

DarQ experiment

Wave-like dark matter searches using superconducting qubits

Shion Chen (Kyoto University) 2026.05.19 ICEPP-QUP workshop

Qubits are sensors

Intrinsic trade off of quantum computers

- Fast control → Strong coupling preferred
- Long coherence time required → Small coupling preferred

The challenge of quantum computers essentially reduces to dealing with this trade-off

The fact that this is now being gradually overcome is the reason of the ongoing Q-buzz

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Good sensors require the same things

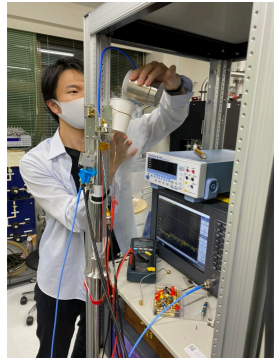
- Sensitivity to weak signal → Strong coupling preferred
- Low noise level → Small coupling preferred

Good qubits = Good sensors

DarQ experiment

Collaboration exploring the use of superconducting qubit sensors for searching dark matter and feeble fields

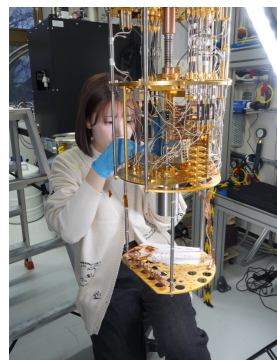
UTokyo ICEPP



Toshiaki Inada



Yuya Mino



Karin Watanabe



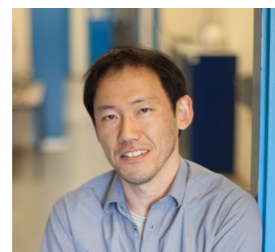
Kan Nakazono



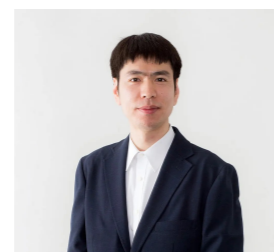
Chikara Kawai



Yutaro Iiyama

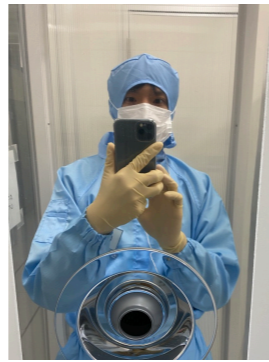


Koji Terashi



Ryu Sawada

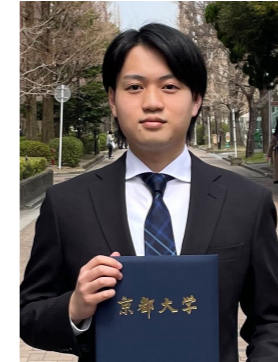
KyotoU HE Lab



Shion Chen



Kosuke Nakamura



Koki Aoyanagi



Koki Aoyanagi

KEK QUP

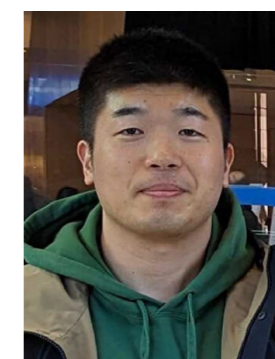


Tatsumi Nitta



Atsushi Noguchi

UTokyo Noguchi Lab / RIKEN RQC



Shotaro Shirai

UTokyo Moroi Lab



Takeo Moroi



Hajime Fukuda



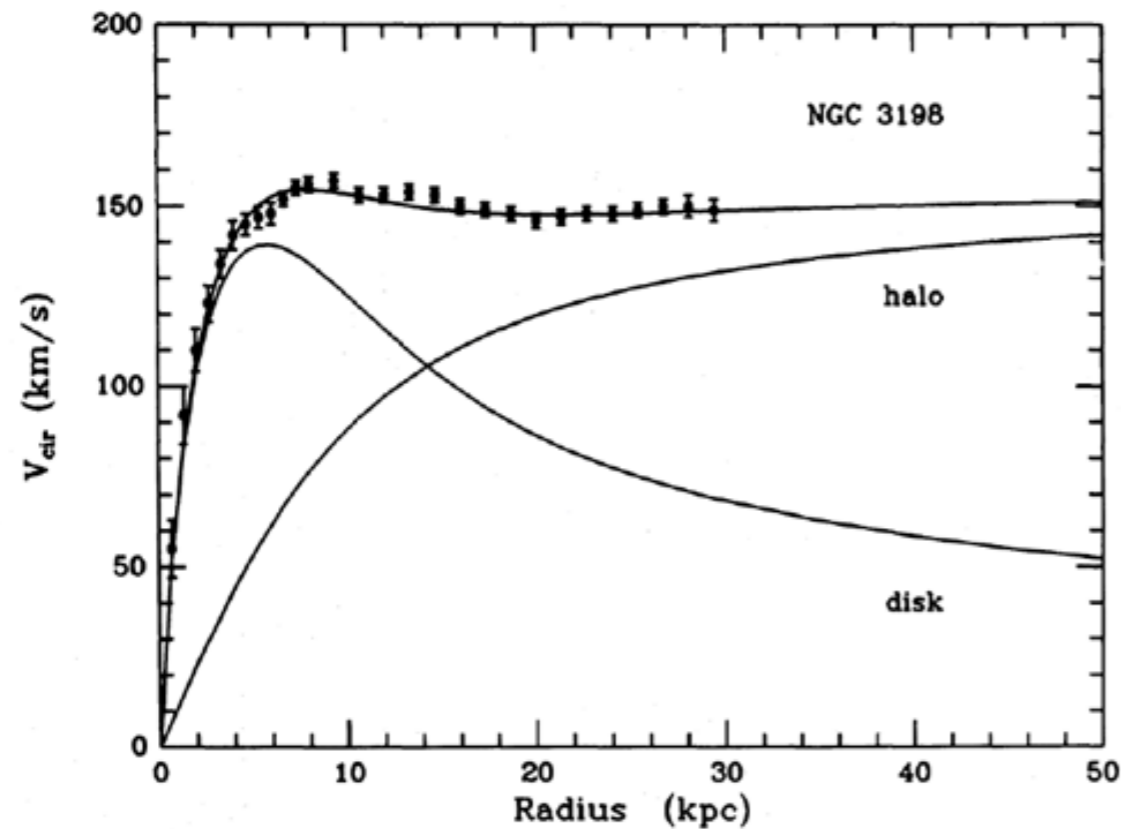
Thanaporn Sichanugrist

[Link](#)

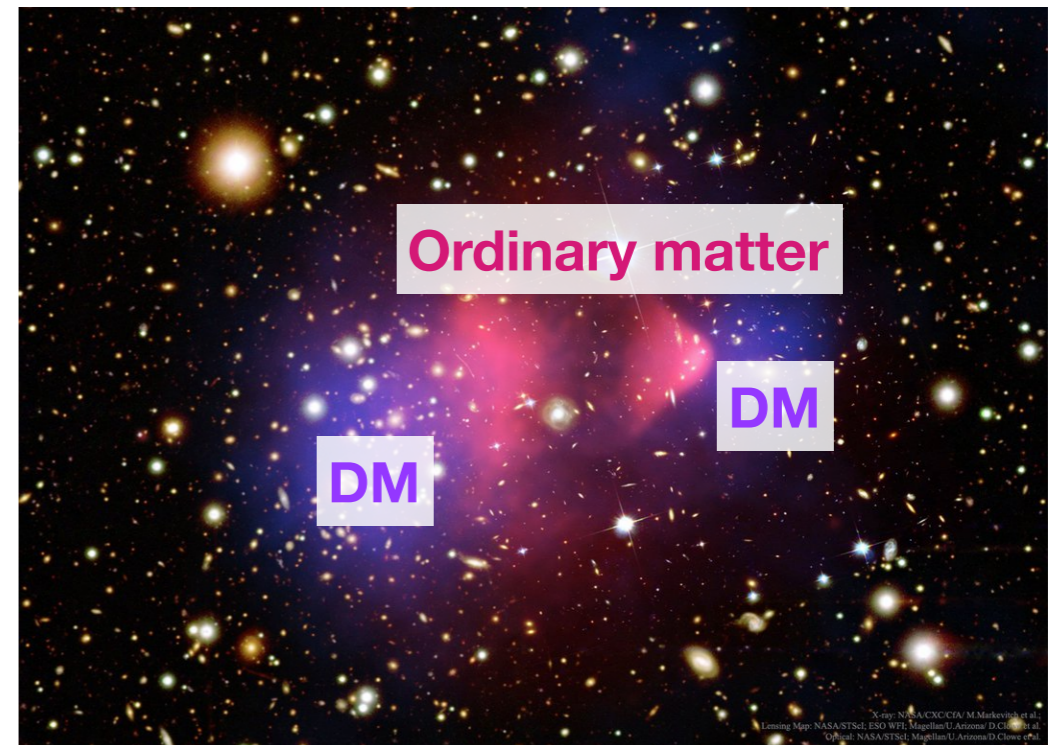


Dark matter is there

Anomaly in galaxy rotation velocity



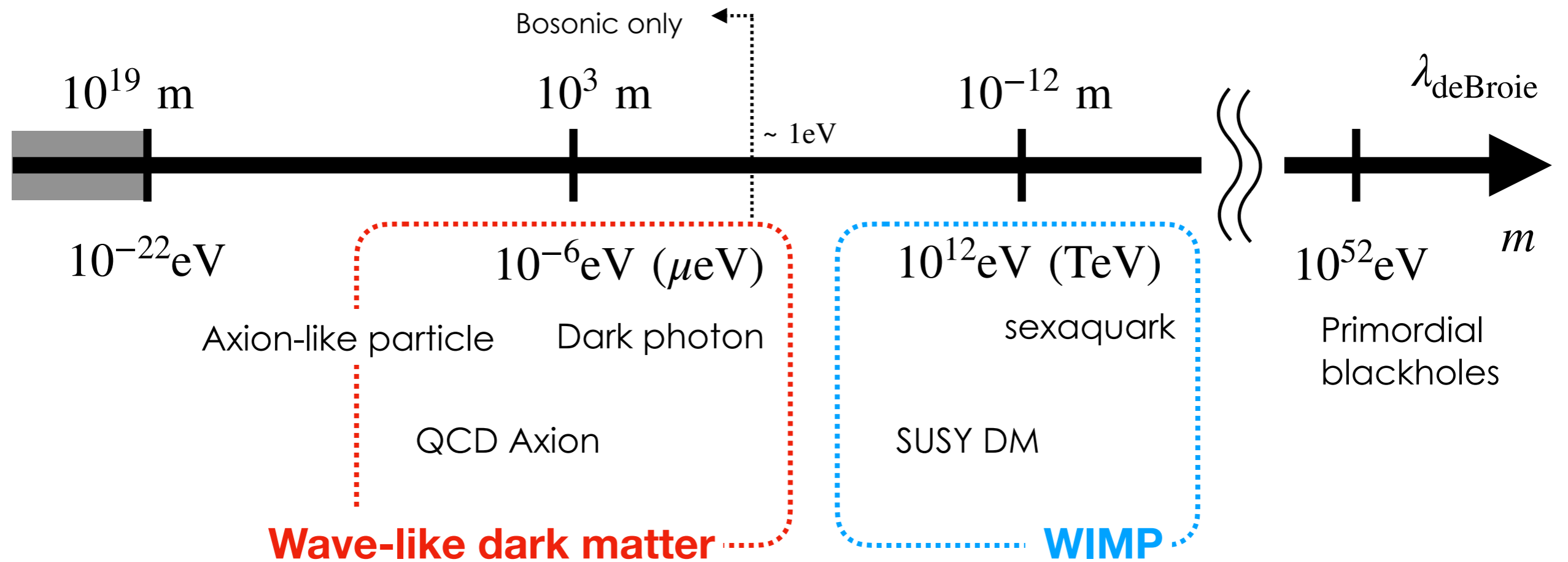
Bullet cluster



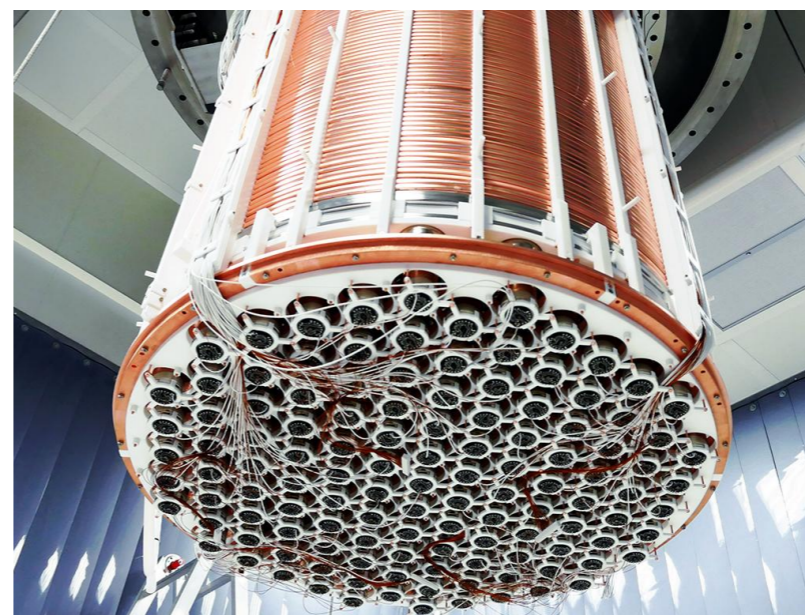
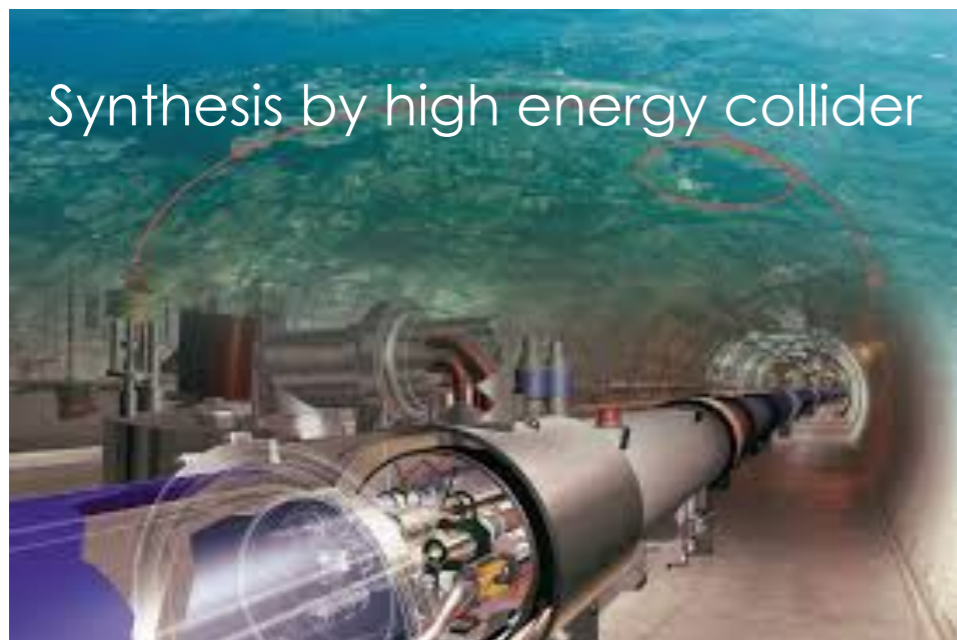
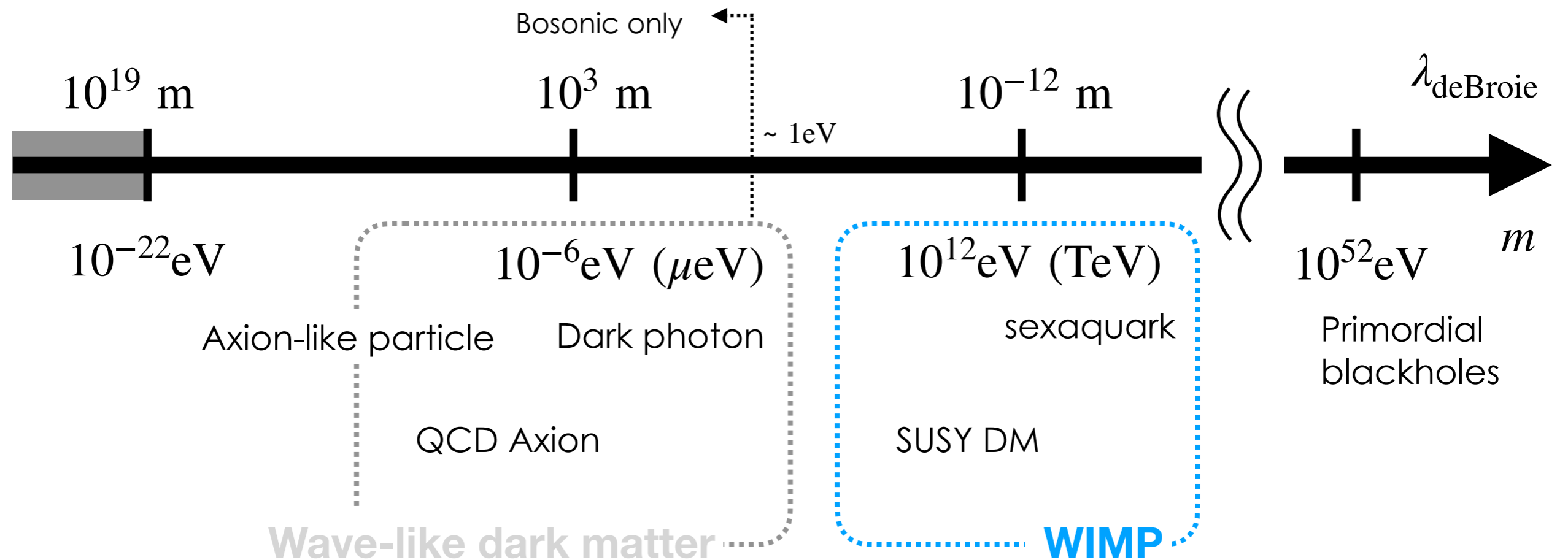
- Charge neutral mass
- Very weak interaction with ordinary matter
- Well-established cosmological properties
- No good candidate in the particle standard model

Neutrinos are found to be massive but they are too light not to wash out the large-scale structure

Dark matter landscape - Two major portals



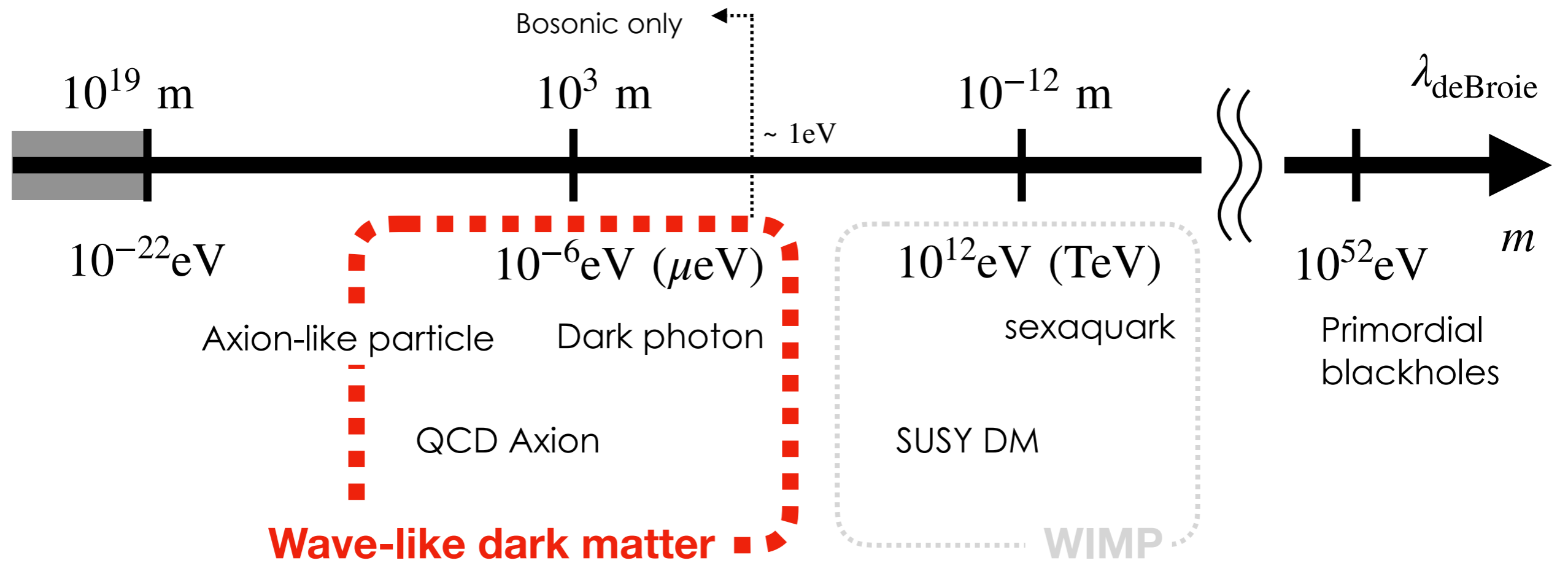
Dark matter landscape - Two major portals



Direct detection of nuclear recoils e.g. XENON experiment

No sign of discovery so far

Dark matter landscape - Two major portals



Boson when $m < \text{eV}$

Long de Broie wavelength $\lambda_{\text{deBroie}} > 1 \text{ m} @ m < \text{eV}$

Large number density $> 10^8 @ m < \text{eV}$

→ Macroscopic interference of coherent waves giant laser pulse ($\sim 100 \text{ m}$)

Target : Wave-like dark matter

AXION

Strong CP problem

→ PQ mechanism → NG boson

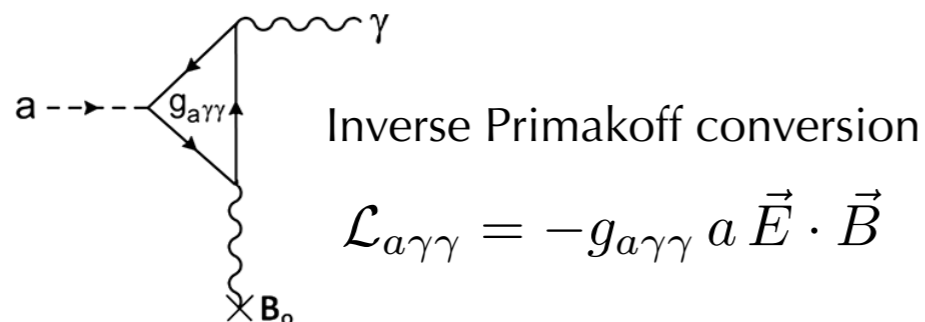
QCD axion condition

$$m_a = 5.691 \left(\frac{10^9 \text{ GeV}}{f_a} \right)$$

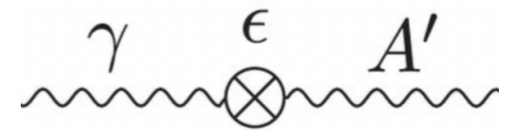
Axions that don't satisfy this are "Axion-Like Particle".
Cool thing still but won't solve the strong CP problem.

Axion-photon coupling

B-field → Photons emerge



DARK PHOTON



mixing parameter

$$X^\mu = \tilde{X}^\mu - \epsilon A^\mu$$

Dark photon
(mass eigen st.)

Dark photon
(interaction eigen st.)

ordinary photon

Fake photon with a bit of ordinary photon

Gauge boson of a new $U(1)_D$

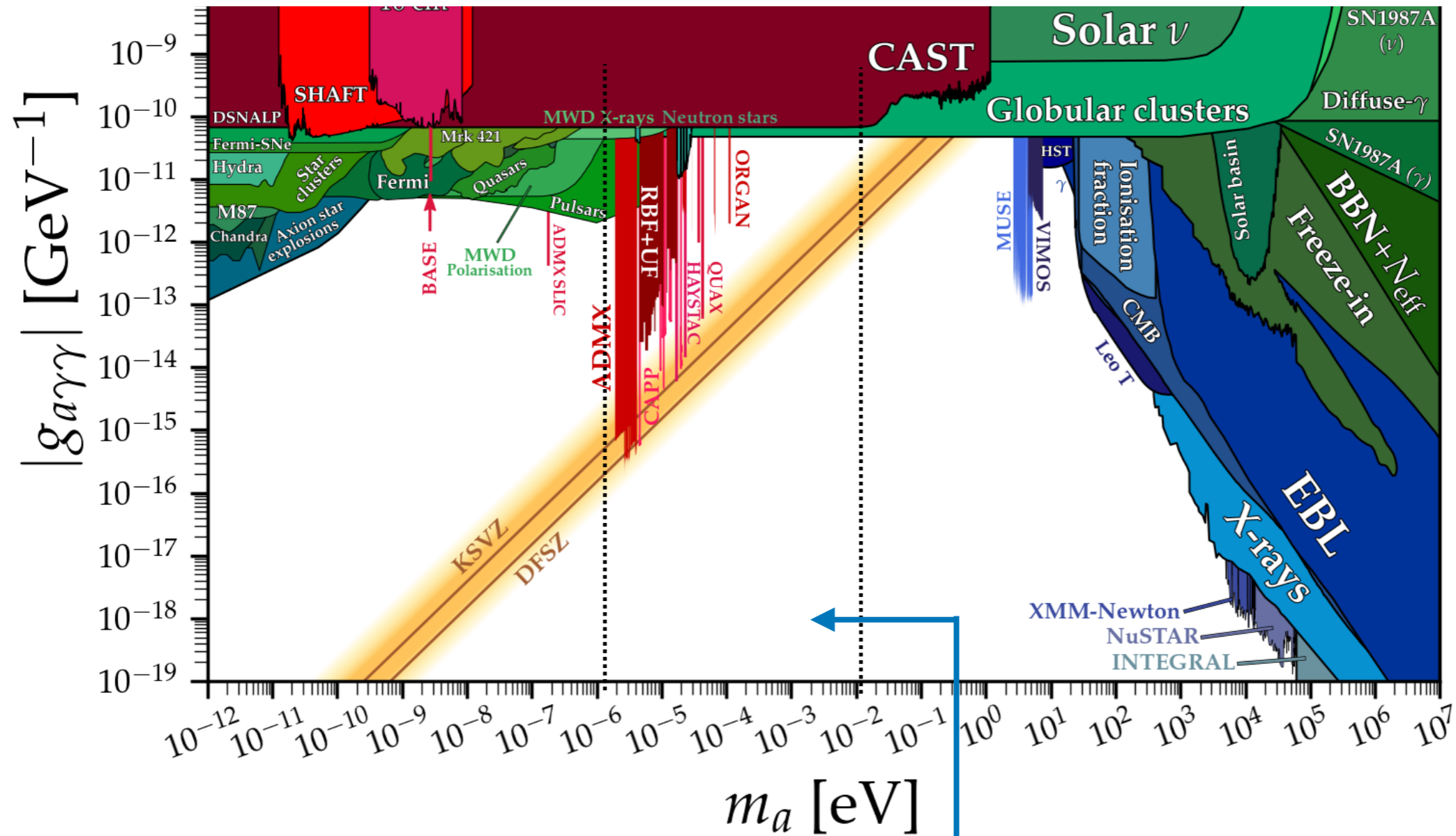
More motivation claimed recently in the context of string

Photon conversion w/o B-field

Tend to be the benchmark of axion search experiments before installing the magnet.

Limit on the axion $g_{a\gamma\gamma}$ coupling

C. O'Hare: [AxionLimits](#)



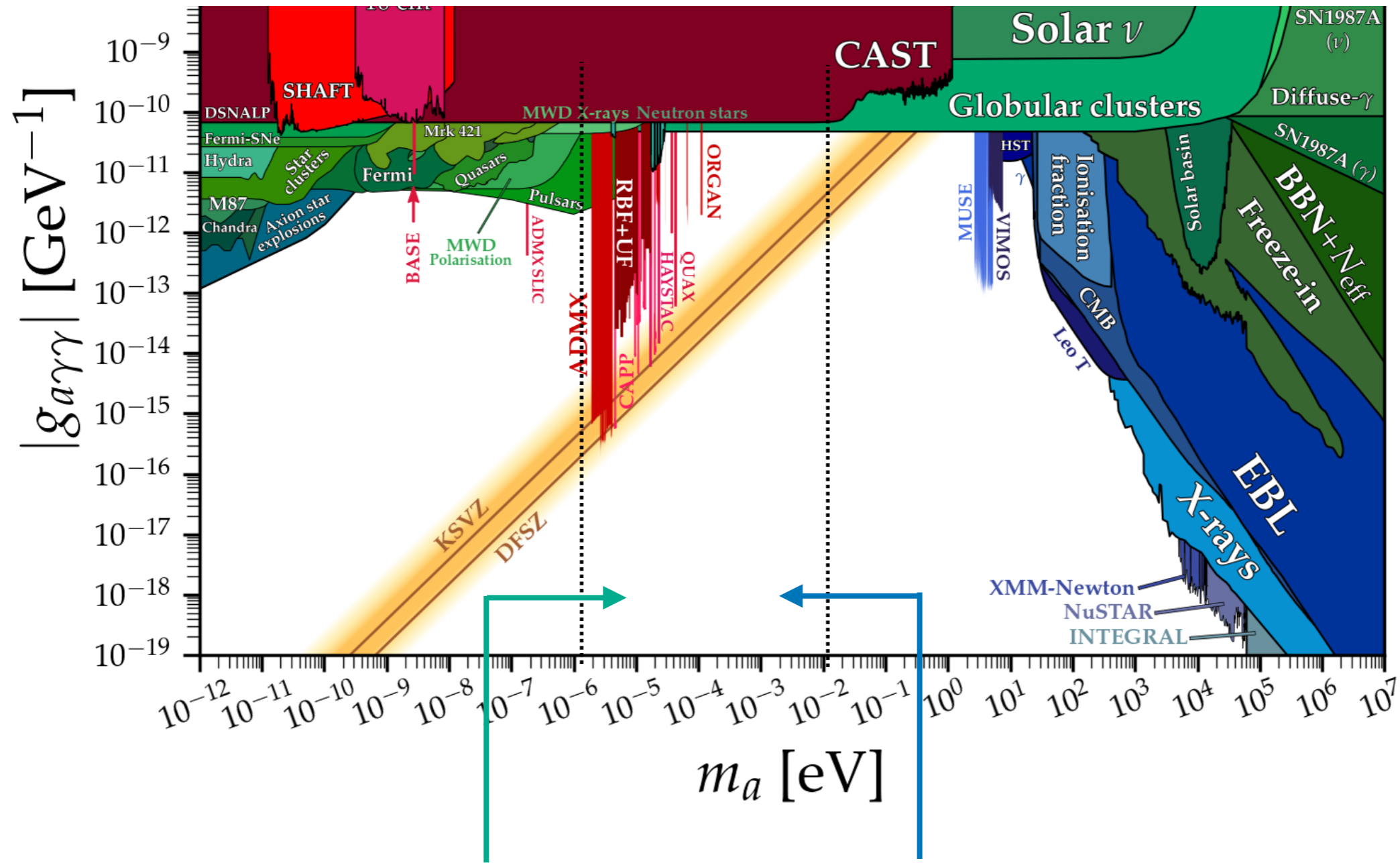
F. Takahashi

DM abundance $\rho = 0.45 \text{ GeV/cm}^3$

Too much DM if too heavy

Limit on the axion $g_{a\gamma\gamma}$ coupling

C. O'Hare: [AxionLimits](#)



"Naturalness"

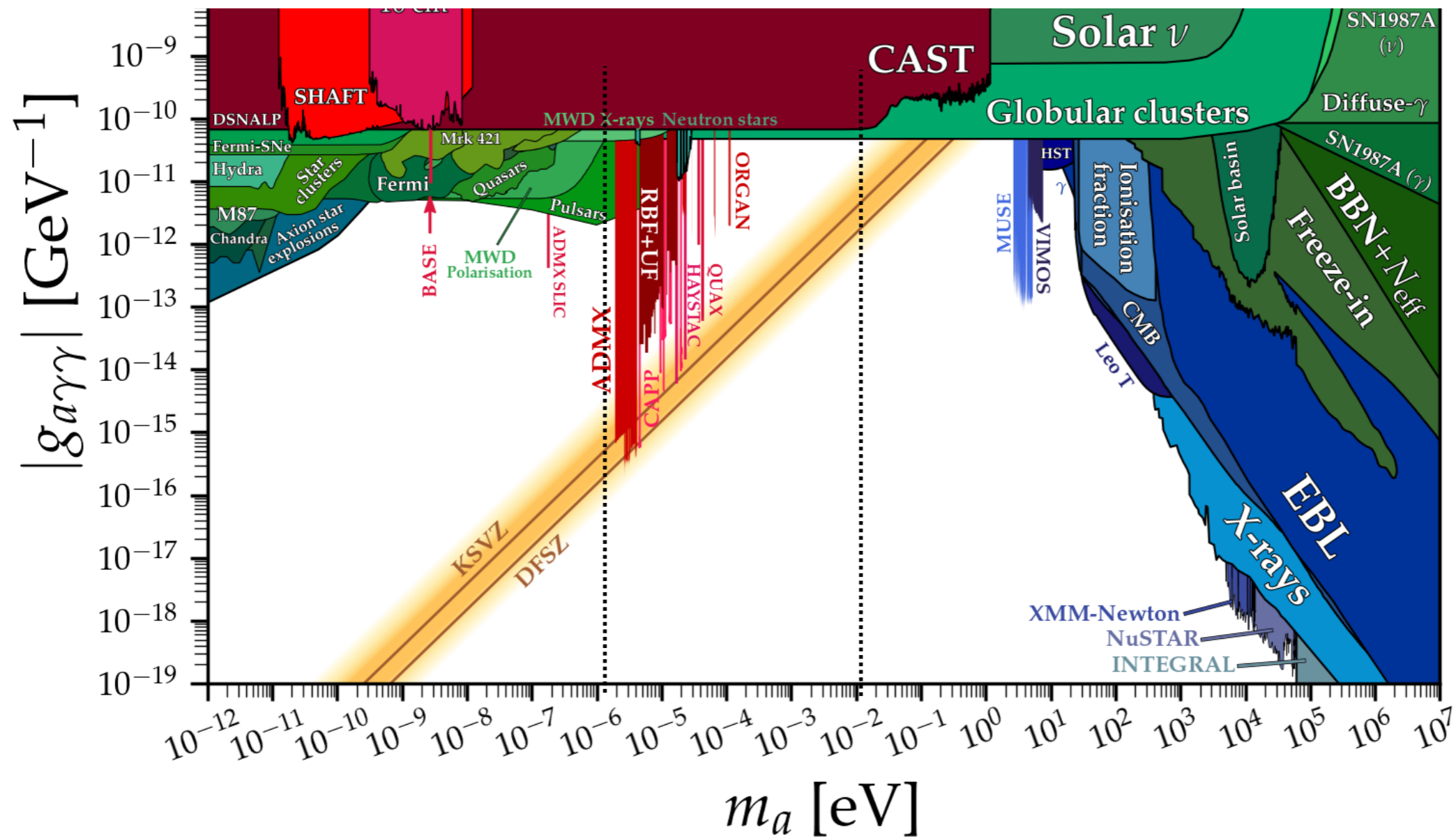
Level of parameter fine-tuning
in theory to achieve the abundance

DM abundance

Too much DM if too heavy

Limit on the axion $g_{a\gamma\gamma}$ coupling

C. O'Hare: [AxionLimits](#)



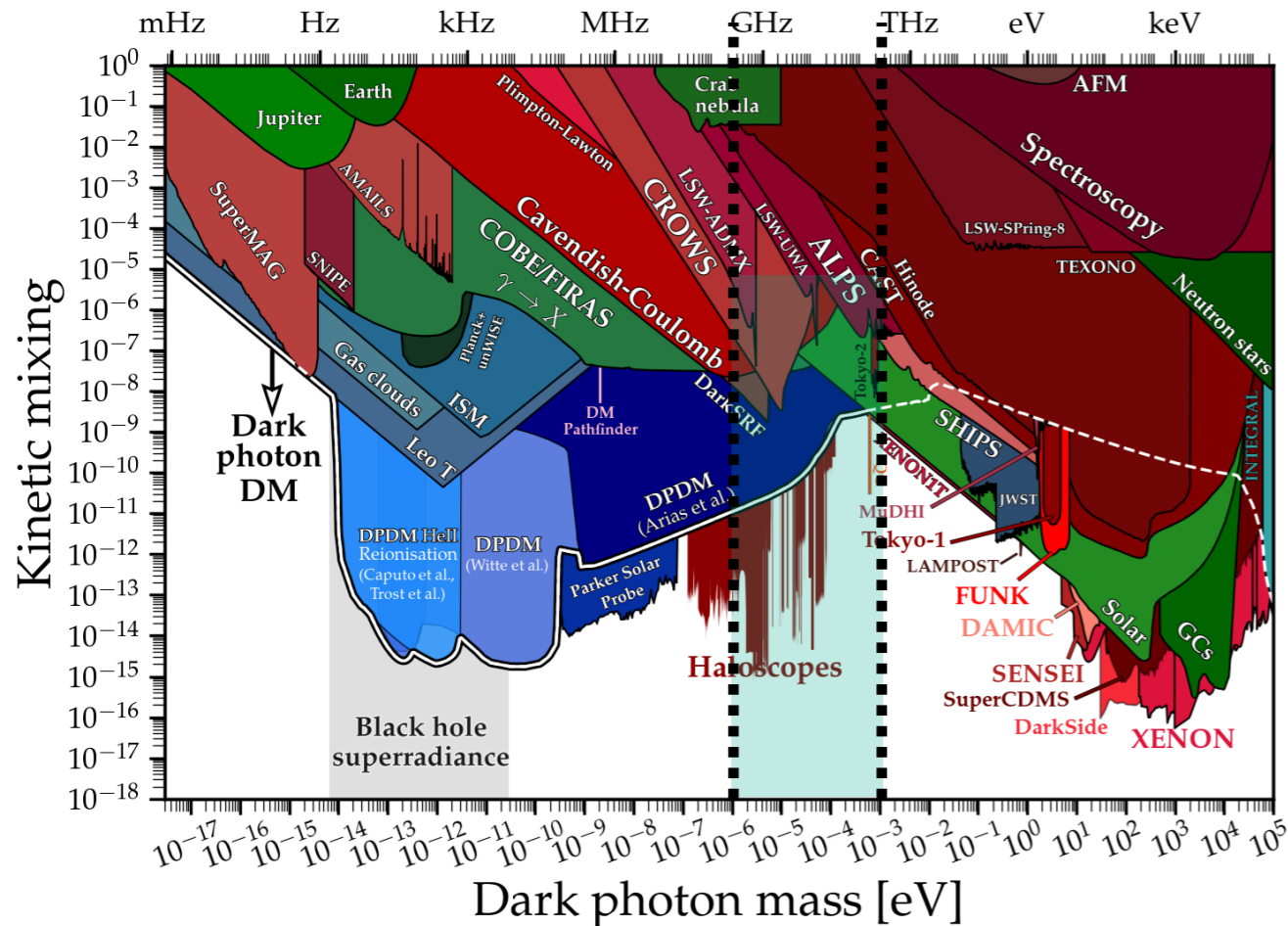
$$m_{\text{DM}} c^2 = h \frac{c}{\lambda_{\text{Compton}}}$$

Typically favored DM mass: μeV - meV

Converted photon: micro-/milli-wave (GHz-THz) \rightarrow **Superconducting qubits?**

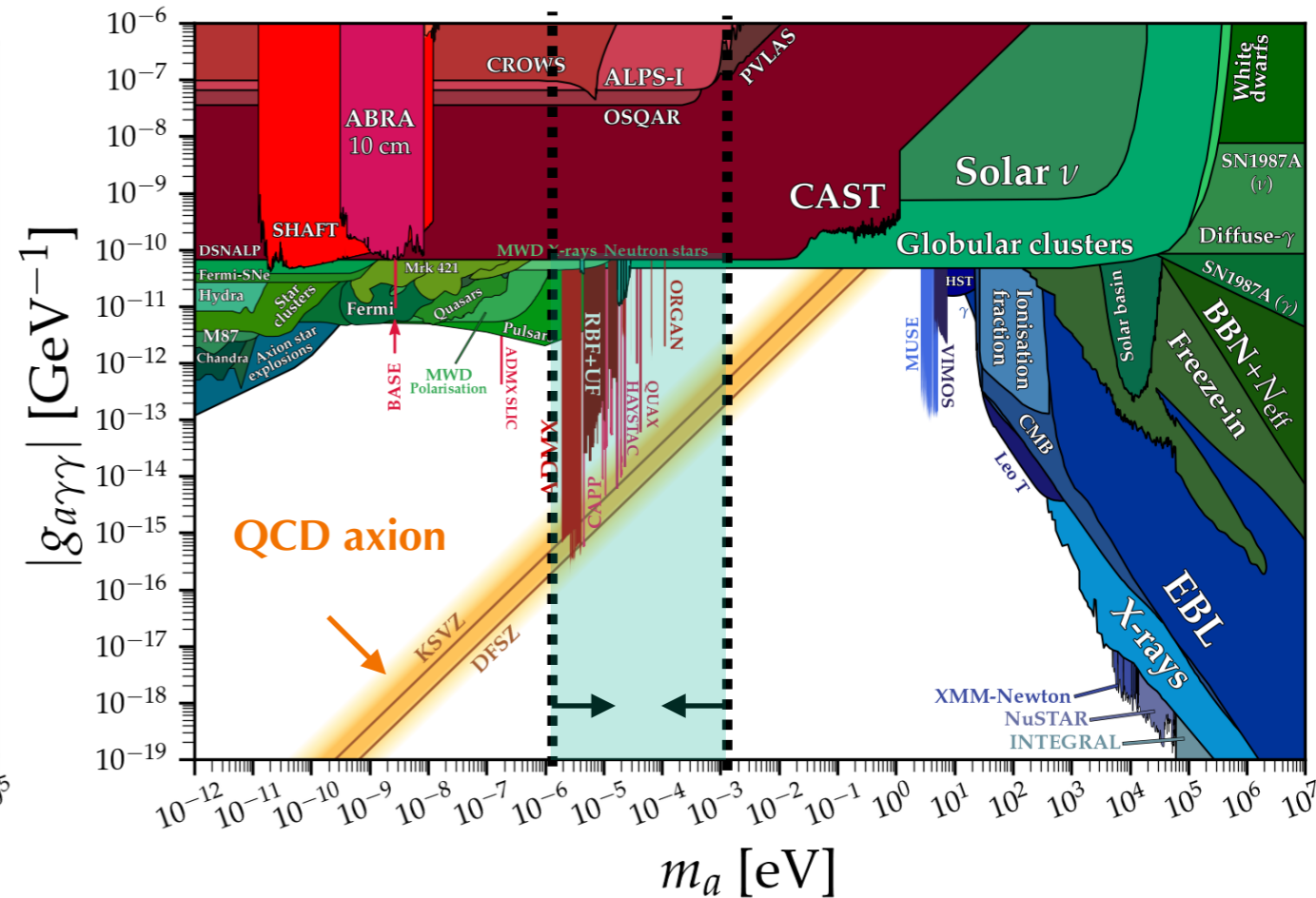
Physics targets : EM-interacting Wave-like dark matter

DARK PHOTON



AXION

Planned in the future

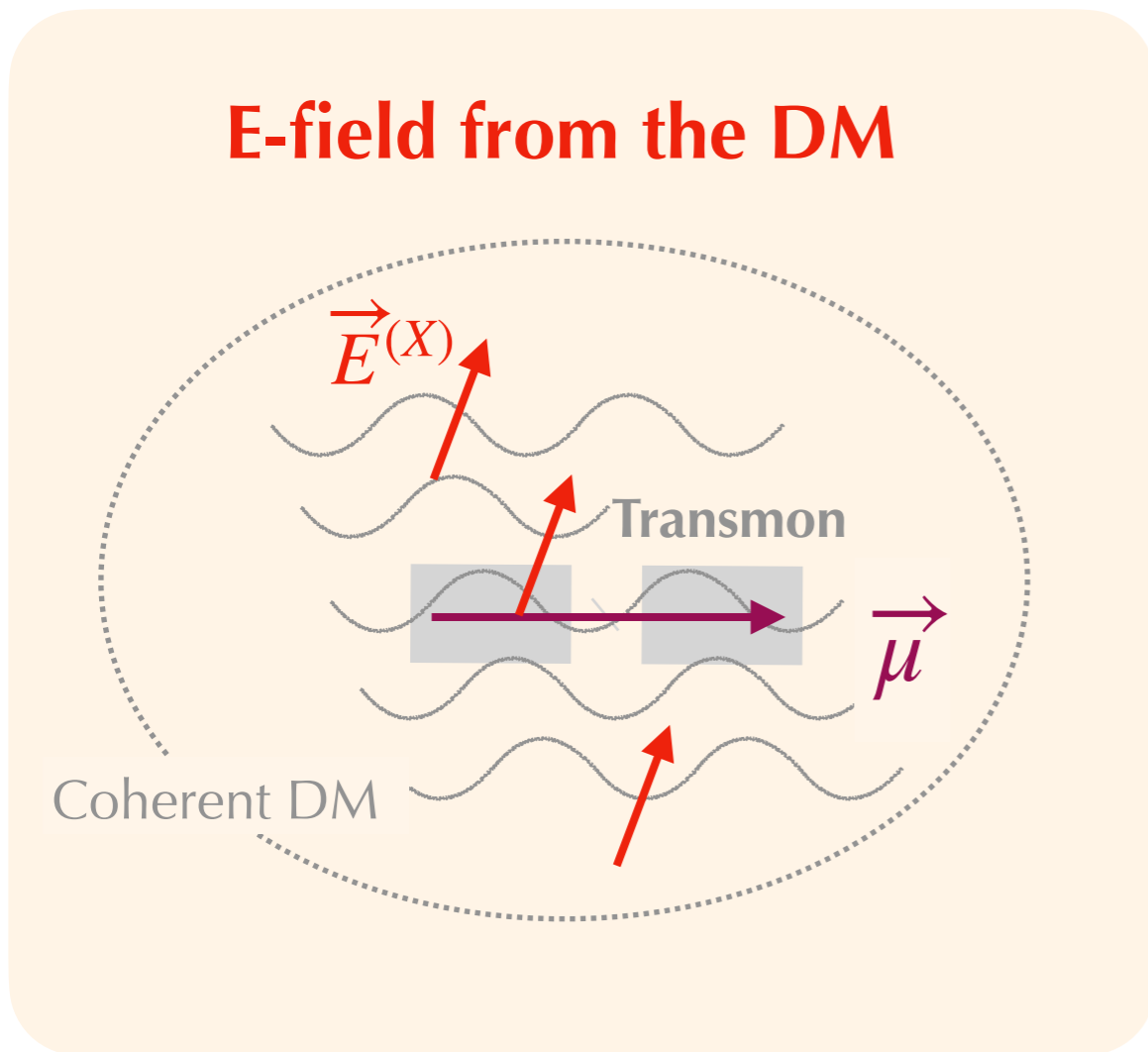


- Signal : feeble converted coherent EM field
- Microwave-Milliwave regime : μeV - meV (GHz-THz)

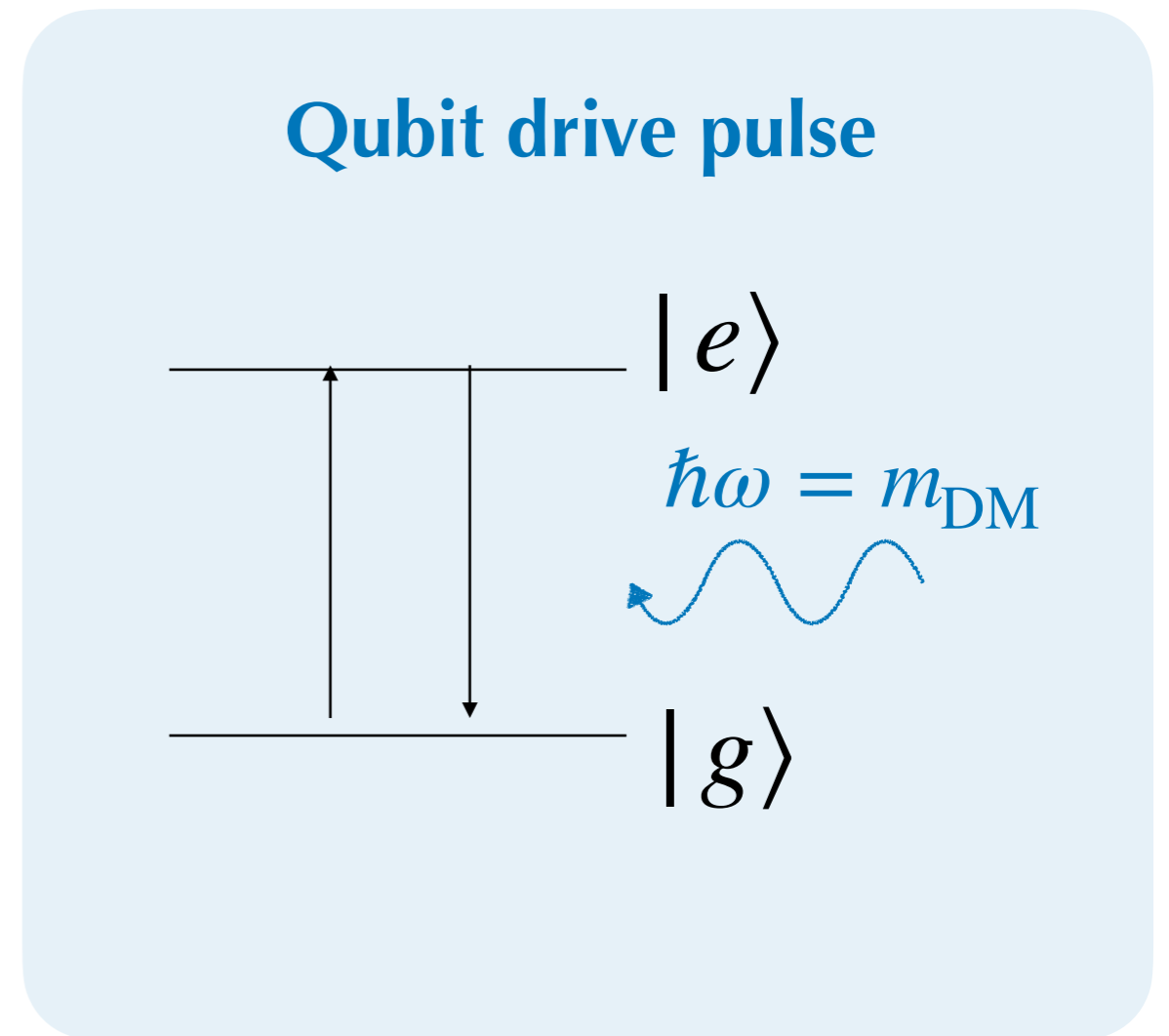
○ Non-relativistic \rightarrow mono-chronic $m_{\text{DM}}c^2 = h \frac{c}{\lambda_{\text{Compton}}}$

"Direct excitation" by dark photon

Moroi et al. PRL 131, 211001



=



Excitation rate after τ :

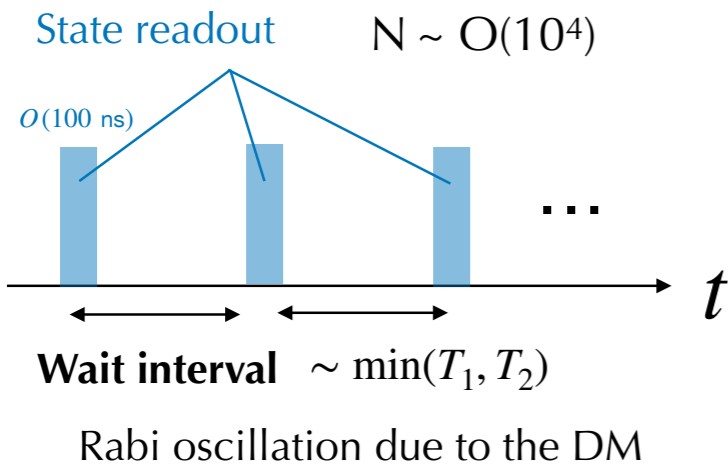
$$p \simeq 0.12 \times \kappa^2 \cos^2 \Theta \left(\frac{\epsilon}{10^{-11}} \right)^2 \left(\frac{f}{1 \text{ GHz}} \right) \left(\frac{\tau}{100 \mu\text{s}} \right)^2 \left(\frac{C}{0.1 \text{ pF}} \right) \left(\frac{d}{100 \mu\text{m}} \right)^2 \left(\frac{\rho_{\text{DM}}}{0.45 \text{ GeV/cc}}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

0.1-10% for $\epsilon=10^{-12} \sim 10^{-11}$

Search protocol

Moroi et al. PRL 131, 211001

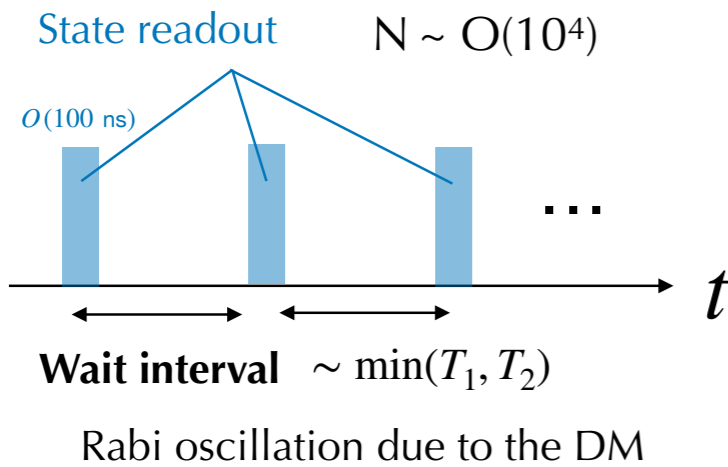
(Wait→Read)^N



Search protocol

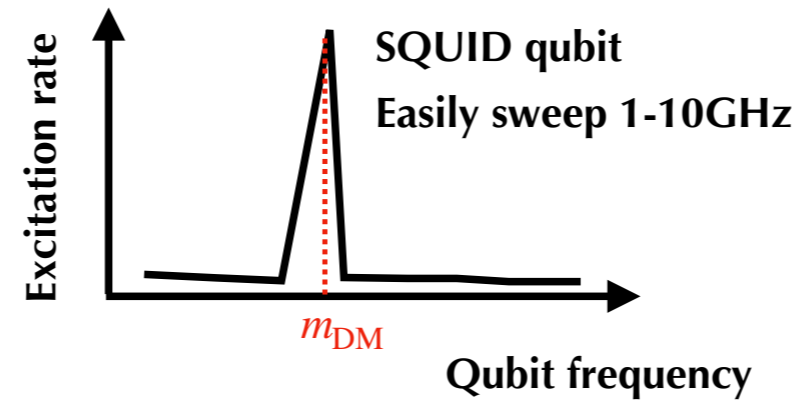
Moroi et al. PRL 131, 211001

(Wait→Read)^N



Frequency scan→bump hunting

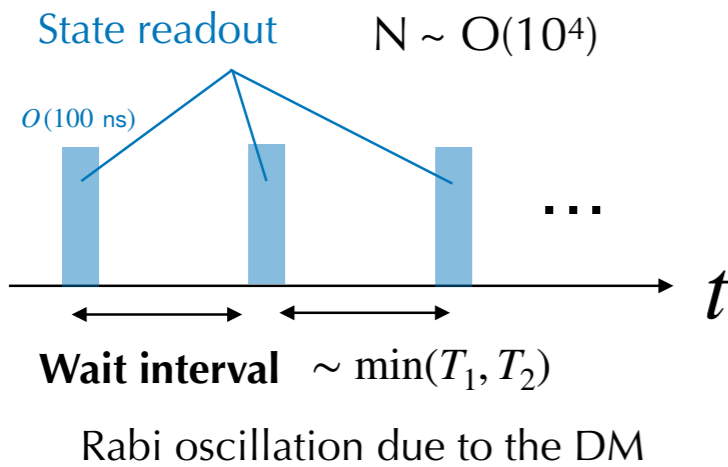
Excitation rate = fraction of $|e\rangle$ readout



Search protocol

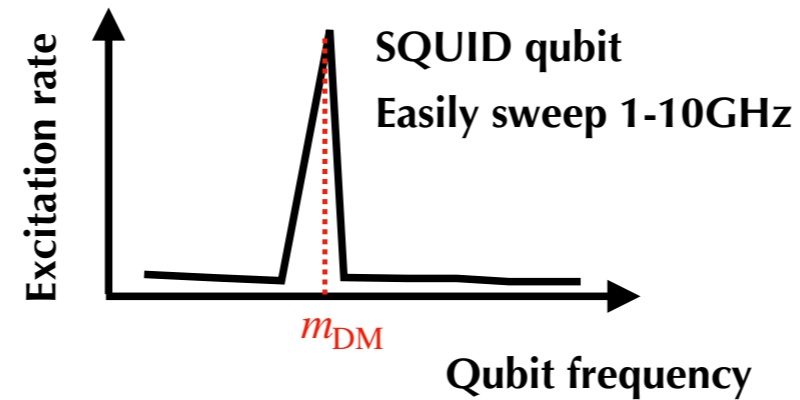
Moroi et al. PRL 131, 211001

(Wait→Read)^N

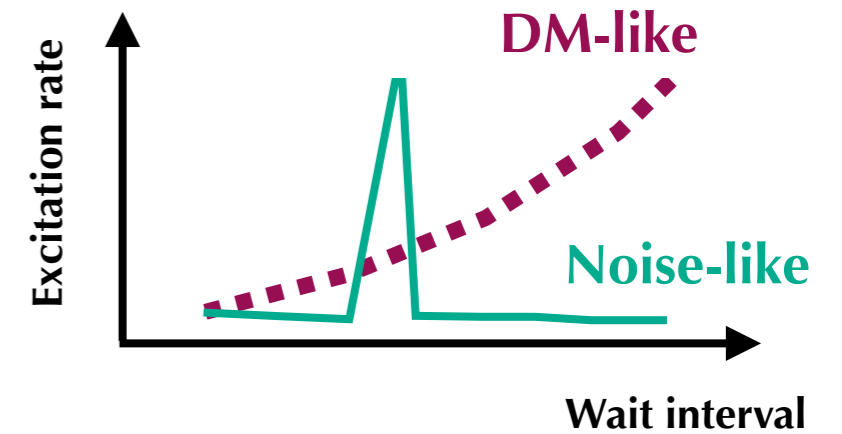


Frequency scan→bump hunting

Excitation rate = fraction of $|e\rangle$ readout



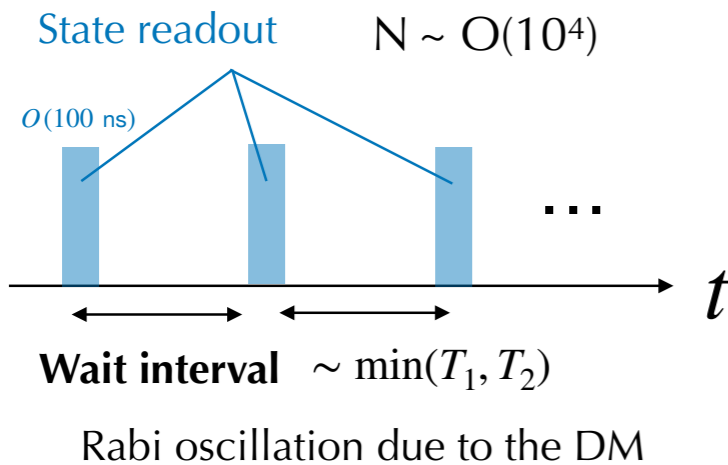
Revisit the suspicious freq.



Search protocol

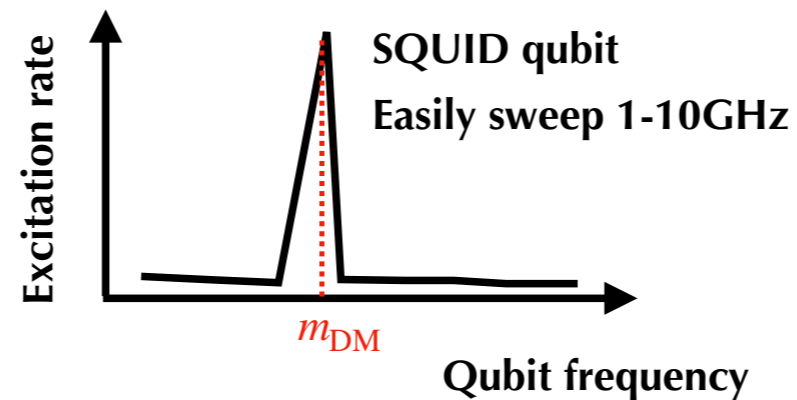
Moroi et al. PRL 131, 211001

(Wait→Read)^N

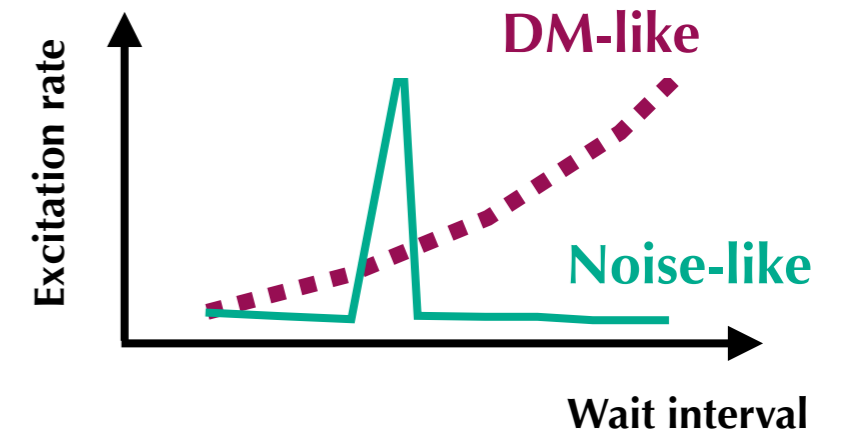


Frequency scan→bump hunting

Excitation rate = fraction of $|e\rangle$ readout



Revisit the suspicious freq.



Not many noises can cause $|g\rangle \rightarrow |e\rangle$

Thermal: $p \sim e^{-\hbar\omega/kT}$ 0.01-1% @30mK

Readout error : ~0.1%

Sensitivity not strongly bounded by coherence time

Short $T_1 \rightarrow$ Faster cycle

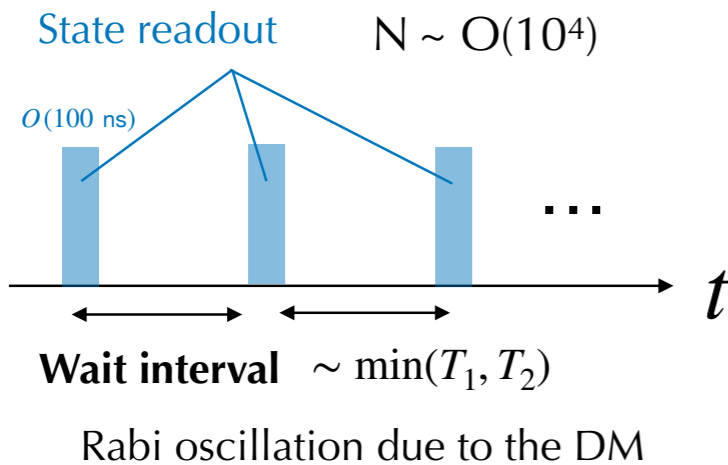
Larger width (fewer step to scan)

- ✓ Relax the fabrication requirement
- ✓ Pursuit of qubits with stronger coupling

Search protocol

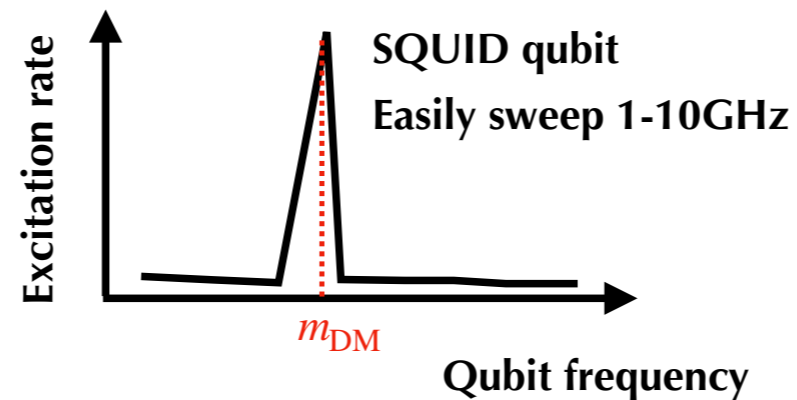
Moroi et al. PRL 131, 211001

(Wait→Read)^N

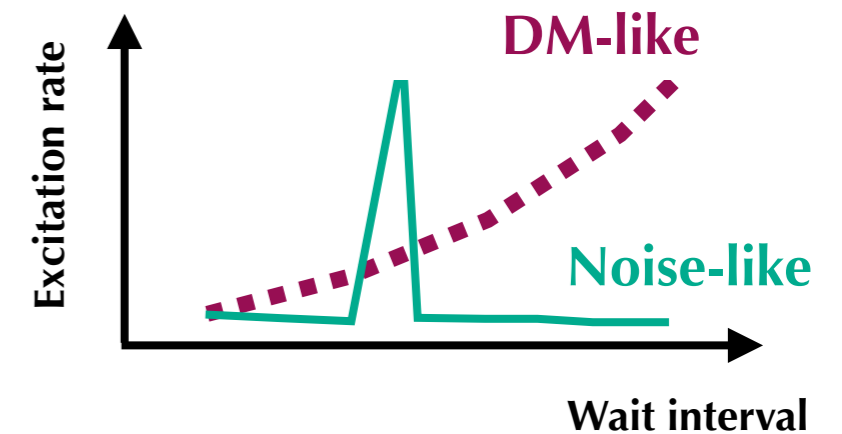


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Distinguishing from the noises?

- Different response against the packaging tightness
- Cross-checking by the other experiments
- "Per-search" for the suspicious frequencies

Sensitivity not strongly bounded by coherence time

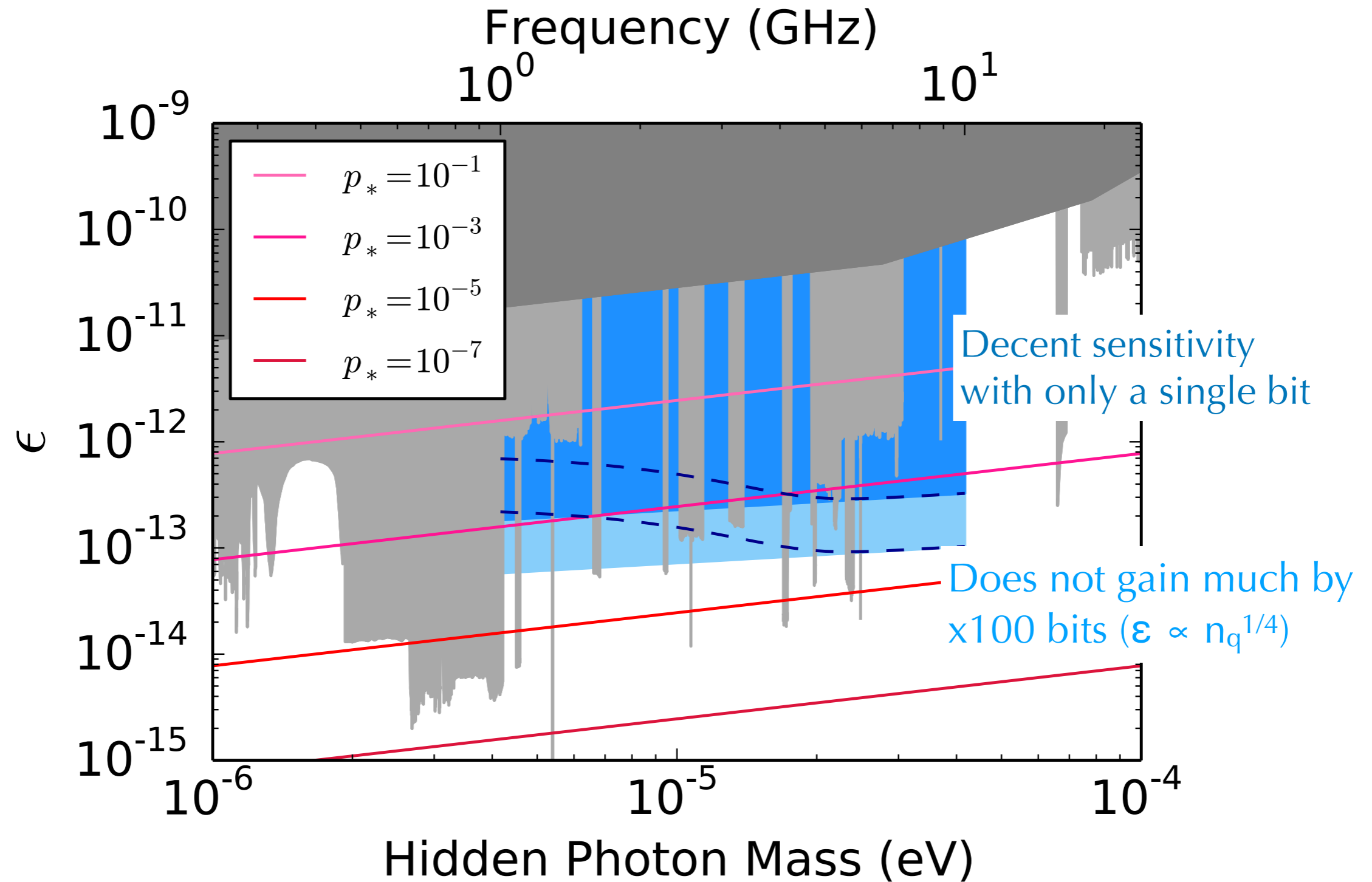
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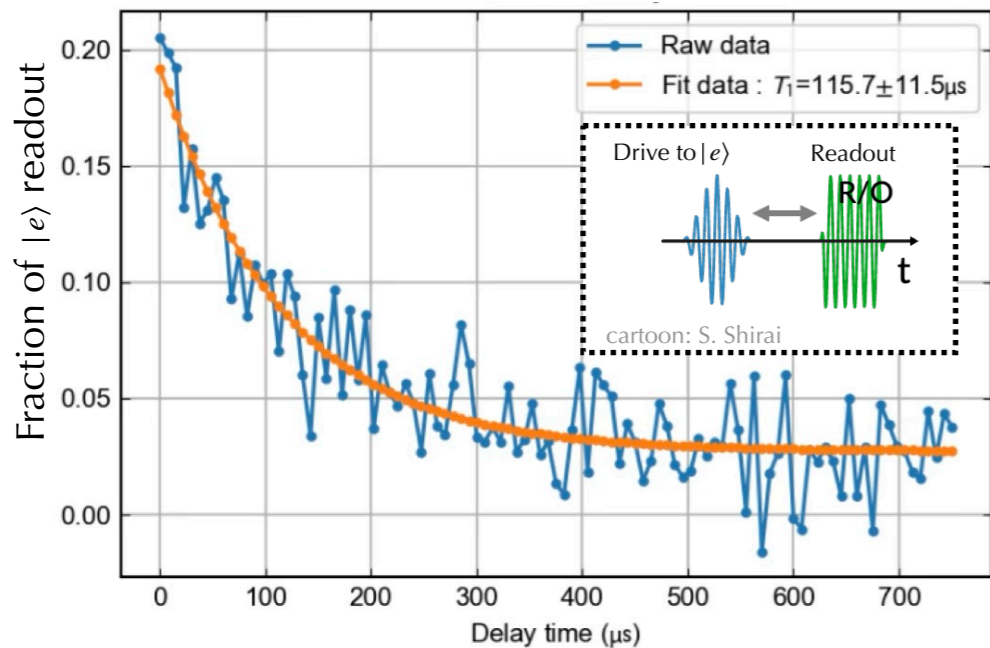
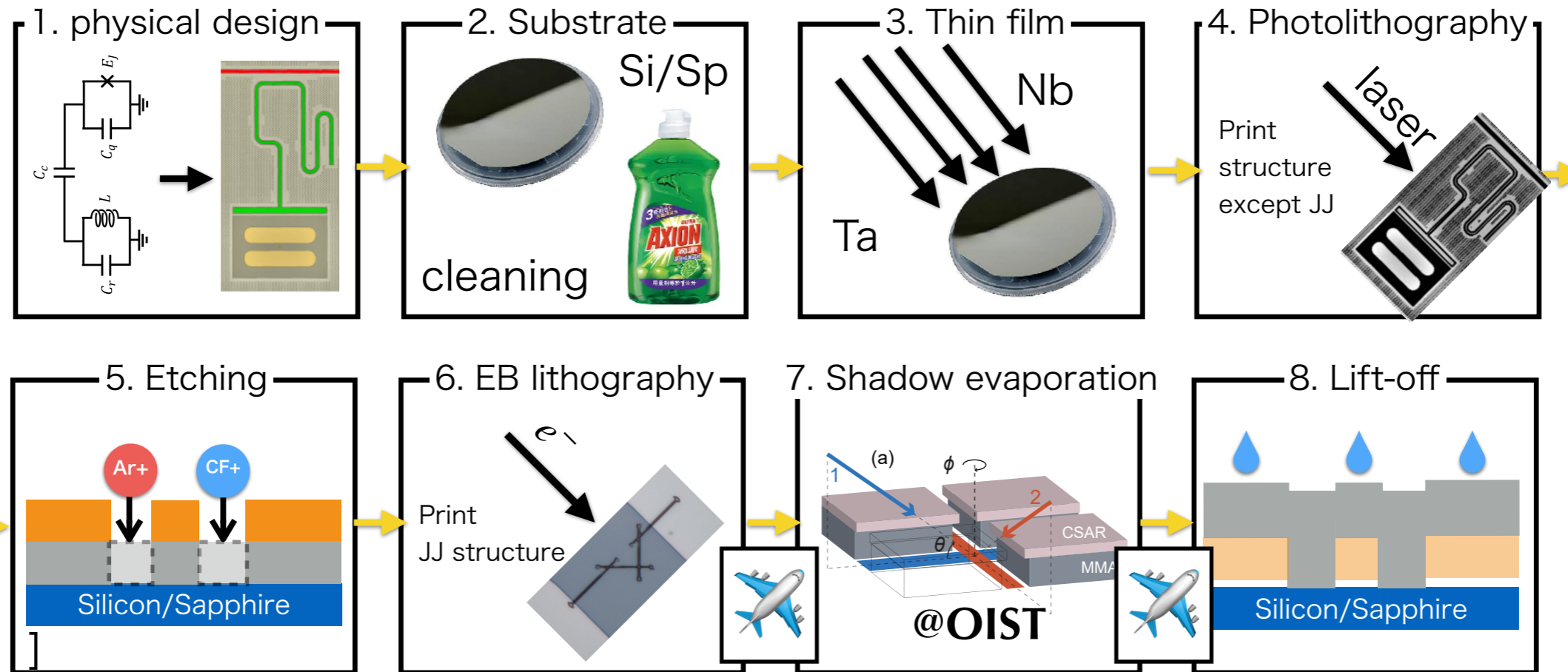
- ✓ Relax the fabrication requirement
- ✓ Pursuit of qubits with stronger coupling

Sensitivity projection

Moroi et al. PRL 131, 211001



Qubit fabrication



○ Fabrication site : UTokyo / KyotoU + OIST

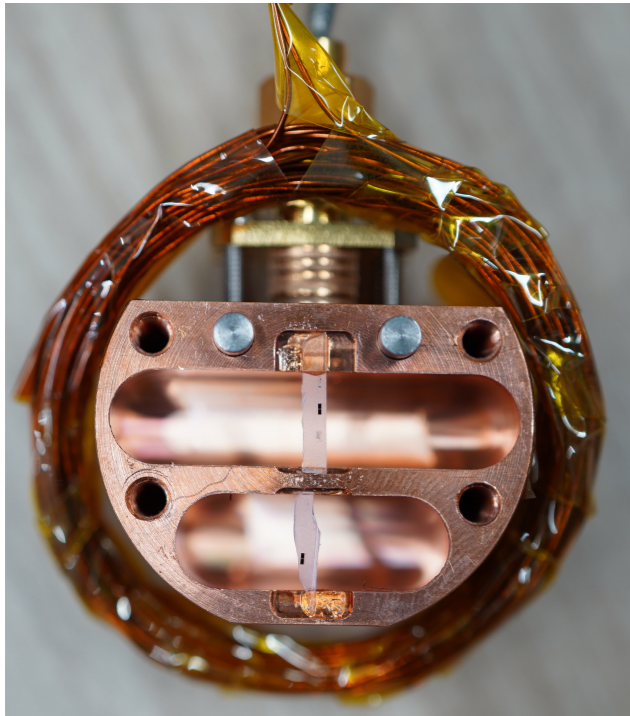
○ Achieved coherence :

3D: $T_1 \sim 10\text{-}30\mu\text{s}$, $T_2 \sim 5\mu\text{s}$

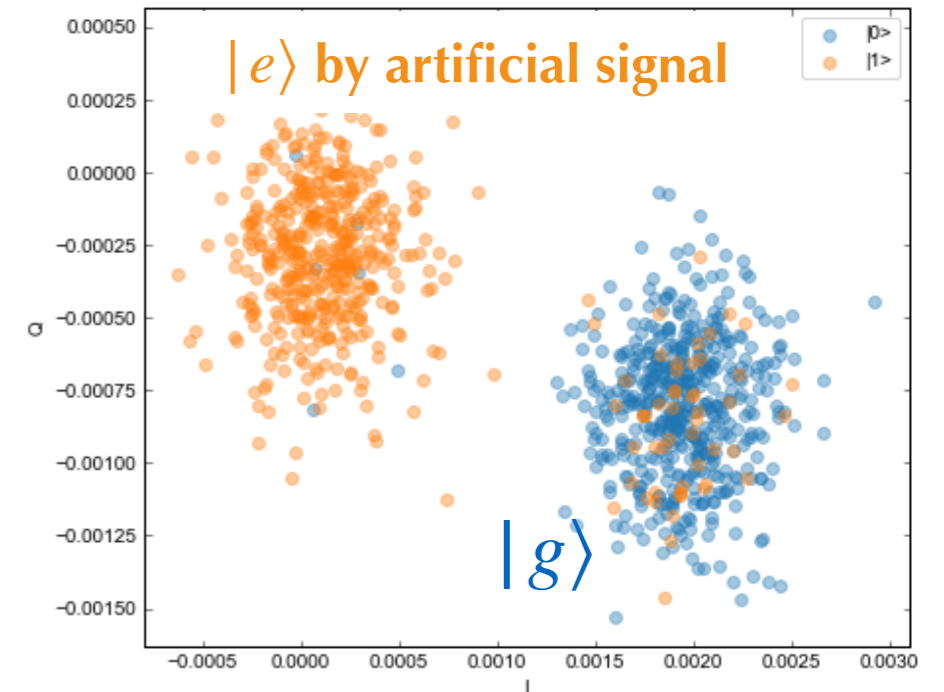
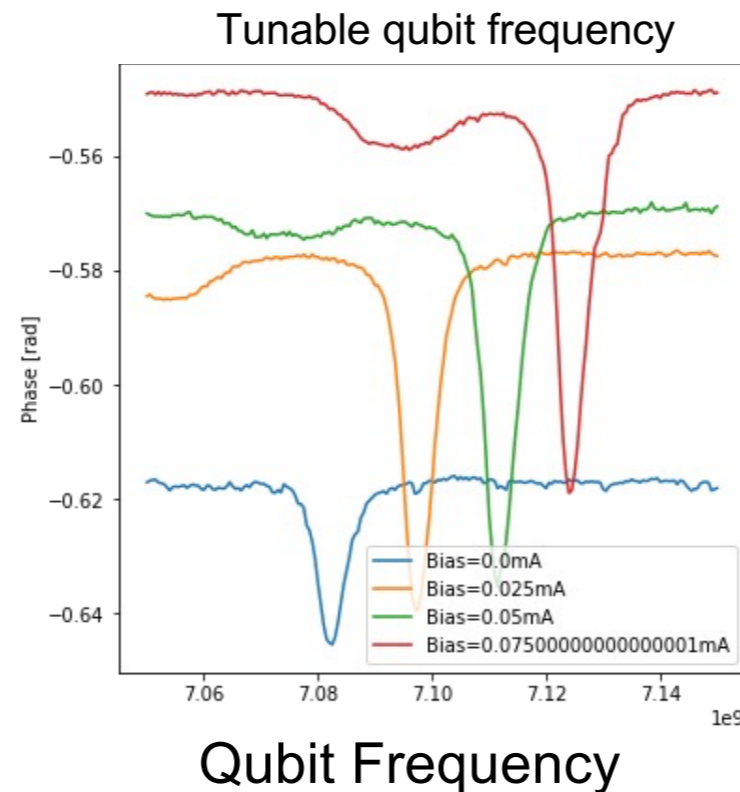
2D: $T_1 > 100\mu\text{s}$, $T_2^* > 200\mu\text{s}$

Best qubits among airplane-involved fabrication recipes?

Demonstration experiment using the 3D implementation



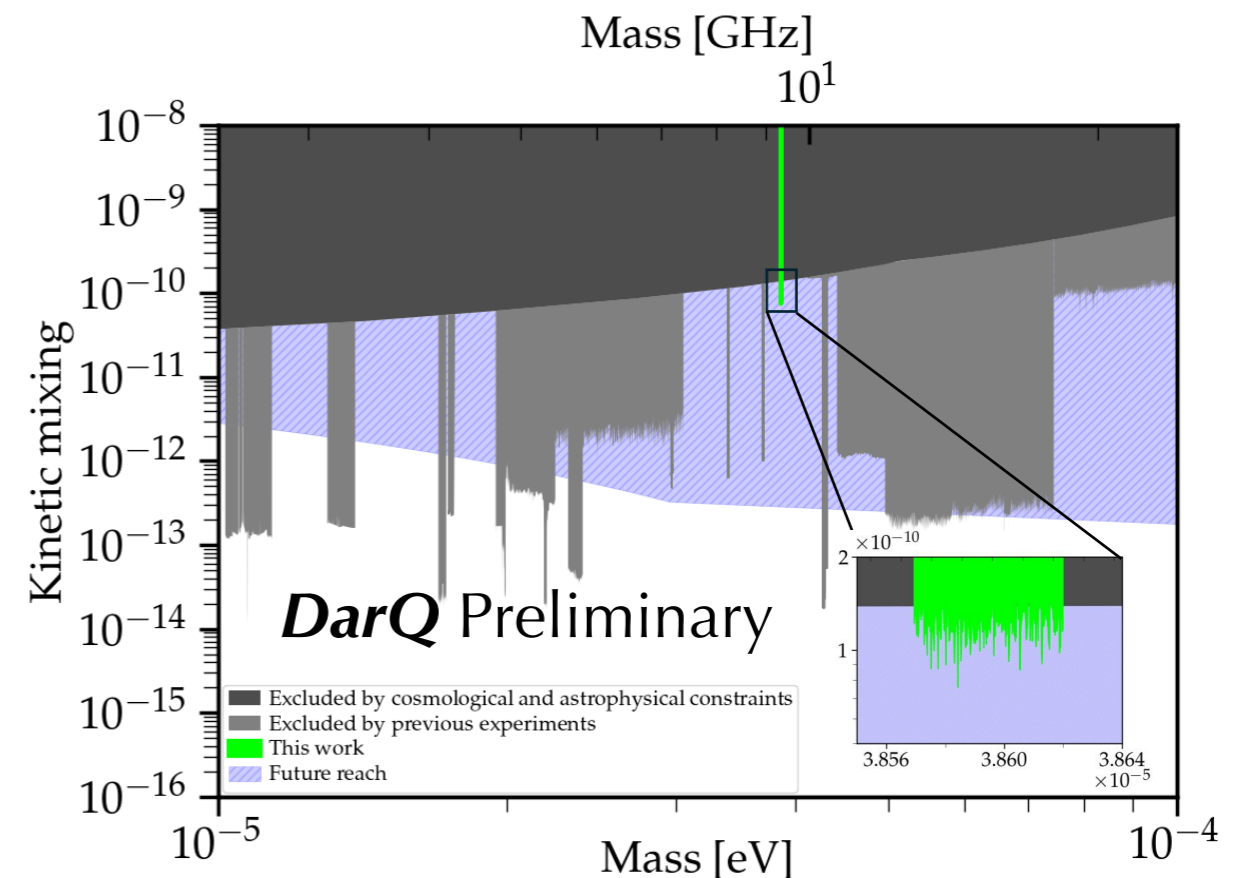
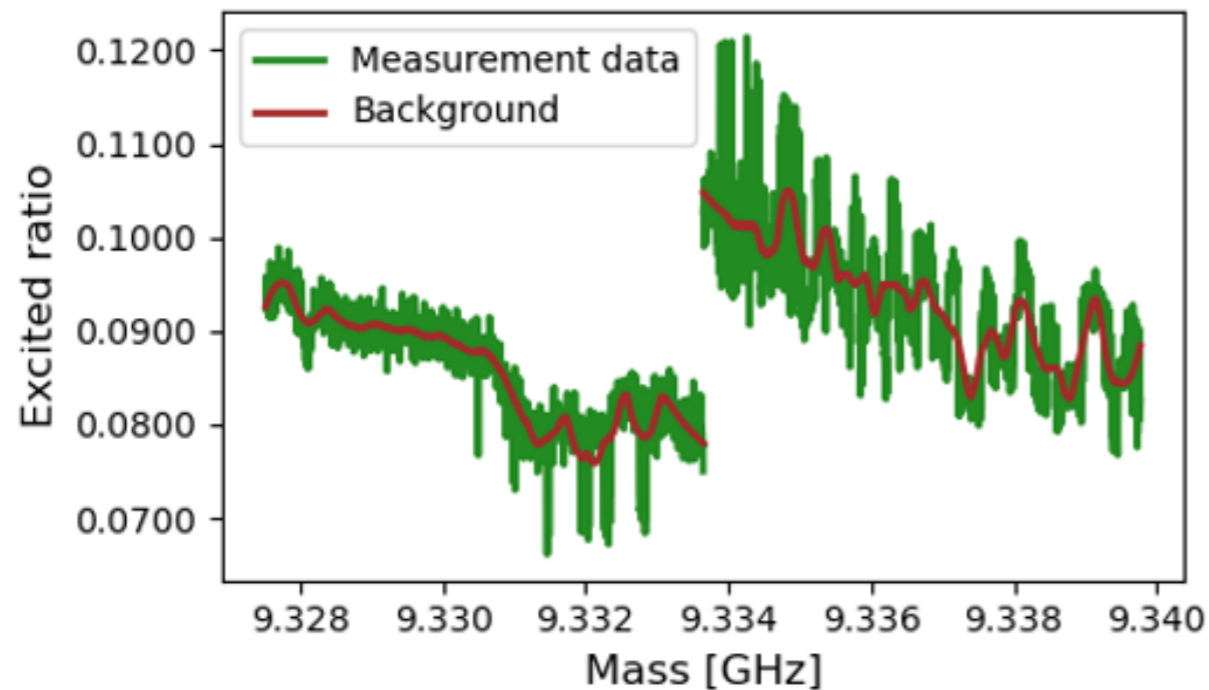
Encapsulated in a readout cavity surrounded by a bias coil



- Experiment sites : UTokyo CRC mili-kelvin quantum platform / KEK-QUP
- Validated the frequency tuning using bias coil
- Readout fidelity / thermal residual characterization
> 95% fidelity for $|0\rangle$ readout

Demonstration experiment using the 3D implementation

12MHz / 22hrs



Planned improvements for the next runs

- Better noise / heat treatment etc.
- Introduction of high quality qubit ($T_1 > 300 \mu\text{s}$, fabricated in RIKEN's CR)

DAQ challenges

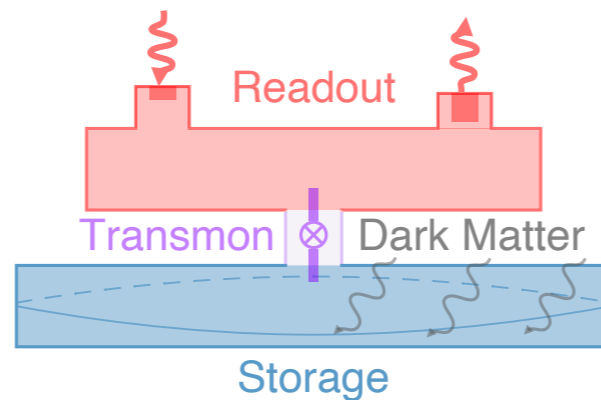
- T_1/T_2 unstable: Need T_1/T_2 measurement on each freq step \rightarrow stabilization?
- Varying pi-pulse, I/Q profile etc. according to freq scan \rightarrow dynamic state determination

Free space photon \rightarrow Accumulated/focused photons



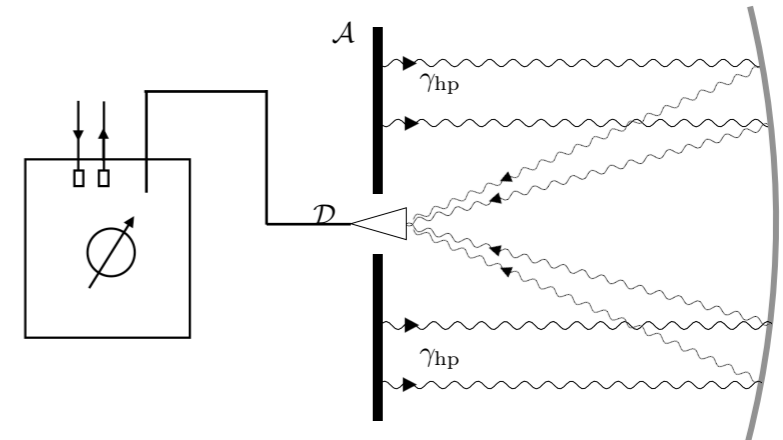
Free space

- $Q=1$
- Easy f tuning (SQUID)



Cavity

- $Q=10^{4-6}$
- Complicated tuning (bar)
- Devastating mode crossings



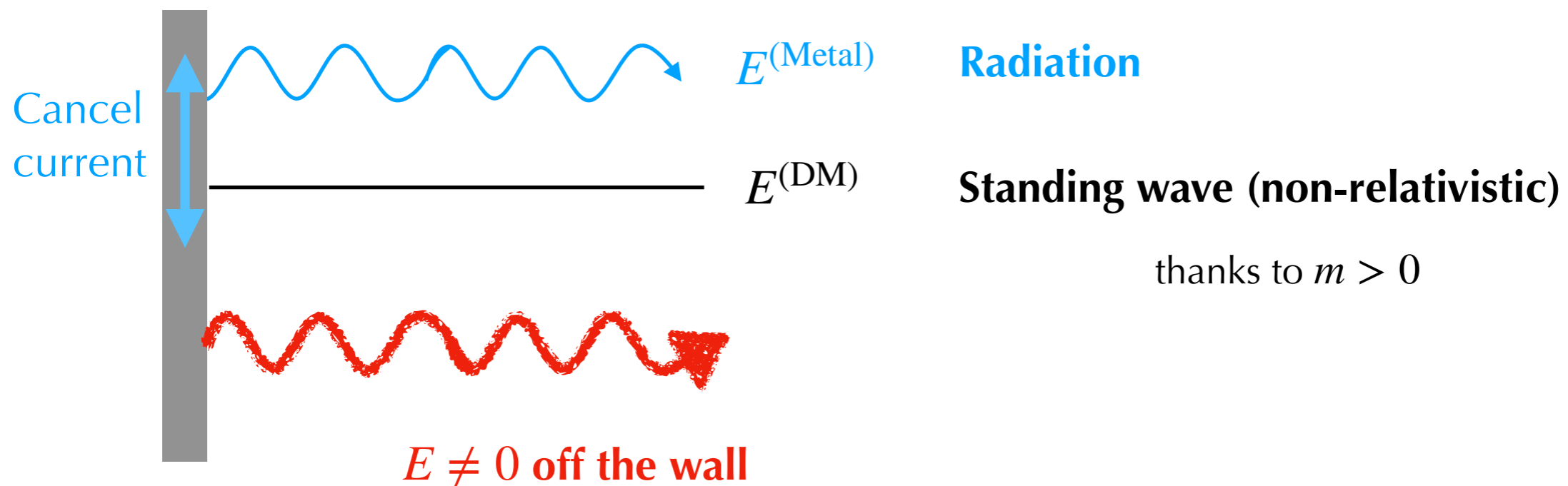
Dish antenna

- $Q=10^{2-3}$
- Easy f tuning (SQUID)

Dish antenna idea

$$\begin{pmatrix} \mathbf{E} \\ \mathbf{E}_{\text{hid}} \end{pmatrix}_{\text{total},\parallel} = \mathbf{E}_{\text{DM},\parallel} \left[\begin{pmatrix} 1 \\ \chi \end{pmatrix} \overset{E^{(\text{Metal})}}{\exp(-i(\omega t - \mathbf{k}\mathbf{x}))} + \frac{1}{\chi} \begin{pmatrix} -\chi \\ 1 \end{pmatrix} \overset{E^{(\text{DM})}}{\exp(-i\omega t)} \right]_{x=0}$$

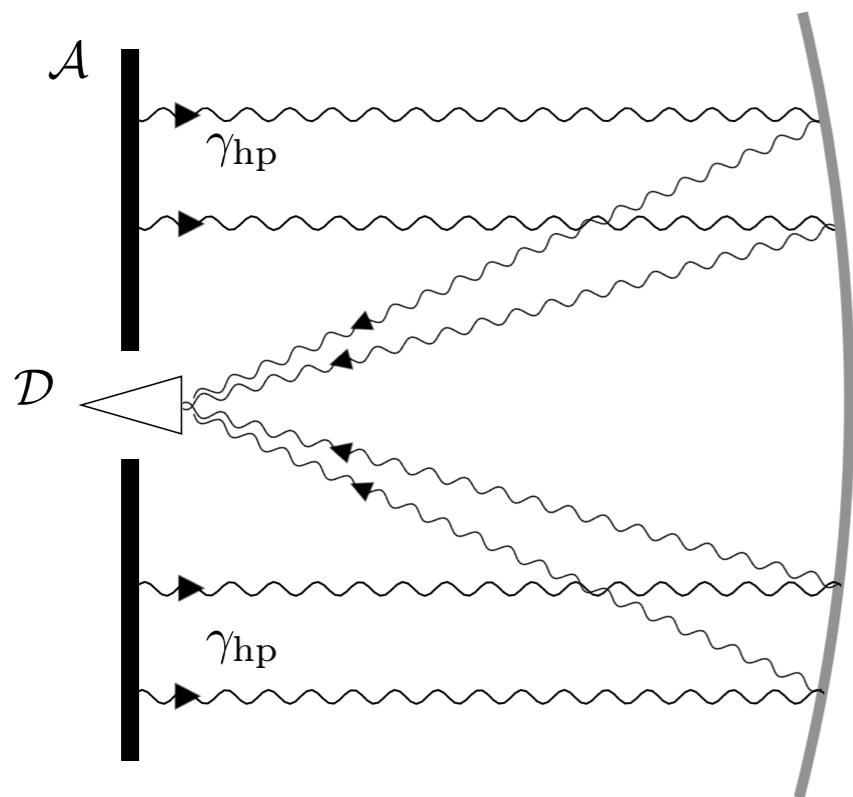
Strictly $E = 0$ inside the wall



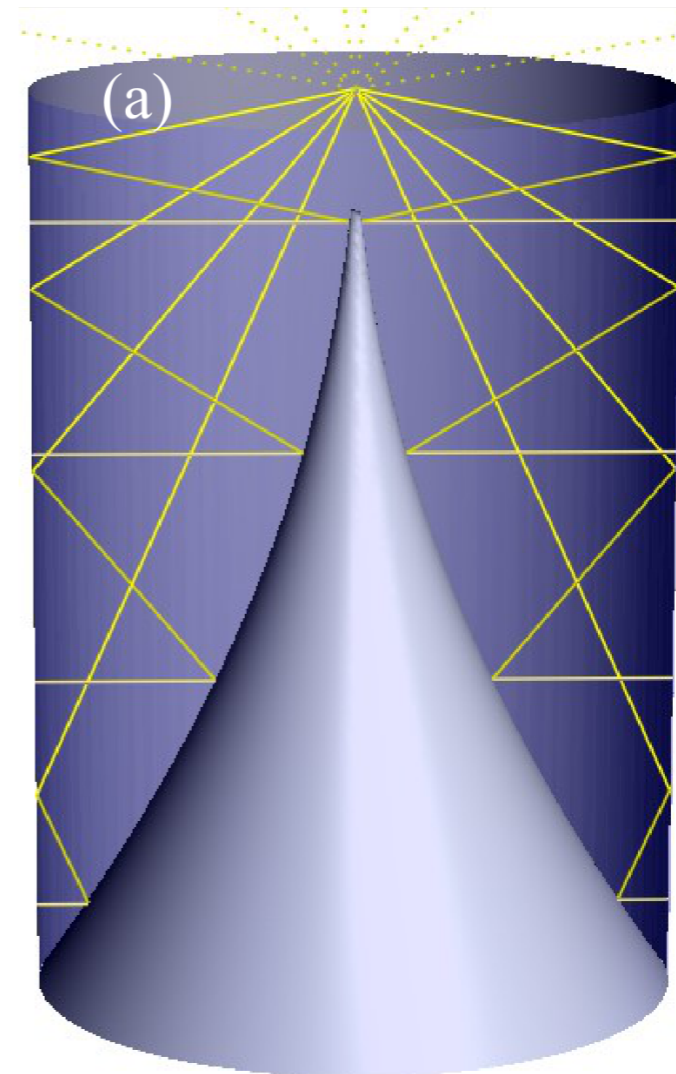
Feeble photon cloud in vacuum, feeble photon "wind" from the wall

Dish antenna idea - Radiation can be "focused"

BRASS-p/DOSUE-RR : RT reflectors

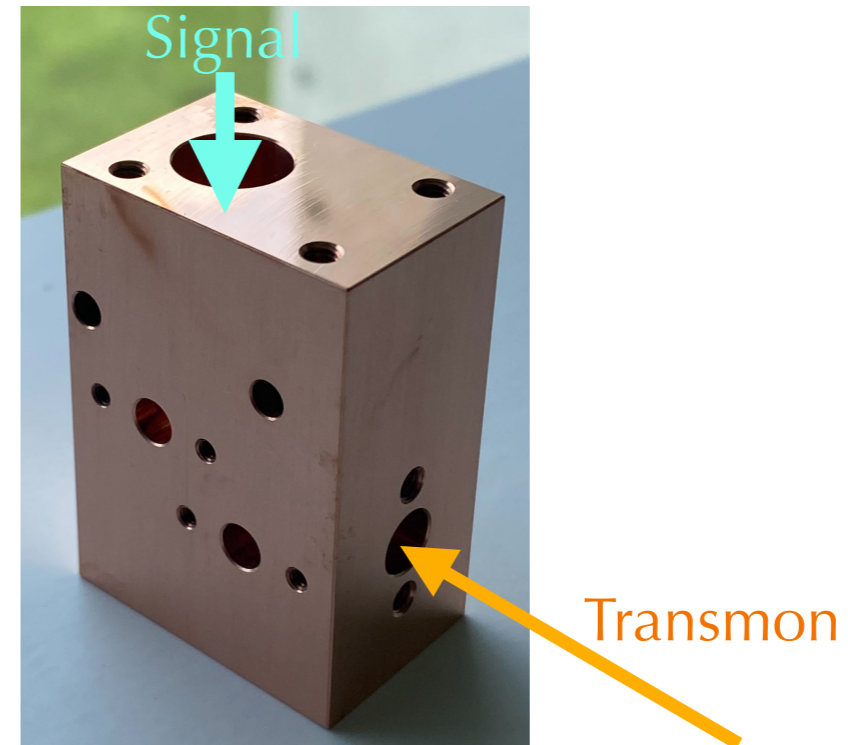
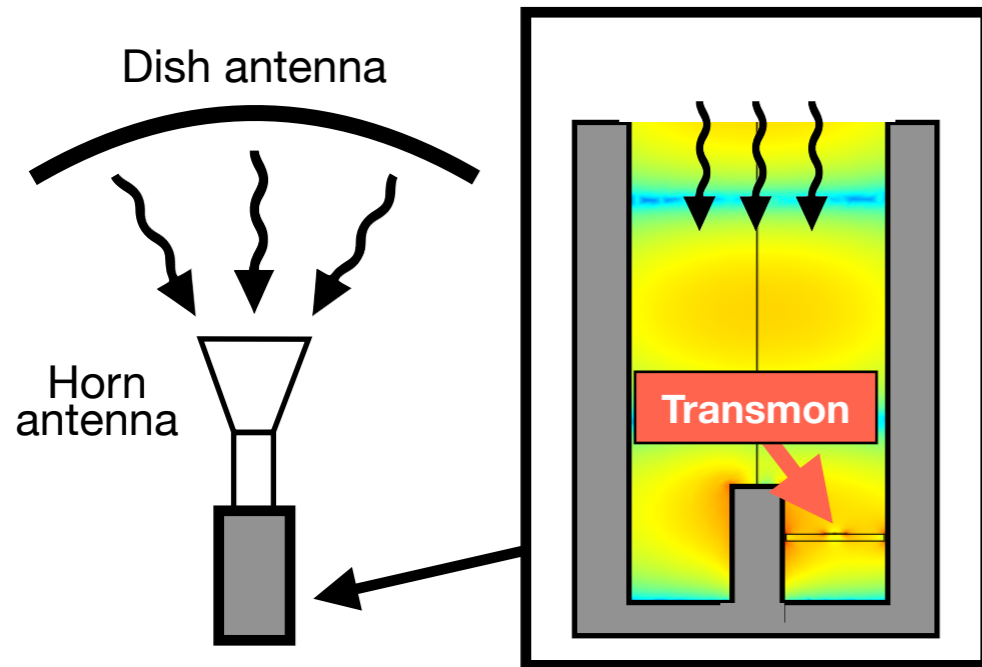


BREAD

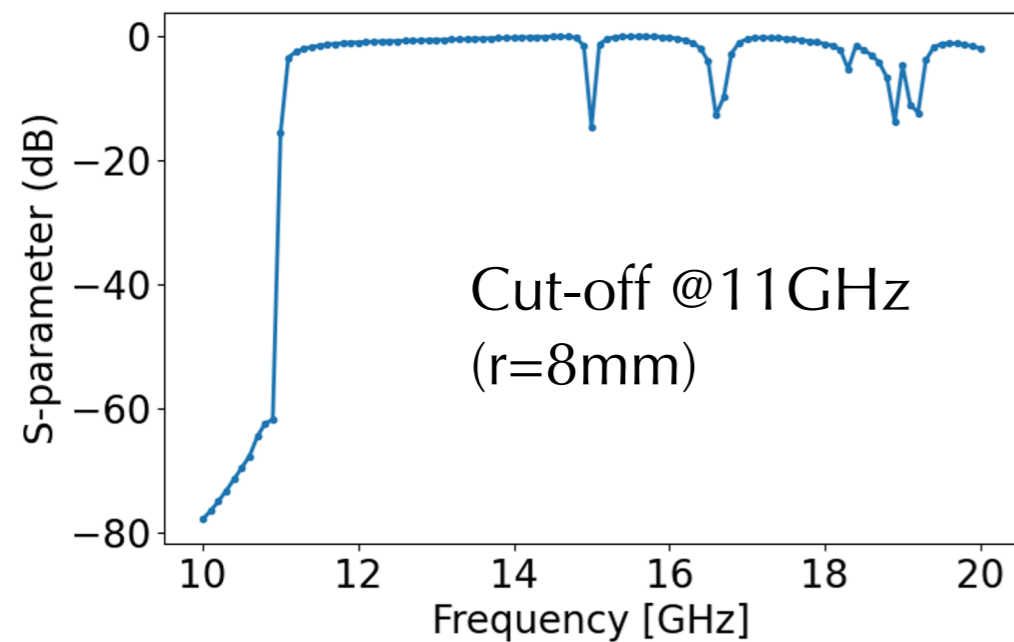


Cryogenic reflector inside the fridge

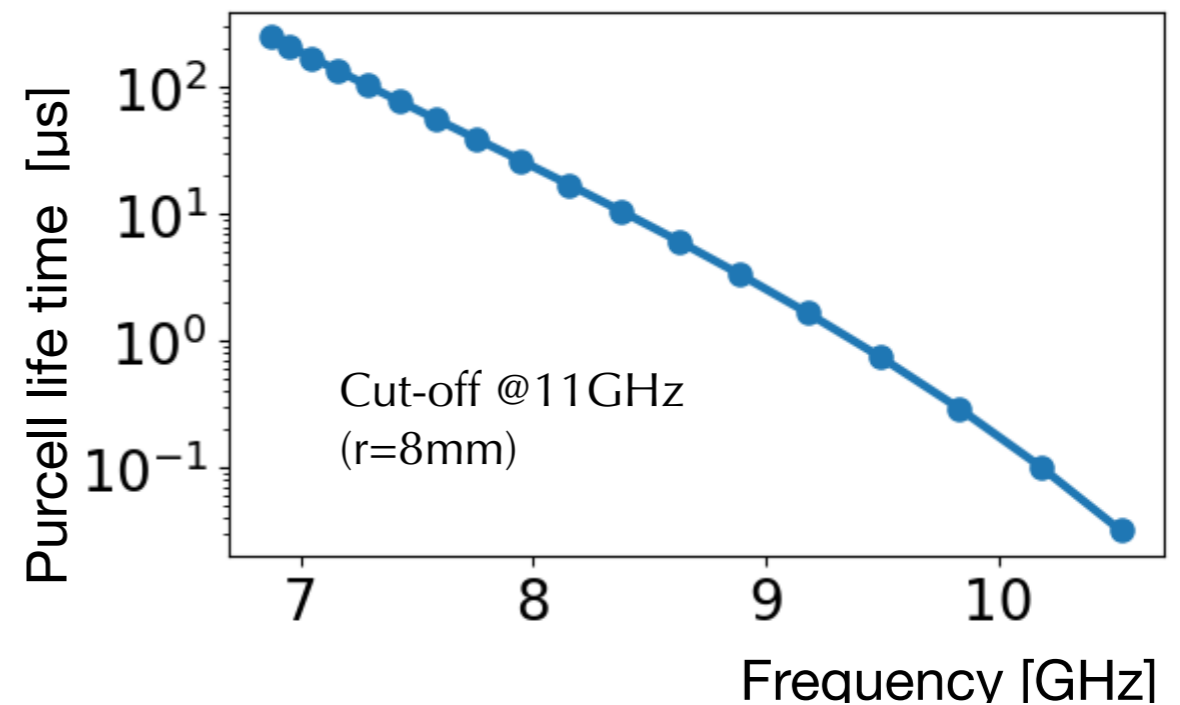
Dish antenna idea - How to introduce the field?



Signal introduction rate vs Purcell trade-off



Off-resonant readout regime being considered
e.g. ac Stark shift based single photon detection

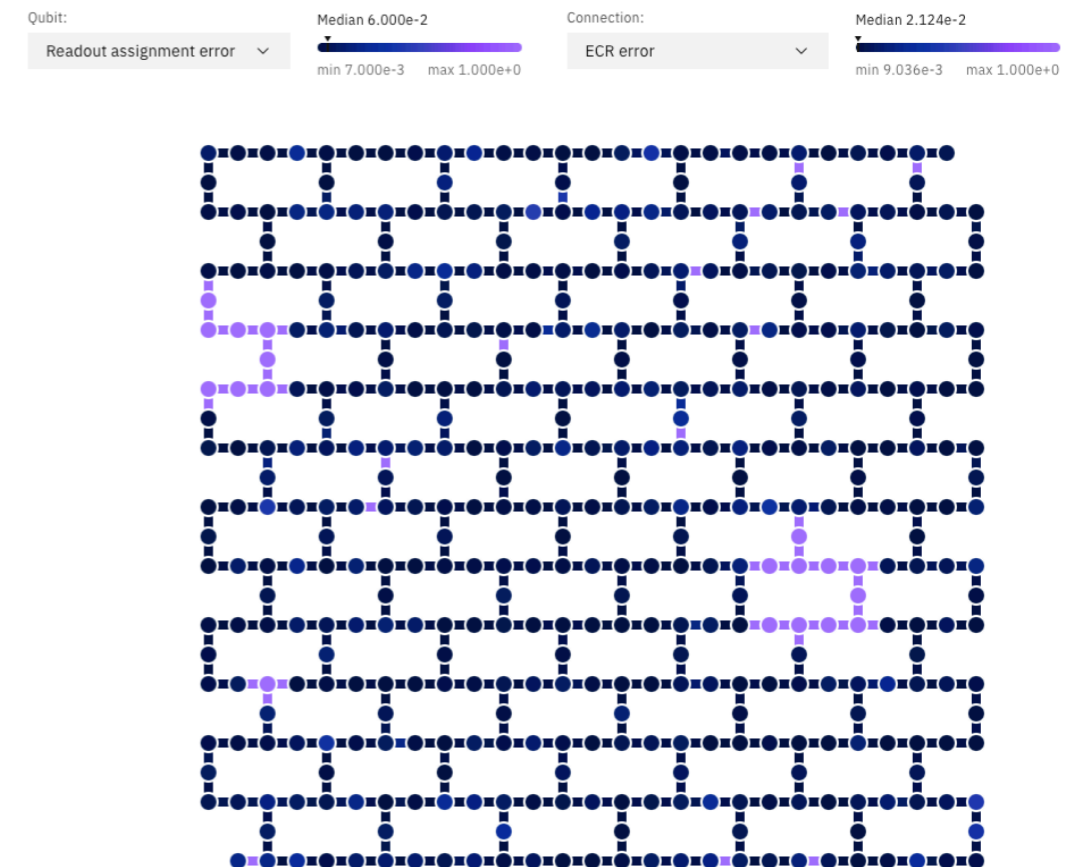


Search in an actual quantum computer?

IBM-Quantum ([link](#))

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
ibmq_kawasaki	27	128	-	● Online	120	Falcon r5.11
ibmq_cairo	27	64	2.4K	● Online - Queue paused	673	Falcon r5.11

Items per page: 10 ▾ 1-10 of 26 items 1 ▾ of 3 pages ◀ ▶



😊 Array of high quality qubits

😊 Regular calibration

😊 Optimal readout & control

😞 Fixed frequency

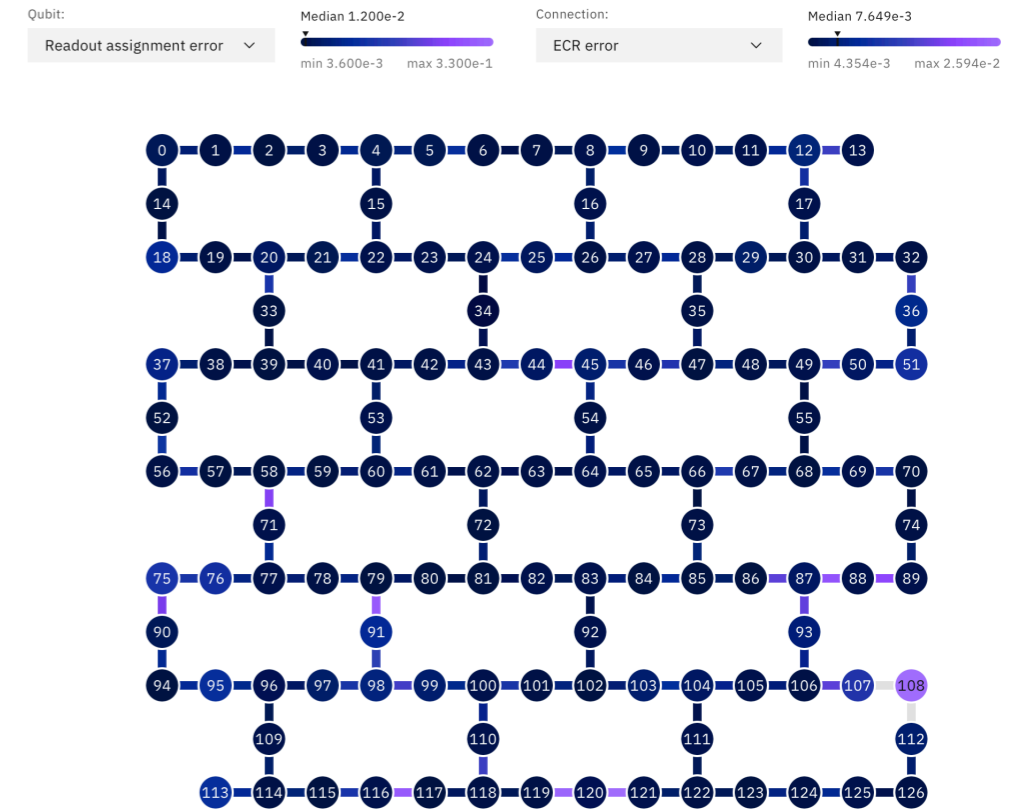
😞 No B-field (→ dark photon only)

😞 Qubit parameter unknown
Discovery only, no limits

Our DM detector



Kawasaki



as of 16th Sep 2024

127

Qubits

3.2%

EPLG

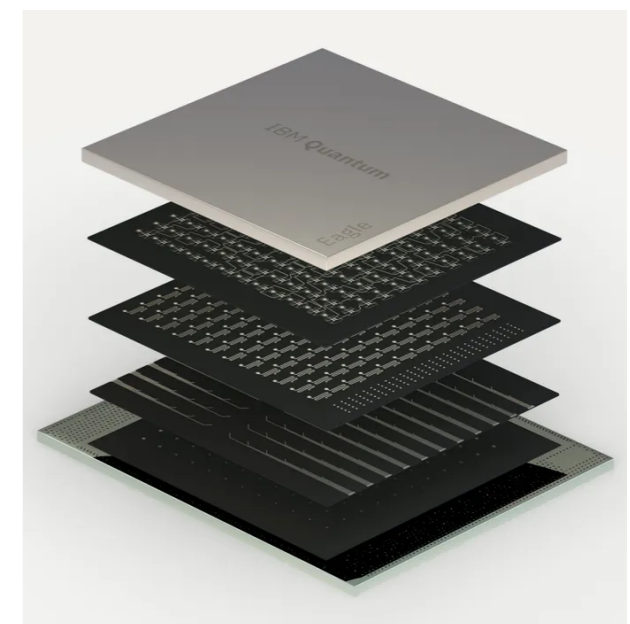
29K

CLOPS

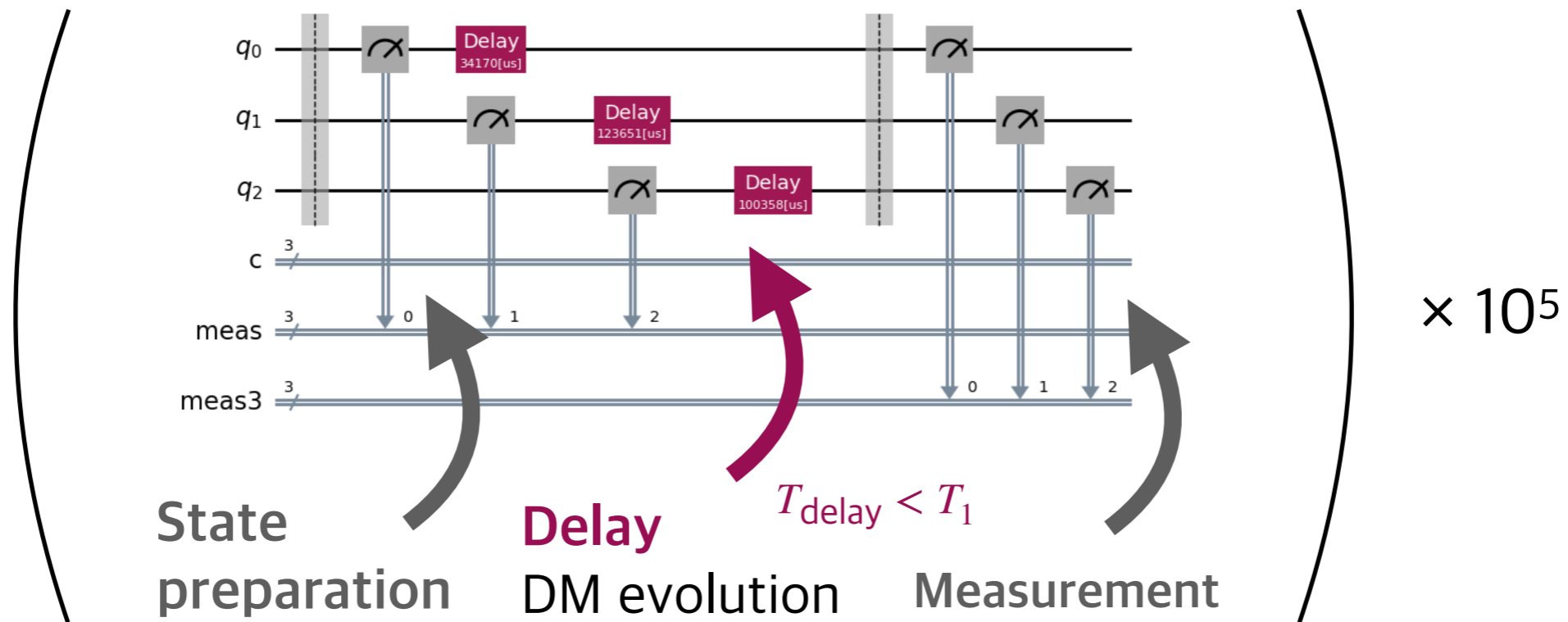
Status:	● Online
QPU region:	us-east
Total pending jobs:	1222 jobs
Processor type ⓘ:	Eagle r3
Version:	2.1.37
Basis gates:	ECR, ID, RZ, SX, X
Your instance usage:	157 jobs

Median ECR error:	7.134e-3
Median SX error:	2.449e-4
Median readout error:	1.130e-2
Median T1:	197.19 us
Median T2:	140.62 us

127-bit Eagle processor



e.g. $n_q=3$ $n_q=127$ in actual experiment



```

def submit(delay, shots=100000, ncircuits=600, session=None, batch=None):
    circuits = []
    for i in range(ncircuits):
        qr = QuantumRegister(nq)
        cr0 = ClassicalRegister(nq)
        cr1 = ClassicalRegister(nq)
        # Create a quantum circuit with 3 qubits and 3 classical bits
        qc = QuantumCircuit(qr, cr0, cr1)

        qc.measure(qr, cr0)

        # Add a delay of T1/2 to each qubit
        for iq in range(nq):
            qc.delay(int(T1/2*1000*delay_factor), iq, 'qs')
            qc.delay(int(delay), iq, 'us')

        # Measure each qubit
        qc.measure(qr, cr1)

        # Visualize the circuit
        qc.draw('mpl')

        circuits.append(qc)

    circuits[0].draw('mpl')

    qc_compiled = transpile(circuits, backend, initial_layout = list(range(nq)), optimization_level=0, scheduling_method='asap')

    sampler = None
    if session:
        sampler = Sampler(session=session)

    elif batch:
        sampler = Sampler(mode=batch)

    job = sampler.run(qc_compiled, shots=shots)
    
```

ID / Name	Status	Created	Completed	Usage	Type	Compute resource	Tags
cvhtxdxkmd10008...	Completed	13 Sep 2024	13 Sep 2024	1m 8s	sampler	ibm_kawasaki	
cvhtx14z17rg008d...	Completed	13 Sep 2024	13 Sep 2024	1m 7s	sampler	ibm_kawasaki	
cvhtwm2vawwg00...	Completed	13 Sep 2024	13 Sep 2024	1m 6s	sampler	ibm_kawasaki	
cvhtw7gkmd10008...	Completed	13 Sep 2024	13 Sep 2024	1m 6s	sampler	ibm_kawasaki	
cvhtvtq8w2g0008e...	Completed	13 Sep 2024	13 Sep 2024	1m 8s	sampler	ibm_kawasaki	
cvhtve5p7drg008m...	Completed	13 Sep 2024	13 Sep 2024	1m 12s	sampler	ibm_kawasaki	
cvhtv1cp7drg008m...	Completed	13 Sep 2024	13 Sep 2024	1m 10s	sampler	ibm_kawasaki	
cvhttm8w2g0008e...	Completed	13 Sep 2024	13 Sep 2024	1m 9s	sampler	ibm_kawasaki	

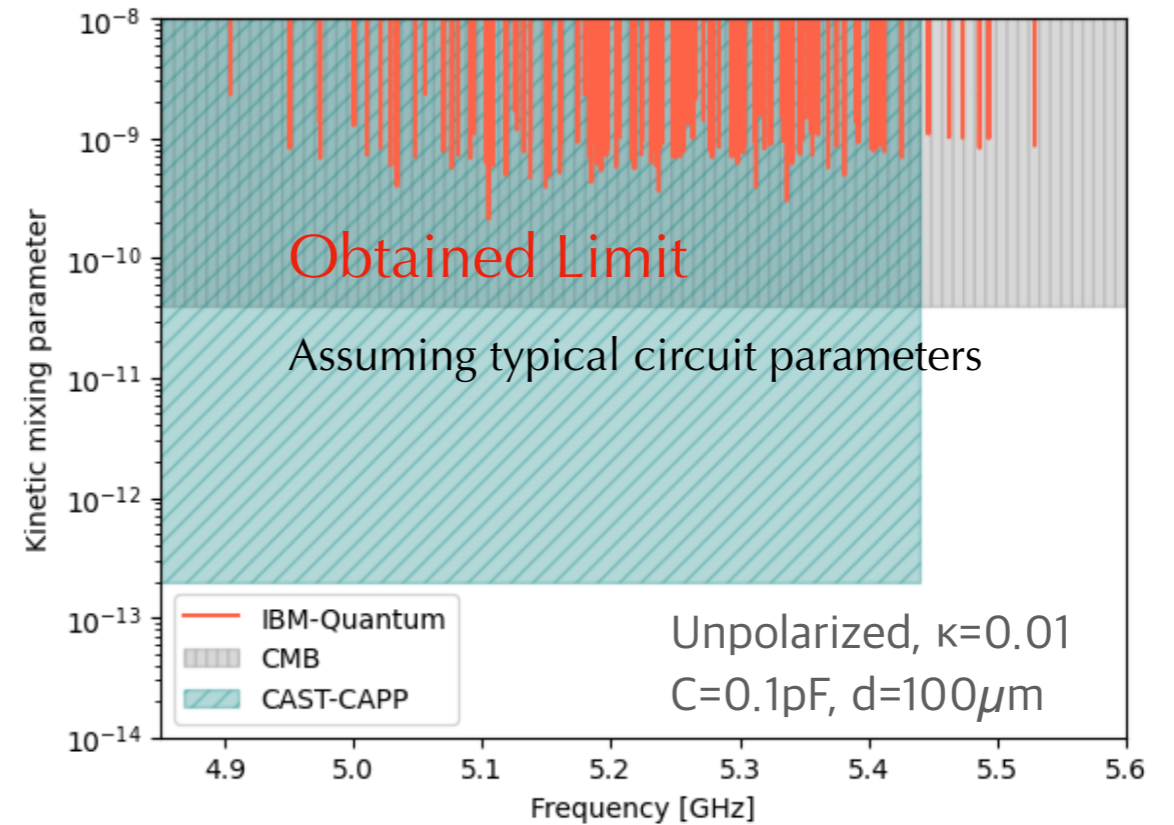
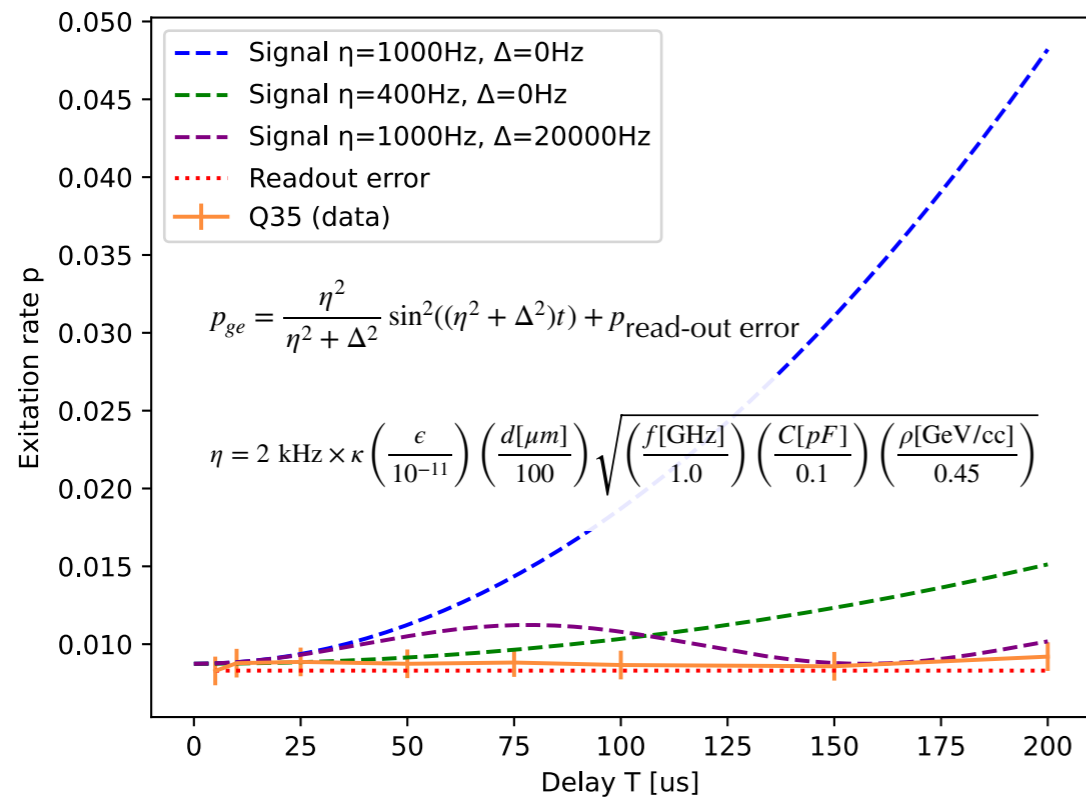
Submit a script like this

5min queue, 1min run time

✔ Script-based dark matter search

Results

Y. Iiyama & S. Chen (Preliminary)



- No spectacularly high excitation rate found
- Pulse-level control in IBM-Quantum has been obsolete
- Started collaboration with IQM since 2025 with frequency tunability**

Issue of package shielding

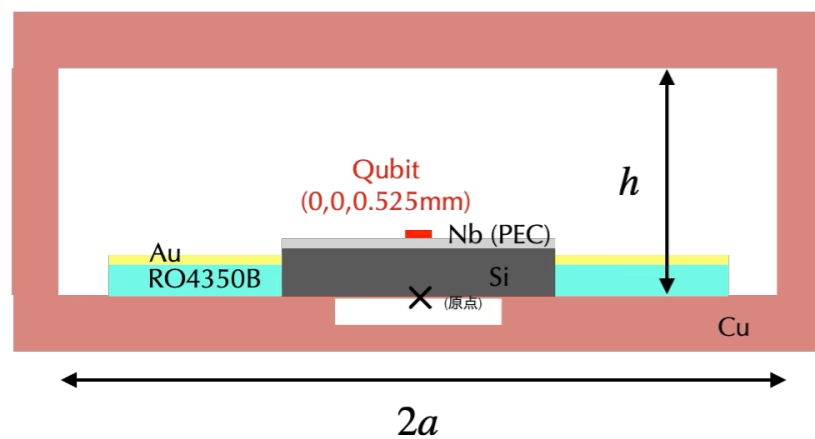
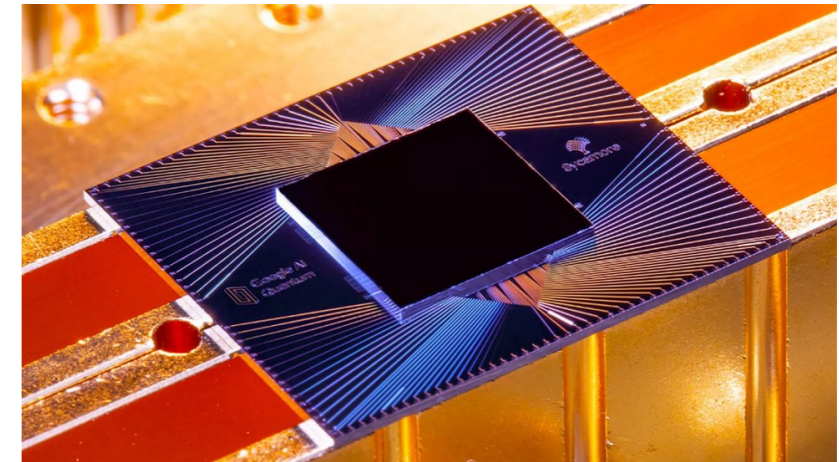
- As said, $E^{(EM)} + E^{(X)} \sim 0$ near the wall
- Tightest possible chip packaging is commonly used in 2D implementation for noise shielding

Typical suppression factor $\kappa \sim O(10^{-3})$

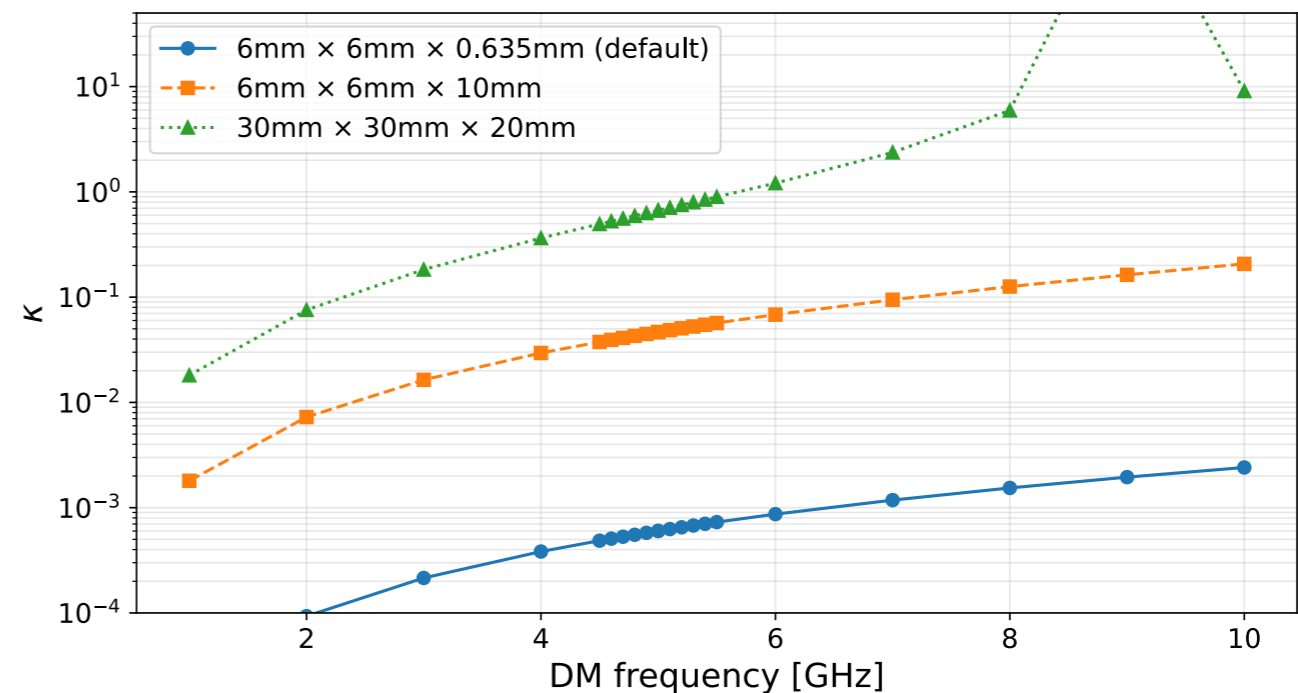
- Loosening the package? → **DM signal vs Purcell limit**

$$\kappa \sim \frac{g^2}{\Delta^2} \quad \Gamma_{\text{Purcell}} \sim \frac{g^2 \gamma}{\Delta^2 + \gamma^2}$$

- Large / high-Q 3D cavity turns out to be an ideal package for the search



US-Japan collaboration started this year to develop a custom package



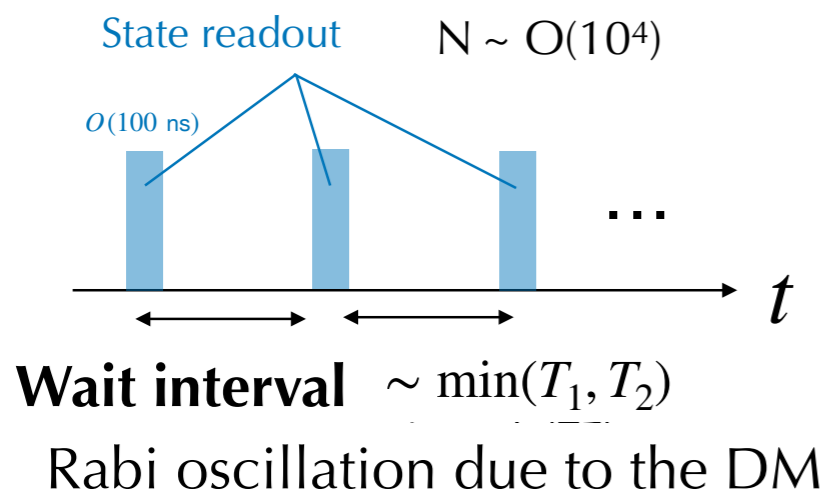
Future extension: Multi-bit interference

Sichanugrist et al. PRL **133** (2), 021801
Ito et al. [arXiv: \[hep-ex\] 2311.11632](https://arxiv.org/abs/2311.11632)

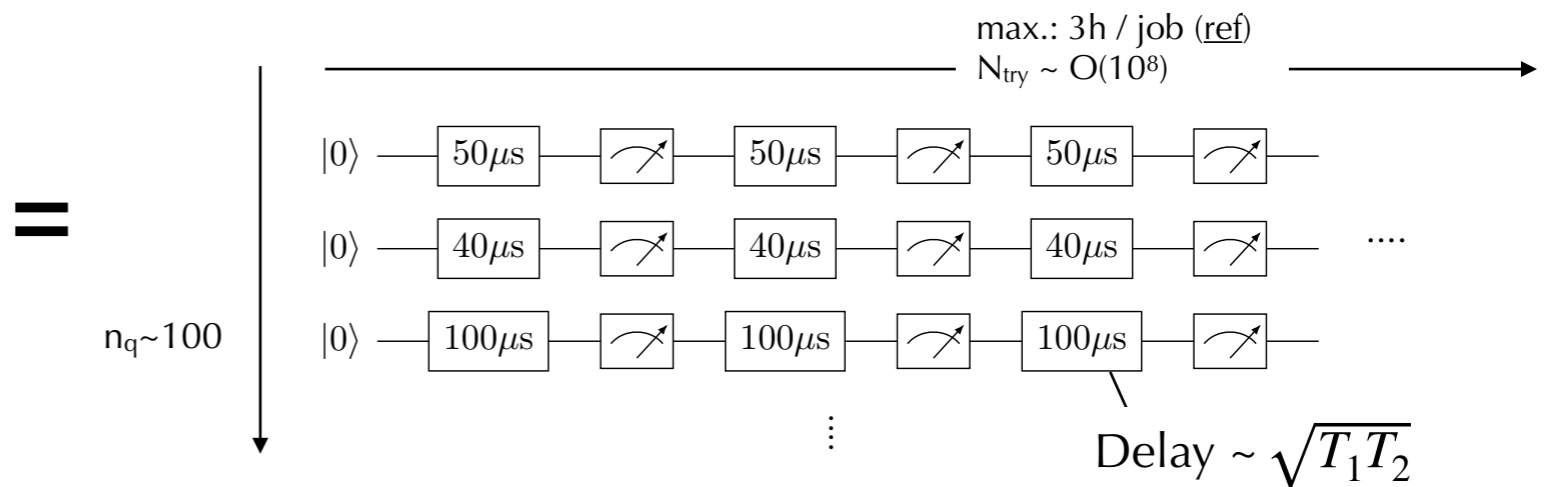
Single bit experiment : nothing quantum

Signal rate $\propto n_q^2$

$(\text{Wait} \rightarrow \text{Read})^N$



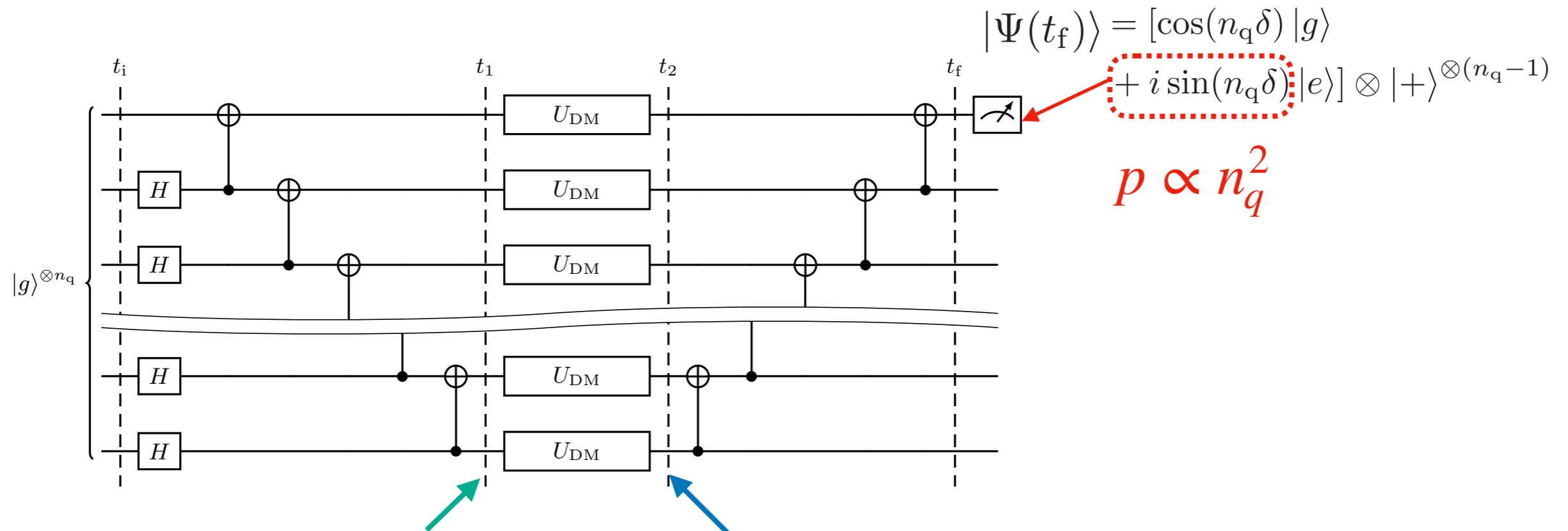
Correspond to this boring circuit operation



Future extension: Multi-bit interference

Multibit entanglement \rightarrow signal rate $\propto n_q^2$

"Decoded" state to be measured



GHZ state: Maximally entangled state

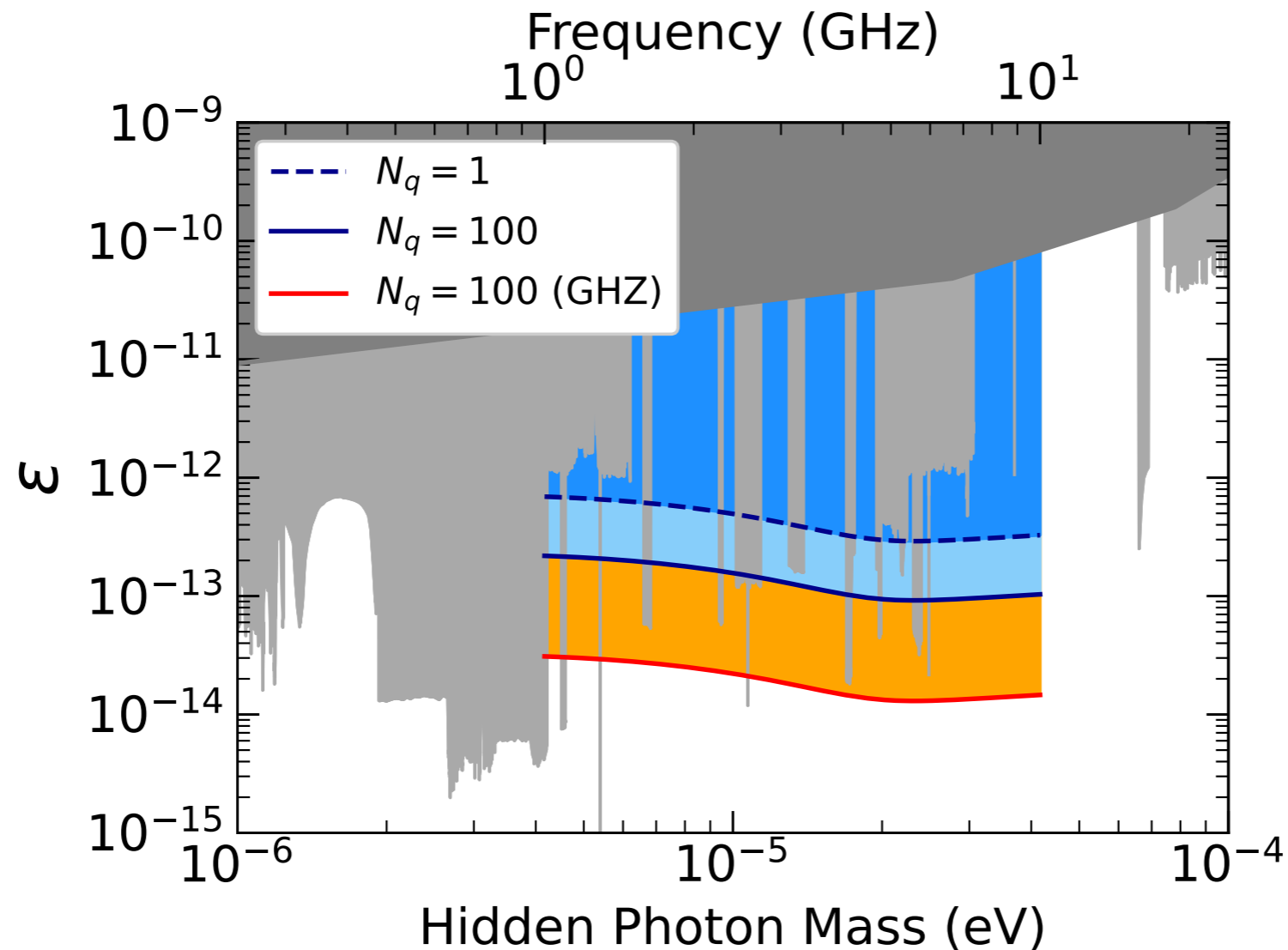
$$|\Psi(t_1)\rangle = \frac{1}{\sqrt{2}} \left(|+\rangle^{\otimes n_q} + |-\rangle^{\otimes n_q} \right)$$

DM evolution: Rabi oscillation

$$|\Psi(t_2)\rangle = \frac{1}{\sqrt{2}} \left(e^{in_q \delta} |+\rangle^{\otimes n_q} + e^{-in_q \delta} |-\rangle^{\otimes n_q} \right)$$

Future extension(2) Multi-bit interference

Sichanugrist et al. PRL **133** (2), 021801
Ito et al. [arXiv: \[hep-ex\] 2311.11632](https://arxiv.org/abs/2311.11632)



Many caveats at this point:

- Coherence time of n-entangled state : $T_n \sim T/n$
- In-situ quantum error correction needed to avoid the dephasing contribution

Many variations actively proposed recently

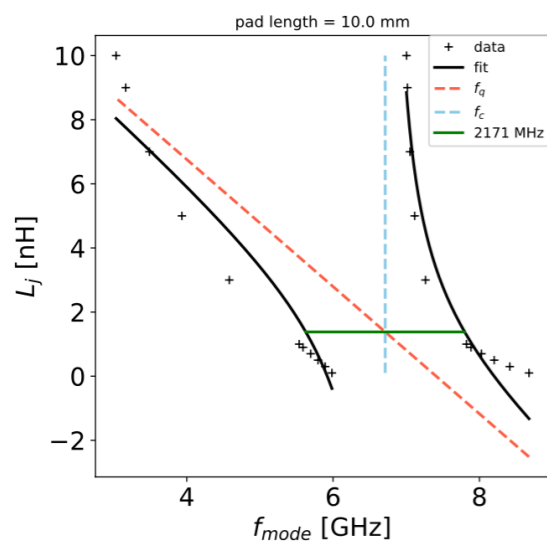
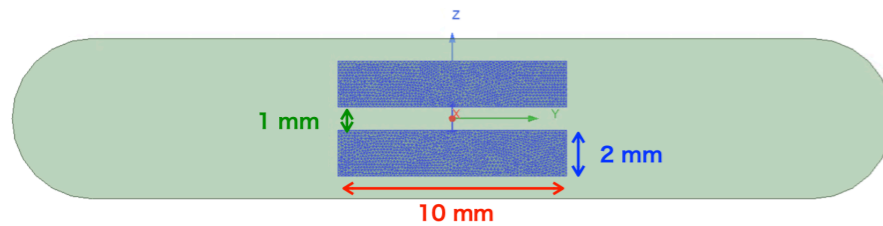
- W state : Fukuda et al. [arXiv: 2510.01816](https://arxiv.org/abs/2510.01816)
- CAT state : Zheng et al. [arXiv: 2507.23538](https://arxiv.org/abs/2507.23538)
- Q-network : Santoso et al. [arXiv: 2505.21188](https://arxiv.org/abs/2505.21188)

Same challenges for the future FTQCs

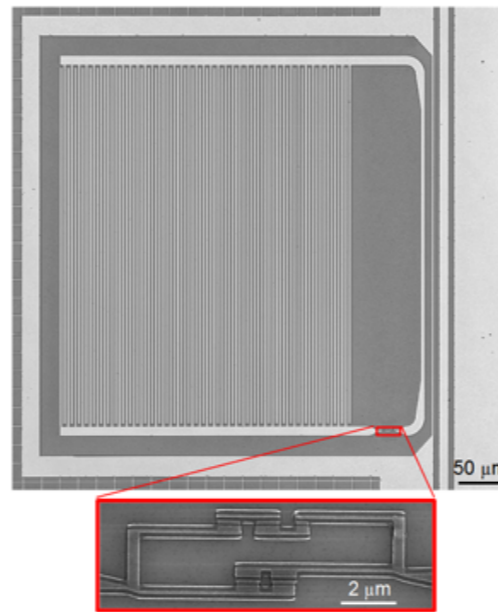
Tailored qubits for sensing purpose

Stronger coupling

Even larger capacitance pads



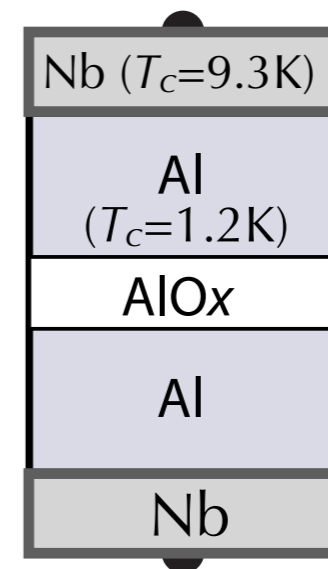
Galvanic coupling



Yoshihara et al (2018)

Higher frequency qubit

Al/Nb bilayer → Lift T_c using the proximity effect



$$E_1 - E_0 \sim \sqrt{8E_C E_J}$$

$$E_J = \frac{\pi \Delta}{2 R}$$

Δ : superconducting gap

All superconducting qubits so far are devised in the context of QCs

- Vastly unexplored circuit parameter space - coupling, frequency etc. ultimate limit unknown

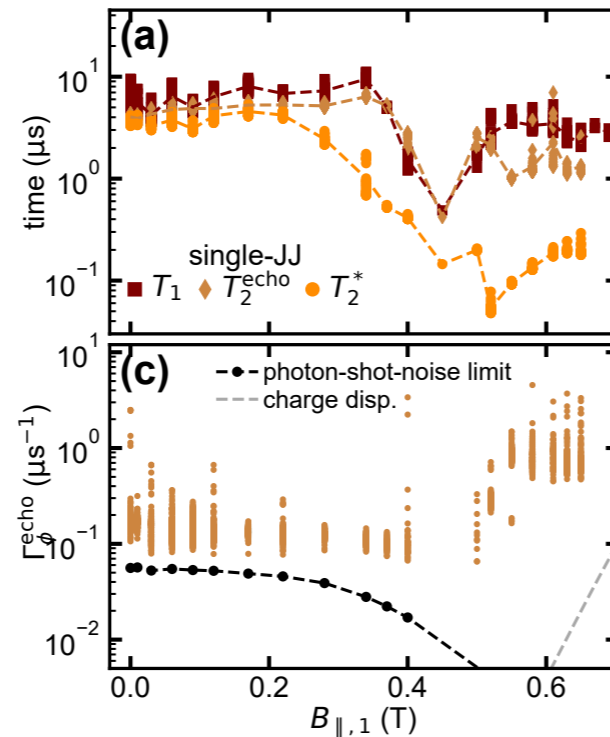
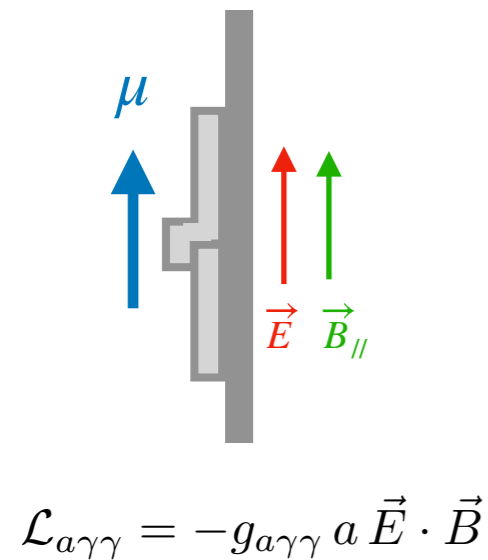
Looser limitation of coherence time can open many new paths for qubit design

- Bad coherence but maximal potential as sensors

Towards axion searches

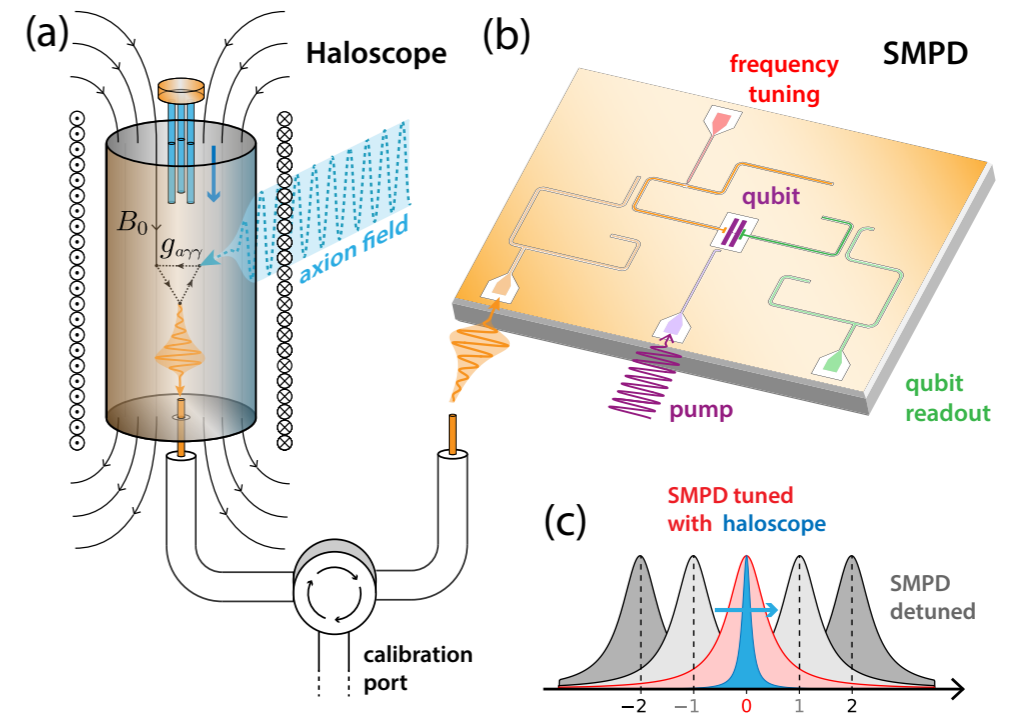
How to apply B-field?

1. Perfect alignment



Krause et al.

2. Geometrically isolate the qubit sensor



Braggio et al.

Generally strong B-field is bad for superconductor and of course to qubits too

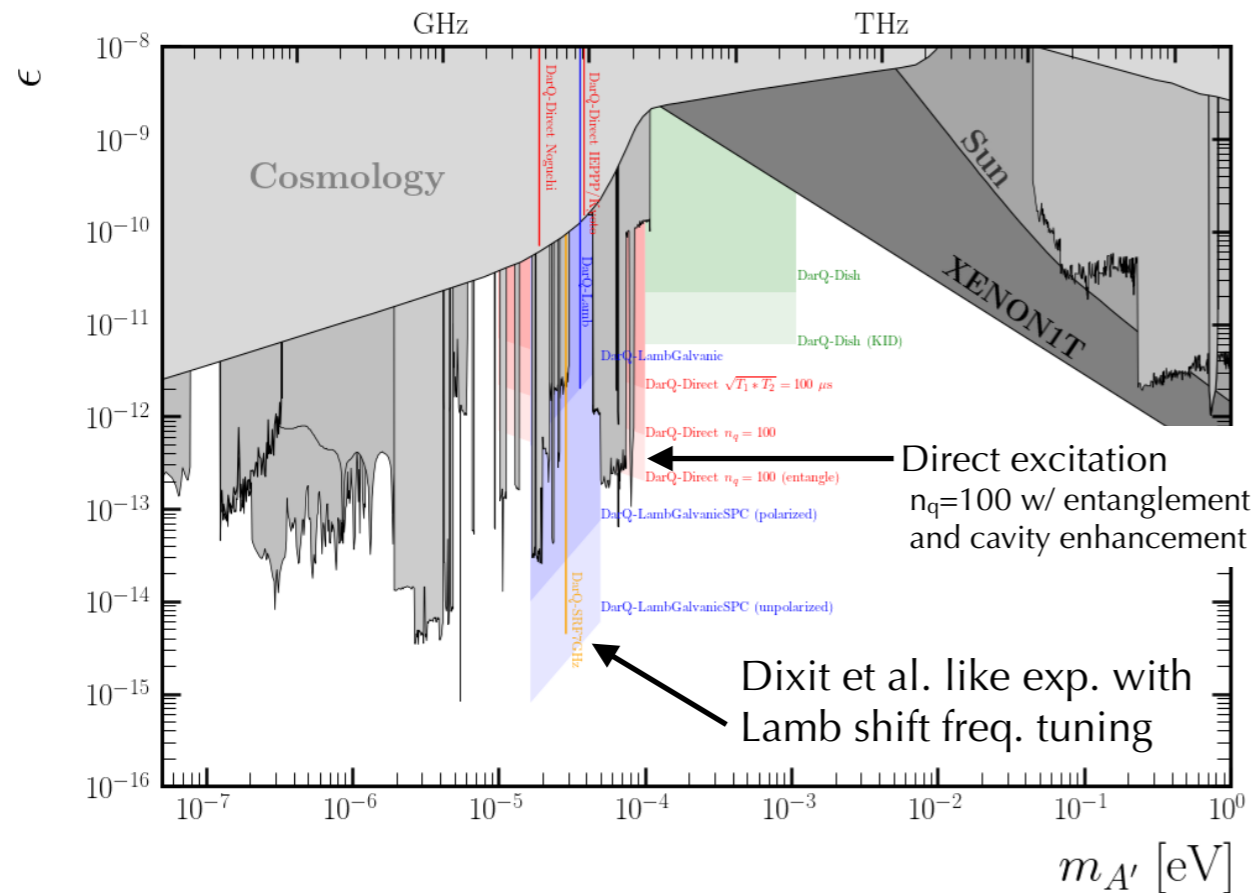
- Qubit inductively couple to flux → decoherence
- Out-of-plane is particularly bad for superconducting thin films

Possible solution

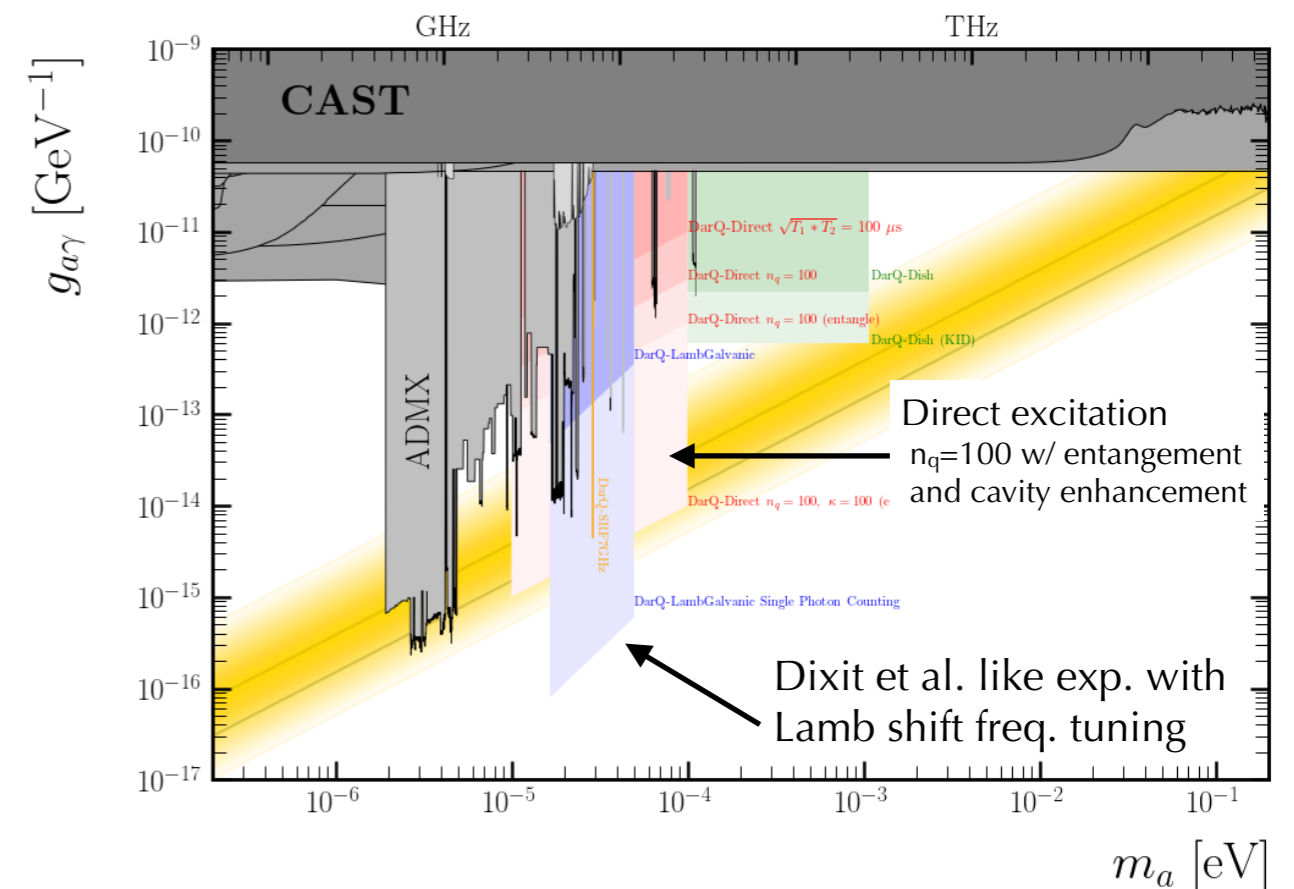
- Precise in-plane alignment of B-field
- Qubits using Nitride-based JJ
- Physical isolation from the B-field

DarQ experiment Sensitivity projection

Dark photon



Axion



Sichanugrist et al. [arXiv: 2407.19755](https://arxiv.org/abs/2407.19755)

- One year operation time
- Long road to go, but ultimately wideband DFSZ sensitivity

Summary

DarQ-Direct experiment : Dark matter search using Quantum bits

- **Qubits are directly used as sensors**
- First single-bit-based search ongoing with custom devices
Extension: focusing system
- **Ultimate goal: FTQCs?**
Unique challenge: chip packaging

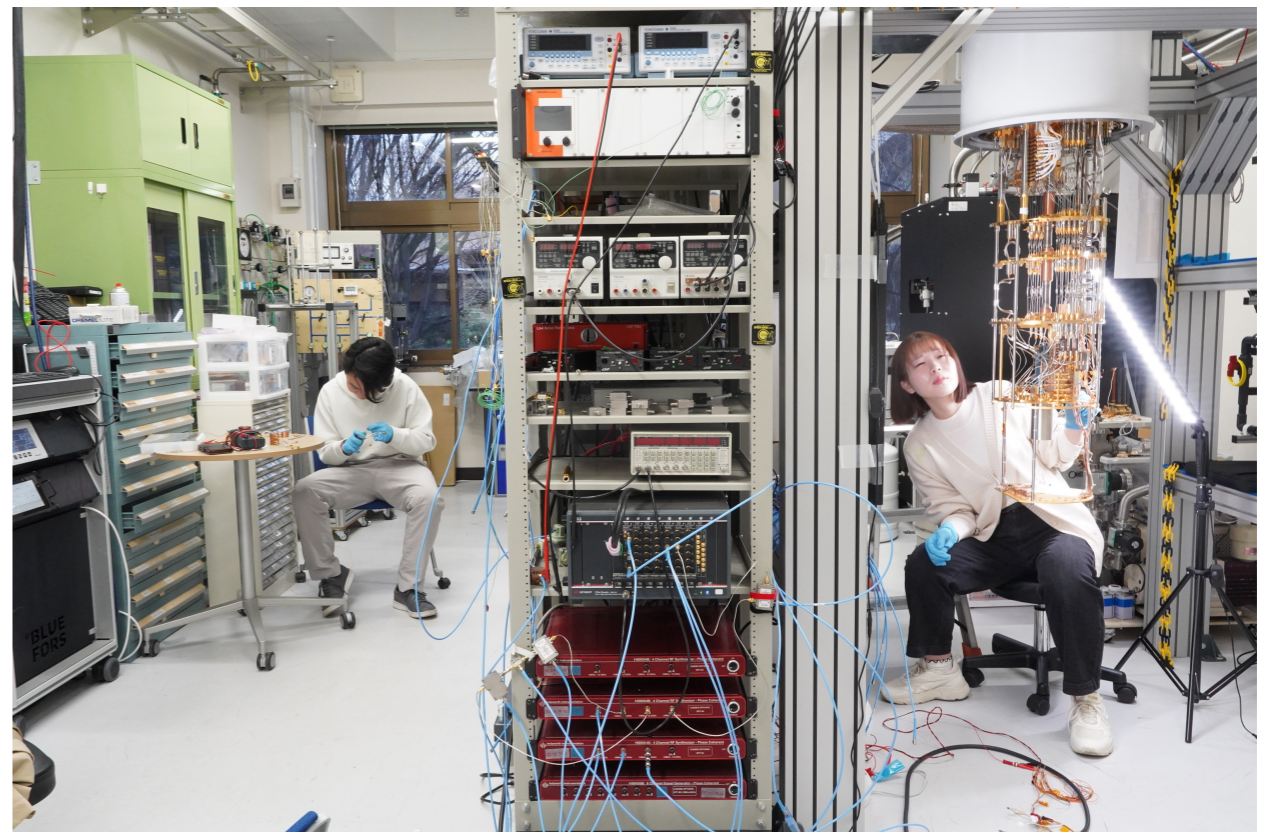
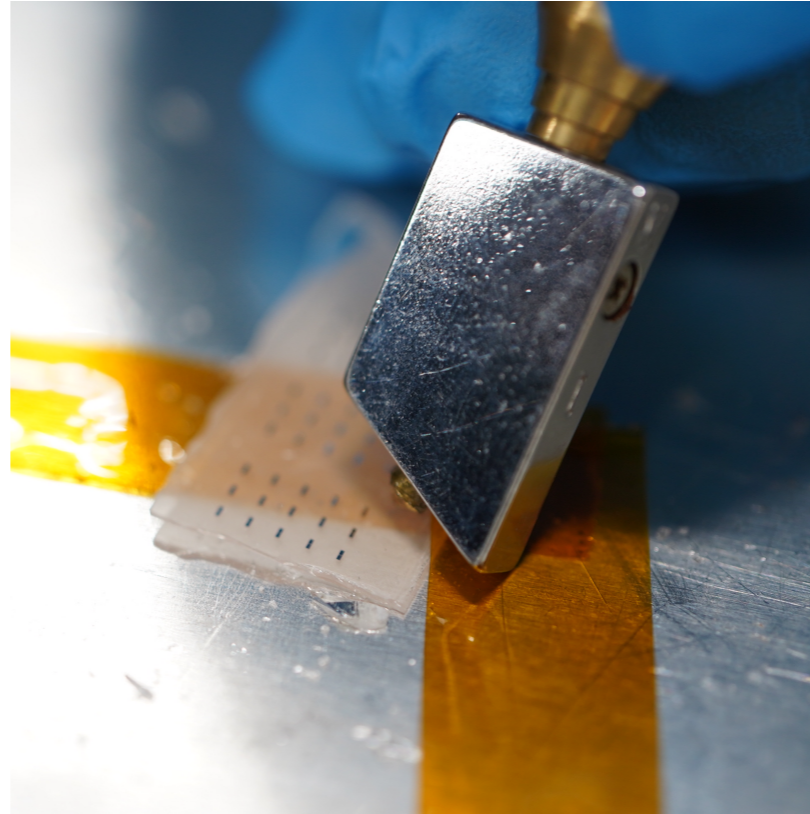
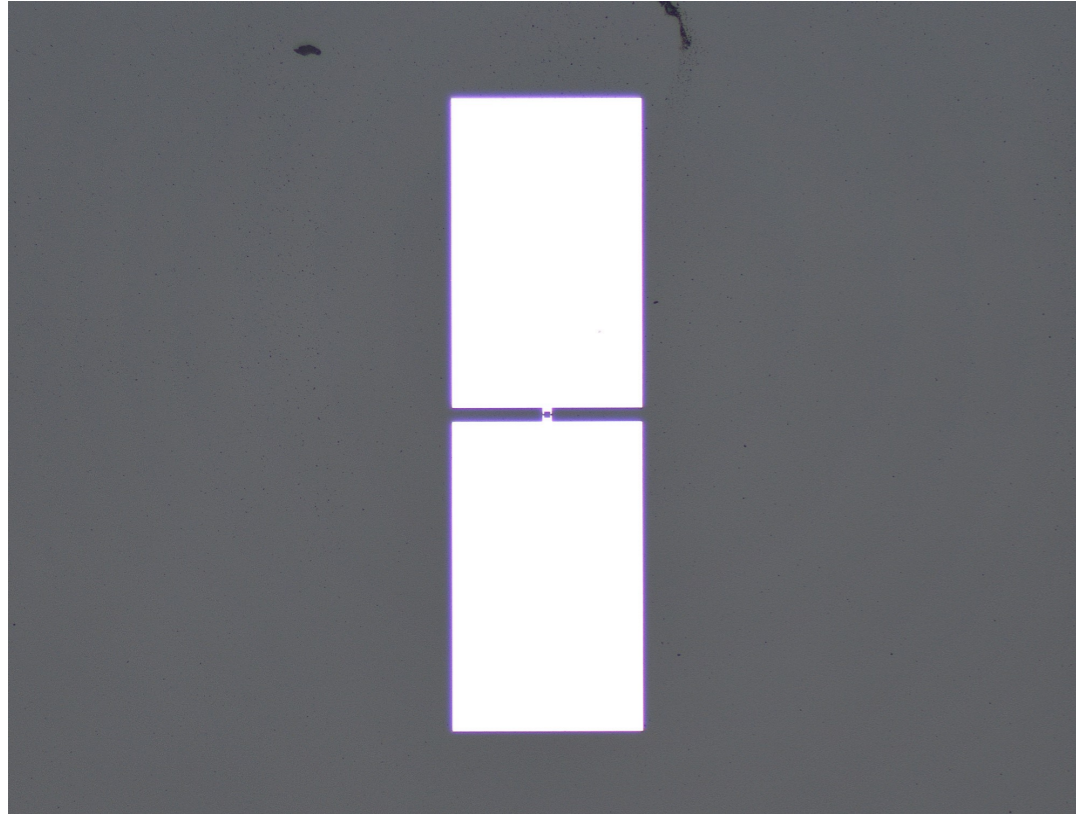
Other DarQ projects

- DarQ-Lamb: Cavity haloscope using transmons as a freq. tuner (→Tatsumi Nitta's talk)
- DarQ-SPC: Cavity + itinerant single photon counter (for axion searches)

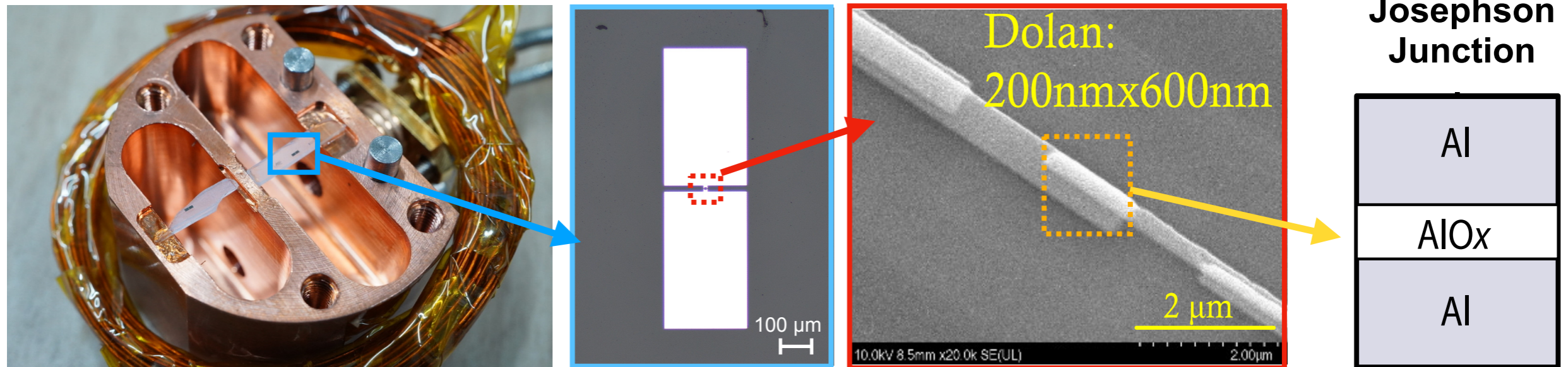
Sensor development - from a computing unit to a dark matter sensors

- Stronger coupling, higher frequency, B-field resilience etc.
- Qubits out of the context of quantum computers

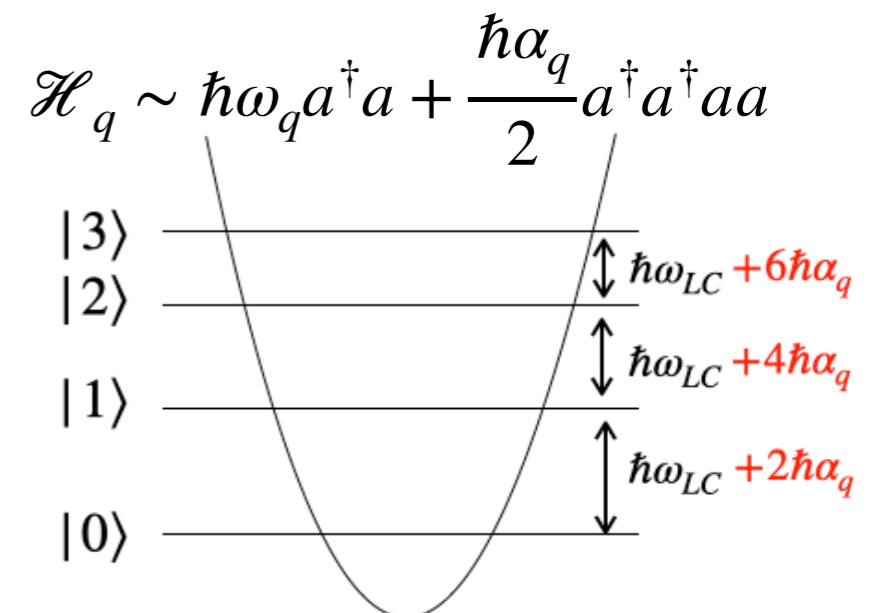
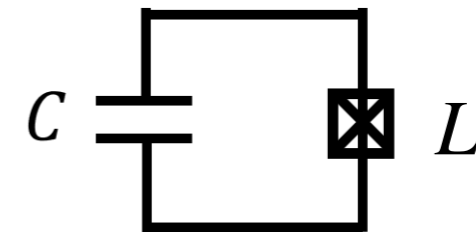
Backup



Superconducting qubits

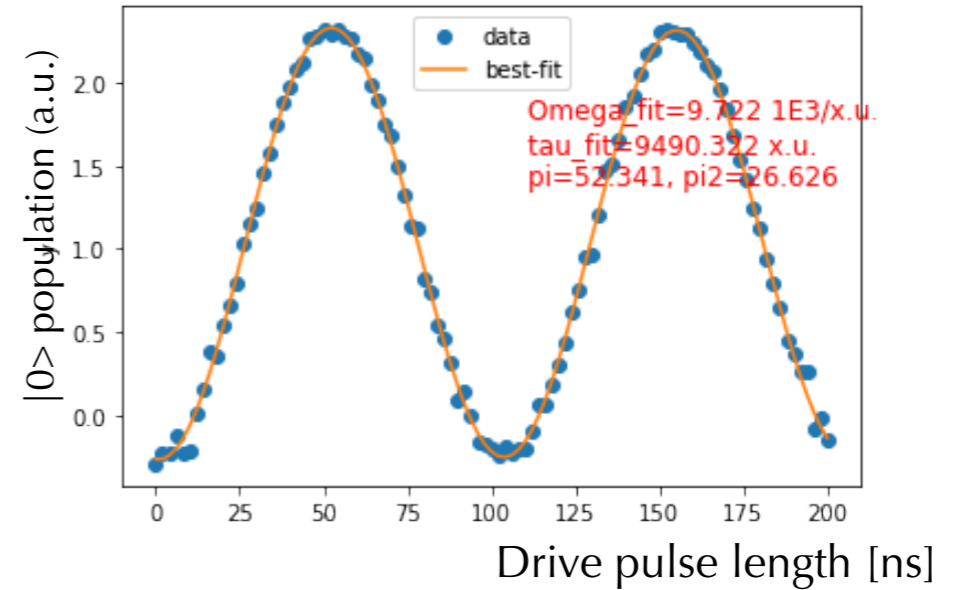
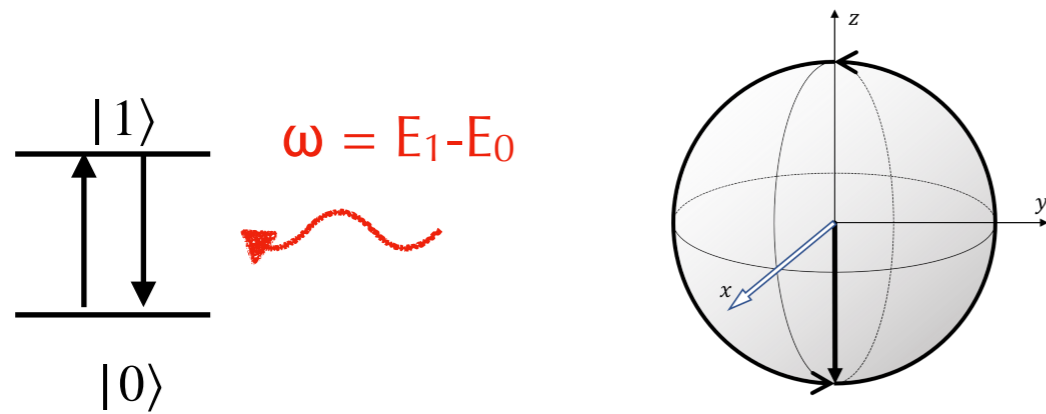


- Non-linear LC circuit
 - Josephson junctions : non-linear inductance
 - Anharmonic energy levels
Essential for state control
- Thin-film superconductor : Low loss

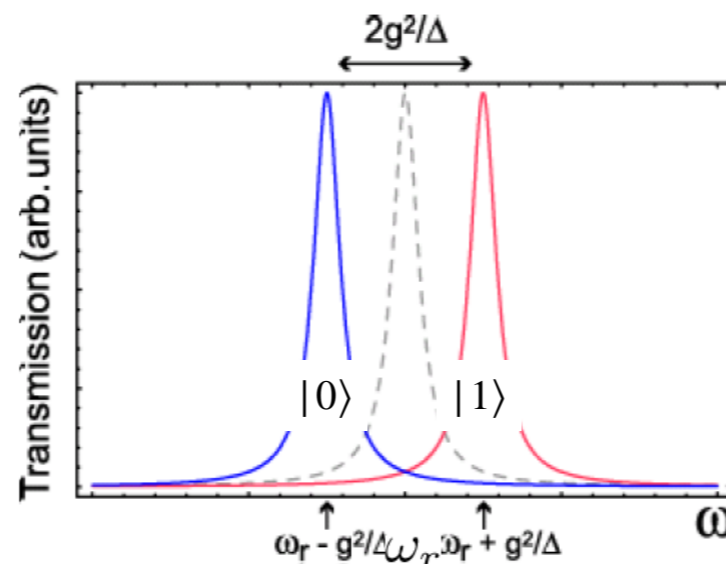
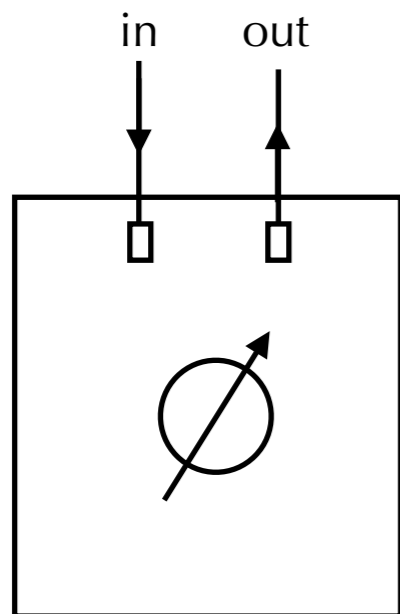


Superconducting qubits

State control : Resonant microwave drive (Rabi oscillation)

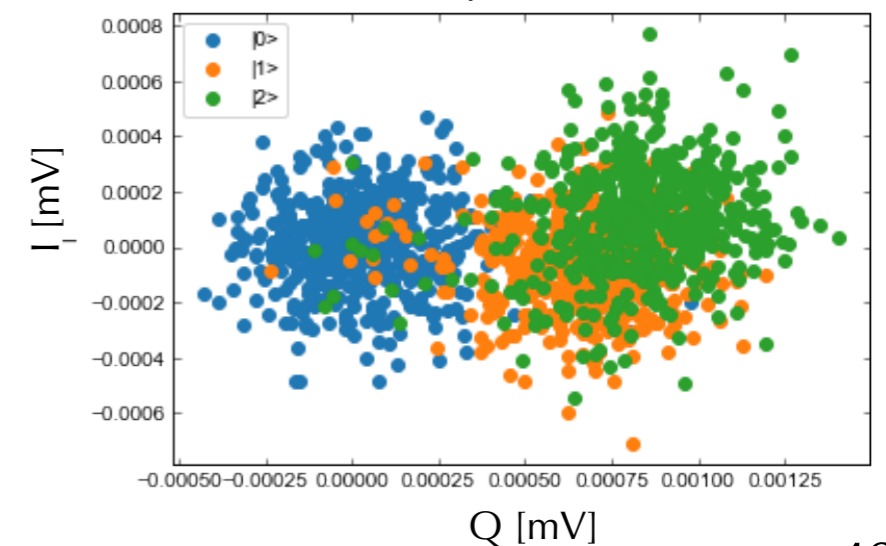


State readout : Transmission of coupled cavity (Dispersive readout)



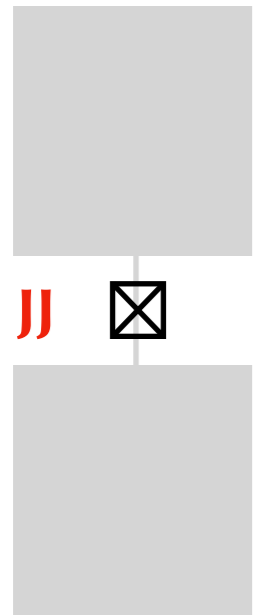
Phase of the transmitted wave

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



Superconducting qubits as photon sensors

Strong coupling to photon



EDM: $\mu \sim Qd$

$d = O(0.1 \text{ mm})$
macroscopic

$\times O(10^6)$ vs single atom

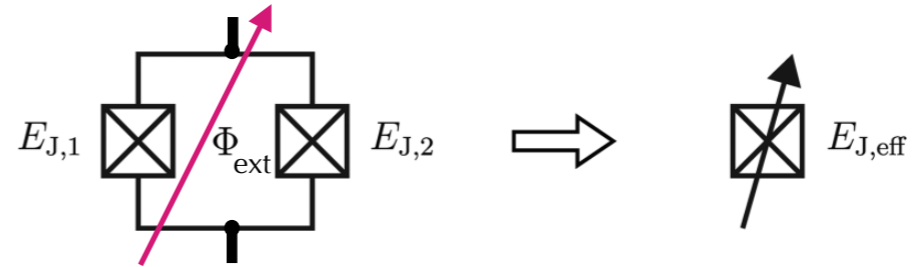
Low threshold

Typically μeV (GHz)

c.f. Superconductor detector $\sim \text{meV}$

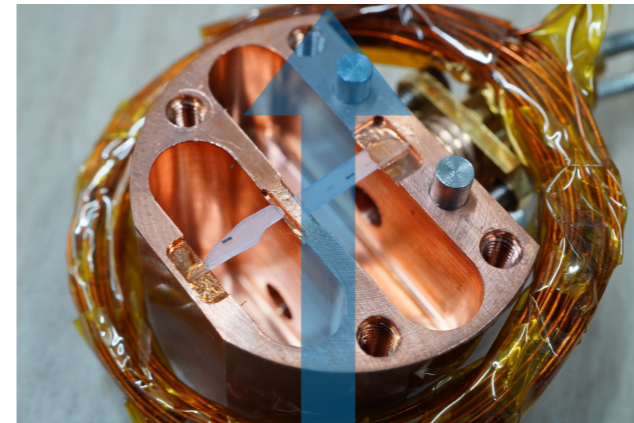
Scintillator / Silicon $\sim \text{eV}$

Wide frequency tunability

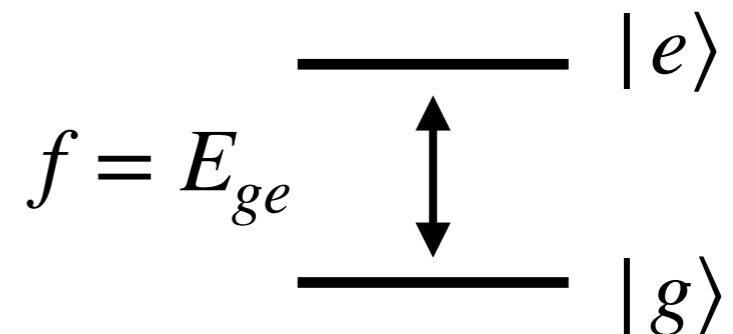


$$E_{J,\text{eff}}(\varphi_{\text{ext}}) = \sqrt{E_{J,1}^2 + E_{J,2}^2 + 2E_{J,1}E_{J,2} \cos \varphi_{\text{ext}}}$$

B-field ($\sim \mu\text{T}$)



Tuning range
 $> \text{GHz}$



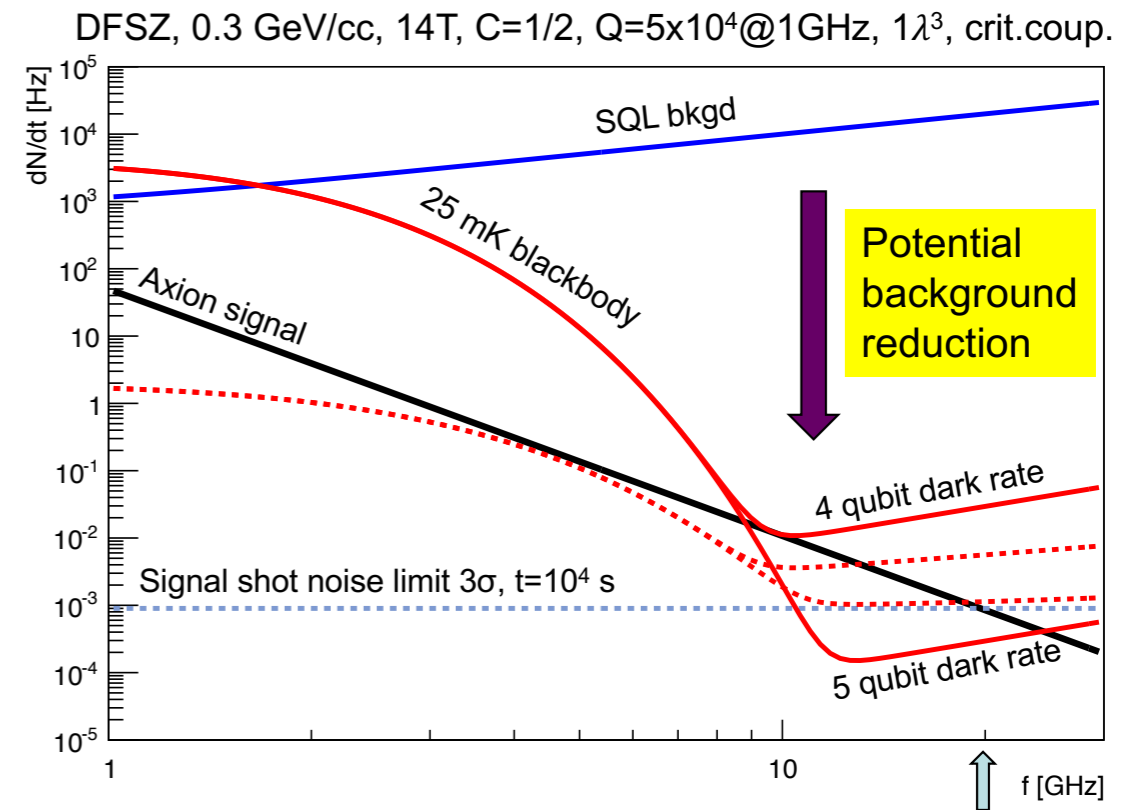
Challenges of cavity experiments

1. Standard Quantum Limit (SQL)

$$\Delta n \cdot \Delta \phi \geq \hbar \quad (n/\phi: \text{number/phase of the photon})$$

Quantum measurement back-action.

Dominant noise source at high freq.



Challenges of cavity experiments

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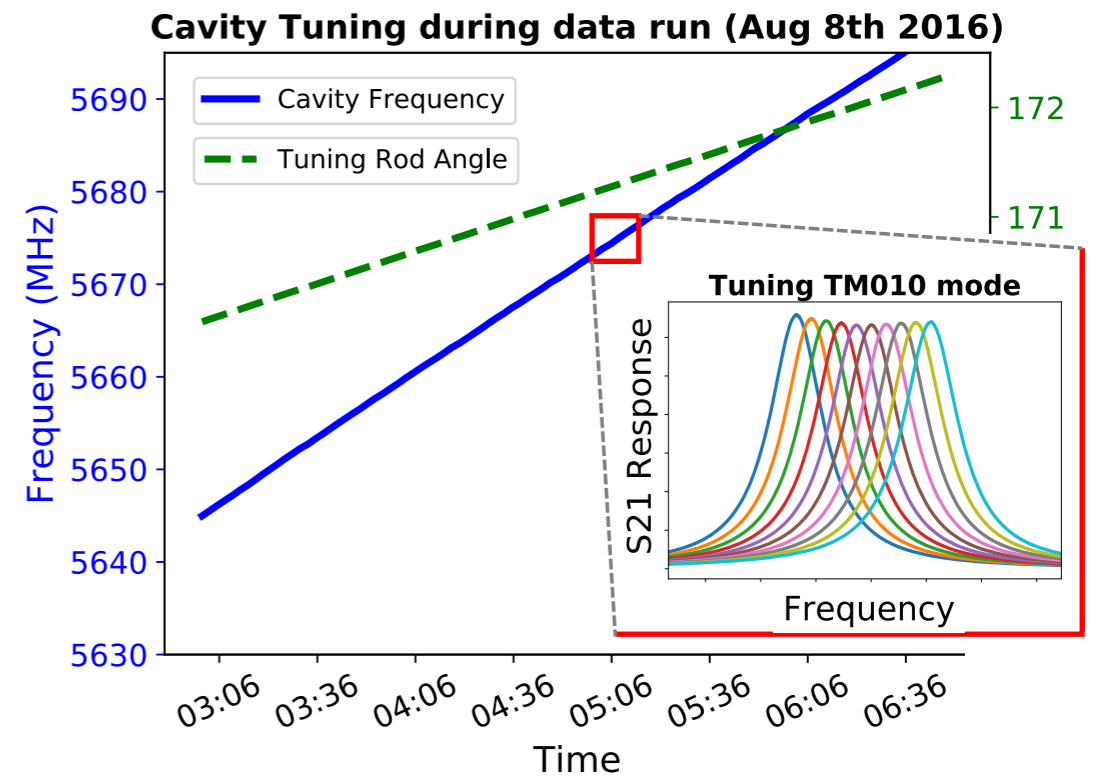
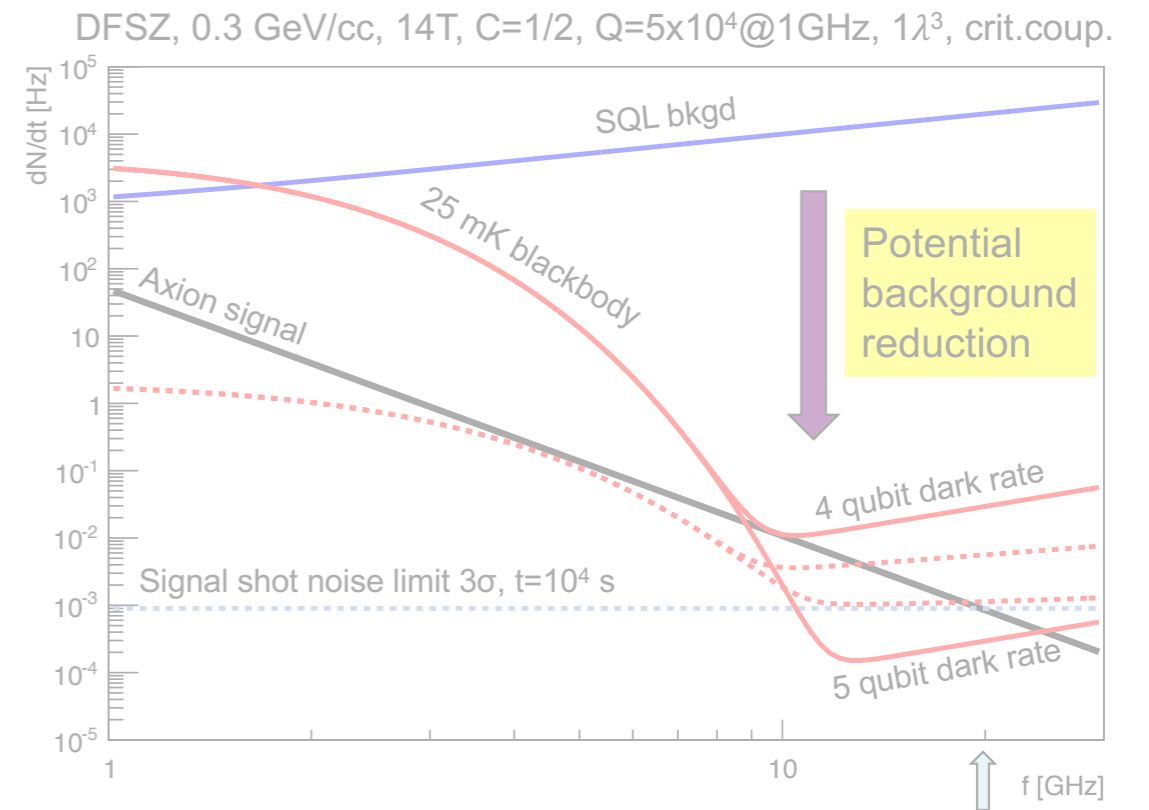
Quantum measurement back-action.

Dominant noise source at high freq.

2. Frequency tuning

Limited tuning range & non-trivial engineering

ADMX: tuning rod



Challenges of cavity experiments

1. Standard Quantum Limit (SQL)

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Quantum measurement back-action.

Dominant noise source at high freq.

2. Frequency tuning

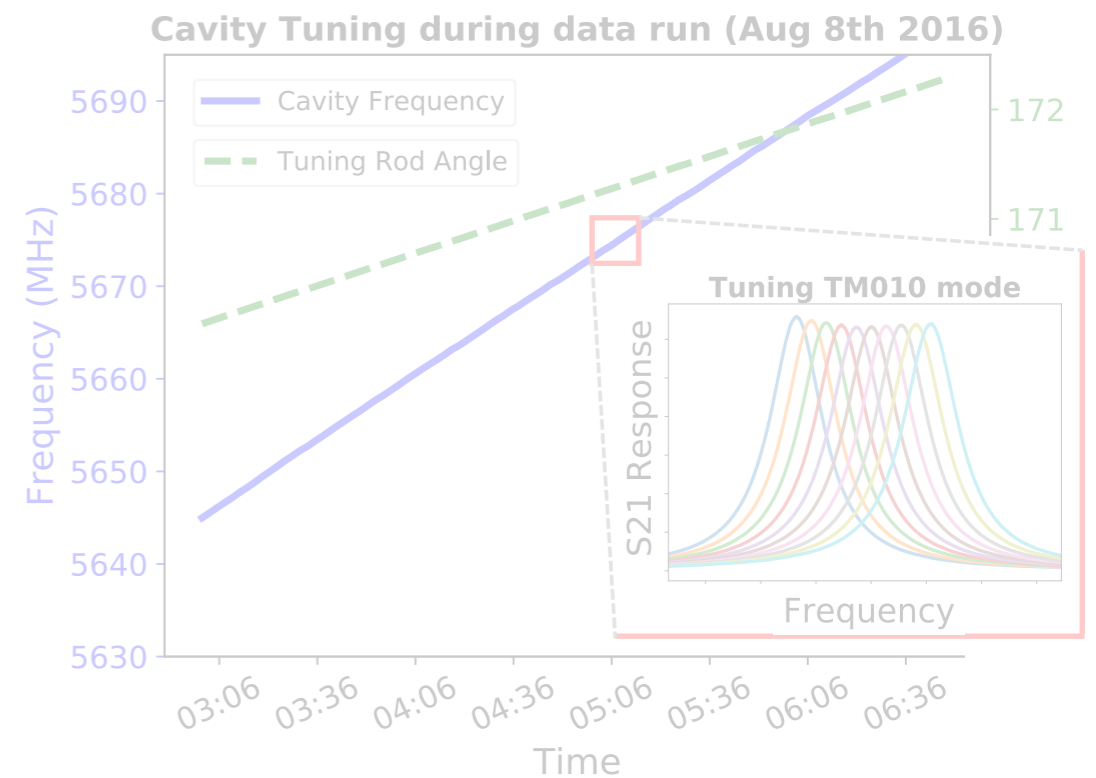
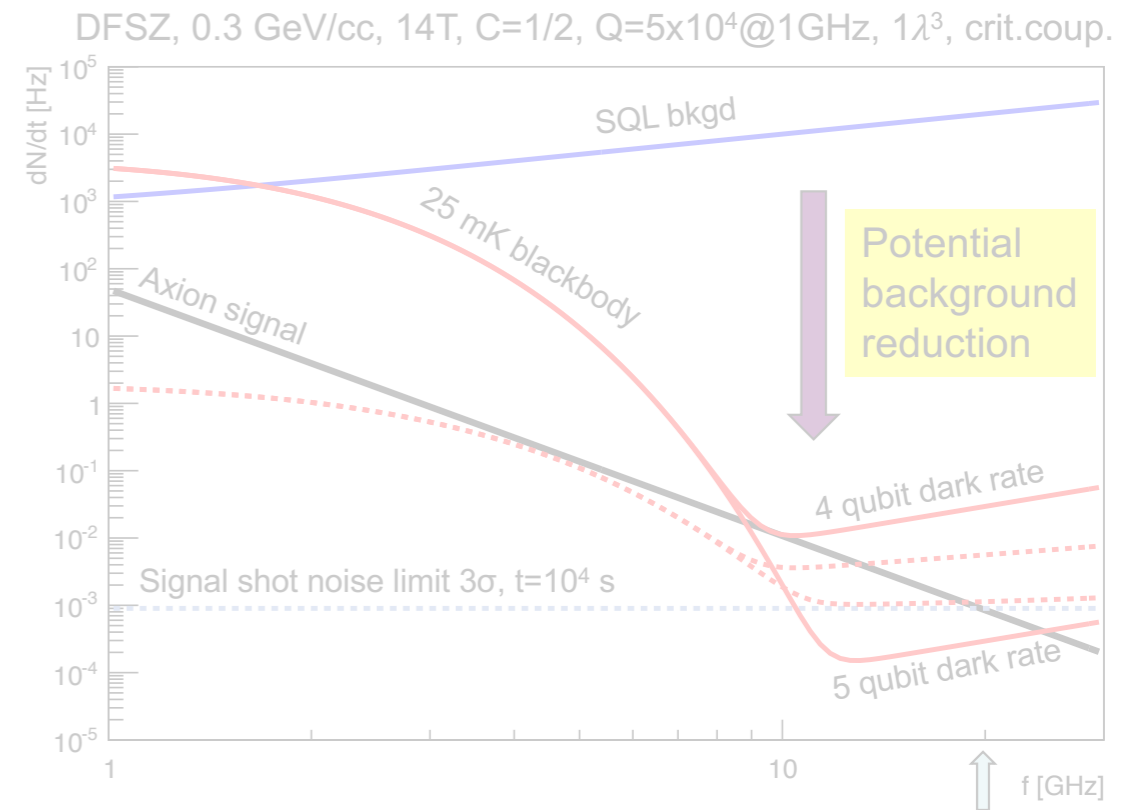
Limited tuning range & non-trivial engineering

ADMX: tuning rod

3. Shrinking detection volume @high freq.

Shorter resonant wavelength

→ Smaller cavity



Package shielding effect

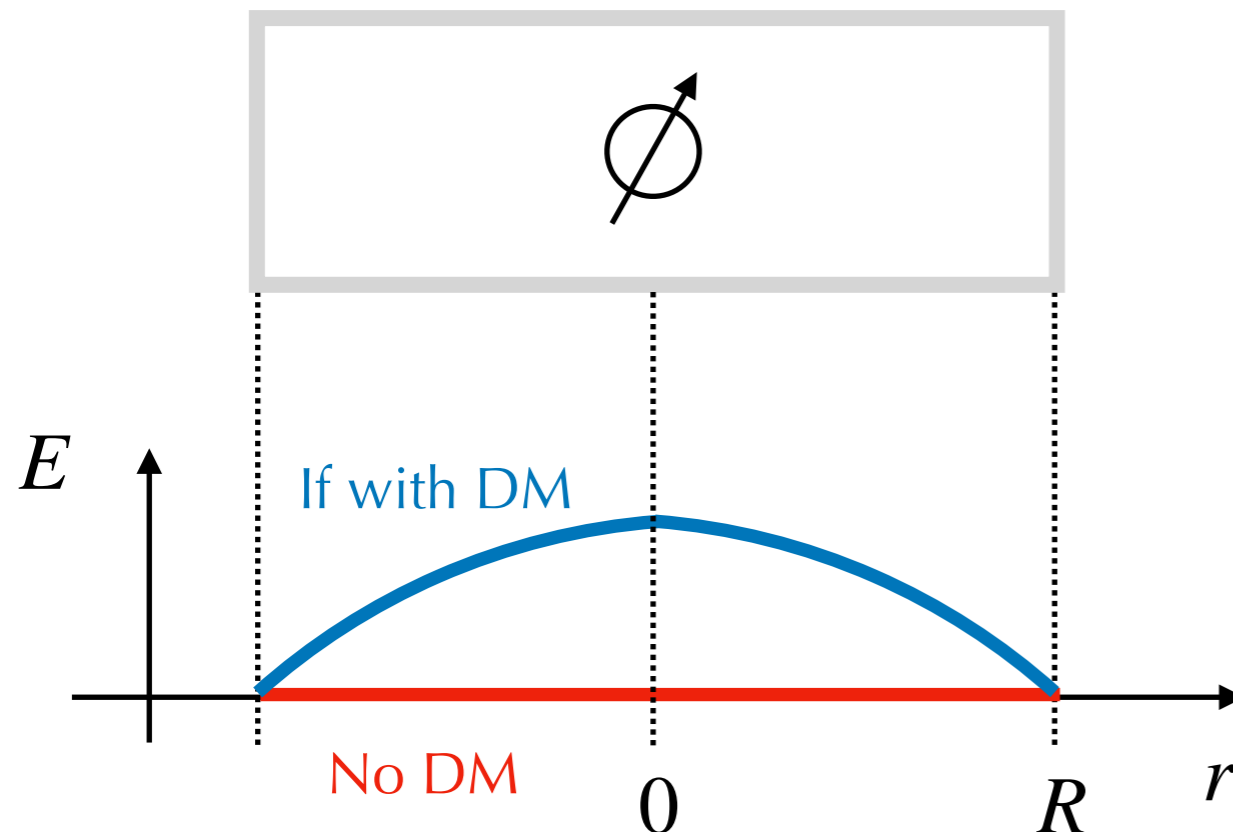
Moroi et al. PRL 131, 211001 (2023)

Metallic shields = cavity

- Off-resonant AC fields in the cavity are canceled by the cavity response
- The field cancellation is not perfect when photons are mixed with dark photon

- $E=0$ on the wall
- $E>0$ off the wall due to $m_{\text{DM}}>0$

→ **No signal reduction when the cavity is large enough** ($L_{\text{shield}} \gg \lambda_{\text{Compton}}$)



e.g. For cylindrical cavity:

$$E_z^{(\text{EM})}(\vec{x}) = - \frac{J_0(m_X r)}{J_0(m_X R)} E_z^{(X)}$$

↑
E-field caused by
the cavity response

↑
DM-induced E-field

Package shielding effect

Moroi et al. PRL 131, 211001 (2023)

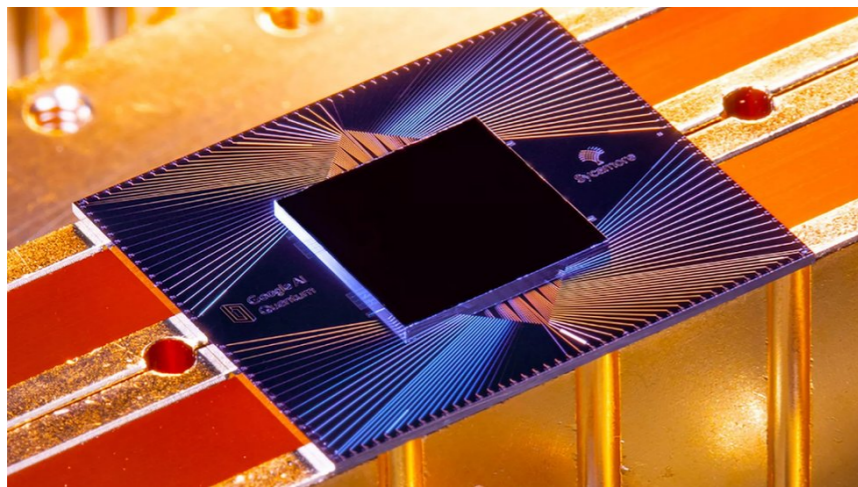
"No signal reduction when the cavity is large enough ($L_{\text{shield}} \gg \lambda_{\text{Compton}}$)"

This is unfortunately usually not the case in quantum computers

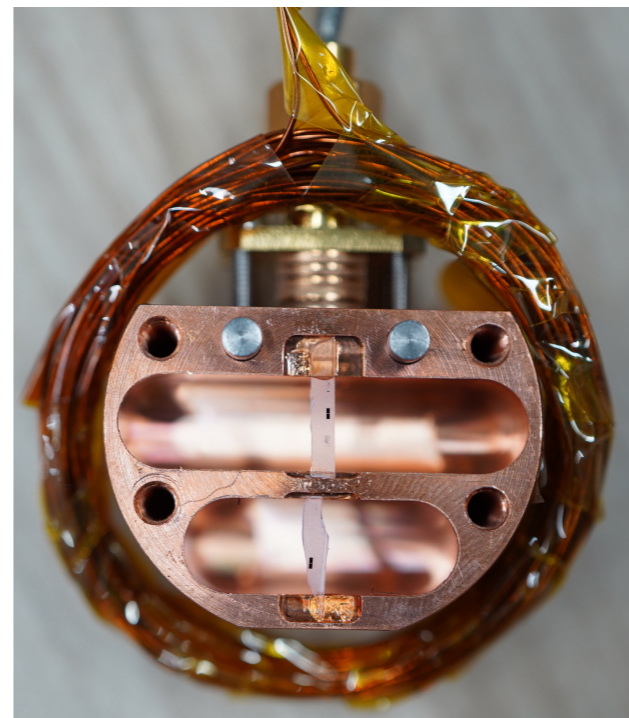
- Very tight package to shield the EM field as much as possible
- Massive DM signal reduction

e.g. 6mm x 6mm x 1.835mm height package → $\kappa=0.004$ @5GHz DM signal

$$\kappa := |1 + E^{(EM)}/E^{(X)}| \quad (0: \text{no signal} \quad 1: \text{no signal reduction})$$



e.g. Google sycamore chip
Height < 1mm?



Less problematic
in the 3D implementation

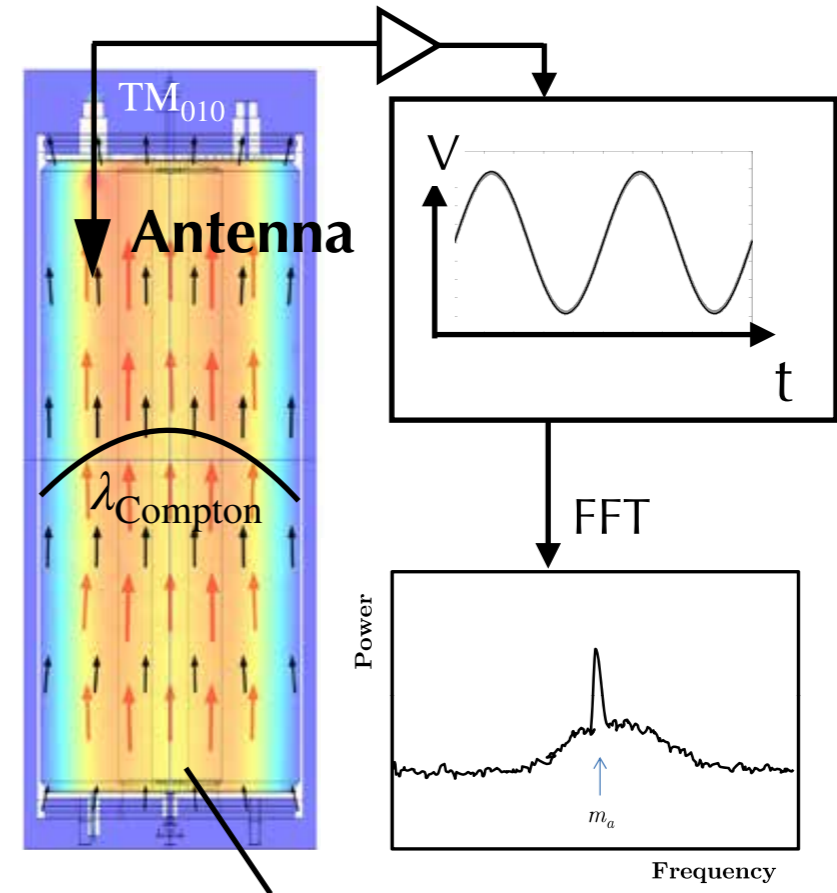
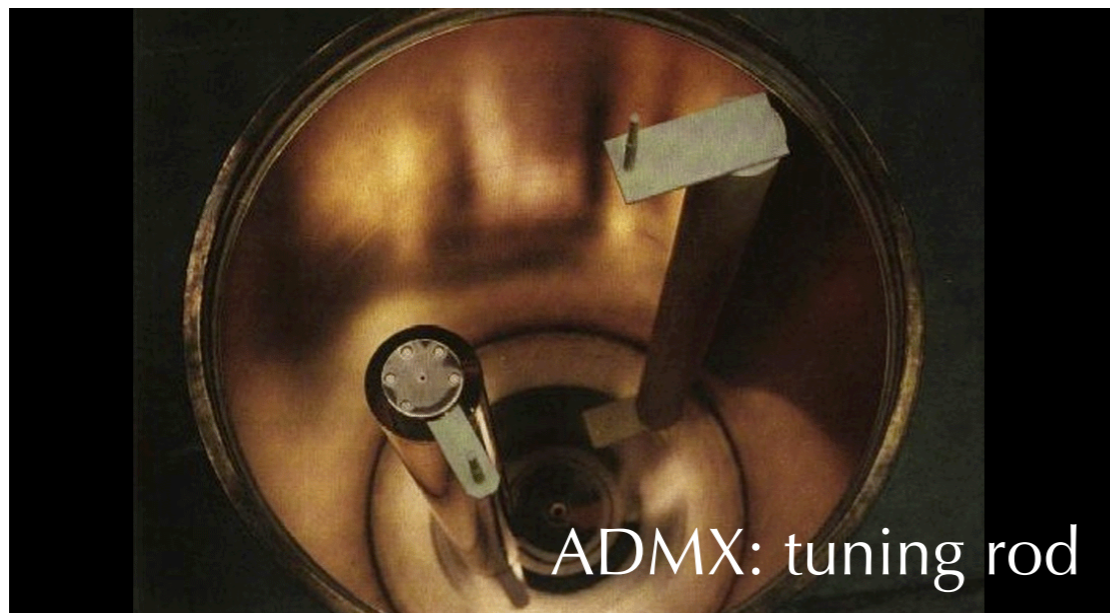
Cavity haloscope

Picked up by an antenna

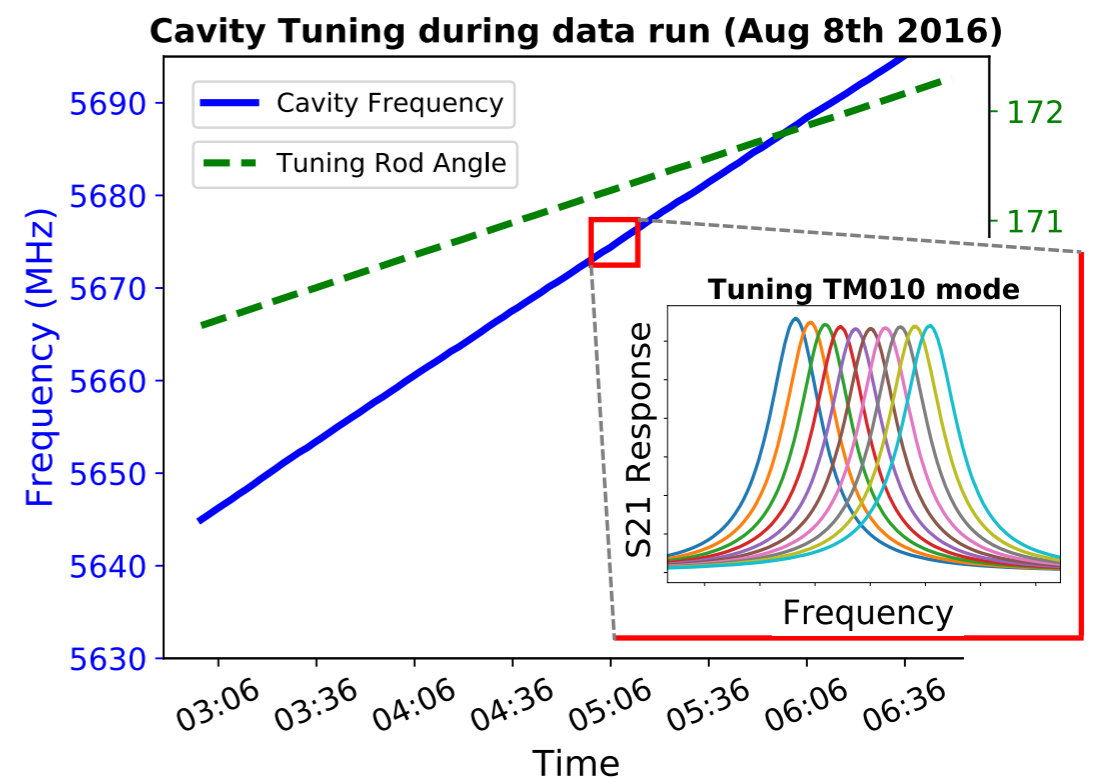
- m_{DM} : resonant to the cavity mode freq.
- Photon phase needs to be coherent
→ Saturate after $\tau_{DM} \sim 1$ ms
- Stored photons = E/B-field intensity

Frequency tuning - mechanical

- Limited range & non-trivial engineering



E-field of the lowest-freq. mode (TM₀₁₀)

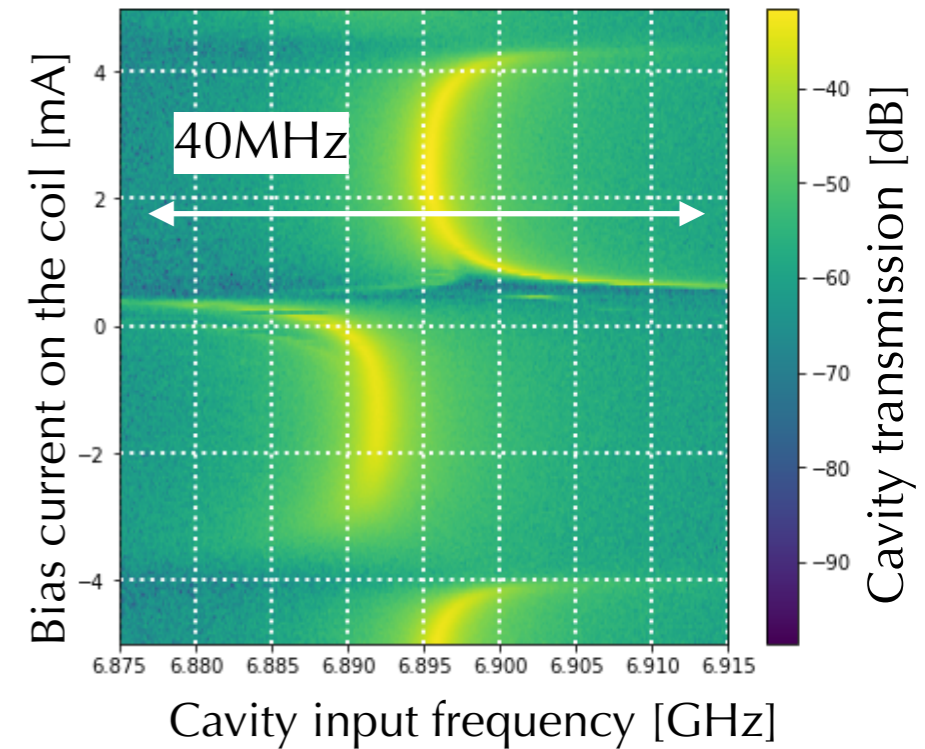
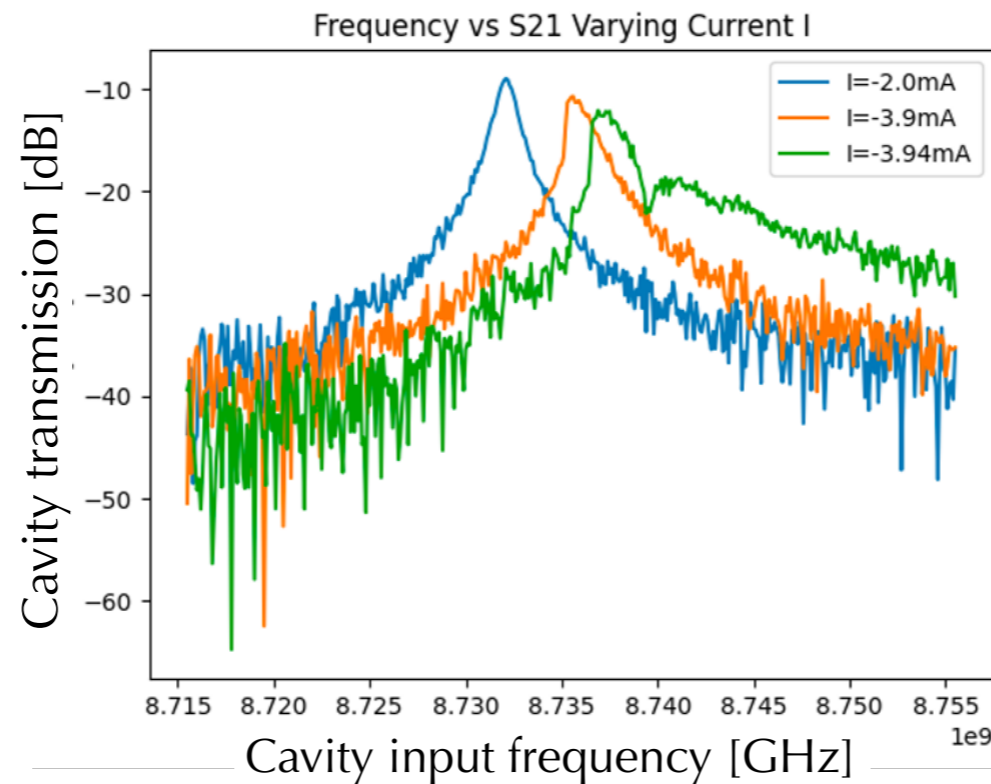
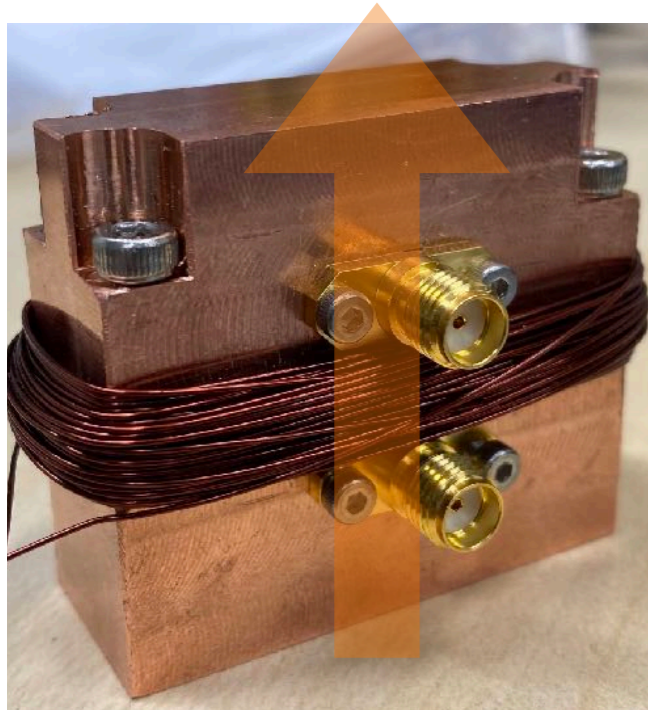


Cavity tuning using the Lamb shift

Preliminary

K. Nakazono

B-field ($\sim \mu\text{T}$)



Cavity resonant freq. varies with coupling with a qubit: $\omega_c^{\text{bare}} \rightarrow \omega_c$ "Lamb shift"

$$\omega_c - \omega_c^{\text{bare}} \sim \begin{cases} g & (\Delta \lesssim g) \\ g^2/\Delta & (\Delta \gg g) \end{cases}$$

$$\Delta := \omega_c^{\text{bare}} - \omega_q$$

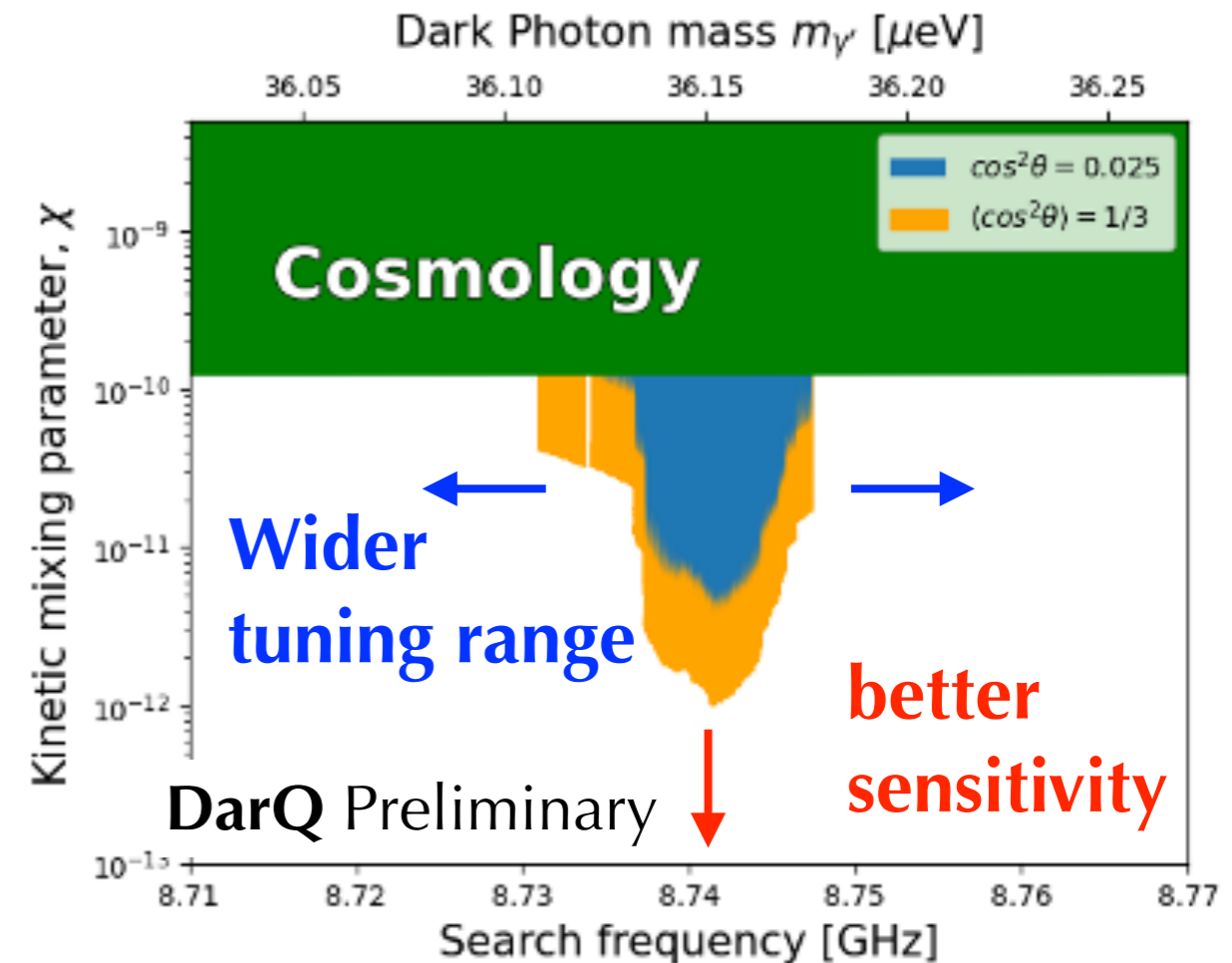
g : cavity-qubit coupling

ω_q variation using SQUID qubit \rightarrow cavity ω_c variation

First results

arXiv: 2505.15619

Variable	explanation	value	others
$m_{\gamma'}$	frequency	~ 8.74 GHz	each measurement
ρ	DM density	0.45 GeV/cm^3	from (Asztalos et al., 2001)
β	coupling constant	~ 0.3	each measurement
T_{sys}	system noise	7.9 K	Y-factor measurement
V_{eff}	effective volume	3.14 cm^3	$V \times \text{form factor}$
Q_L	(Loaded) Quality factor	~ 5000	each measurement
η	attenuation factor	1.02	SG filtering
N	number of data	100	per measurement
b	bandwidth	200 Hz	bandwidth of spectrum analyzer



- Cavity $Q \sim 5000$
- 20s per step, ~ 1000 steps to cover $\sim 10\text{MHz}$ without damaging much on cavity's Q