma^- + \sigma^-\sigma^+) \quad J = 50 - 250\ \mathrm{MHz}$$

3D Transmon coupled to a Resonator

Large mode volume compensated by large "Dipolemoment" of the qubit





$$\left|\vec{d}\right| = 2e \cdot 1mm \approx 10^7 \text{Debye}$$

Observed Q's up to 5 M

$T_1, T_2 \leq 100\ \mu s$

Superconducting qubits for analog quantum simulation of spin models

Phys. Rev. B 92, 174507 (2015)

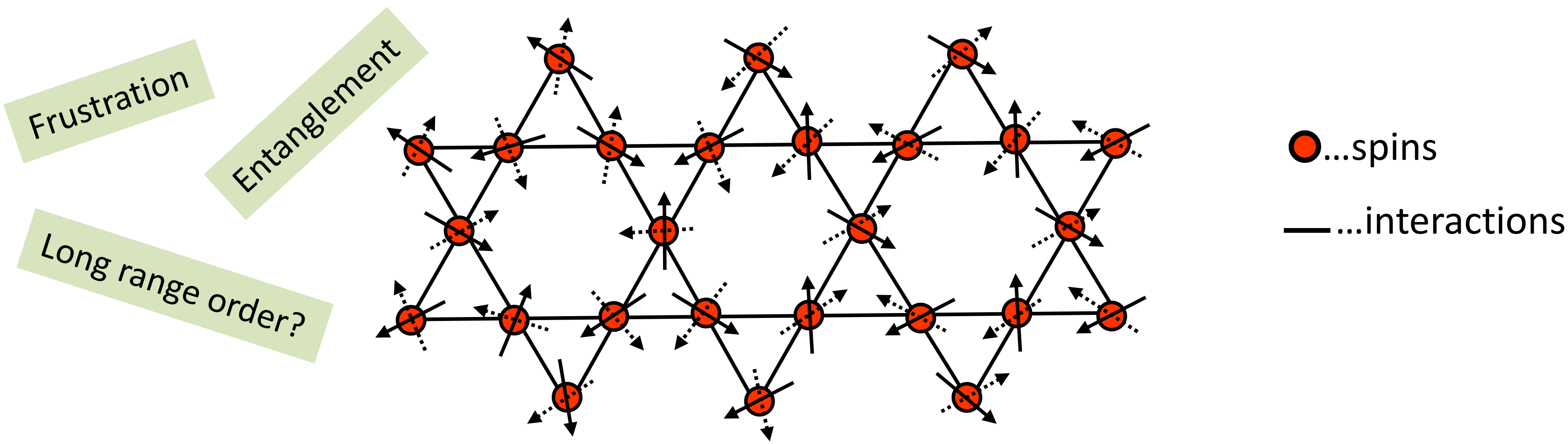
Viehmann et.al. Phys. Rev. Lett. 110, 030601 (2013) & NJP 15, 3 (2013)

European Research Council

Established by the European Commission

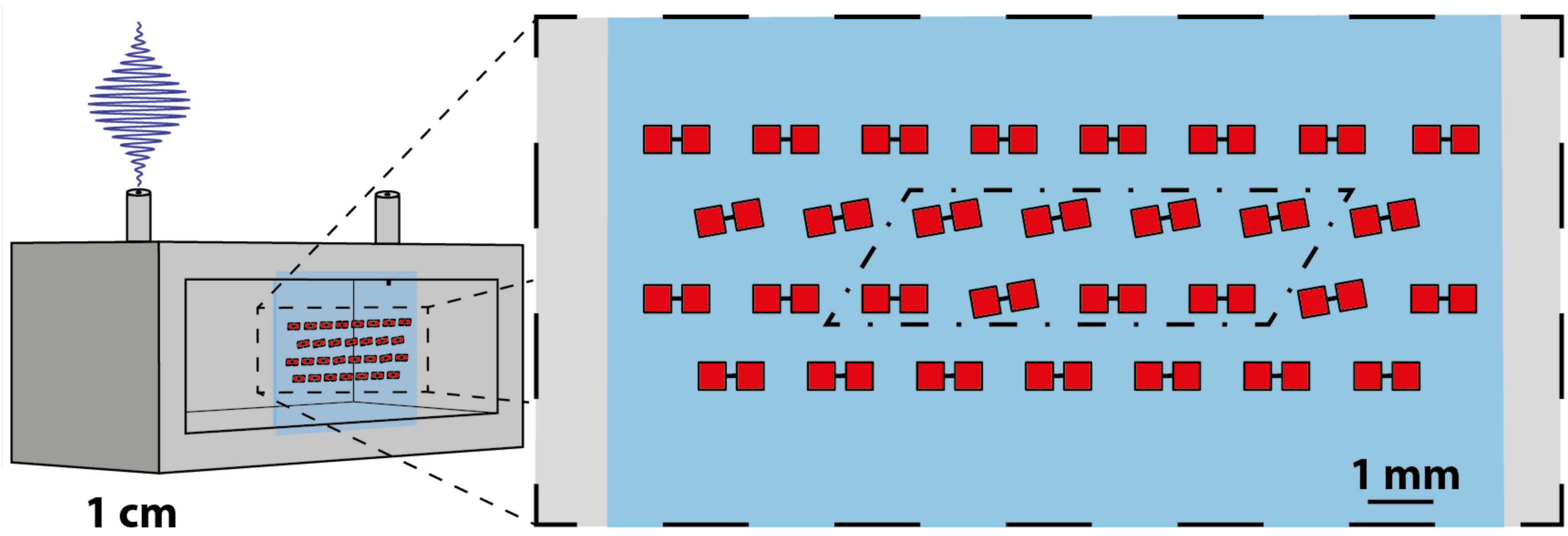
Quantum Simulation

The problem: Simulating interacting quantum many-body systems on a classical computer is very hard.

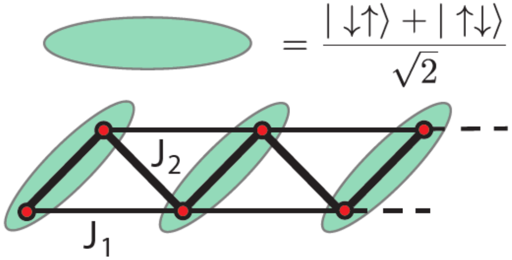


The approach: Engineer a well controlled system that can be used as a **quantum simulator** for the system of interest.

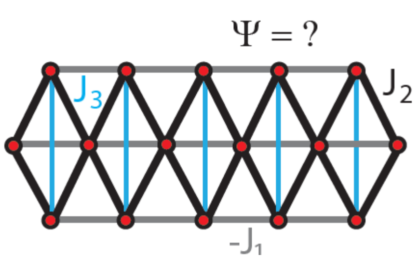
The basic idea & some systems of interest…



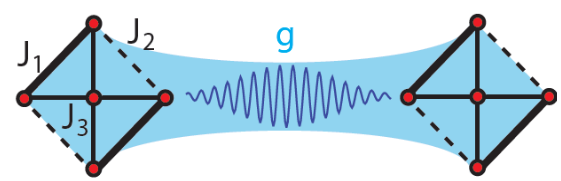
Spin chain physics



2D spin lattice

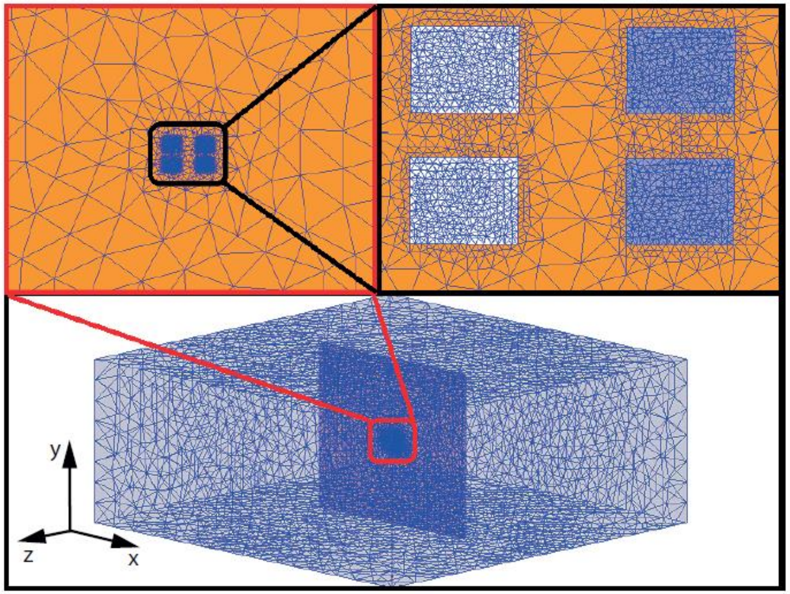


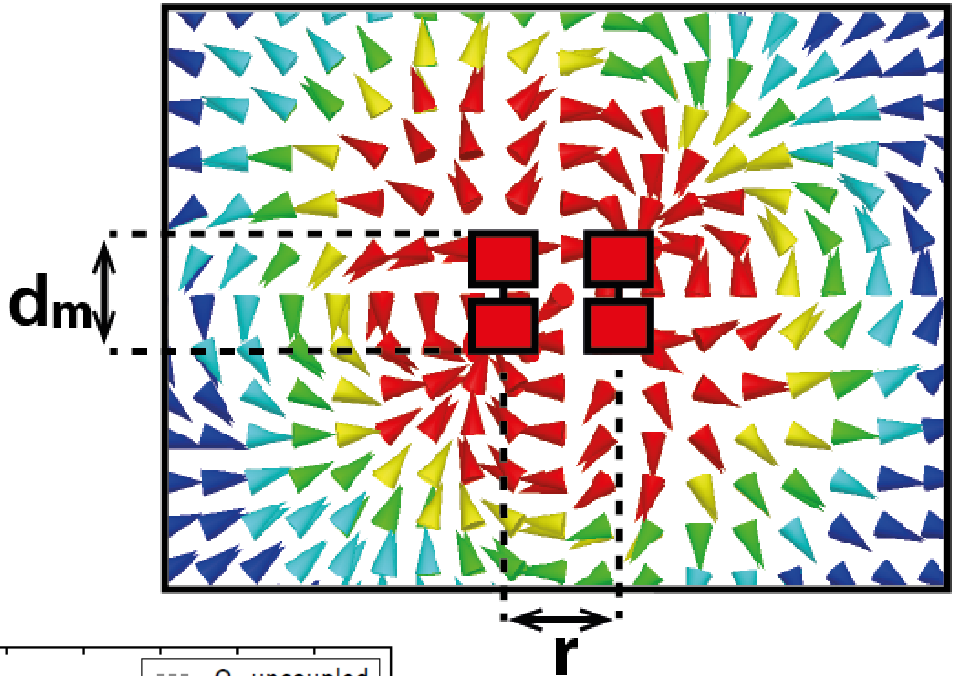
Open quantum systems



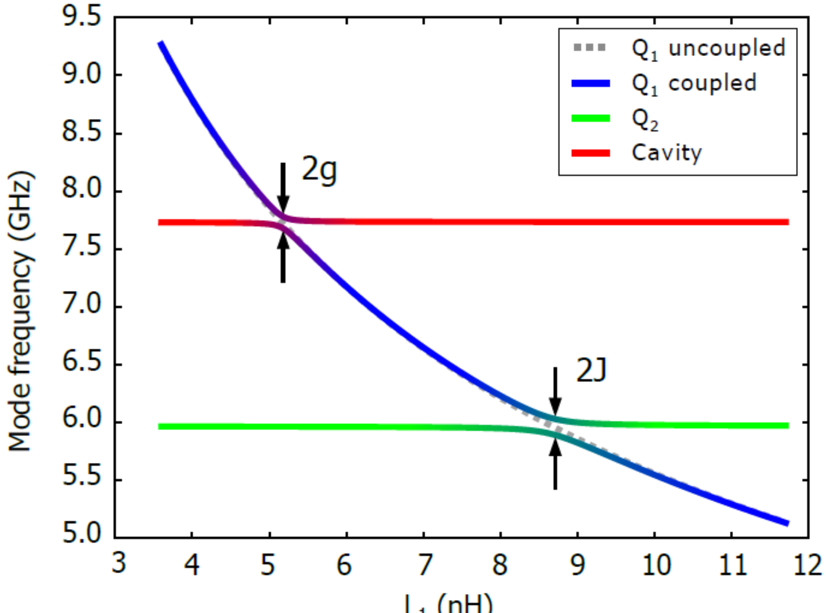
…spins …interactions

Finite Element modeling - HFSS



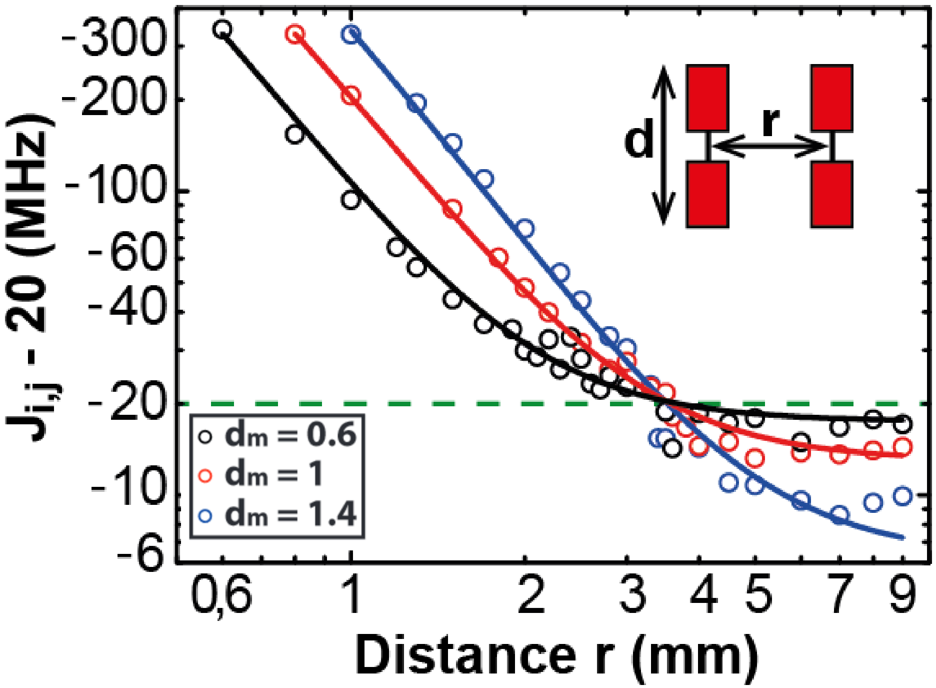


Eigenmodes of the system:



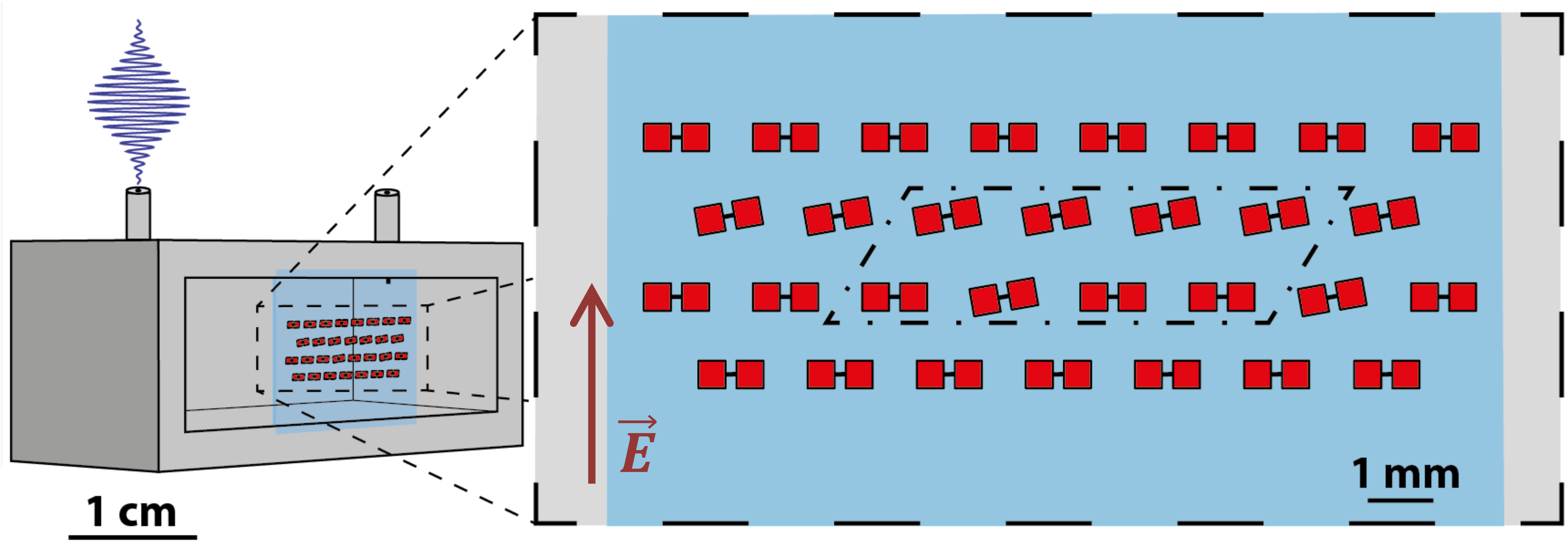
Phys. Rev. B 92, 174507 (2015)

Qubit – Qubit interaction

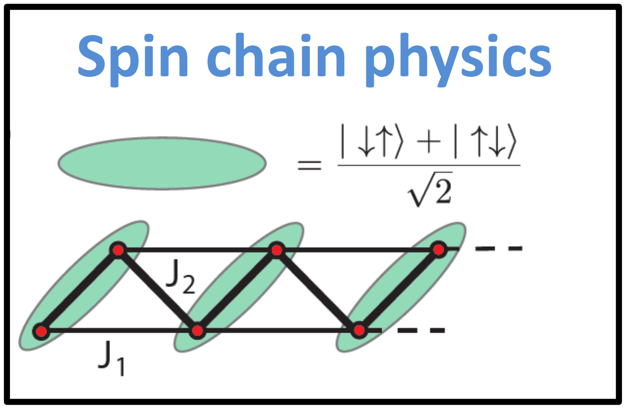


$$J\,(r,\theta_1,\theta_2) = J_0 d_m^2 \frac{\cos(\theta_1-\theta_2) - 3\cos\theta_1\cos\theta_2}{r^3} + J_{cav}$$

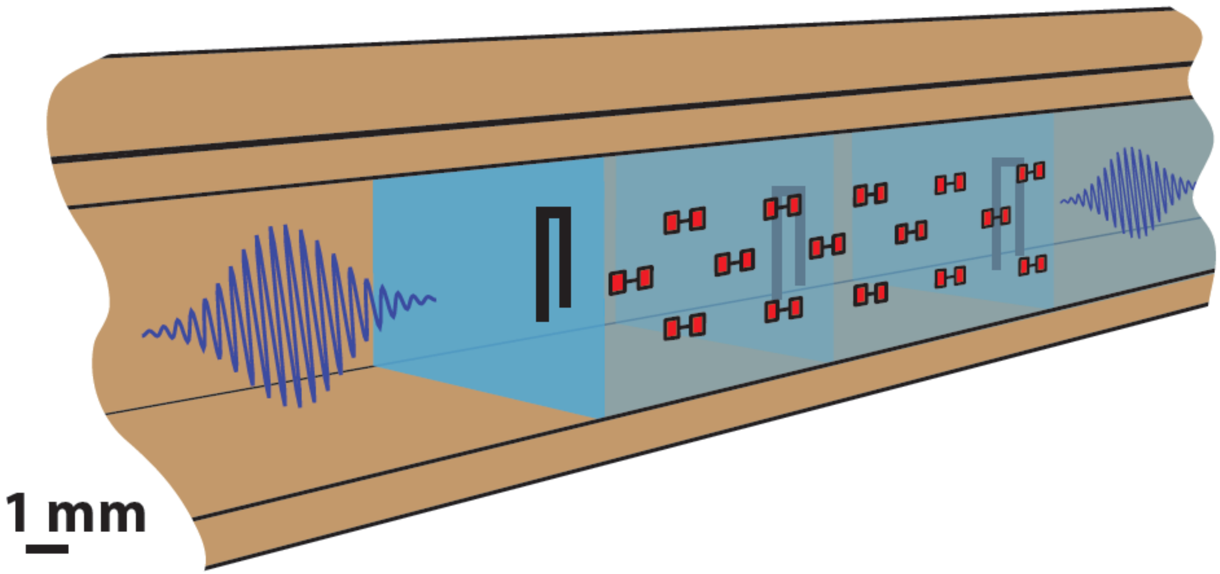
Interaction tunability

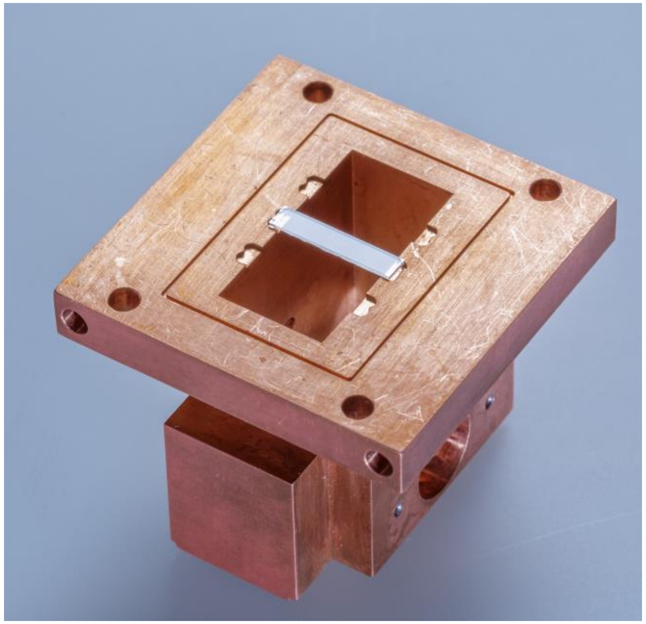


- Qubit - Qubit angle and position
  - tailor interactions
- Qubit - Cavity angle
  - tailor readout & driving
  - measure correlations



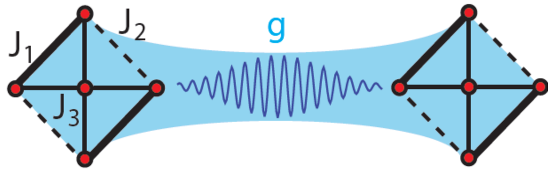
Scaling the system





- Fine grained readout
- Competition between short range dipole and long range photonic interaction
- Band engineering is possible
- Inbuilt Purcell protection
- Dissipative state engineering

Open quantum systems



To do list – theory input

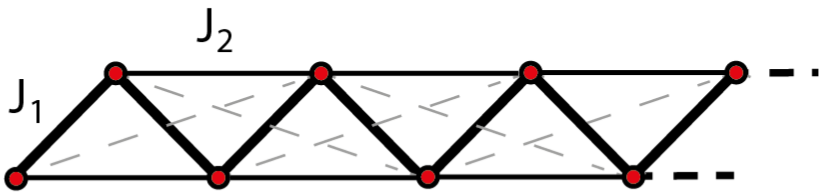
- How to best **characterize** these systems?
- What do we want to **measure**?
- How do we **verify/validate** our measurements
- How does it work in the **open system** case?

Simulating dipolar quantum magnetism

Phys. Rev. B 92, 174507 (2015)

Model to simulate

XY model on a ladder: Superfluid and Dimer phase



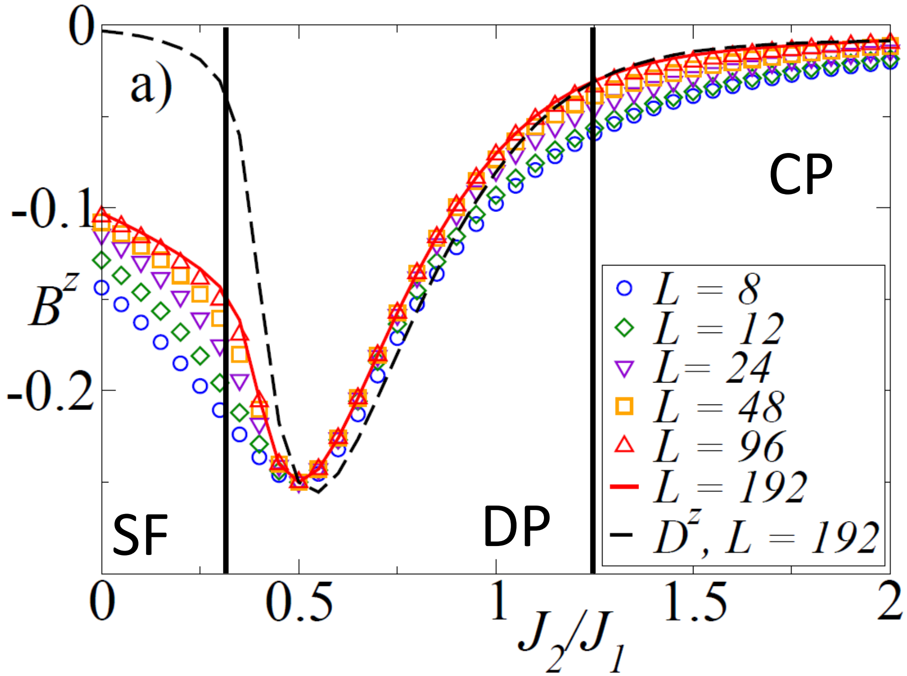
Analogue Quantum Simulation with Superconducting qubits

$$H = \sum_{i,j} \frac{J(\theta_1, \theta_2)}{|r_{i,j}|^3} \left(S_i^+ S_j^- + h.c.\right) + \sum_i h_j S_i^z$$

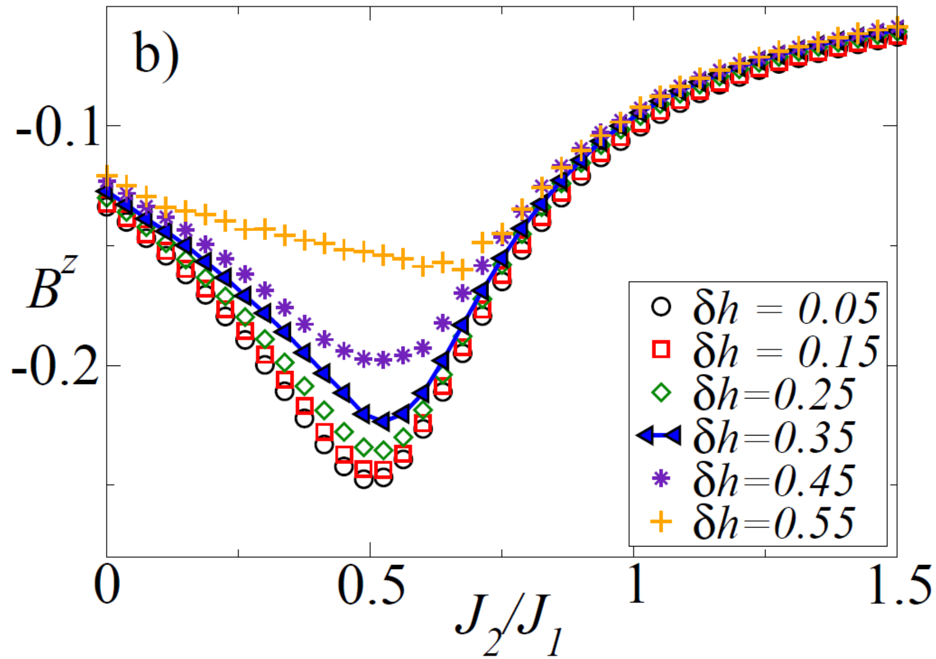
In Collaboration with M. Dalmonte & D. Marcos & P. Zoller

Static properties of the model

Order parameter and Bond Correlation



Disorder influence on the Bond Correlation

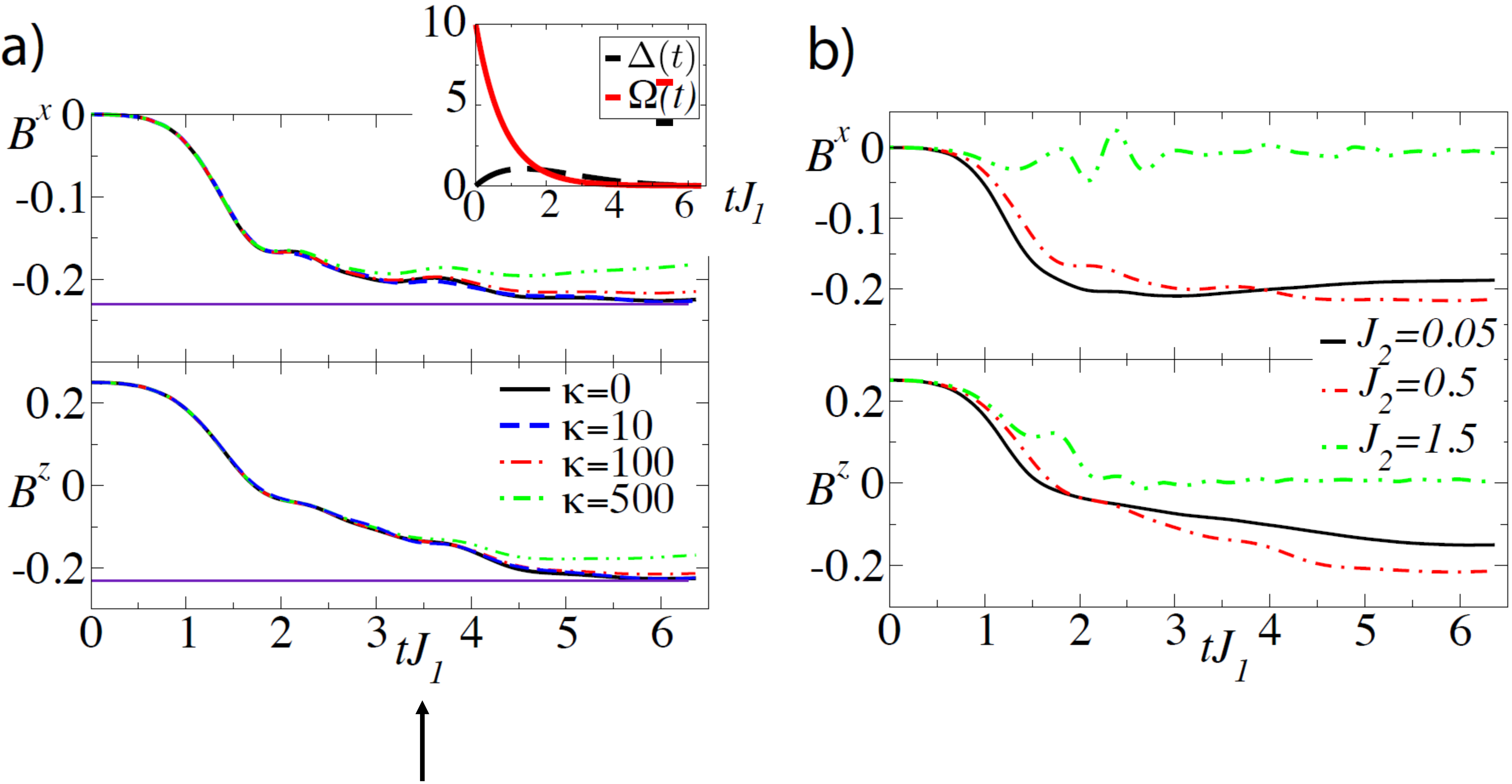


$$D^\alpha = \left\langle \sum_{j=1}^{L-1} D_j^\alpha \right\rangle \qquad D_j^\alpha = (-1)^j S_j^\alpha S_{j+1}^\alpha \qquad \alpha = x, z \qquad B^z = D_{L/2}^z$$

Bond order parameter shows formation of triplets for $J_2/J_1=0.5$

Adiabatic state preparation

System size: L = 6, $2J_2 = J_1 = 2\pi$ 100 MHz,



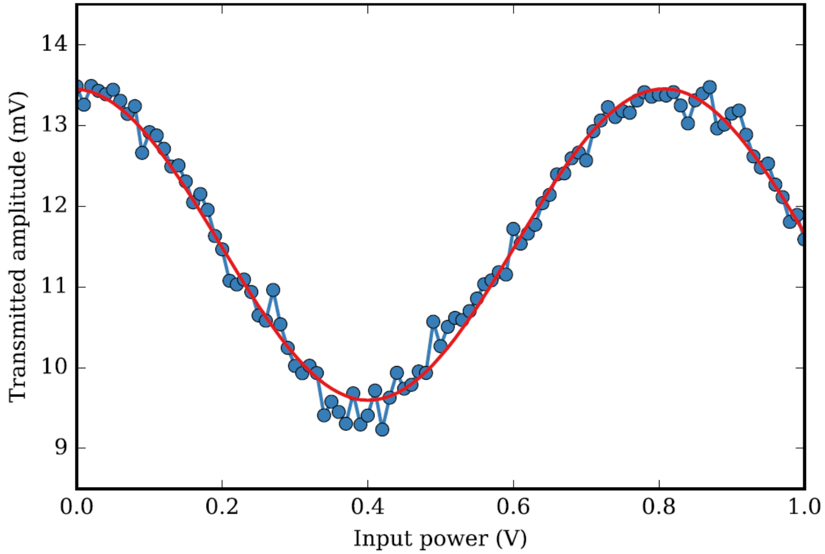
Including disorder $\delta h/J_1$=0.25

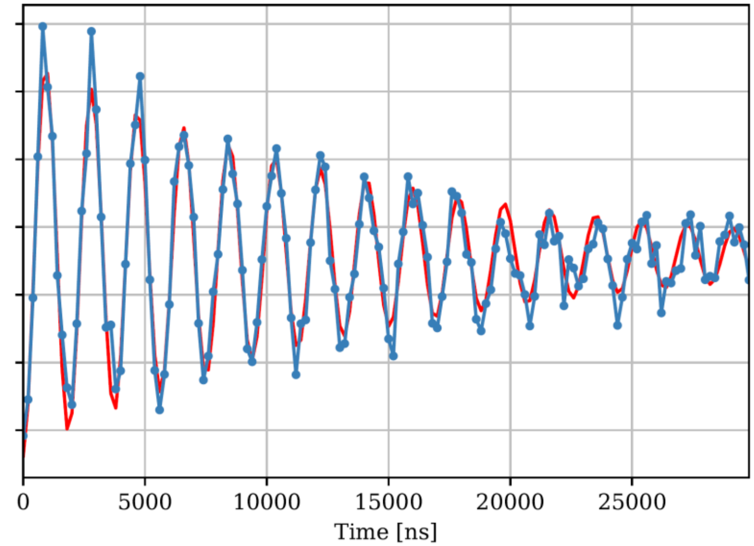
Experimental progress

Experimental progress - Qubits

✓ Single qubit control, frequency tunable

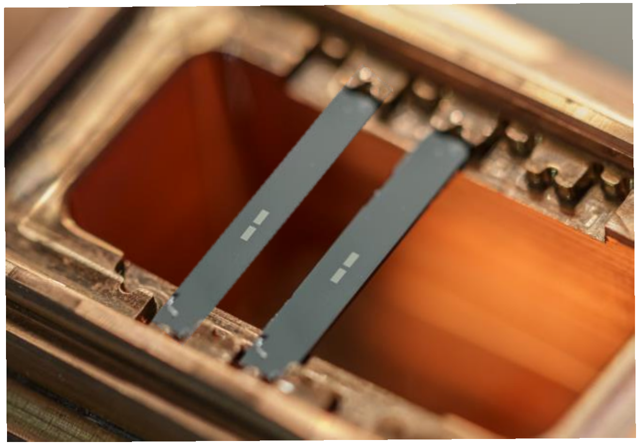
$T_1 \approx 40\ \mu s$, $T_2 \leq 25\ \mu s$



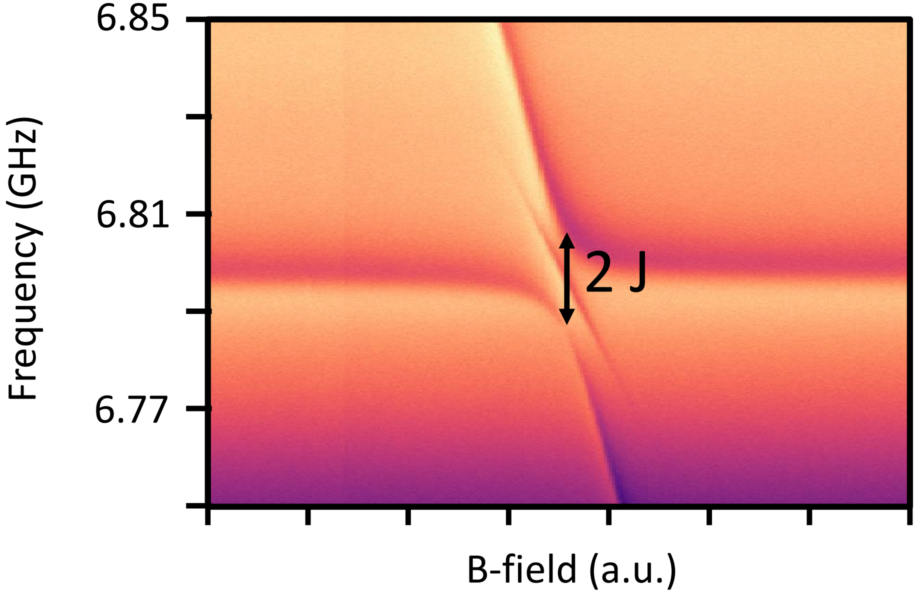


Experimental progress - Qubits

✓ Multiple qubits and interactions



$$H_{int} = \hbar J(\sigma^{+}\sigma^{-} + \sigma^{-}\sigma^{+})$$



$J \approx 70$ MHz

Qubit measurements & state preparation

- During the simulation:

$$\omega_i = \omega_j \ \forall \ _{i,j}$$

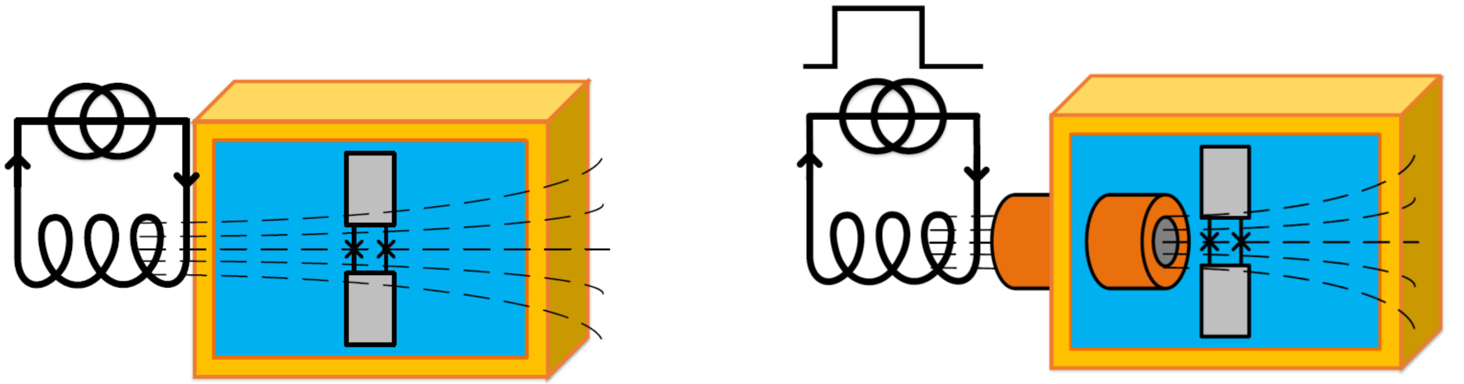
- We want to measure:

$$\sigma_i^m \otimes \sigma_j^m$$

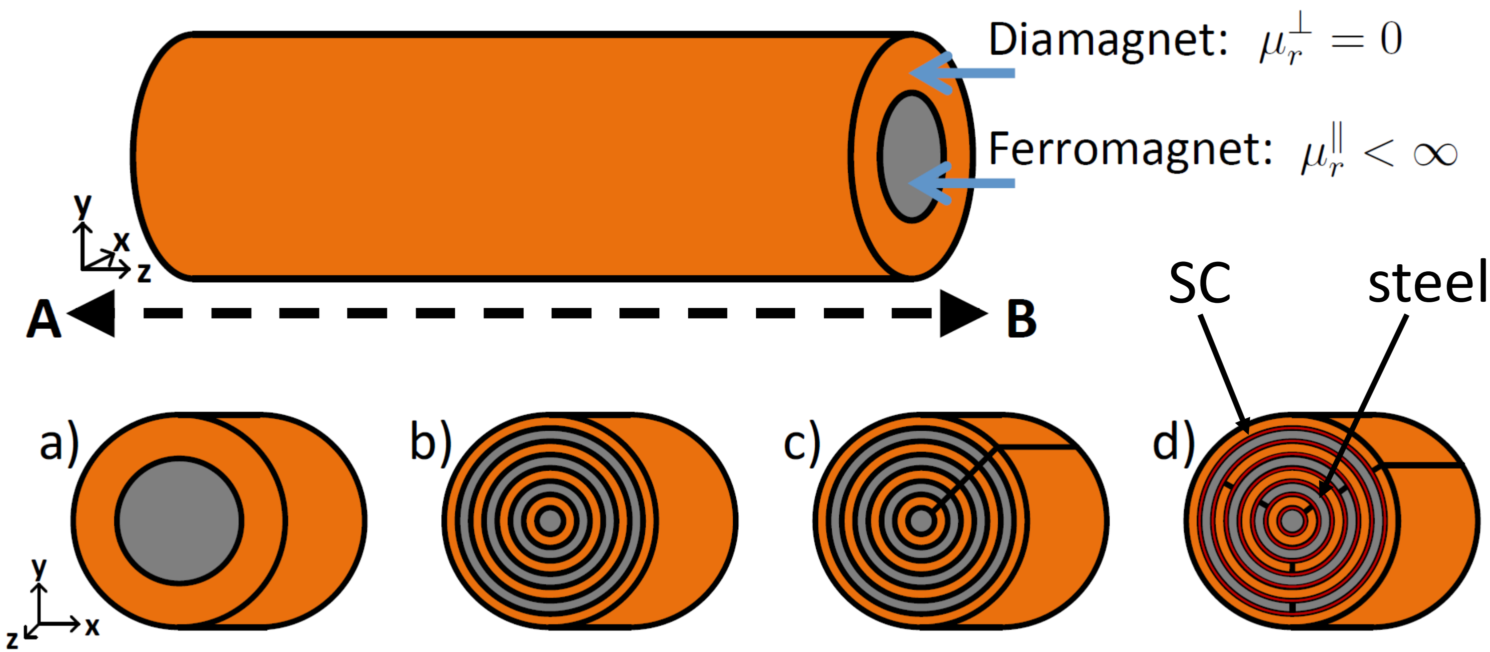
- We want to be able to bring excitations into the system

➔ fast flux tunability necessary

Tuning fields with a Magnetic Hose

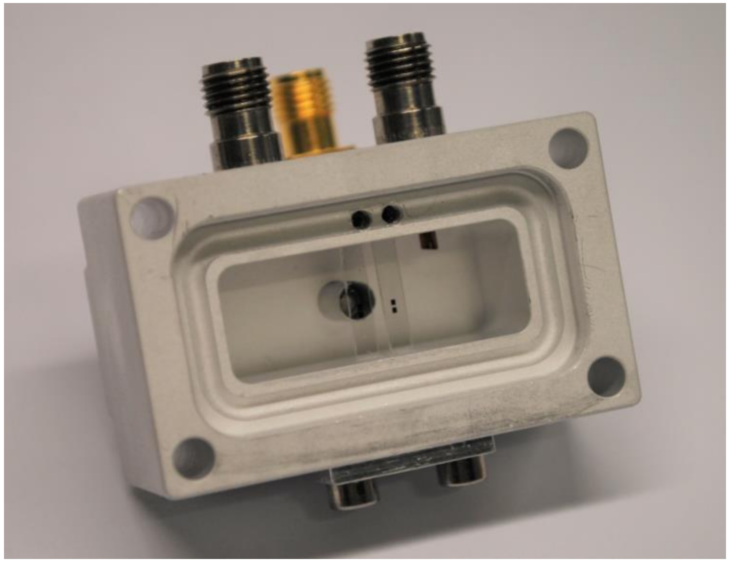


- Transport B-field from **A** to **B**



Long-distance Transfer and Routing of Static Magnetic Fields
Phys. Rev. Let. **112**, 253901(2014)

Experimental progress - Magnetic Hose



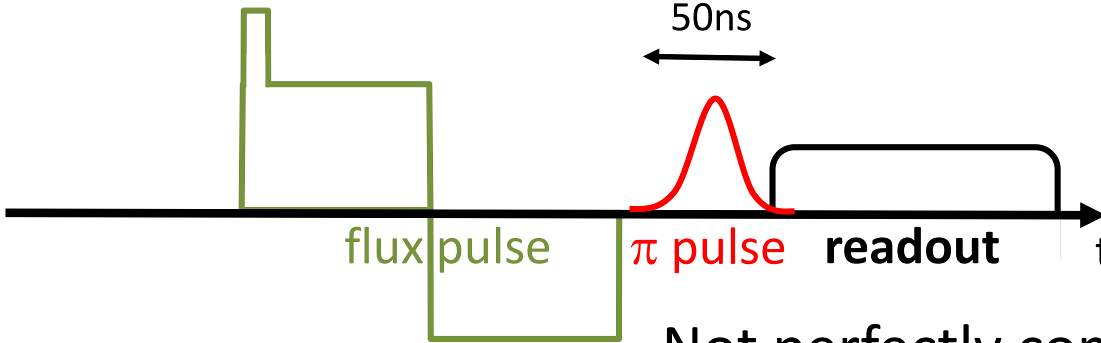
$T_1 \geq 15\ \mu s$

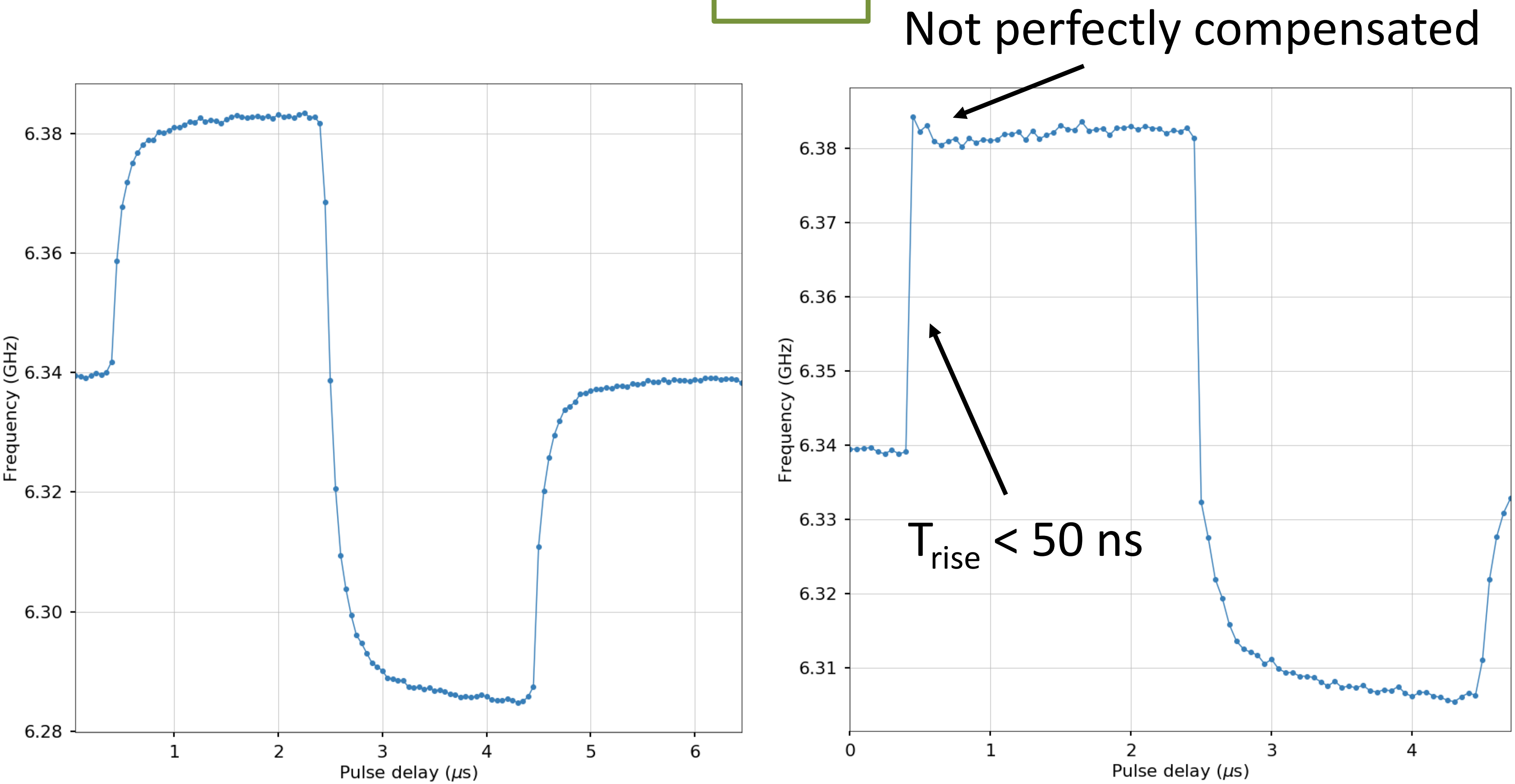
Purcell limited

$T_2 < 15\ \mu s$

depends on flux bias

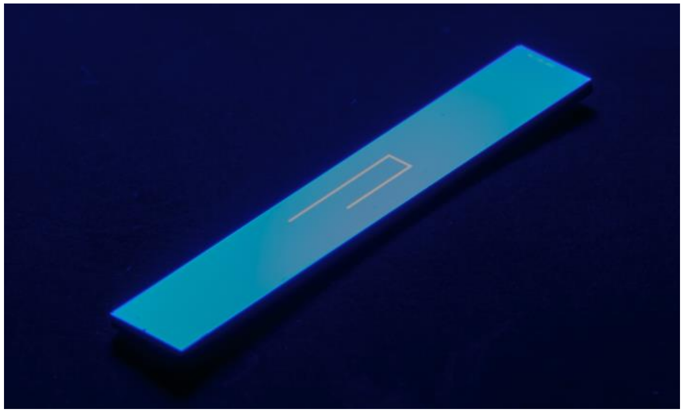
Experimental progress - Magnetic Hose

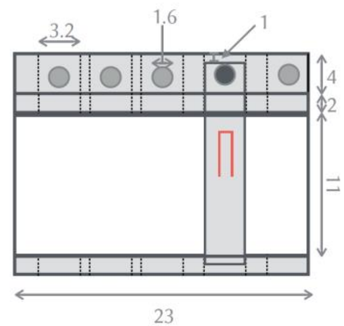


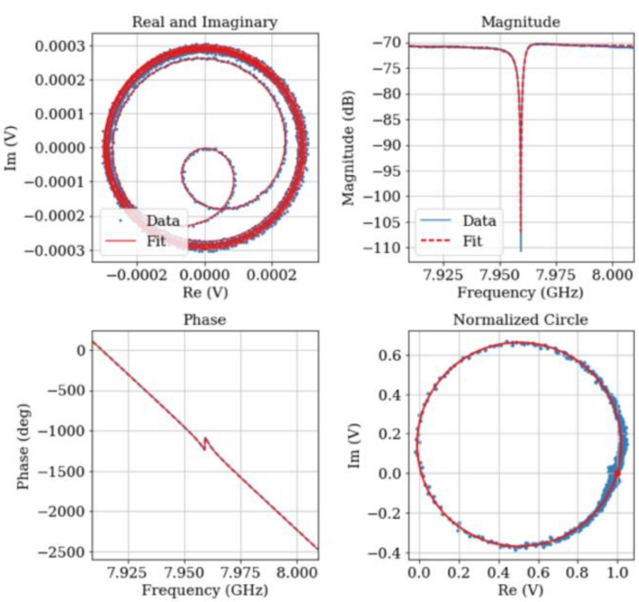


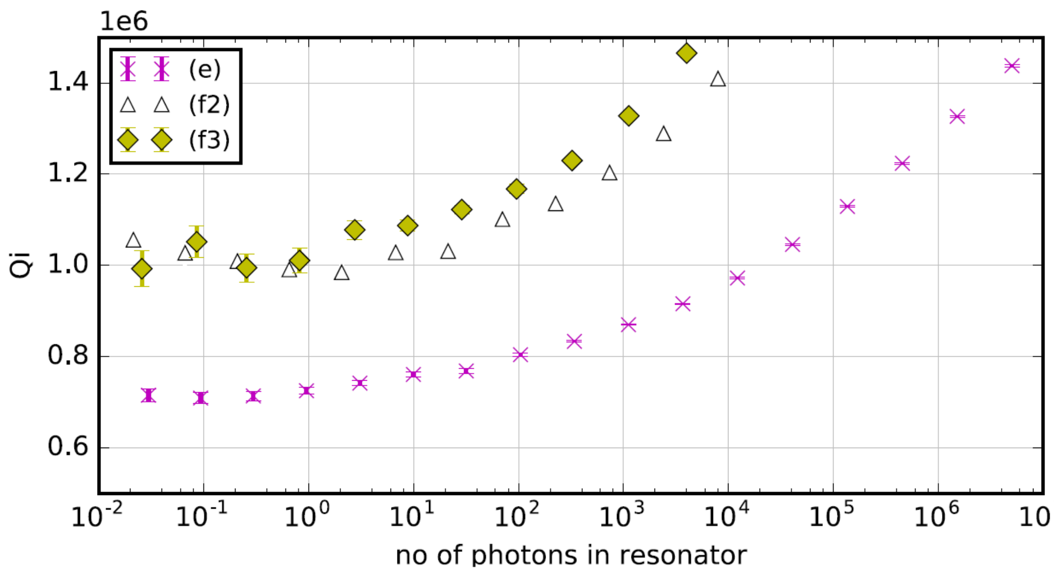
Experimental progress – Waveguides

✓ High Q Stripline resonators for waveguides





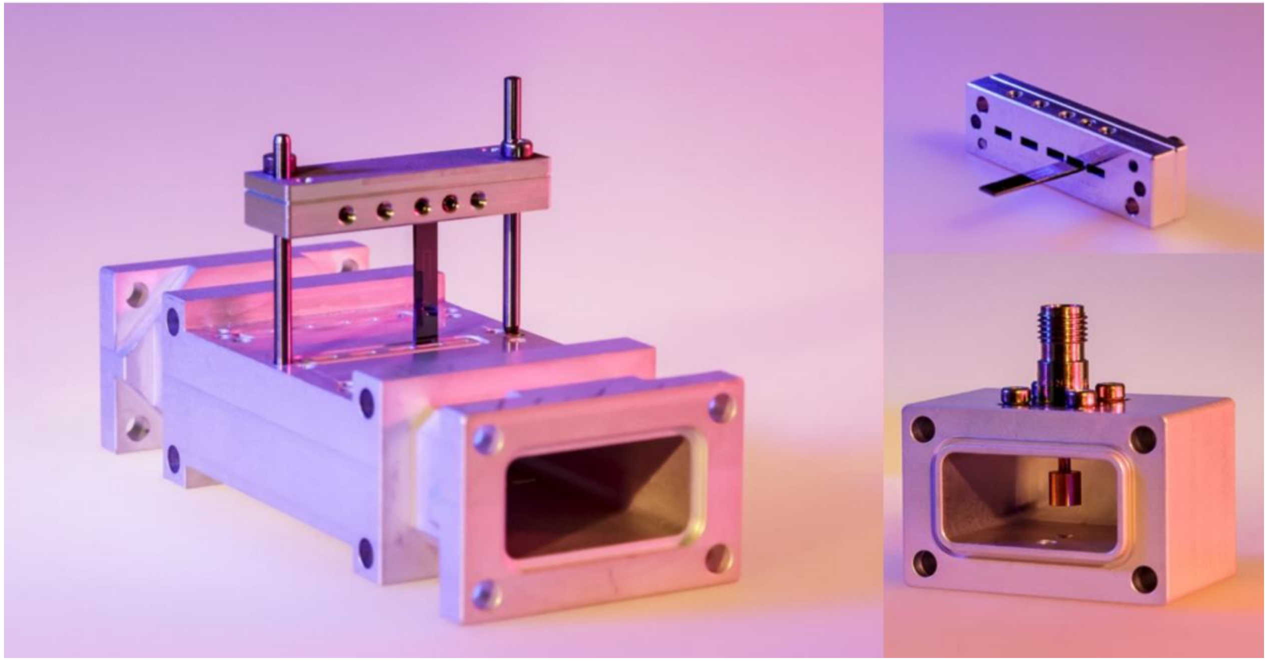


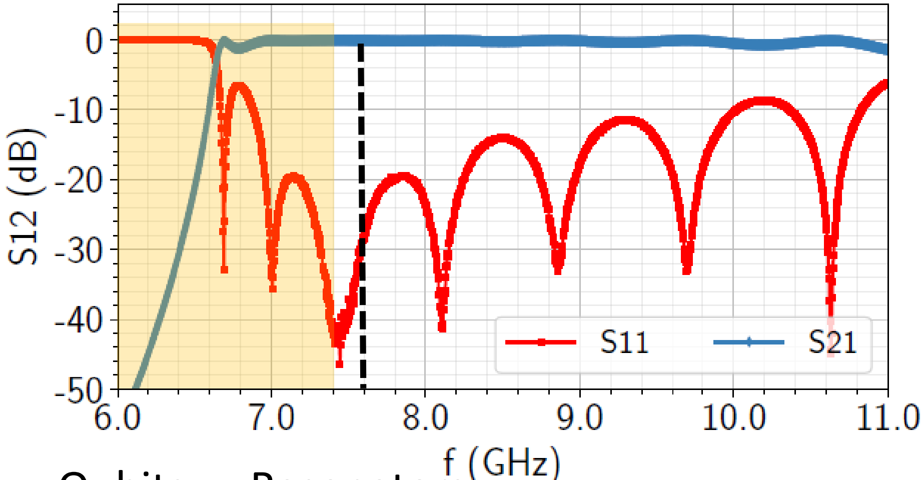


AIP Advances **7**, 085118 (2017)

Experimental progress - Waveguides

- Waveguides with resonators and qubits

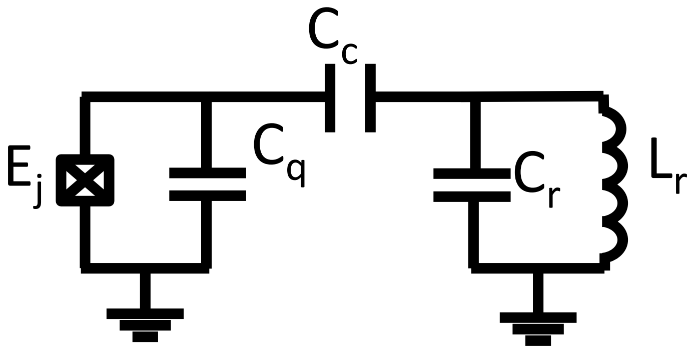


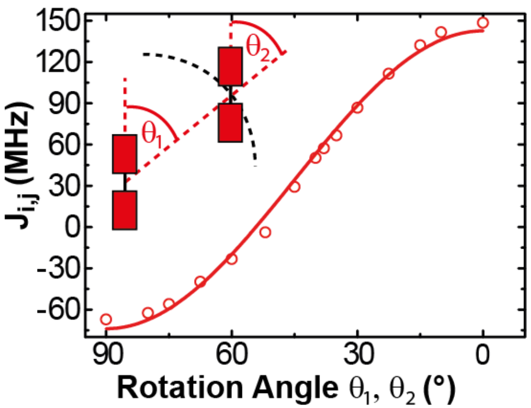


Qubits Resonators

Conclusion

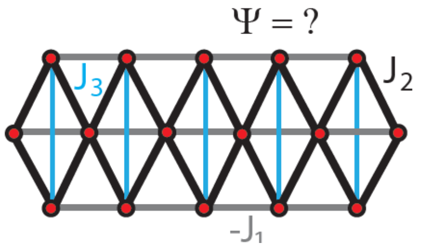
- Circuit QED



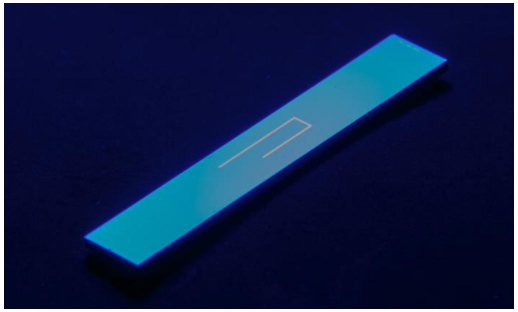


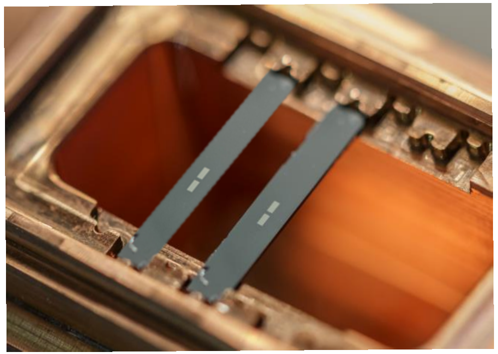
- 3D Transmons behave like dipoles

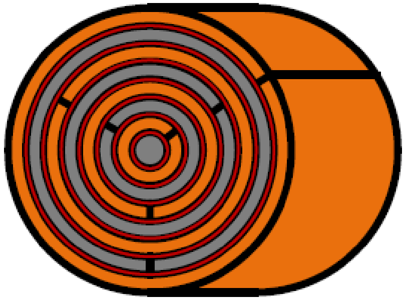
- Simulate models on 1D and 2D lattices



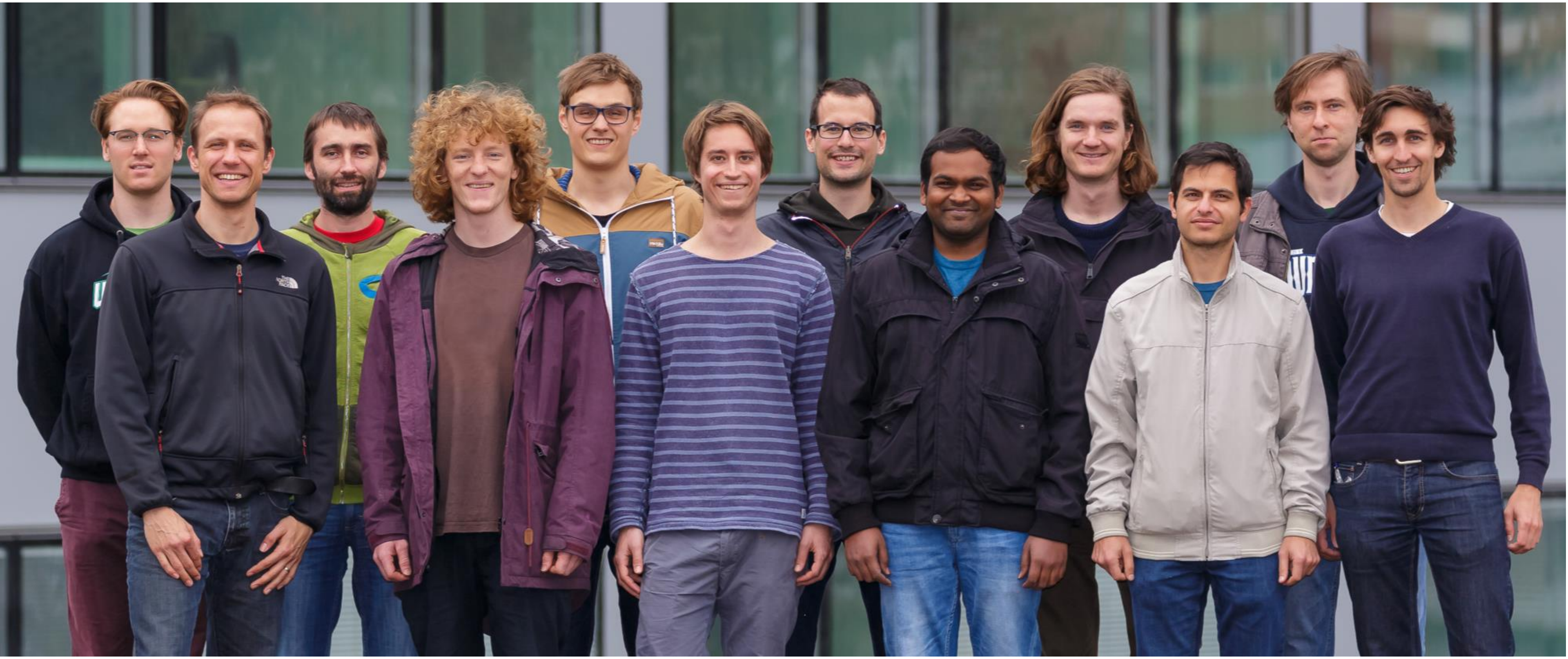
- Work in progress





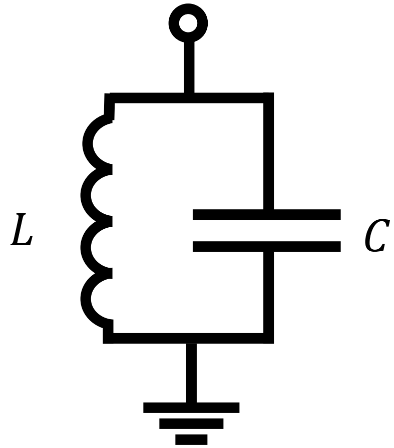


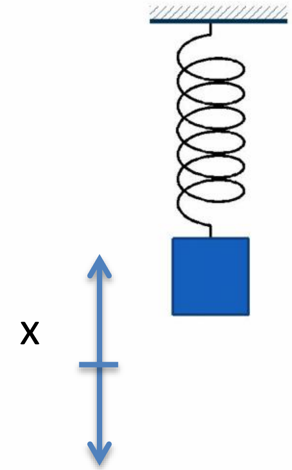
Quantum Circuits Group Innsbruck – April 2017



Quantum Circuits

Around a resonance:





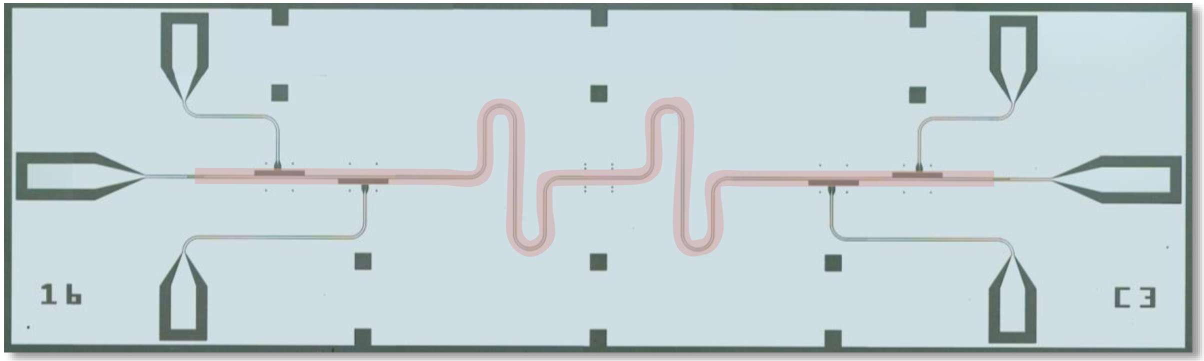
Lagrangian ⟶ $H = \frac{\hat{Q}^{\,2}}{2\,C} + \frac{\hat{\Phi}^{\,2}}{2\,L}$ ⇔ $H = \frac{\hat{p}^{\,2}}{2\,m} + \frac{m\omega^2 \hat{x}^{\,2}}{2}$

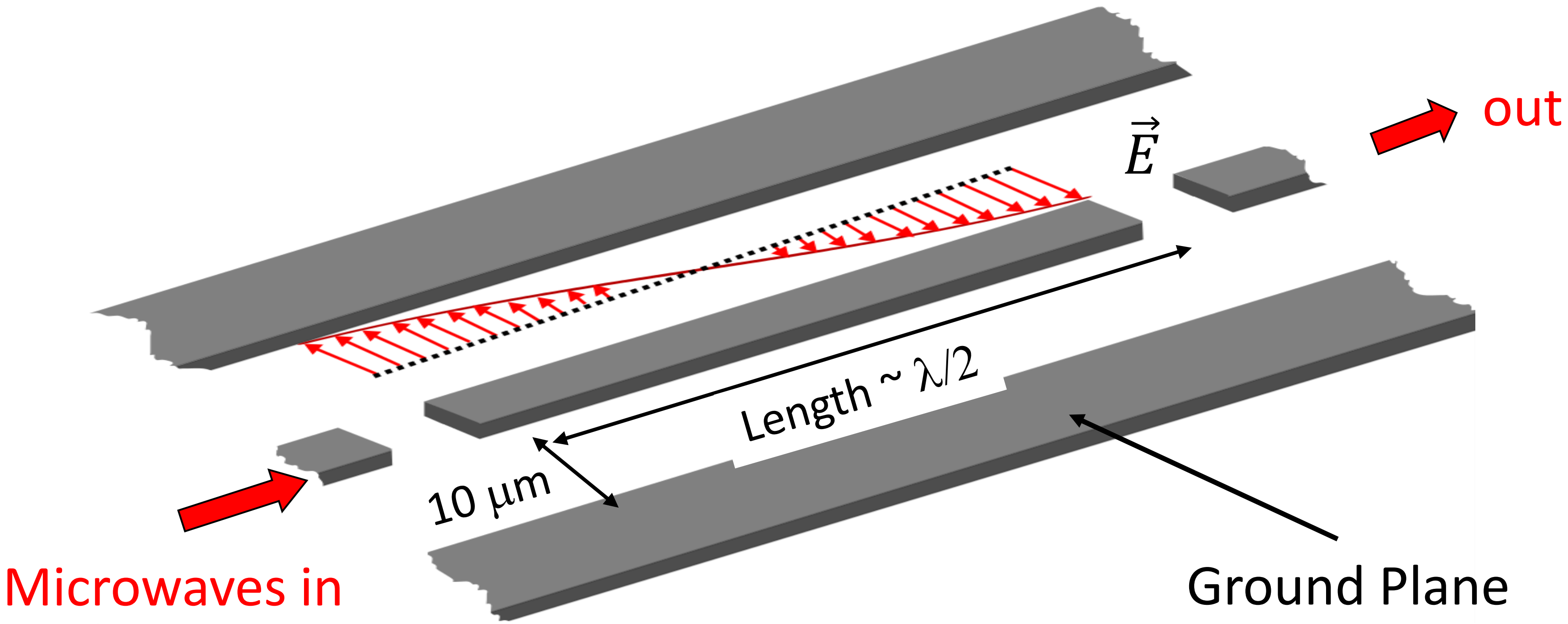
energy in magnetic field ⇔ potential energy

energy in electric field ⇔ kinetic energy

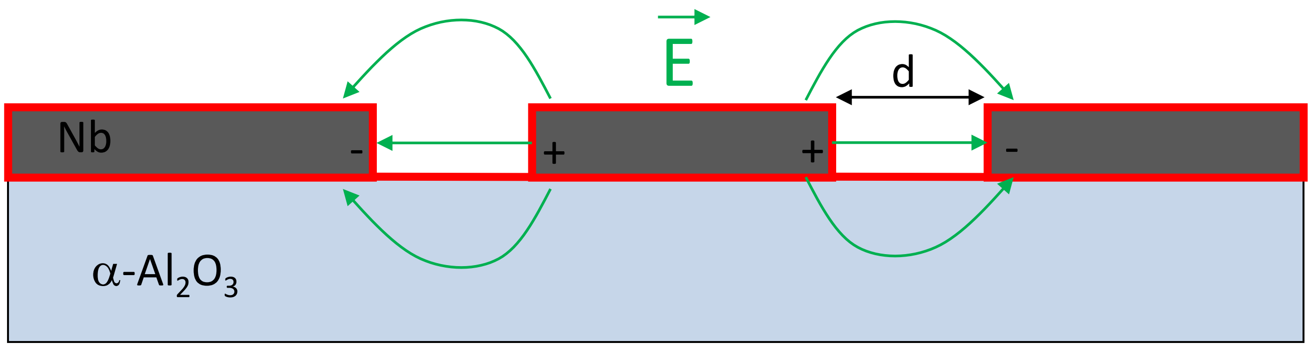
Resonators and Cavities

Coplanar Waveguide Resonators





Why interfaces matter… dirt happens



"participation ratio" = fraction of energy stored in material

even a thin (few nanometer) surface layer
will store ≈ 1/1000 of the energy

If surface loss tangent is poor ($\tan\delta \approx 10^{-2}$) would limit $Q \approx 10^5$

Increase spacing
- decreases energy on surfaces
- increases Q

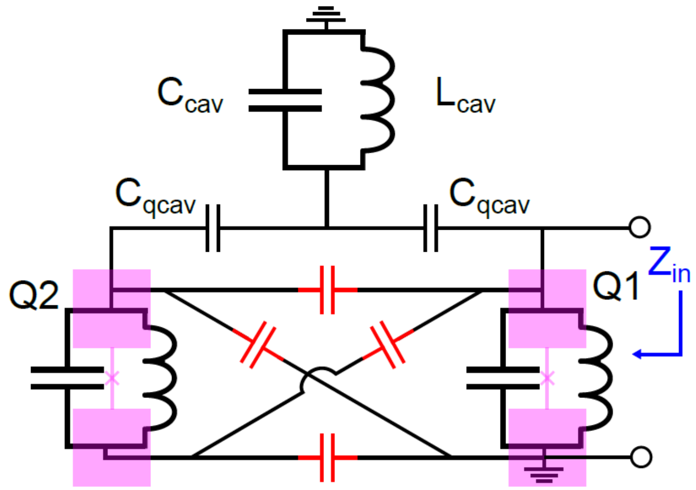
as shown in:

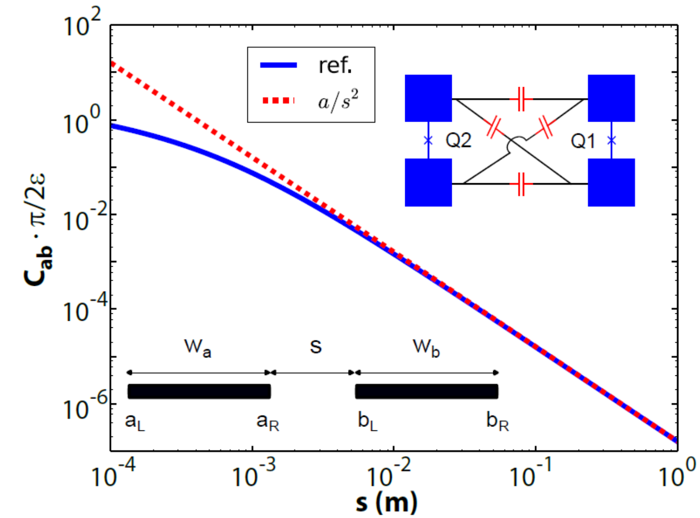
Gao et al. 2008 (Caltech)
O'Connell et al. 2008 (UCSB)
Wang et al. 2009 (UCSB)

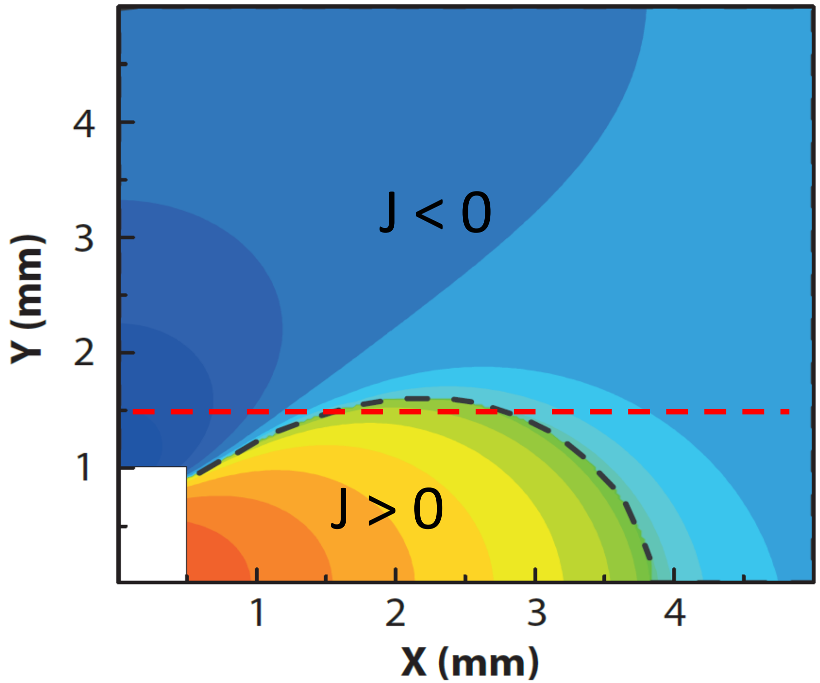
tech. solution:

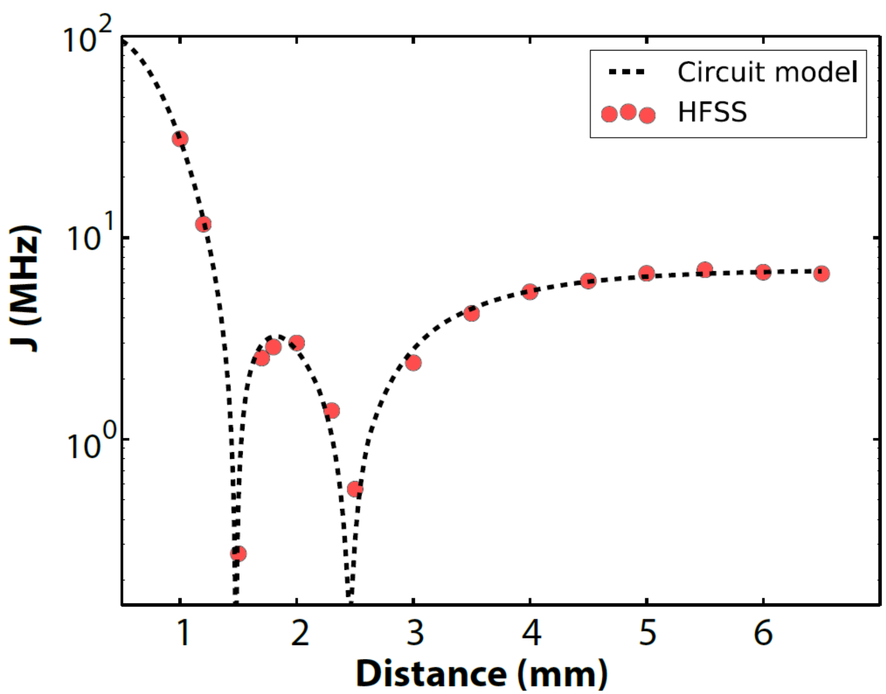
Bruno et al. 2015 (Delft)

Circuit model explanation

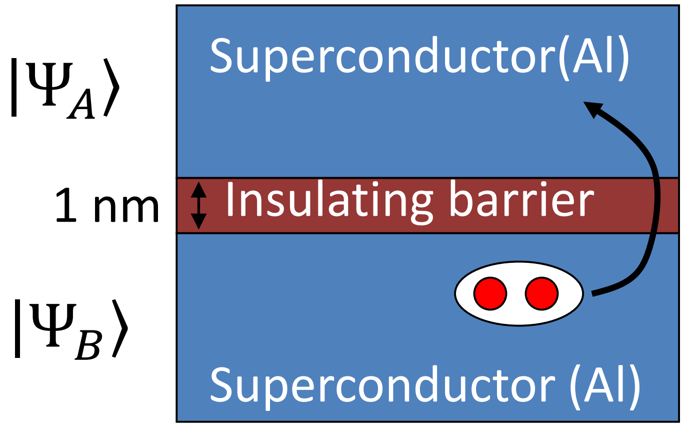








Josephson Junction

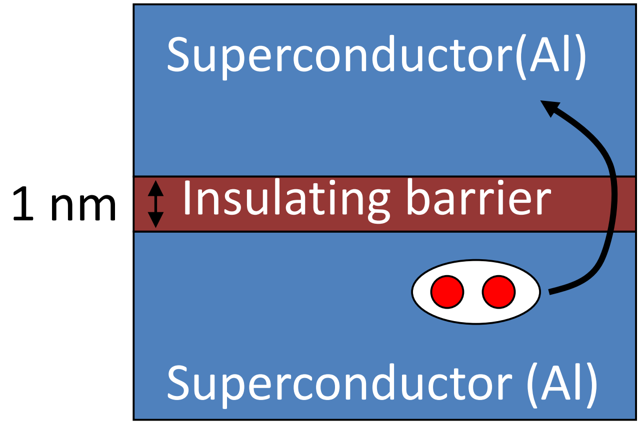


Josephson relations: $I(\varphi) = I_c \sin\varphi$ $\quad \dot{\varphi} = \frac{2e}{\hbar} V(t)$

Regular inductance		Josephson Junction
$V_L = L\dot{I}$	$\Leftrightarrow$	$V_{jj} = \frac{\hbar}{2e} \frac{1}{I_c \cos\varphi} \dot{I}$
$E = \frac{\Phi^2}{2L}$	$\Leftrightarrow$	$E = -E_j \cos(\varphi) \approx E_j \frac{\varphi^2}{2} - E_j \frac{\varphi^4}{12} + \cdots$

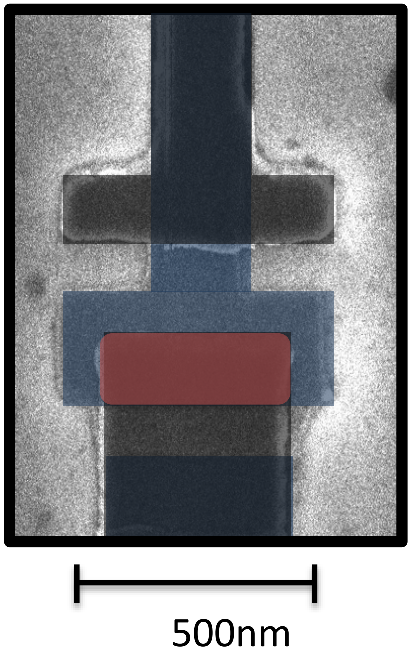
$$\varphi = \frac{2e}{\hbar}\Phi = 2\pi \frac{\Phi}{\Phi_0}$$

Josephson Junction

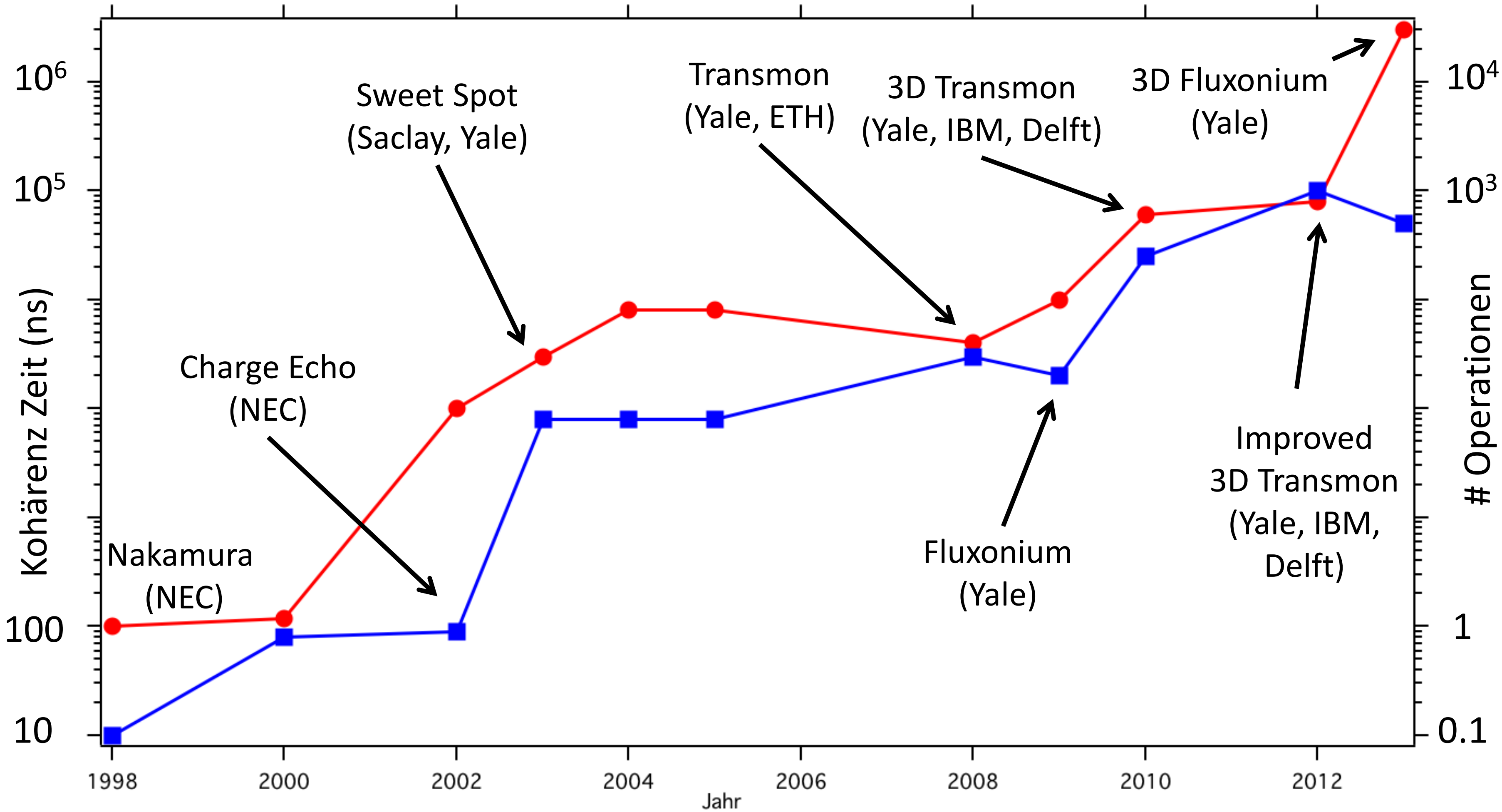


Junction fabrication:

- thin film deposition
- Shadow bridge technique



Charge Qubit Coherence



Jahr