2.5D cQED

From Whispering Photons to Transmons

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Thanks to:

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Luigi Frunzio
Matt Reagor
Teresa Brecht
Leonid Glazman
Rob Schoelkopf
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QuLab
RSL Lab

Yale Institute for Nanoscience and Quantum Engineering

Outline

1. Whispering gallery mode resonators:

   Concept & coherences

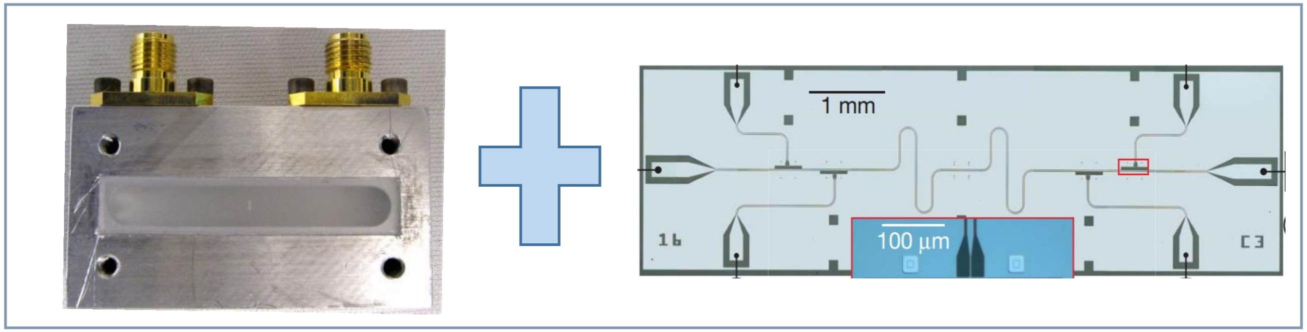
2. "Energy BBQ"

3. Integrated two cavity – one Transmon device

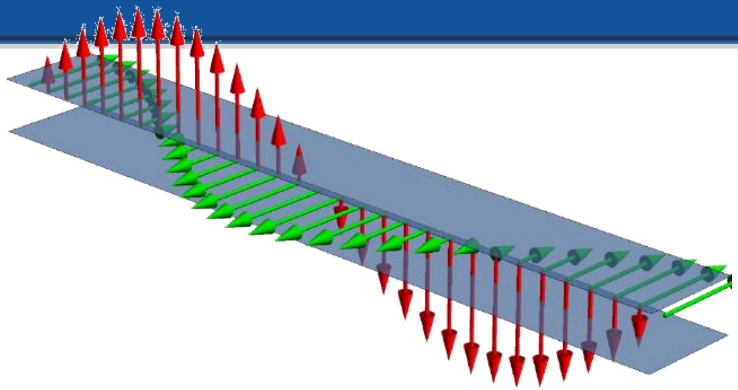
Motivation

I. Marry wafer scalability & 3D quality?
- Coupled resonators & multiple qubits
- On chip control lines

II. Test materials at the single photon level
- Thin films
- Dielectrics

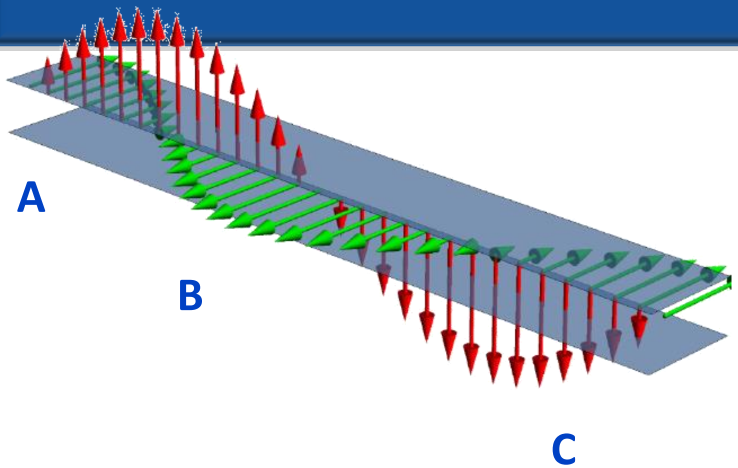


Design strategy:

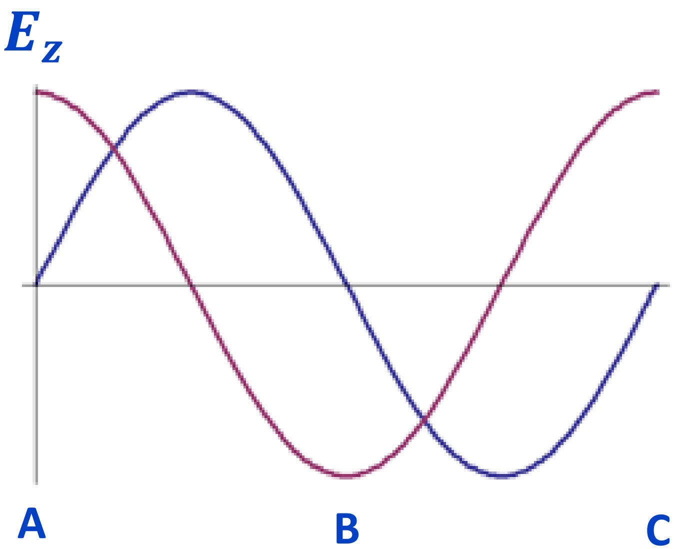


- Confine energy in lossless vacuum
- No seams
- Keep geometry & design parameters simple

How to form a resonator

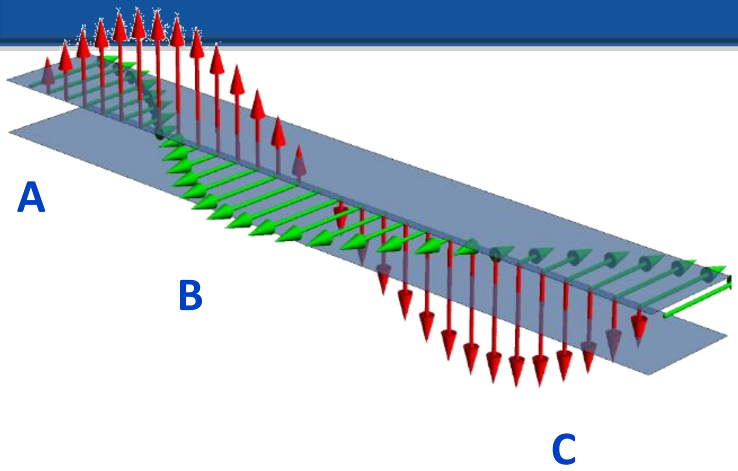


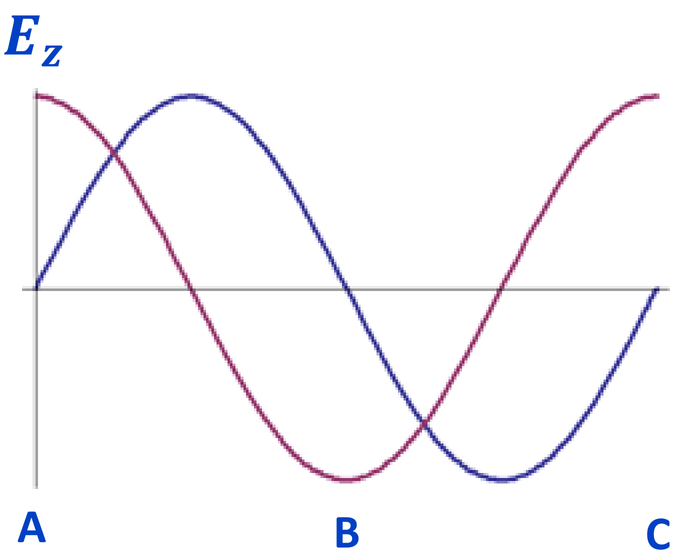
Periodic boundary conditions

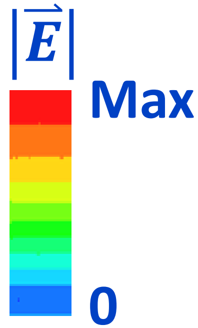


Degenerate ground state

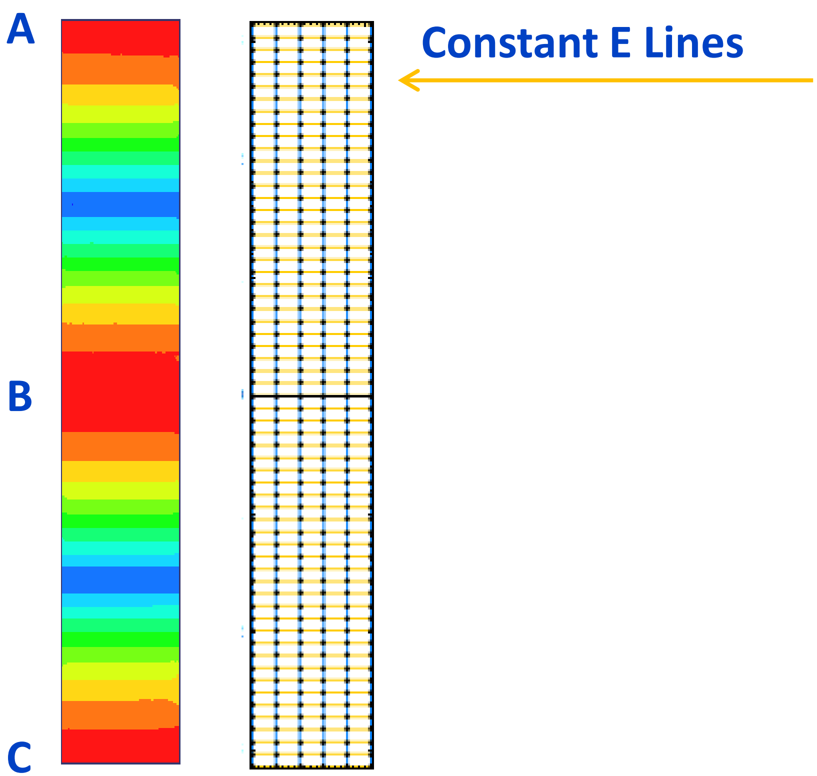
But it's `2D`: The color map



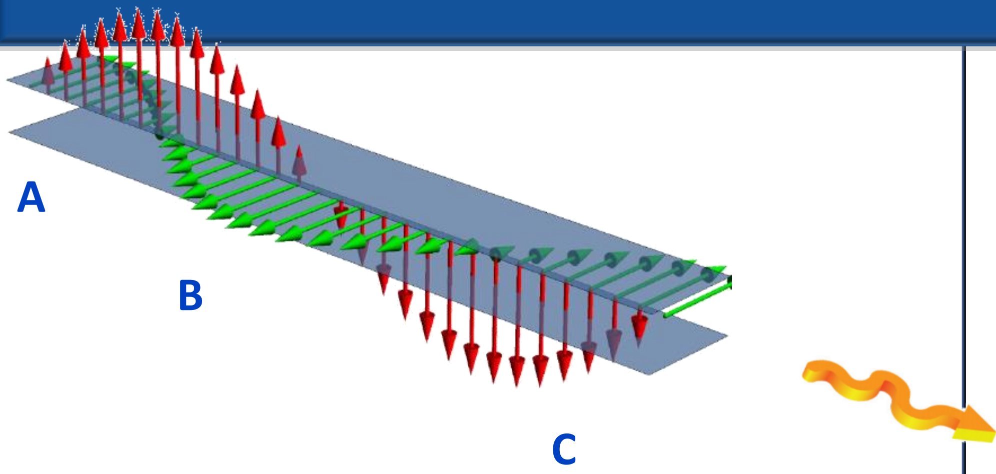


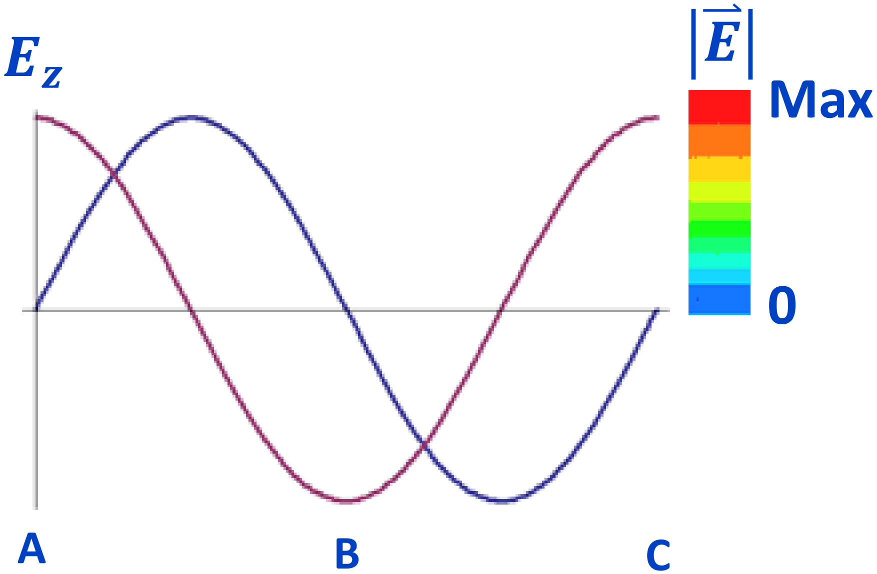


Top View ($|\vec{E}|$)

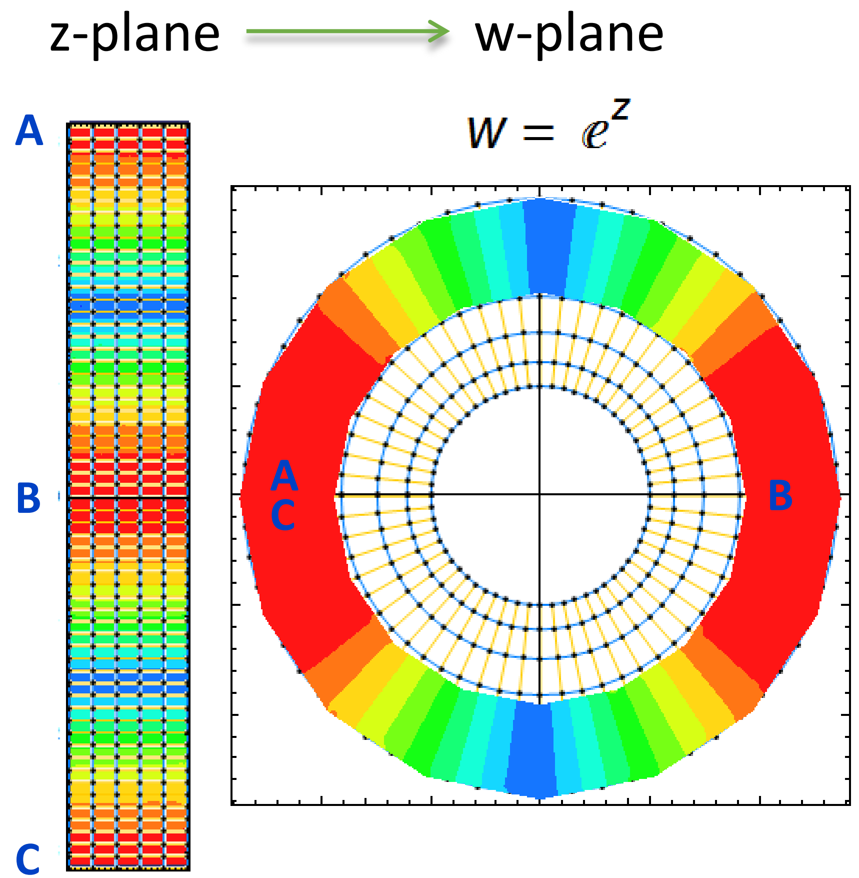


Physical periodic boundary conditions: Hello ring

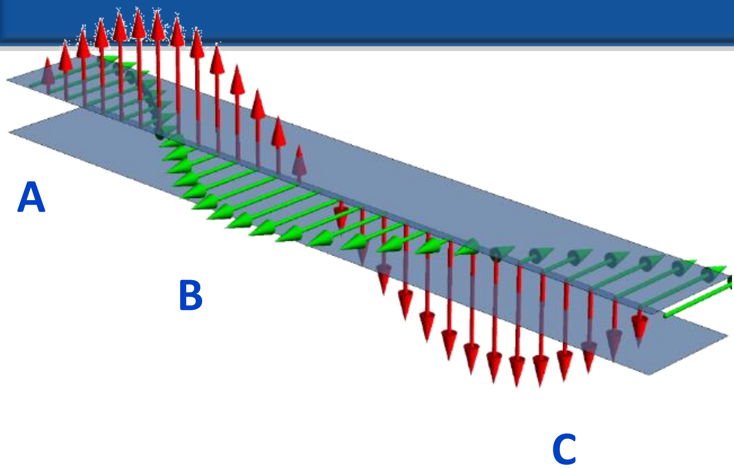


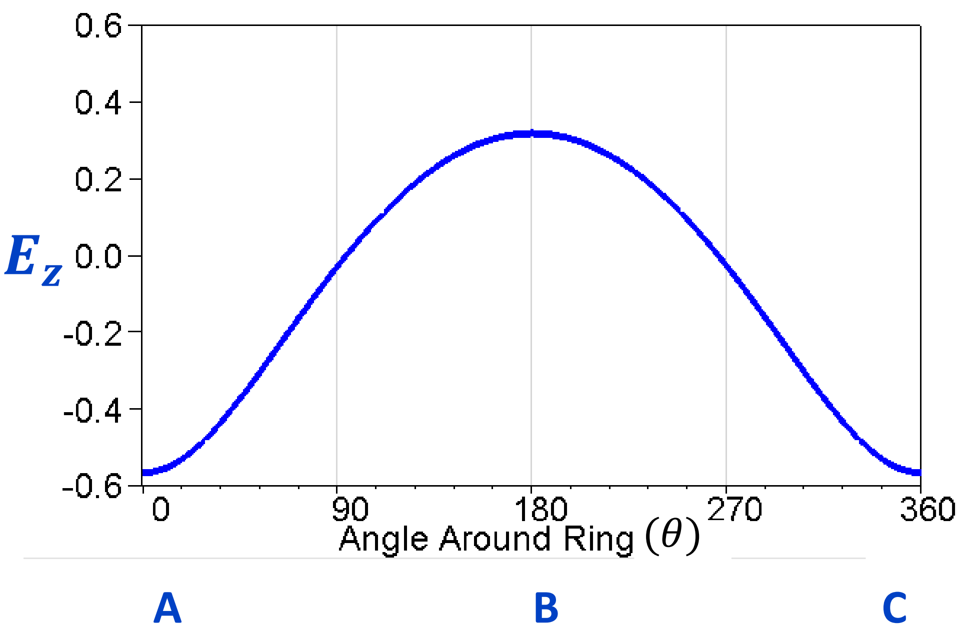


Top View ($|\vec{E}|$)



Warped Ring

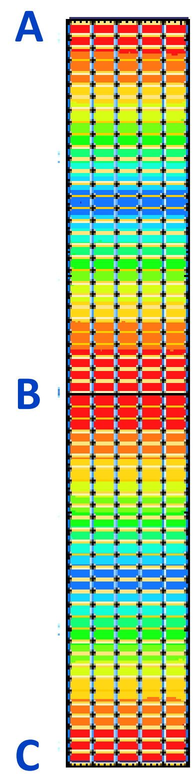


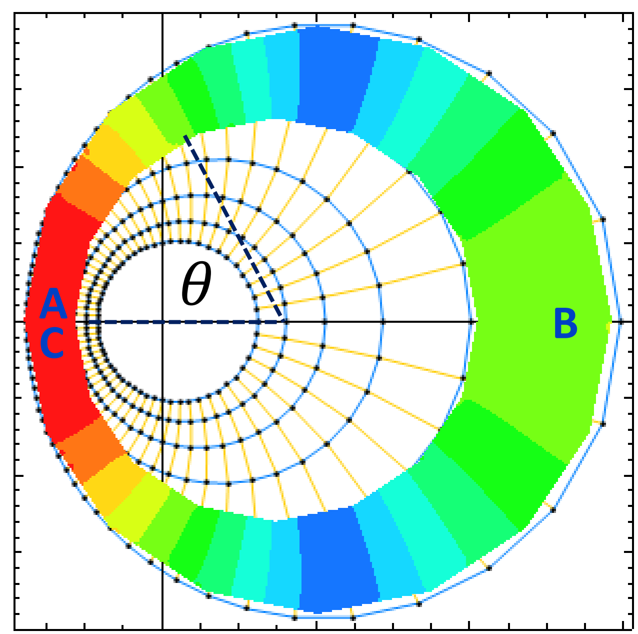


Top View ($|\vec{E}|$)

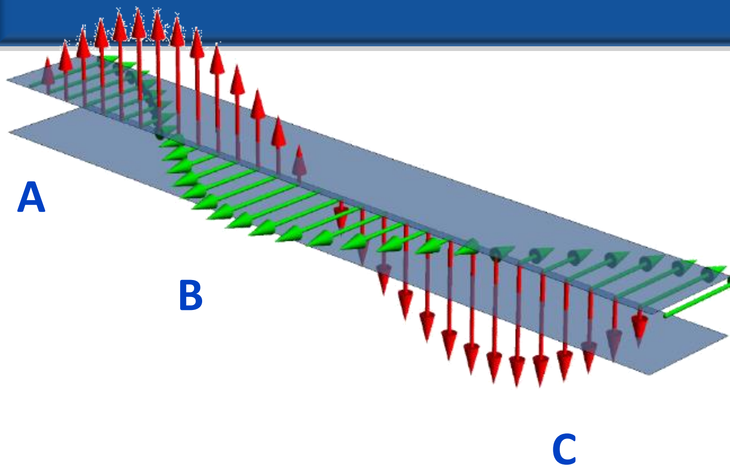
z-plane → w-plane

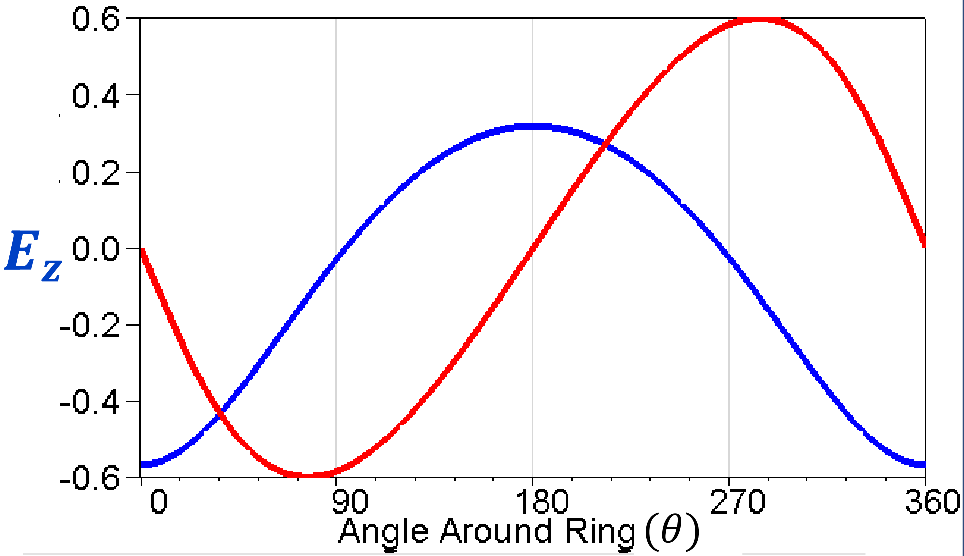
$$w = \frac{e^z}{1 - s\,e^z}$$





Warped Ring



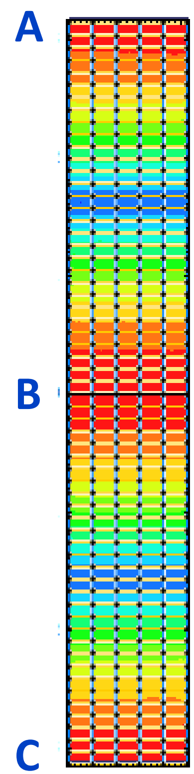


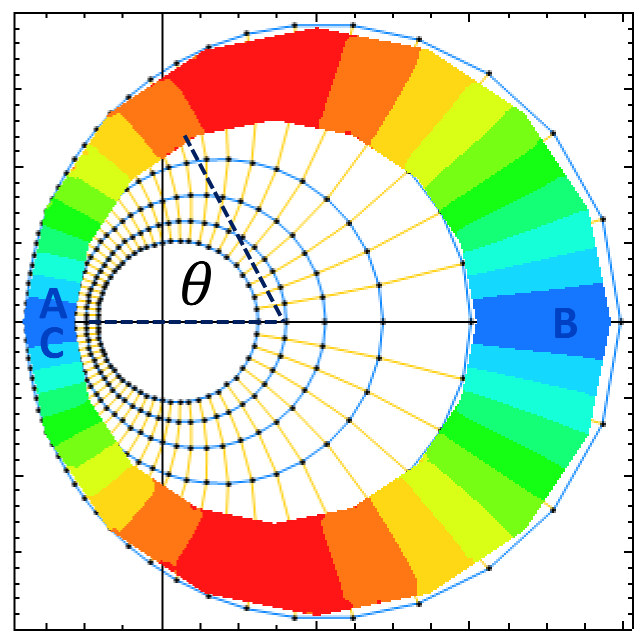
A B C

Top View ($|\vec{E}|$)

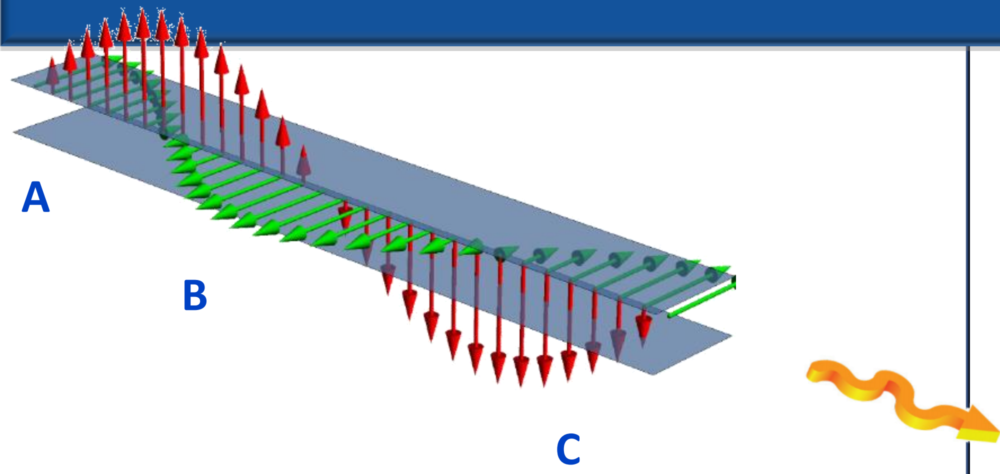
z-plane → w-plane

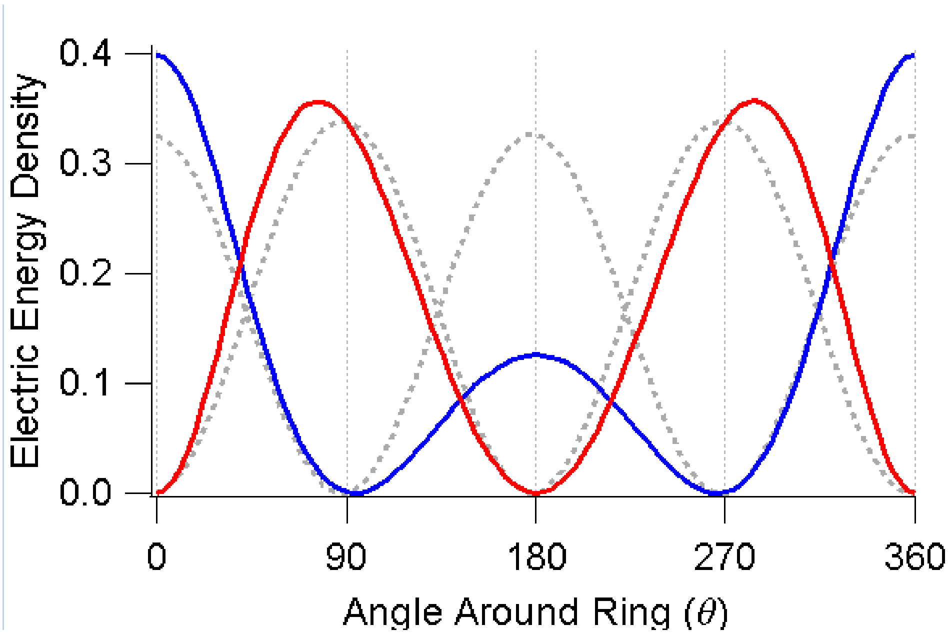
$$w = \frac{e^z}{1 - s\,e^z}$$



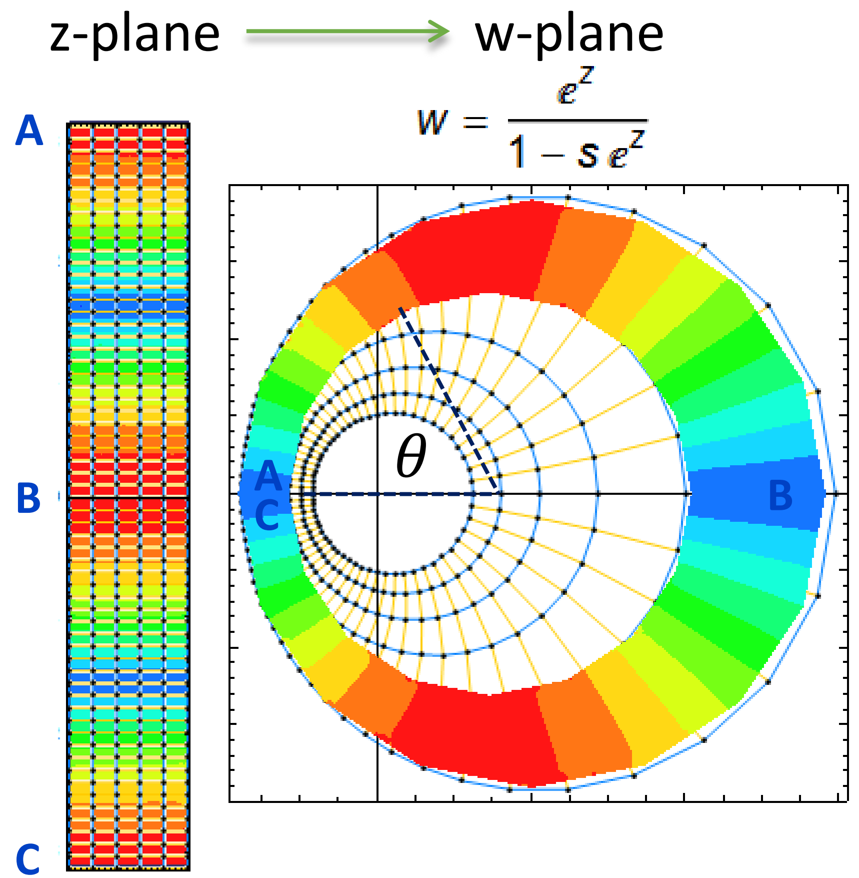


Warped Ring

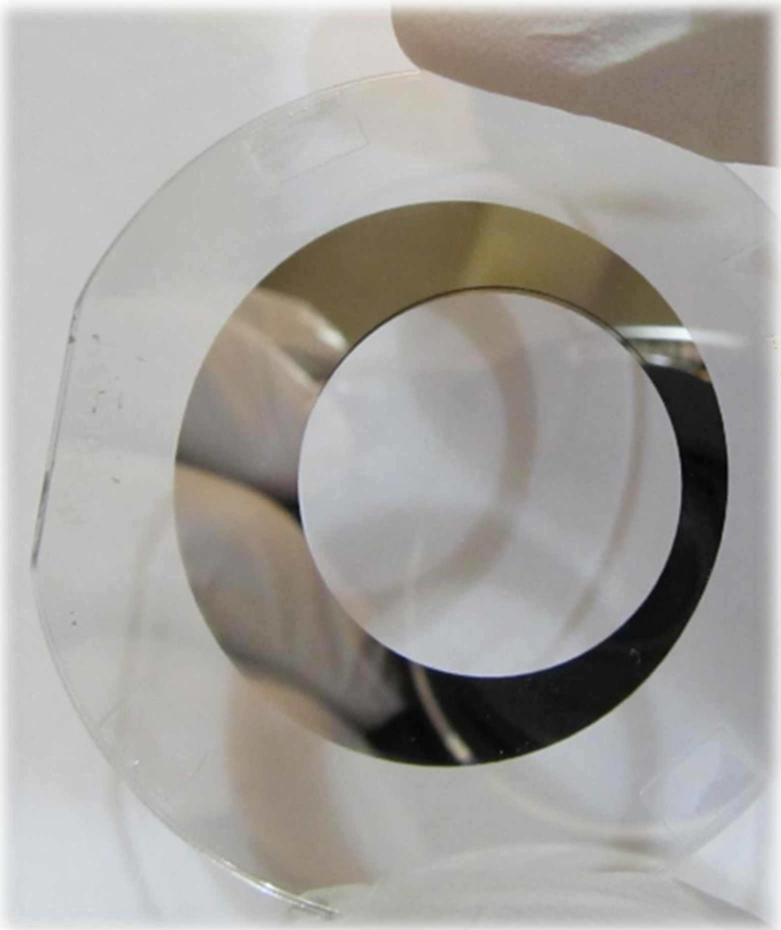




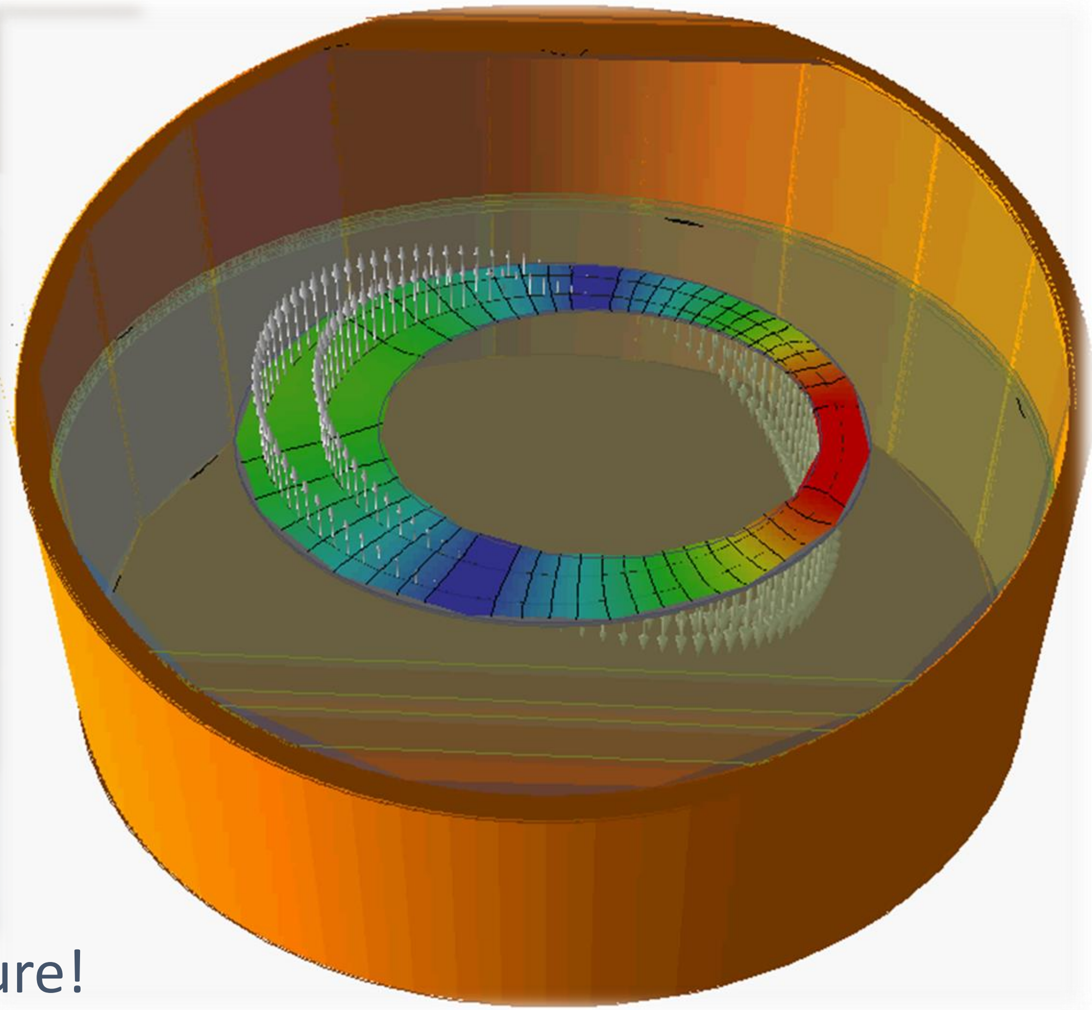
Top View ($|\vec{E}|$)



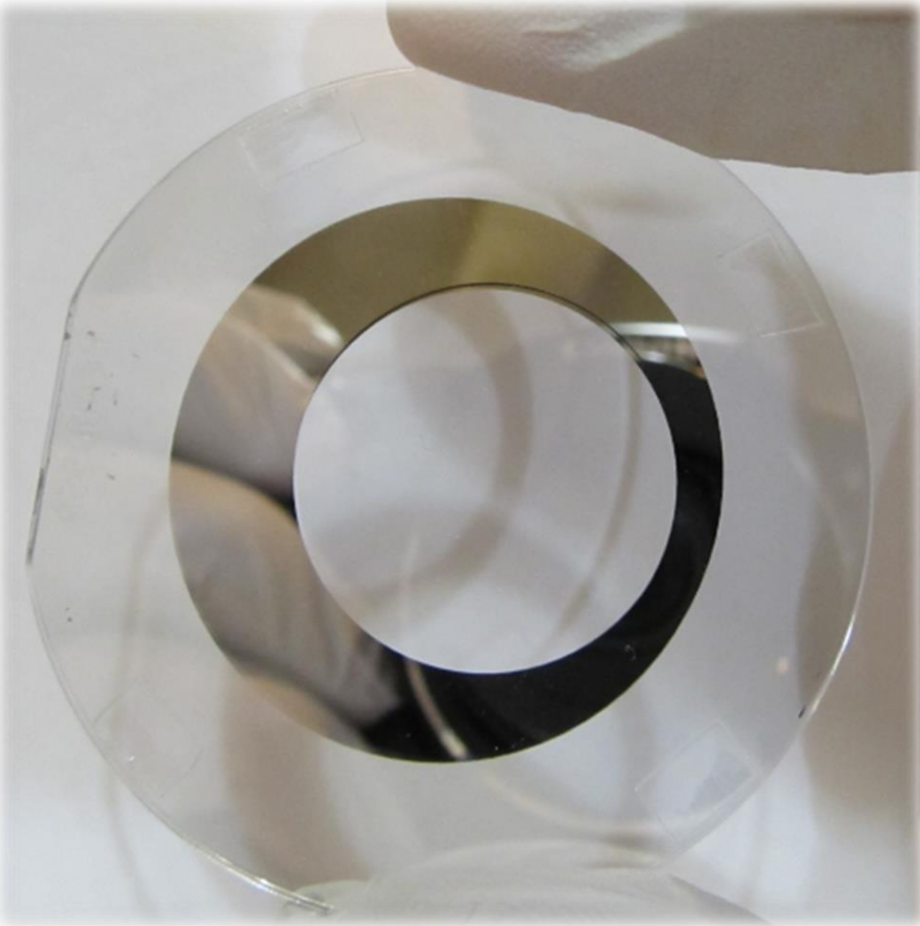
Towards `Wafer-Scalable` cQED architecture



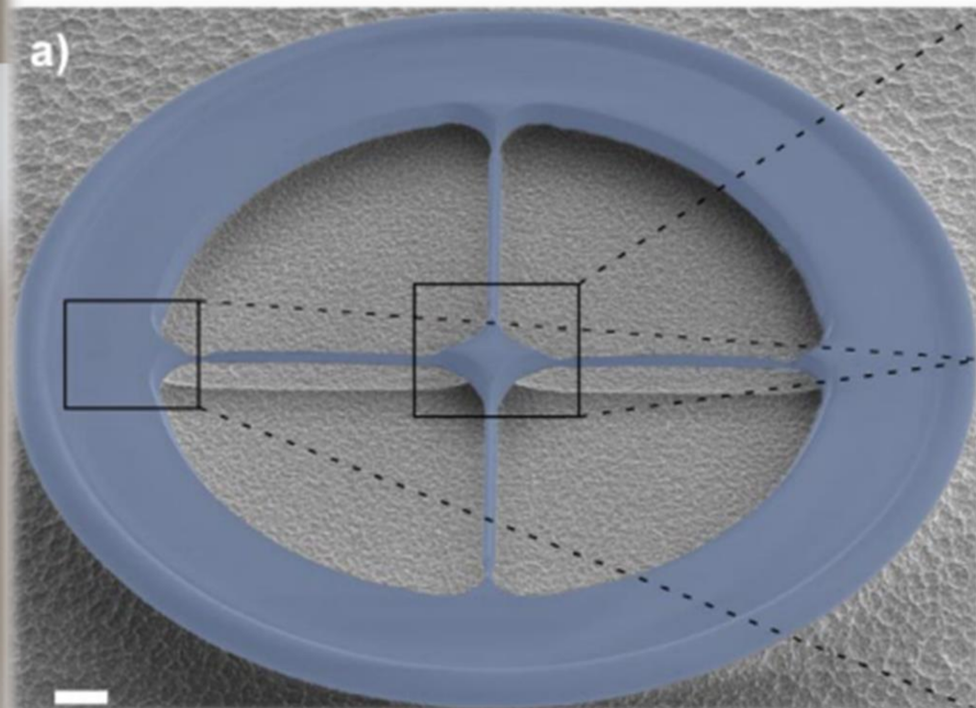
There are **2 rings** in this picture!



Whispering Gallery Modes

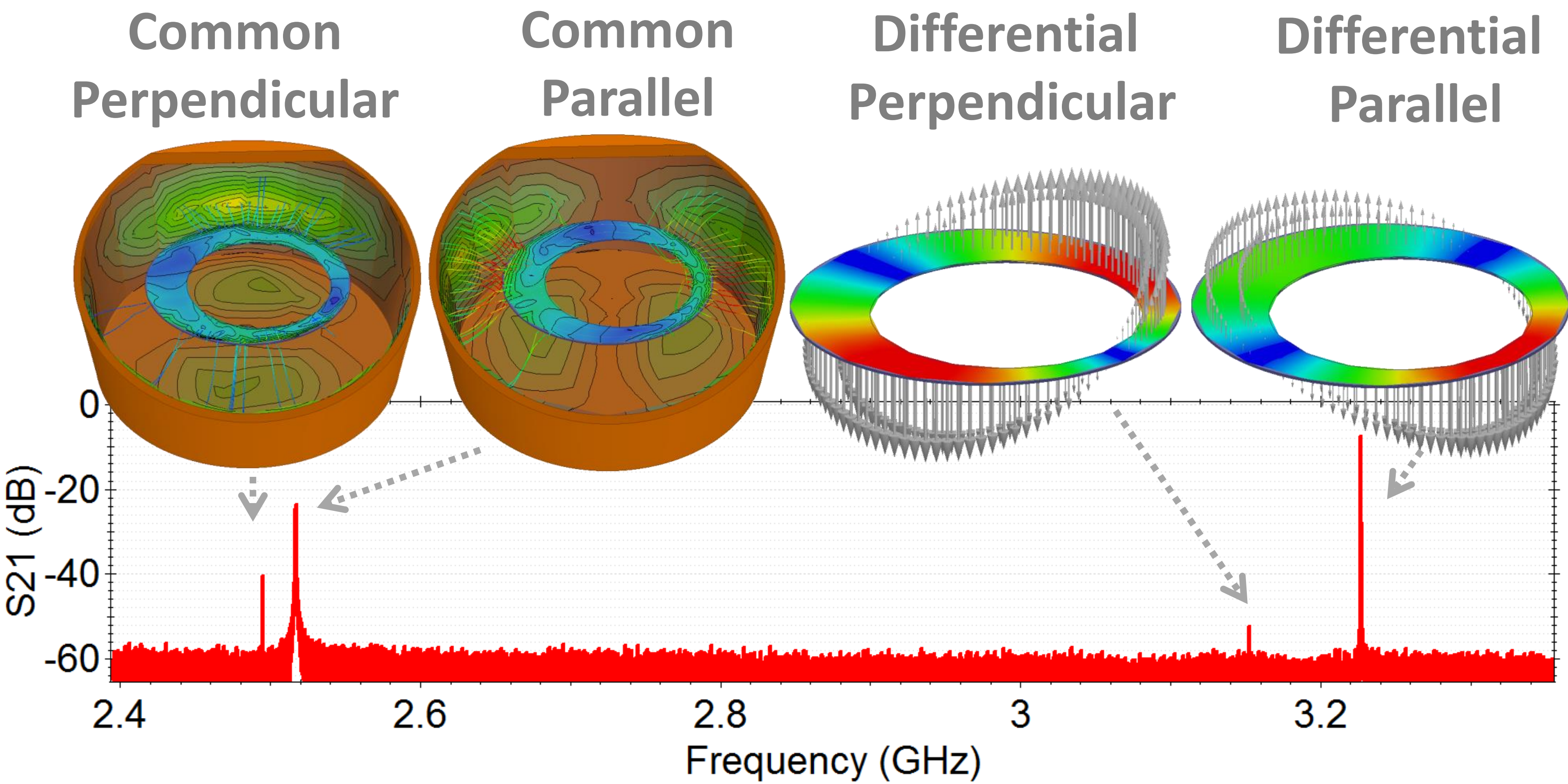


Similar to optical whispering gallery mode resonators



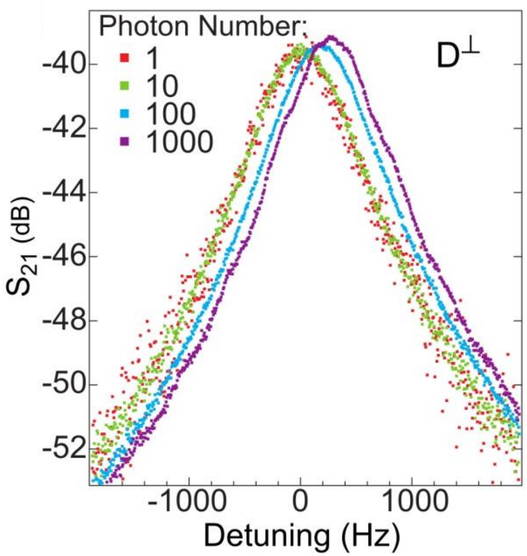
EPFL, *Nature Photonics* **2**, 627 - 633 (2008)

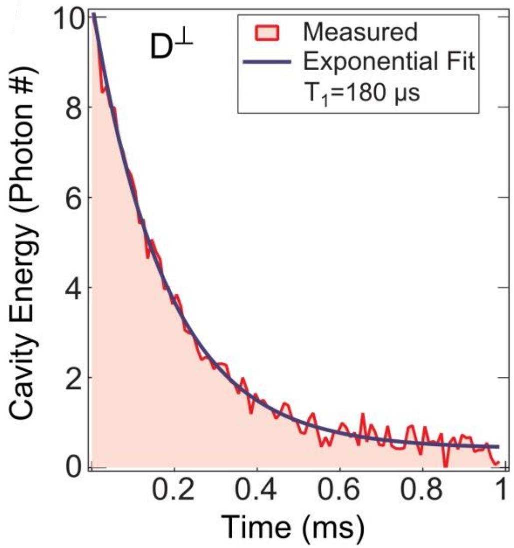
Identifying Modes (S_{21})

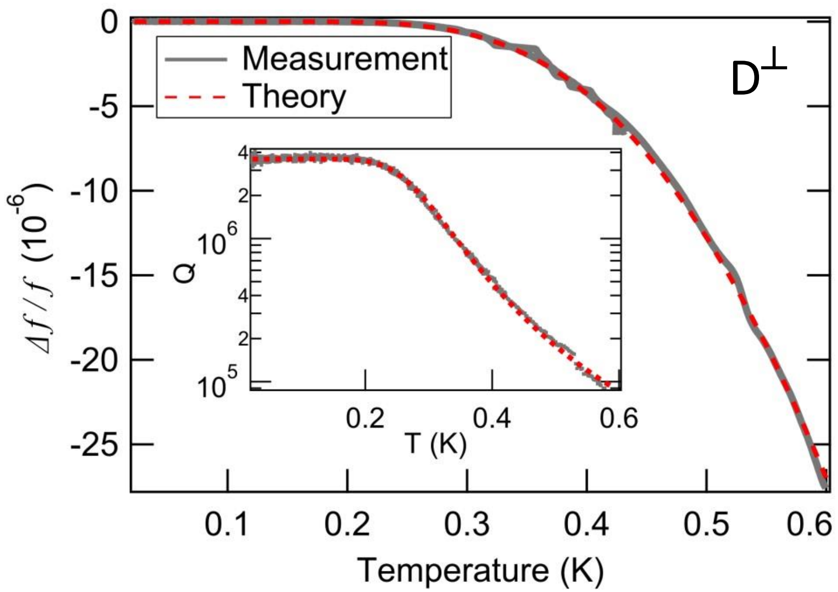


- **Differential modes contain > 98% of mode energy in between the rings**

Summary Superconducting WGMR Coherences







T_1 = 180 μs

$Q_i = 3.4 \cdot 10^6$

$T_\phi \geq 1$ ms

Thin-film Al — $R_s \leq 250 n\Omega$

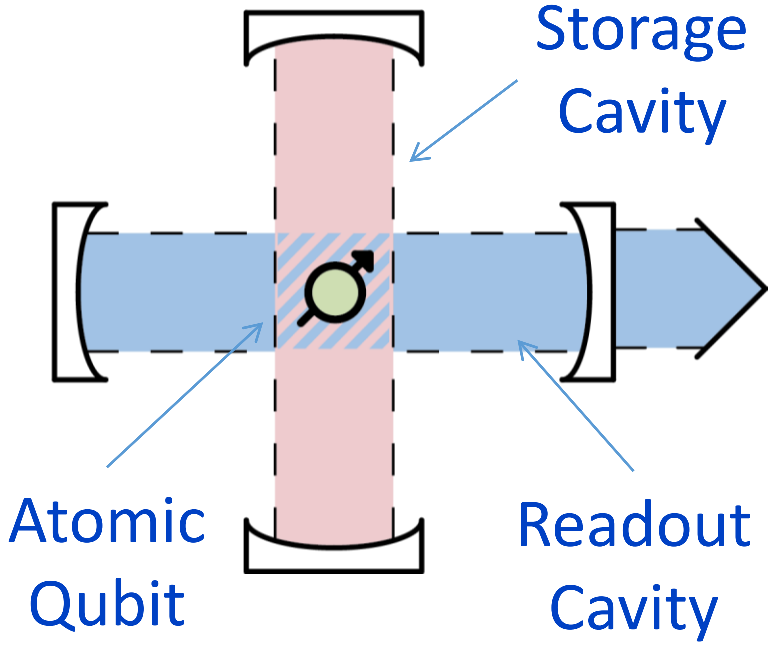
Sapphire — $\tan\delta \leq 10^{-6}$

- Long-lived ($T_1 = 180\mu s$) and coherent ($T_\phi \geq 1$ ms) resonators
- We place an upper bound on thin-film Al resistance $R_s \leq 250 n\Omega$ ($Q_s \geq 4{,}800$) at the single photon level
- We place an upper bound on the single photon loss tangent of sapphire $\tan\delta \leq 10^{-6}$

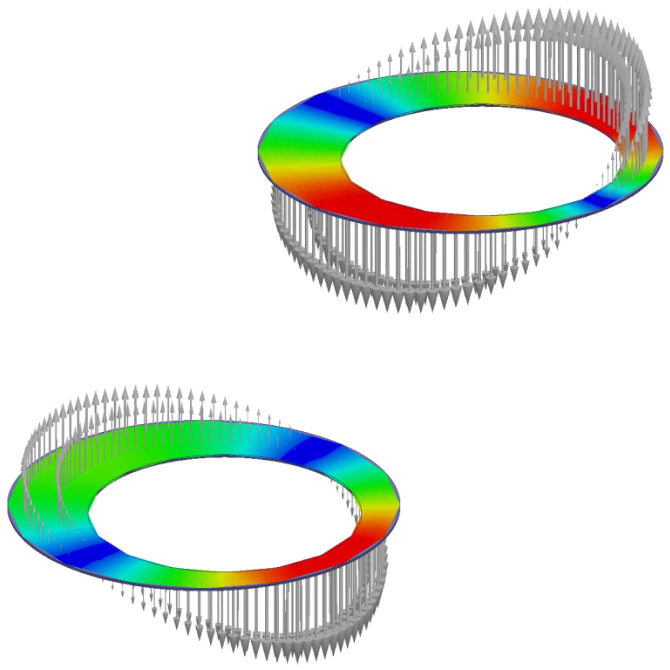
Minev, Pop & Devoret, Appl. Phys. Lett. 103, 142604 (2013)

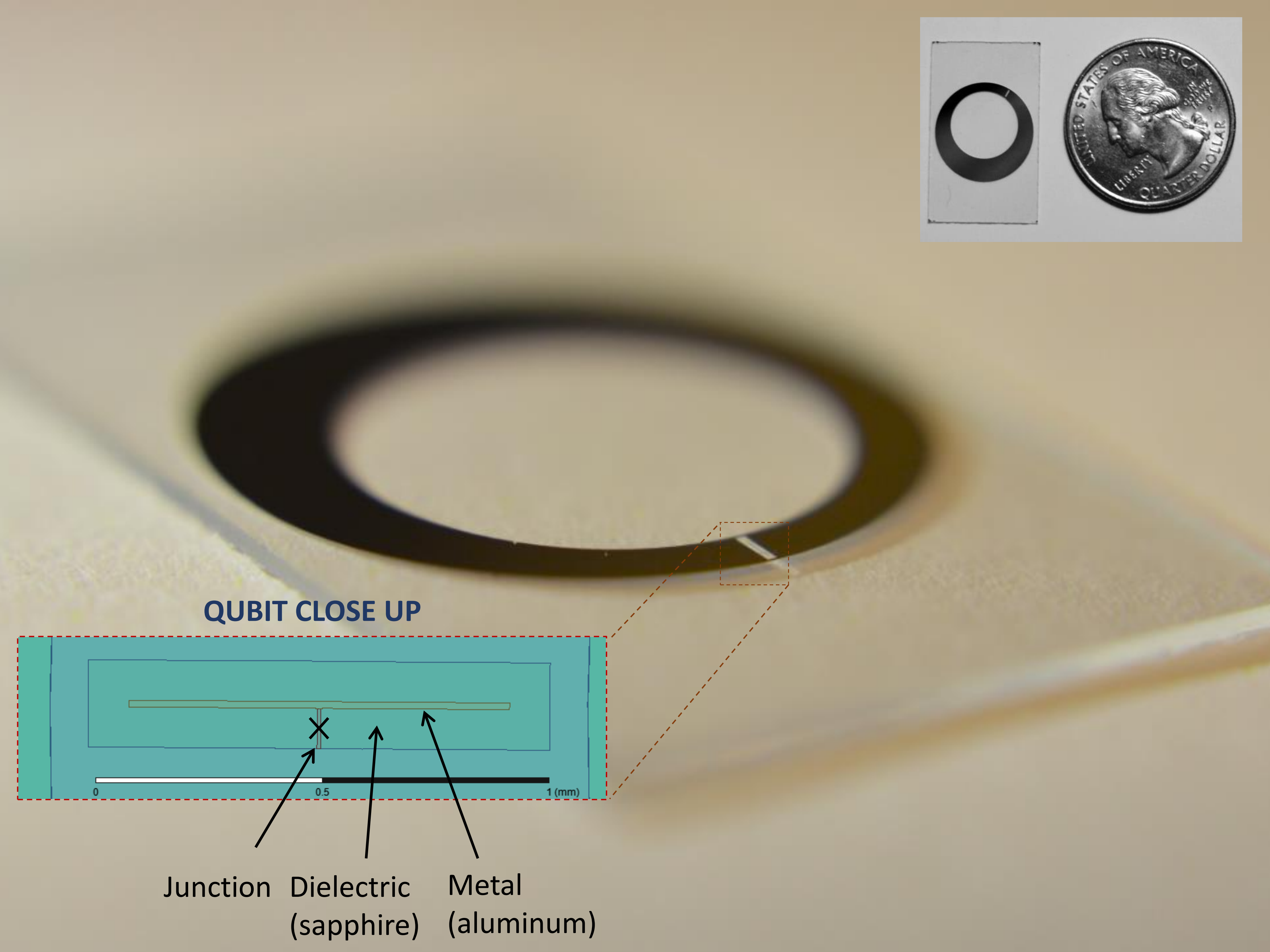
Qubit coupling to superconducting whispering gallery mode resonator

Cavity QED Equivalent



Ring Resonator





QUBIT CLOSE UP
0
0.5
1 (mm)
Junction
Dielectric
(sapphire)
Metal
(aluminum)

Device Hamiltonian

In terms of the phase through the junction (φ), the system is described by:

$$H = \omega_r a^\dagger a + \omega_q b^\dagger b + \omega_m c^\dagger c - E_J \left[\cos(\varphi) - \frac{\varphi^2}{2}\right]$$

$$\varphi = \varphi_r (a^\dagger + a) + \varphi_q (b^\dagger + b) + \varphi_m (c^\dagger + c)$$

$\varphi_r, \varphi_q, \varphi_m$ refer to the zero point fluctuations of the junction phase in their respective mode.

These 6 parameters can be efficiently calculated with large precision O(1%).
The relevant lowest order non-linear (NL) pieces of the Hamiltonian then follow:

$$H_{NL} = \frac{1}{2}\alpha_r (a^\dagger a)^2 + \frac{1}{2}\alpha_q (b^\dagger b)^2 + \frac{1}{2}\alpha_m (c^\dagger c)^2$$

$$+\chi_{qr} a^\dagger a b^\dagger b + \chi_{qm} c^\dagger c b^\dagger b$$

Anharmonicity (self-Kerr):

$\alpha_r, \alpha_q, \alpha_m$

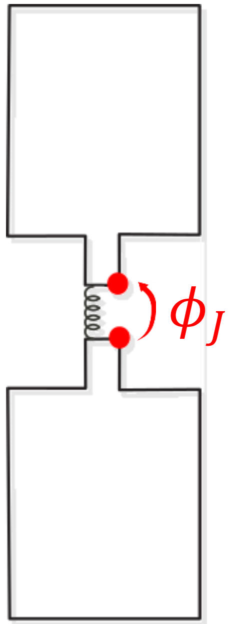
Cross-Kerr

χ_{qr}, χ_{qm}

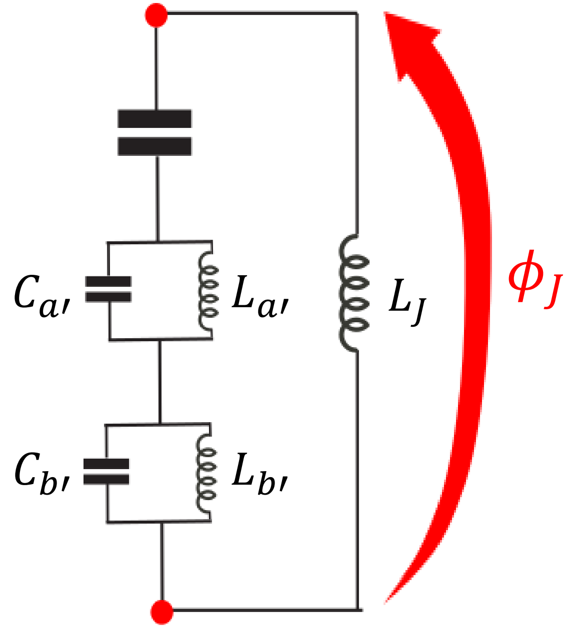
For instance: $\alpha_r = \frac{1}{2} E_J \phi_r^{\ 4}$

BBQ: from device to circuit to Hamiltonian

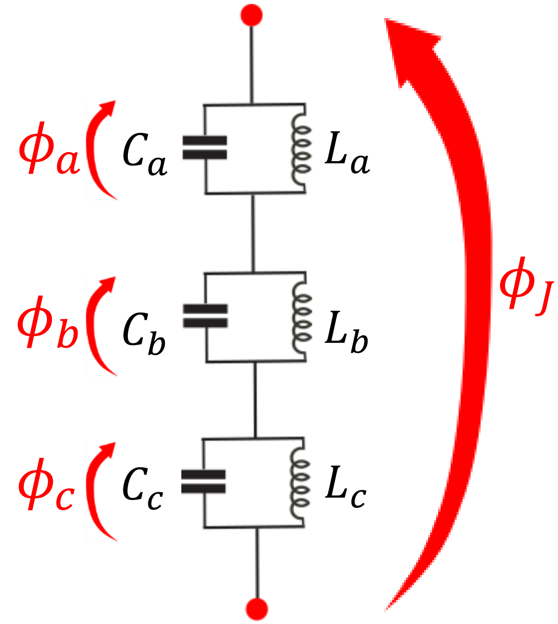
Physical (Linear)



Undressed (Linear)



Dressed (Linear)



$$\hat{\phi}_J = \hat{\phi}_a + \hat{\phi}_b + \ldots$$
$$= \phi_a^{\mathrm{ZPF}}\left(a + a^\dagger\right) + \phi_b^{\mathrm{ZPF}}\left(b + b^\dagger\right) + \ldots$$

Can we reformulate BBQ in terms of energy participation ratios?

$$\boxed{\phi_a^{\mathrm{ZPF}} = \sqrt{\frac{\hbar}{2} Z_a^{\mathrm{eff}}} = \sqrt{\frac{\hbar}{\omega_a \operatorname{Im} Y'(\omega_a)}}}$$

Nigg et al. PRL 108, 240502 (2012)

Energy Participation Ratios

$$\text{Energy in Mode } a = \overline{U_E} + \overbrace{\left(\overline{U_M} + \overline{U_K}\right)}^{\text{from HFSS}} = 2\,\overline{U_E}$$

$$p_J^a \equiv \frac{\text{Energy stored in Junction}}{\text{Energy stored in mode } a} = \frac{\overline{U_K}}{2\,\overline{U_E}} = \frac{\overline{U_E}-\overline{U_M}}{2\,\overline{U_E}}$$

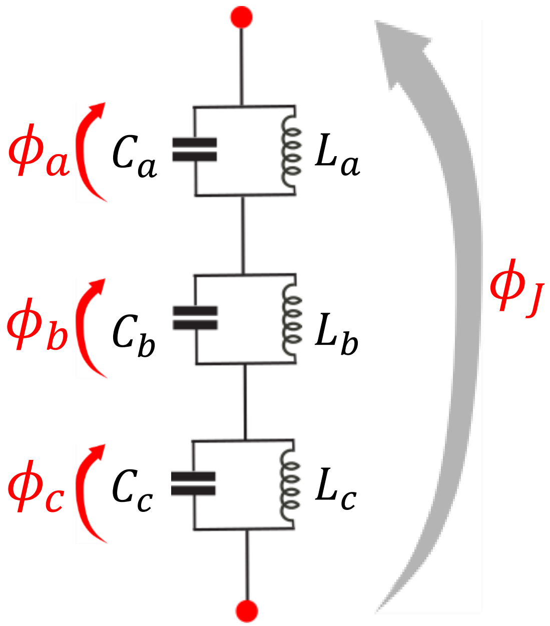
$$= \frac{\left\langle n_a \middle| \frac{1}{2} E_J \hat{\phi}_J{}^2 \middle| n_a \right\rangle}{\left\langle n_a \middle| H \middle| n_a \right\rangle} = \frac{E_J}{\hbar\,\omega_a} \phi_a^{\mathrm{ZPF}\,2}$$

$$\boxed{\phi_a^{\mathrm{ZPF}\,2} = p_J^a \frac{\hbar\,\omega_a}{E_J}}$$

$$\boxed{\alpha_a = \frac{1}{2} E_J \phi_a^{\mathrm{ZPF}\,4} = \frac{1}{2} \frac{(p_J^a\,\hbar\,\omega_a)^2}{E_J}}$$

$$\boxed{\chi_{ab} = p_J^a\, p_J^b \frac{\hbar\,\omega_a\,\hbar\,\omega_b}{E_J}}$$

Dressed (Linear)

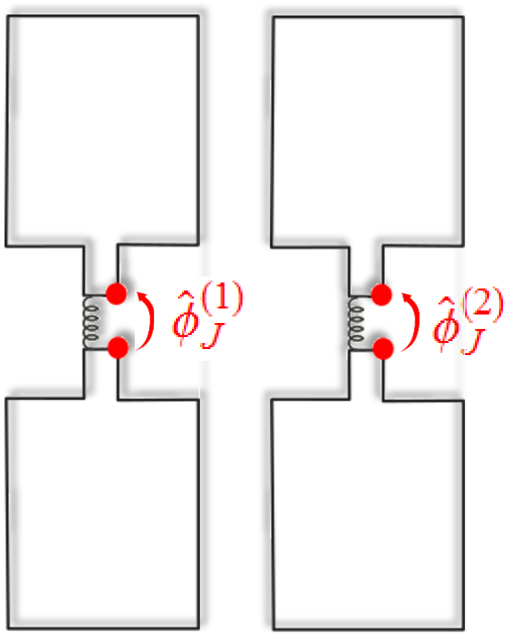


$$\hat{\phi}_J = \hat{\phi}_a + \hat{\phi}_b + \ldots$$
$$= \phi_a^{\mathrm{ZPF}}\left(a + a^\dagger\right) + \phi_b^{\mathrm{ZPF}}\left(b + b^\dagger\right) + \ldots$$

$$\boxed{\begin{aligned} L_a &= 2\, p_J^a\, L_J \\ C_a^{-1} &= \omega_a{}^2\, L_a \end{aligned}}$$

$$\boxed{\sum_i p_J^{a_i} = \frac{1}{2}}$$

Multi-Junction BBQ



$$H = \sum_i \omega_i \, a_i^{\dagger} \, a_i - \sum_p E_J^p \left[\cos(\hat{\phi}_p) - \frac{\hat{\phi}_p{}^2}{2} \right]$$

$$\hat{\phi}_J^{(1)} = \hat{\phi}_a^{(1)} + \hat{\phi}_b^{(1)} + \ldots = \phi_a^{(1)\,\mathrm{ZPF}} \left(a + a^{\dagger}\right) + \phi_b^{(1)\,\mathrm{ZPF}} \left(b + b^{\dagger}\right) + \ldots$$

$$\hat{\phi}_J^{(2)} = \hat{\phi}_a^{(2)} + \hat{\phi}_b^{(2)} + \ldots = \phi_a^{(2)\,\mathrm{ZPF}} \left(a + a^{\dagger}\right) + \phi_b^{(2)\,\mathrm{ZPF}} \left(b + b^{\dagger}\right) + \ldots$$

$$\vdots$$

$$\hat{\phi}_J^{(p)} = \sum_{i=1}^{M} \ldots a_i^{\dagger})$$

$$\boxed{\phi_a^{(p)\,\mathrm{ZPF}^2} = p_a^{(p)} \frac{\hbar\, \omega_a}{E_J^{(p)}}}$$

Nigg et al. PRL 108, 240502 (2012)

$$\text{Dissipationless} \Rightarrow \phi_i^{(k)} \in \mathbb{R}$$

Exploring all the consequences of the phase of ϕ^{ZPF} is subject matter for another talk.

Where is the Energy?

From "Energy BBQ" we can extract:

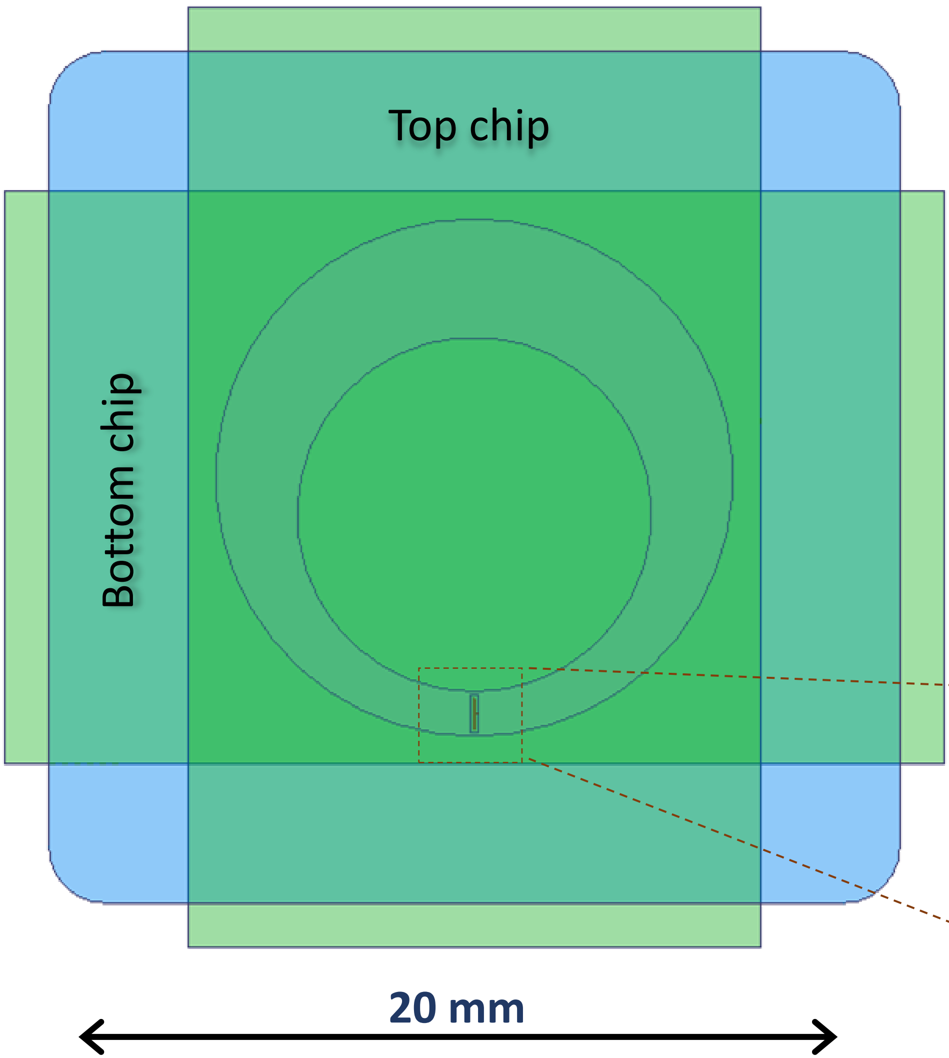
Hamiltonian	$H = H(a^\dagger, a)$
Interactions	$\alpha_r, \alpha_q, \alpha_m, \chi_{qr}, \chi_{qm}, \ldots$
I/O rates	$\kappa_r, \kappa_q, \kappa_m, \ldots$
Dissipation budget	$R_s, \ \tan\delta, \ldots$

Advantages:

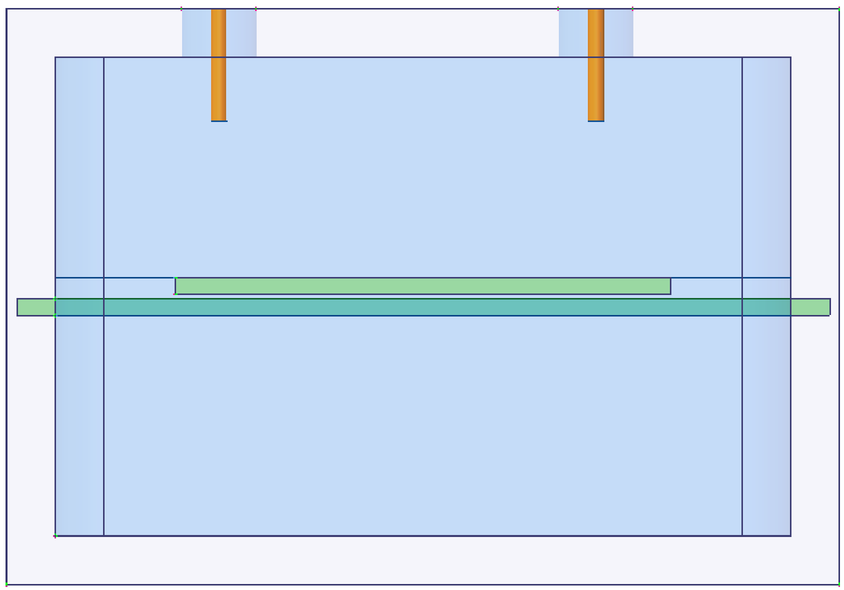
- **Conceptually simple framework**
- **Only one HFSS simulation**
- **Predicts limitations - ex. bright state**

Sample holder idea

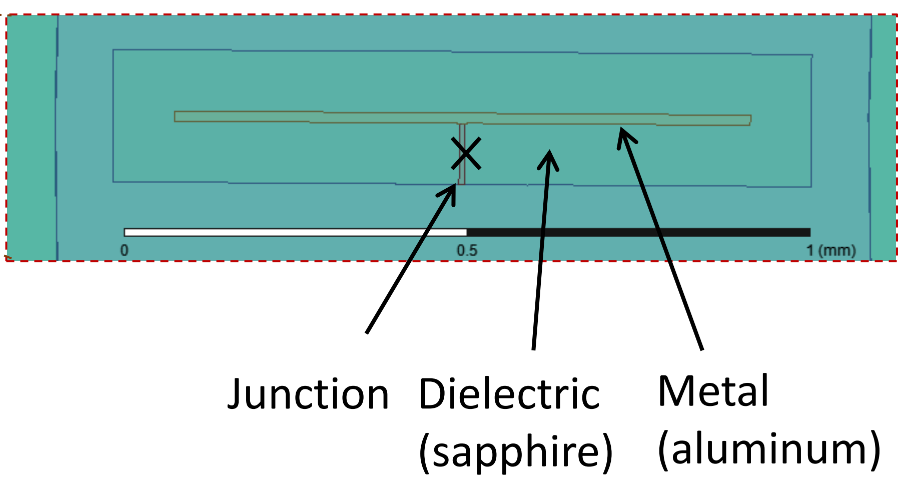
TOP VIEW



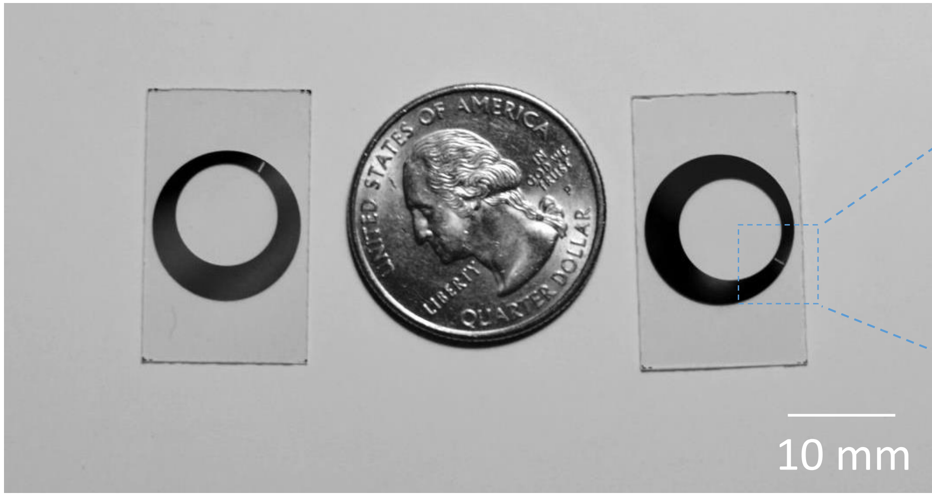
SIDE VIEW

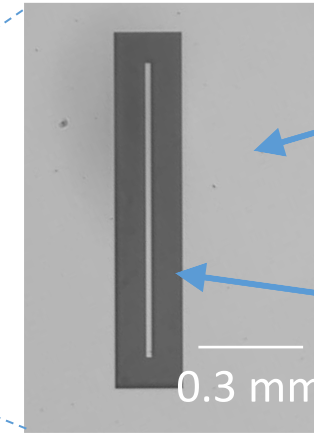


QUBIT CLOSE UP



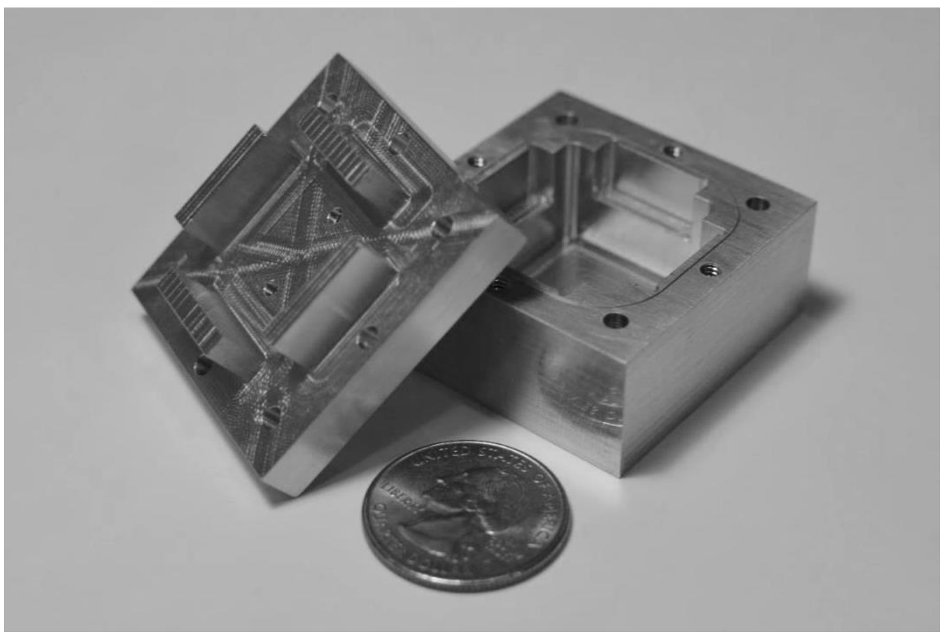
The device

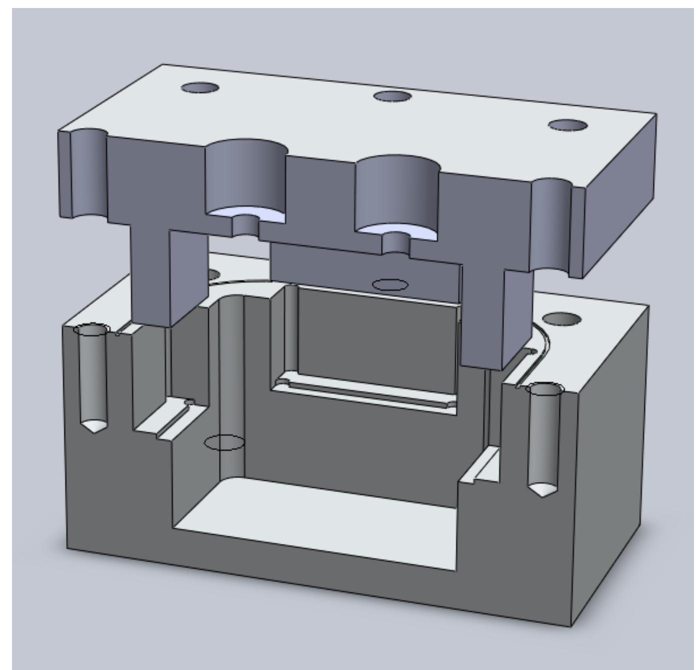




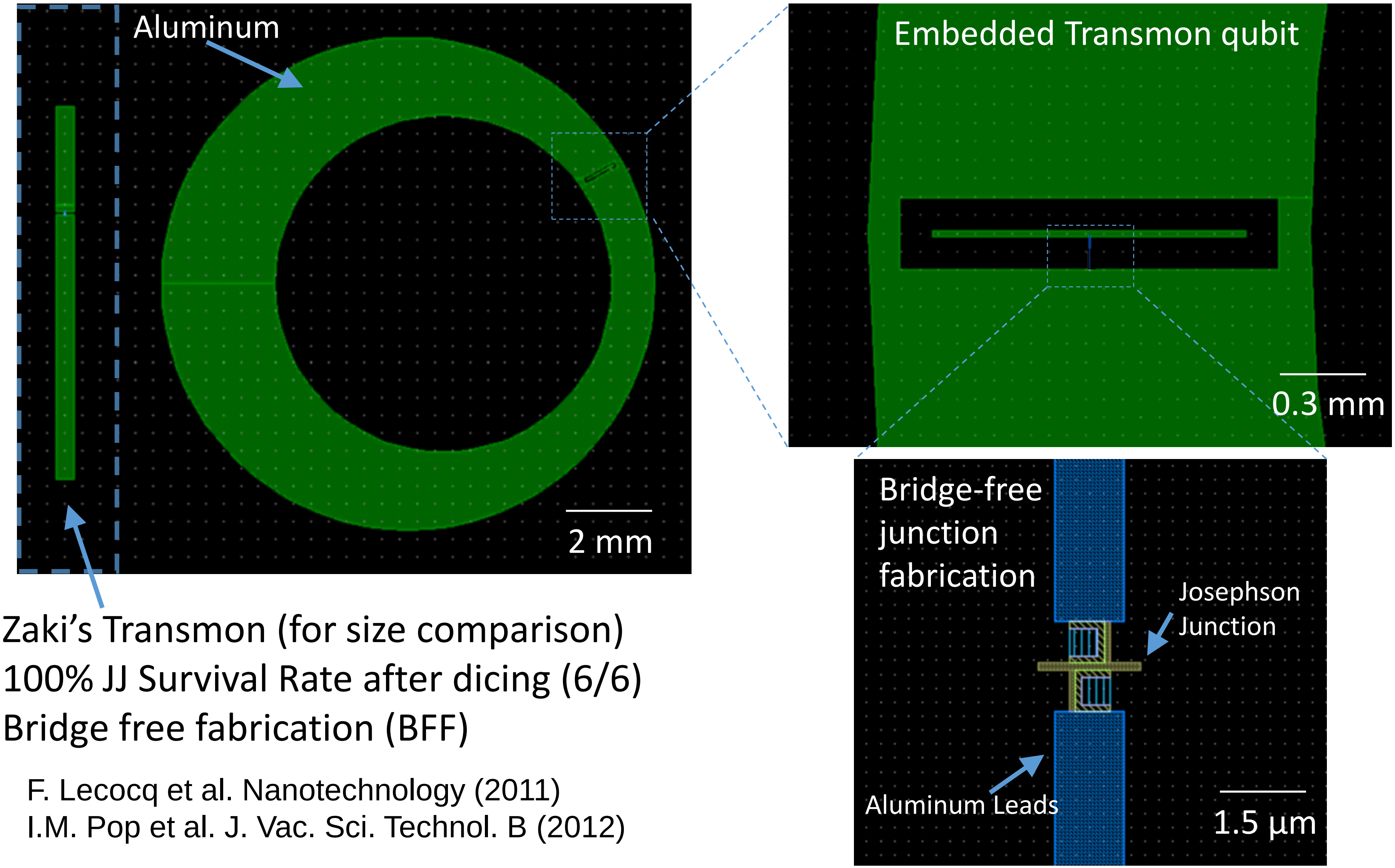
50 nm Aluminum

Al_2O_3 substrate, 430 μm thick





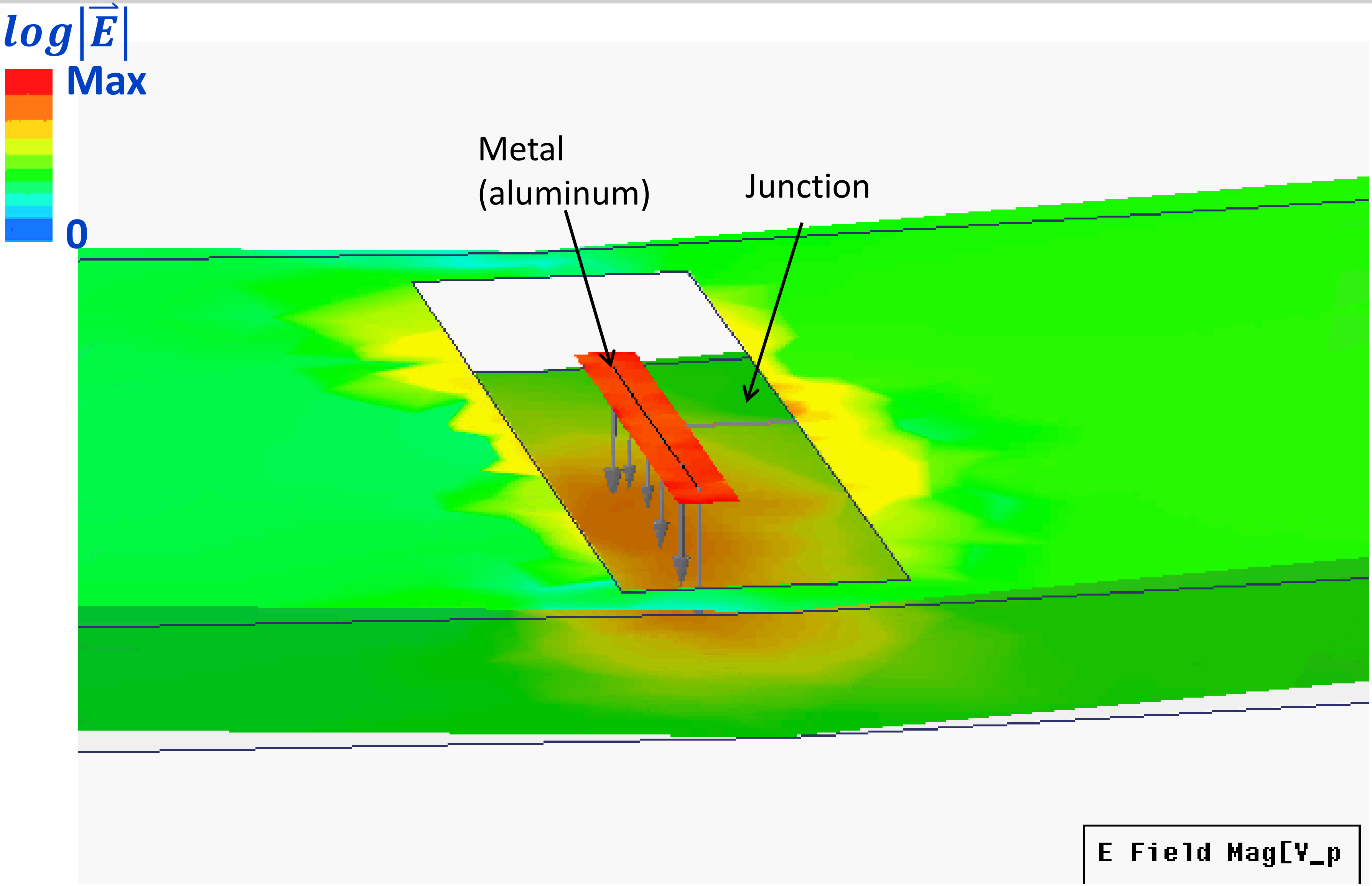
Fabrication: e-Beam Lithography



Zaki's Transmon (for size comparison)
100% JJ Survival Rate after dicing (6/6)
Bridge free fabrication (BFF)

F. Lecocq et al. Nanotechnology (2011)
I.M. Pop et al. J. Vac. Sci. Technol. B (2012)

Qubit Mode



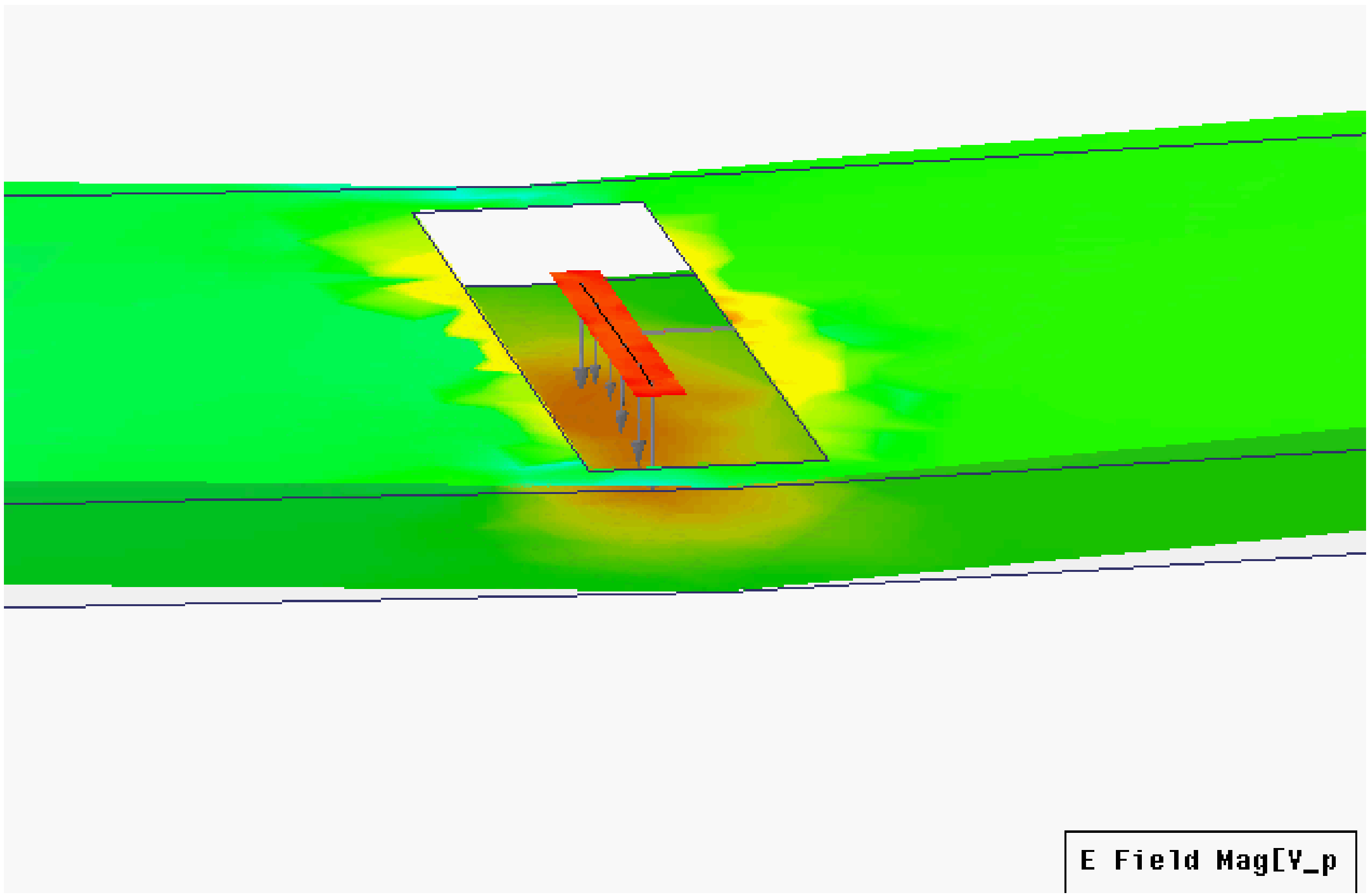
Qubit Mode

$\log|\vec{E}|$

Max

0

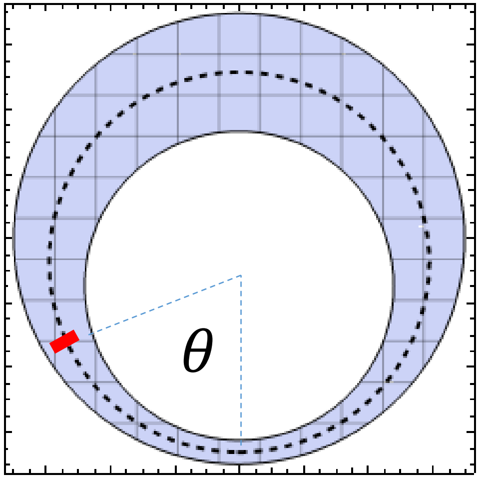
$|\overrightarrow{J_{surf}}|$

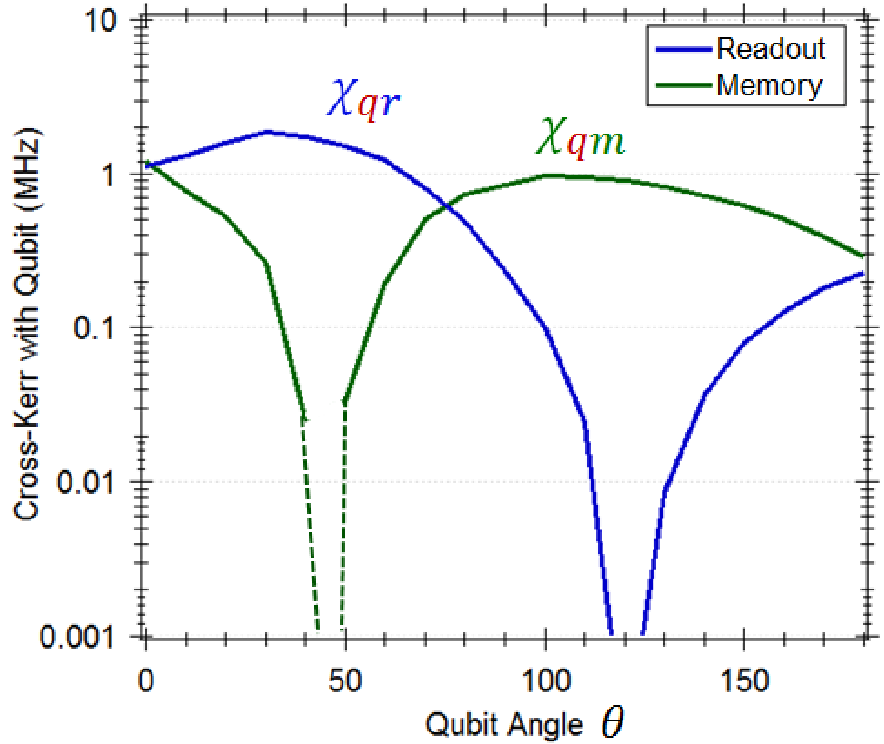


Key idea: can vary qubit angle around the ring

Qubit frequency and anharmonicity are independent of angle.

Tuning Cross-Kerr



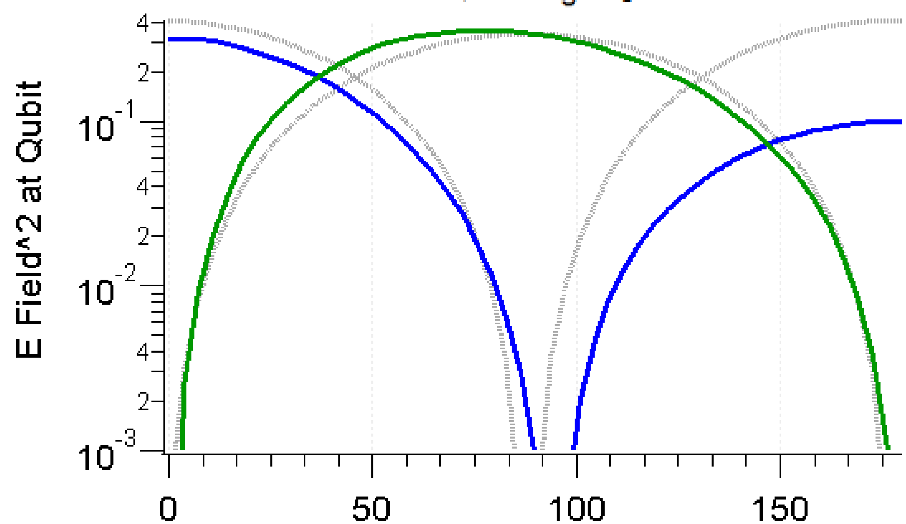


$$\omega_q/_{2\pi} = 6.1\ \text{GHz}$$

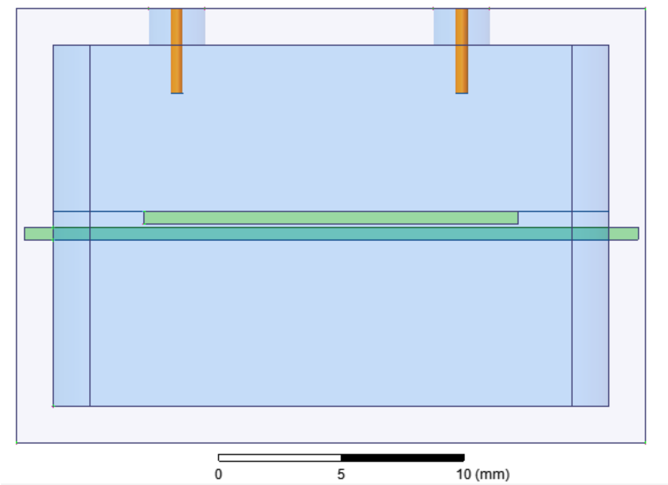
$$\omega_m/_{2\pi} = 7.2\ \text{GHz}$$

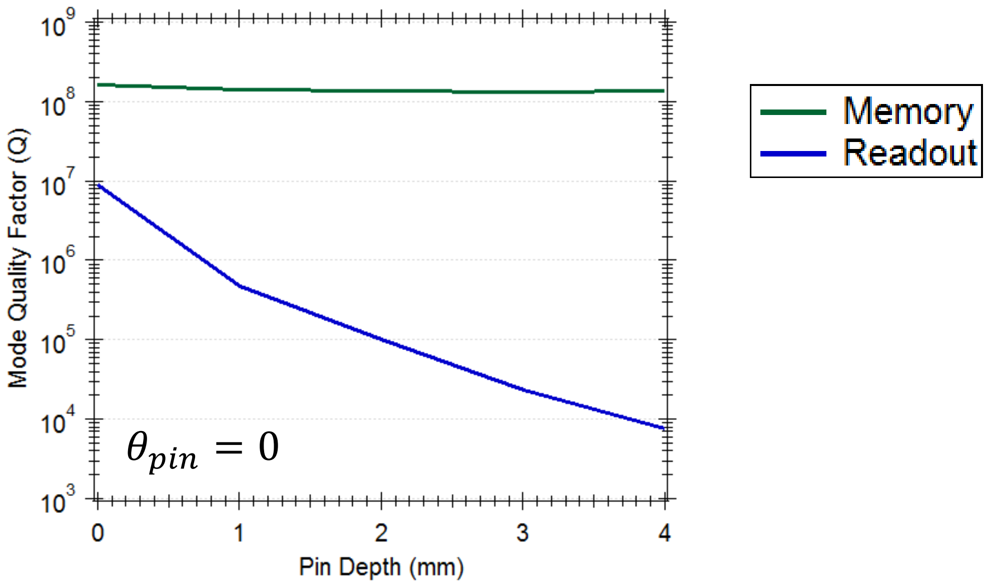
$$\omega_r/_{2\pi} = 7.6\ \text{GHz}$$

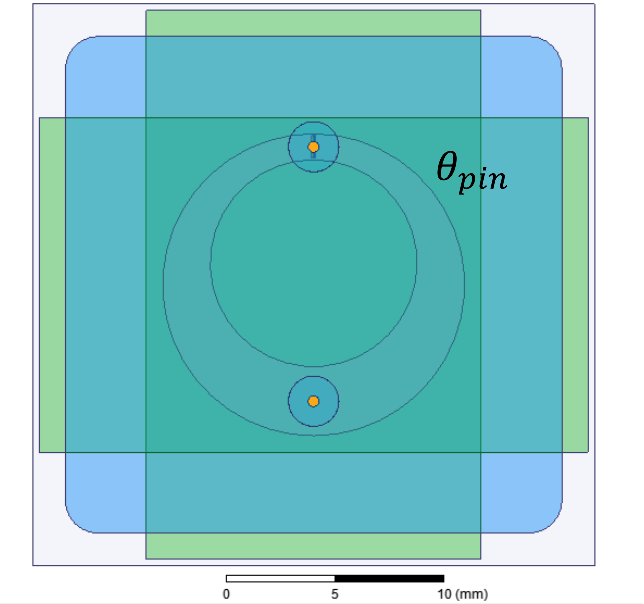
$$\alpha_q/_{2\pi} = 250\ \text{MHz}$$

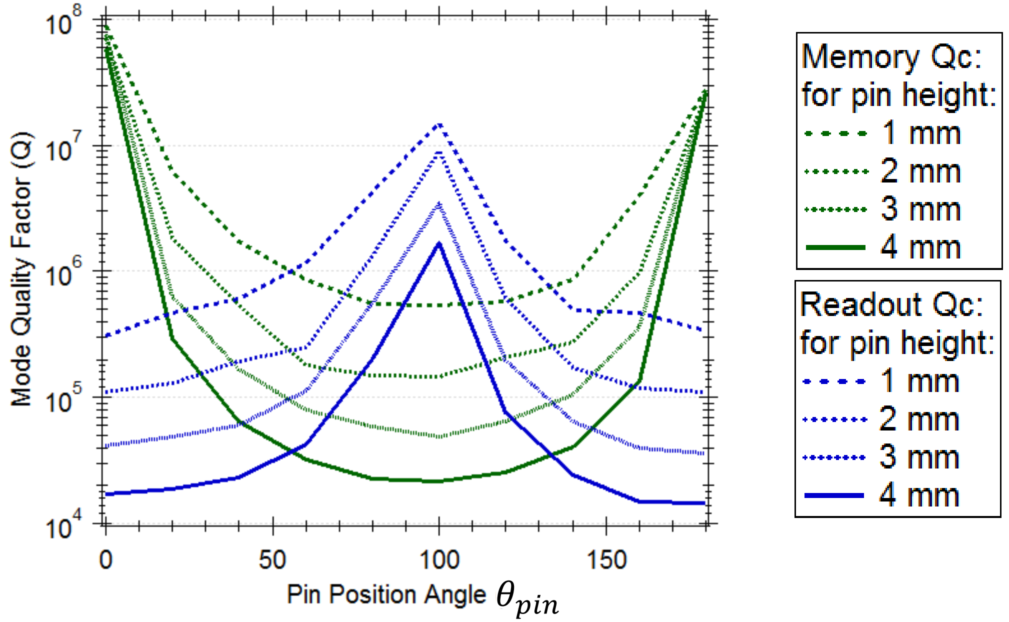


Selective mode coupling

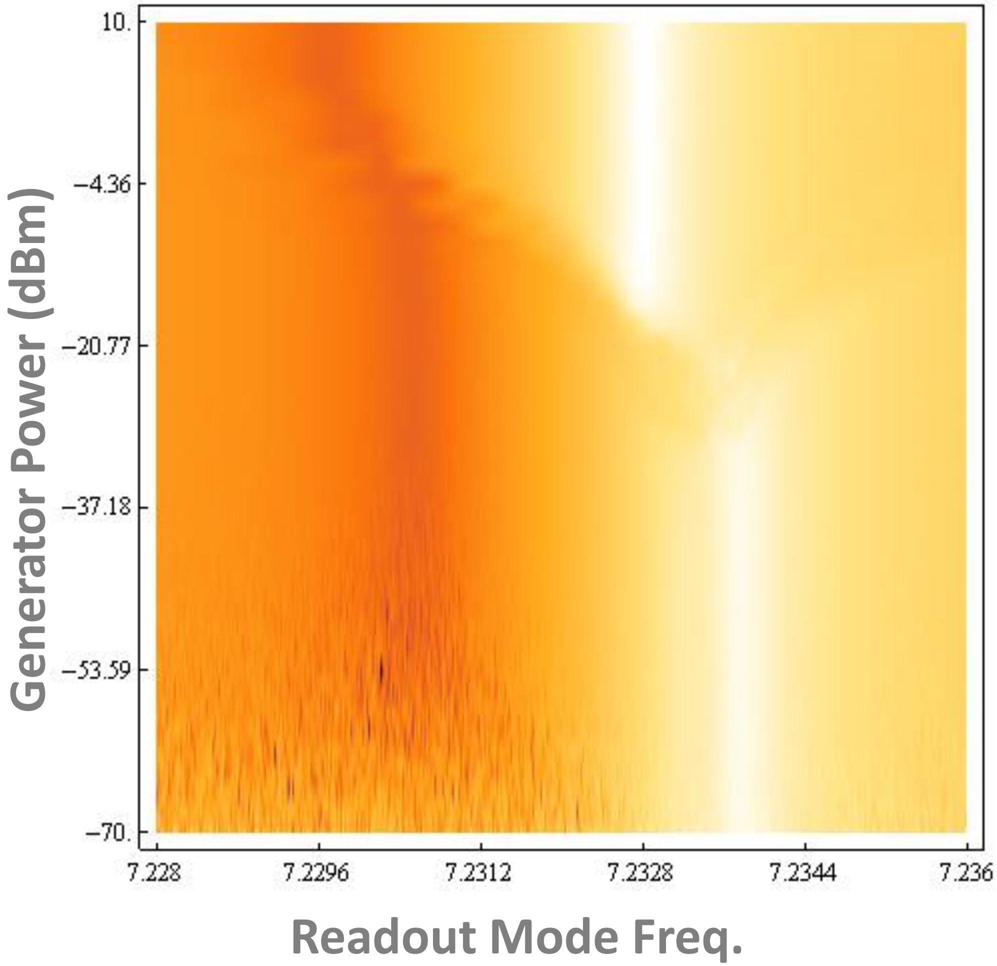








0^{th} iteration preliminary results



Readout:

7.23 GHz (4%)

Q ~ 16K

Memory:

7.02 GHz (3%)

$\boxed{T_m = 6.3\ \mu s}$

Qubit:

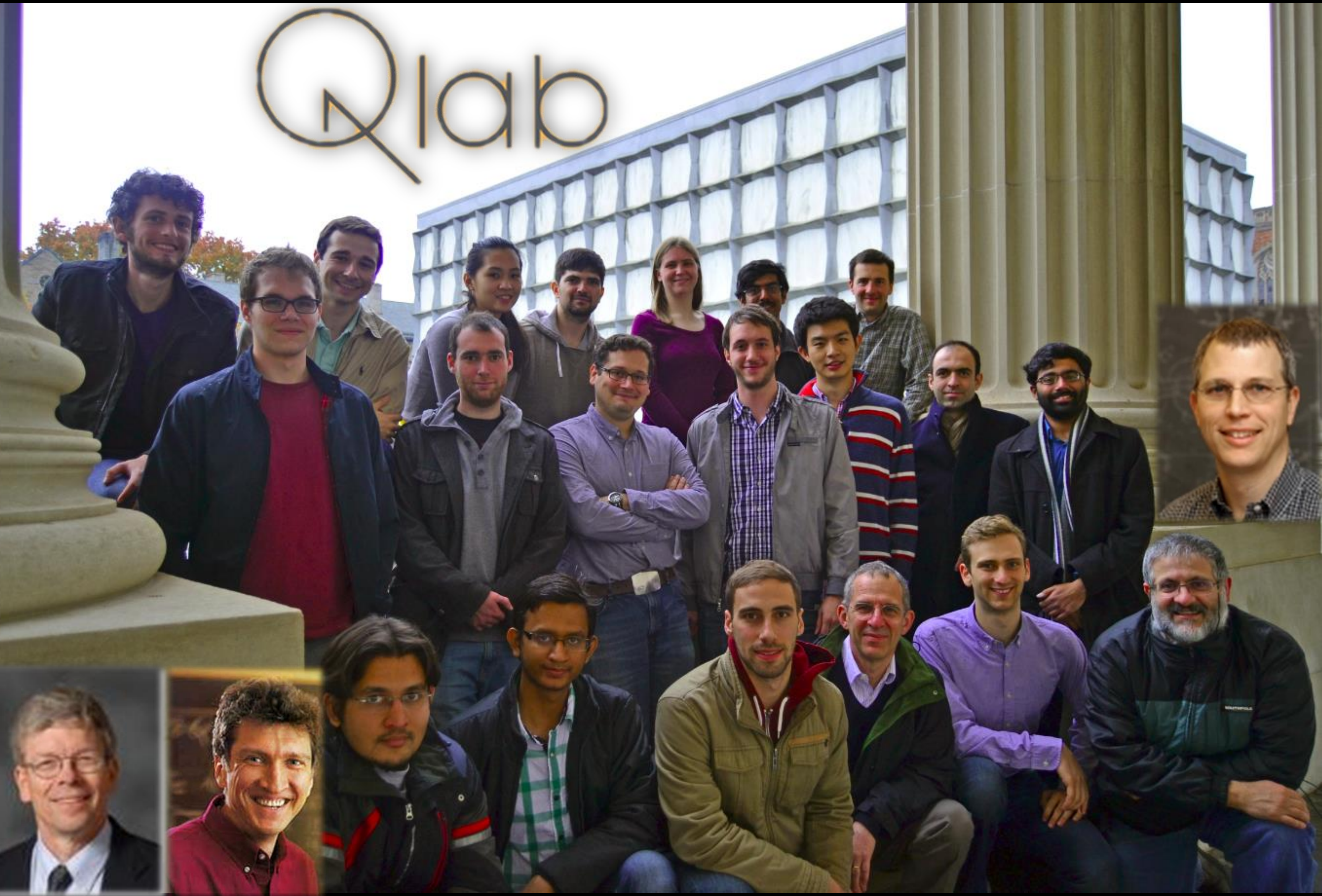
5.6 GHz (4%)

$\boxed{T_1 = 15 \mu s}$

Limited by alignment error induced coupling to pins.

Conclusion / Future Directions

- 2.5D resonators can be coherent at the level of parts per million
- “Energy BBQ” is fast, scalable and intuitive
- 2.5 planar qubit can achieve strong electric and magnetic coupling to ring resonators.
- Improve coherence
- Quantum optics with 2.5D cQED (multi-qubit)


Qlab