RESEARCH AND DEVELOPMENT TOWARDS AN AXION SEARCH EXPERIMENT USING QUANTUM SENSING OF MAGNONS

15TH INTERNATIONAL WORKSHOP ON FUNDAMENTAL PHYSICS USING ATOMS
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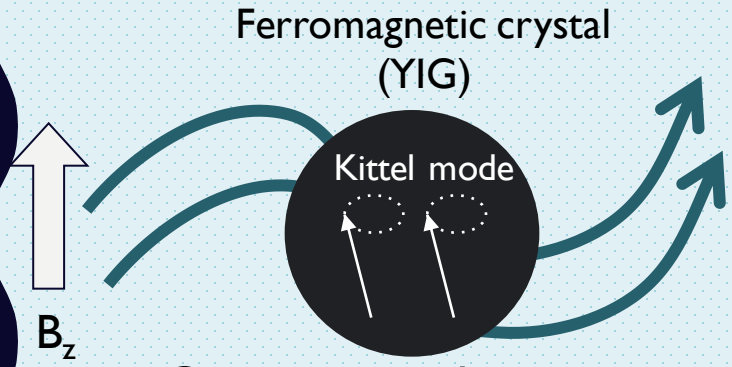
FoPM

研究拠点形成事業
Core-to-Core Program

CONTENT

1. Axions search with magnon
2. Overcoming Standard Quantum Limit with qubit
3. R&D @ Kusaka lab

AXION (DARK MATTER) AS EFFECTIVE MAGNETIC FIELD



Our expected target:

m_a : 5~10 GHz → 20~30 μeV

Magnon

Elementary excitation of uniform spin wave mode i.e. "Kittel mode" (Harmonic oscillator)

Axions ~ Effective magnetic field (B_a)

(DFSZ axion etc.)

$$B_a = \frac{g_{aee}}{2e}\nabla a$$

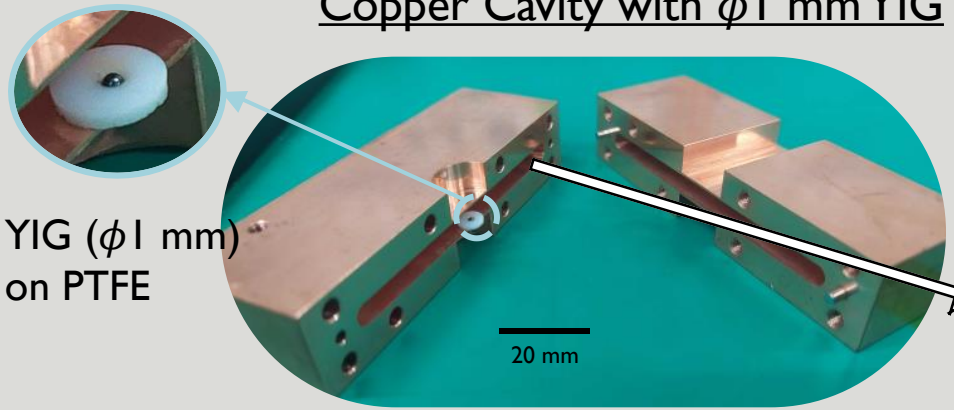
Increase in YIG volume → Increased signal

$$B_a^{sens} \propto \frac{1}{\sqrt{N}}$$

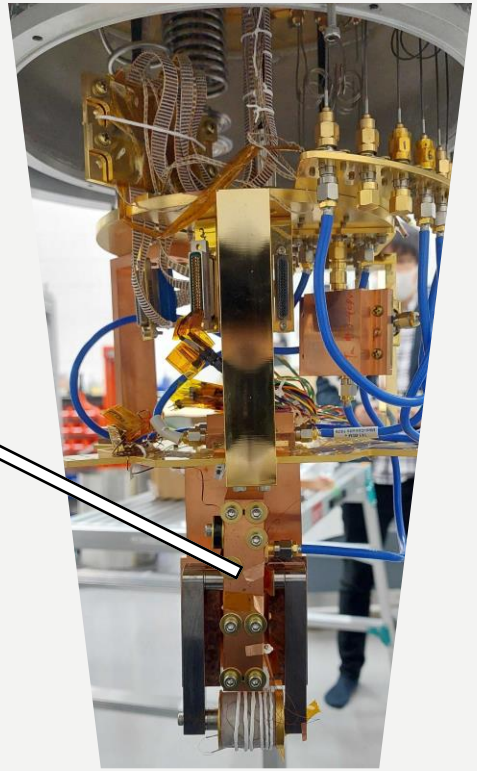
g_{aee} : Axion-electron coupling
N : Number of spins in YIG
∇a : Axion field gradient
ω_a : Axion frequency

MAGNON READOUT WITH CAVITY-KITTEL MODE HYBRID

Copper Cavity with ϕ1 mm YIG



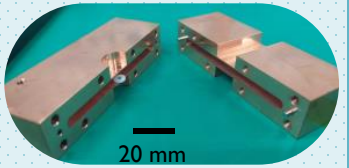
Cavity-magnon hybrid
@ Kusaka lab DR



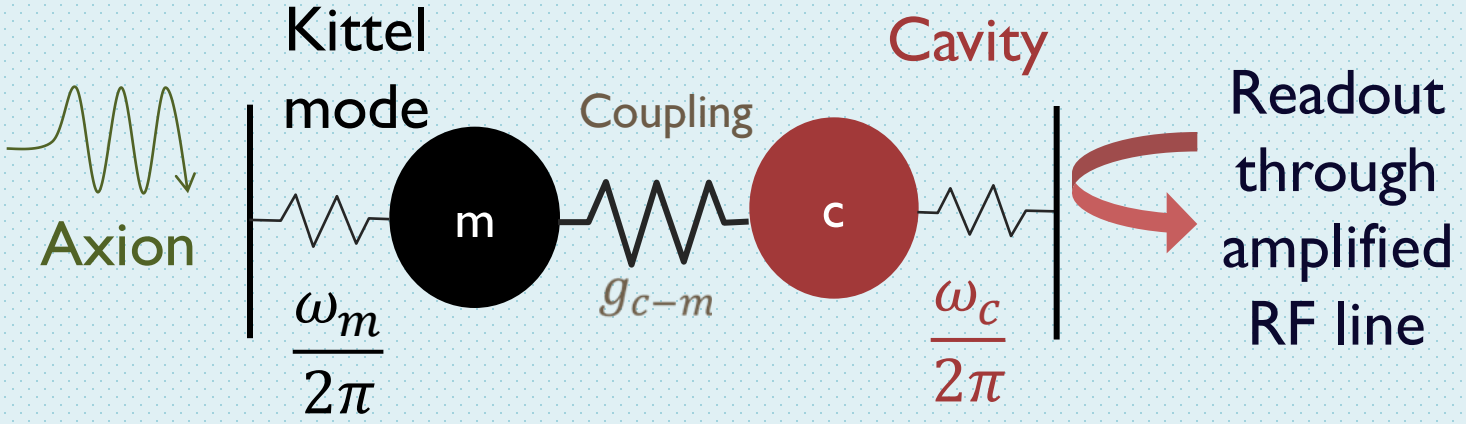
Cryogenic readout of magnon

- Kittel mode (magnon) readout through microwave cavity (photon)
- DR-cooled below 100 mK
- Sensitivity limited by cryogenic amplifier noise

CONVENTIONAL AXION SEARCH
(WITH CAVITY-KITTEL MODE HYBRID)



Coupled Harmonic Resonator Model for cavity – Kittel mode hybrid



Detection scheme

Axion ⇨ Magnon ⇨ Photon ⇨ Quantum Limited Readout

CONVENTIONAL AXION SEARCH
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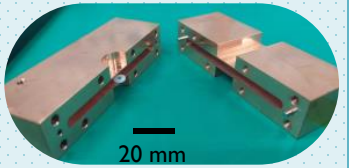

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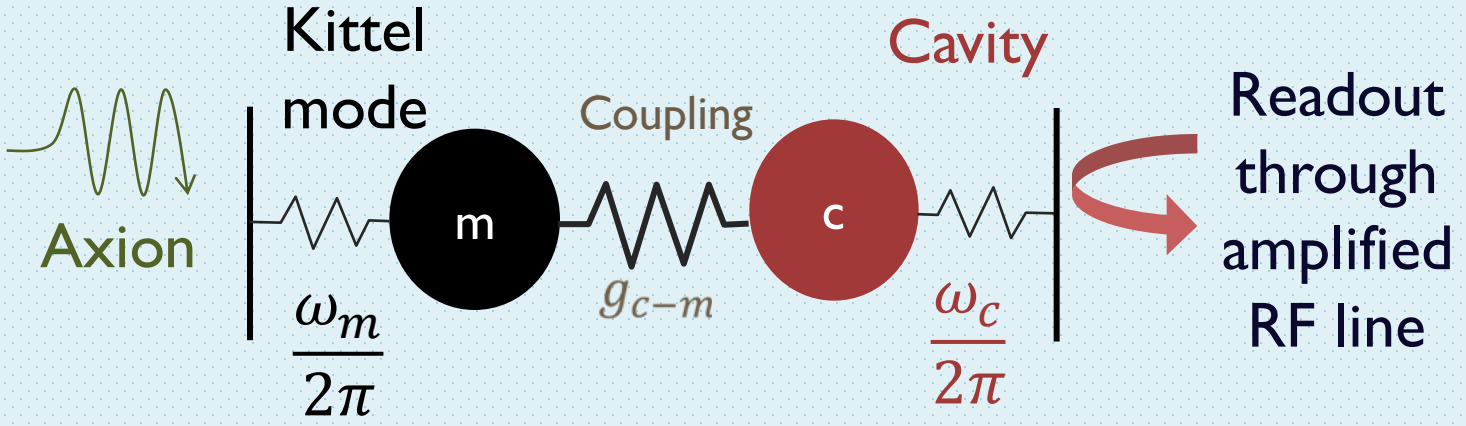
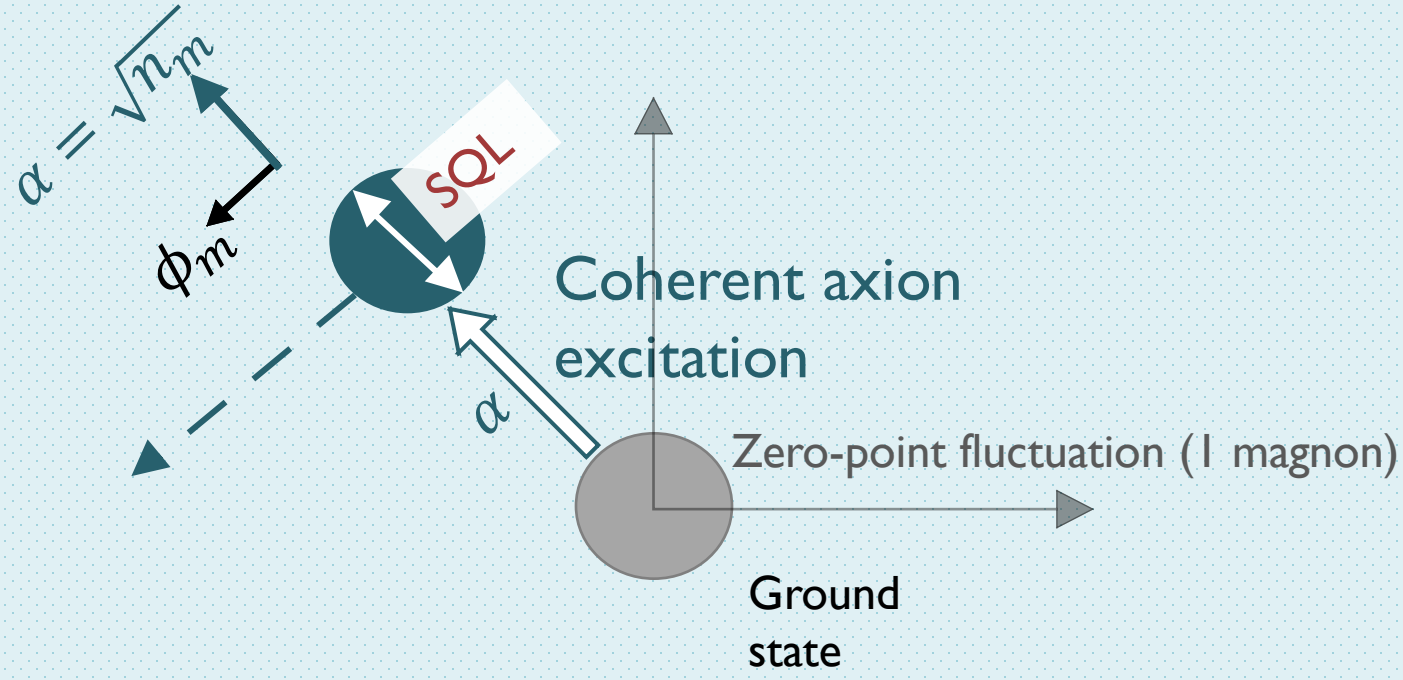


Detection scheme

Axion ⇨ Magnon ⇨ Photon ⇨ Quantum Limited Readout

OVERCOMING STANDARD QUANTUM LIMIT (SQL)

Phase space of Kittel mode (Harmonic oscillator)



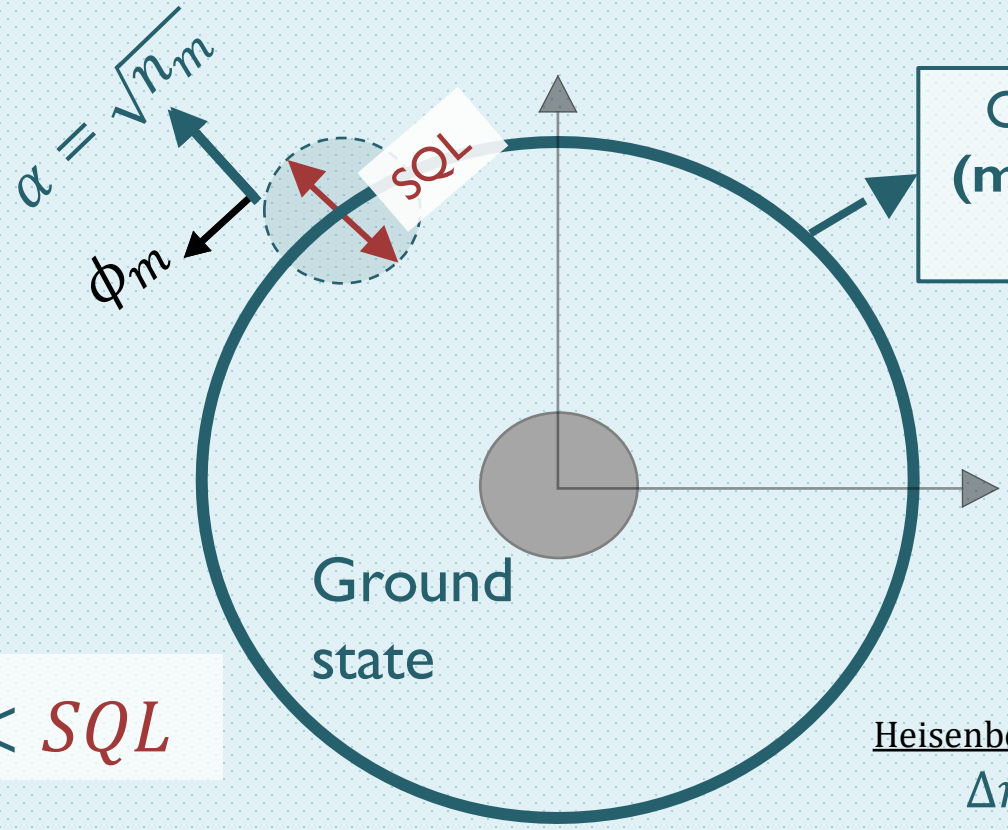
Heisenberg uncertainty principle

$$\Delta n_m \cdot \Delta \phi_m \gtrsim 1$$

Δn_m: Uncertainty in magnon number

$\Delta \phi_m$: Uncertainty in phase

OVERCOMING STANDARD QUANTUM LIMIT (SQL)



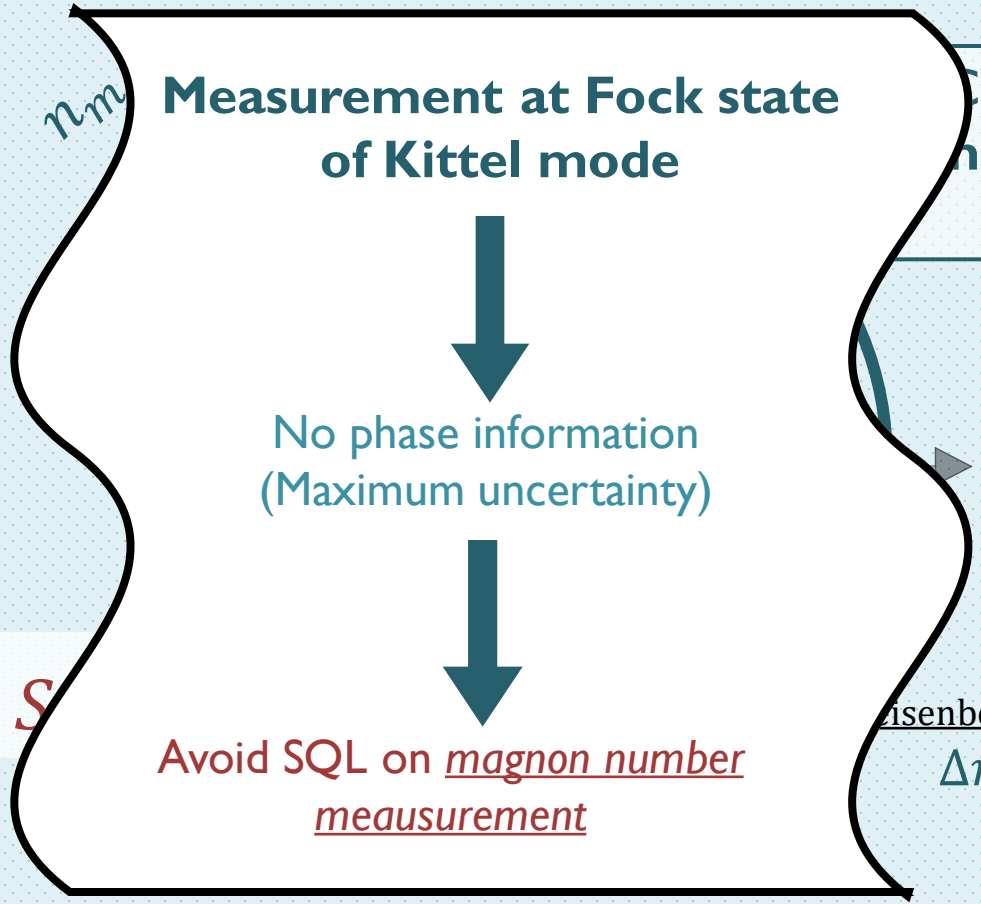
$$\Delta n_m^{fock} < SQL$$

Heisenberg uncertainty principle

$$\Delta n_m \cdot \Delta \phi_m \gtrsim 1$$

Fig. Phase space of Kittel mode

OVERCOMING STANDARD QUANTUM LIMIT (SQL)



collapse into **Fock magnon number) state**

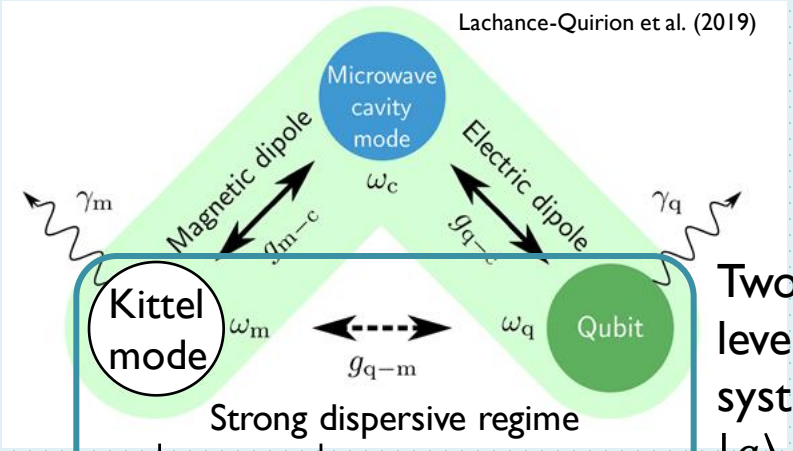
$\Delta n_m^{fock} < S$

isenberg uncertainty principle

$\Delta n_m \cdot \Delta \phi_m \geq 1$

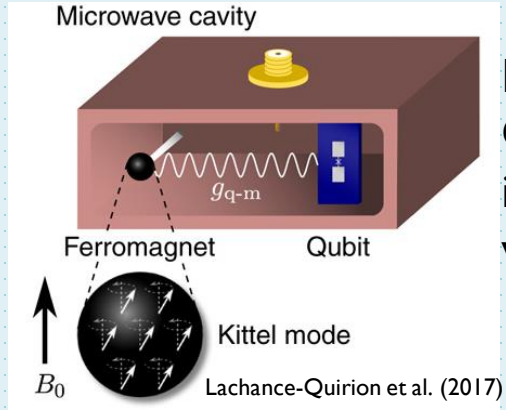
SUPERCONDUCTING QUBIT AS MAGNON COUNTER

Qubit-Kittel mode hybrid



Two level system $|g\rangle$ *or* $|e\rangle$

Experimental setup



Kittel mode-Qubit hybrid implemented with *0.5 mm YIG*

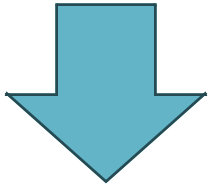
χ_{q-m}: Qubit - Kittel mode dispersive shift
g_{q-m}: Qubit - Kittel mode coupling strength

Magnon number dependent Qubit frequency:

$$\widetilde{\omega_q^{n_m}} = (\omega_q + 2\chi_{q-m} n_m)$$

SUPERCONDUCTING QUBIT AS MAGNON COUNTER

Measurement of magnon number with qubit



Unconstrained by SQL

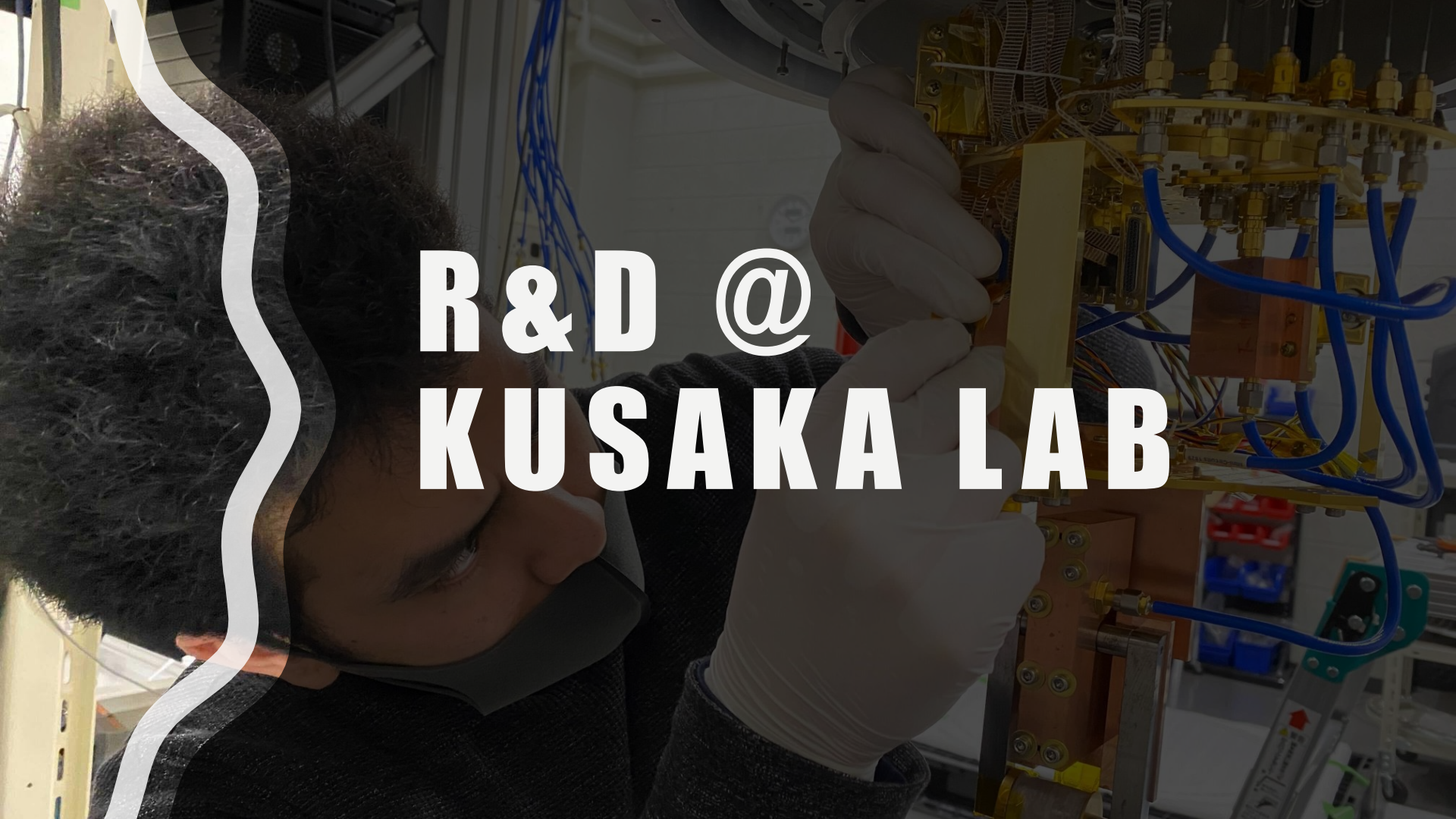
Magnon number dependent Qubit frequency:

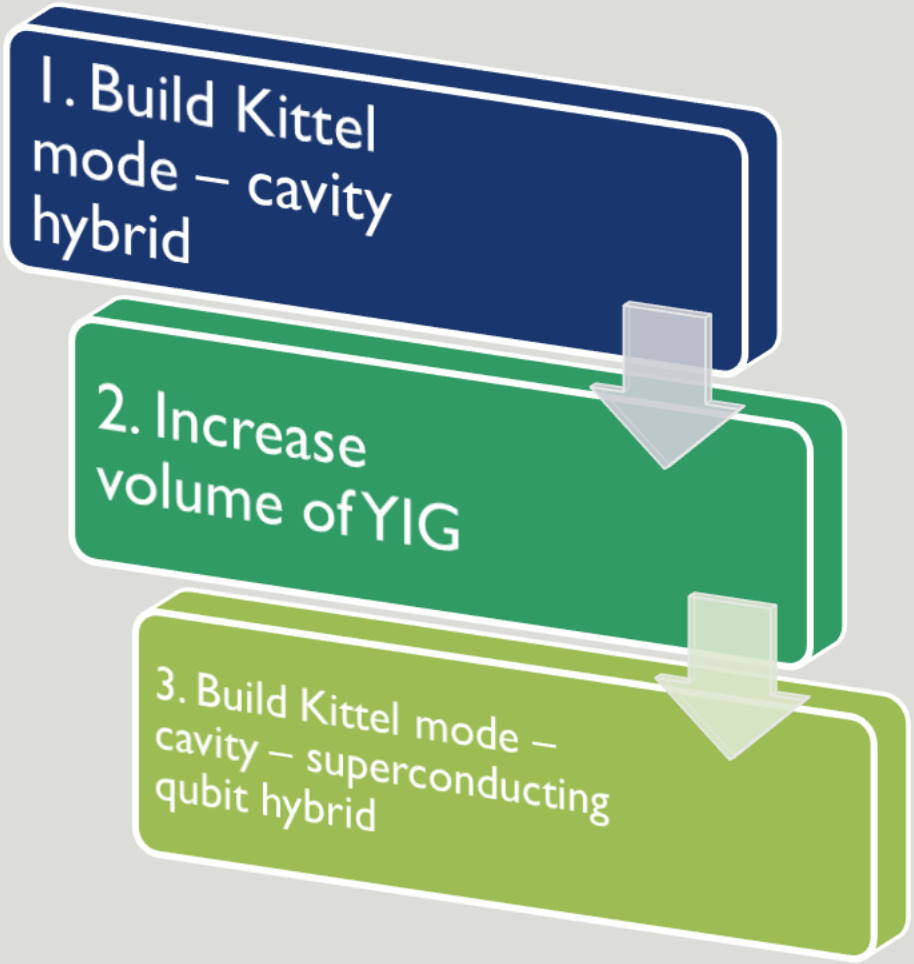
$$\omega_q^{n_m} = \left(\omega_q + 2\chi_{\mathrm{q-m}} n_m\right)$$

IMPROVING AXION SENSITIVITY

INCREASE YIG VOLUME

OVERCOME STANDARD QUANTUM LIMIT WITH QUBITS


R&D @
KUSAKA LAB



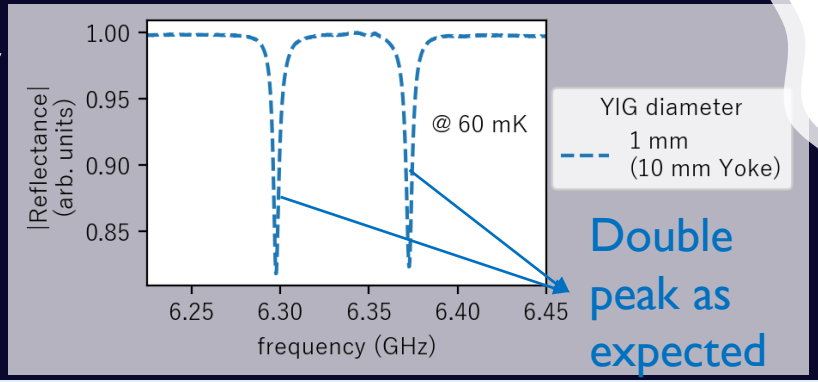
OUR R&D GOALS

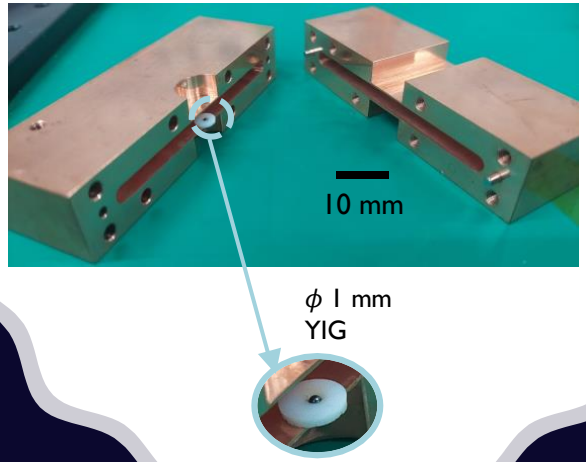
We are working to build a Kittel mode – superconducting qubit hybrid system for BSM particle (axions, hidden photons, gravitons) search.

1. BUILD KITTEL MODE –CAVITY HYBRID

- *Two peaks* of cavity – Kittel mode hybrid system.
  - (single cavity peak in absence of hybridization)

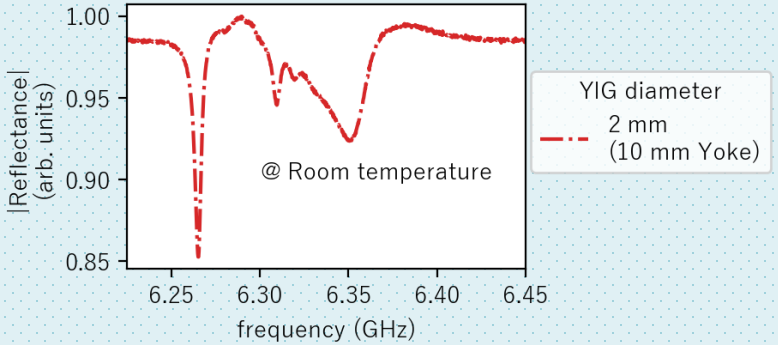
Reflectance of cavity measured with VNA

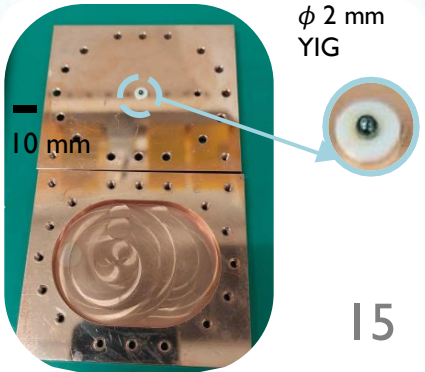




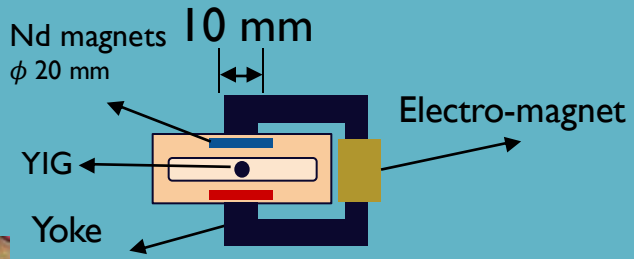
2. INCREASE VOLUME OF YIG

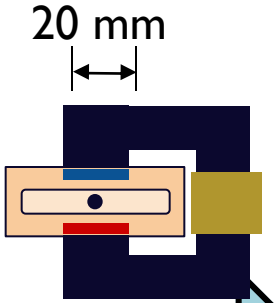
- Appearance of undesirable higher modes due to non-uniform magnetic field





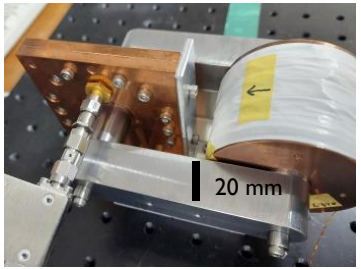
2. IMPROVED FIELD UNIFORMITY FOR LARGER YIG



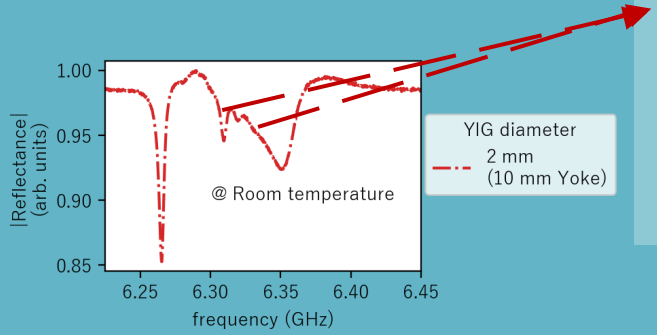


Setup with 10 mm yoke

Setup with 20 mm yoke

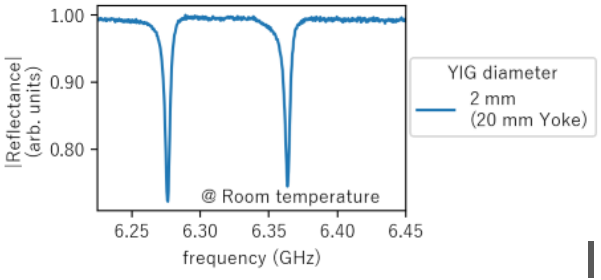


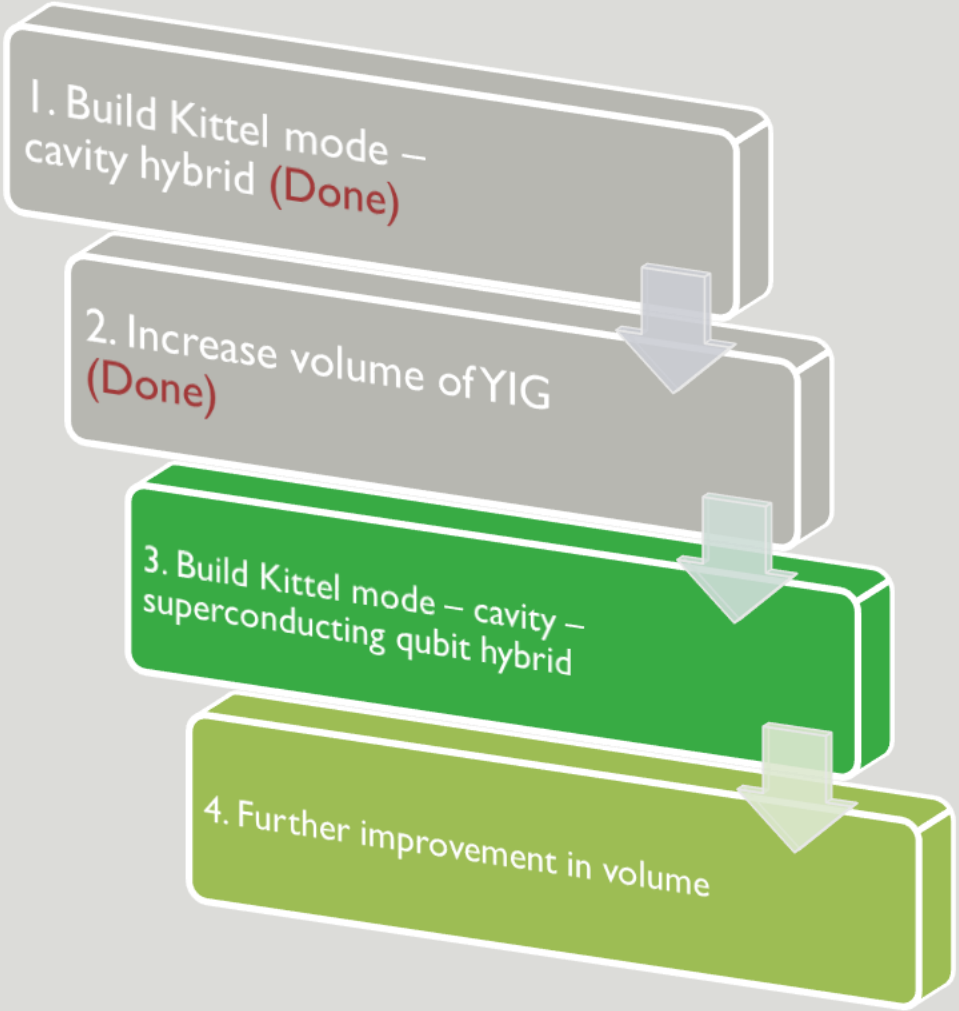
Larger Magnetic Yoke



Undesirable higher modes due to non-uniform magnetic field

Elimination of undesirable higher mode



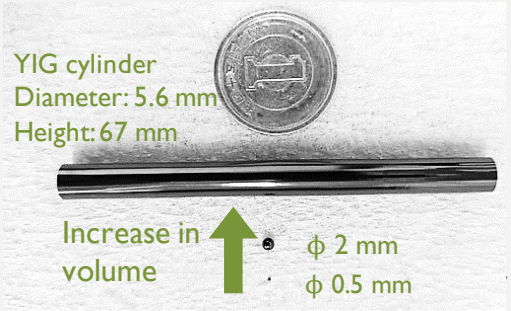


NEXT STEPS

→ Kittel mode - cavity - superconducting qubit hybrid with ***2 mm YIG***

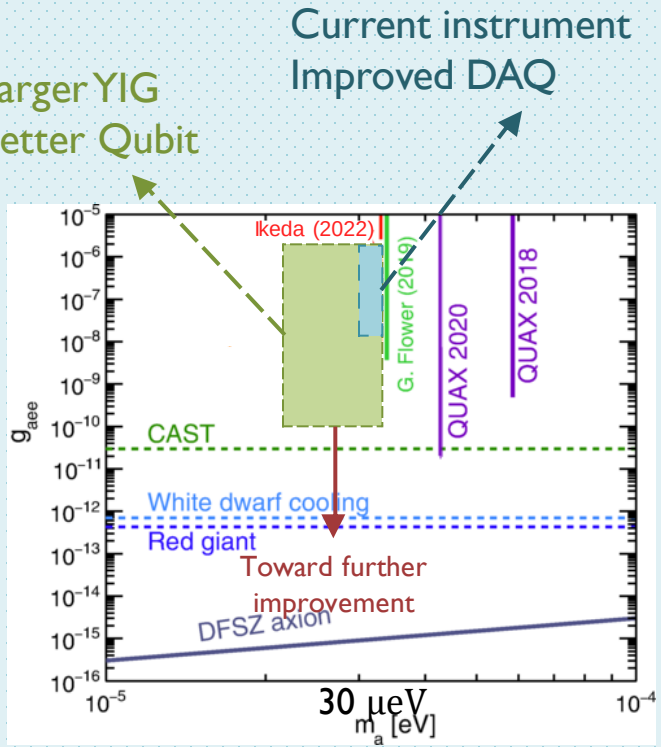
- cf. current design has 0.5 mm YIG

Future improvement in volume



SUMMARY

- Axion search is possible through magnons
- Current search constrained by Standard Quantum Limit
- Superconducting Qubit offers way to overcome Standard Quantum Limit
- R & D on-going to optimize the superconducting qubit – Kittel mode (magnon) system for particle searches.



THANK YOU!