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Superconducting Whispering Gallery Mode Resonators

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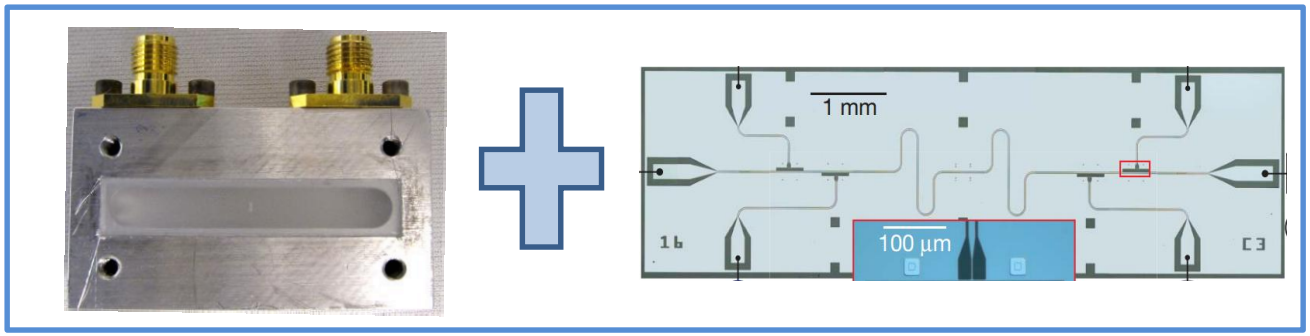
Thanks to: *Kurtis Geerlings* *Nick Masluk* *Matt Reagor* *Leonid Glazman* *Luigi Frunzio* *Rob Schoelkopf*

Yale Institute for Nanoscience and Quantum Engineering

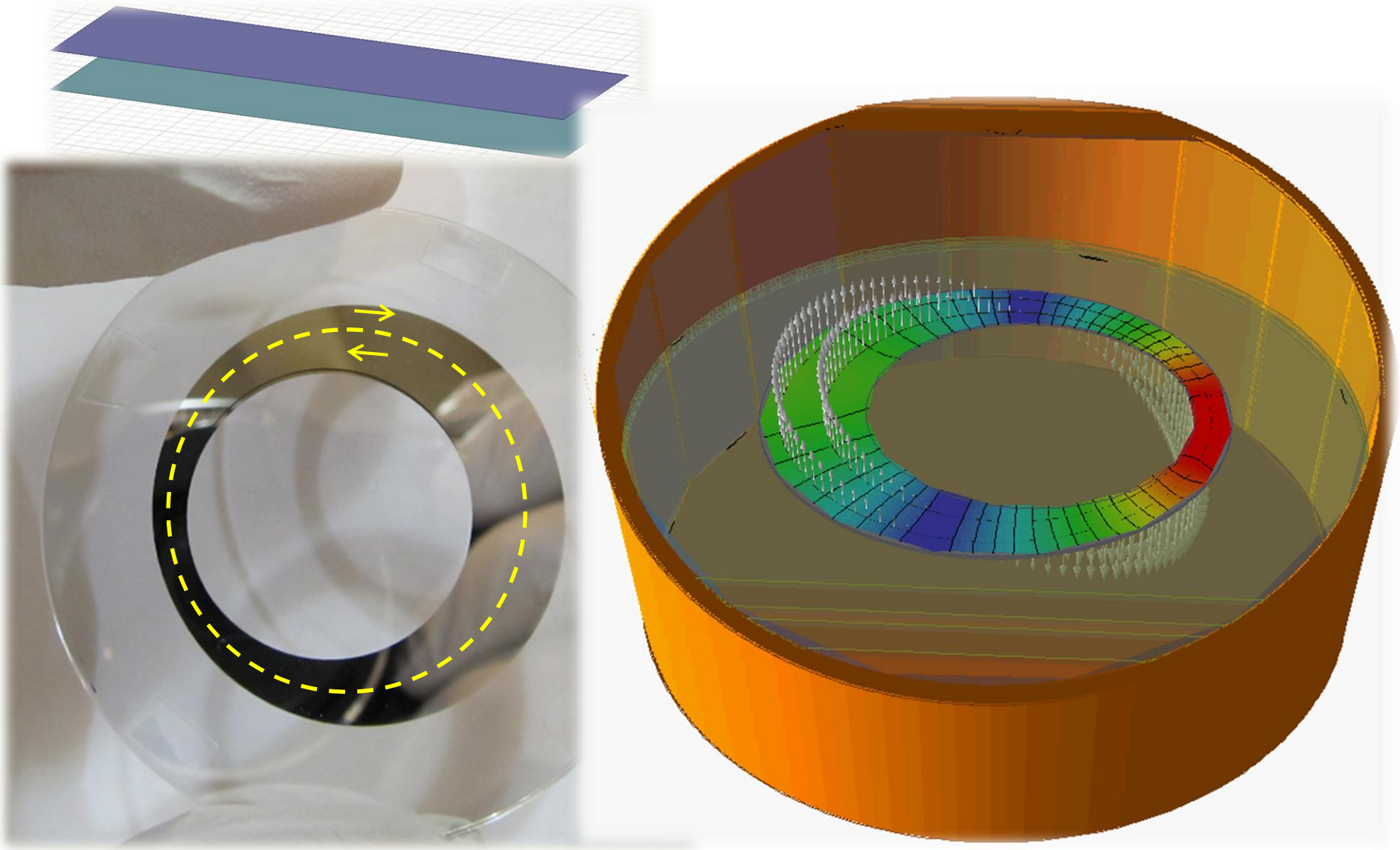
Motivation

I. Marry wafer scalability & 3D quality?
   - Coupled resonators & large number of qubits
   - Flux bias lines

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

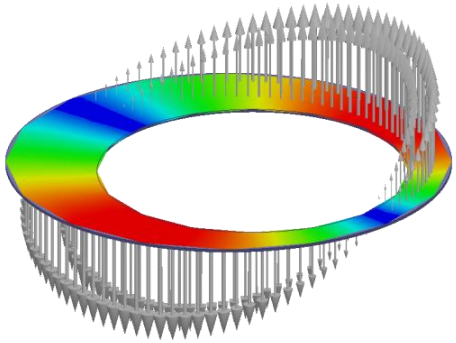


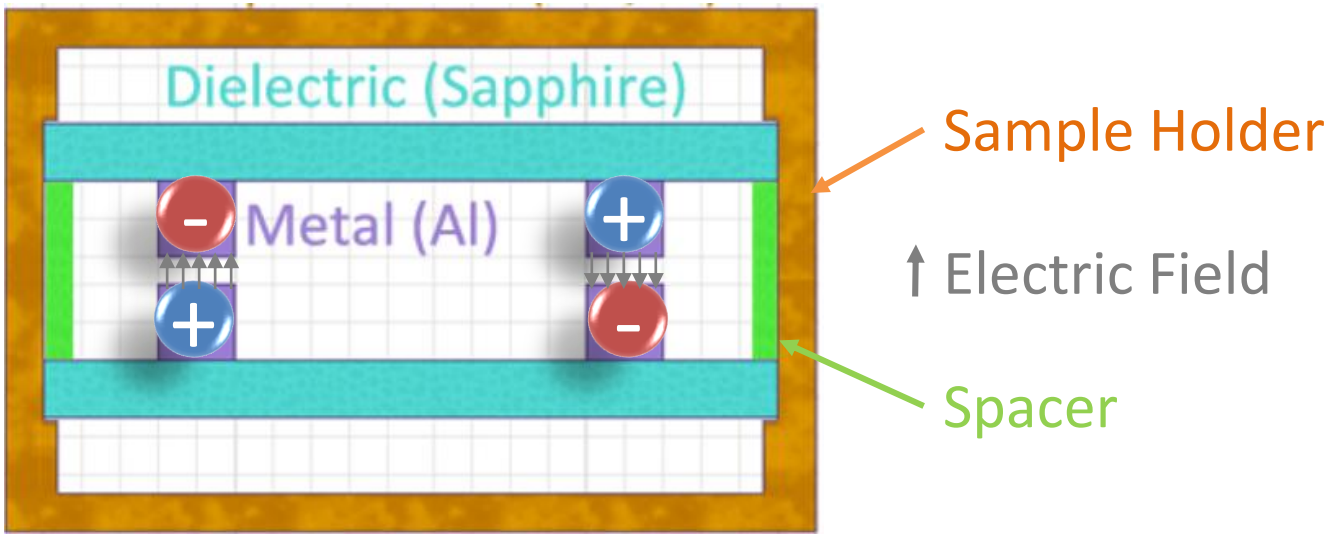
Towards `Wafer-Scalable` cQED architecture



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

Differential Mode

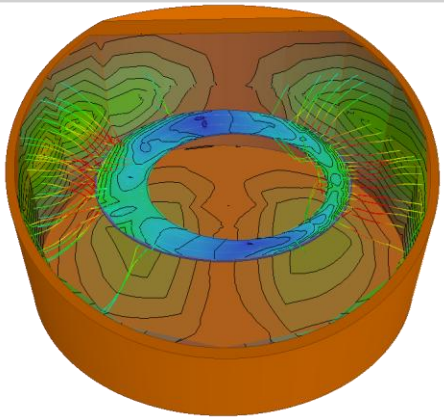


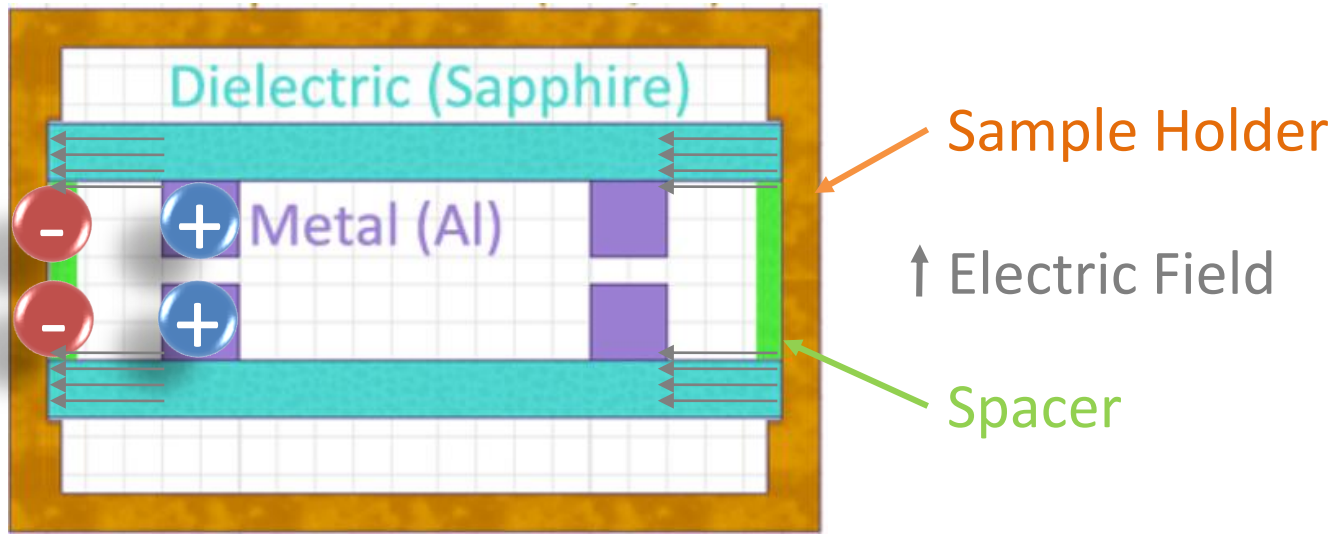


Not To Scale!

- **98 % of field energy is in vacuum**

Common Mode





Not To Scale!

- **44% of field energy is in dielectric.**

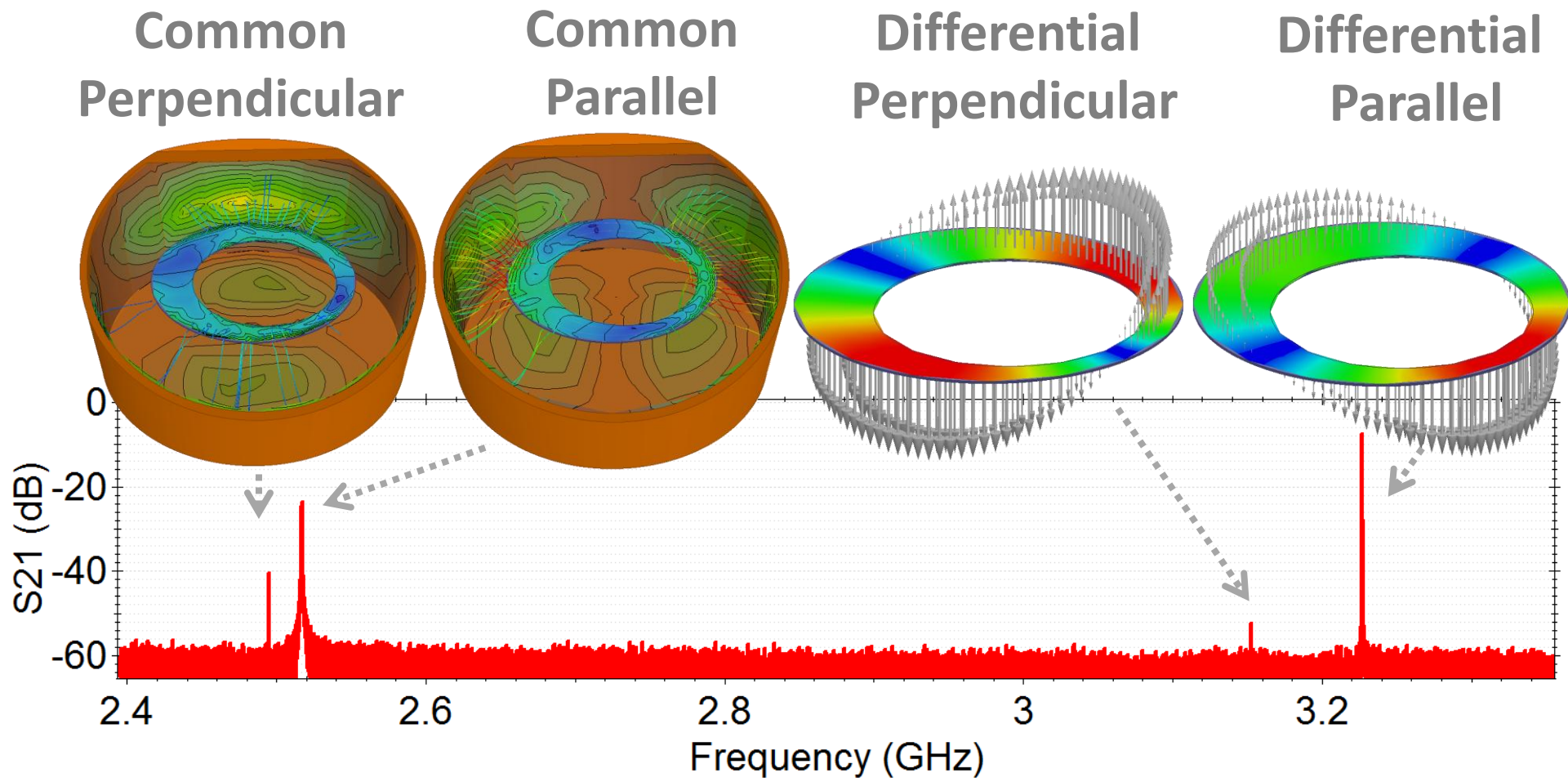
Modular Cavity & Experimental Sample Holder

Non Magnetic
SMA Pin Coupler

Technical Parameters:

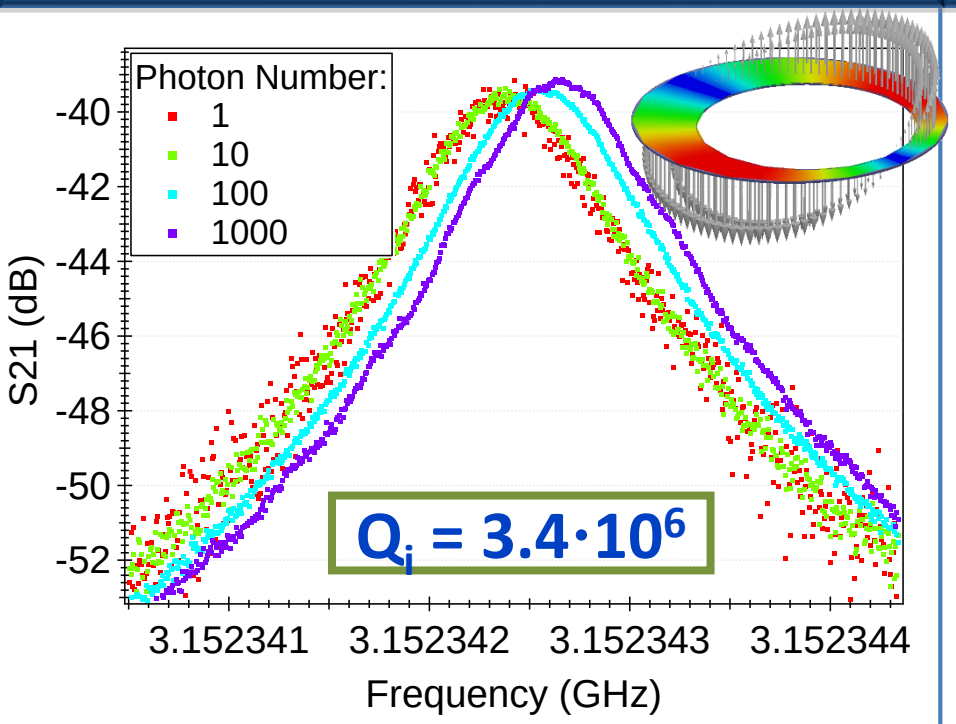
Al film thickness	300 nm
Sapphire wafer thickness	450 μm
Wafer spacing	200 μm
Wafer diameter	2.0 in

Identifying Modes (S_{21})



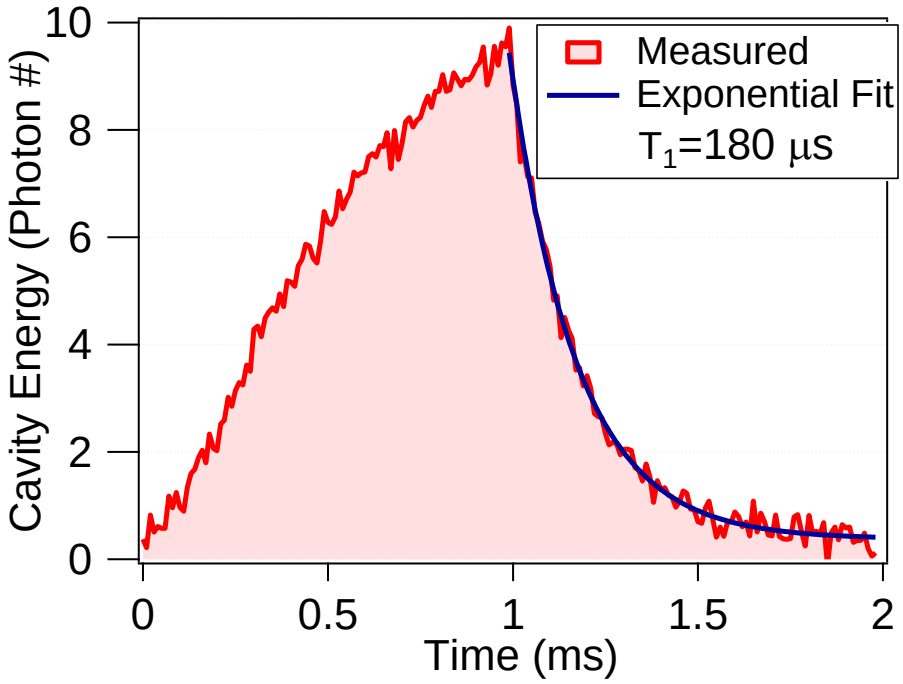
- **Differential modes contain > 98% of mode energy in between the rings**

Total Q vs Power (S_{21})

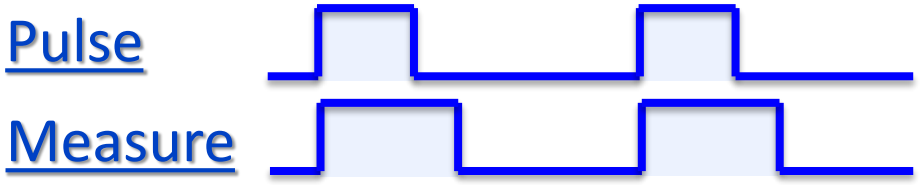


- **Undercoupled differential perpendicular mode**
- **Aluminum sample holder**

Energy Relaxation (T_1)

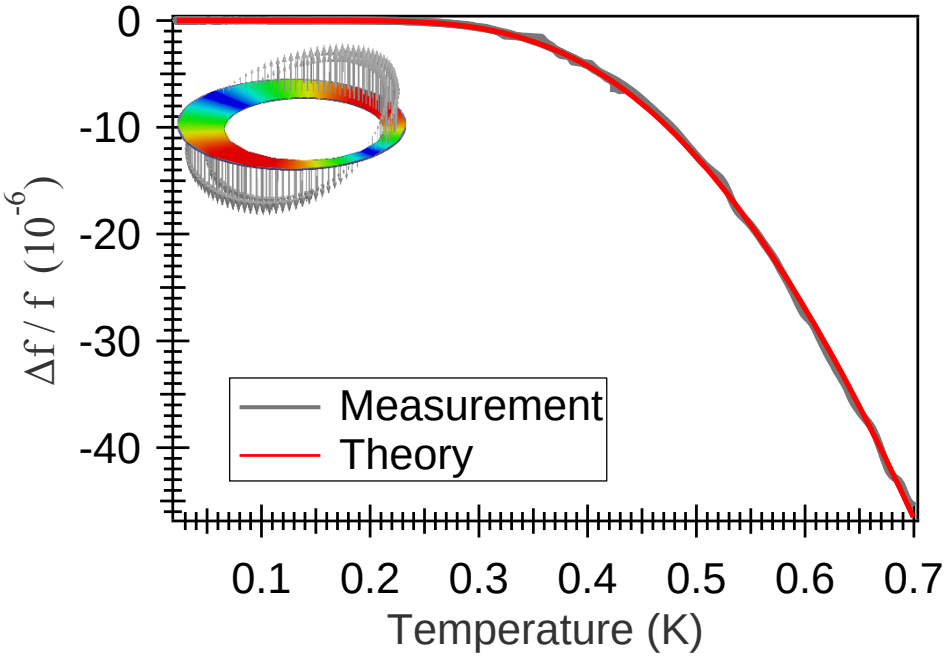


- **Heterodyne Measurement**
- ***$T_2 \cong 2\,T_1$***



Aluminum

Differential perpendicular mode

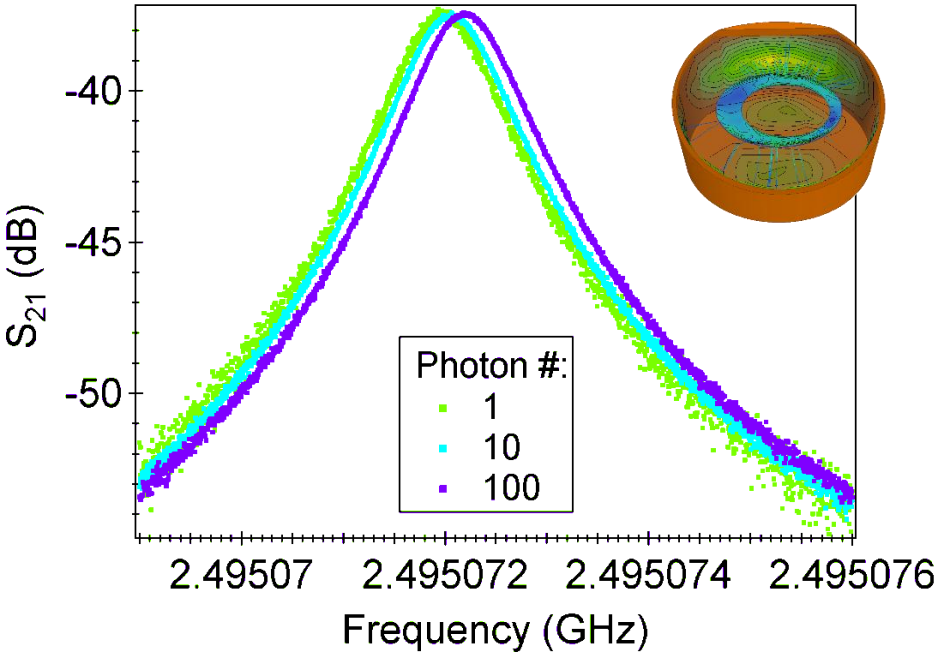


- **Extracted upper bound of the surface square resistance of thin film aluminum:**

$$R_{\square} \leq 250\ n\Omega$$
$$Q_s > 5000$$

Sapphire

Common perpendicular mode

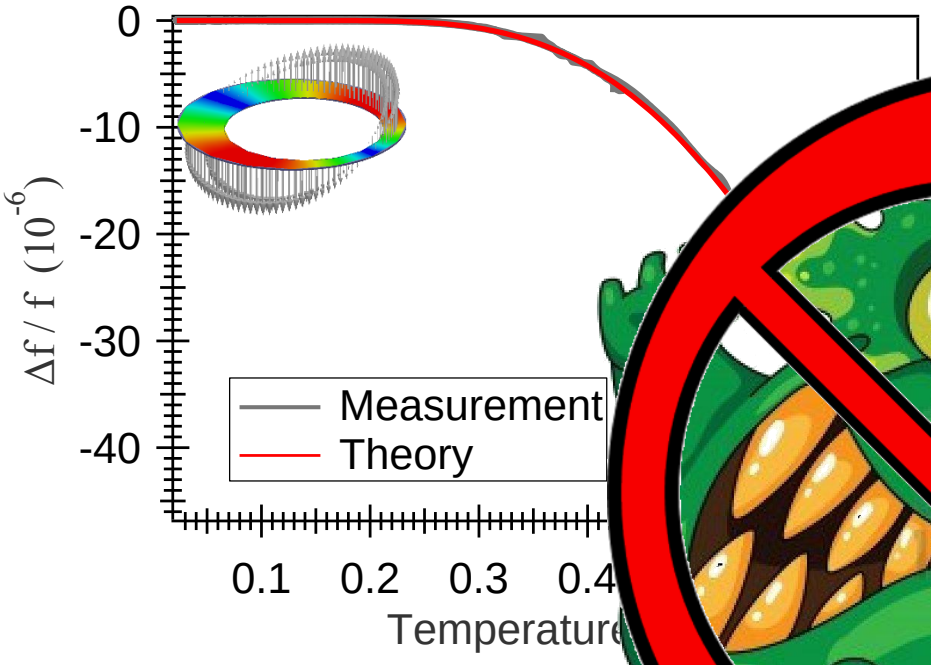


- **HFSS participation ratio: 44%**
- **Extracted sapphire properties at the single photon level:**

$$Q = 2.1 \cdot 10^{6}$$
$$\tan\delta < 1 \cdot 10^{-6}$$

Aluminum

Differential perpendicular mode



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  surface square resist
  film aluminum:

$R_{\square} \leq 250\ n\Omega$

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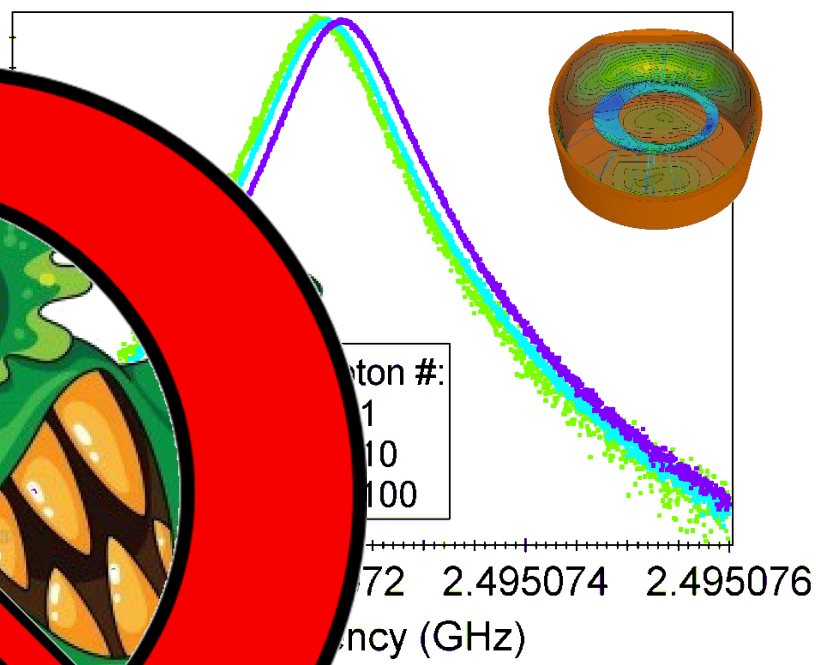
Sapphire

Common perpendicular mode



- pation ratio: 44%
  sapphire properties at
  photon level:

$Q = 2.1 \cdot 10^{6}$

$\tan \delta < 1 \cdot 10^{-6}$

Future Directions of `2.5D` Resonators

- **Integration with multiple qubits and resonators**
- **Quantum Bus**
- **Study of *cryogenic material properties***
- ***Galvanic cavity-qubit coupling***