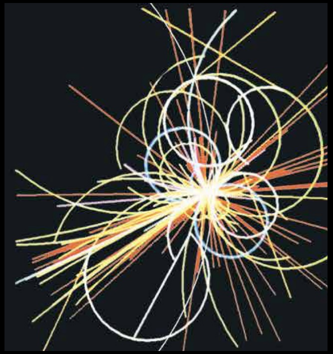
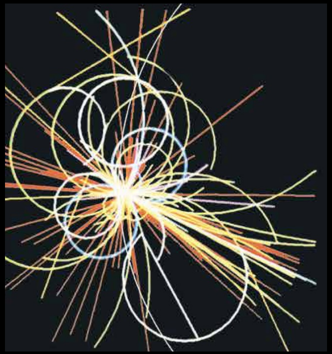


16th Pisa meeting on Advanced Detectors

La Biodola – Isola d’Elba

26 May - 1 June, 2024

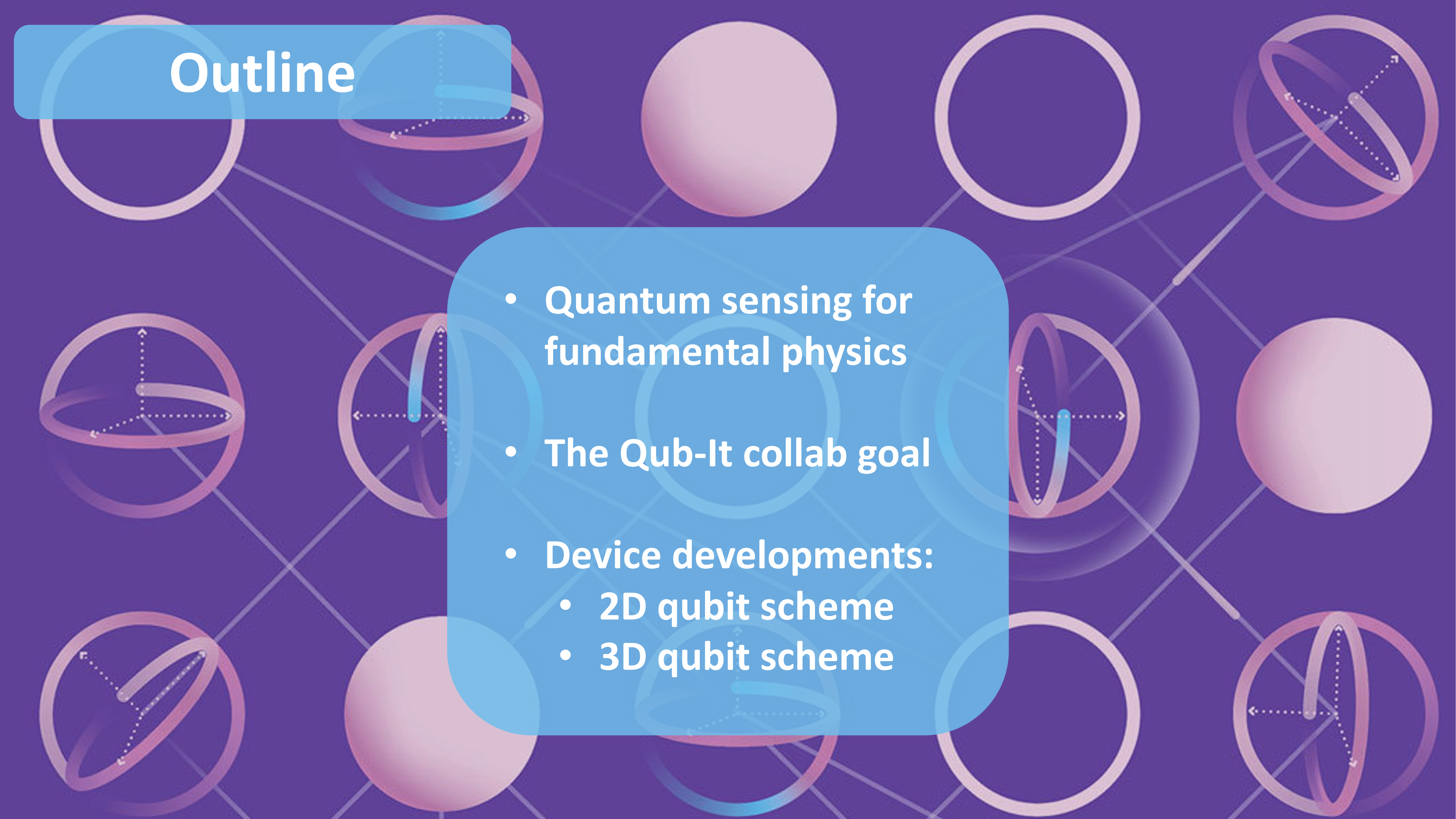


Qubit-based superconducting circuits for single microwave photon quantum sensing

Alessio Rettaroli[1]

on behalf of the QubIt collaboration

1. INFN – Laboratori Nazionali di Frascati



Outline

- Quantum sensing for fundamental physics
- The Qub-It collab goal
- Device developments:
  - 2D qubit scheme
  - 3D qubit scheme

Introduction – Quantum Non-Demolition (QND) detection

Fundamental physics demands single-photon detection, an essential component in many experiments in the microwave domain, but yet it remains challenging

10.1103/PhysRevX.8.021003

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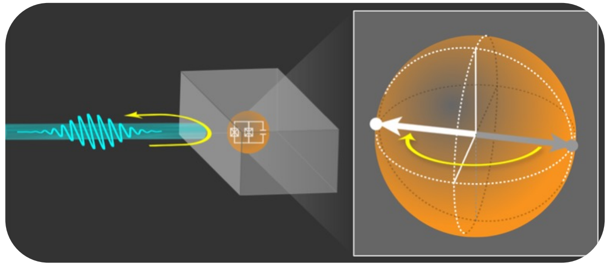
Achieving Quantum non-demolition (QND) techniques allows a detector to be completely transparent to itinerant photons while still acquiring information about them

Nature Physics | VOL 14 | JUNE 2018 | 546–549



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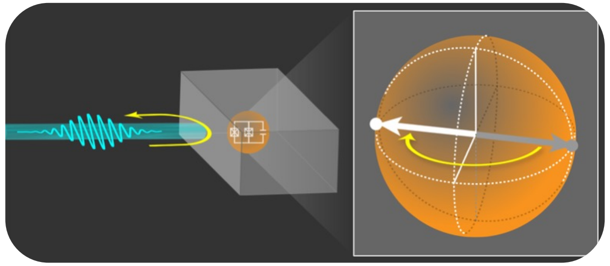
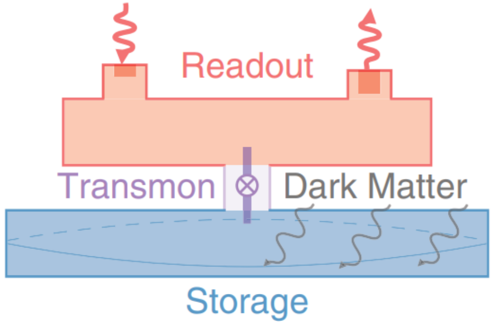


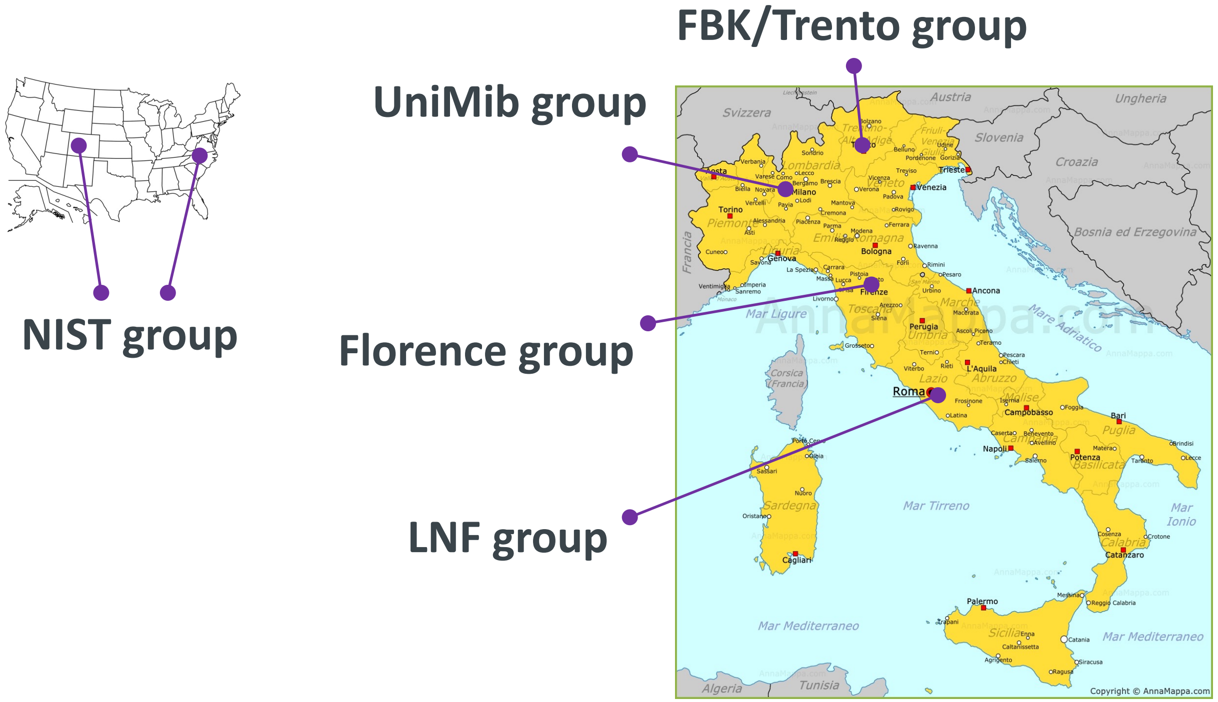
Applications of QND to fundamental physics (such as light Dark Matter searches, e.g. axions and hidden photons) will break down the sensitivity to the DM signal, where sub-Standard Quantum Limit detection is required

PRL 126, 141302 (2021)



Qub-It collaboration

Main target: develop a qubit-based single-photon counter read with high fidelity and suppressed dark count rate.



FBK/Trento group

UniMib group

NIST group

Florence group

LNF group

UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA

BIQUTE

FONDAZIONE BRUNO KESSLER

INFN Istituto Nazionale di Fisica Nucleare

CSN5 Technological research

Qub-IT

NIST

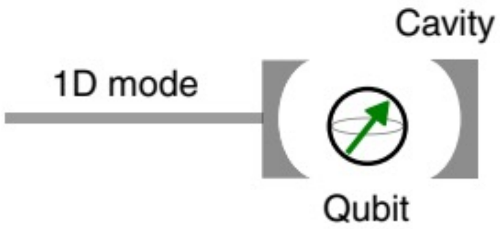
UNIVERSITAS STUDIORUM FLORENTINA

TIFPA

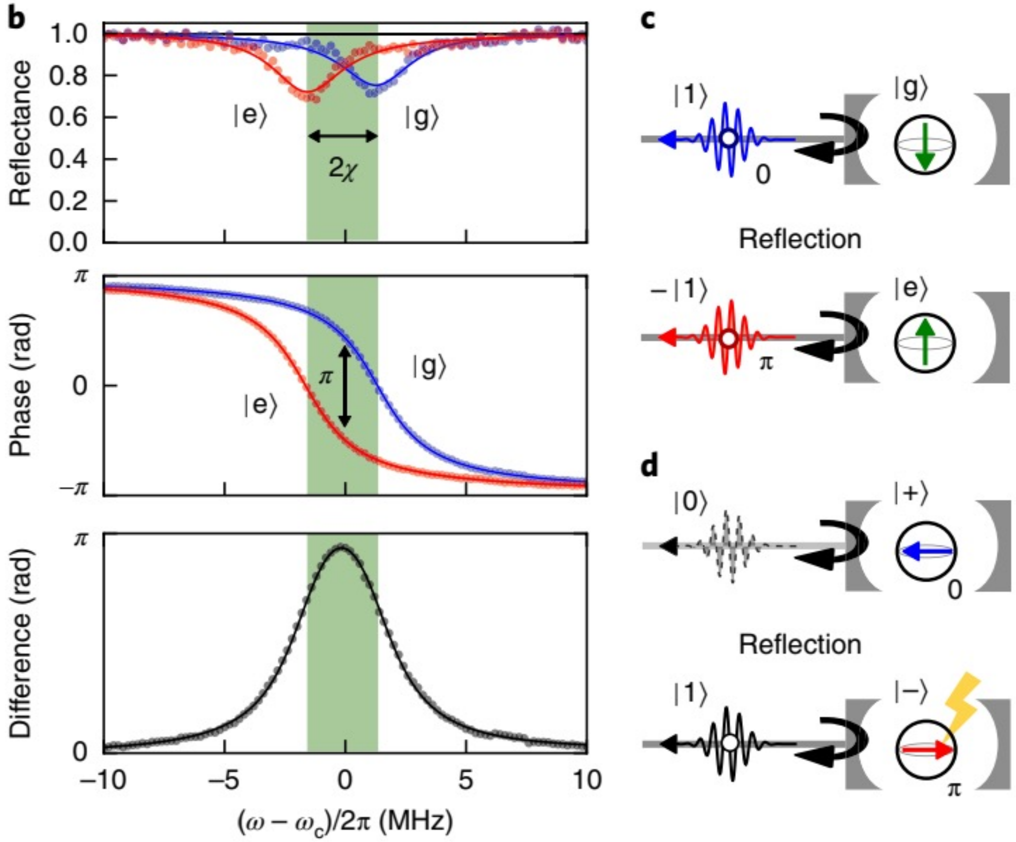
CNR IFN Istituto di Fotonica e Nanotecnologie

State of the art – Kono et al. (2018)

The entanglement between a qubit and an itinerant microwave photon reflected by a cavity containing the qubit causes a phase difference equal to π



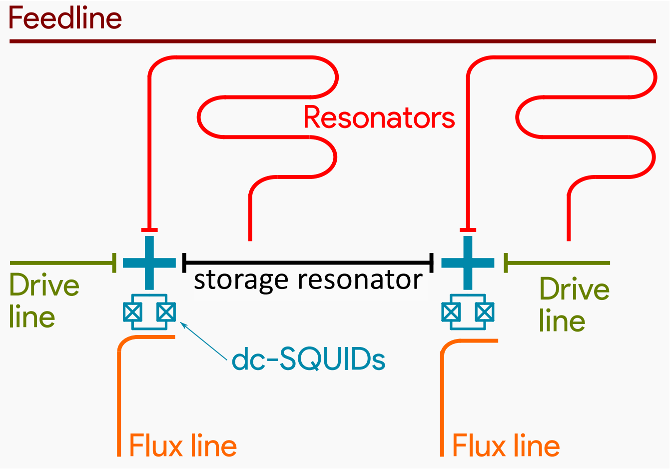
$$H/\hbar = \omega_c a^\dagger a + \frac{\omega_q}{2}\sigma_z - \chi a^\dagger a \sigma_z$$



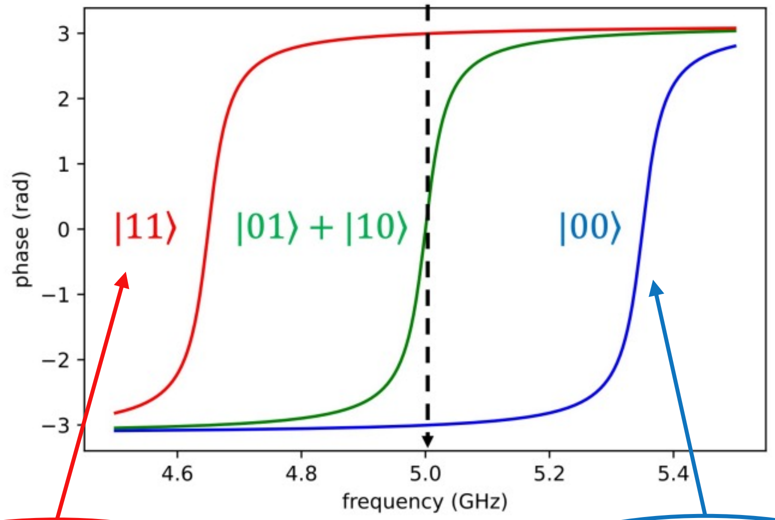
Nature Physics | VOL 14 | JUNE 2018 | 546–549

Beyond state of the art: 2 coupled qubits

2 qubits dispersively coupled to the same resonator (a quantum bus)



$$H_{JC} = [\omega_r + \chi(\sigma_1^z + \sigma_2^z)]a^\dagger a + \sum_{i=1}^{2} \frac{\omega_i}{2}\sigma_i^z$$



Reflected photon

$$|Q_1Q_2\rangle_\gamma = |1\rangle \times |1\rangle$$

No photon

$$|Q_1Q_2\rangle_{\overline{\gamma}} = |0\rangle \times |0\rangle$$

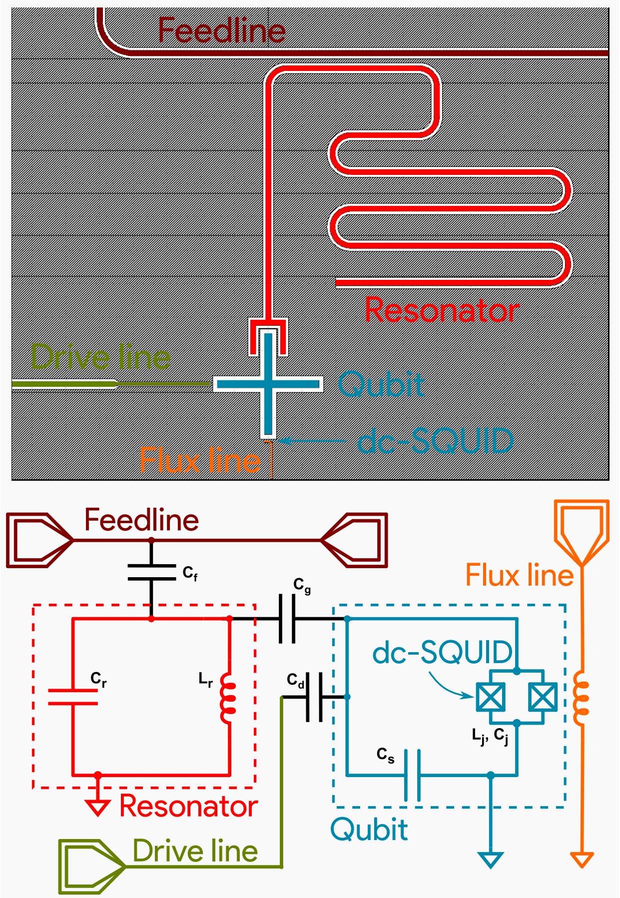
Individually reading the qubits:

Dark count = p_{err}^2

A. D'Elia et al., Appl. Sci. **2024**, 14(4), 1478

2D developments

2D qubit – single qubit design



- **Grounded Xmon transmon**
  - Drive line directly coupled (left)
  - Flux bias (bottom)
  - Transmission/readout $\lambda/4$ resonator (top) is capacitively coupled to feedline

- **Design with *qiskit-metal***
  - Definition of Hamiltonian
  - Definition of lines and geometry

- **Simulations with ANSYS**
  - Packages HFSS and Q3D
  - Analyses with EPR and LOM (consistent)

doi: 10.1109/TASC.2024.3350582

2D 2-qubit (not coupled) – Preliminary fabrication

Production at NIST

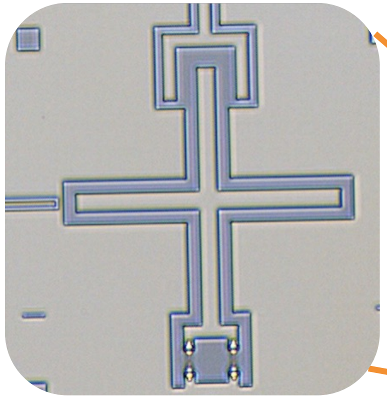
Qubit 1: single JJ, fixed levels

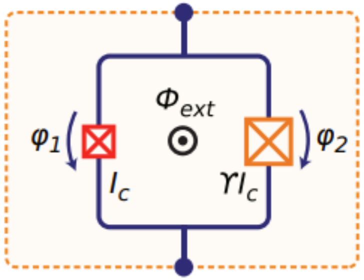
Qubit 2: asymmetric DC-SQUID, tunable levels

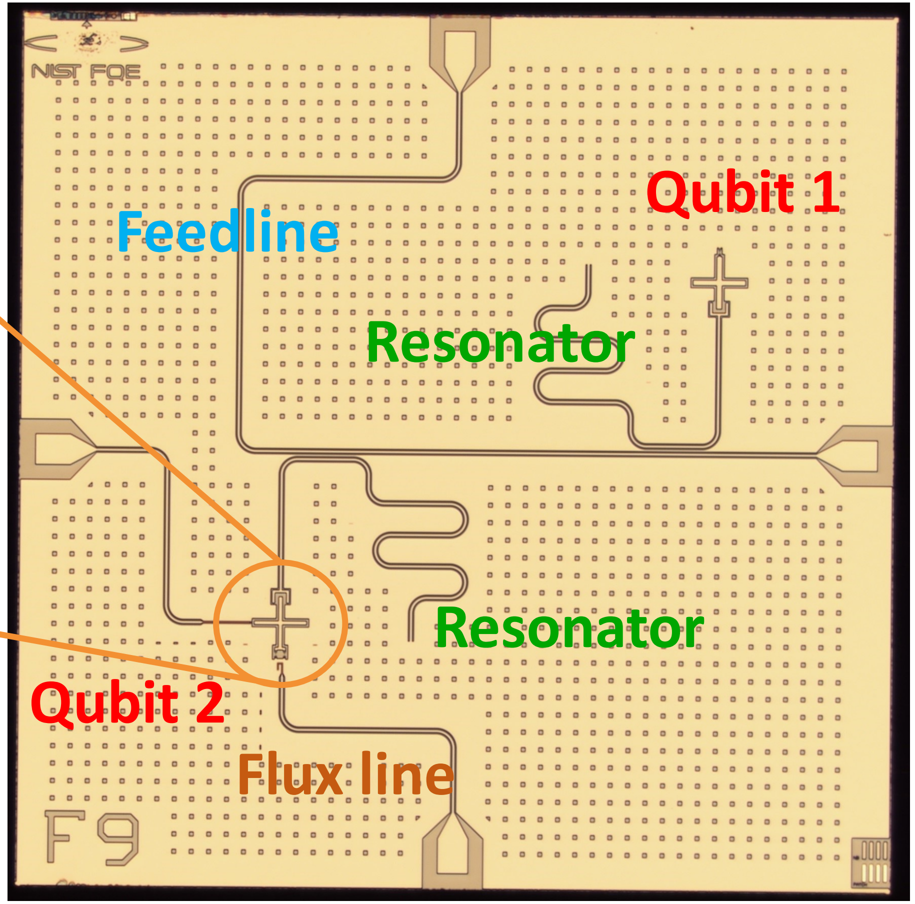
Substrate: 380 nm high-resistive silicon

Metal: 100 nm Niobium

Junctions: Al-AlOx-Al

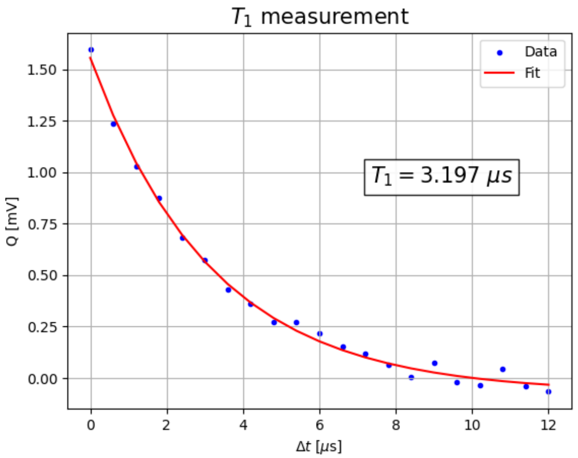


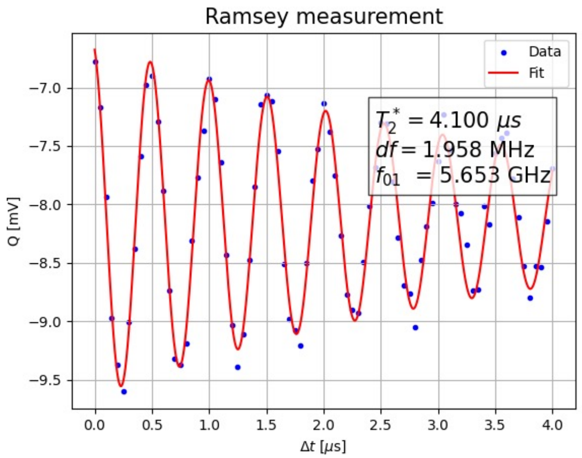


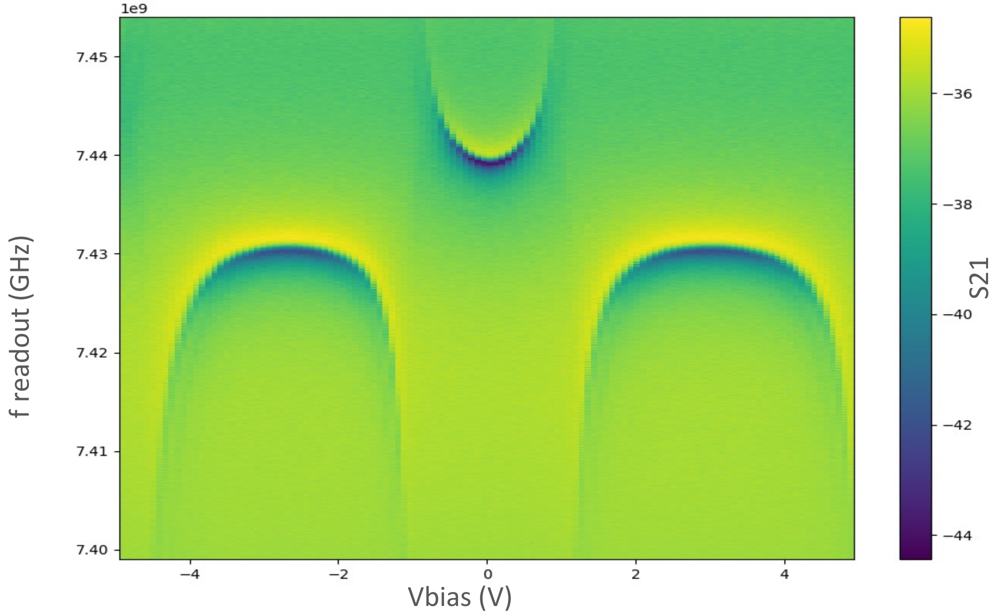


2D 2-qubit (not coupled) – Characterizations at NIST and LNF

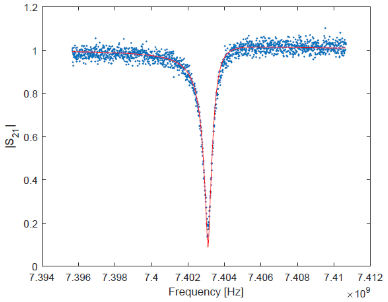
Gain experience in controlling the qubit: Spectroscopy, flux tuning, time-domain measurements (T1, Rabi, Ramsey)

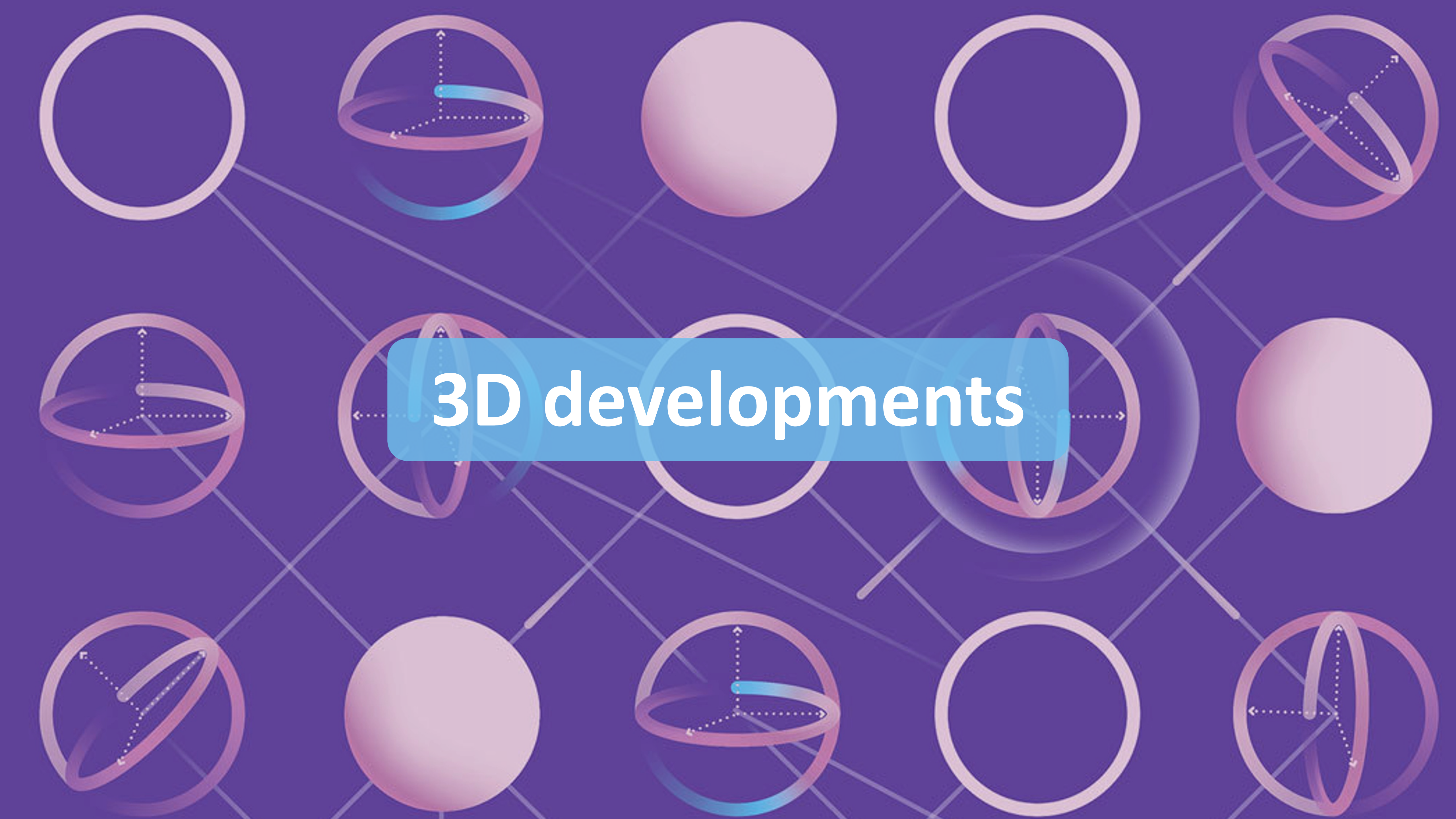






- **Measurements in good agreement with simulations**
- **Decoherence times lower than expected (1 order), due to resonator's low Q**
- **Investigate if due to desing issue or fabrication issue**

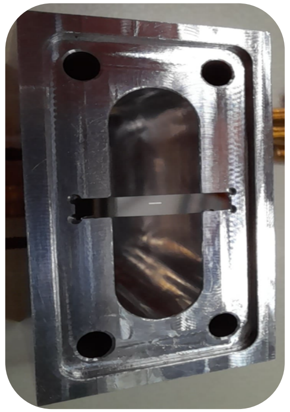




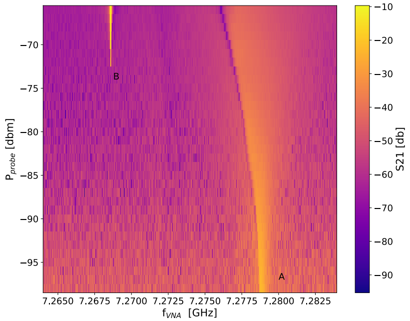
3D developments

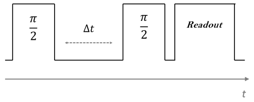
3D single qubit characterization at LNF

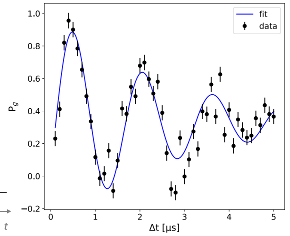
- Qubit by Abu Dhabi TII
- 3D cavity by INFN - LNL



Technology Innovation Institute



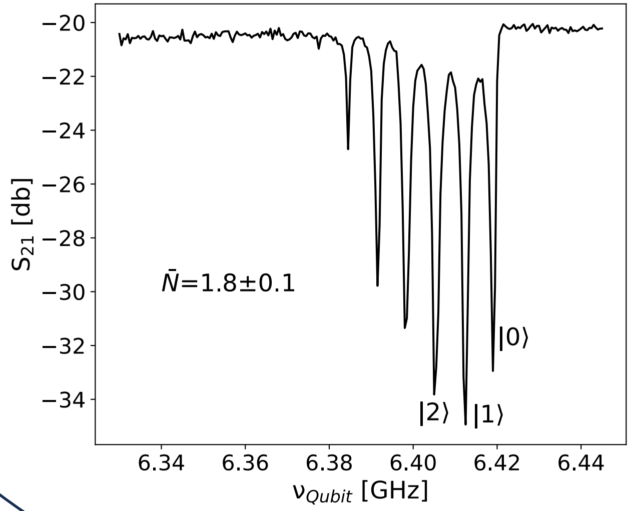




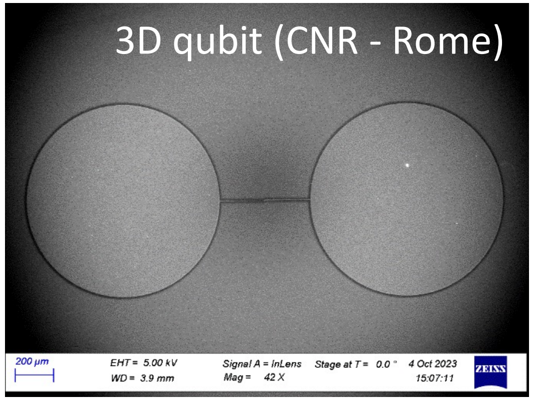
It is possible to resolve single microwave photons

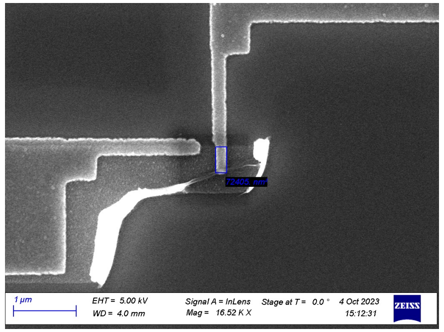
Already demonstrated by Schuster et al 2007

Our measurement:
1.8 average photons in the cavity



3D single qubit fabrications



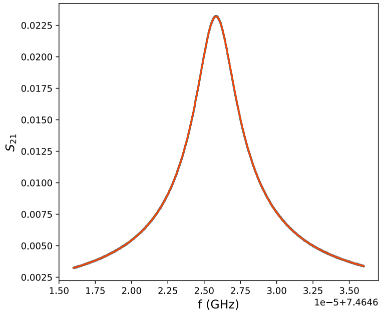


IFN

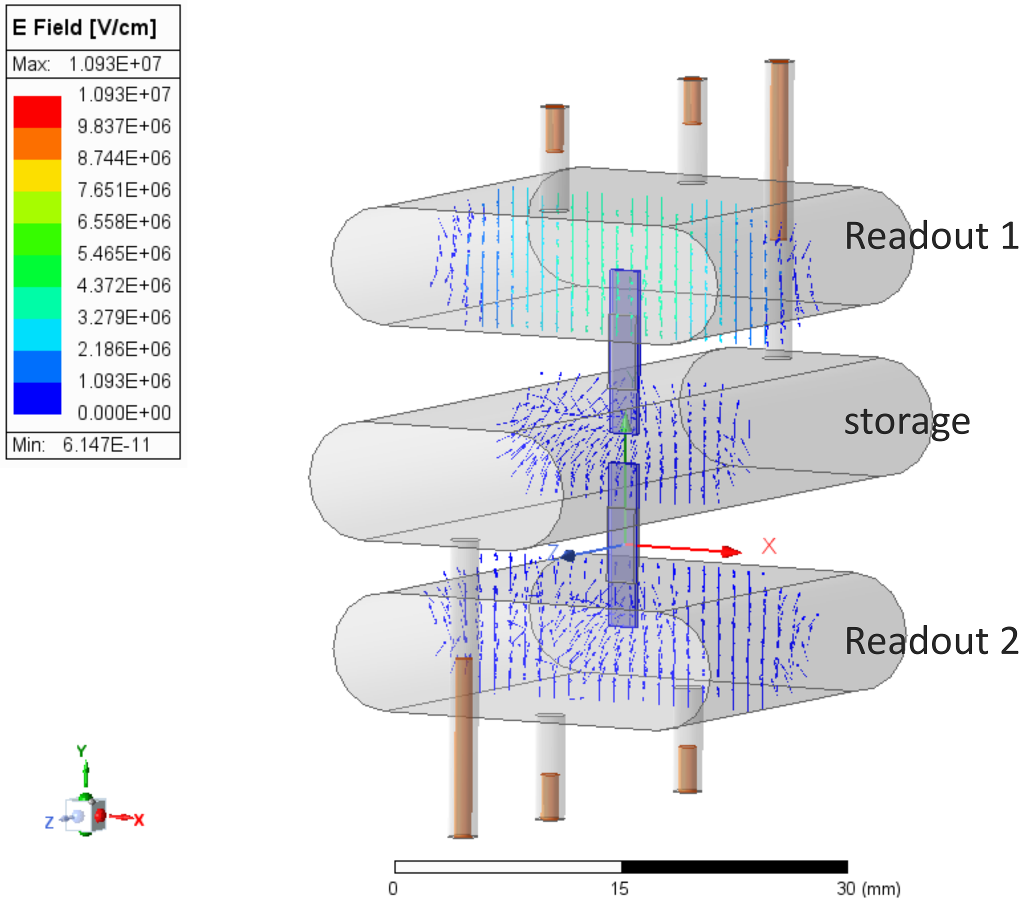
- **New design already fabricated at CNR and soon to be tested**
- **Expected T1 improvement of 30%**

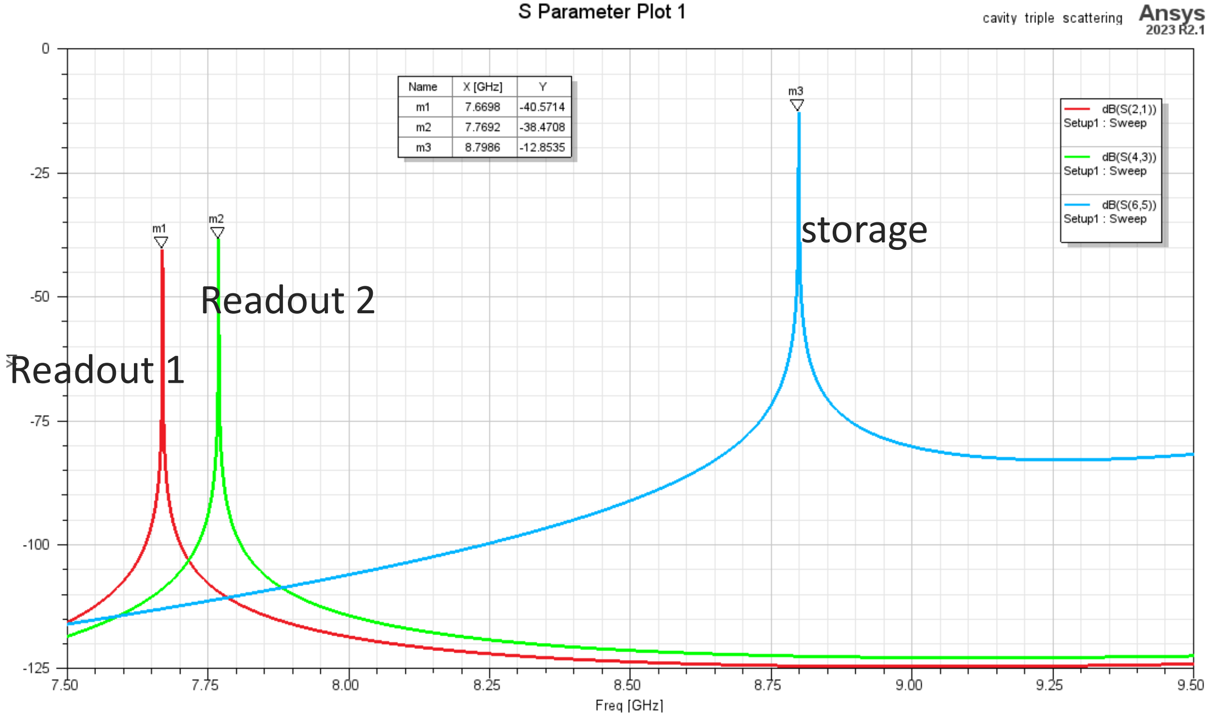
- **Advantage with 3D Al cavities: high Q**
- **Fabricated at INFN - LNL**
- **Annealing and electropolishing ->** $Q_0 = 3.7\times10^6$

INFN
LNL
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Legnaro



3D 2-qubit photon counter design





Name	X [GHz]	Y
m1	7.6698	-40.5714
m2	7.7692	-38.4708
m3	8.7986	-12.8535

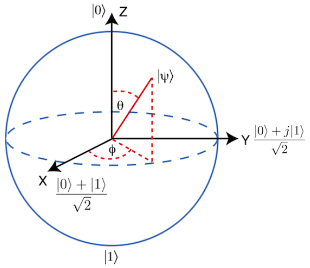
	Frequency (GHz)	Q0
Readout 1	7.67232	1.34E+6
Readout 2	7.77227	1.35E+6
Storage	8.80820	1.41E+6

Ansys simulations by S. Tocci

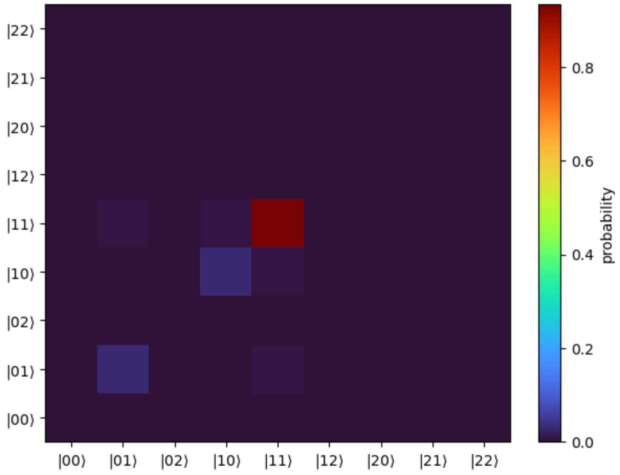
3D 2-qubit photon counter design

Calculate time evolution of state |0,0> after the application of rotations on both qubits:

Rx = π/2
Rz = π
Rx = −π/2

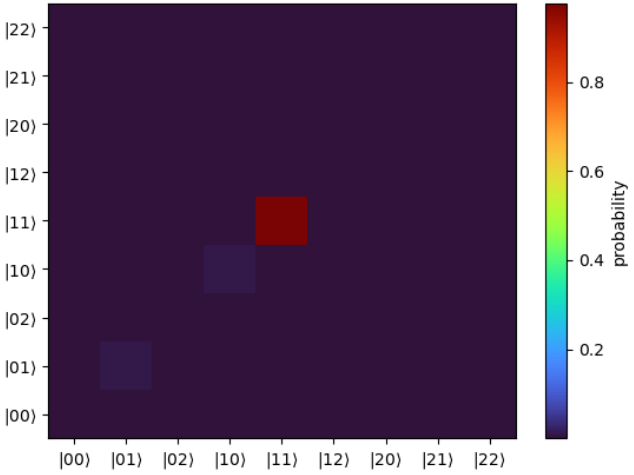


Fidelity with |1,1> = 0.96



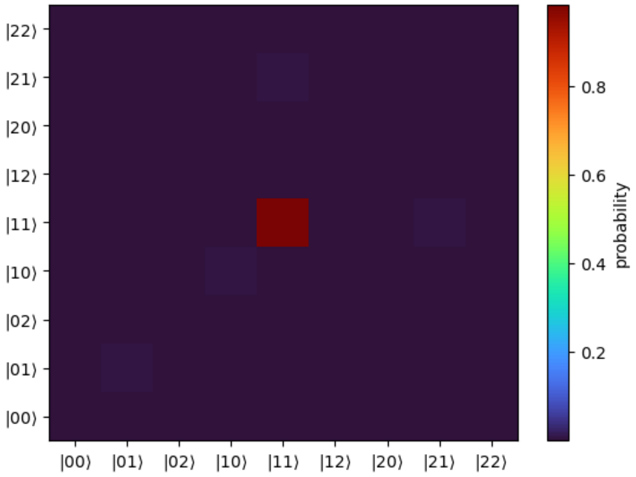
Ωx=Ωy=10 MHz

Fidelity with |1,1> = 0.98



Ωx=Ωy=30 MHz

Fidelity with |1,1> = 0.99



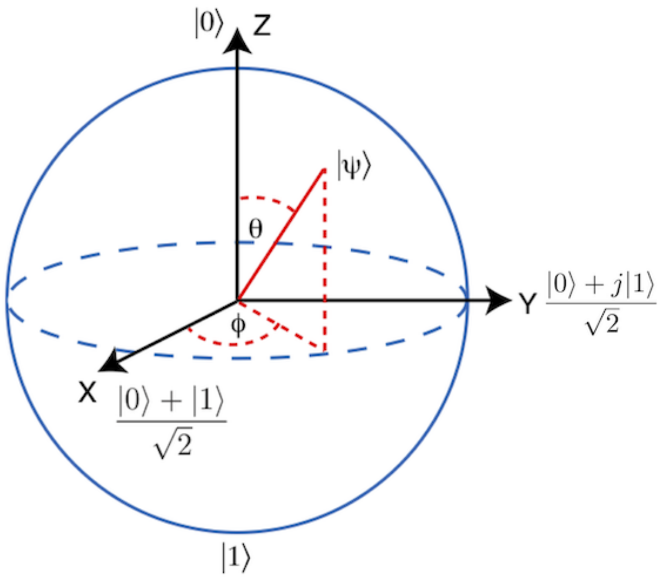
Ωx=Ωy=60 MHz

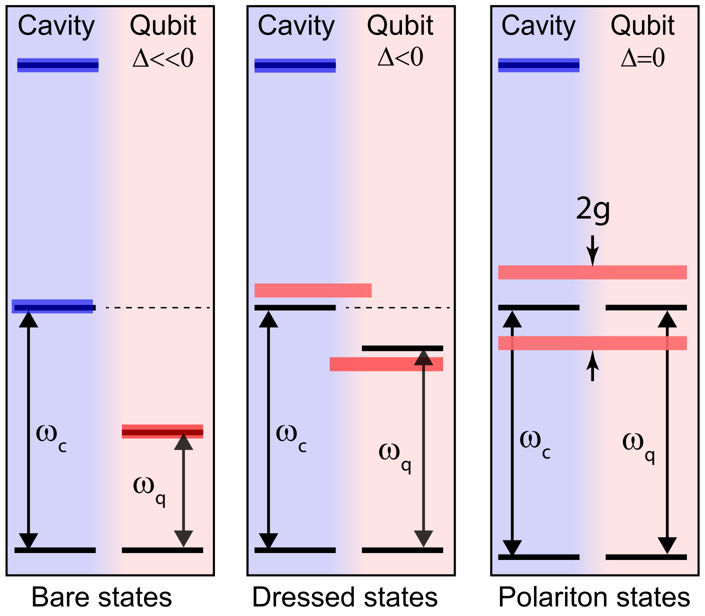
Courtesy of A. D’Elia

Conclusions

- Qub-IT goal: develop a **2-qubit** microwave **single photon counter** to surpass the state-of-the-art quantum sensing, with applications to **frontier physics**
- We are refining the **assembly** line:
    - Ability in **designing quantum circuits** with requested parameters
    - **Simulation** of the designed devices
    - Ability in **fabricating quantum circuits** (from NIST to FBK and CNR)
    - Ability in the **single-qubit control** (decoherence times, dispersive shift and couplings, qubit spectroscopy, qubit tunability)
- **Ongoing**: design and simulation of **2 qubits** coupled to the same resonator

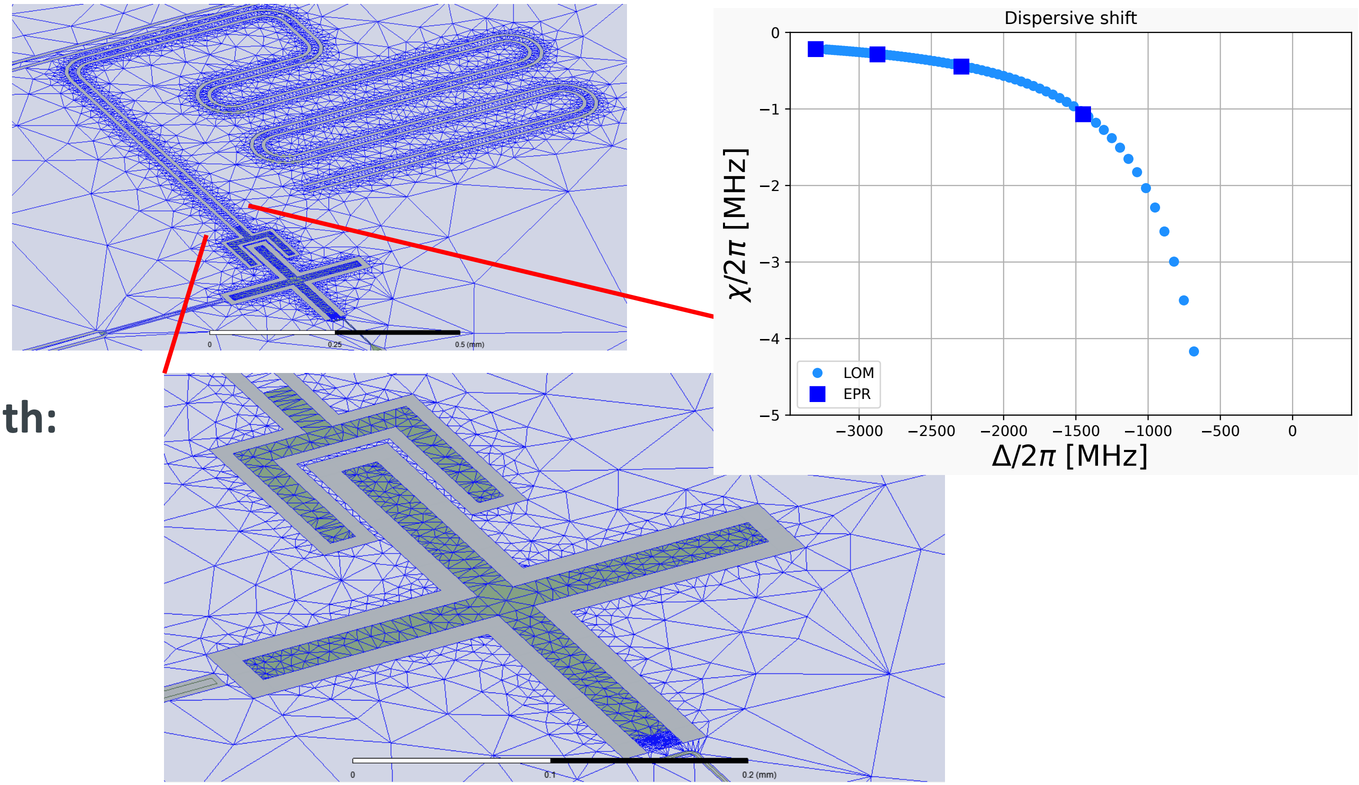
backup


$|0\rangle$
Z
$|\psi\rangle$
θ
ϕ
Y
$\frac{|0\rangle + j|1\rangle}{\sqrt{2}}$
X
$\frac{|0\rangle + |1\rangle}{\sqrt{2}}$
$|1\rangle$


Cavity
Qubit
$\Delta<<0$
ω_c
ω_q
Bare states
Cavity
Qubit
$\Delta<0$
ω_c
ω_q
Dressed states
Cavity
Qubit
$\Delta=0$
2g
ω_c
ω_q
Polariton states

2D qubit - Simulation

- **Electromagnetic simulations with:**
  - **ANSYS HFSS** (eigenmode) to extract frequencies and quality factors
  - **ANSYS Q3D** to extract inductances and capacitances



- **Analysis of the quantization problem both with:**
  - Energy Participation Ratio (**EPR**) method
  - Lumped Oscillator Model (**LOM**) method

- **EPR and LOM analyses consistent with theory**
- **Agreement between EPR and LOM**

3D 2-qubit photon counter design

Quantum circuit simulation with *qutip-qip*

$$H = H_{\mathrm{d}} + \sum_{j=0}^{N-1} \Omega_j^x (a_j^\dagger + a_j) + \Omega_j^y i (a_j^\dagger - a_j) + \sum_{j=0}^{N-2} \Omega_j^{\mathrm{cr1}} \sigma_j^z \sigma_{j+1}^x + \Omega_j^{\mathrm{cr2}} \sigma_j^x \sigma_{j+1}^z,$$

$$H_{\mathrm{d}} = \sum_{j=0}^{N-1} \frac{\alpha_j}{2} a_j^\dagger a_j^\dagger a_j a_j.$$

- **2 qubits (3-level transmons) coupled to 1 readout resonator**
- **Different frequencies:** $\omega_{q1} \neq \omega_{q2}$
- **Same dispersive shift** χ

$\omega_{q1}/2\pi$ = 6.7 GHz

$\omega_{q2}/2\pi$ = 6.6 GHz

Ωcr = 0

$\Omega x = \Omega y$ = 10 MHz

T1 = 9 μs

T2 = 4 μs

$\omega r/2\pi$ = 8.8 GHz

g01 /2π = 100 MHz

Courtesy of A. D’Elia