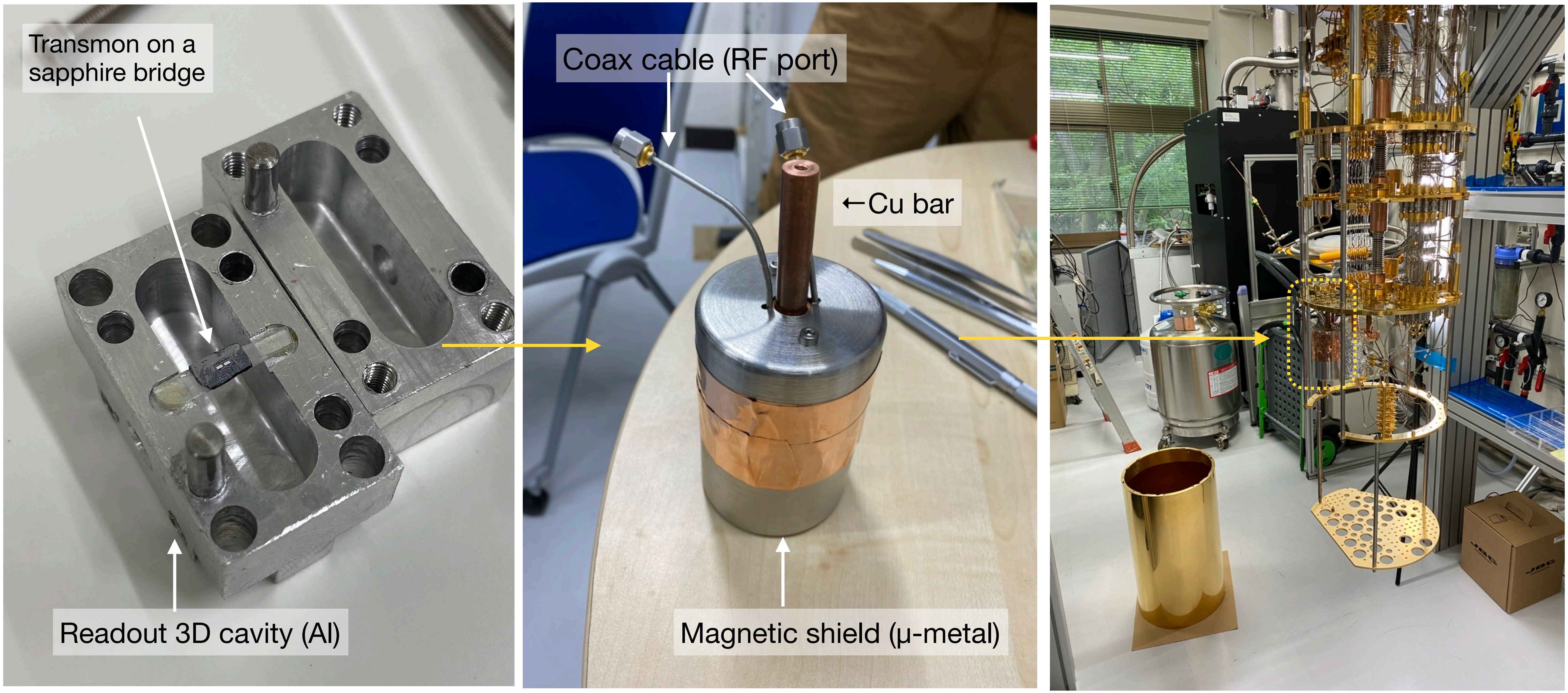
How to use superconducting qubits

Measurement setup & sensor application

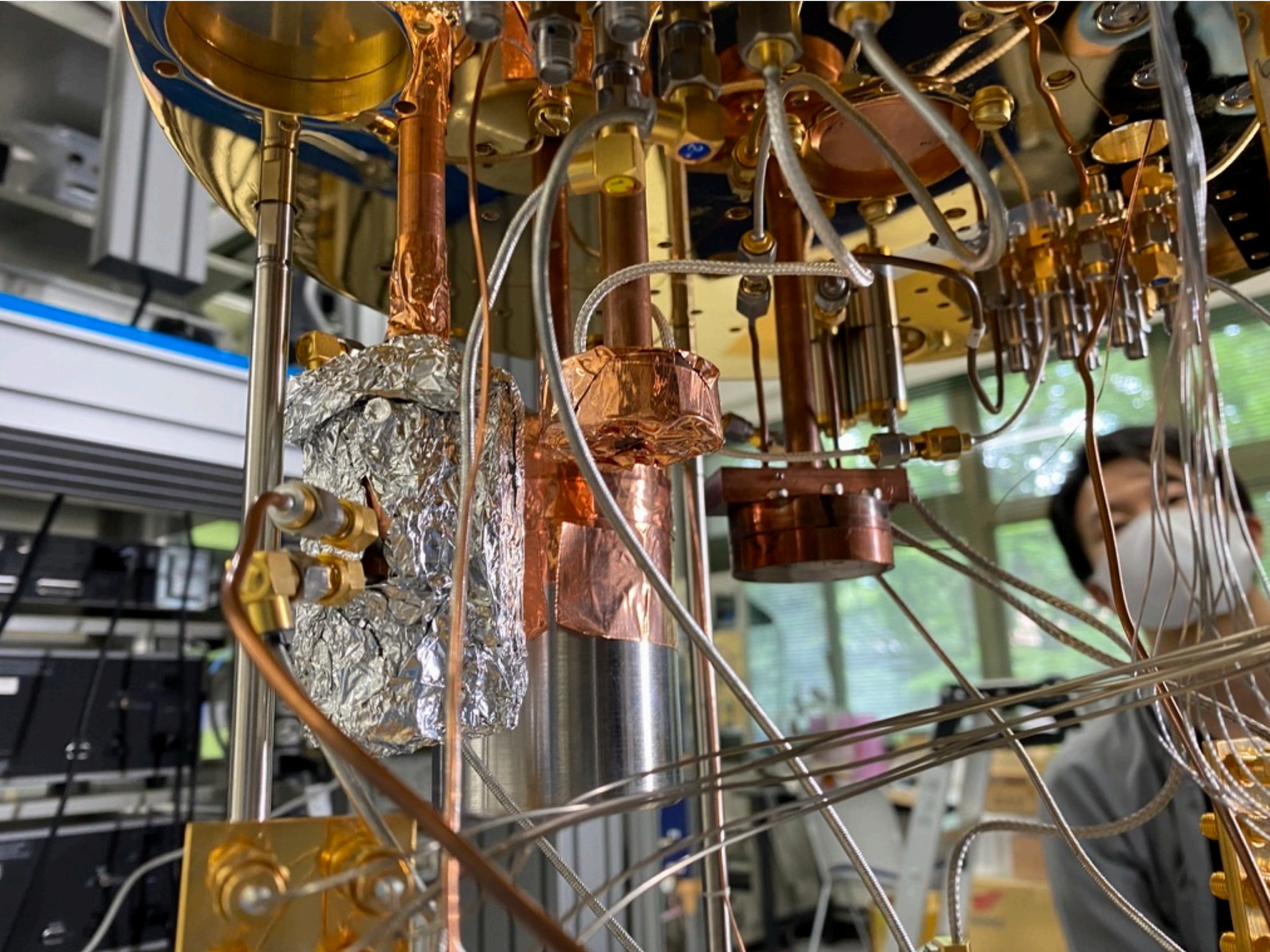
2024.3.7 KMI school 2024 lecture series (6-2)
Shion Chen (UTokyo/ICEPP)

Packaging & Installation



○ Mechanically attached to the coldest plate of the dilution refrigerator (10mK)

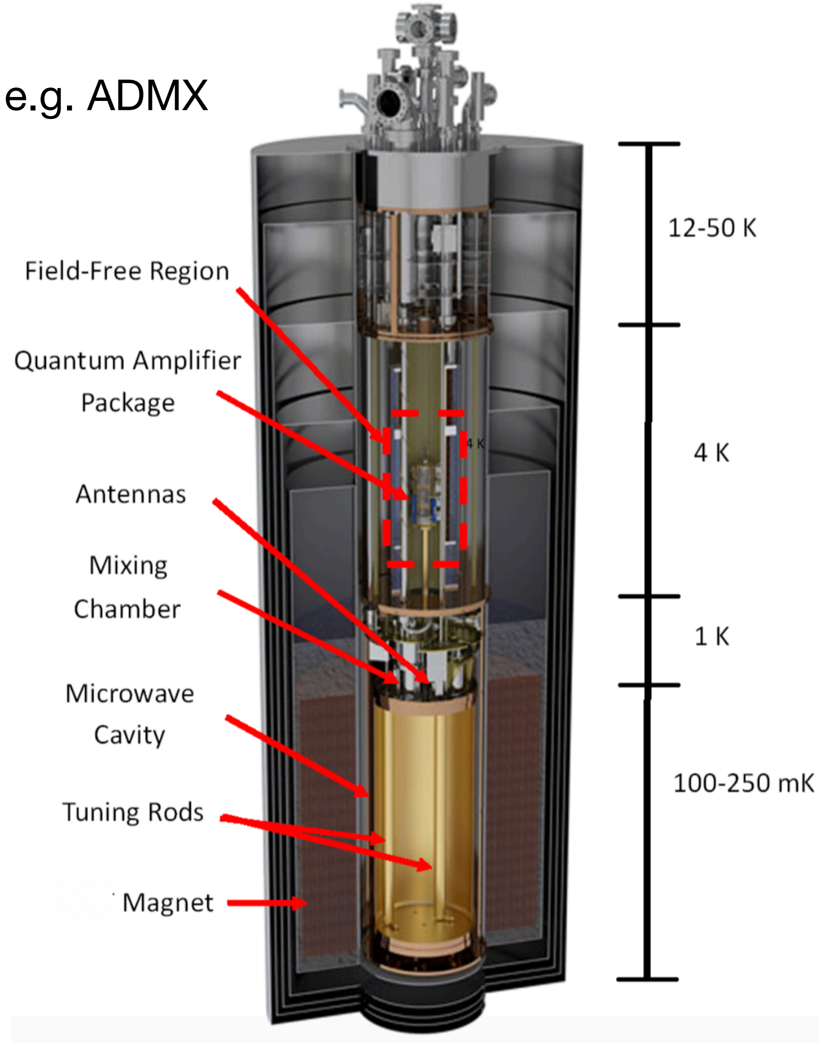
○ All microwave operation (1-10 GHz)

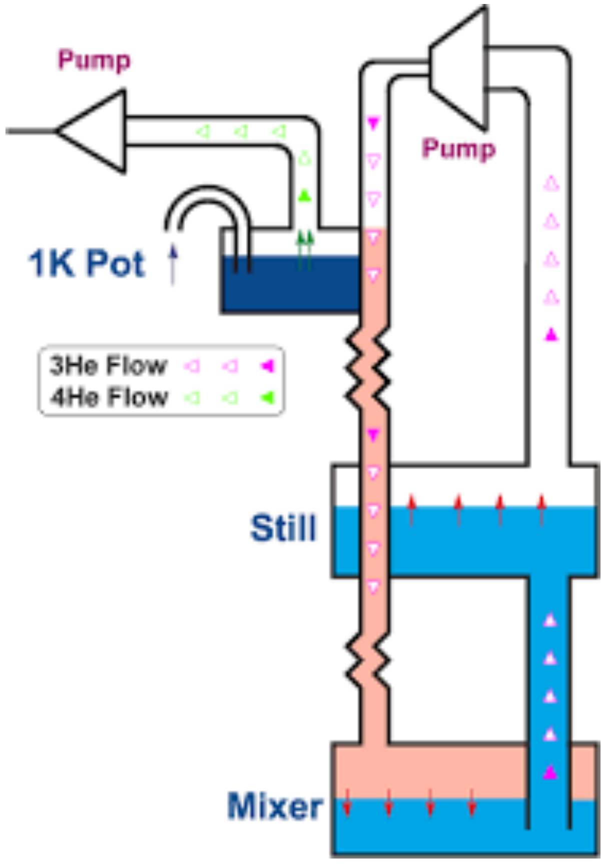

2
1

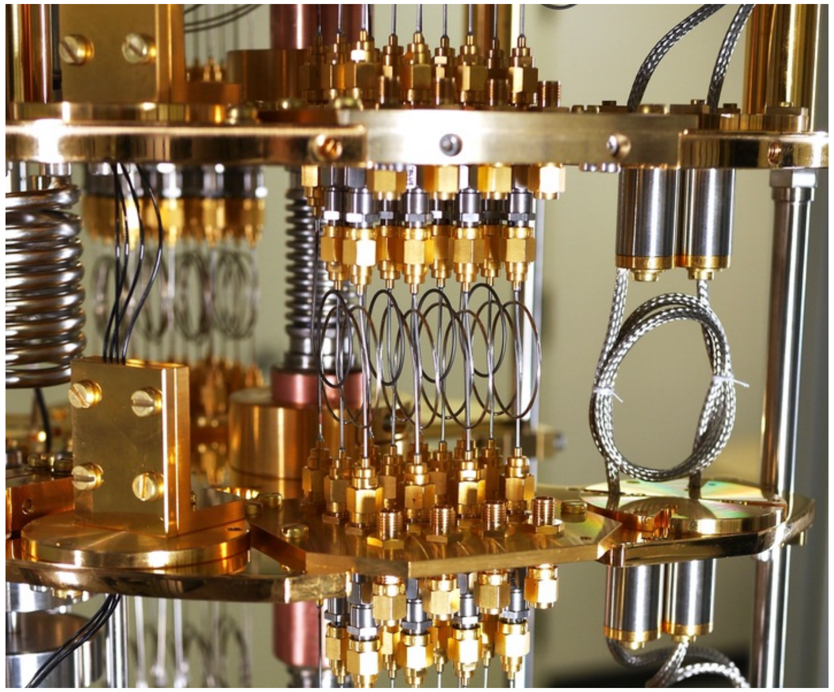
Dilution refrigerator

Coldest available large-volume fridge (~10mK)

e.g. ADMX







He^3 evaporates from LHe^3 to LHe^4 phase
→ cooled ⛄

Main heat sources

Conduction (via pipes/cables) → make them long, low conducting materials

Convection (via gases in the fridge) → high vacuum

Radiation (from outside) → metal shielding

<< Cooling power: 100-1000μW

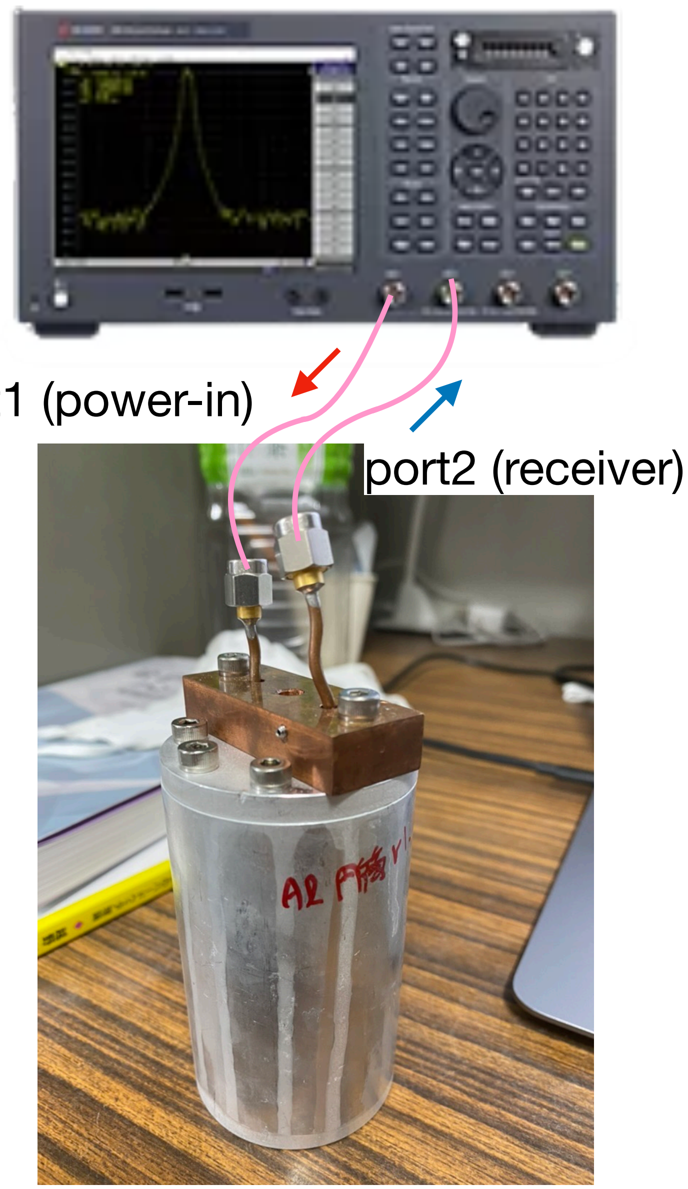
Takes 2-10 days to reach the lowest temperature

Measurements = checking the microwave RF response

Inject a RF to the sample → See the amp. & phase of the transmission (reflection)

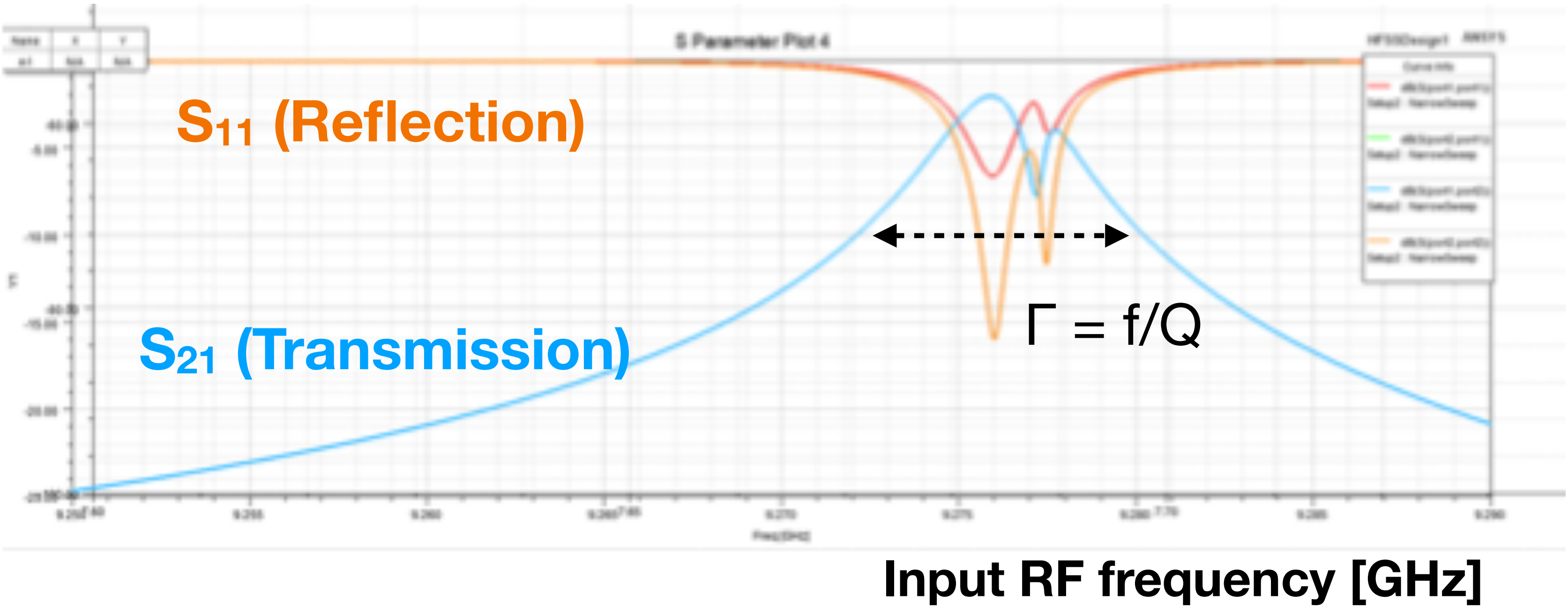
e.g. Cavity measurement

Vector network analyzer (VNA)



port1 (power-in)

port2 (receiver)



Cavity = Photon storage

- Store photons at the resonant frequency
- Reflect photons at the other frequencies
- Figure of merit of stored photons: Q-value

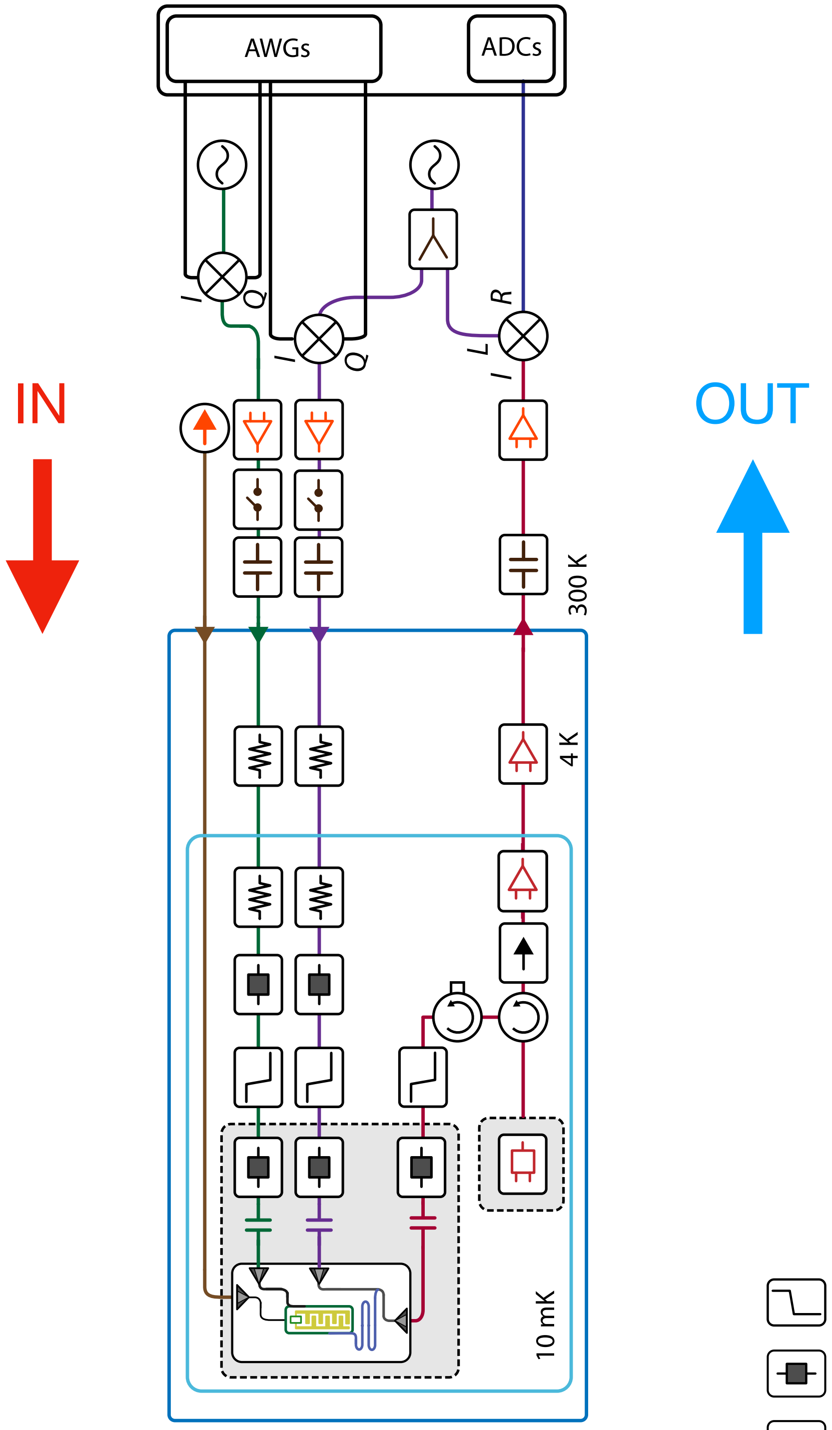
  e.g. holes (escape), rough surfaces (absorption) → low-Q

Any metallic containers are effectively MW cavities

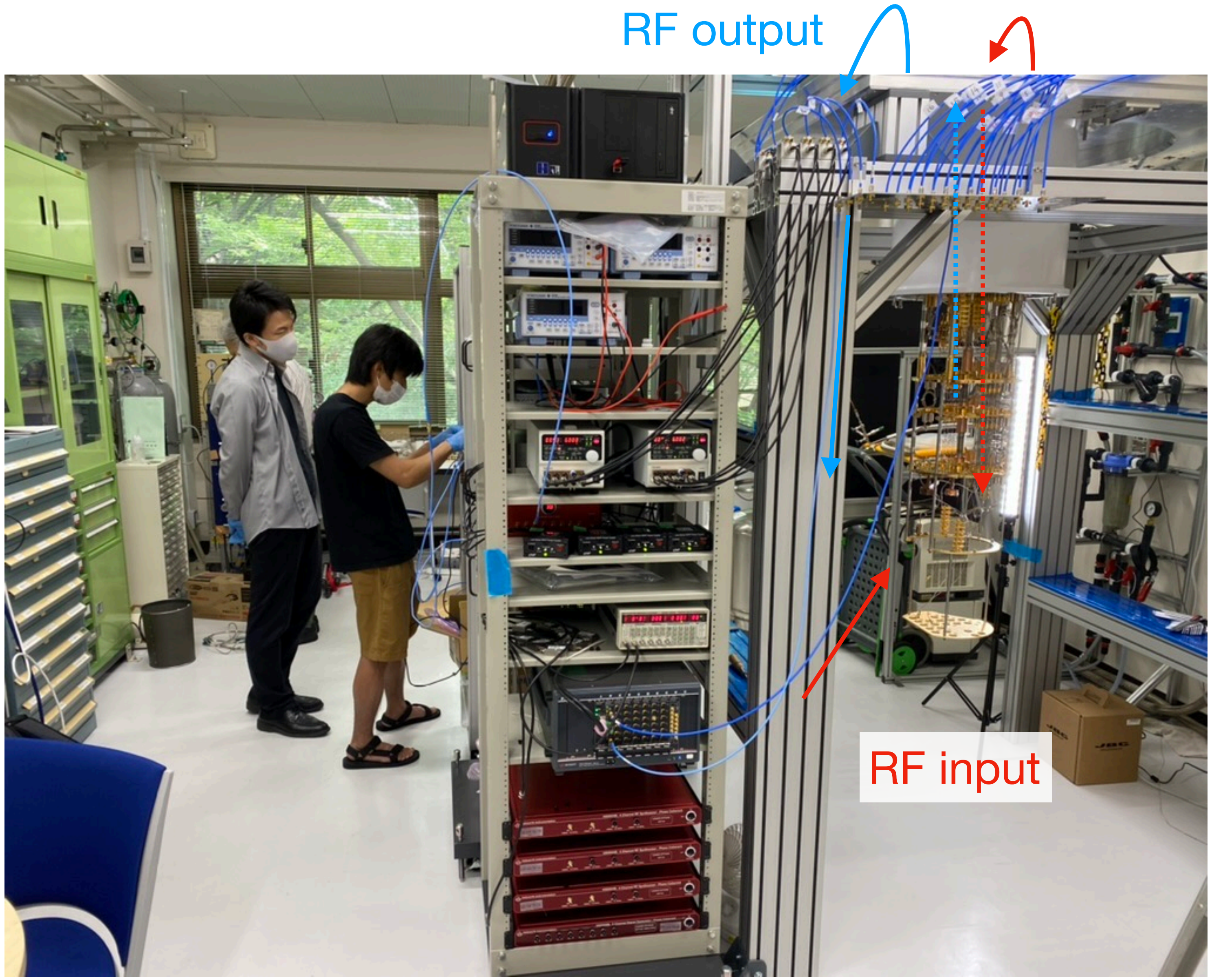
Typical RF chain setup

Mili-Kelvin Quantum Platform

Cryogenic Research Center @UTokyo Asano campus



Y. Y. Gao et al. PRX Quantum 2, 040202



10-GHz LPF

Circulator

20-dB attenuator

Fast switch

dc block

Eccosorb filter

Isolator

Cryoperm shield

Signal generator

Power splitter

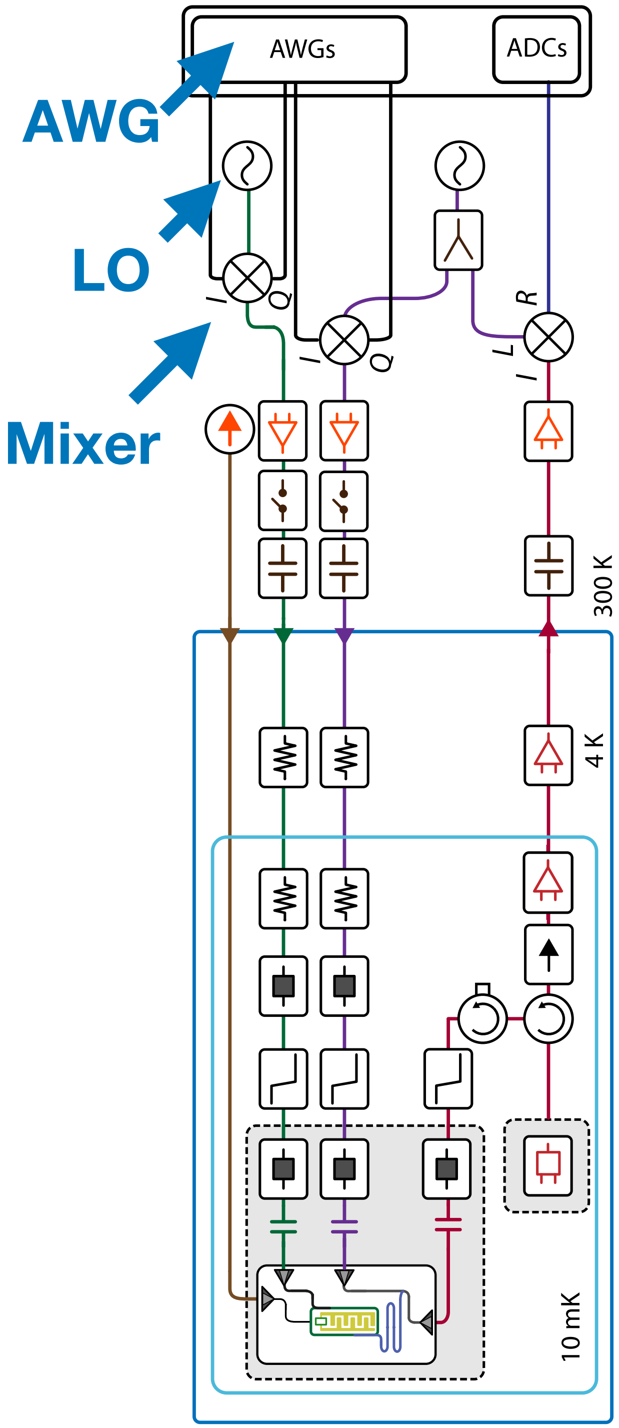
Quantum-limited amplifier

Amplifer

Microwave mixer

Current source

Typical RF chain setup

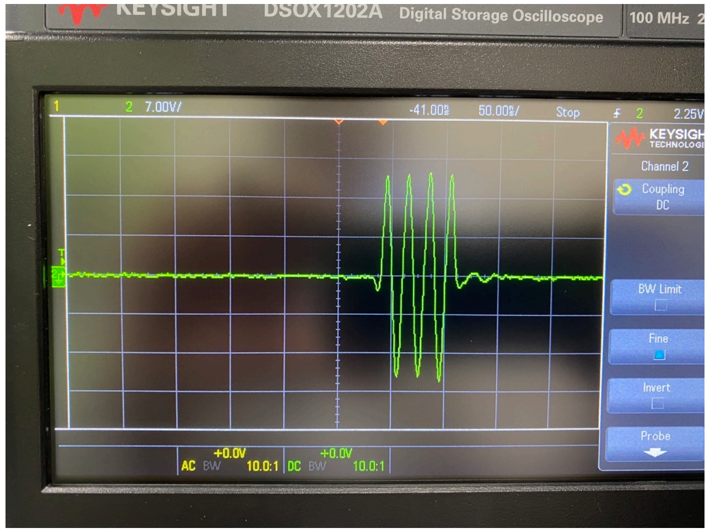


Y. Y. Gao et al. PRX Quantum 2, 040202

AWG (Arbitrary Wave Generator)

Low freq. pulse with finite time width

30-100MHz



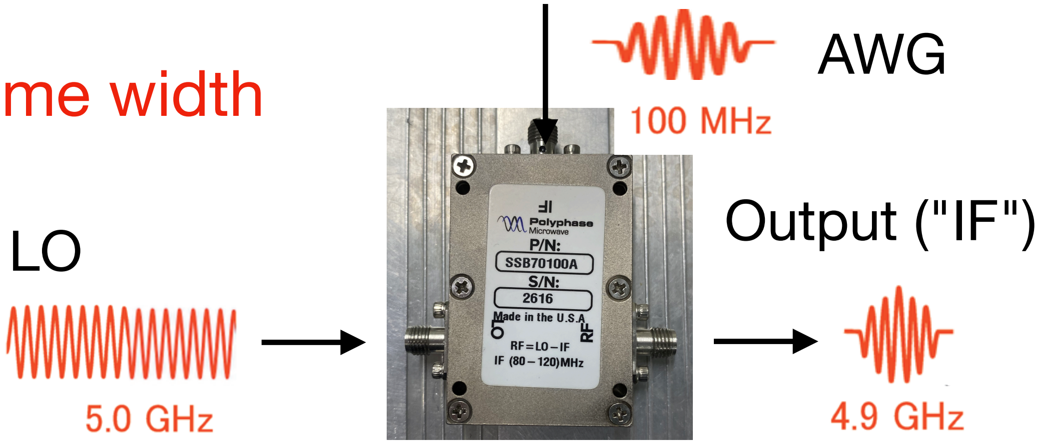
Leading oscillator (LO)

High freq. continuous wave

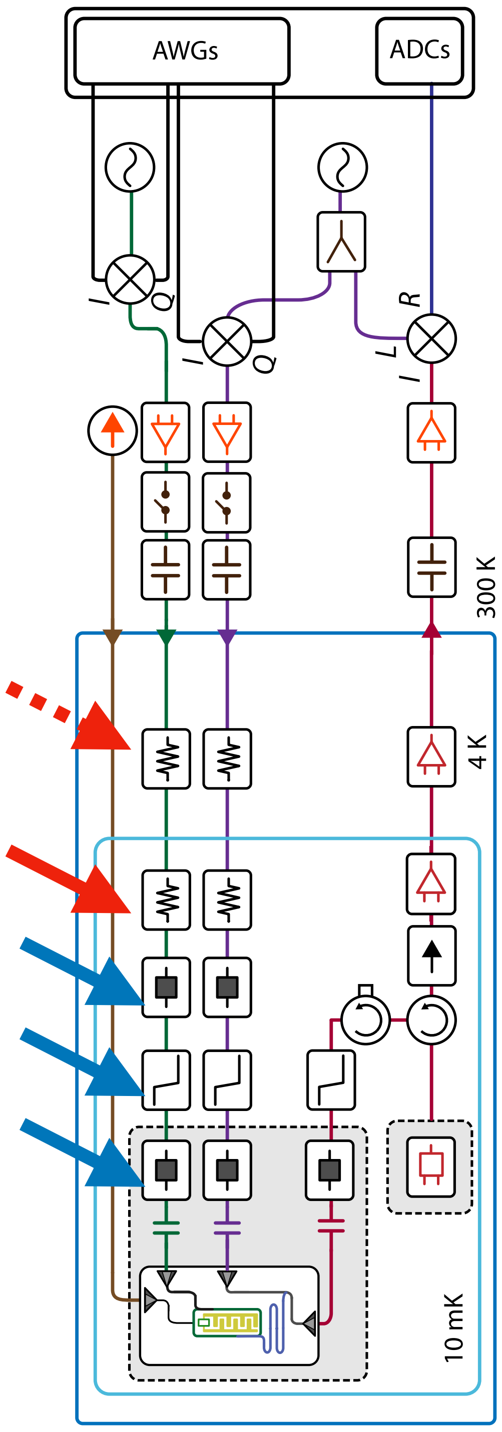
O(1-10GHz)

Mixer

High freq. pulse with finite time width

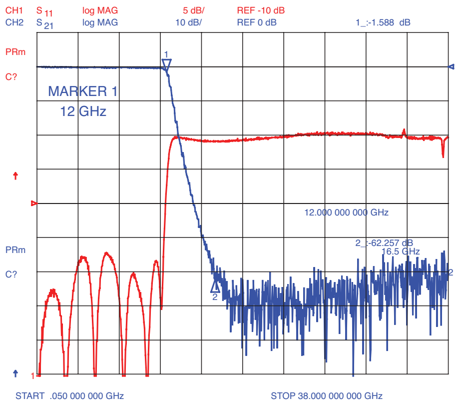


Typical RF chain setup



Y. Y. Gao et al. PRX Quantum 2, 040202

K&L 6L250-12000



Attenuators

Too strong RF: Heats up the 10mK stage

Bad for qubit coherence

→ Dump the power at the higher temp stage

Noise filter

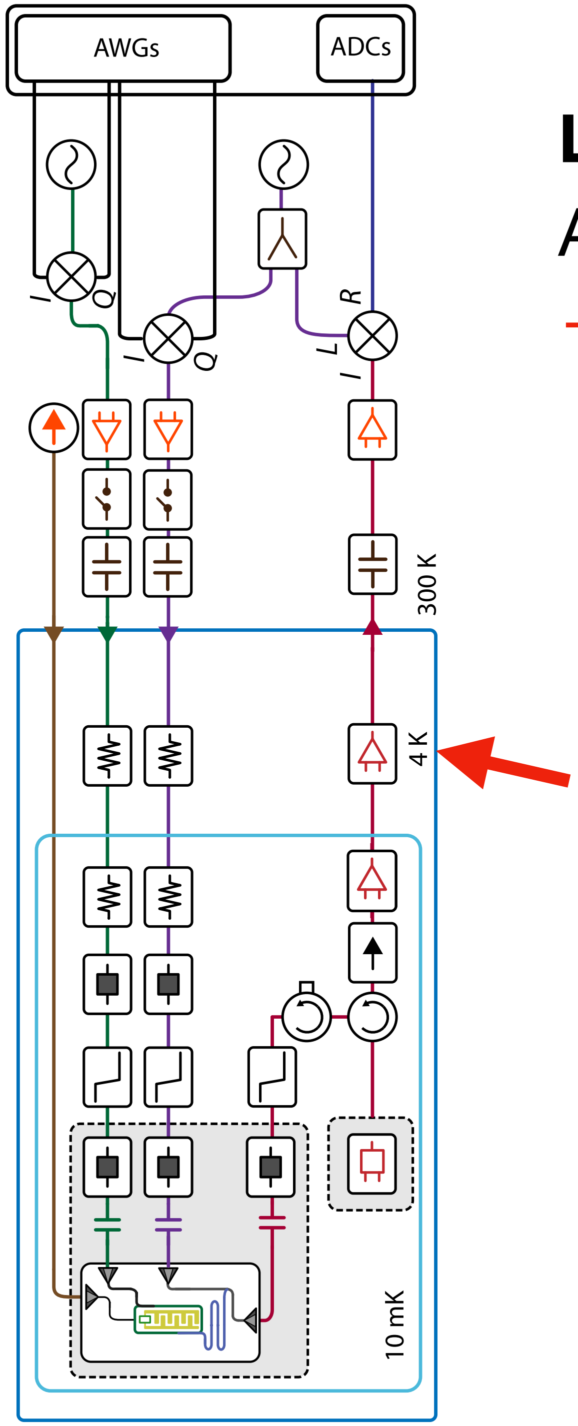
Shutout the stray wave, higher harmonics etc.

Low-pass filter: eliminate >O(10GHz)

Ecosorb filter: eliminate > 1THz

etc.

Typical RF chain setup



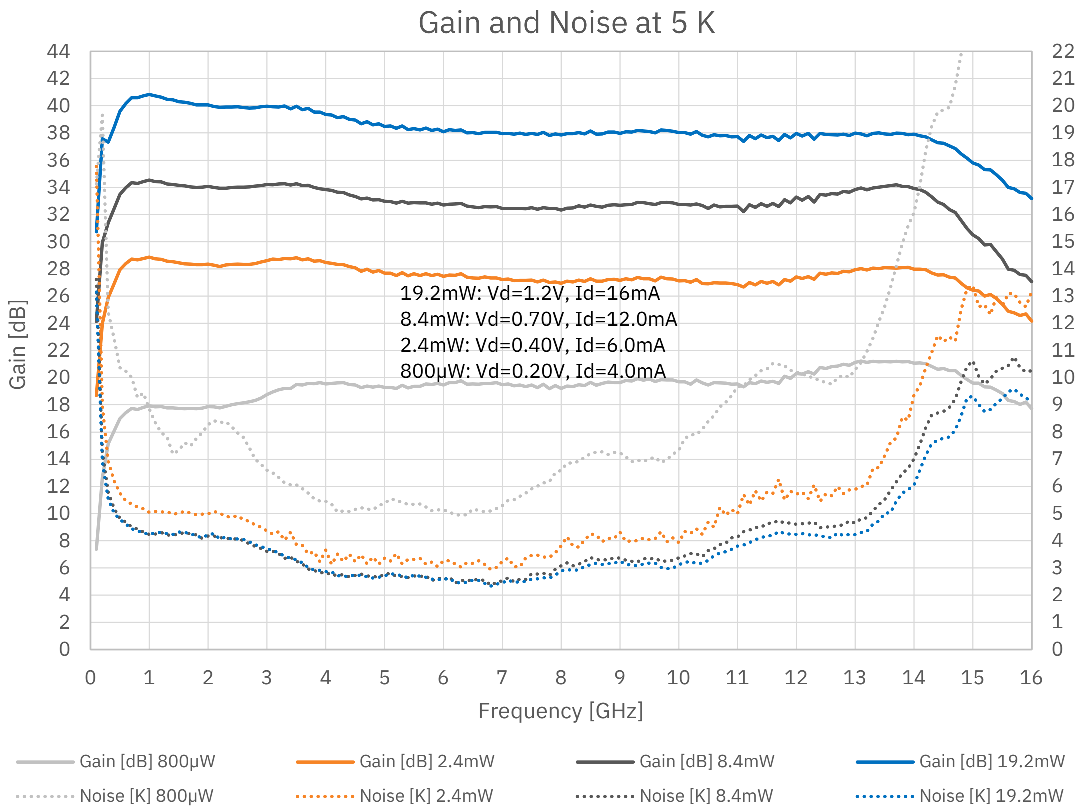
Y. Y. Gao et al. PRX Quantum 2, 040202

Low temperature amplifier @4K

Amp. itself adds noise.

→ First amp. needs to be cool otherwise signal gets buried.

High Electron Mobility Transistor (HEMT)

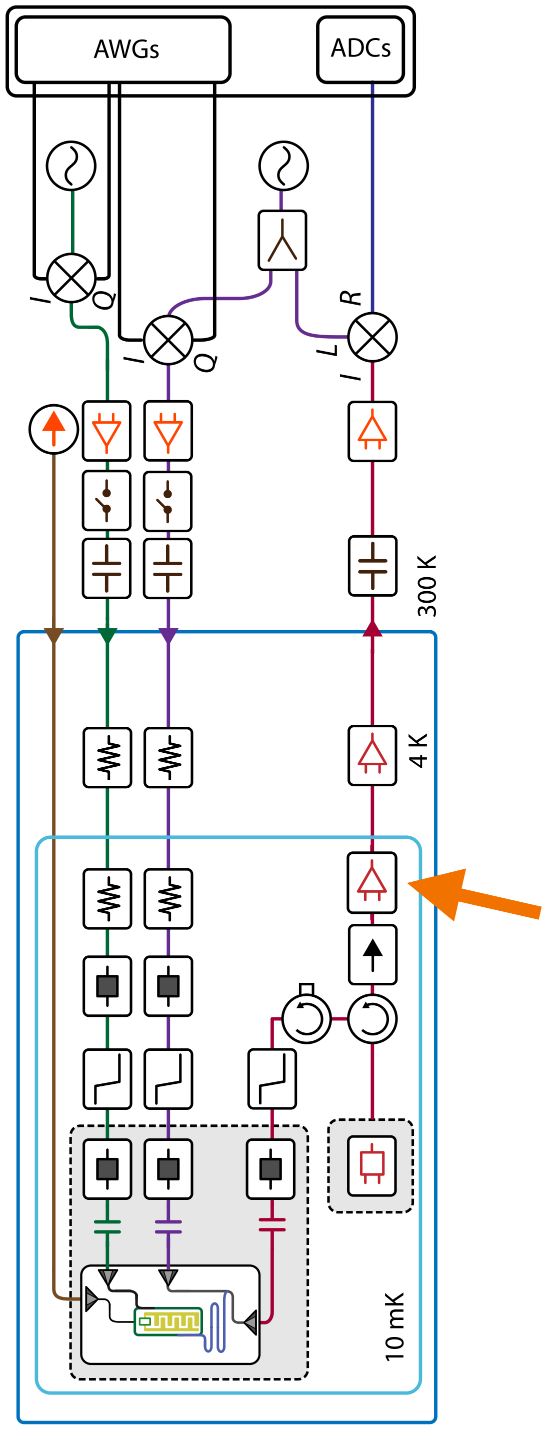


LNF-LNC0.3_14B

Gain: ~30dB

Noise temperature: ~1.5K (equivalent to 1.5K black-body radiation)

Typical RF chain setup



Y. Y. Gao et al. PRX Quantum 2, 040202

Quantum amp. (e.g. JPA/TWPA) @10mK

Can we put the HEMT on the 10mK stage?

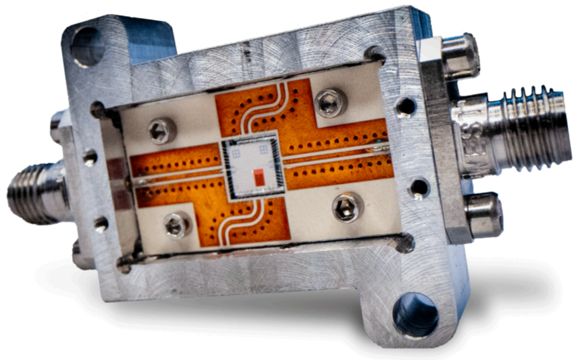
→ No, because of the power dissipation generating heat 😞

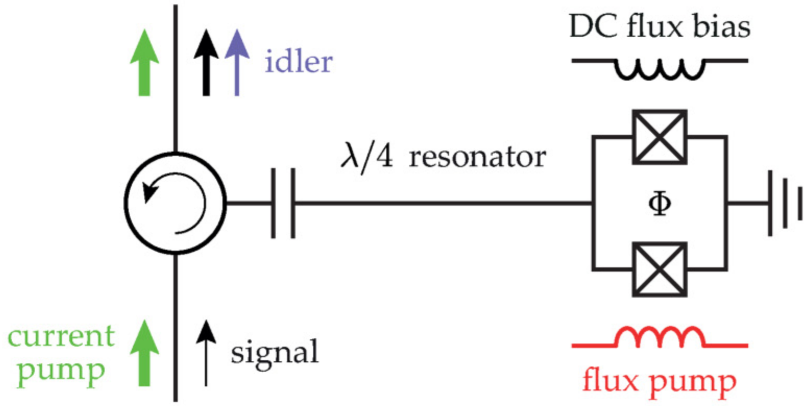
→ **"Passive" amplifier without DC power consumption**

e.g. Josephson Parametric Amplifier (JPA)

Non-linearity of JJ → wave mixing

Quantum Microwave Inc.

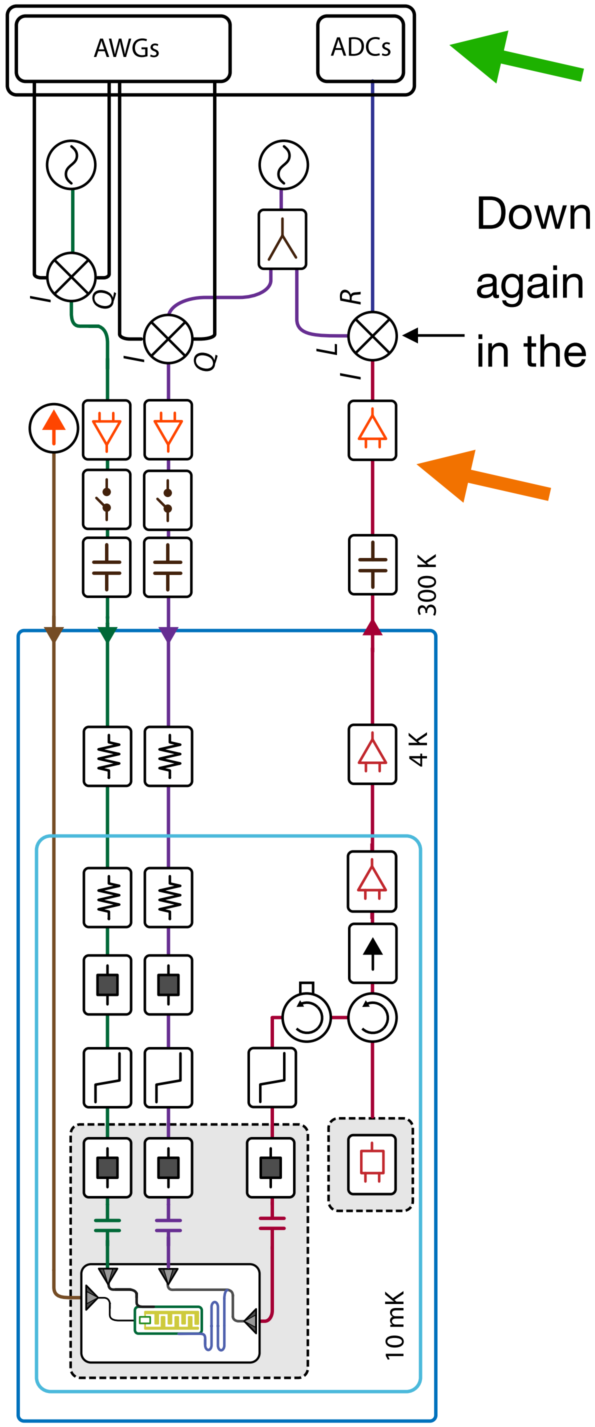




Pump power moves to signal → amplification 😂

Gain: 20dB   Noise temperature: 0.2-0.4K

Typical RF chain setup



Down-convert again to ~100MHz in the mixer

Y. Y. Gao et al. PRX Quantum 2, 040202

Room temperature amp.

Signal is large enough at this point. T_{noise}~300K is now ok.

Digitizer (ADC)

Sample to obtain the outgoing pulse amp/phase.

Gate operation $|g\rangle \rightleftarrows |e\rangle$ ("drive")

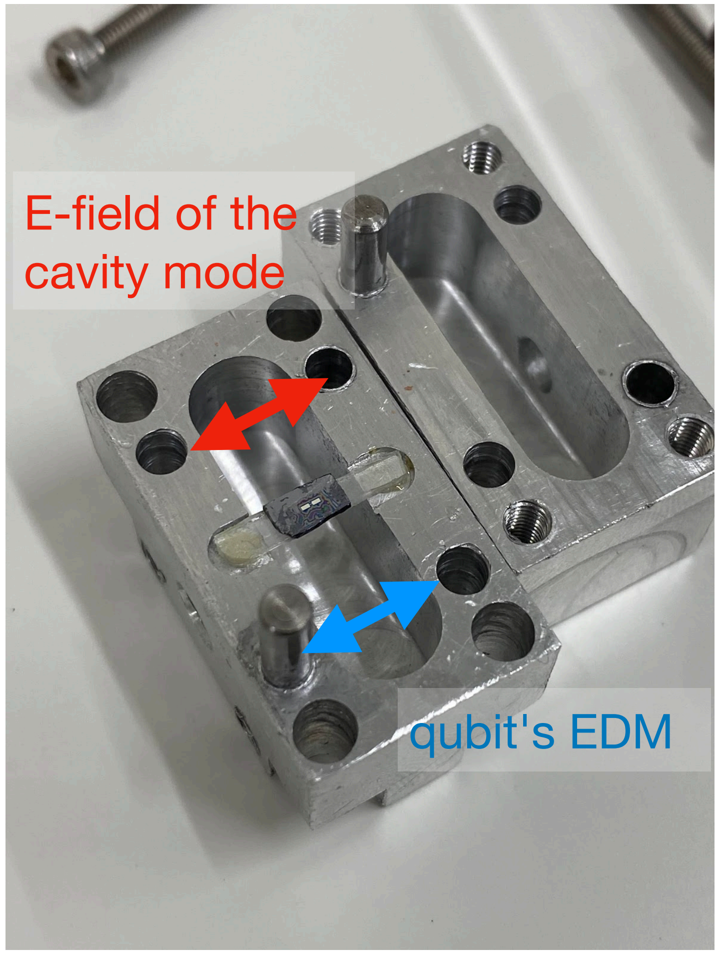
Coupling between cavity E-field & qubit EDM

Jaynes-Cummings Hamiltonian

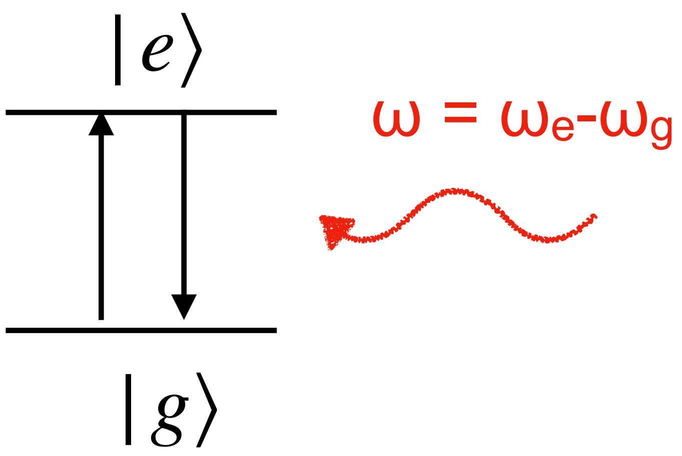
$$\mathcal{H}_{\rm JC} = \underbrace{\frac{\hbar\omega_q}{2}\sigma_z}_{\text{free qubit H}} + \underbrace{\hbar\omega_c a^\dagger a}_{\text{free photon H}} + \underbrace{\hbar g(\sigma_+ a + a^\dagger \sigma_-)}_{\text{qubit-photon interaction}}.$$

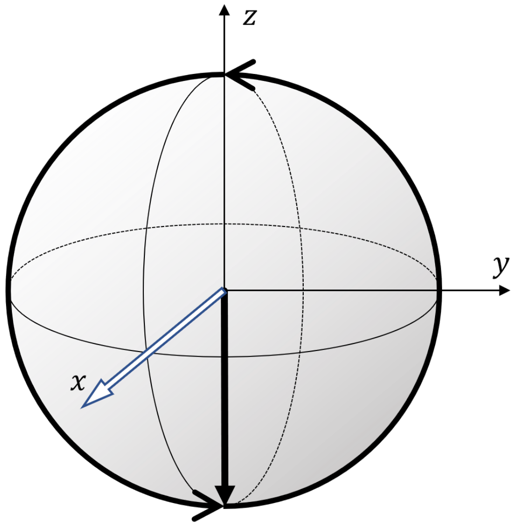
Coupling const. ~ $\boldsymbol{\mu} \cdot \boldsymbol{E}$

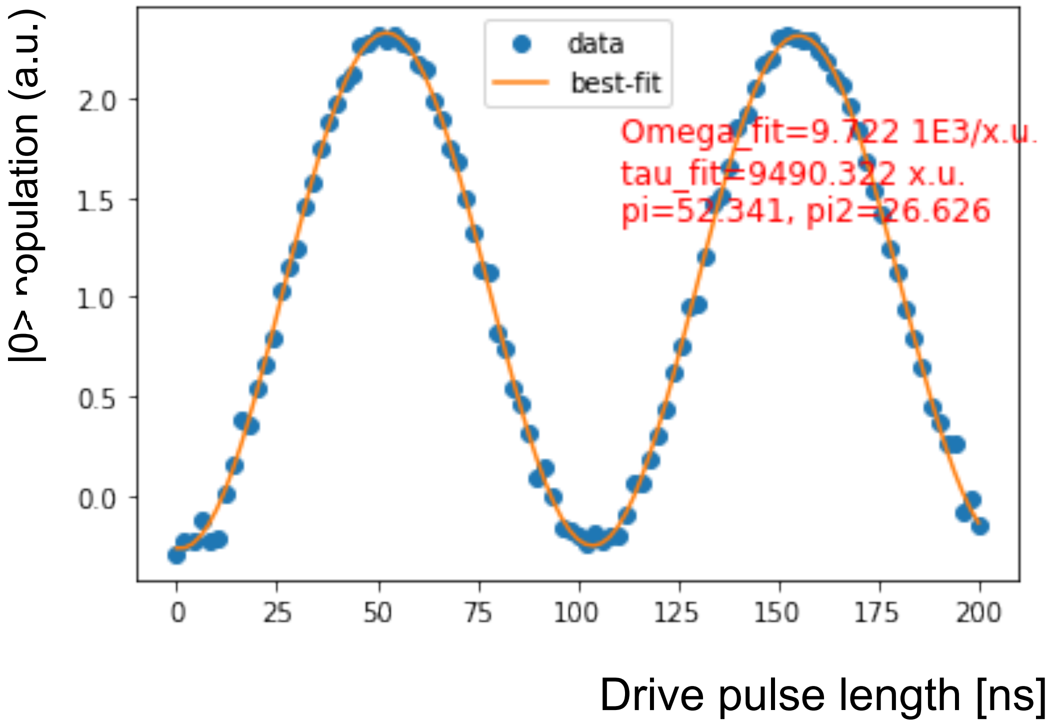
μ: qubit EDM **×O(10^6) stronger than a single atom**



Resonant microwave pulse → Rabi oscillation







Two bit gate operation: "Cross resonance"

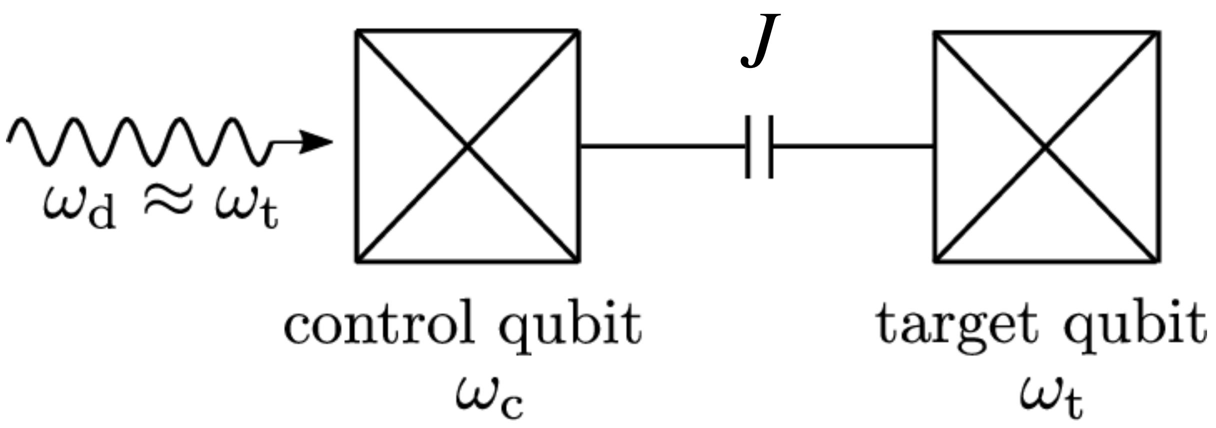
Send the control bit a resonant drive to the target bit

Doesn't drive the control bit

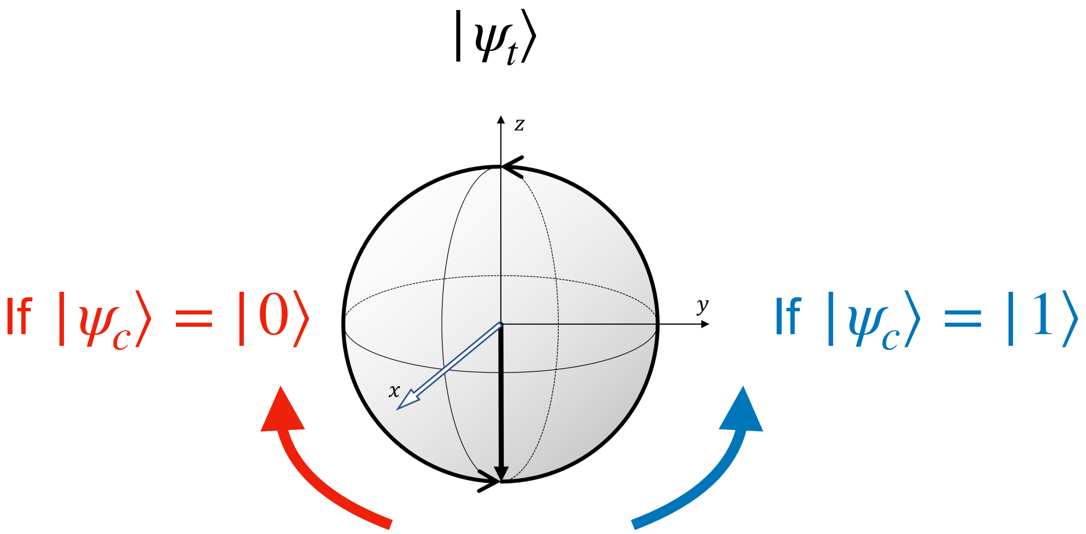
- Since it's off-resonant

Target qubit gets drive

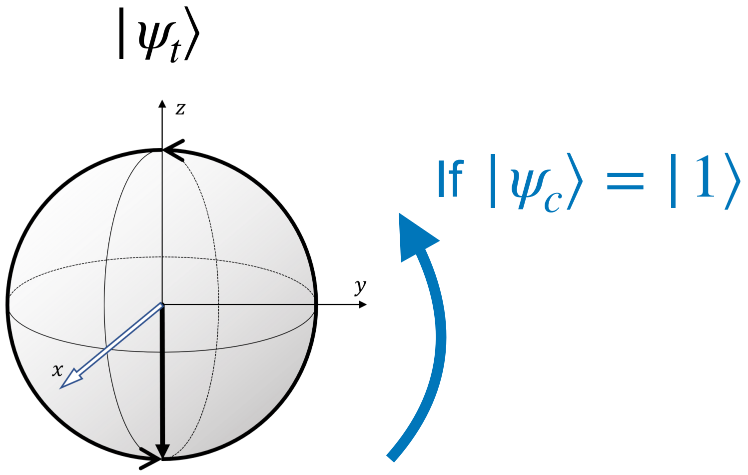
- Through the J coupling
- The polarity of the drive depends on control bit's state



$$H_{int} = JZ_1Z_2$$



Adding a Hadamard gate to the target bit



CNOT gate

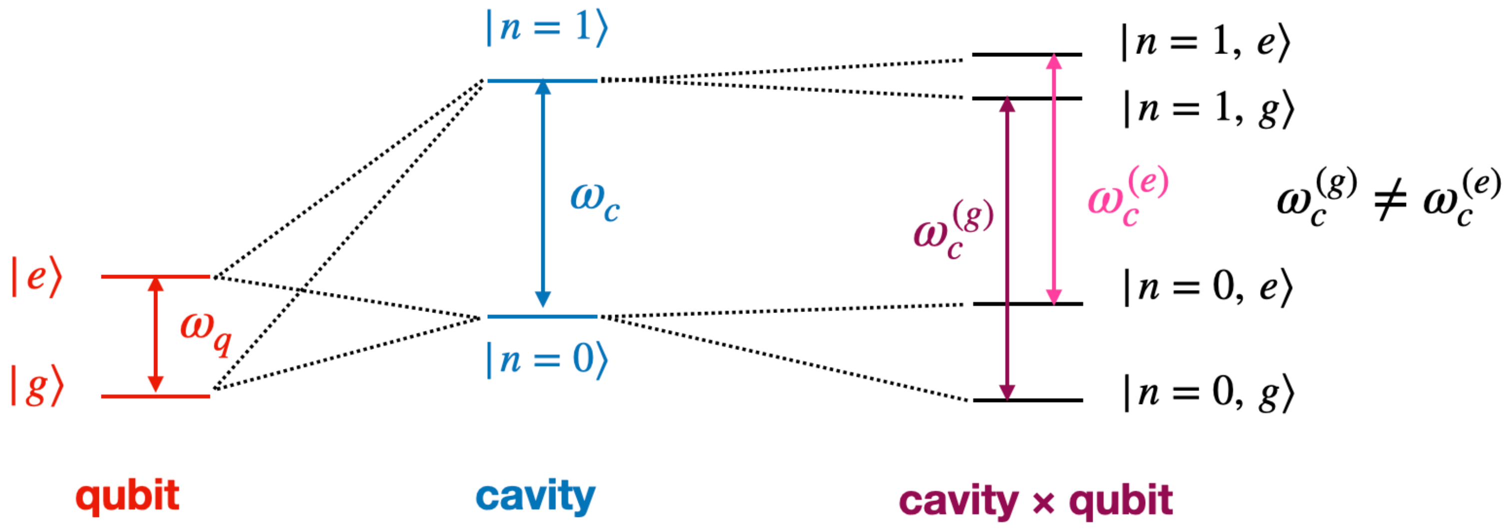
Readout through the cavity

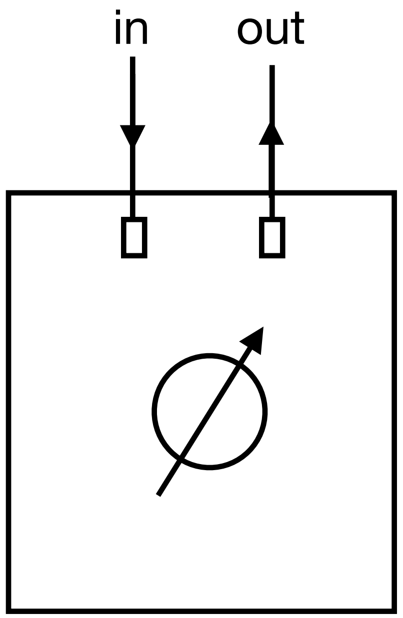
Cavity frequency varies according to the qubit state (vice versa)

State mixing

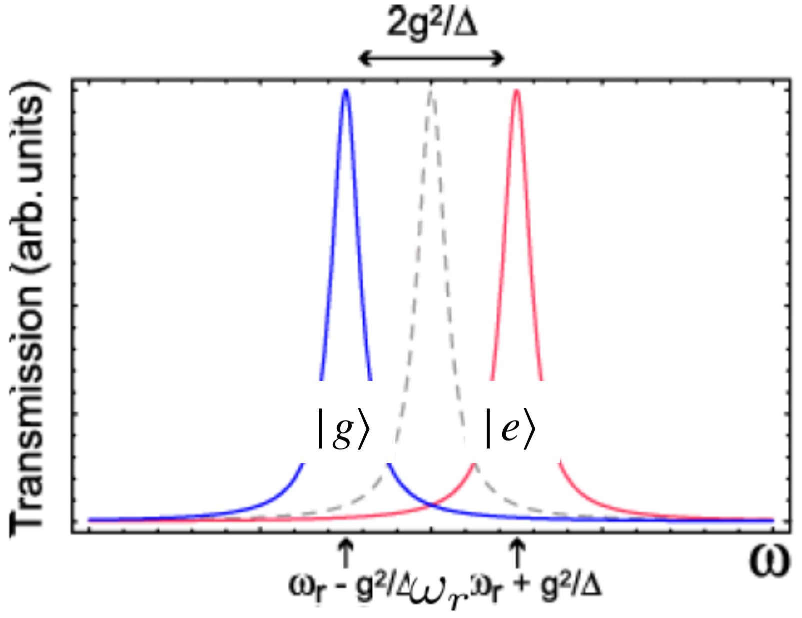
$$\mathcal{H}_{\mathrm{JC}} = \frac{\hbar\omega_q}{2}\sigma_z + \hbar\omega_c a^\dagger a + \hbar g(\sigma_+ a + a^\dagger \sigma_-).$$

$$\mathcal{H}_{\mathrm{JC}}^{(n)} = \begin{pmatrix} -\frac{\hbar\omega_q}{2} + \hbar\omega_c n & \hbar g\sqrt{n} \\ \hbar g\sqrt{n} & \frac{\hbar\omega_q}{2} + \hbar\omega_c(n-1) \end{pmatrix}$$



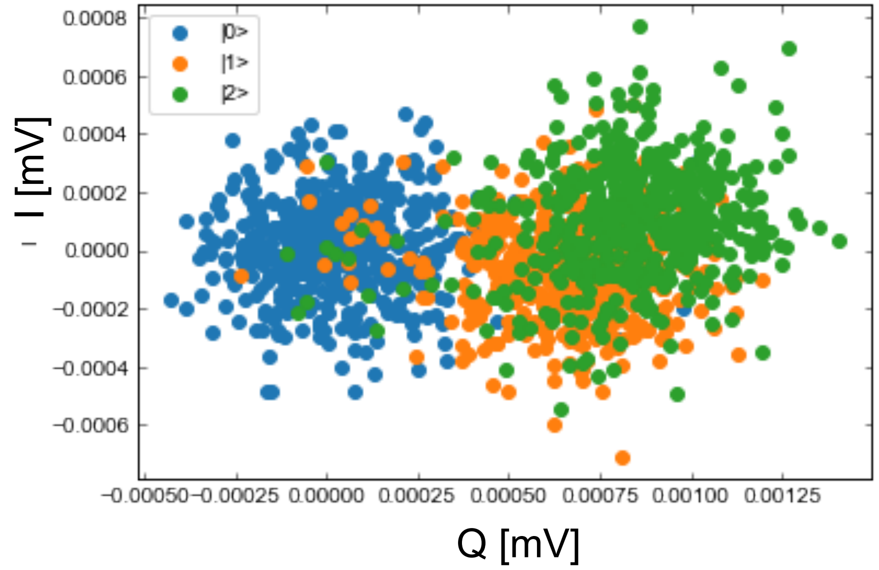


Transmission of the cavity



Phase of the transmitted pulse (in I/Q plane rep.)

$$A\sin(\omega t + \phi) = I\sin(\omega t) + Q\cos(\omega t)$$



Decoherence - modes and sources

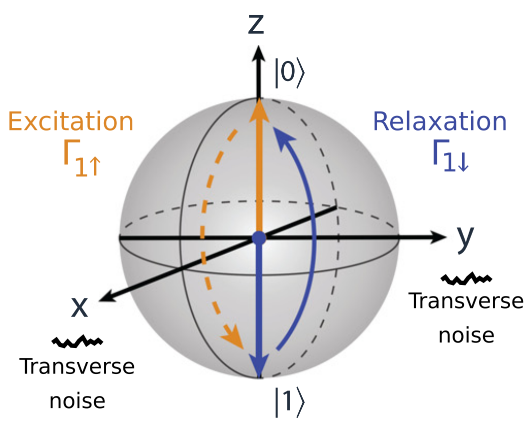
Longitudinal relaxation (T_1): |e>→|g> de-excitation

- Spontaneous emission
- Cooper pair breaking (cosmic rays?)
- Coupling to high-loss two-level systems (TLSs) in the material

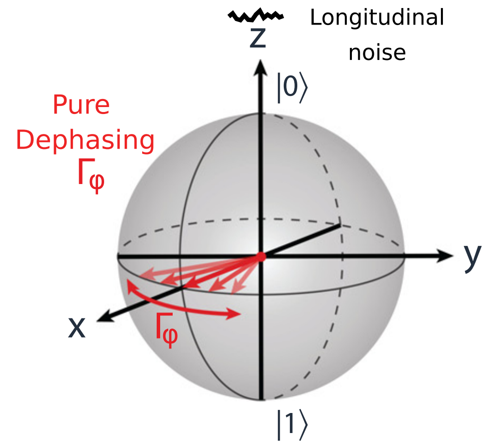
Transverse relaxation (T_2^*): randomization of the |e>/|g> coeff.

- Charge/flux noises
- Residual thermal photons in the cavity etc.

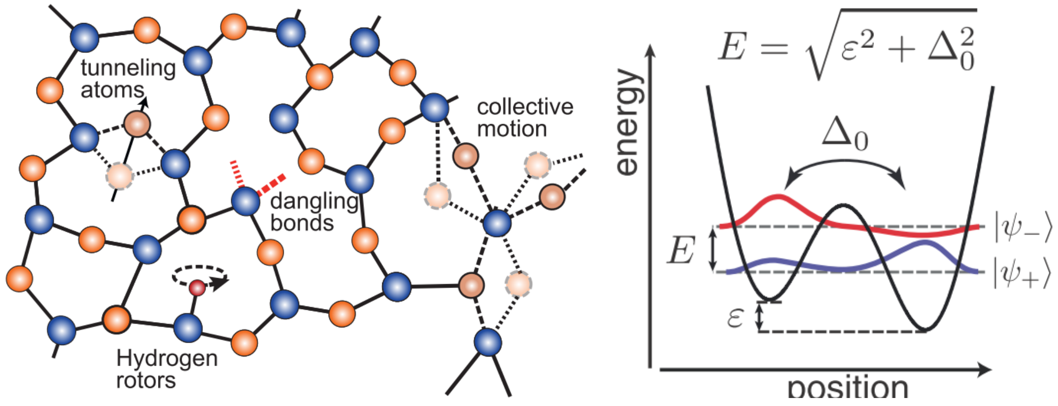
(b) Longitudinal relaxation



(c) Pure dephasing

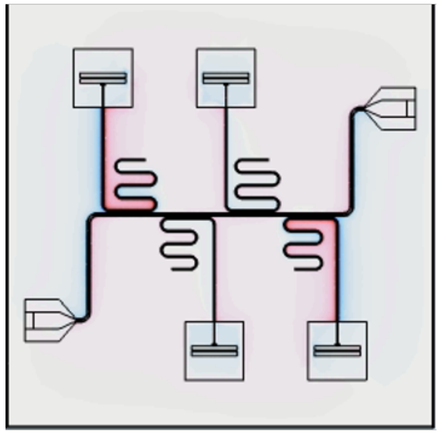


Müller et al. (2019)



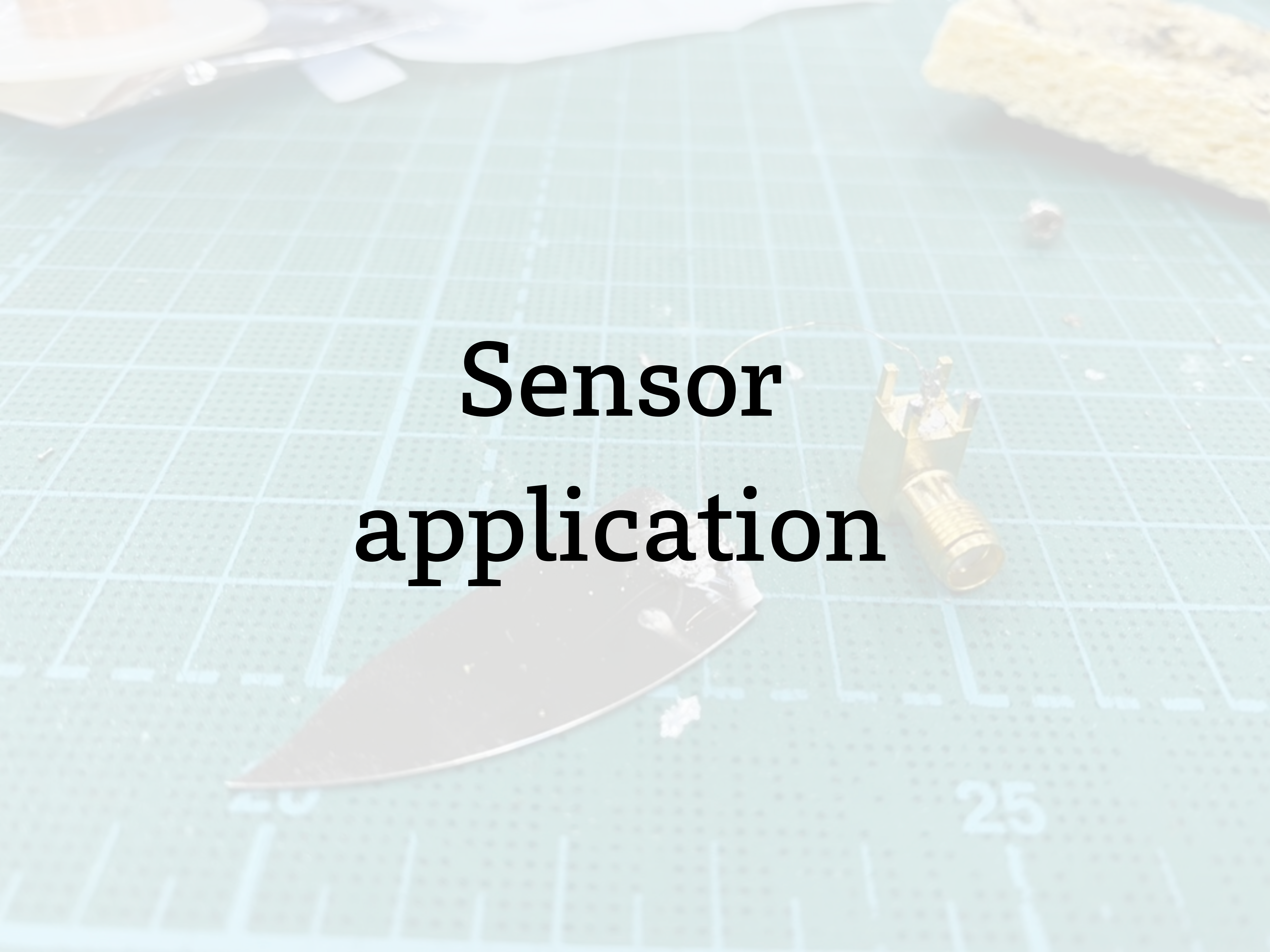
TLSs form in the amorphous

Metalic shield to suppress the spontaneous emission (2D impl.)



Intra-chip mode (2D impl.)

Sensor application

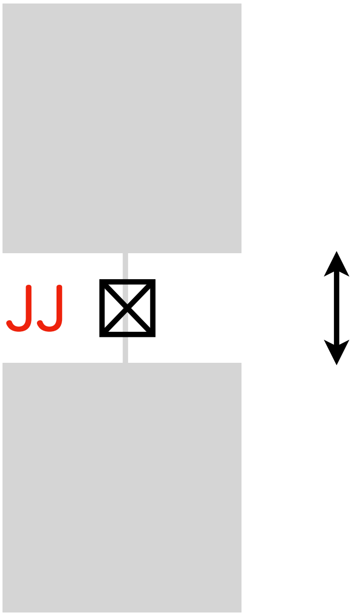


Why qubits are good sensors

- ○ Low (μeV) & variable energy threshold
- ○ Access to phase information (analog & interference)
- ○ Yet acceptably low noise level

Superconducting qubits:

- ○ Strong coupling to photon: **10^6 stronger than single atom**



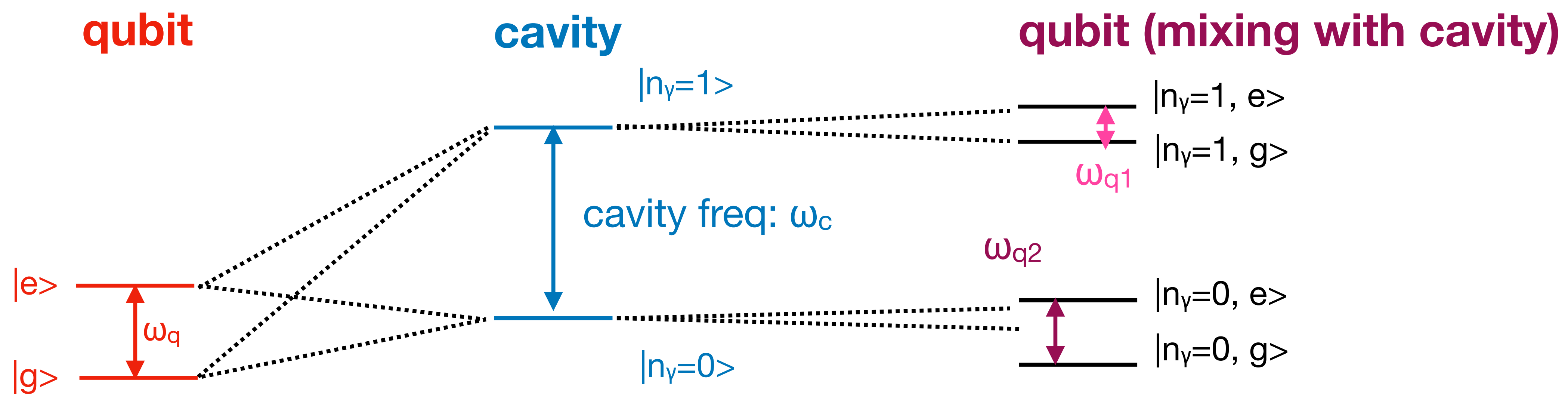
EDM: $\mu \sim Qd$

d = O(0.1mm)

macroscopic

Single photon counting using superconducting qubits

Photons in the cavity → qubit frequency changes ("ac Stark shift")



qubit

cavity

qubit (mixing with cavity)

$|e>$

$|g>$

ω_q

$|n_\gamma=1>$

cavity freq: ω_c

$|n_\gamma=0>$

$|n_\gamma=1, e>$

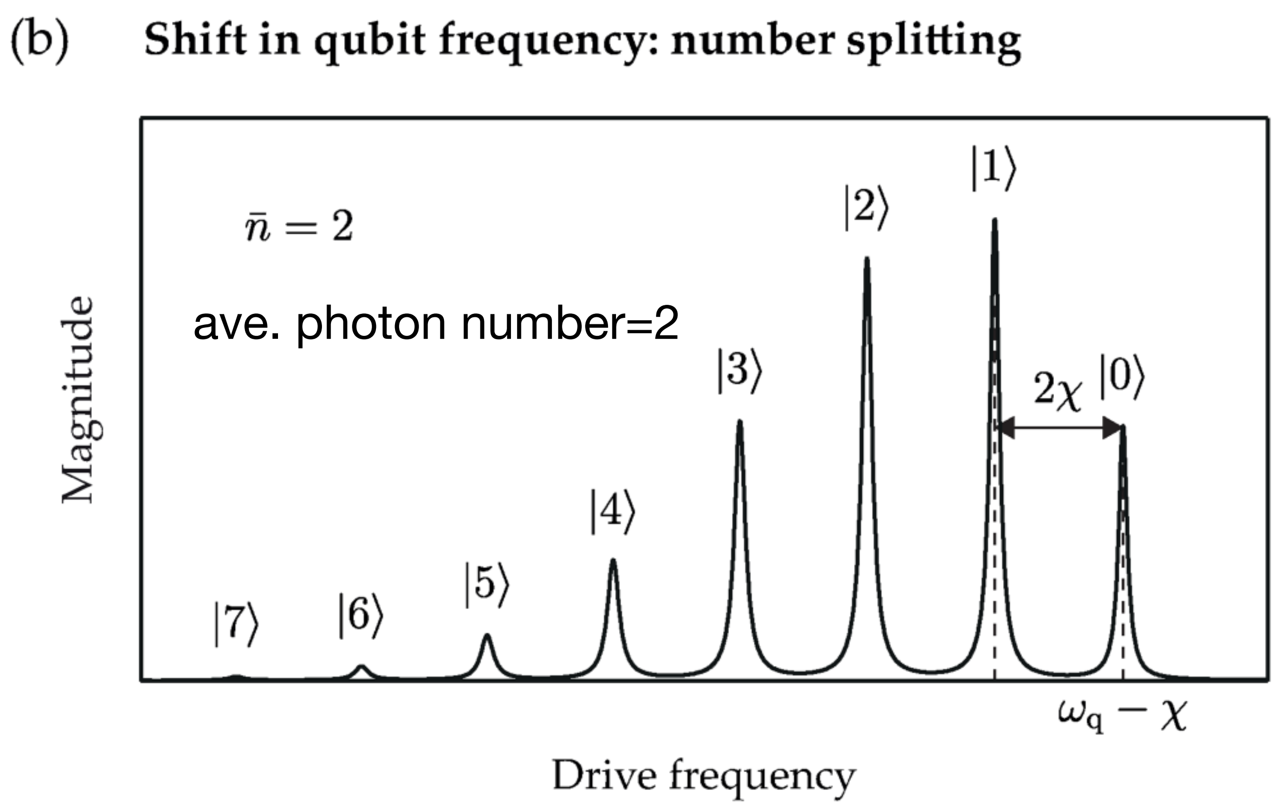
$|n_\gamma=1, g>$

ω_{q1}

ω_{q2}

$|n_\gamma=0, e>$

$|n_\gamma=0, g>$



Detuning can be detected

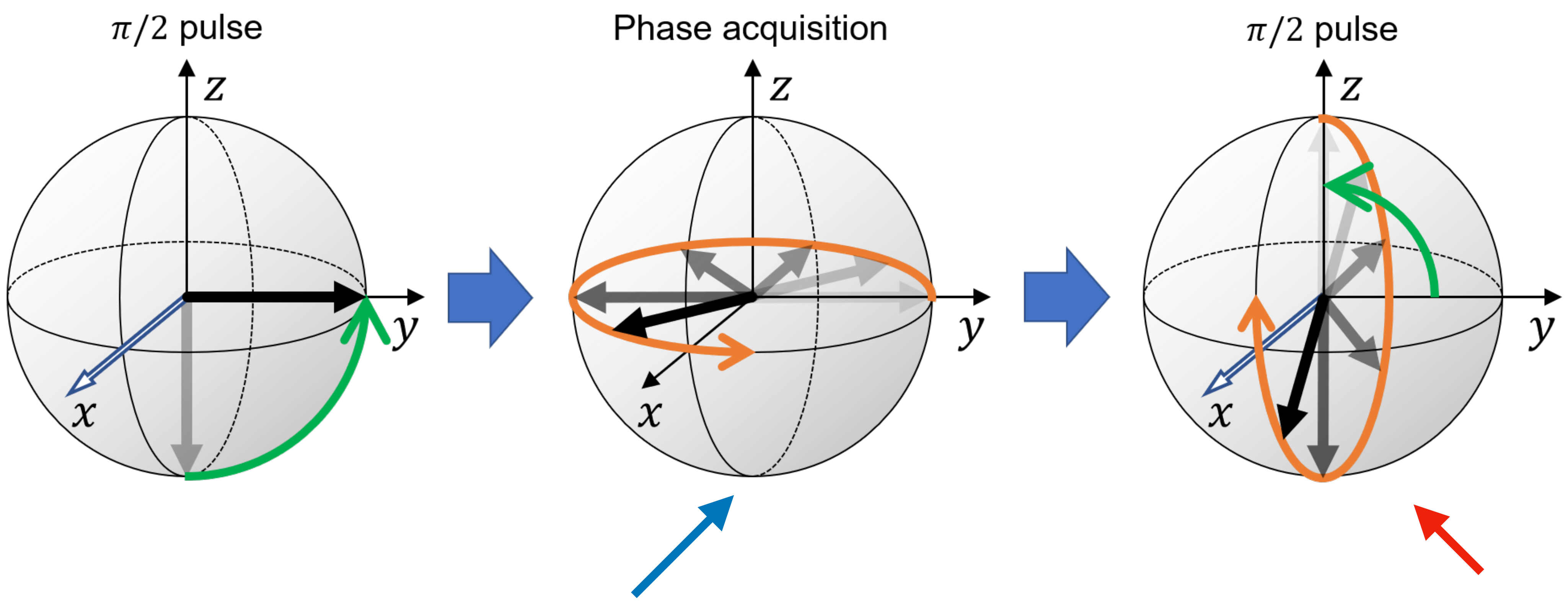
by the Ramsey spectroscopy

Ramsey spectroscopy for ac Stark shift detection

90° flip

Wait

Another 90° flip
around the same axis



Transverse rotation during the wait is projected to z-position

○ Stay unrotated if nothing special happens

○ **Rotate transversely if there is something e.g.**

- Shift/drift of qubit freq.
- Imperfect π/2 flip in the previous step
- Phase drift due to noise

etc.

e.g. no rotation →|e>

90° rotation → (|g>+|e>)/√2

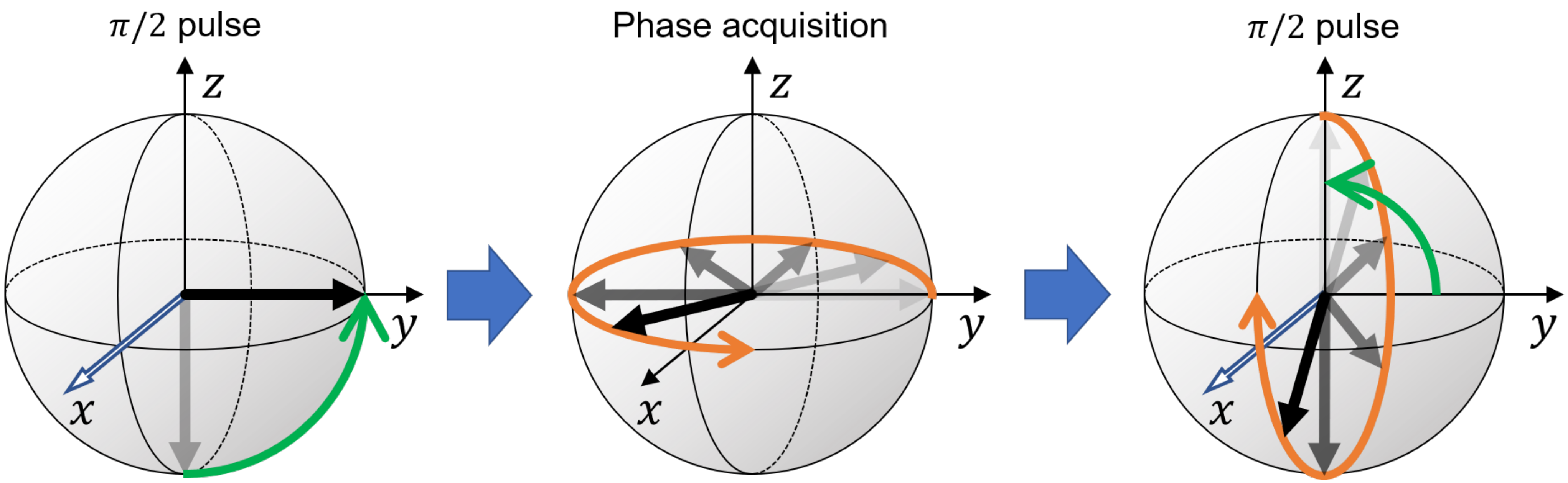
180° rotation → |g>

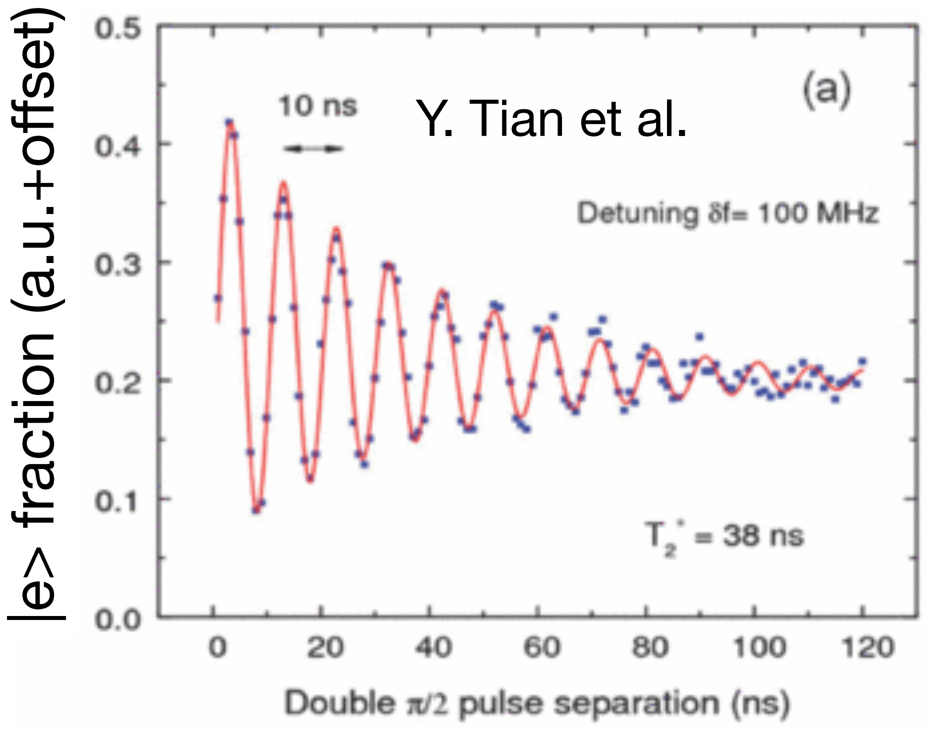
Ramsey spectroscopy for ac Stark shift detection

90° flip

Wait

Another 90° flip
around the same axis





← Drive pulse off-resonance (detune): 100MHz

f (Transverse rotation during the hold) = f (detune)

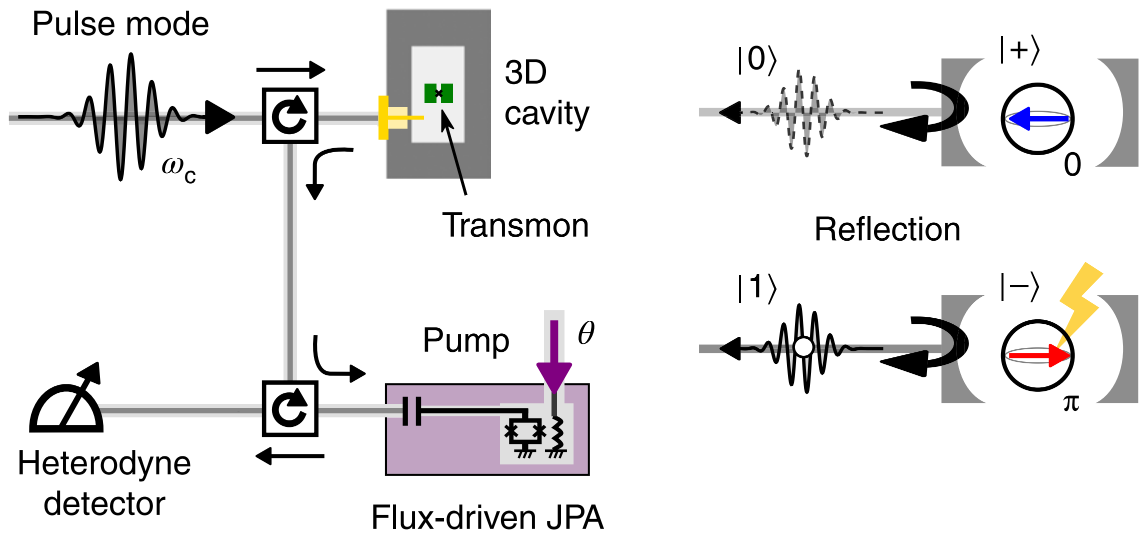
Obs. of the "Ramsey fringe"

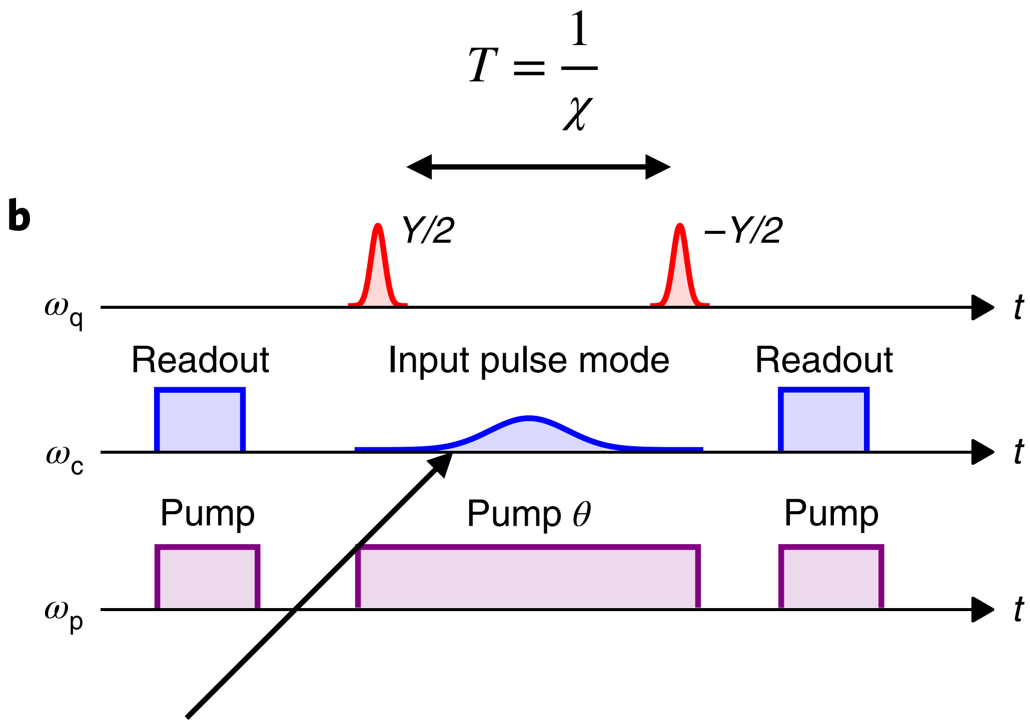
→ Project to number state

→ Δn=0

Itinerant photon counting

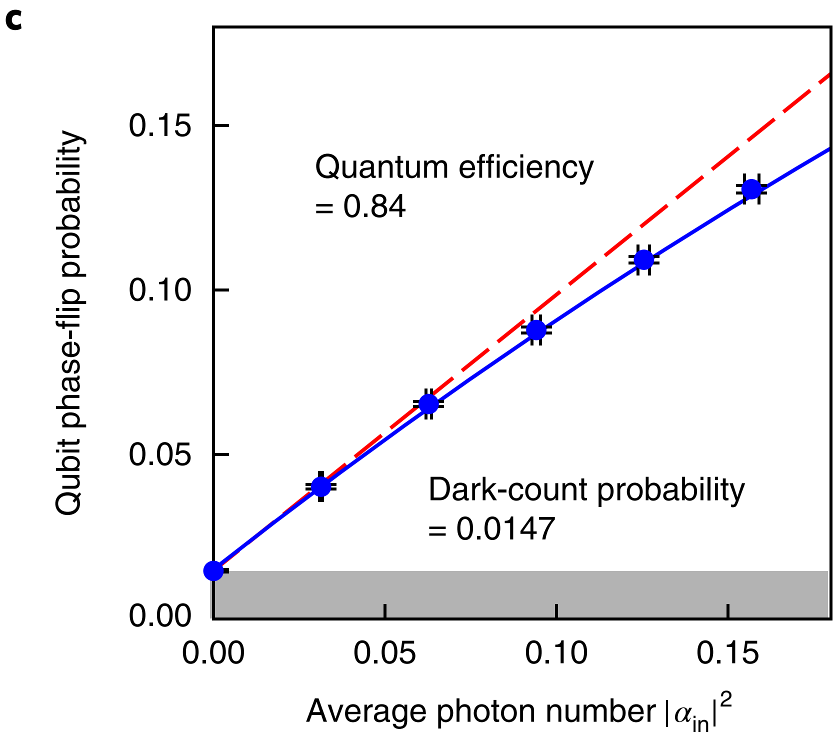
Kono et al. (2018)





Photon comes during the hold period of Ramsey

- ac Strak shift caused by the RF pulse (~500ns)
- 50-85% efficient



HEP application: Wave-like DM search

DM converted to photon

Axion: by B-field

Dark photon: by it own

Cavity haloscope experiment

Accumulate photons from DM resonant to the cavity freq.

Many photons = EM mode

→ voltage picked up by the antenna

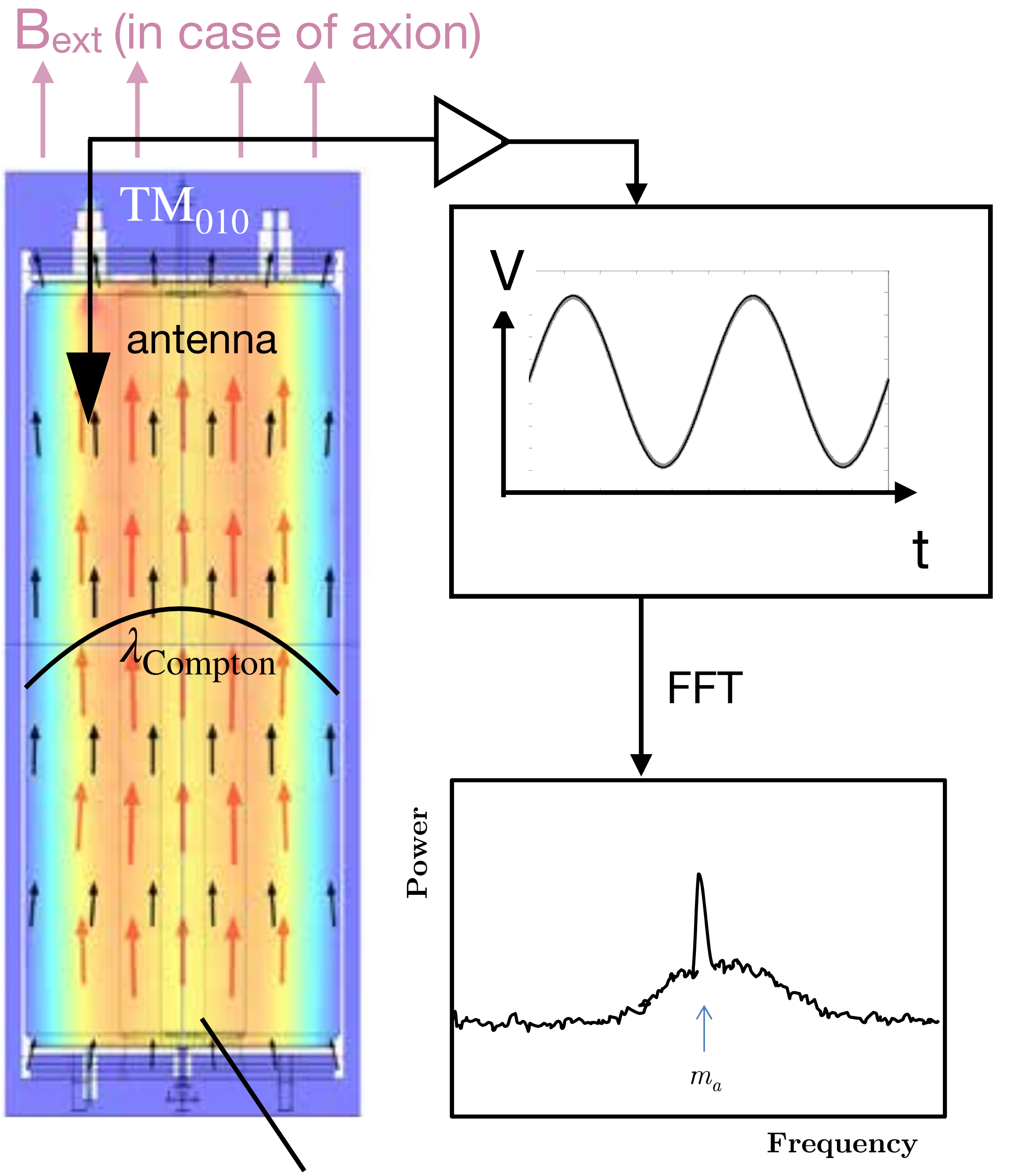
$$P_{\text{axion}} = 1.9\times10^{-22}\,\mathrm{W}\left(\frac{V}{1361}\right)\left(\frac{B}{6.8\,\mathrm{T}}\right)^2\left(\frac{C}{0.4}\right)\left(\frac{g_\gamma}{0.97}\right)^2 \times\left(\frac{\rho_a}{0.45\,\mathrm{GeV\,cm^{-3}}}\right)\left(\frac{f}{650\,\mathrm{MHz}}\right)\left(\frac{Q}{50\,000}\right)$$

Standard Quantum Limit (SQL)

$\Delta n \cdot \Delta\phi \geq \hbar$ (n/ϕ: photon number/phase)

○ Seen as n＝Δn even if n=0 in the cavity due to the measurement back-action.

○ Dominant noise source at >5GHz

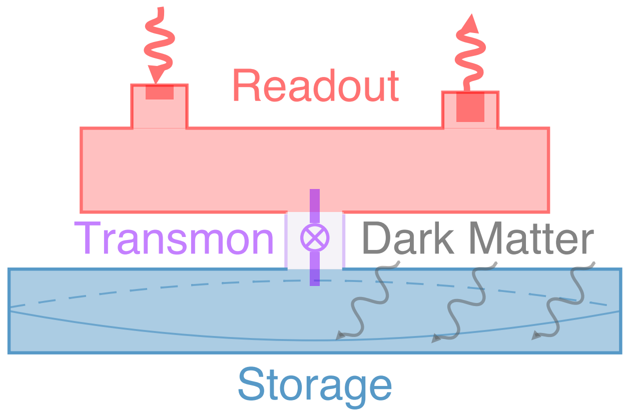


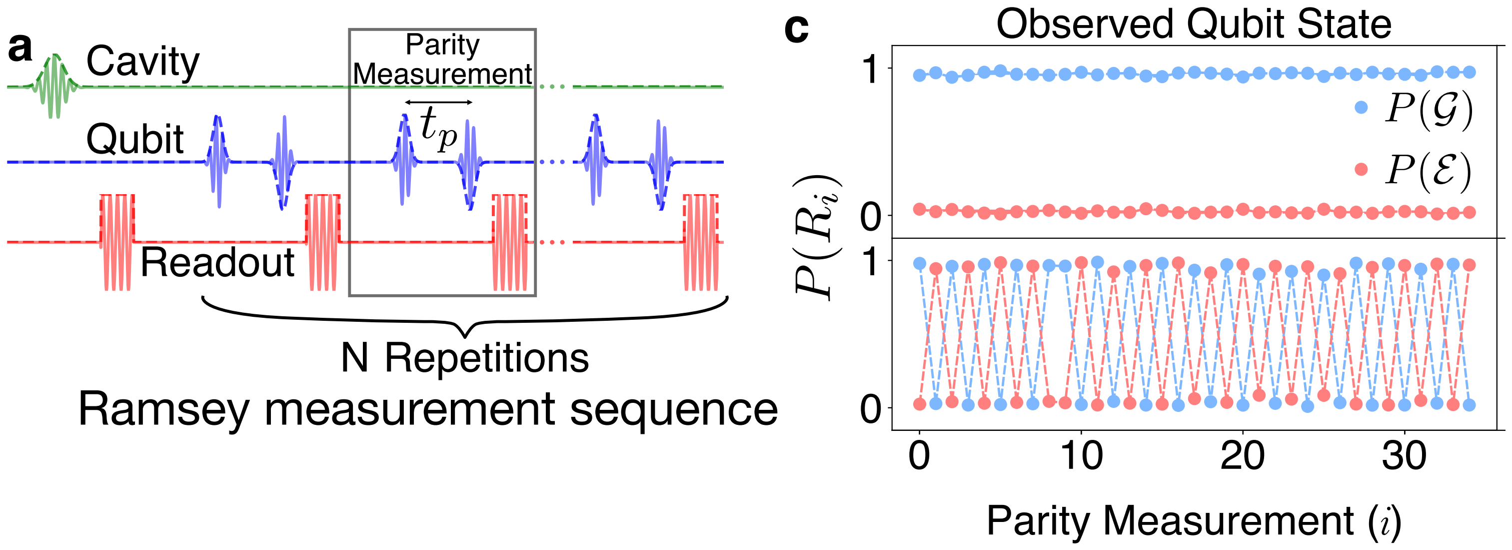
E-field of the lowest resonant mode (TM_{010})

Single photon counting → Evade the SQL

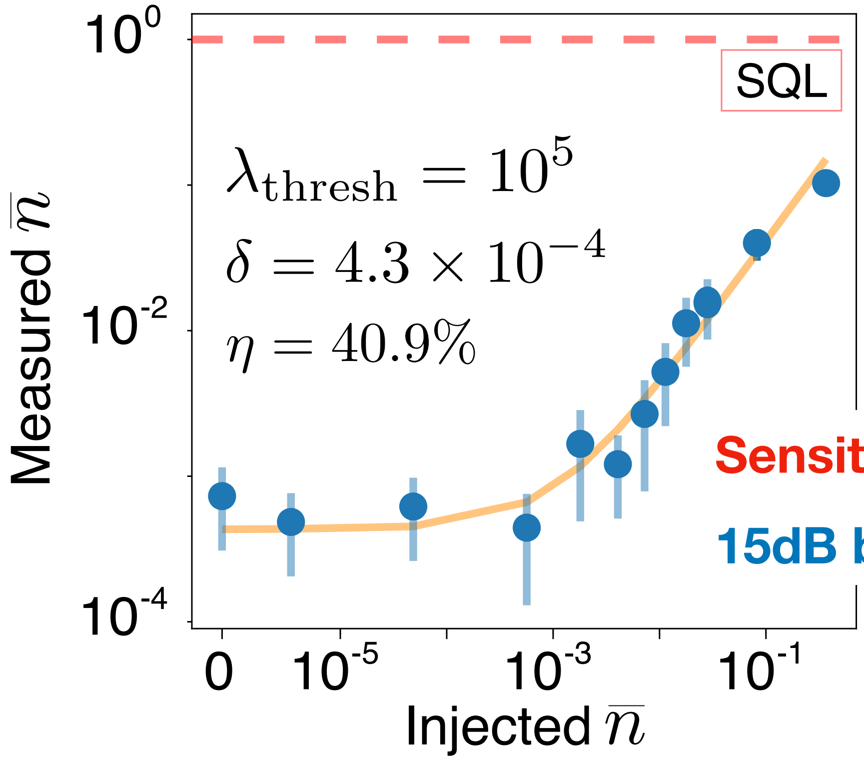
A. Dixit et al. (2021)

Readout from another cavity on the back



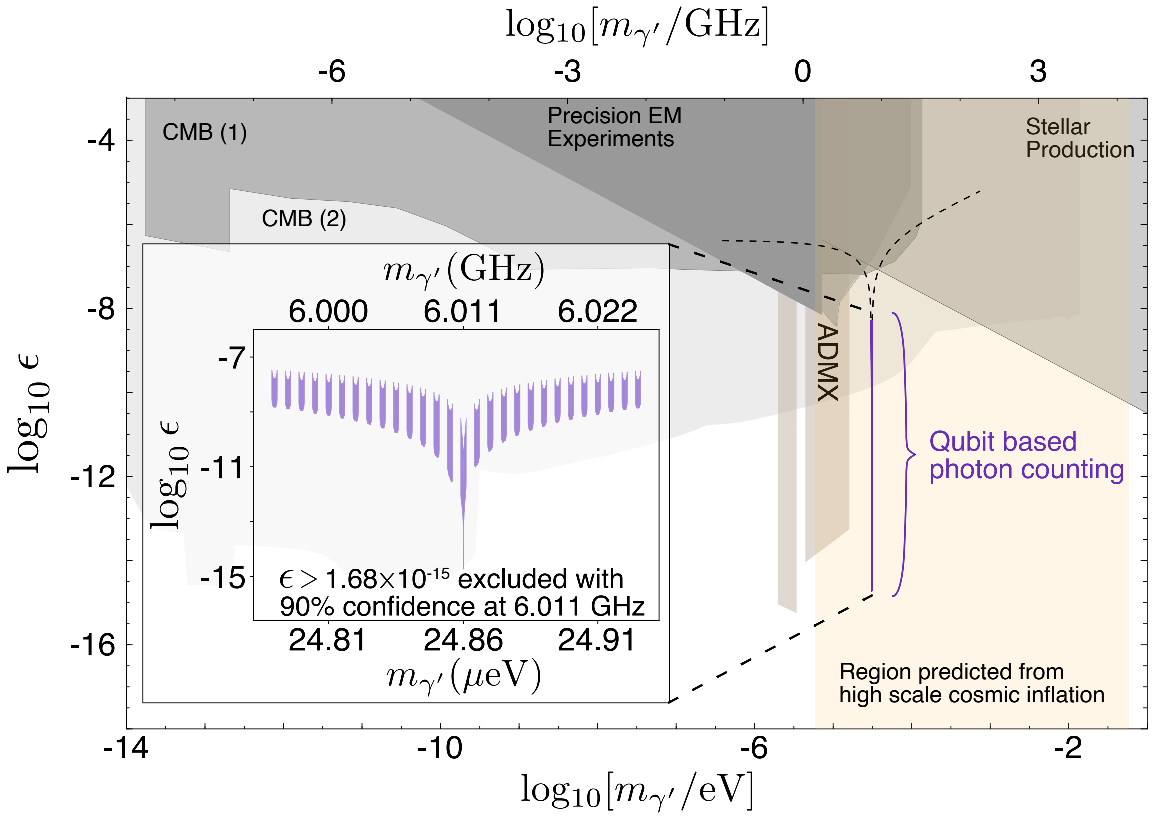


Accumulate photons in the storage cavity



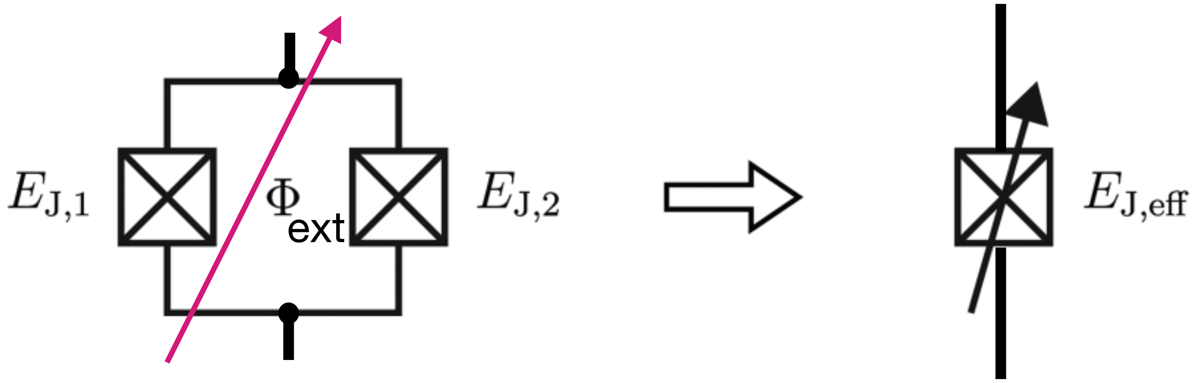
Sensitivity: <n>~10^{-3}

15dB below the SQL

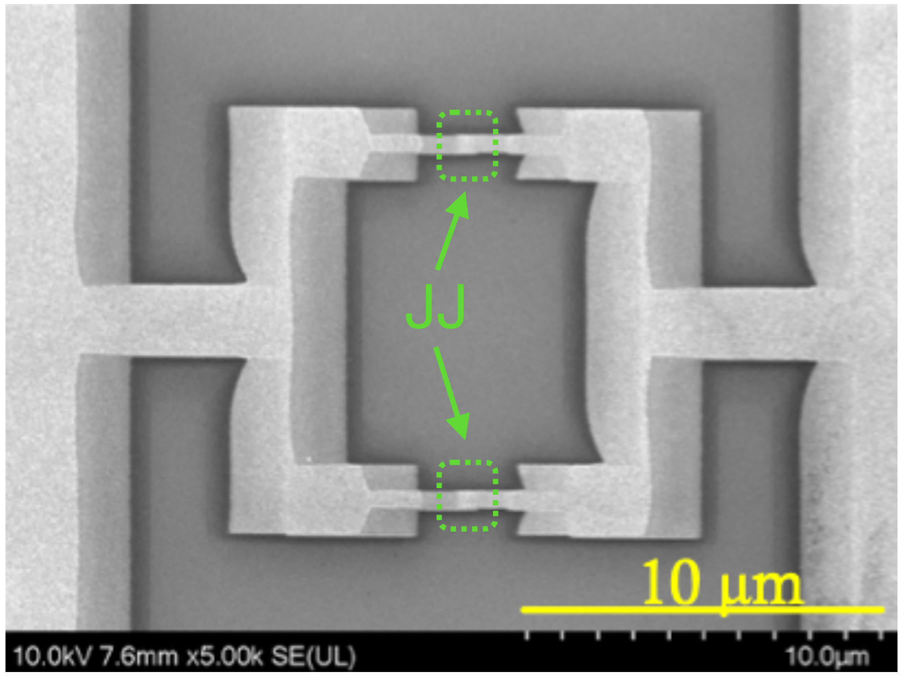


JJ×2 = SQUID → Freq. tunable qubit

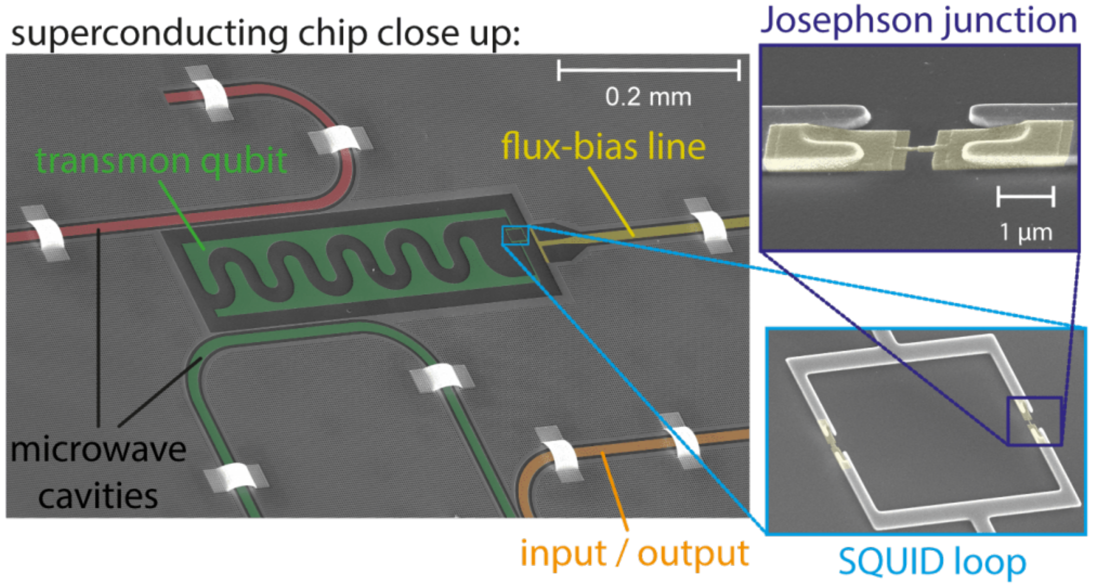
Flux bias → E_J variation → Qubit frequency variation



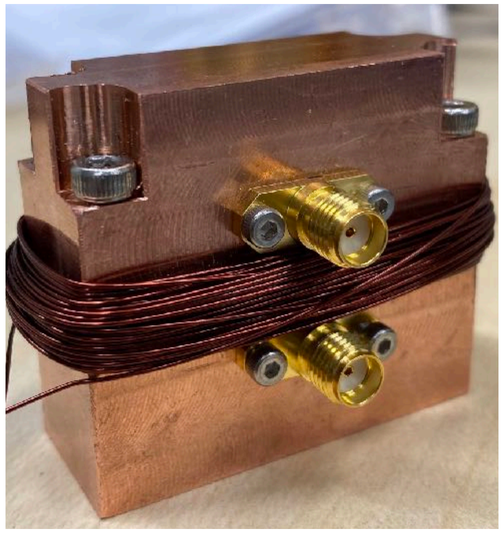
$$E_{\mathrm{J,eff}}(\varphi_{\mathrm{ext}}) = \sqrt{E_{\mathrm{J},1}^2 + E_{\mathrm{J},2}^2 + 2E_{\mathrm{J},1}E_{\mathrm{J},2}\cos\varphi_{\mathrm{ext}}},$$



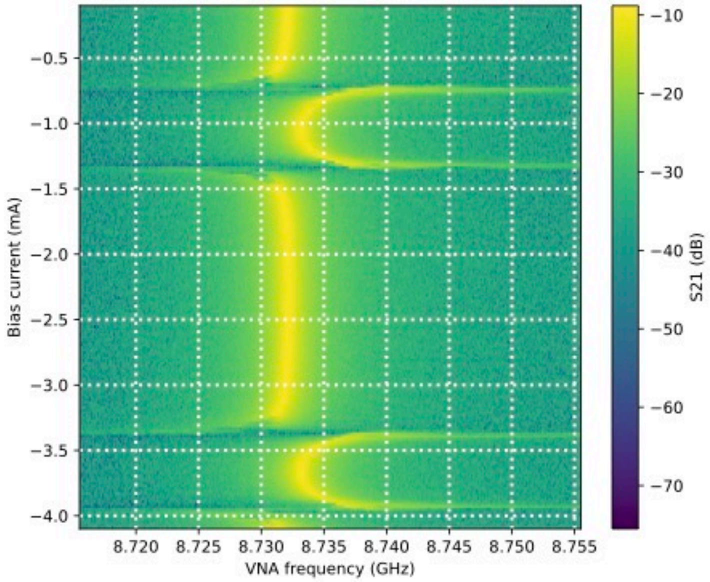
2D: DC current→flux



3D: Coil



Can also tune the cavity coupled to the qubit



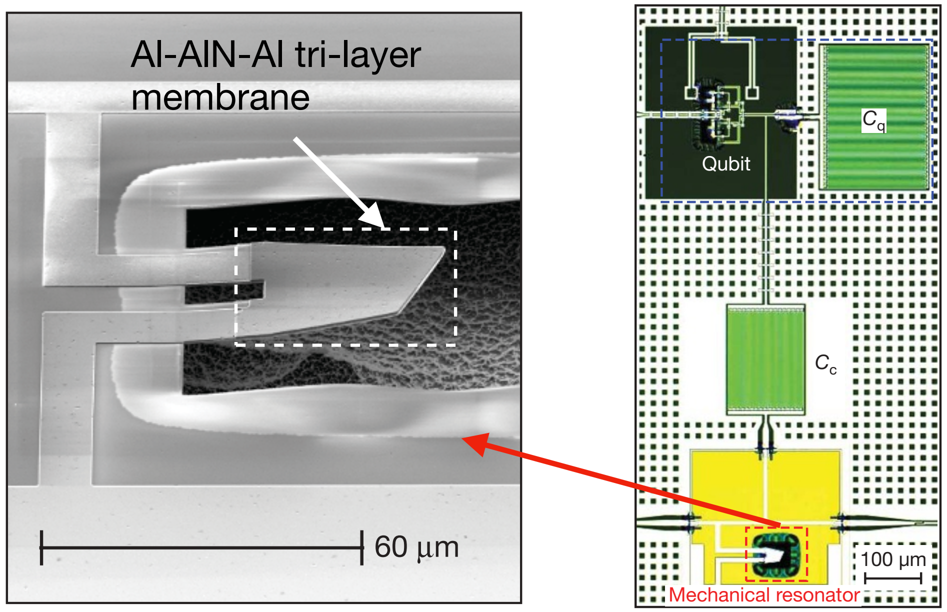
See also Kan Nakazono's poster

Beyond the photon detection

Hybrid quantum system → Access to:

- ○ other field/particles than EM interaction/photons
- ○ other quantities e.g. pressure, temperature etc.

Mechanical resonator × SCQ O'Connel et al. (2010)

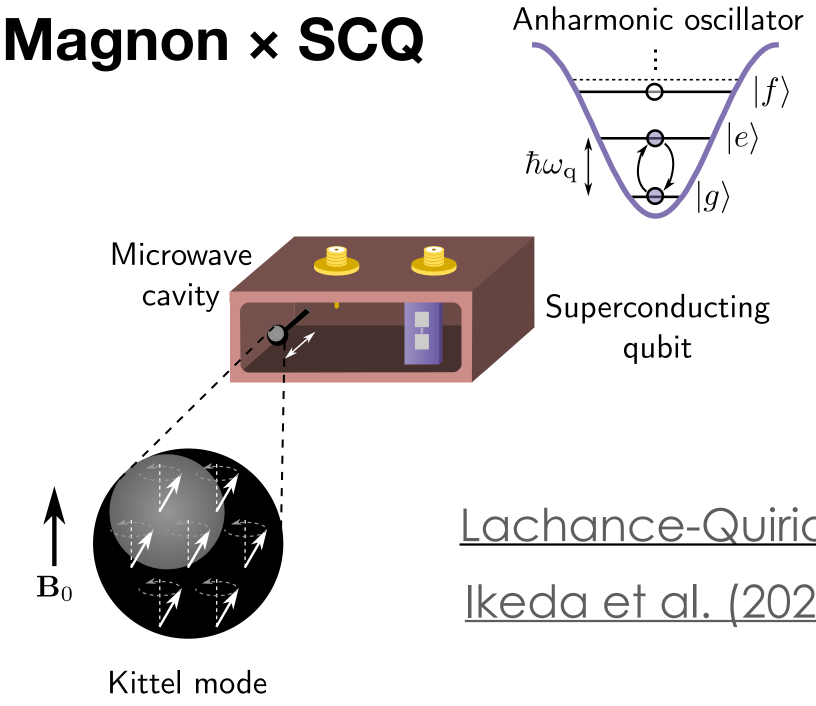


Observe the detune in the coupled SCQ

HEP application:

5th force search, gravitational wave?

Magnon × SCQ



Lachance-Quirion et al. (2020)

Ikeda et al. (2022)

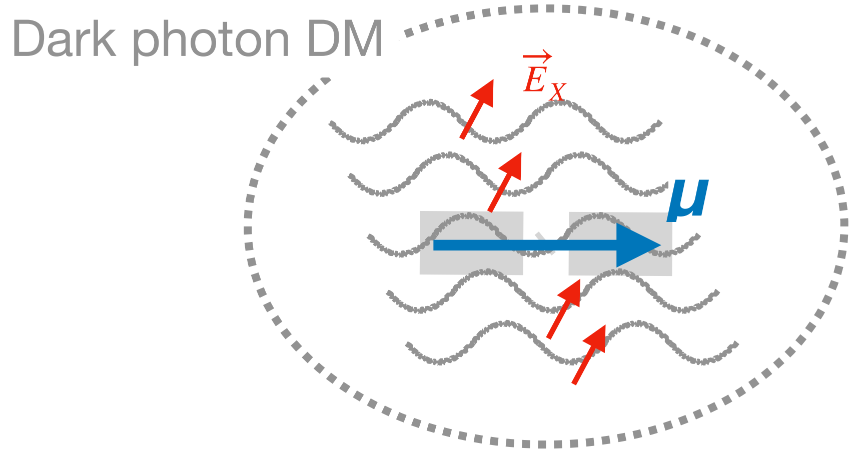
HEP application: Axion-electron search

Direct excitations by the dark matter

PRL 131, 211001 (2023)

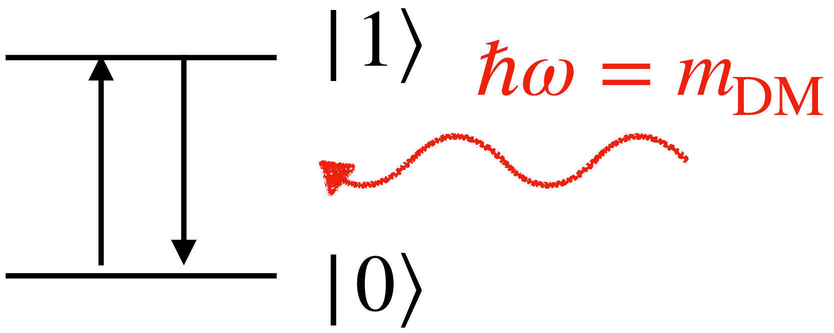
See also Karin Watanabe's poster

Coherent E-field from DM-converted photons



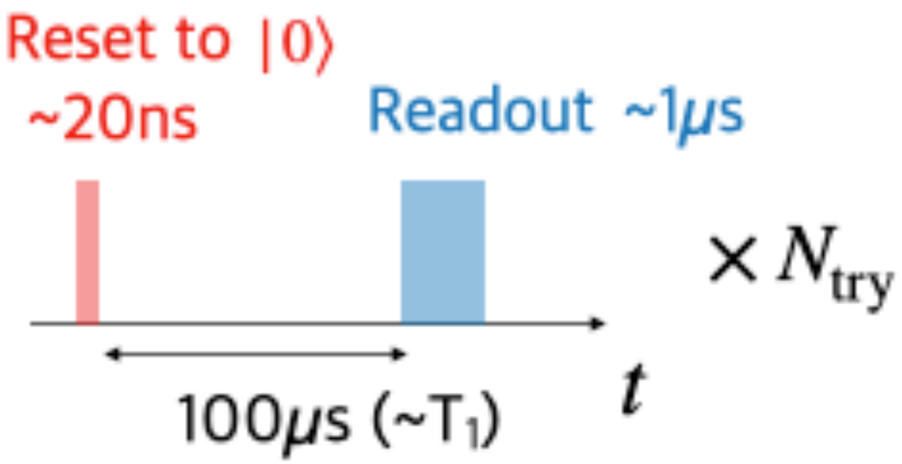
=

Drive pulse for qubits



Initialize to $|0\rangle$, pause and measure

Repeat $N_{\rm try}$ times & count the number of $|1\rangle$



Excitation rate after a 100μs pause: 0.01%-10%

$$p_{ge}(\tau) \simeq 0.12 \times \kappa^2 \cos^2\Theta \left(\frac{\epsilon}{10^{-11}}\right)^2 \left(\frac{f}{1\ \rm GHz}\right) \times \left(\frac{\tau}{100\ \mu s}\right)^2 \left(\frac{C}{0.1\ \rm pF}\right) \left(\frac{d}{100\ \mu m}\right)^2 \left(\frac{\rho_{\rm DM}}{0.45\ {\rm GeV/cm}^3}\right)$$

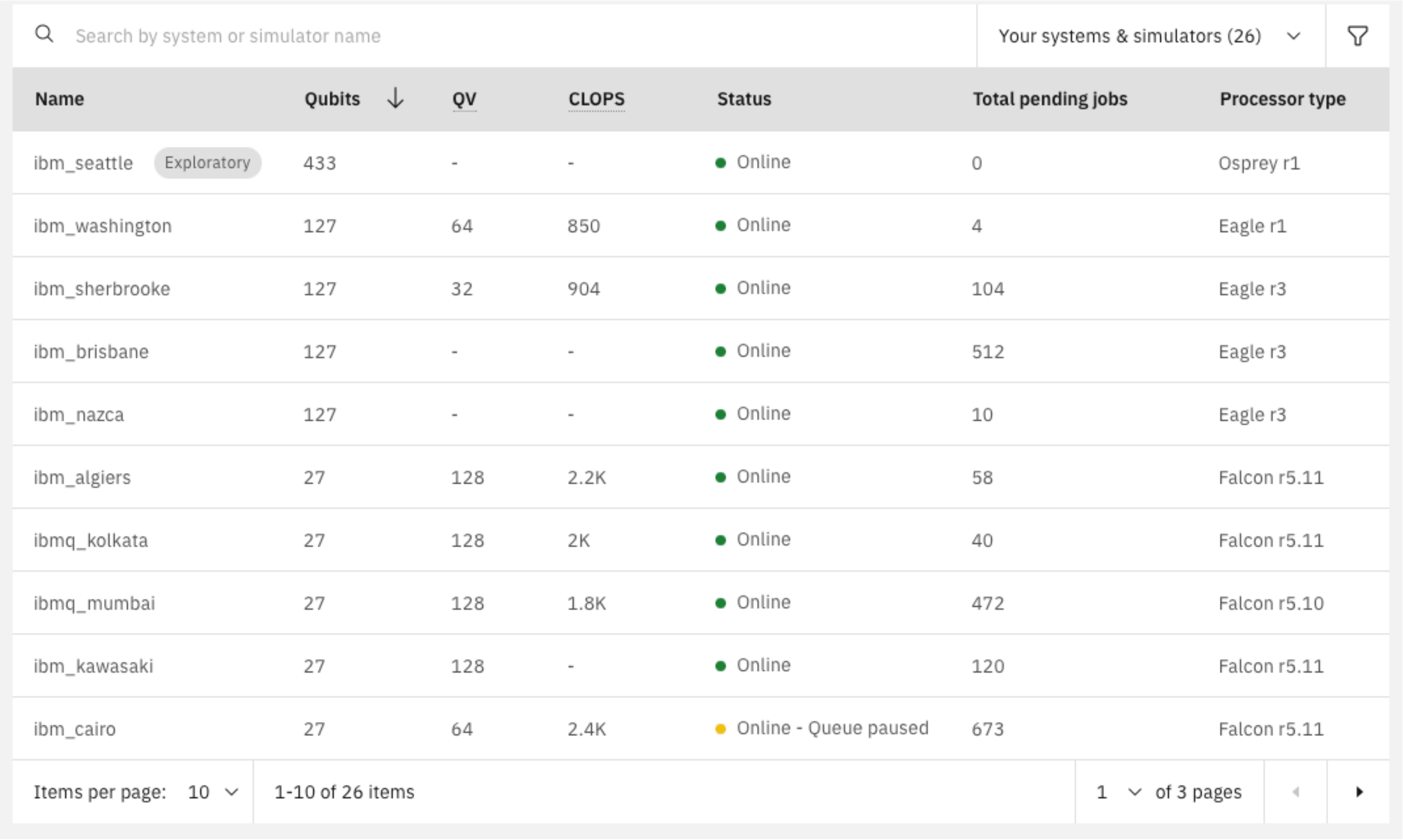
Counting experiment

$N_{\rm try}$ ~ 10^4 within ~10sec

Quantum computer = Dark matter detector?

e.g. IBM-Q: 5-bit machine free to anybody

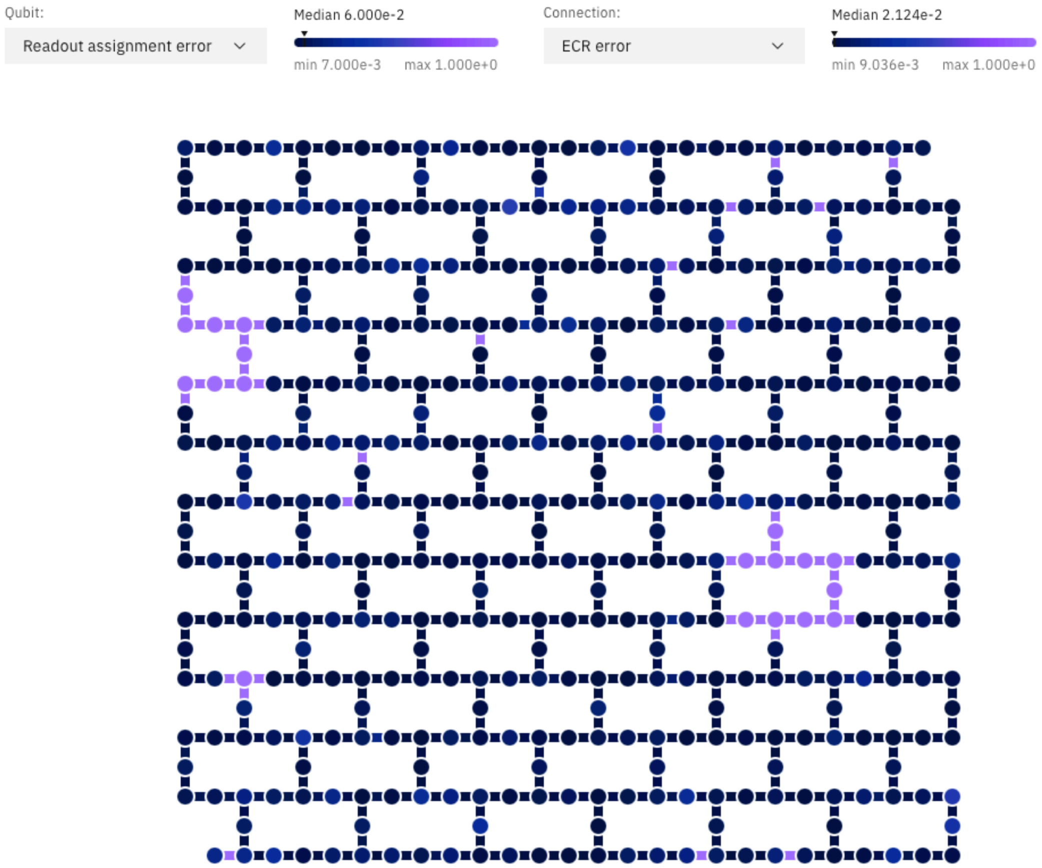
Full capability with subscription



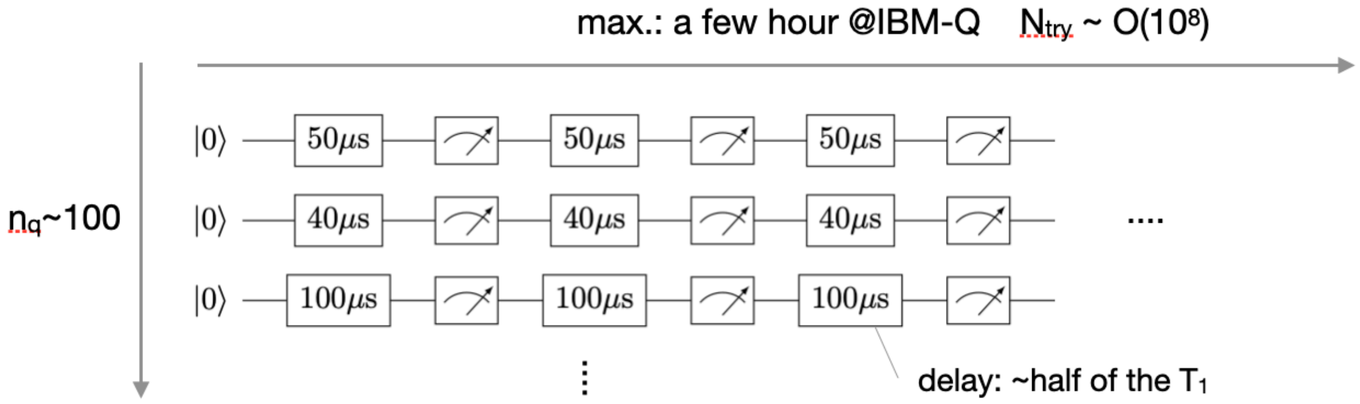
Name	Qubits	QV	CLOPS	Status	Total pending jobs	Processor type
ibm_seattle Exploratory	433	-	-	● Online	0	Osprey r1
ibm_washington	127	64	850	● Online	4	Eagle r1
ibm_sherbrooke	127	32	904	● Online	104	Eagle r3
ibm_brisbane	127	-	-	● Online	512	Eagle r3
ibm_nazca	127	-	-	● Online	10	Eagle r3
ibm_algiers	27	128	2.2K	● Online	58	Falcon r5.11
ibmq_kolkata	27	128	2K	● Online	40	Falcon r5.11
ibmq_mumbai	27	128	1.8K	● Online	472	Falcon r5.10
ibm_kawasaki	27	128	-	● Online	120	Falcon r5.11
ibm_cairo	27	64	2.4K	● Online - Queue paused	673	Falcon r5.11

Ospray processor (433 bit)

T_1, T_2, error rate etc. displayed for each bit



Direct excitation searches embedded in the circuit



max.: a few hour @IBM-Q $N_{try} \sim O(10^8)$

$n_q \sim 100$

delay: ~half of the T_1

- ✔ **Many bits**
- ✔ **Regularly calibrated**

  Performance guaranteed to some extent

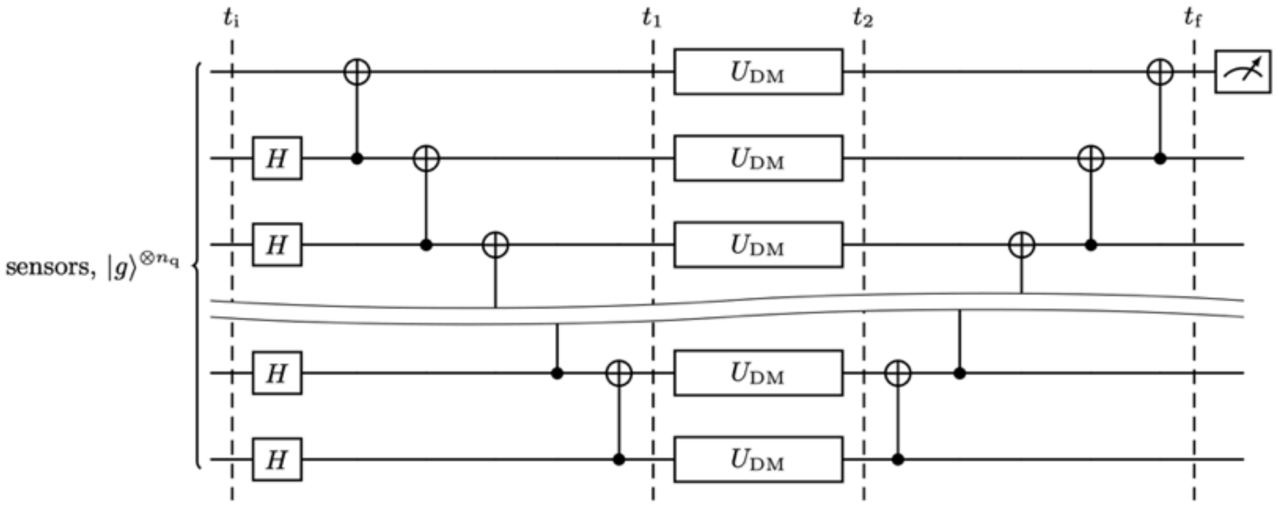
  Bad qubits marked
- ✔ **Optimized control & readout**

Quantum computer = Dark matter detector?

More serious circuit execution?

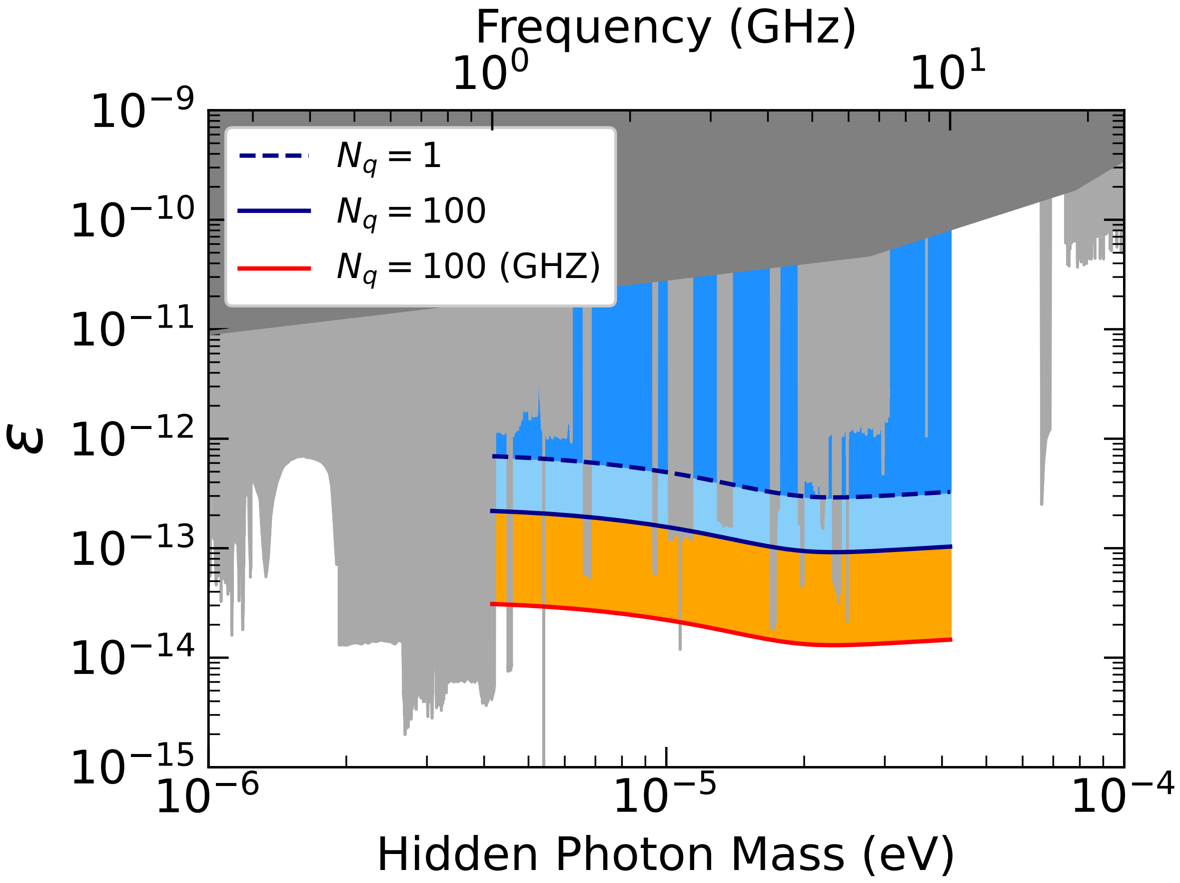
Entanglement → $\propto n_q^2$ excitation rate

e.g. GHZ state



Merge the DM-driven phase evolution on each bit

Amplitude sum (as opposed to probability sum)



arXiv: [hep-ex] 2311.10413
arXiv: [hep-ex] 2311.11632

- **Prerequisites: more bits, more accurate gate operation/readout, error correction**

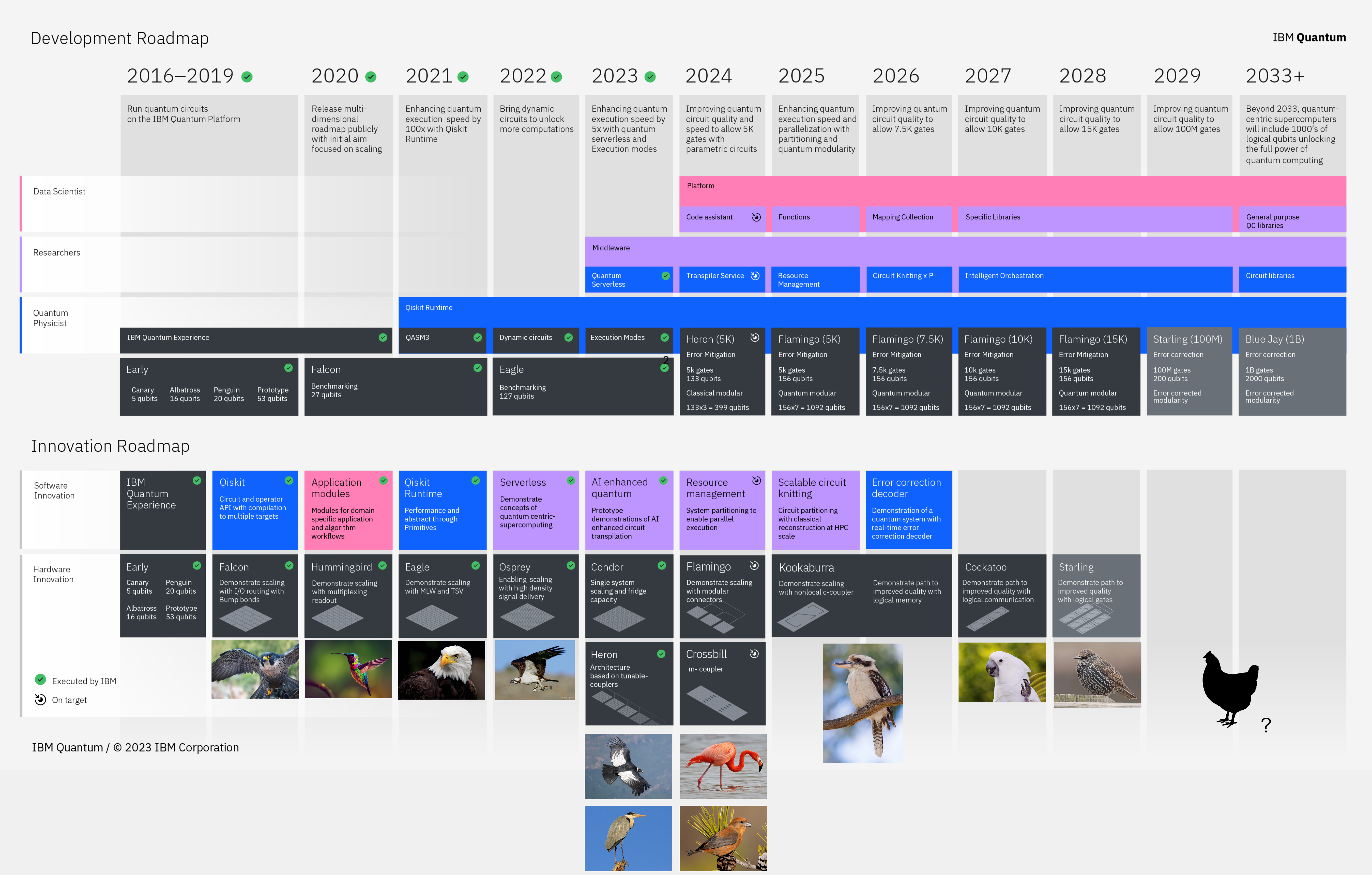
  None of them is available but all of them are the requirements for future quantum computers.

- **Promising if the search can be entirely embedded to circuit program**

  Parasitic to the QC operation, no HW changes needed.

How far the "future" is

IBM-Q roadmap



Development Roadmap

IBM Quantum

2016–2019 ✓	2020 ✓	2021 ✓	2022 ✓	2023 ✓	2024	2025	2026	2027	2028	2029	2033+
Run quantum circuits on the IBM Quantum Platform	Release multi-dimensional roadmap publicly with initial aim focused on scaling	Enhancing quantum execution speed by 100x with Qiskit Runtime	Bring dynamic circuits to unlock more computations	Enhancing quantum execution speed by 5x with quantum serverless and Execution modes	Improving quantum circuit quality and speed to allow 5K gates with parametric circuits	Enhancing quantum execution speed and parallelization with partitioning and quantum modularity	Improving quantum circuit quality to allow 7.5K gates	Improving quantum circuit quality to allow 10K gates	Improving quantum circuit quality to allow 15K gates	Improving quantum circuit quality to allow 100M gates	Beyond 2033, quantum-centric supercomputers will include 1000's of logical qubits unlocking the full power of quantum computing

Data Scientist

- Platform
- Code assistant ⟳ · Functions · Mapping Collection · Specific Libraries · General purpose QC libraries

Researchers

- Middleware
- Quantum Serverless ✓ · Transpiler Service ⟳ · Resource Management · Circuit Knitting x P · Intelligent Orchestration · Circuit libraries

Quantum Physicist

- Qiskit Runtime
- IBM Quantum Experience ✓ · QASM3 ✓ · Dynamic circuits ✓ · Execution Modes ✓
- Heron (5K) ⟳: Error Mitigation; 5k gates, 133 qubits; Classical modular; 133x3 = 399 qubits
- Flamingo (5K): Error Mitigation; 5k gates, 156 qubits; Quantum modular; 156x7 = 1092 qubits
- Flamingo (7.5K): Error Mitigation; 7.5k gates, 156 qubits; Quantum modular; 156x7 = 1092 qubits
- Flamingo (10K): Error Mitigation; 10k gates, 156 qubits; Quantum modular; 156x7 = 1092 qubits
- Flamingo (15K): Error Mitigation; 15k gates, 156 qubits; Quantum modular; 156x7 = 1092 qubits
- Starling (100M): Error correction; 100M gates, 200 qubits; Error corrected modularity
- Blue Jay (1B): Error correction; 1B gates, 2000 qubits; Error corrected modularity
- Early ✓: Canary 5 qubits · Albatross 16 qubits · Penguin 20 qubits · Prototype 53 qubits
- Falcon ✓: Benchmarking 27 qubits
- Eagle ✓: Benchmarking 127 qubits

2

Innovation Roadmap

Software Innovation

- IBM Quantum Experience ✓
- Qiskit ✓: Circuit and operator API with compilation to multiple targets
- Application modules ✓: Modules for domain specific application and algorithm workflows
- Qiskit Runtime ✓: Performance and abstract through Primitives
- Serverless ✓: Demonstrate concepts of quantum centric-supercomputing
- AI enhanced quantum ✓: Prototype demonstrations of AI enhanced circuit transpilation
- Resource management ⟳: System partitioning to enable parallel execution
- Scalable circuit knitting: Circuit partitioning with classical reconstruction at HPC scale
- Error correction decoder: Demonstration of a quantum system with real-time error correction decoder

Hardware Innovation

- Early ✓: Canary 5 qubits · Penguin 20 qubits · Albatross 16 qubits · Prototype 53 qubits
- Falcon ✓: Demonstrate scaling with I/O routing with Bump bonds
- Hummingbird ✓: Demonstrate scaling with multiplexing readout
- Eagle ✓: Demonstrate scaling with MLW and TSV
- Osprey ✓: Enabling scaling with high density signal delivery
- Condor ✓: Single system scaling and fridge capacity
- Heron ✓: Architecture based on tunable-couplers
- Flamingo ⟳: Demonstrate scaling with modular connectors
- Crossbill ⟳: m- coupler
- Kookaburra: Demonstrate scaling with nonlocal c-coupler · Demonstrate path to improved quality with logical memory
- Cockatoo: Demonstrate path to improved quality with logical communication
- Starling: Demonstrate path to improved quality with logical gates

✓ Executed by IBM

⟳ On target

?

IBM Quantum / © 2023 IBM Corporation

Backup

元日に鶏の鳴き声を放送(1929年)

Credit: NHK放送博物館
(NHK broadcast museum)

Chicken shouts live streaming @New Year 1929

References

Review articles

- "超伝導量子ビット研究の進展と応用" 中村泰信
- "超伝導回路を用いた量子計算機の研究を理解するための基礎知識" 山本剛
- "Practical Guide for Building Superconducting Quantum Devices" Y. Y. Gao et al. (2021)
- "Materials in superconducting quantum bits" W. D. Oliver and P. B. Welander (2013)
- "Engineering high-coherence superconducting qubits" I. Sidiqqi (2021)

Textbooks

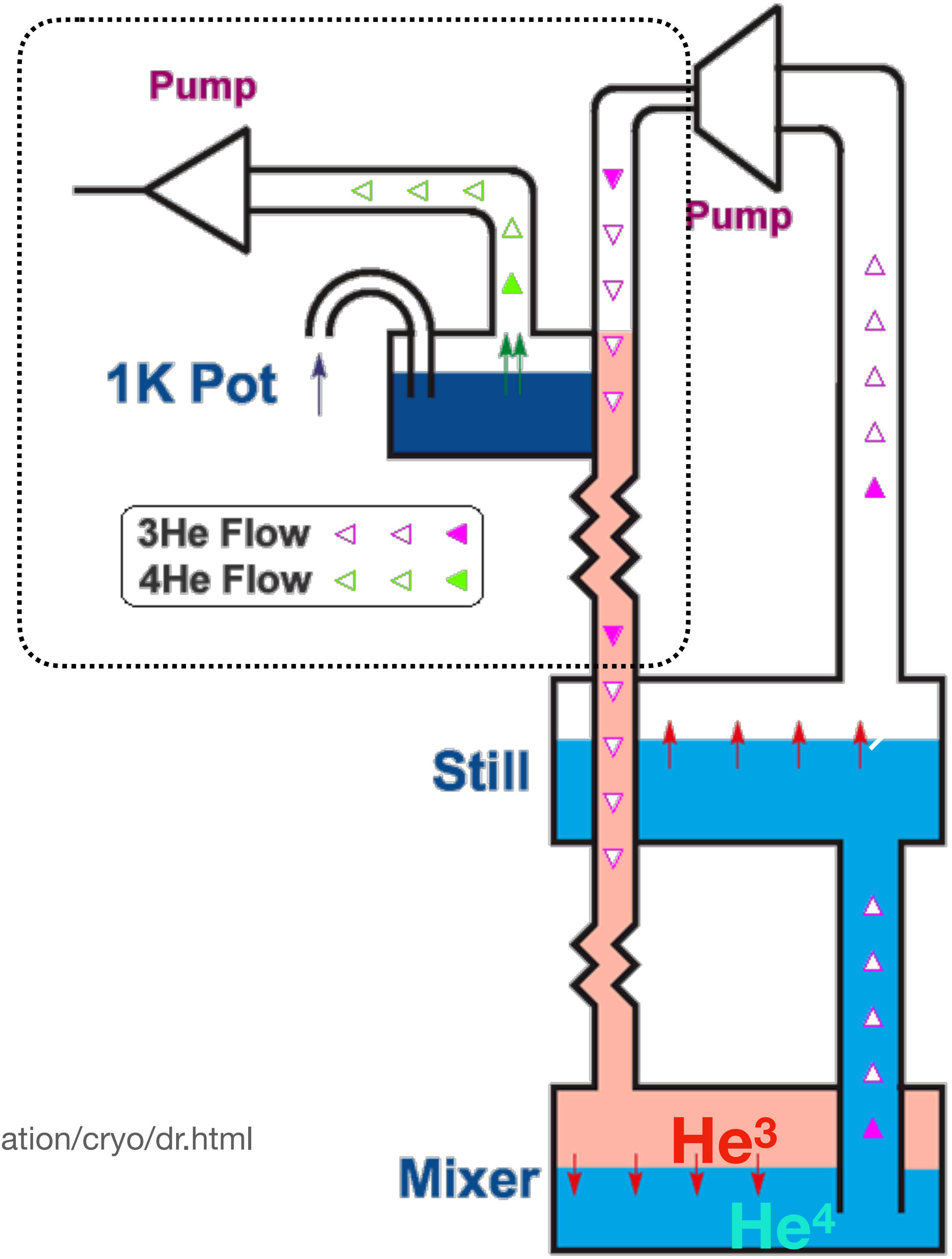
- "量子技術序論" 長田有登, 山崎歴舟, 野口篤史
- "The Physics of the Dark Photon: A Primer" M. Fabbrichesi et al.
- "Quantum Computation and Quantum Information" A. M. Nielsen & I. Chuang

Dilution refrigerator - Working principle

Cooling through solving the He^3 into super-fluid He^4 ("dilution")

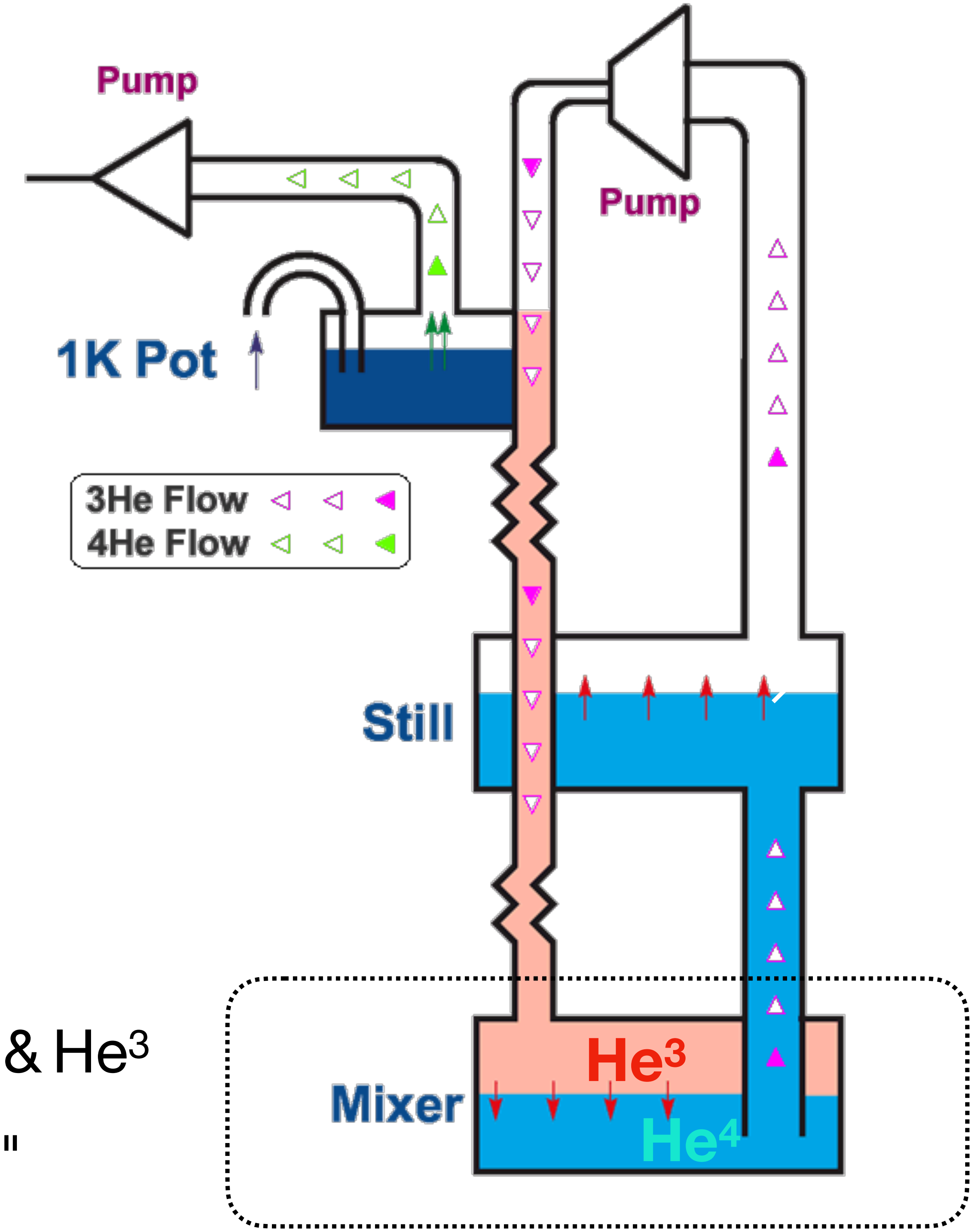
① Pre-cool He^3 to ~1K

→ liquefied



Credit: https://www.sci.osaka-cu.ac.jp/phys/ult/invitation/cryo/dr.html

Dilution refrigerator - Working principle



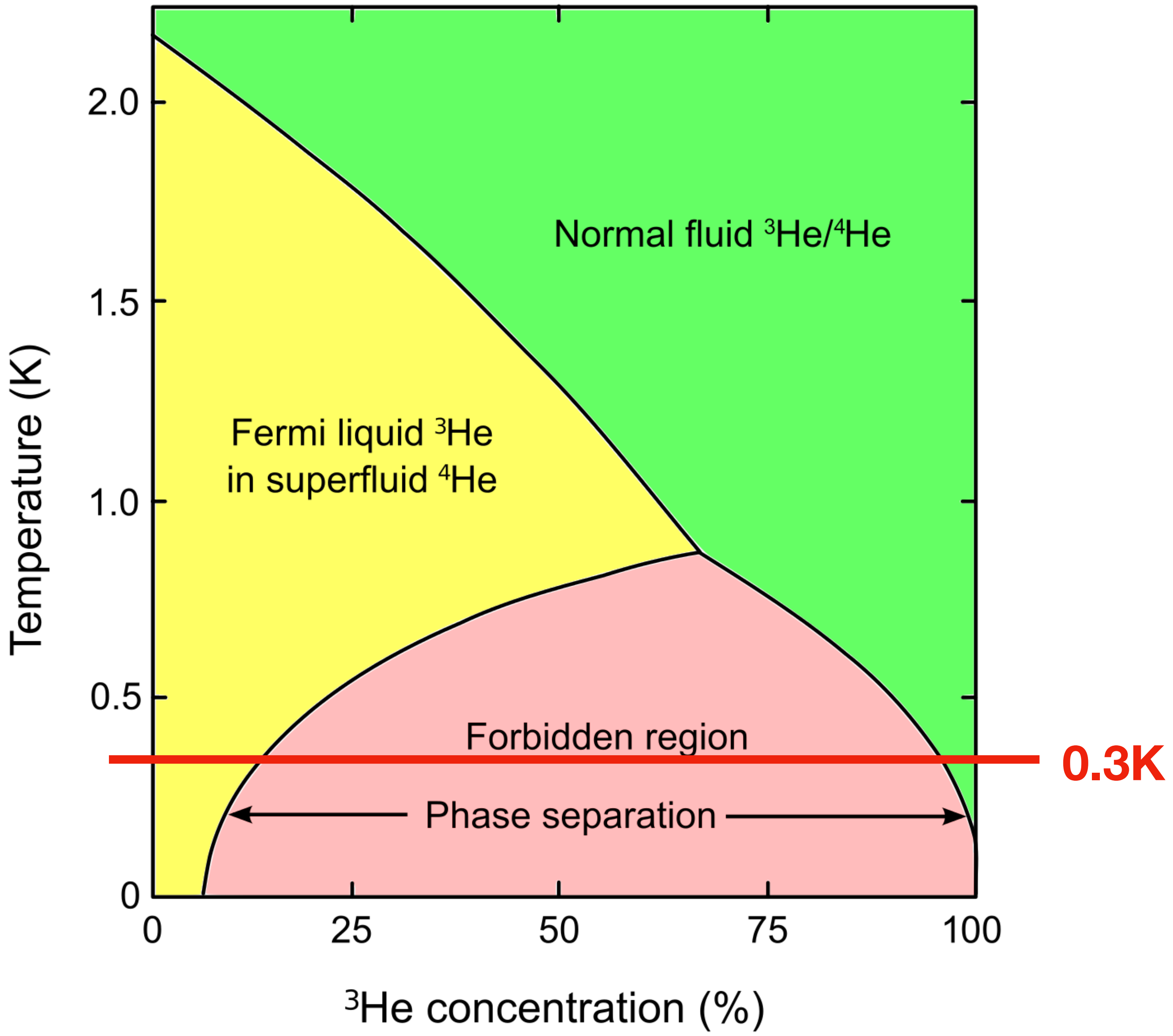
② Create a mixture of He^4 & He^3

at the "mixing chamber"

Dilution refrigerator - Working principle

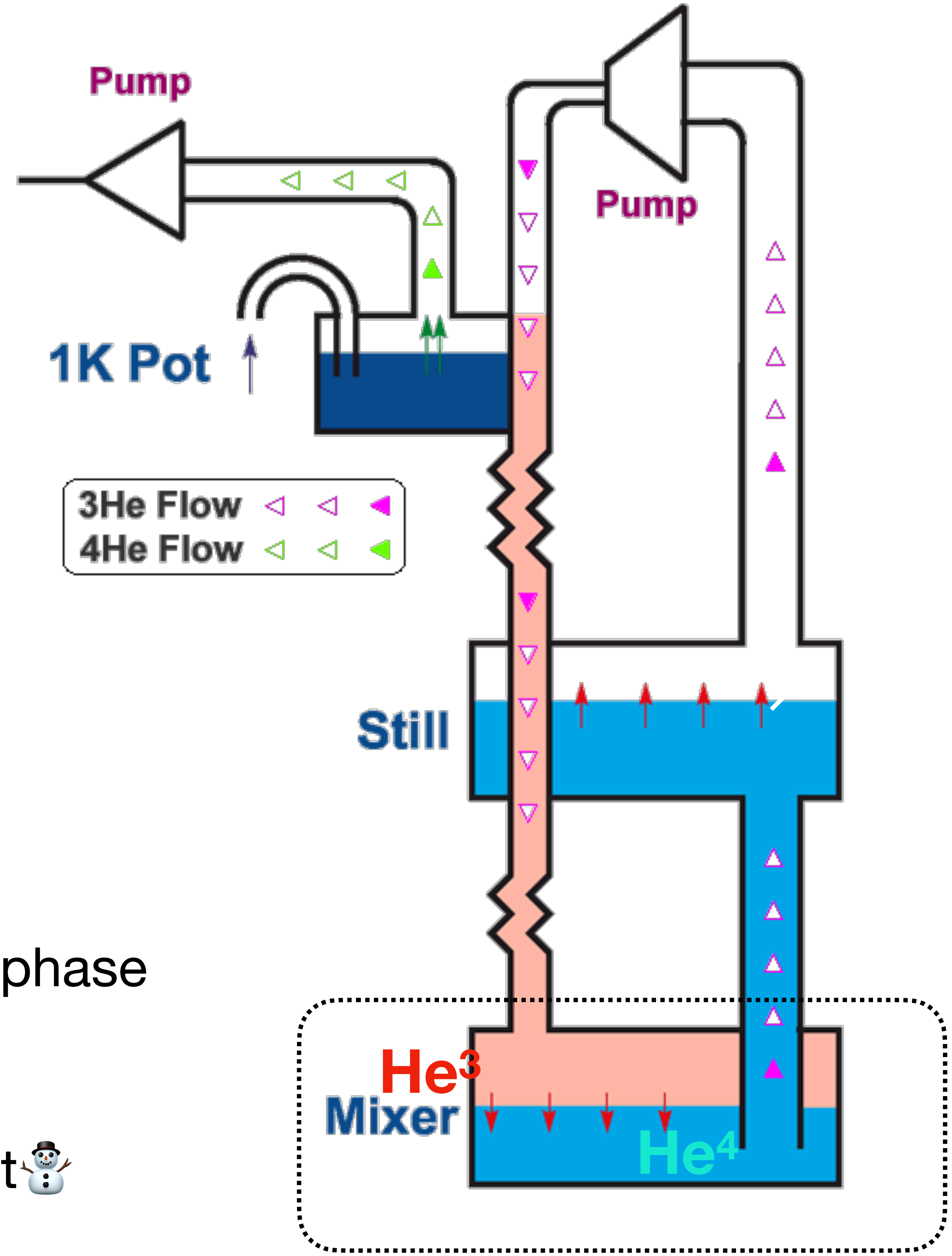
That's said, they don't mix much

Separated to a He^3-dominant and He^4-dominant phase



Ref: https://ja.wikipedia.org/wiki/3He-4He希釈冷凍法

Dilution refrigerator - Working principle

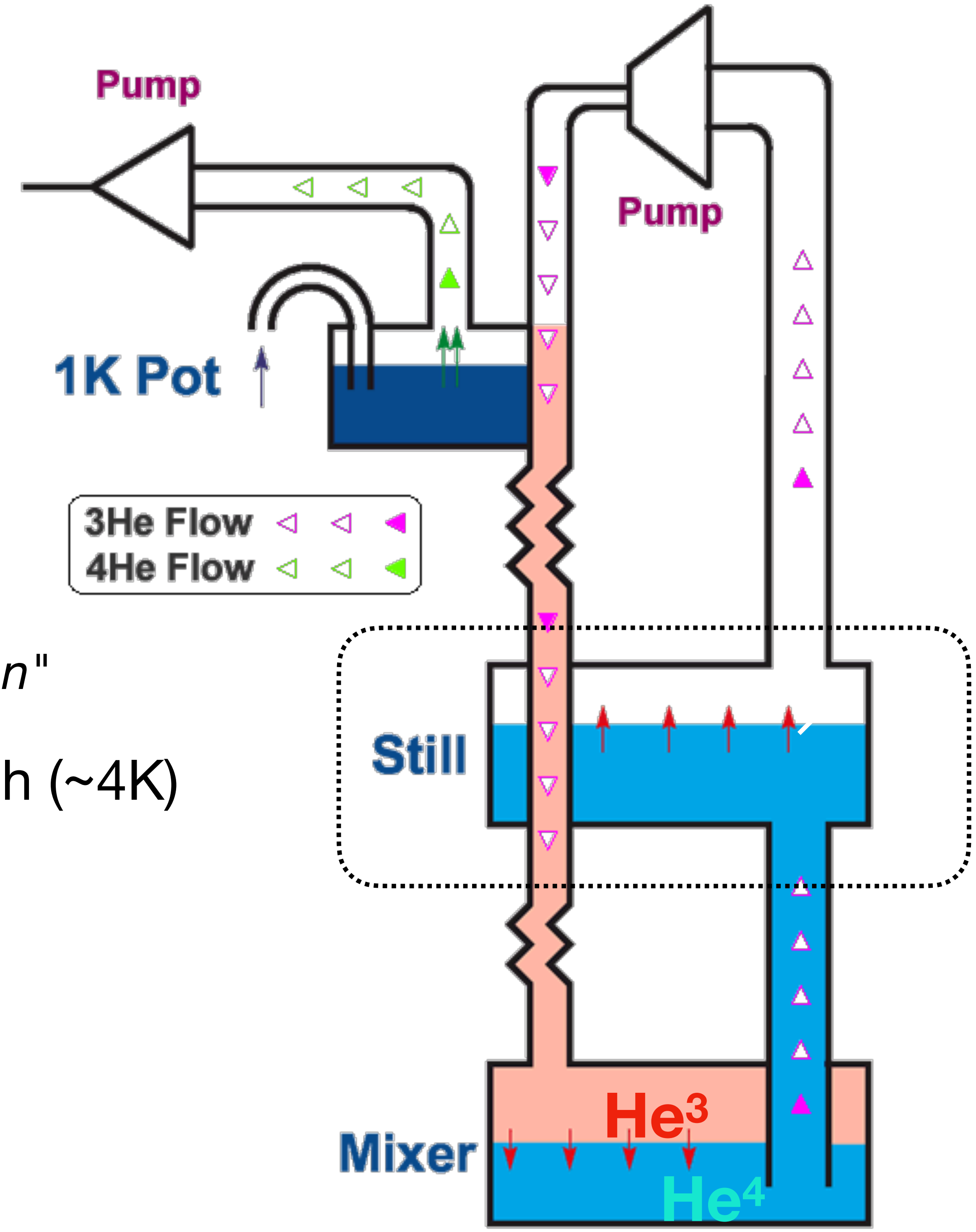


③ He³ evaporates to the He⁴-dominant phase

He⁴: superfluid → behave like a gas

Cooling through the evaporation heat⛄️

Dilution refrigerator - Working principle



"distillation"

④ Get rid of the He^3 at the high temp. bath (~4K)

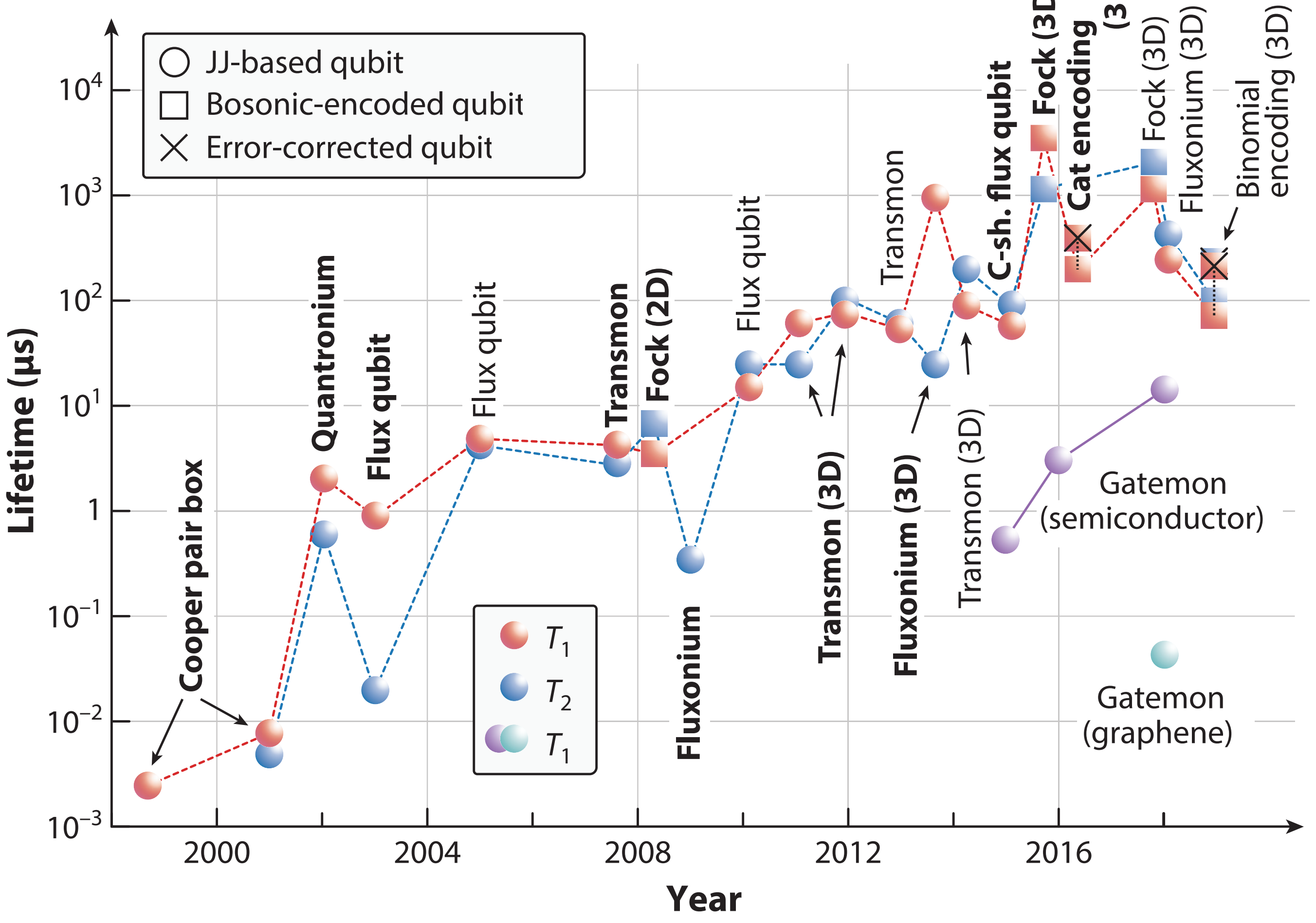
→ Put back in the pre-cool bath

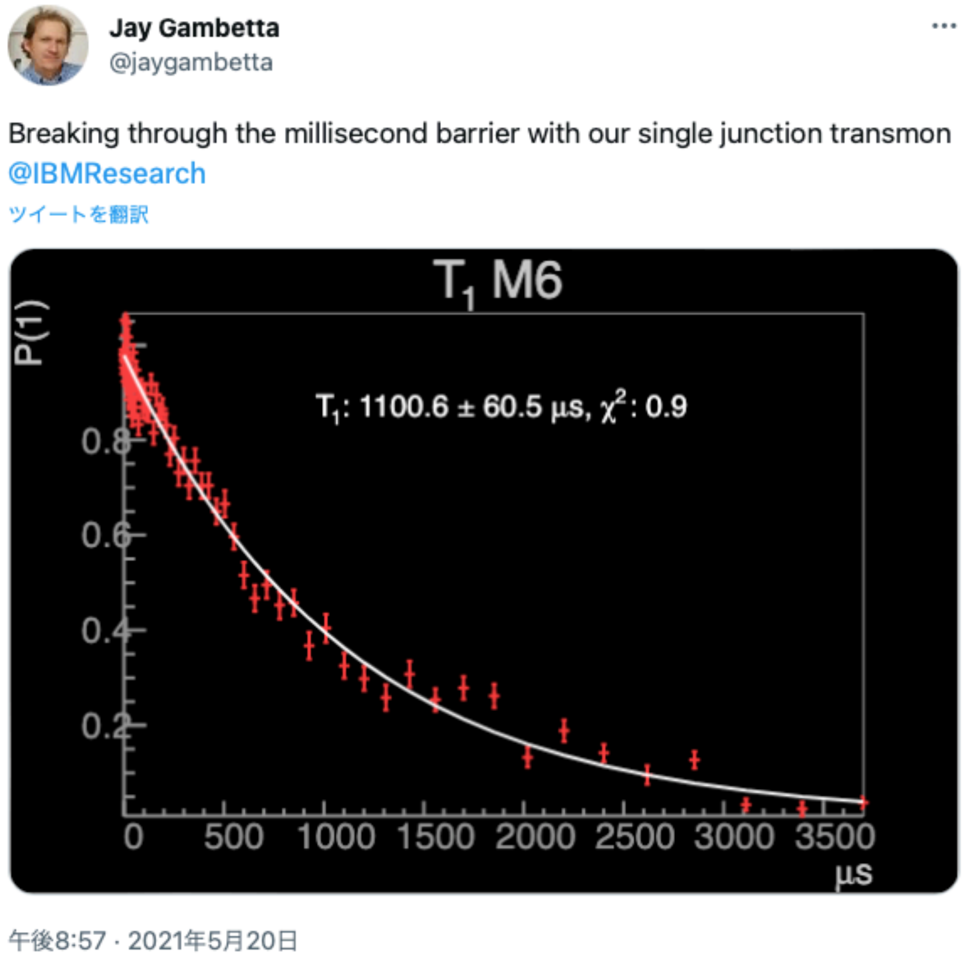
Repeat the cycle

Qubit coherence time

$\times 10^6$ improvement over the 20 years

I. Sidiqqi (2021)




Jay Gambetta
@jaygambetta

Breaking through the millisecond barrier with our single junction transmon @IBMResearch

ツイートを翻訳

午後8:57 · 2021年5月20日

Noise-resilient design

e.g. Transmon → big leap in T_2

Noise reduction

shield, low-loss packaging

RF filters, Purcell filters

Thin film material studies

Low amorphous surface: Nb, Ta

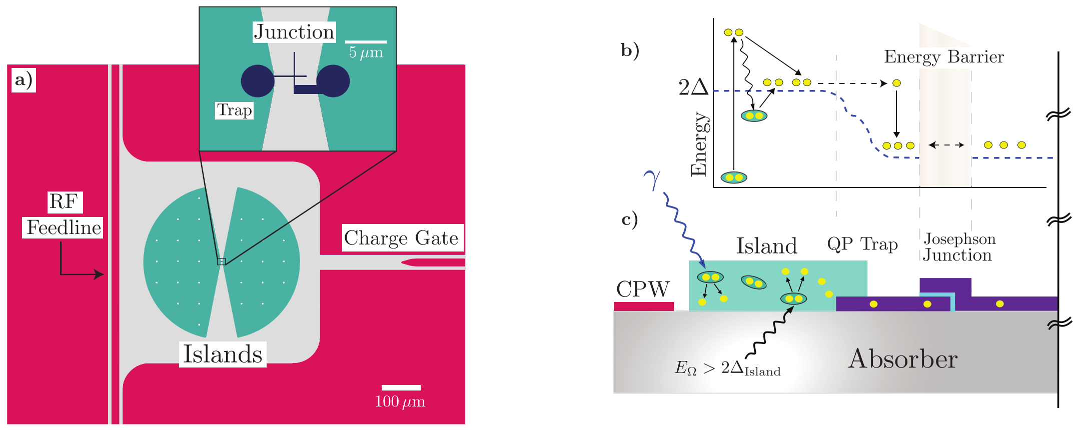
Low oxidation surface: TiN, Ta, NbN, AlN

Clean interface: epitaxially grown TiN film

Sophistication of the cleaning processes

Phonon detectors

Quasiparticle amplifier

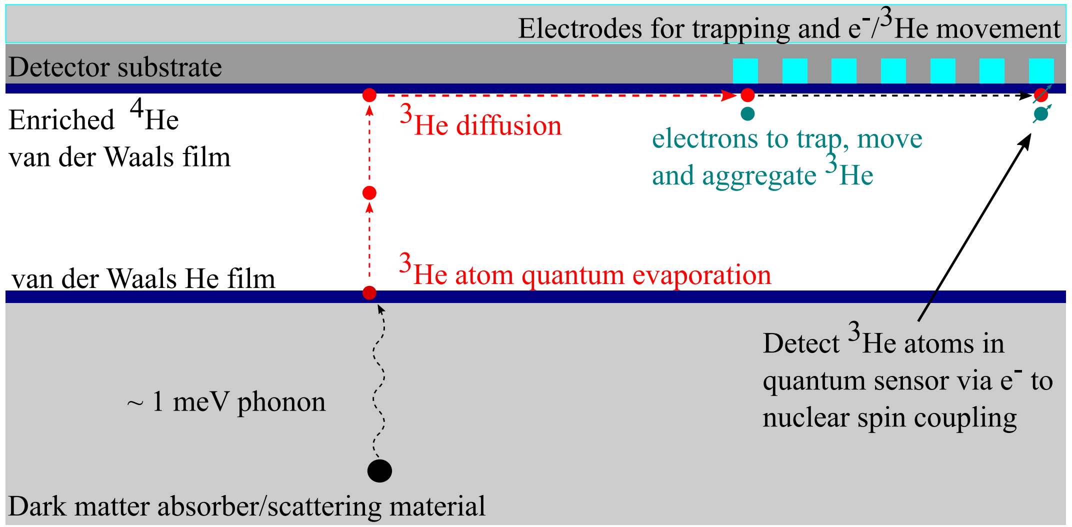


Fink et al. (2023)

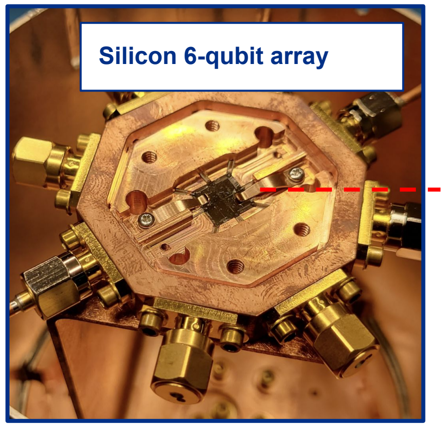
Phonon evaporate He³ → spin detection

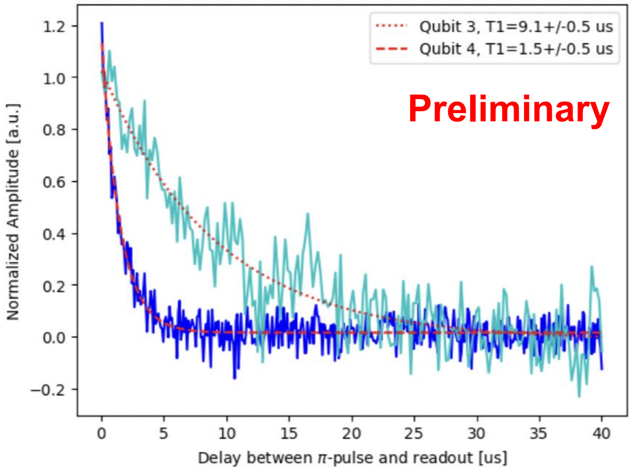
"Quantum evaporation"

Lyon et al. (2023)



Phonon detection through SCQs' T_1





R. Linehan (TAUP2023)

Junction fabrication (top: JJ, bottom: SQUID) SEM images