Dark Wave Lab Workshop
at Fermilab

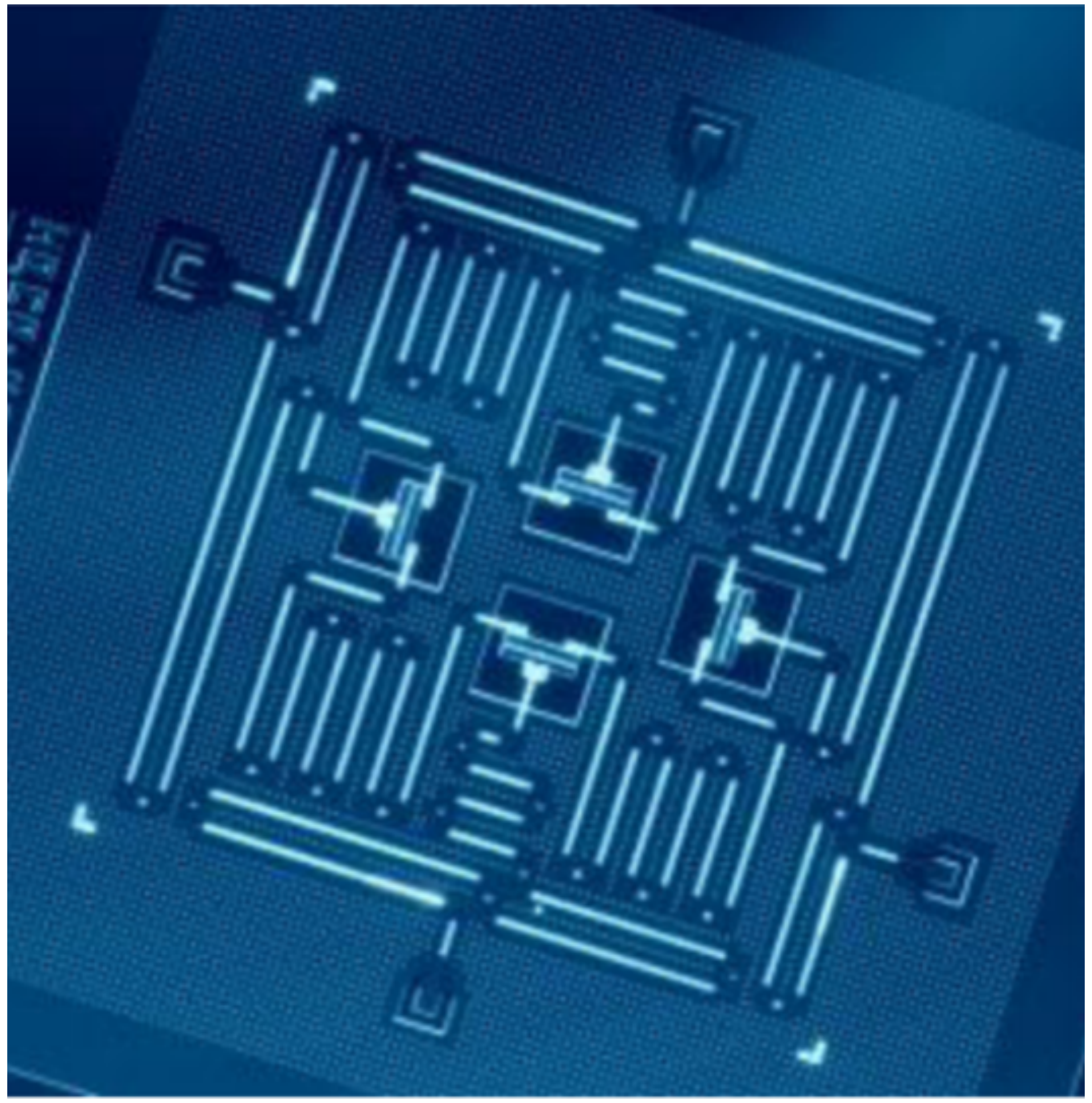
Possibility of superconducting qubits in a strong magnetic field

April 15, 2024

The University of Tokyo / ICEPP   Tatsumi Nitta

Why superconducting qubits?

Superconducting Quantum Computer		***Quantum sensor***
Large electric coupling $O(10^6) \times$ atom	→	High sensitivity to weak EM field
Fast drive & long coherence O(10) ns & $T_1 > O(100)\ \mu s$	→	Fast measurement & complex operation
non-demolition readout	→	Low stat. uncertainty
Designable circuit	→	Circuit for physics
Low noise environment	→	Low dark count

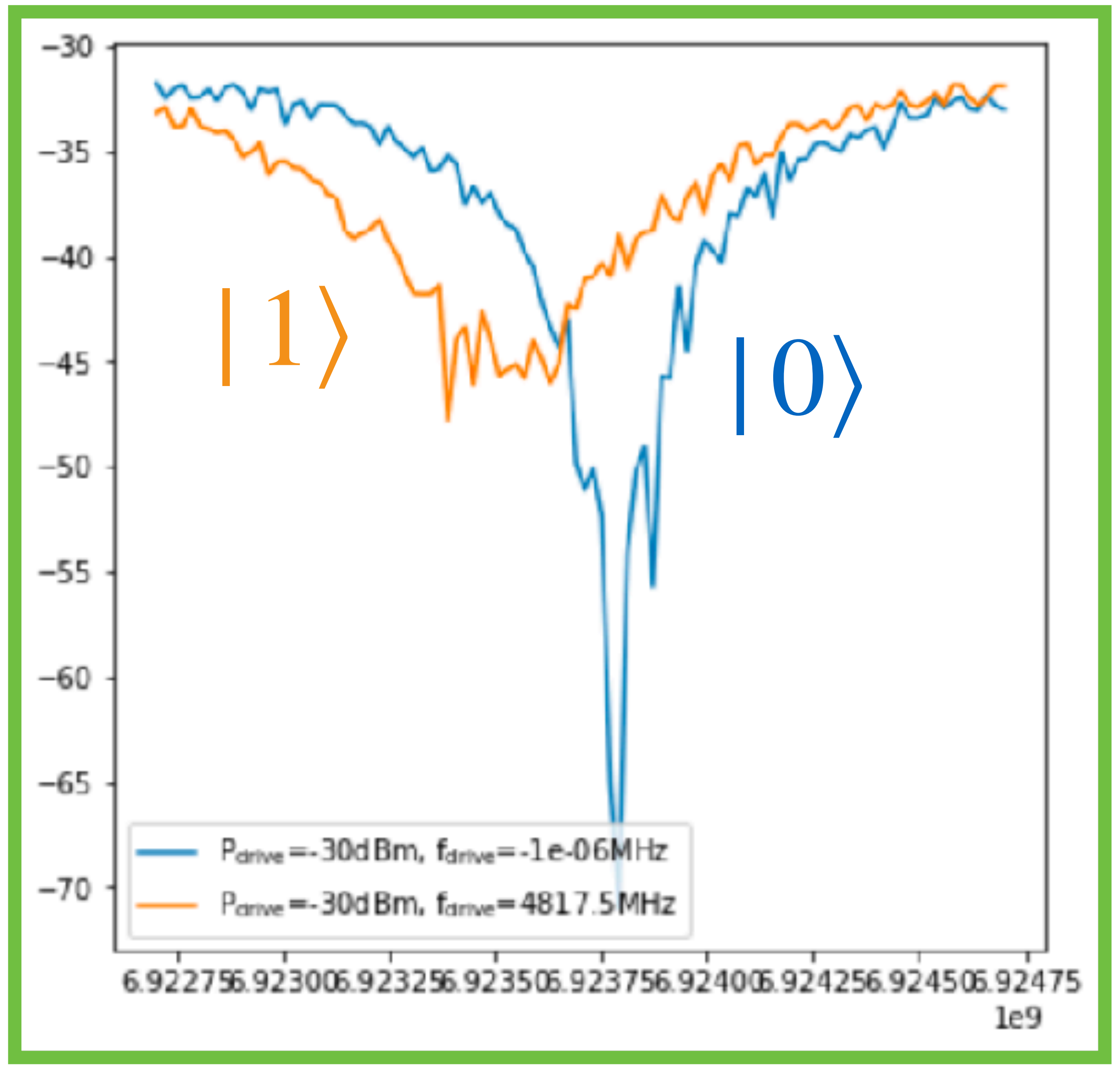


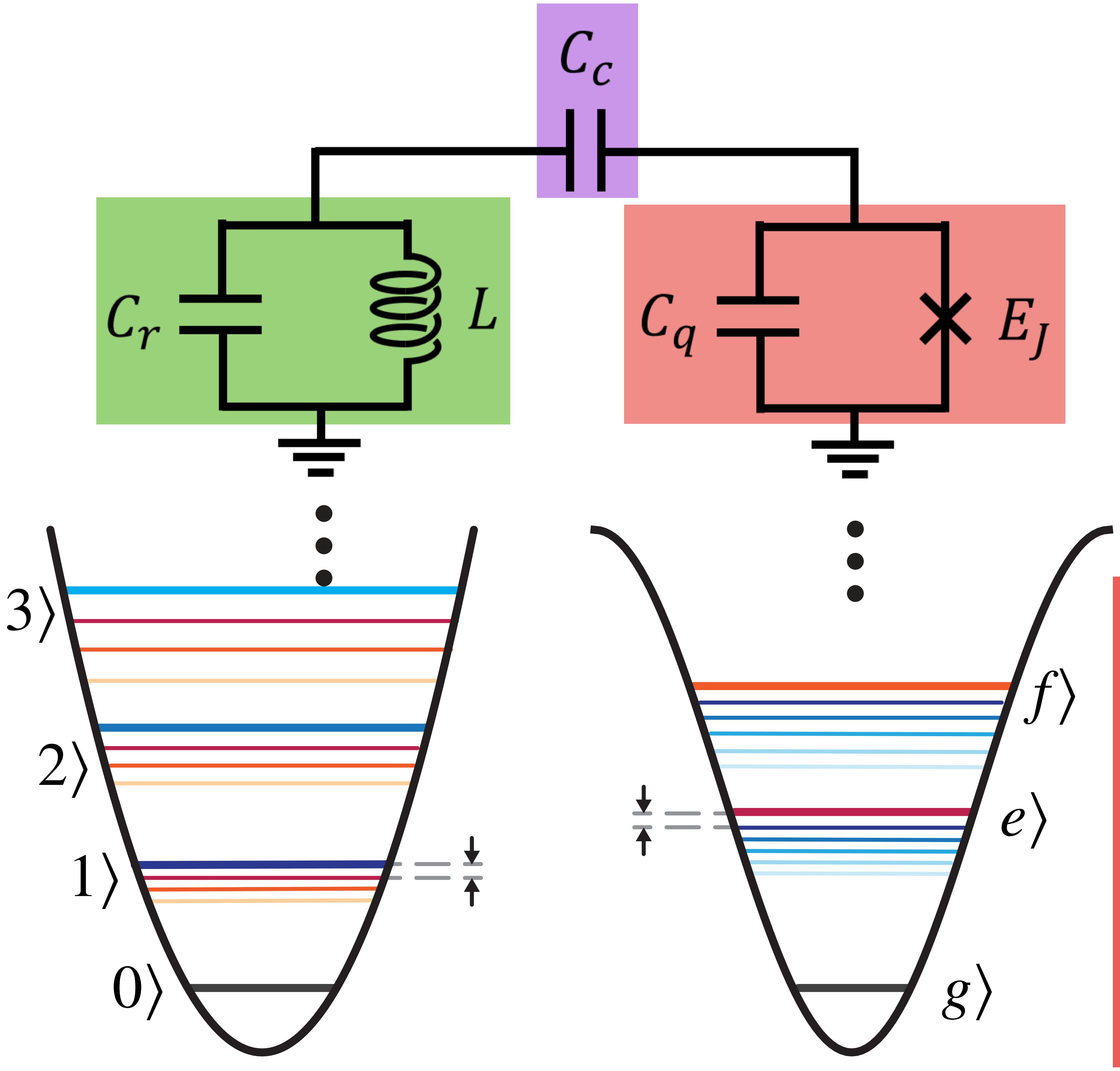
Superconducting qubit is a wonderful playground for HEP

Superconducting Qubits

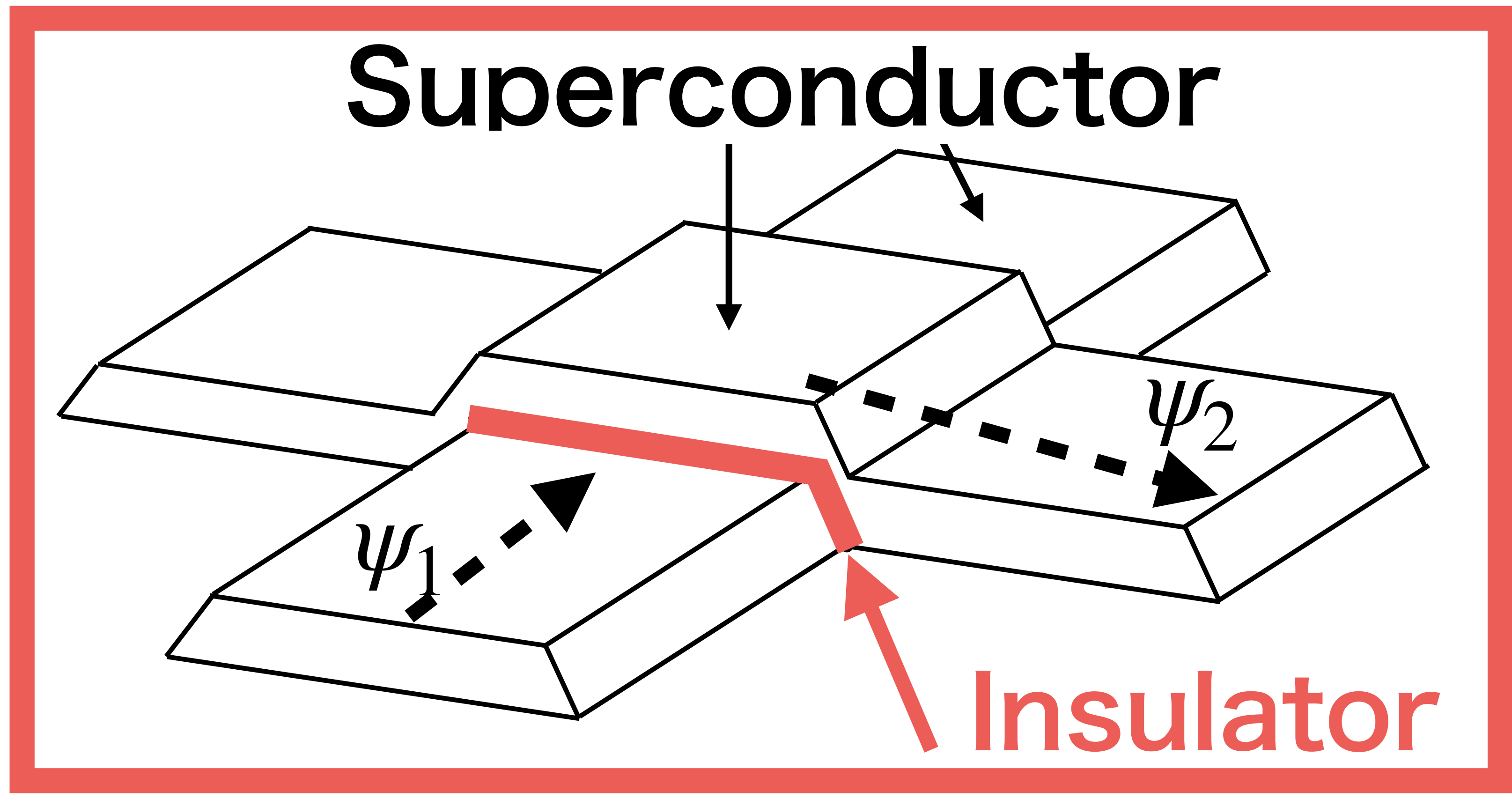
resonator is weakly **coupled** with qubit

LC resonator with nonlinear inductor



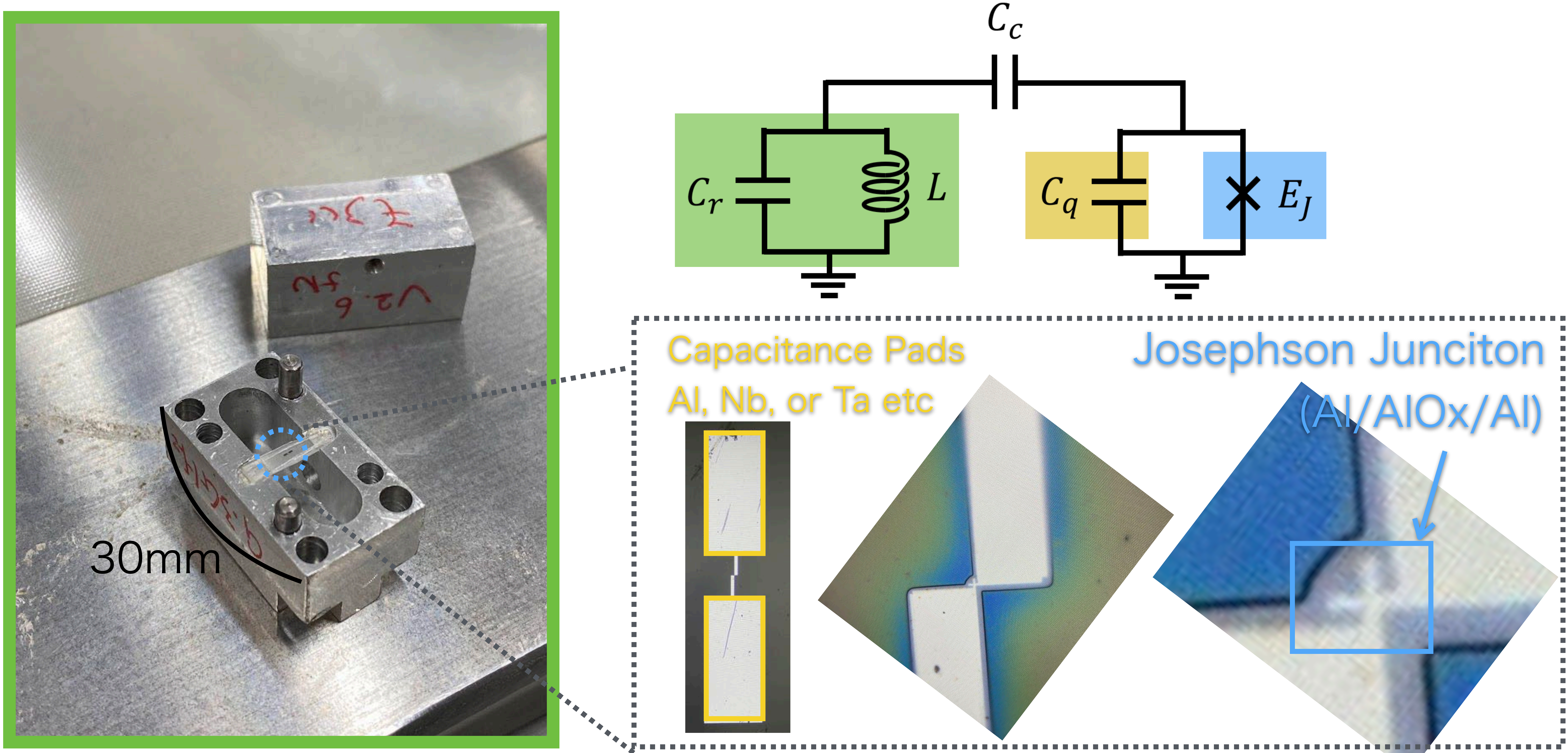


$$\mathscr{H} = \frac{\hbar}{2}\left(\omega_q + \frac{g^2}{\Delta}\right)\sigma_z + \hbar\left[\omega_c + \frac{g^2}{\Delta}\sigma_z\right]a^\dagger a$$

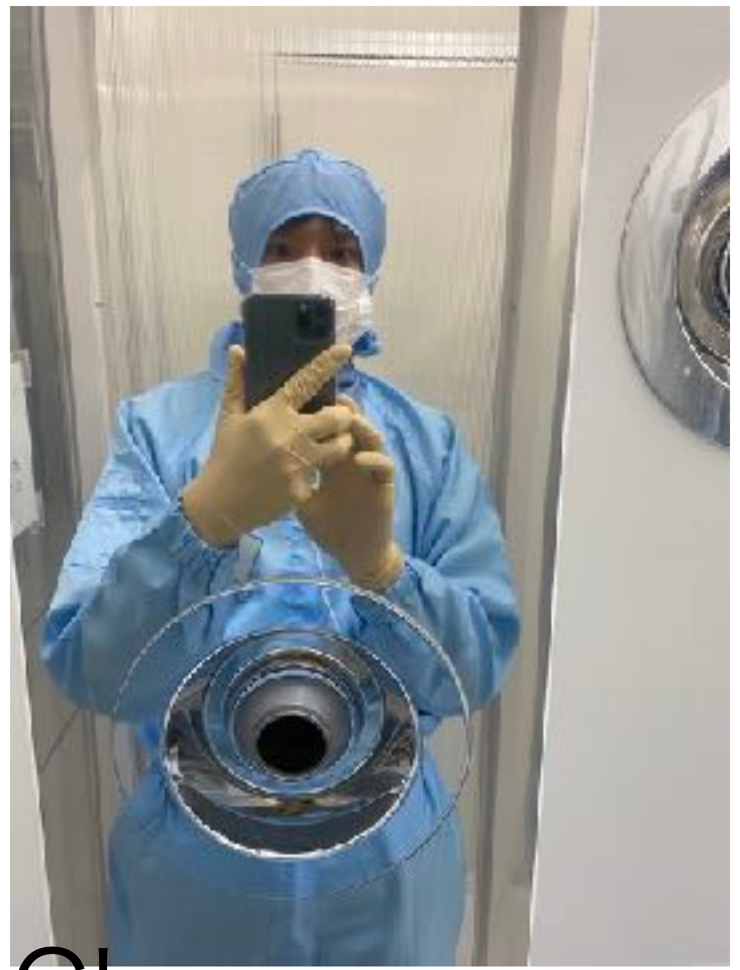


Josephson Junction (JJ)

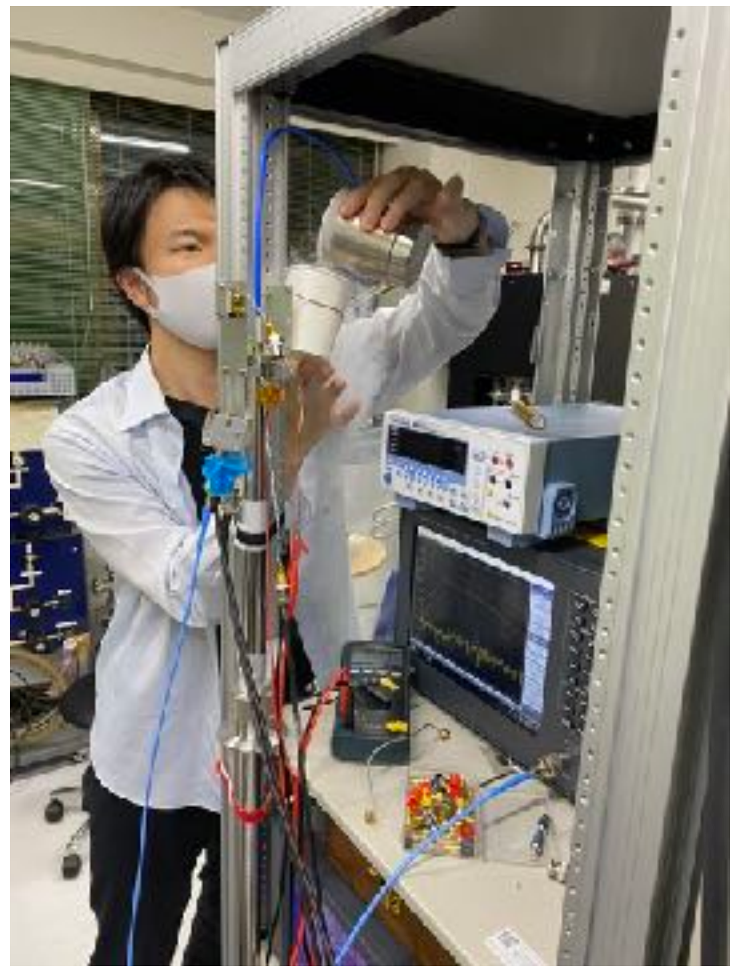
Physical design（3D Resonator）



Quantum hardware team in ~~ICEPP~~ Japan



Shion Chen
→ Move to Kyoto soon



Toshiaki Inada

Tatsumi Nitta

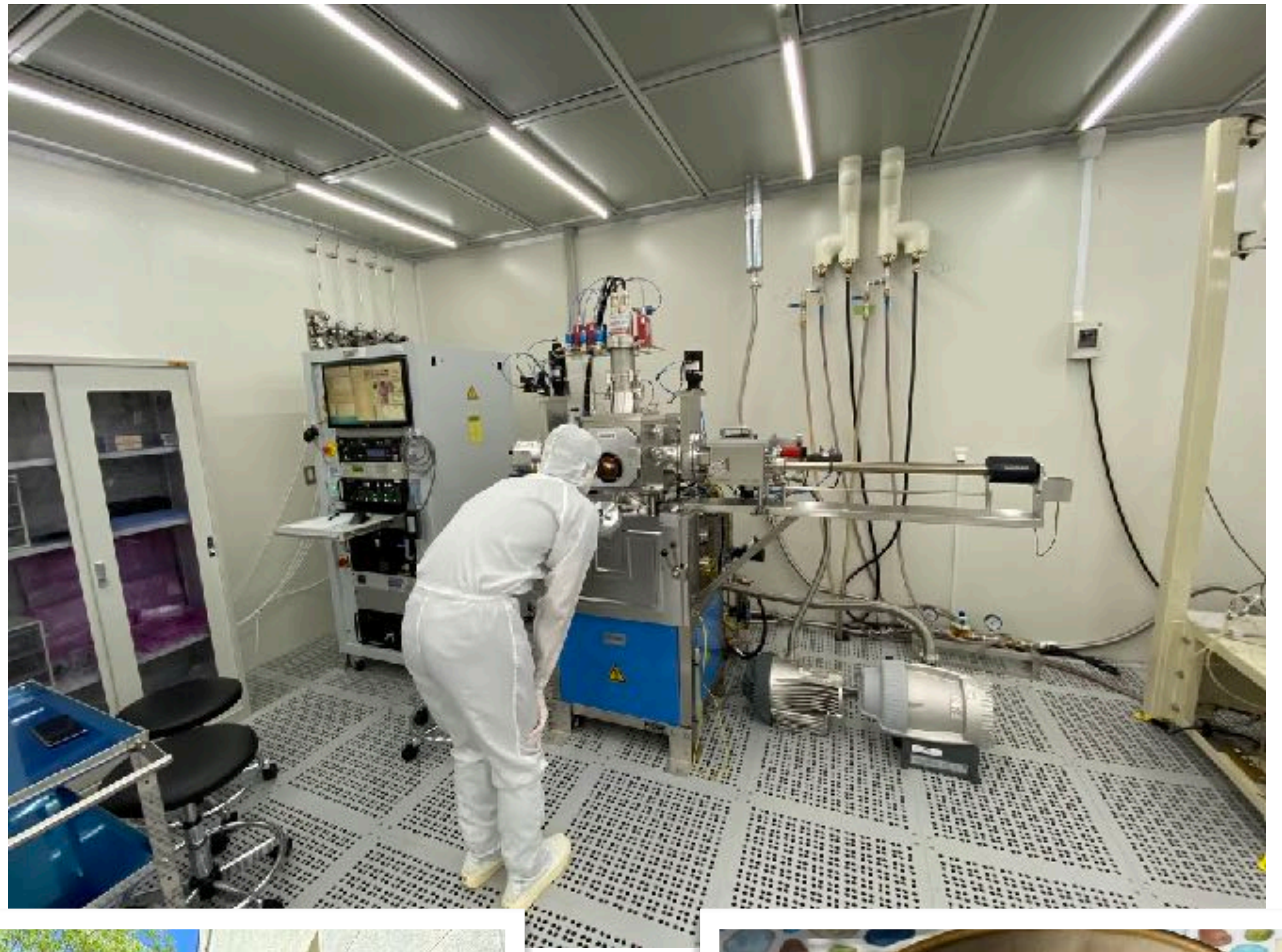
Kirill Shulga

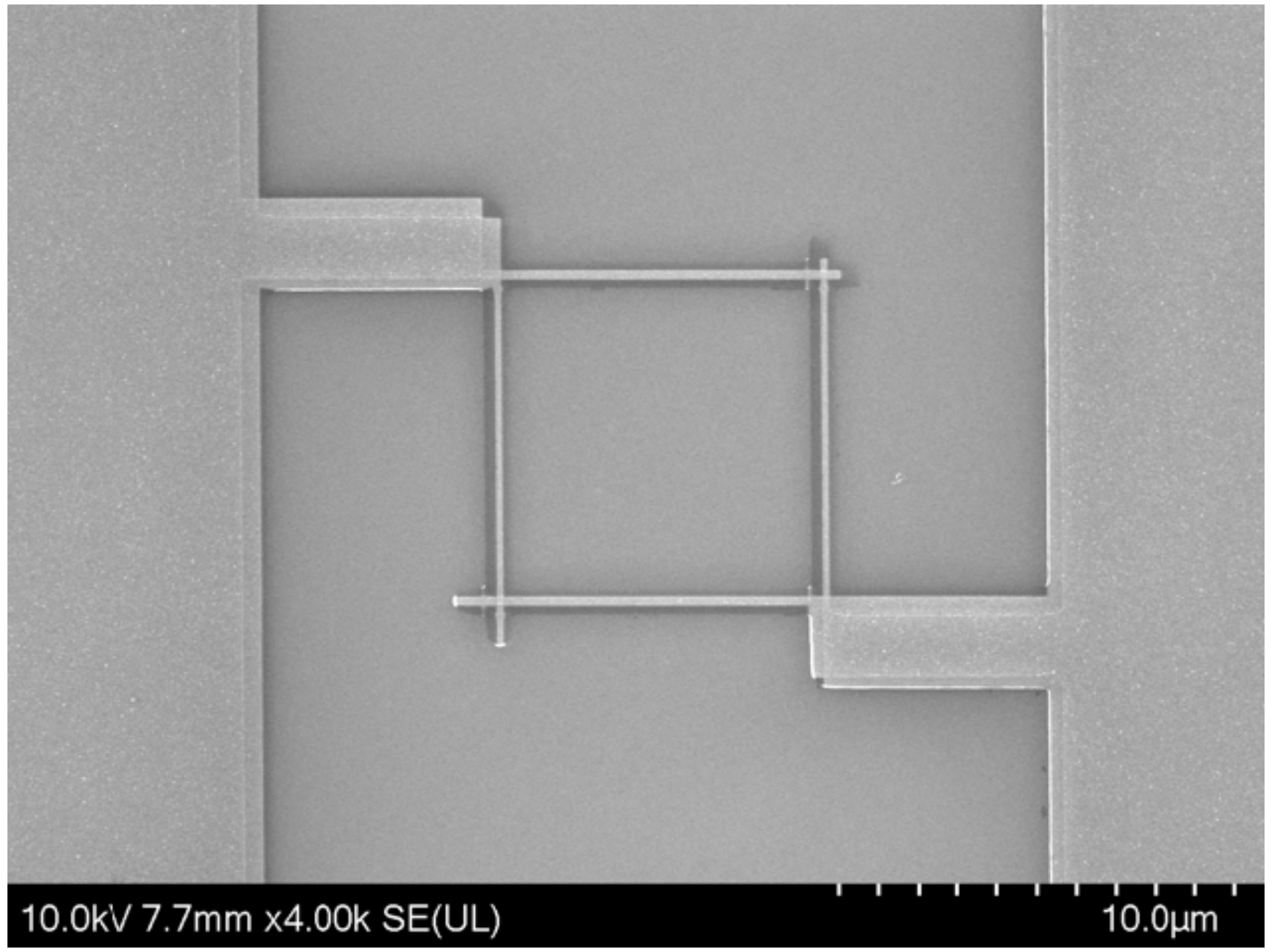
Karin Watanabe

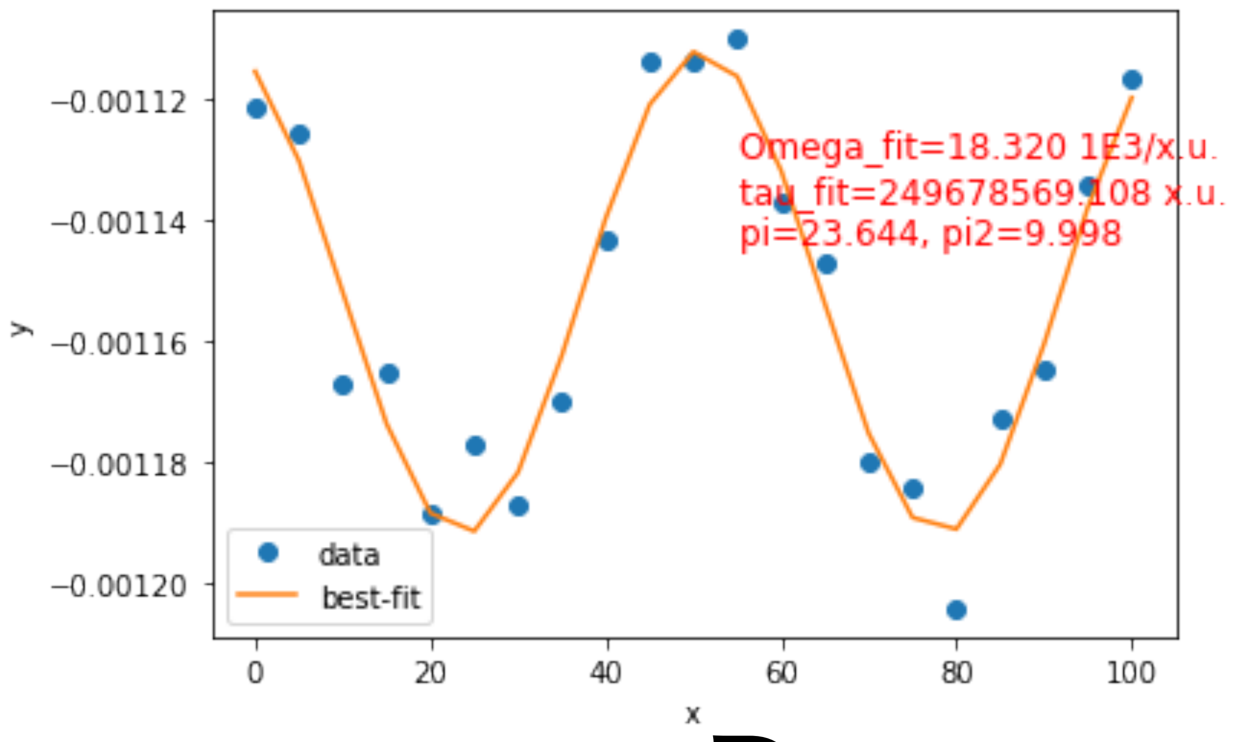
Kan Nakazono

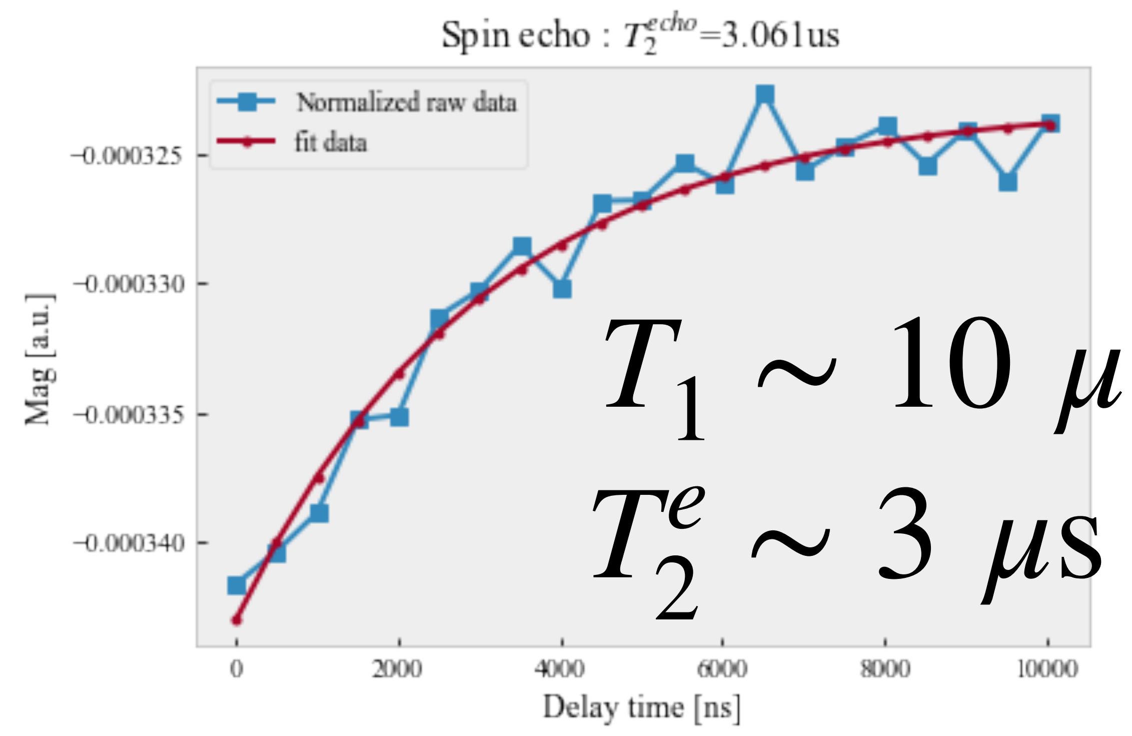
- Superconducting qubit fabrication
- DM searches using qubits
- QC related R&Ds (IBM sponsored research)
- High-freq. gravitational wave search (w/ FNAL/KEK)
- Analogue blackhole emulation using SQUID arrays

Activities: Qubit Fabrication









$T_1 \sim 10\ \mu s$

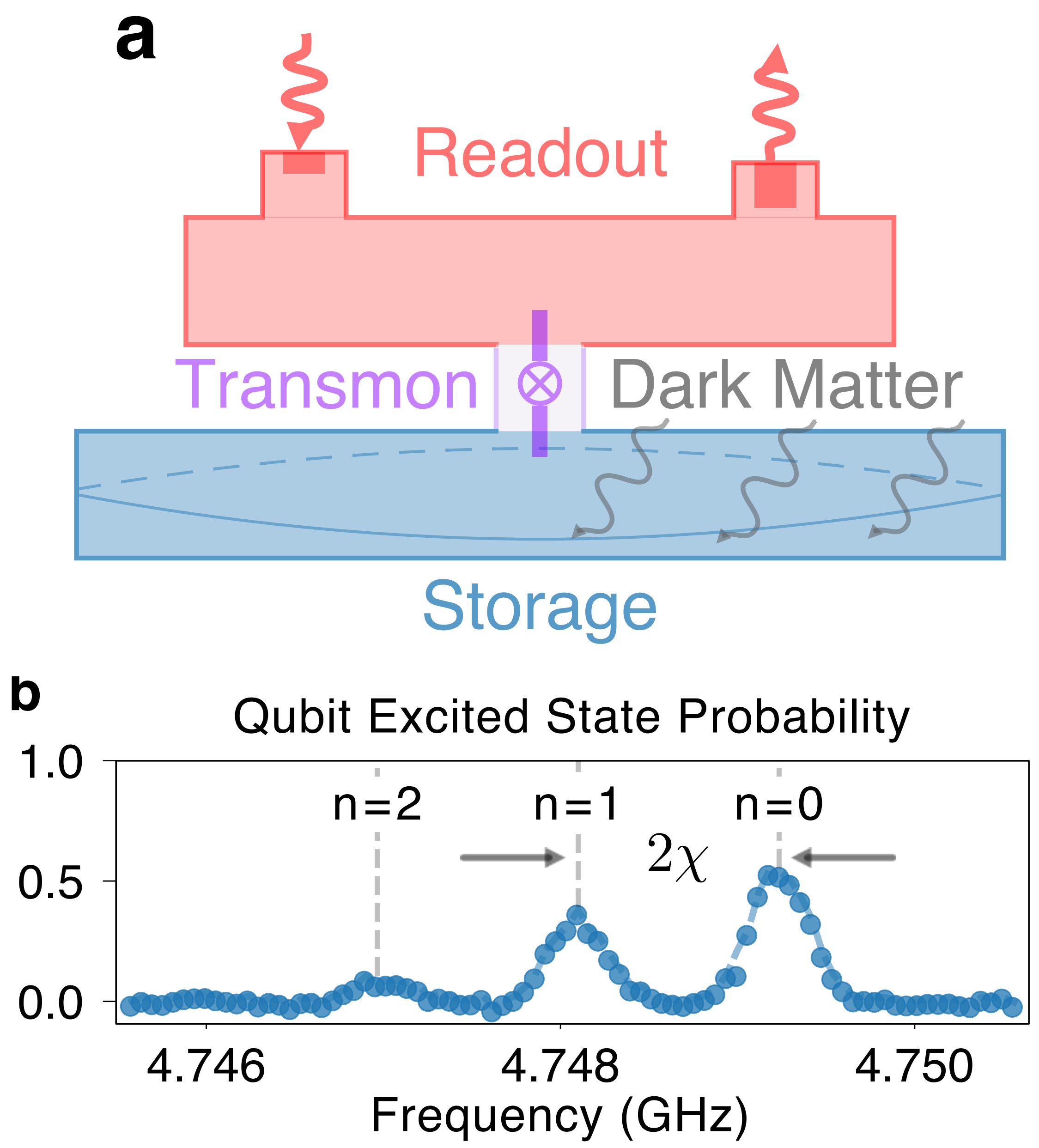
$T_2^e \sim 3\ \mu s$

Decent performance!

Activities: Dark wave searches

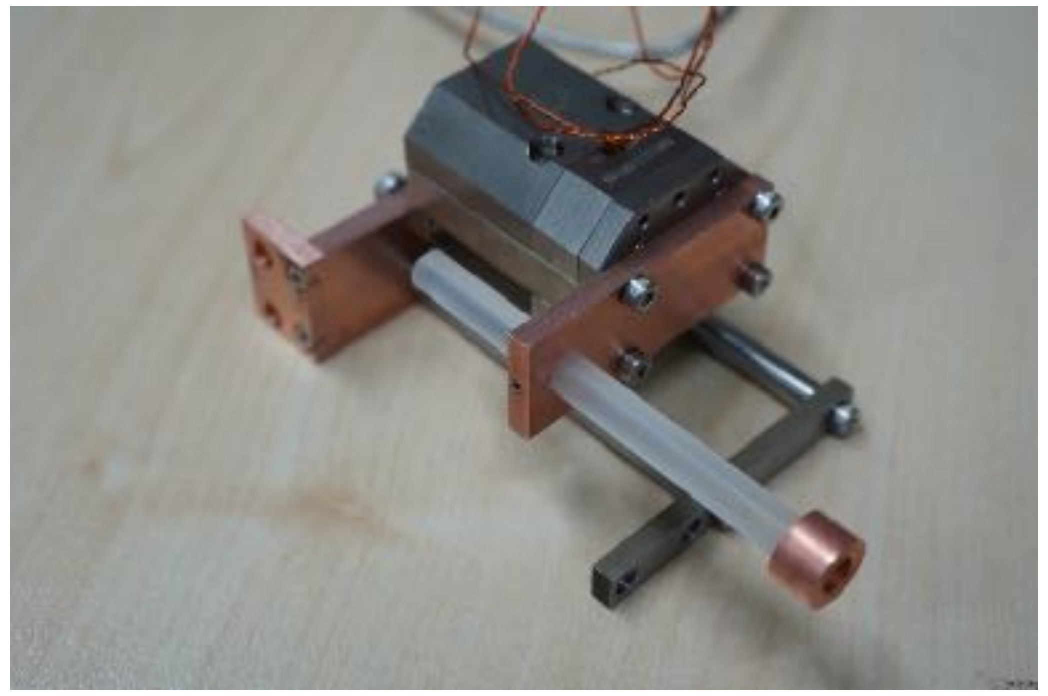
$$\mathscr{H}/\hbar = \left(\omega_q + g^2/\Delta\right)\sigma_z/2 + \left(\omega_c + g^2/\Delta\sigma_z\right)a^\dagger a$$

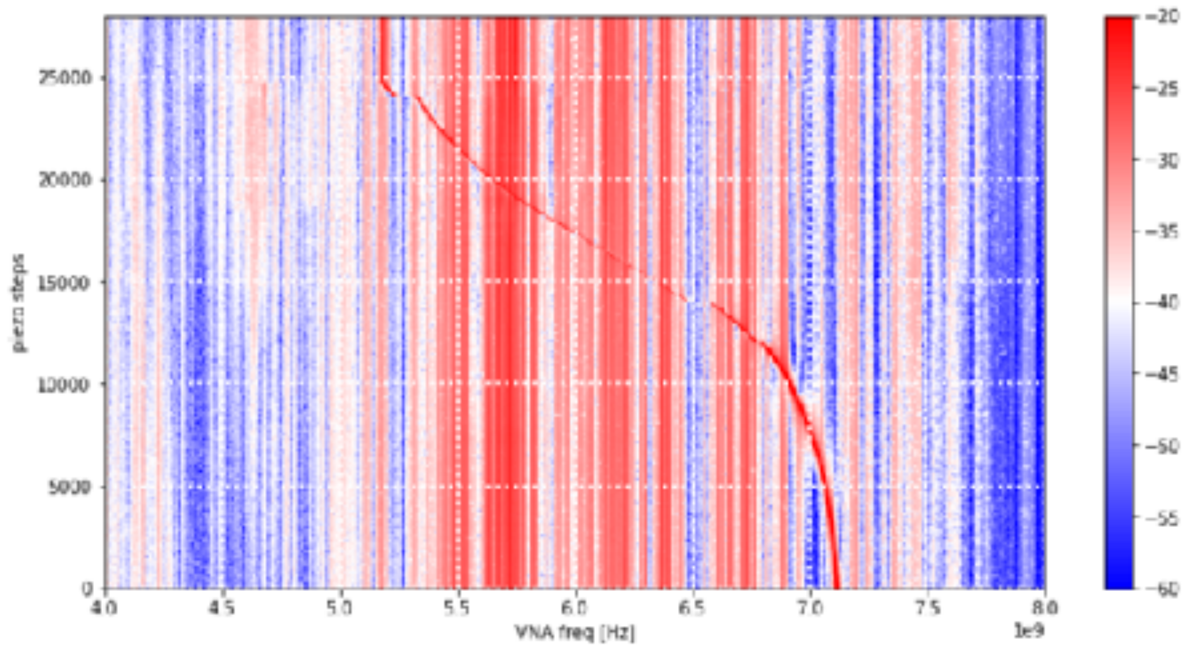
Single Photon Counter at GHz



Aaron et.al.

PRL 126 141302 (2021)





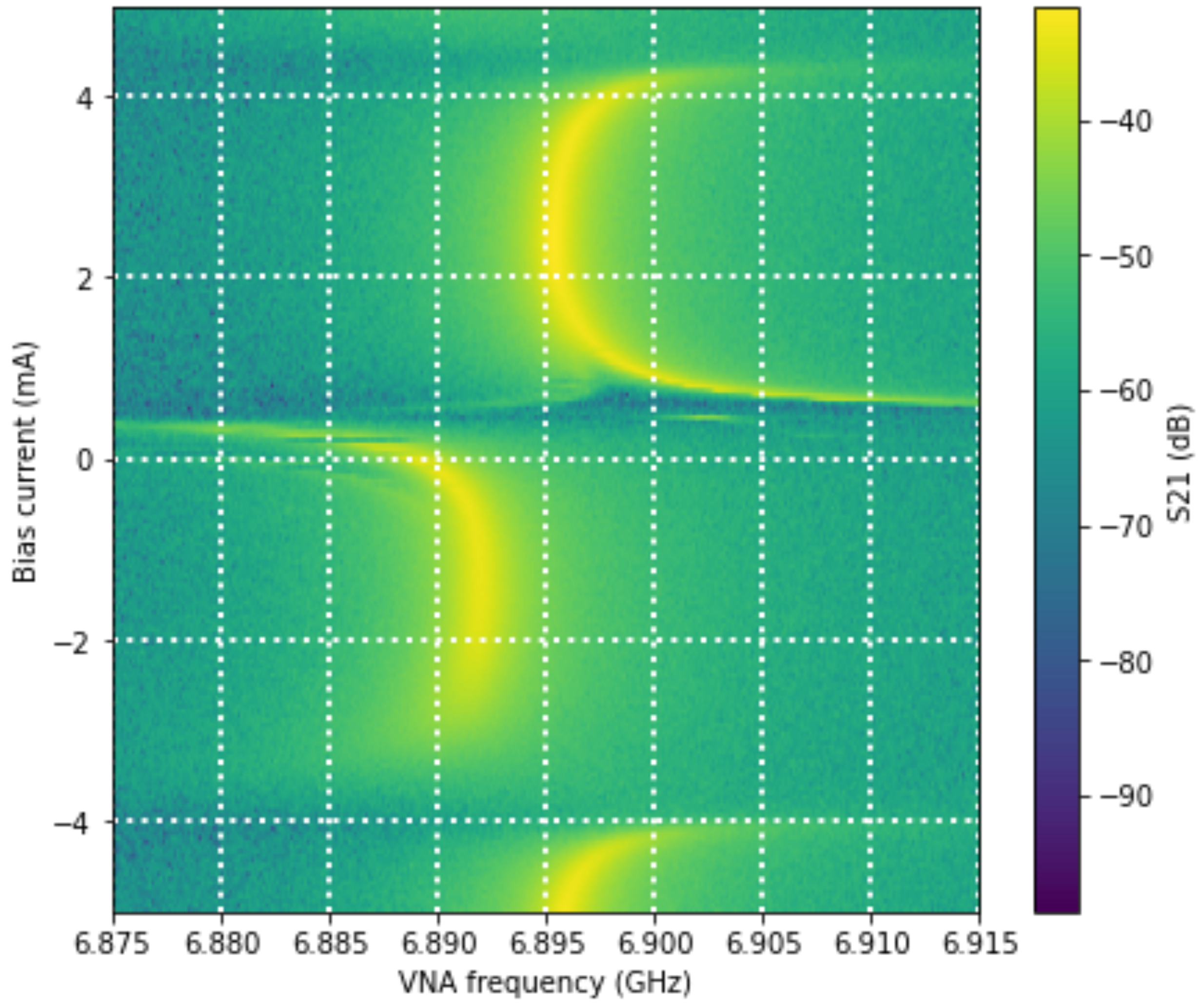
4-7 GHz wideband tunability

Tuning cavity resonance with qubit

$\Delta = \omega_c - \omega_q$

ω_q tuning

~ ω_c tuning!

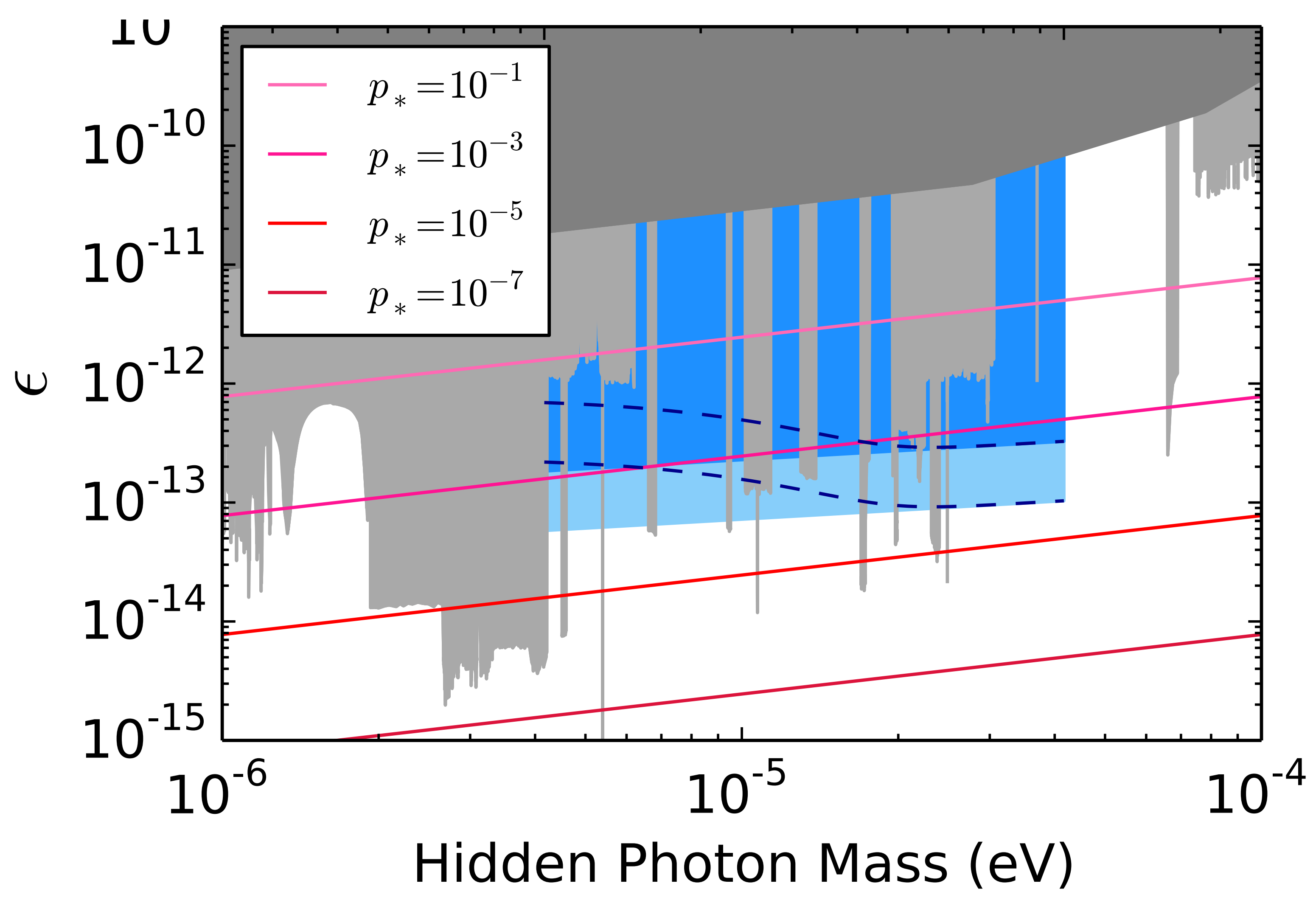


- Cavity tuning without rods
- g is designable → ~ GHz tuning

Activities: Dark wave searches

Qubit excitation with dark photons

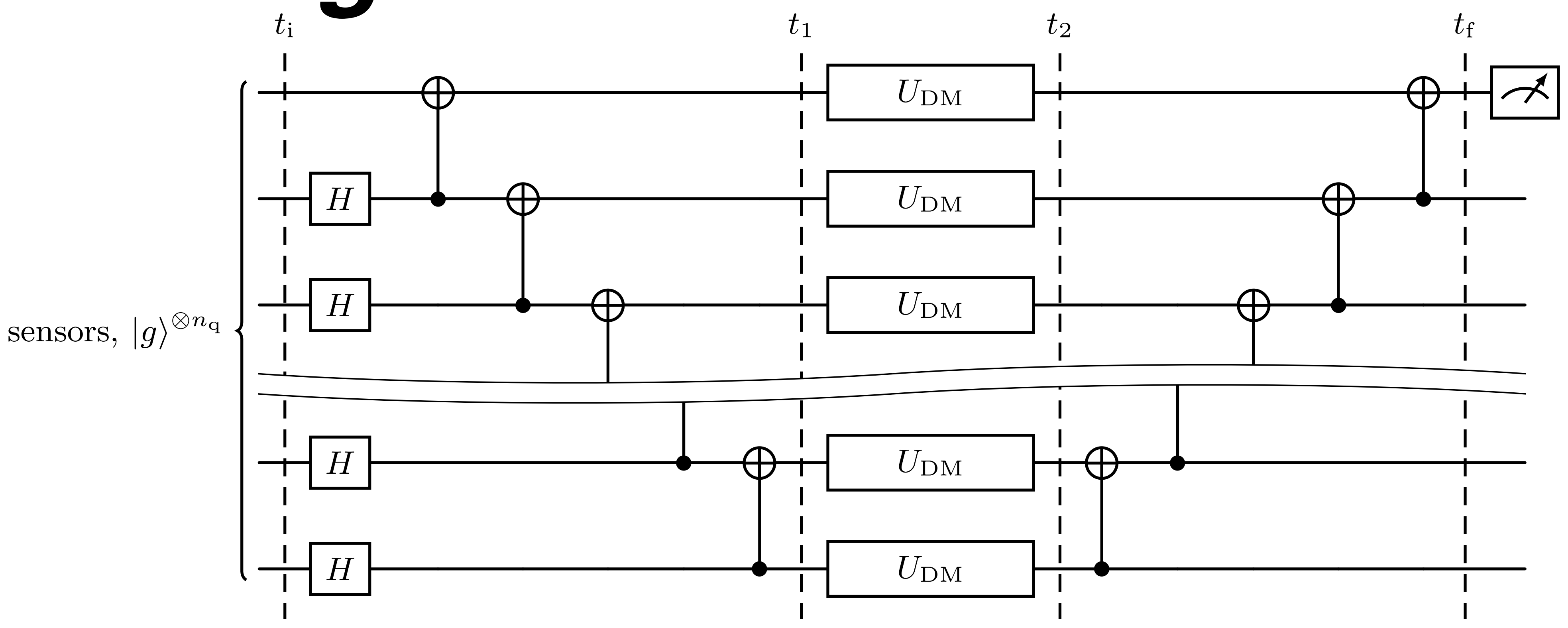
DP can excite qubit directly



S. Chen et.al.
Phys. Rev. Lett.
131, 211001

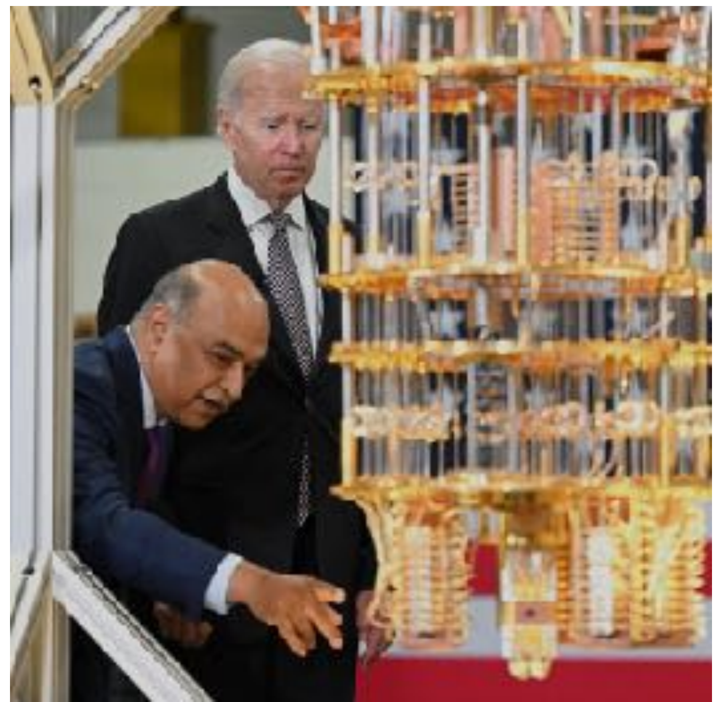
Wideband sensitivity

Entanglement enhances sensitivity



arxiv: 2311.10413

Multiple qubits entanglement enhances signal $P_{sig} \propto N^2_{qubits}$!



Any quantum computer is possibly a DM sensor

Worth putting qubit in B-field?

Yes! Many applications…

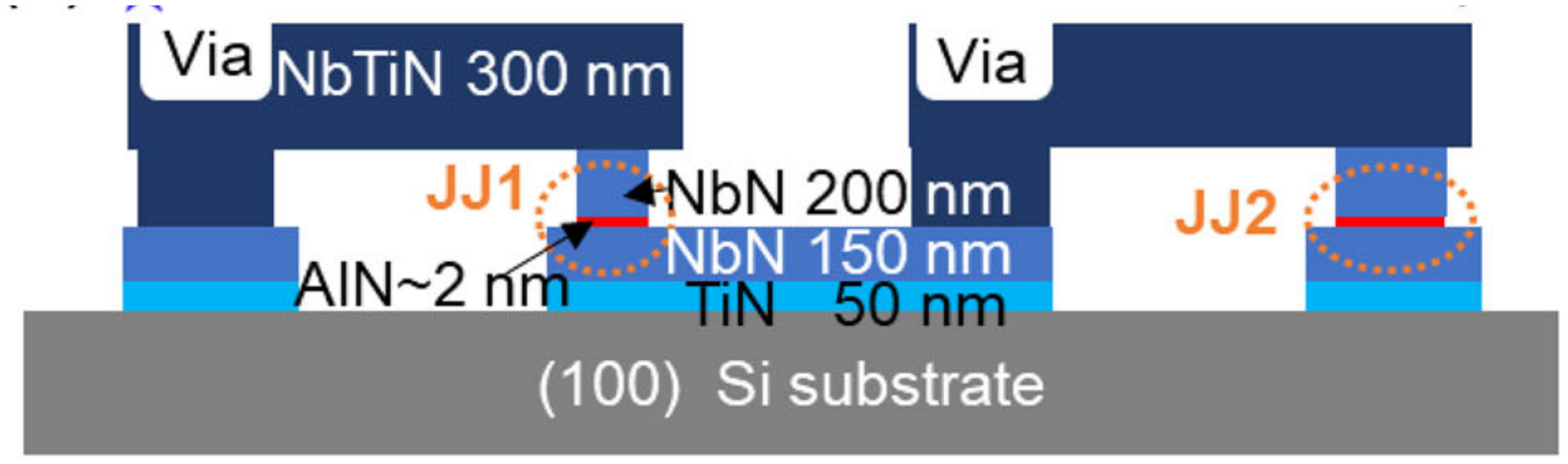
- Dark photon searches -> Axion searches !
  with JPA/TWPA without zero-field reagion
  with single photon counter / direct detection
- Other JJ based quantum device (JPC as switch etc)
- Condensed matter application like quantum spin liquid in $\alpha - \mathrm{RuCl_3}$
- Readout of the other quantum system (NV-center, Magnons)

Does qubit survive in B-field?

No, but some ideas…

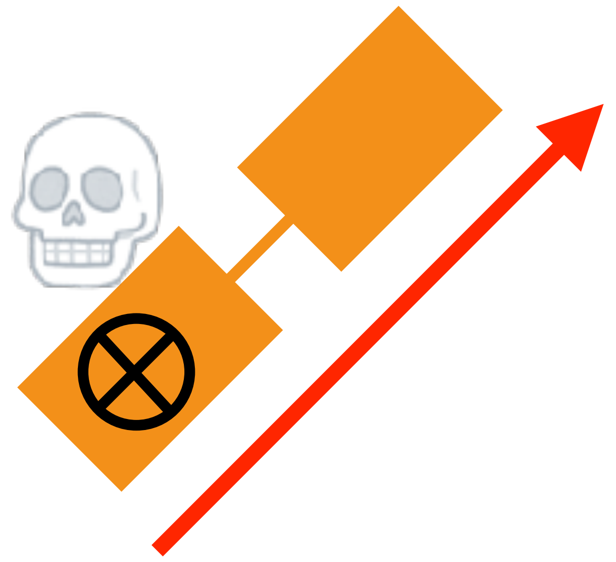
Use high T_C materials

		SC type	H_C
Conventional	Al	Type- I	~0.01 T
	Nb	Type- II	~0.2 T
	Ta	Type- I	~0.08 T
Might worth?	NbTi	Type- II	~12 T
	NbAl	Type- II	~34 T



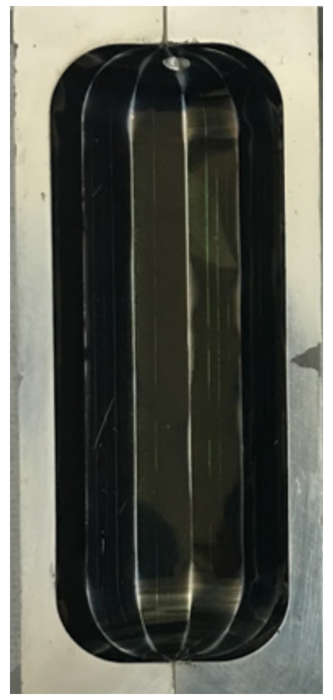
Nature Commun Mater 2, 98 (2021)

Avoiding penetrating thin films



Applying B-field along with thin film

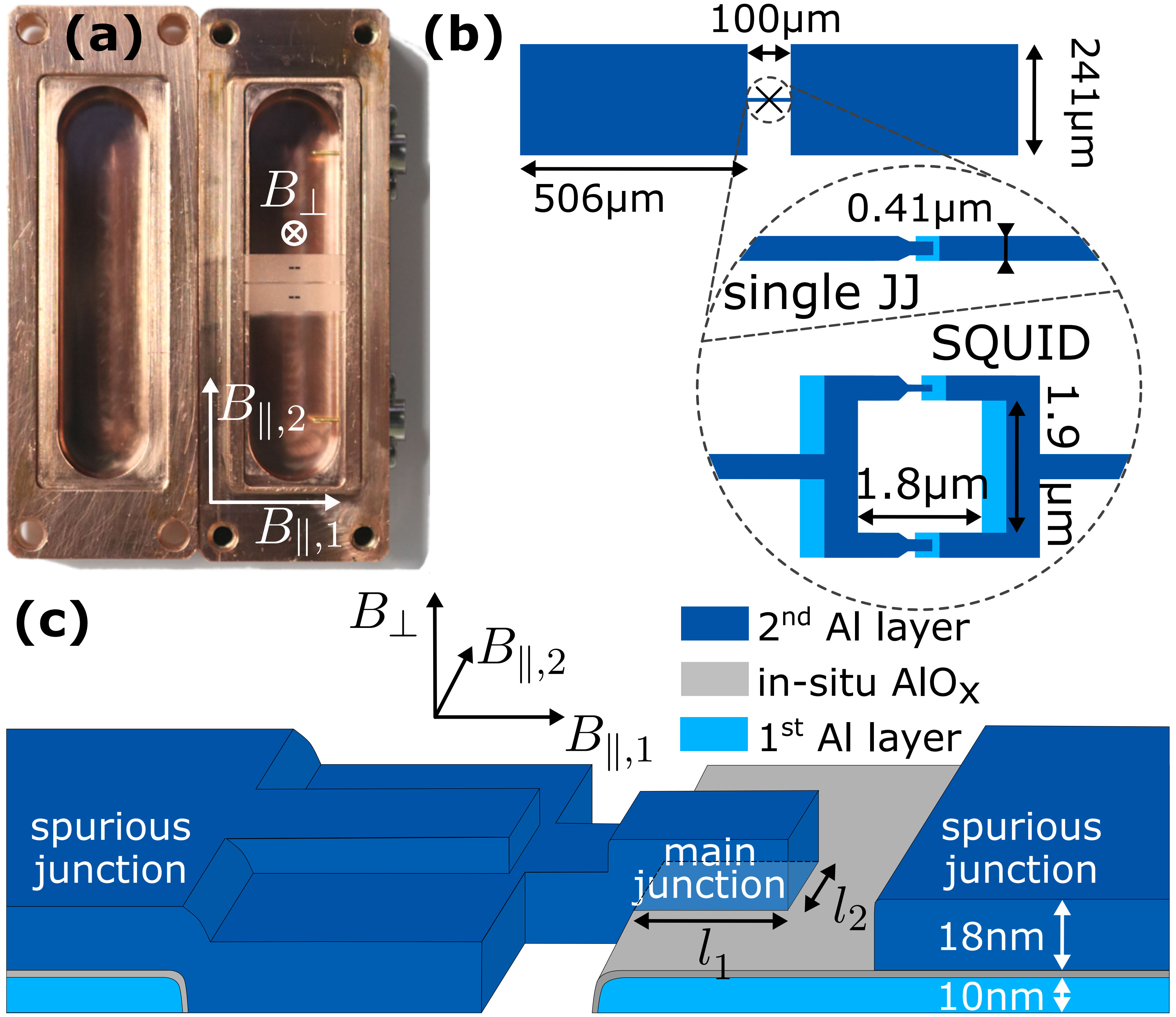
Similar situation in
YBCO cavity at CAPP
NbTi cavity at INFN

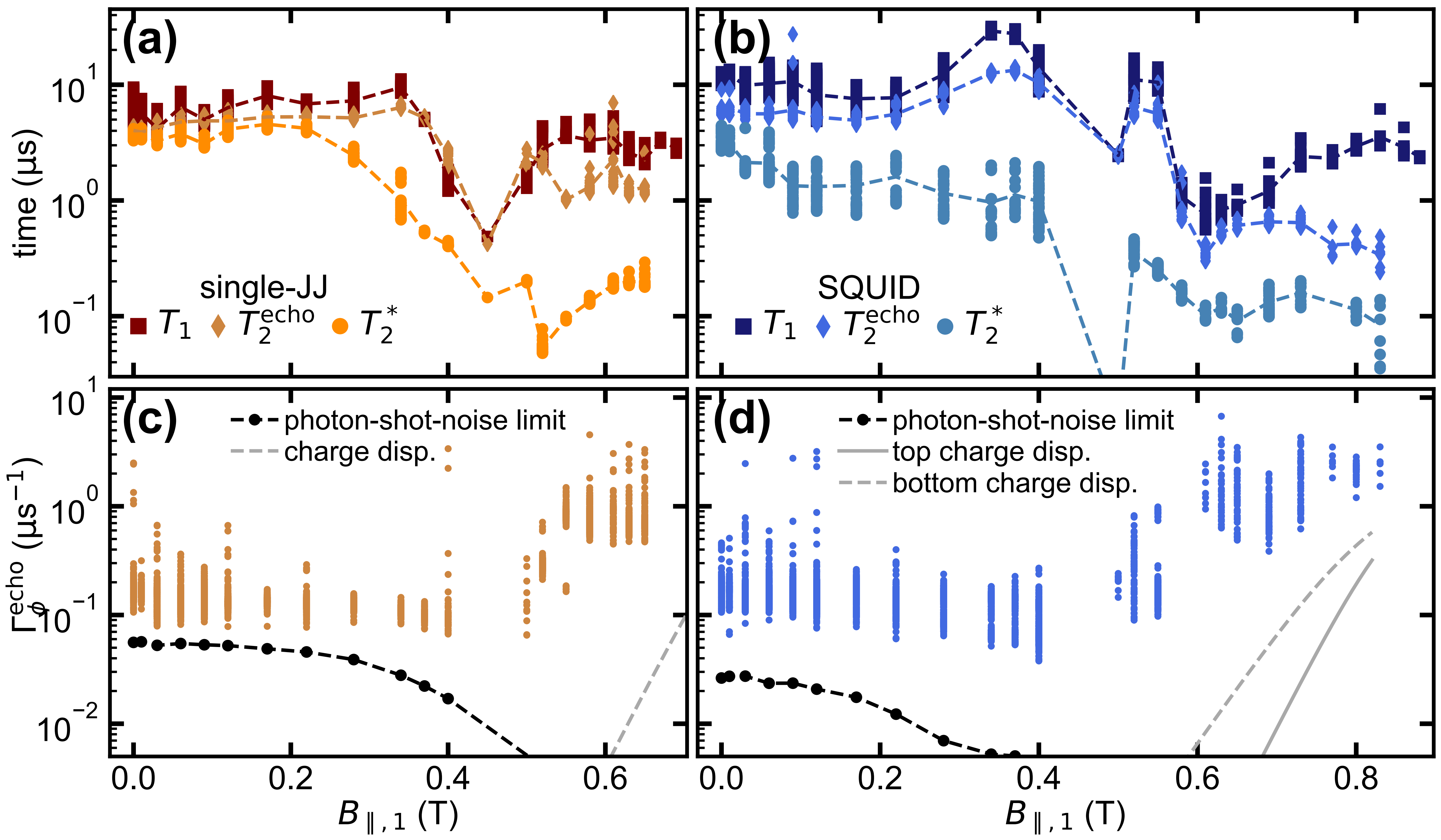


Thin fim ~ 100 nm
Cross section is extremely low

Highest Magnetic Field Ever Applied

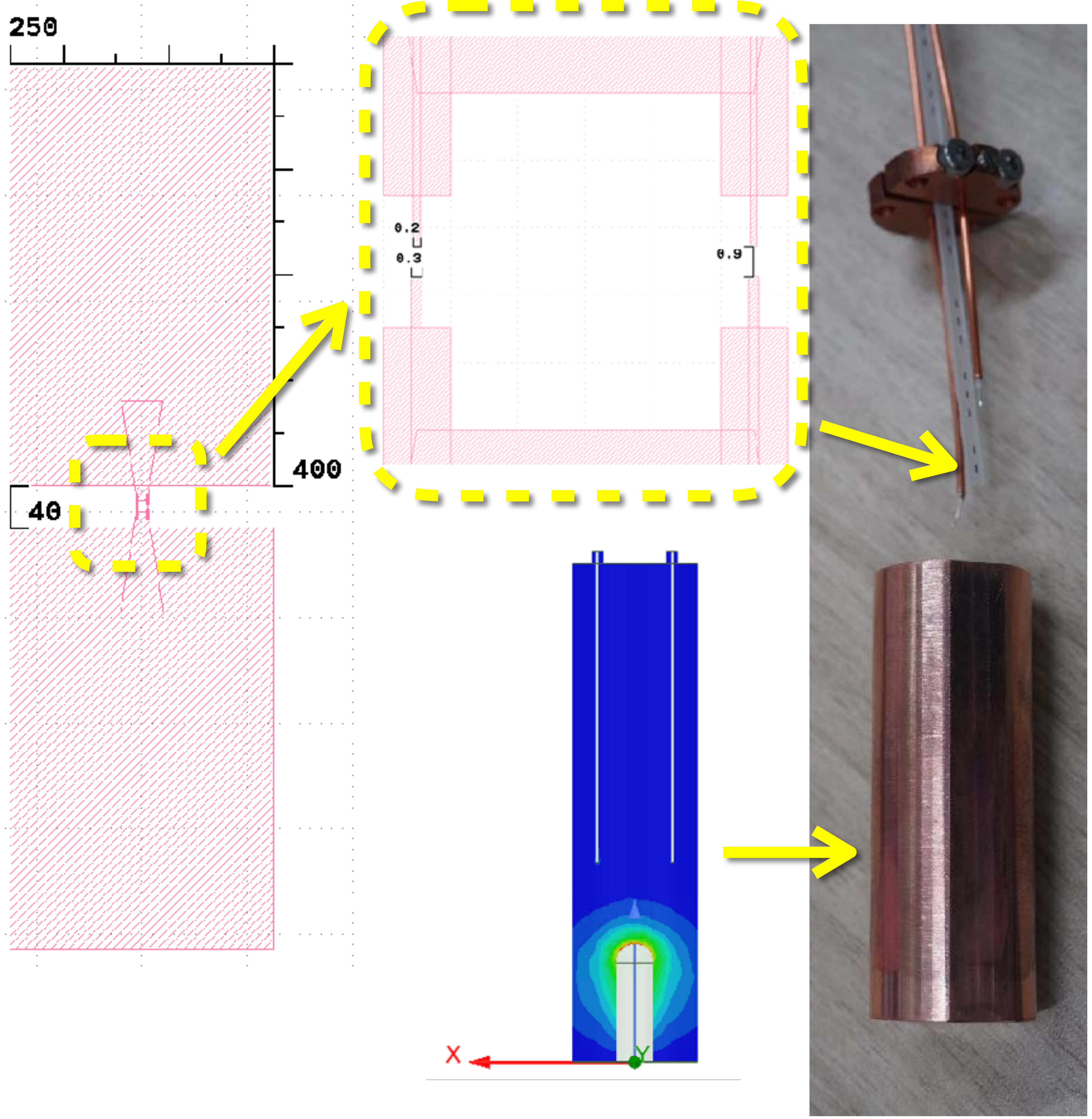
Phys. Rev. Applied 17, 034032

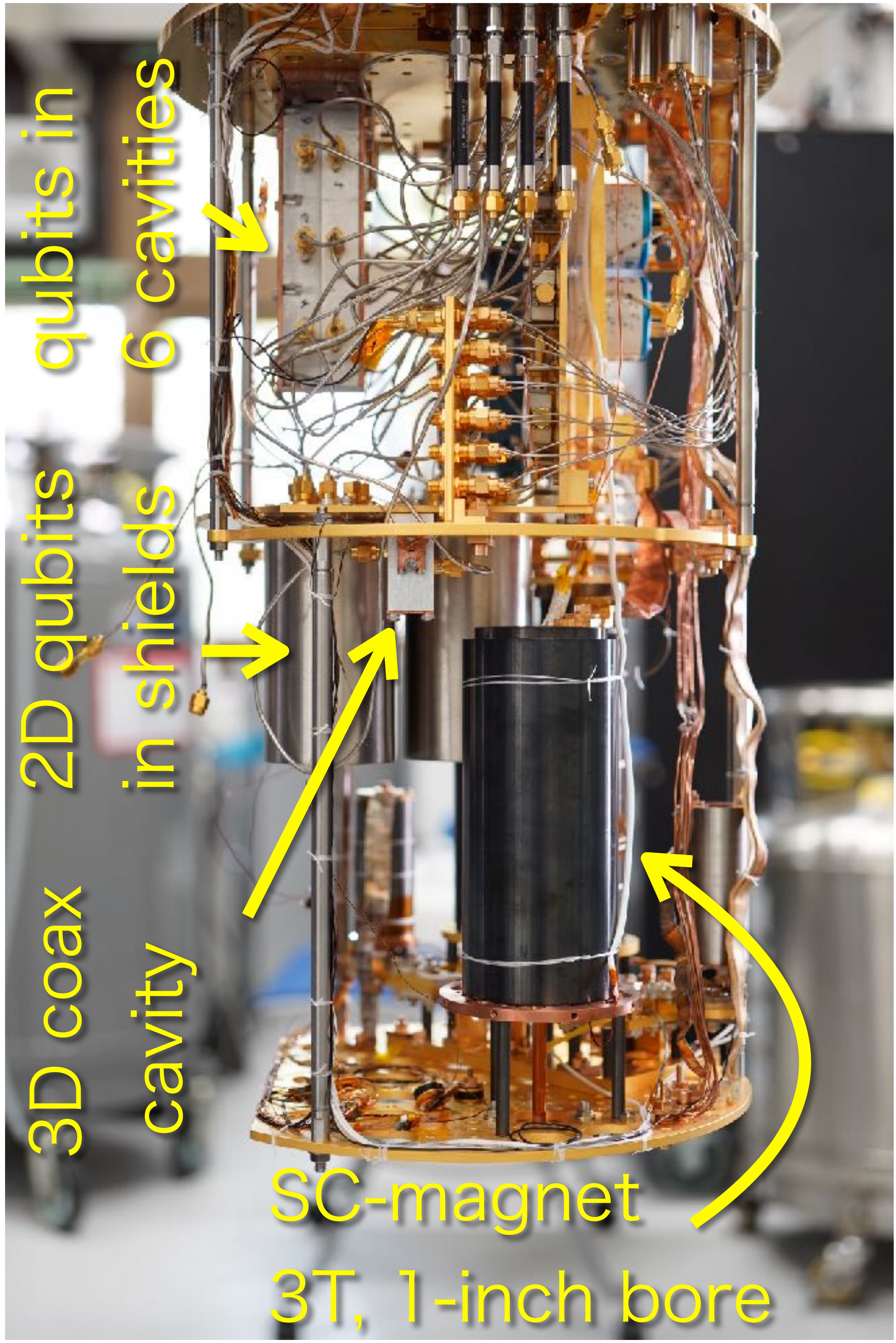




Al-AlOx-Al Junction has 1 Tesla tolerance

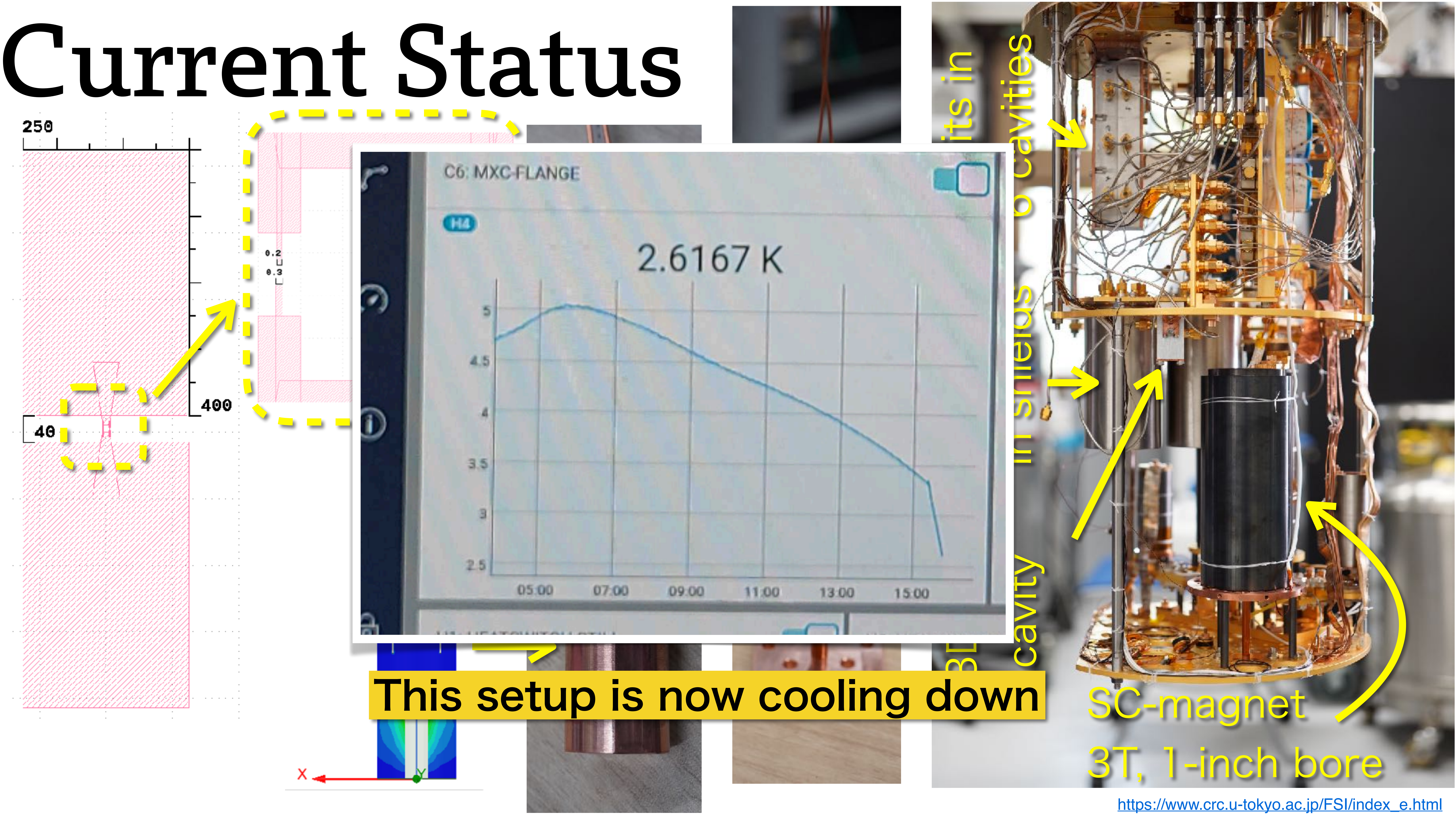
Current Status





https://www.crc.u-tokyo.ac.jp/FSI/index_e.html

Current Status



This setup is now cooling down

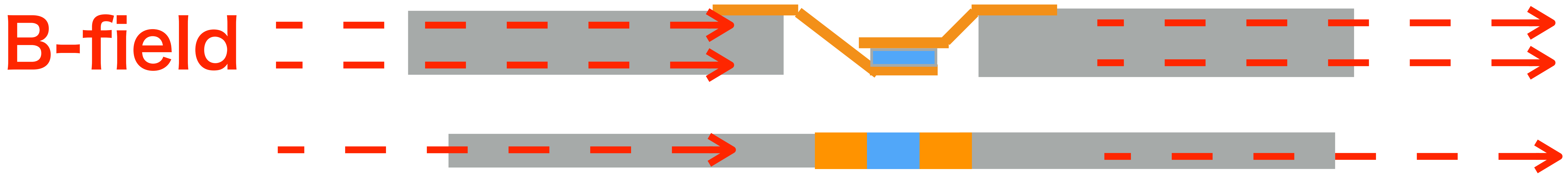
https://www.crc.u-tokyo.ac.jp/FSI/index_e.html

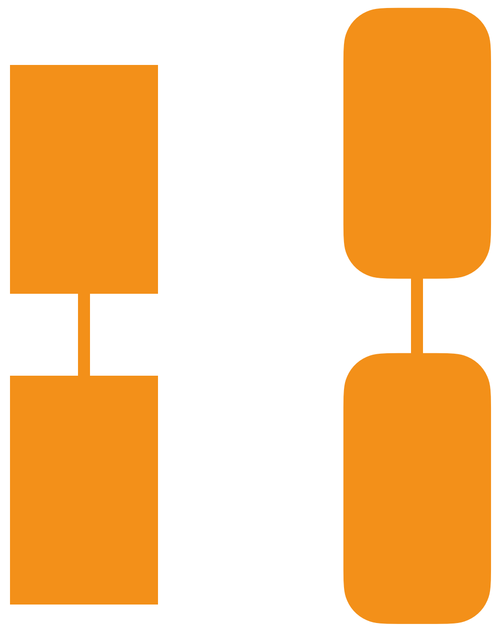
Future Plans / Possibilities

1. Test qubit in ~ 3 Tesla -> Now ongoing

2. Sneak in the 9.4 T magnet at FNAL?
   Our setup is very small: **1 inch diameter, less than 2 inches length**

3. Test dedicated design for escaping magnetic flux





4. Test fancy material for higher tolerance

Summary

- Superconducting qubits have many application to HEP
- Qubit in a strong magnetic field opens various possibilities

  Especially, axion searches with extreme sensitivity

- Qubit is proved working under 1 Tesla

  → We are now expanding it towards ~10 Tesla

- There are several options to make it more B-field tolerant