ENHANCING AXION DETECTION WITH QUANTUM SENSING OF MAGNONS: A MAGNON COUNTER WITH A SUPERCONDUCTING QUBIT

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JSR Fellowship

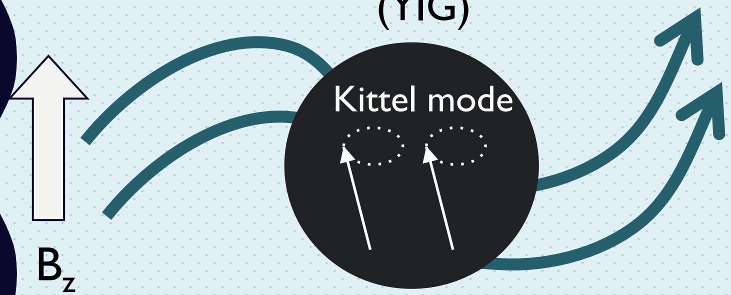
FoPM

CONTENT

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

AXION (DARK MATTER) AS EFFECTIVE MAGNETIC FIELD

Ferromagnetic crystal
(YIG)



Our expected target:

m_a : 5~10 GHz → 20~30 μeV

<u>Magnon</u>

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

Axions ~ Effective magnetic field (B_a)

(DFSZ axion etc.)

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

Increase in YIG volume → Increased signal

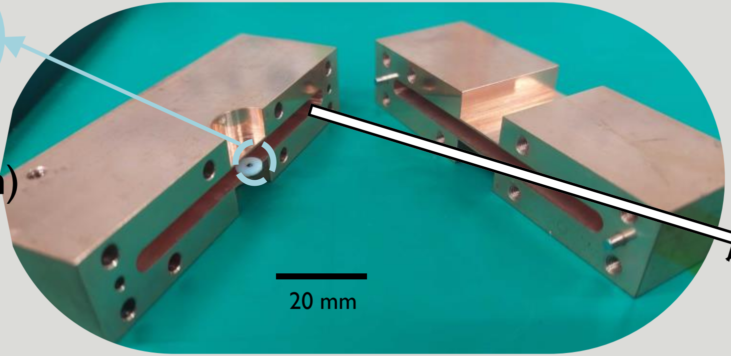
$$B_a^{sens} \propto \frac{1}{\sqrt{N}}$$

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

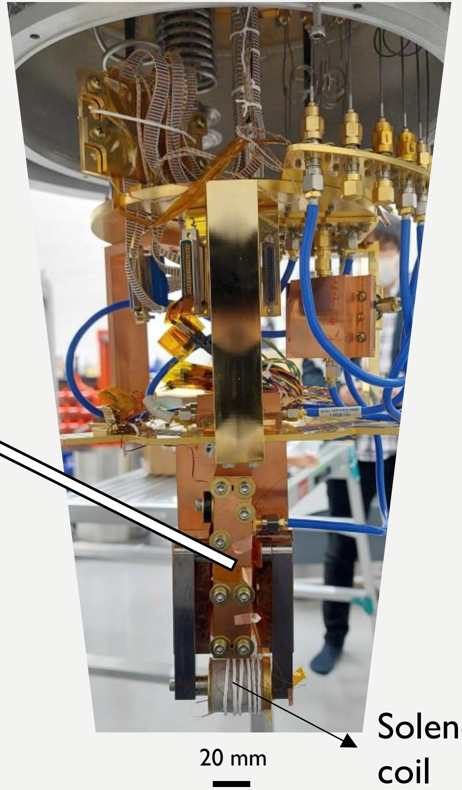
Copper Cavity with ϕ1 mm YIG

YIG (ϕ1 mm) on PTFE



Microwave cavity resonator

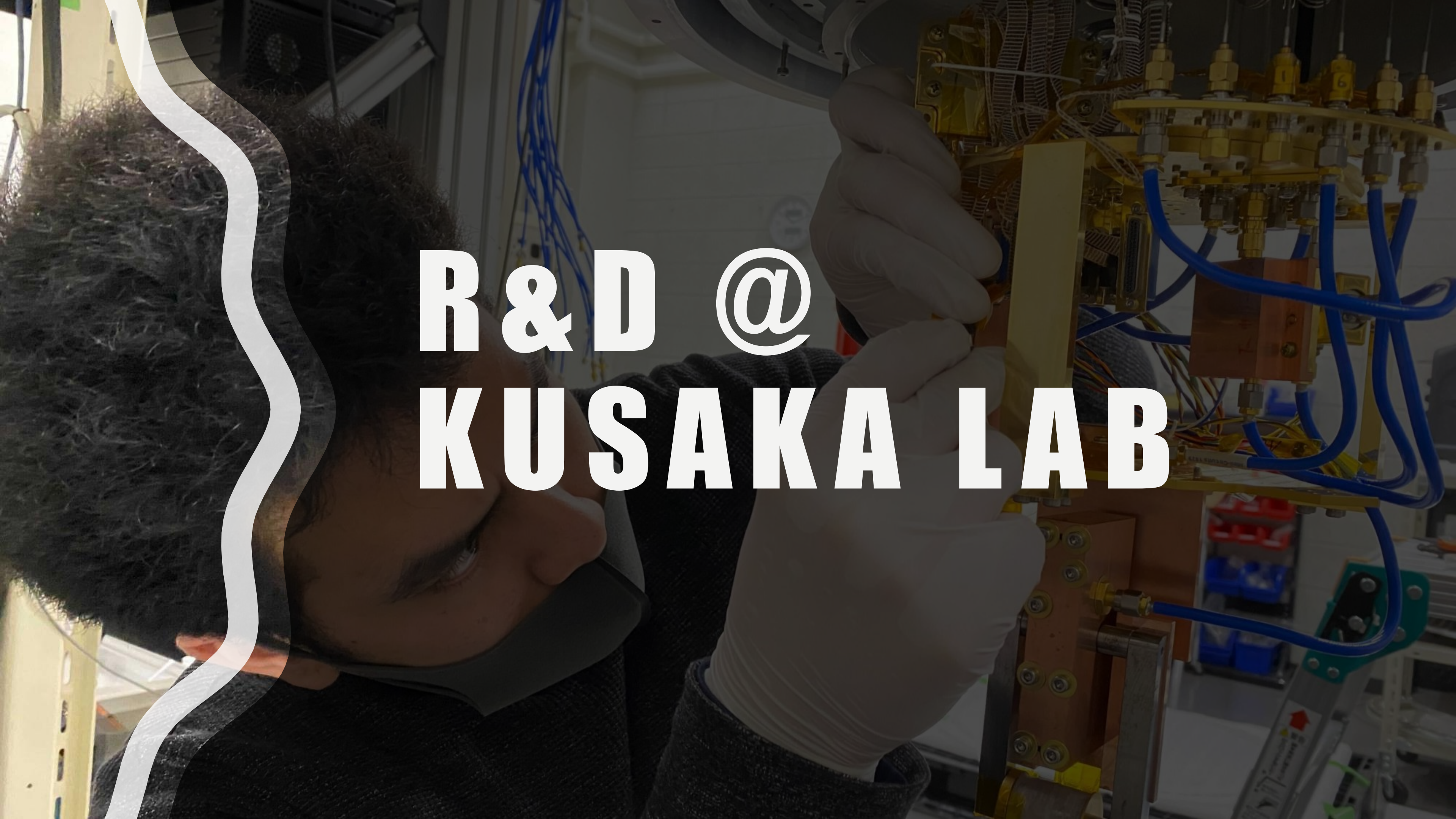
Cavity-magnon hybrid @ Kusaka lab DR

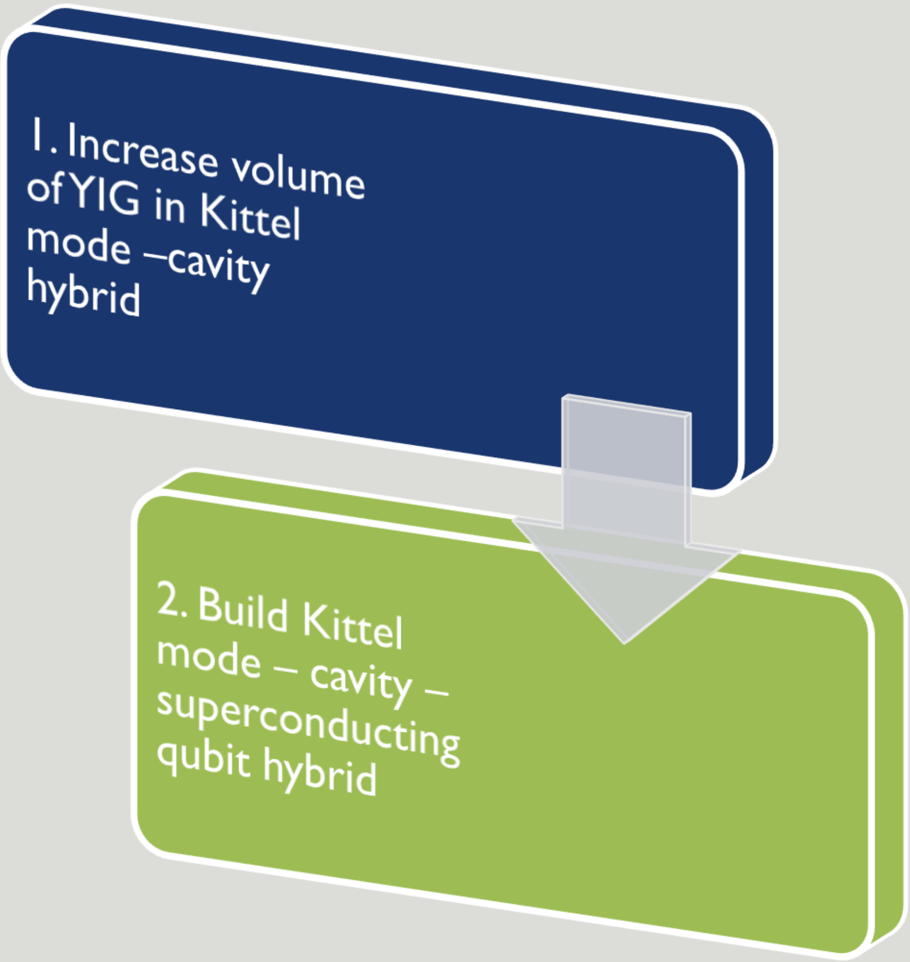


Solenoid coil

Cryogenic readout of magnon

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


R&D @
KUSAKA LAB



OUR R&D GOALS

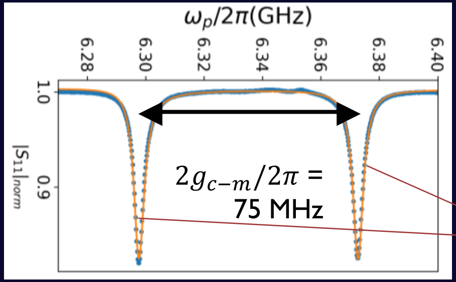
We are working to build a Kittel mode – superconducting qubit hybrid system for BSM particle (axions, hidden photons, gravitons) search.

KITTEL MODE –CAVITY HYBRID

YIG SPHERE, ϕ = 1 MM

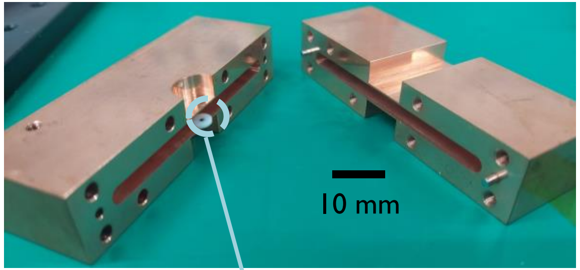
Reflectance of cavity measured with VNA

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



@60 mK

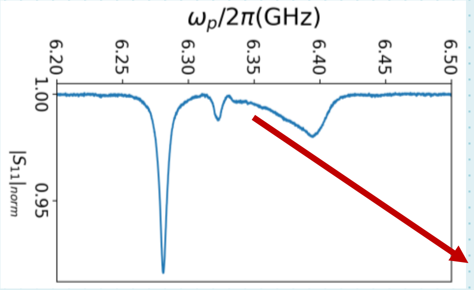
Double peak as expected



ϕ 1 mm
YIG

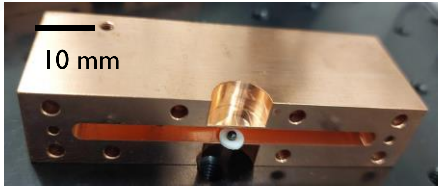
INCREASE VOLUME OF YIG, ϕ = 2 MM

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



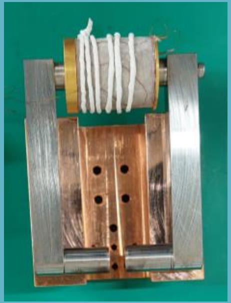
@100 mK

coupling with higher modes

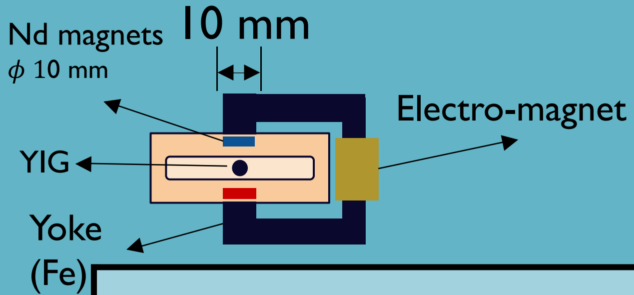


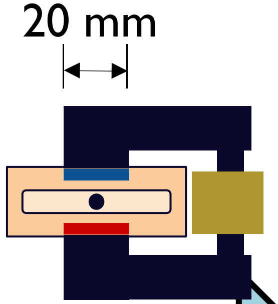
IMPROVED FIELD UNIFORMITY FOR LARGER YIG

Setup with 10 mm yoke

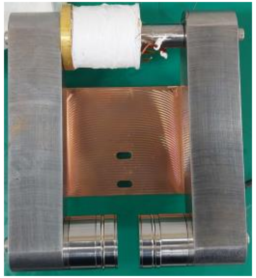


10 mm





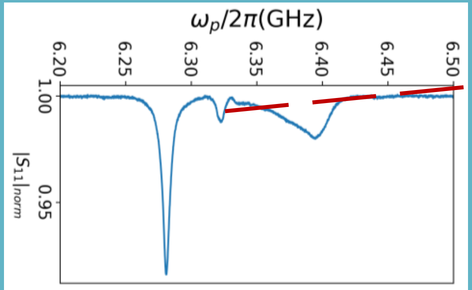
Setup with 20 mm yoke



20 mm

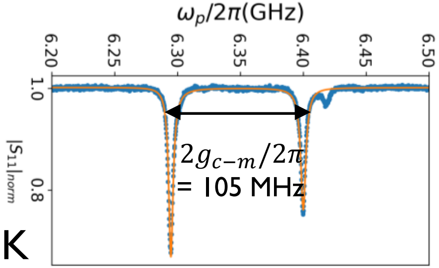
Larger Magnetic Yoke

Elimination of undesirable higher mode



Undesirable higher modes due to non-uniform magnetic field

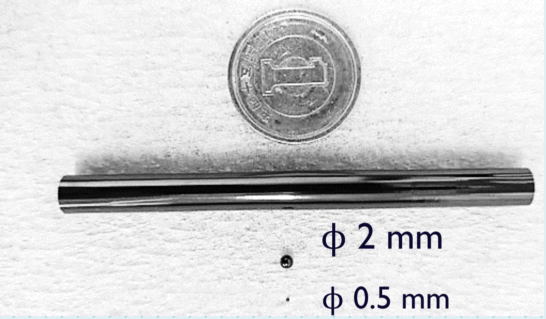
@100 mK



@100 mK

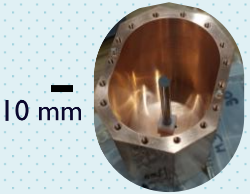
LARGE CYLINDRICAL YIG

YIG CYLINDRICAL
DIAMETER: 5.6 MM
LENGTH: 67 MM



Increase in volume by ~400 compared to ϕ 2 mm sphere

Experimental setup at KEK



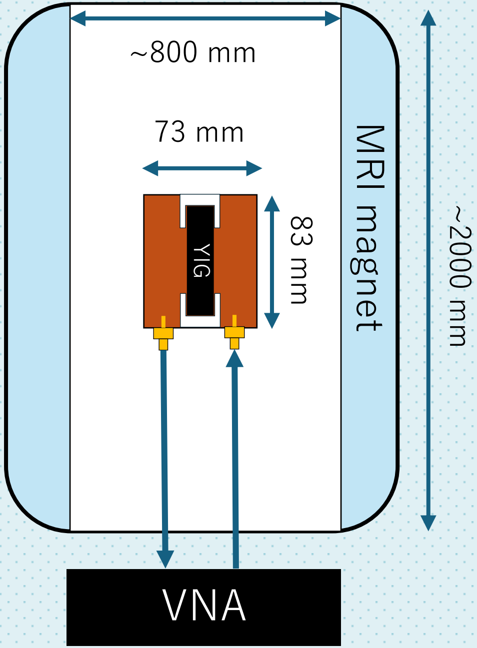
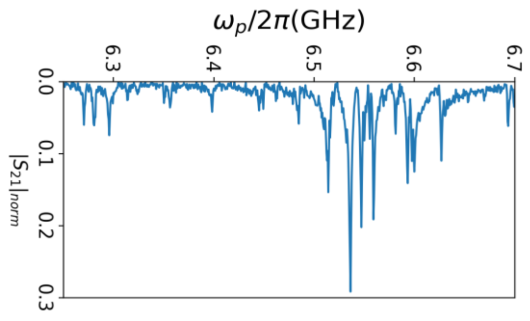
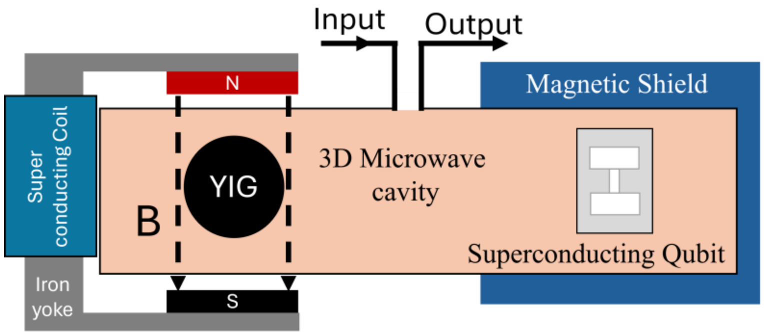


Diagram not in scale

Result at room temperature



Non-uniformity in demagnetizing field due to *<u>cylindrical shape</u>* cause many higher order modes

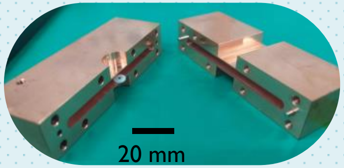


MAGNON COUNTER WITH A SUPERCONDUCTING QUBIT

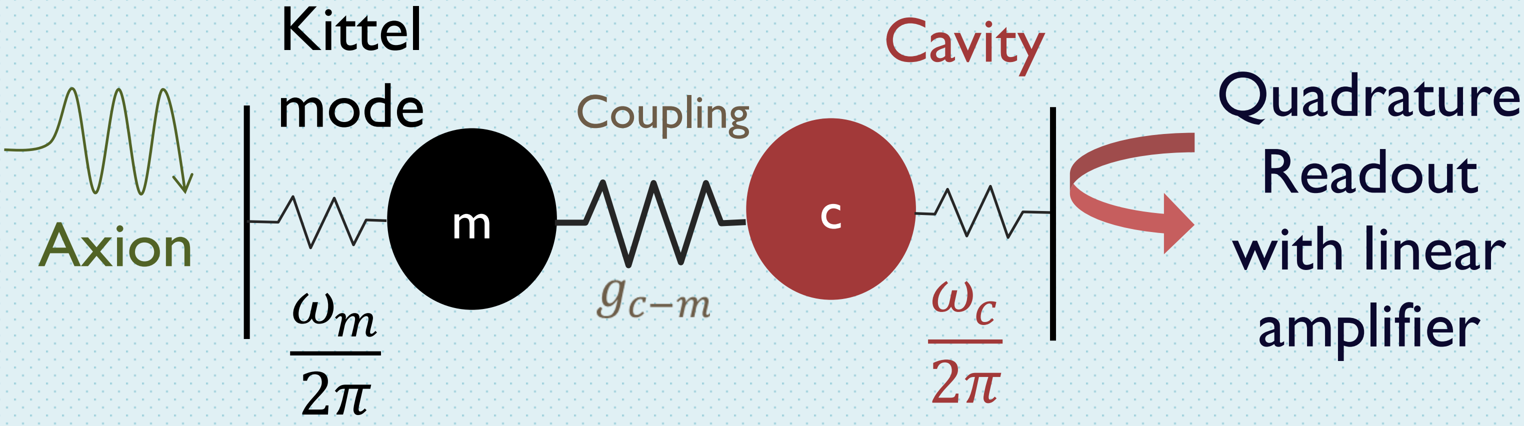
Prospects and challenges to overcome SQL

With realistic qubit and experimental parameters, overcoming the SQL is non-trivial. Simulation study in progress

CONVENTIONAL AXION SEARCH
(WITH CAVITY-KITTEL MODE HYBRID)



Coupled Harmonic Resonator Model for cavity – Kittel mode hybrid

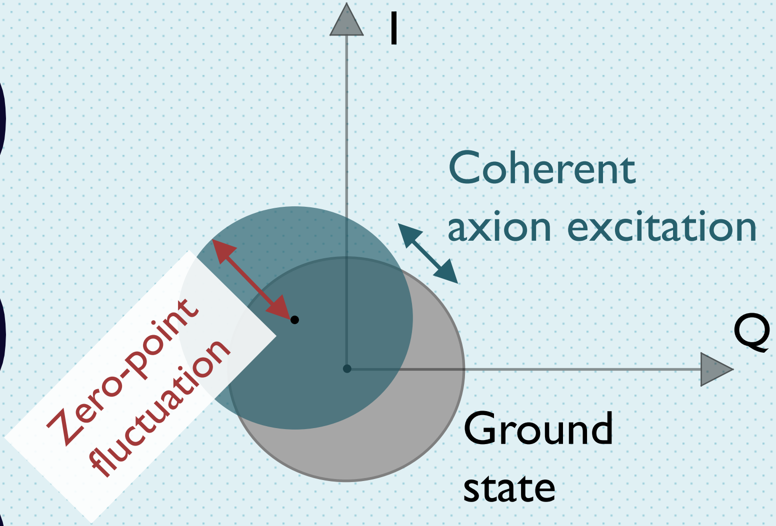


Detection scheme

Axion ⇨ Magnon ⇨ Photon ⇨ Quantum Limited Readout

OVERCOMING STANDARD QUANTUM LIMIT (SQL)

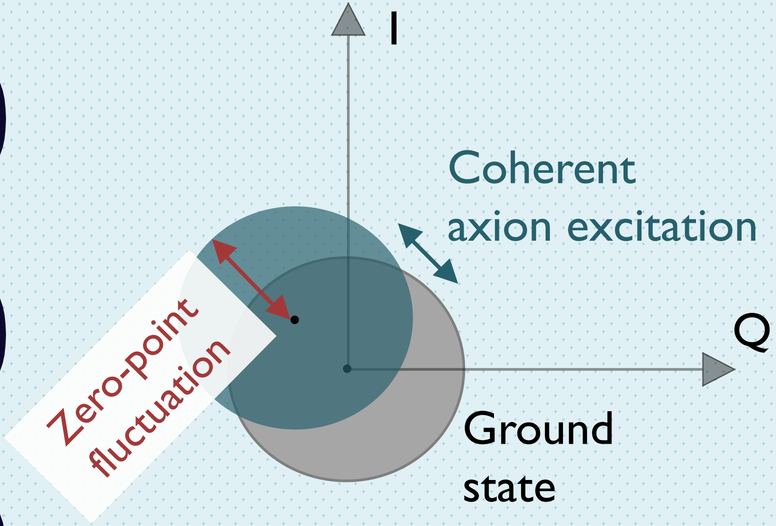
Readout in quadrature basis



- Zero-point fluctuation present in quadrature measurement with linear amplifier.
  - Readout of two conjugate variables (both I and Q quadrature)
- Magnon occupation no. (noise) at frequency ω and temperature T.
  - $n(\omega, T) = \underbrace{\frac{1}{e^{\hbar\omega/k_B T} - 1}}_{\text{Thermal noise}} + \underbrace{1}_{\text{Zero-point fluctuation}}$

OVERCOMING STANDARD QUANTUM LIMIT (SQL)

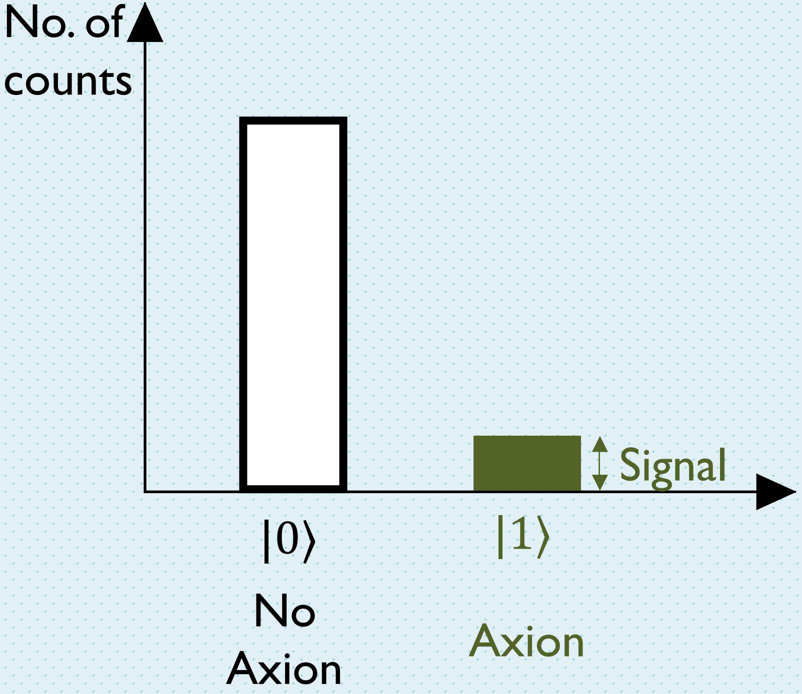
Readout in quadrature basis



- For $\omega/2\pi$ = 6 GHz, at T <100 mK, easily attainable with dilution refrigerator, contribution of thermal noise, $\frac{1}{e^{\hbar\omega/k_B T}-1}$ is negligible.
- Zero-point fluctuation equivalent to 1 magnon sets a **fundamental lower limit** in noise (**SQL**).

OVERCOMING STANDARD QUANTUM LIMIT (SQL)

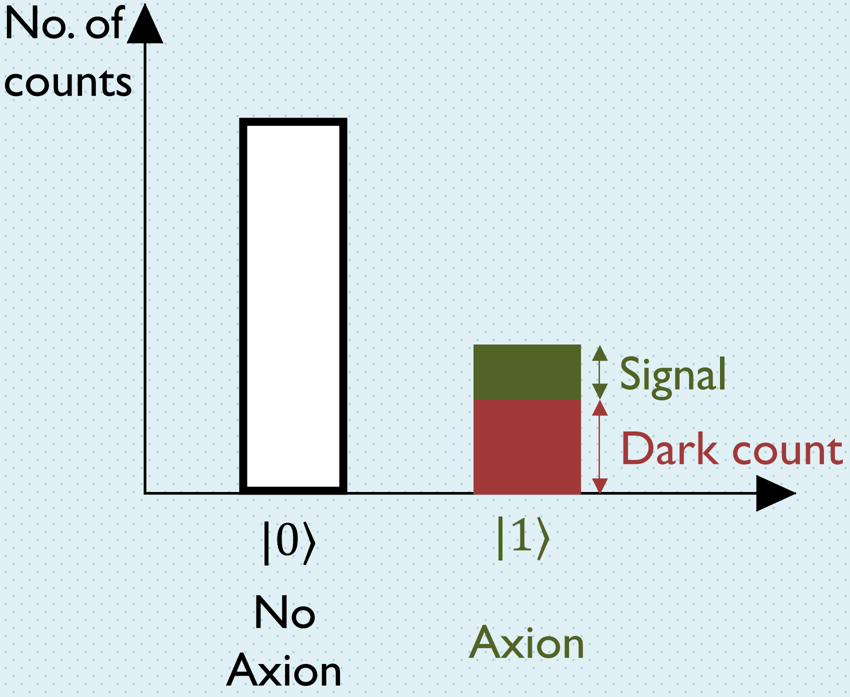
Readout in number basis



- No effect from zero-point fluctuation of Kittel mode in number basis.
  - No phase information in number basis.
- Ideally, shot noise from axion signal is the only noise.

OVERCOMING STANDARD QUANTUM LIMIT (SQL)

Readout in number basis (Magnon counter)

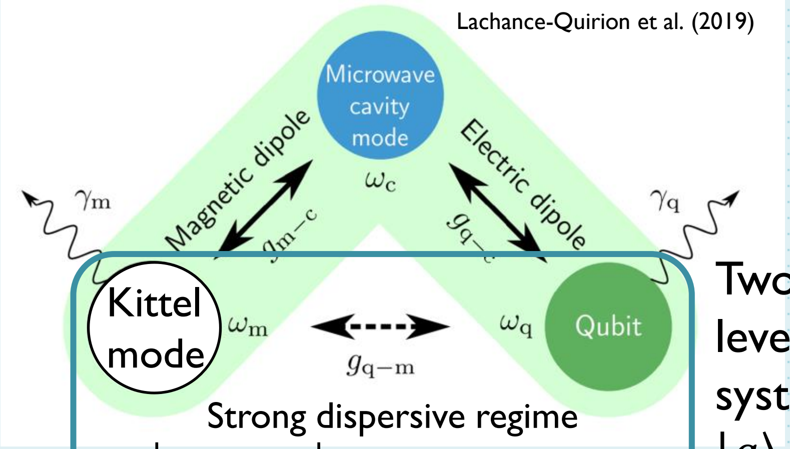


- Dark count still present in magnon counter
  - Error in magnon counter readout
  - Temperature dependent thermal noise
- **Sensitivity beyond SQL** possible by *reducing dark count*

SUPERCONDUCTING QUBIT AS MAGNON COUNTER: DISPERSIVE INTERACTION

Qubit-Kittel mode hybrid

Lachance-Quirion et al. (2019)

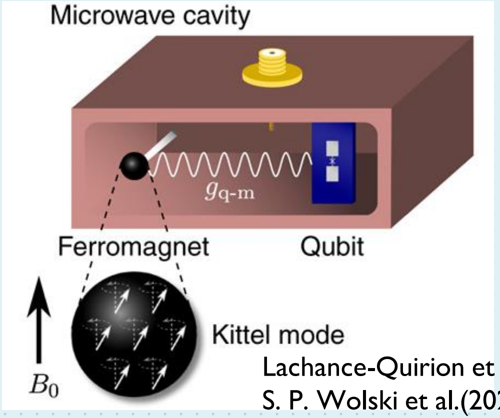


Strong dispersive regime

$(|\omega_m - \omega_q| \gg g_{q-m} \gg \gamma_m, \gamma_q)$

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

Experimental setup



Kittel mode-Qubit hybrid implemented with *0.5 mm YIG* at Nakamura lab

Lachance-Quirion et al. (2017,2020)
S. P. Wolski et al.(2020)

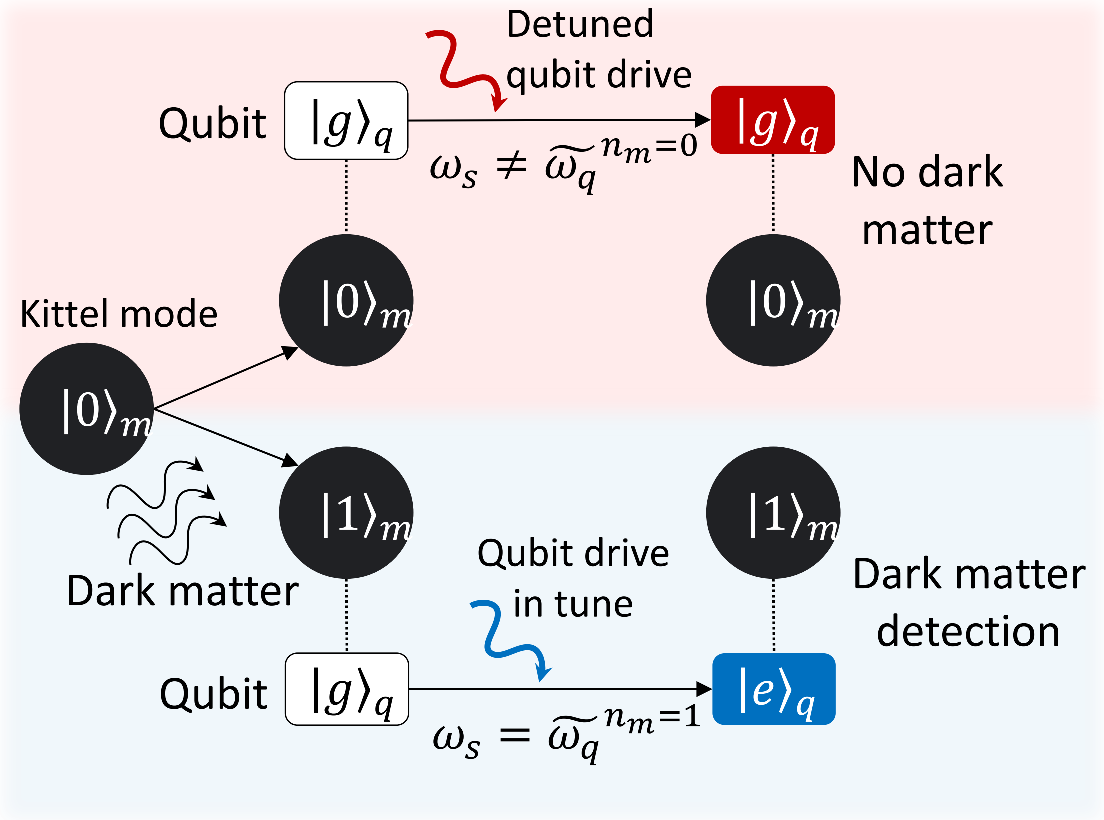
χ_{q-m}: Qubit - Kittel mode dispersive shift
g_{q-m}: Qubit - Kittel mode coupling strength

Magnon number dependent Qubit frequency:

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

Use SC qubit to build a magnon counter in collaboration with Nakamura lab

ENTANGLEMENT BASED PROTOCOL



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

Change in qubit frequency upon magnon excitation by axion allows entanglement of qubit state with magnon state

SCHEMATIC OF QUBIT-KITTEL MODE HYBRID

κ_i: Internal decay rate of cavity

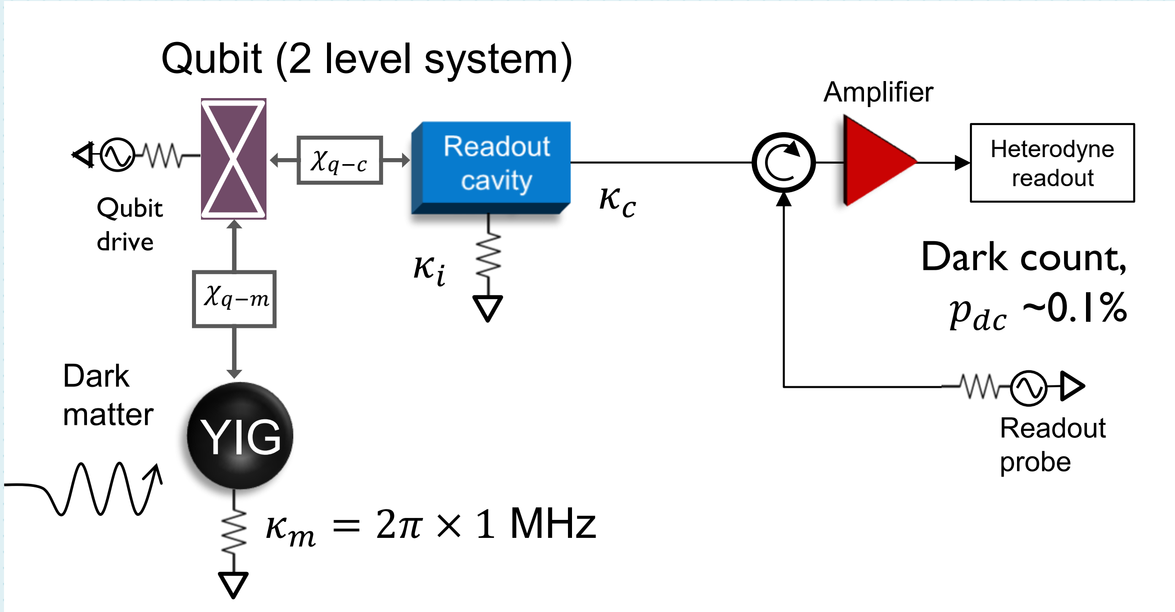
κ_c: External coupling rate of readout cavity

κ_m : Kittel mode linewidth

χ_{q-c}: Dispersive shift between qubit and cavity

χ_{q-m}: Dispersive shift between qubit and Kittel mode

$\Delta\nu_a$: Axion linewidth



Ideally,

$$R^{ideal} = \frac{\tau_{SQL}}{\tau_{ent}} = \frac{2\Delta\nu_a}{p_{dc}\kappa_m} = 1.6 \text{ times faster than SQL}$$

LOSS OF EFFICIENCY DUE TO DECOHERENCE

Qubit decoherence causes loss of efficiency

At optimal configuration

$$R = 0.07 \times 0.8 \times 1.6$$

R^{ideal}

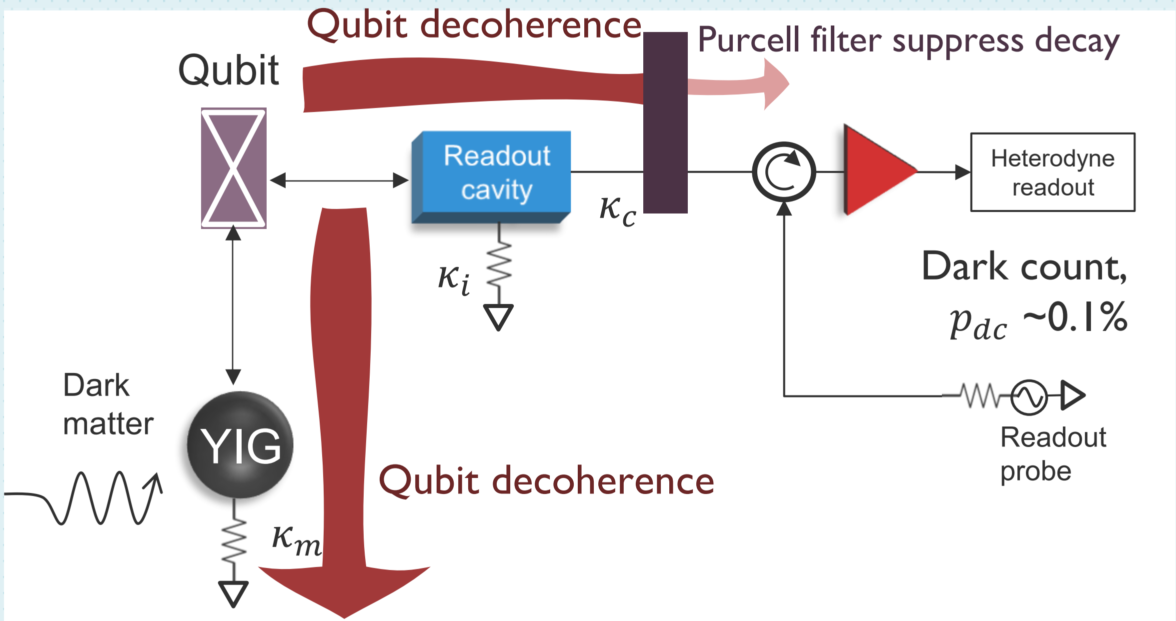
Kittel mode induced inefficiency

Readout cavity induced inefficiency

Optimized with Purcell filter

$$\boxed{R \approx 0.1 < 1}$$

Still below SQL



To achieve sensitivity beyond SQL:

1. Narrower Kittel mode linewidth
2. Smaller dark count
   - Readout through multiple qubits

Details in Workshop week

MAGNON COUNTING USING DISPERSIVE INTERACTION WITH QUBIT

1. Entanglement based protocol
2. Dissipation based protocol

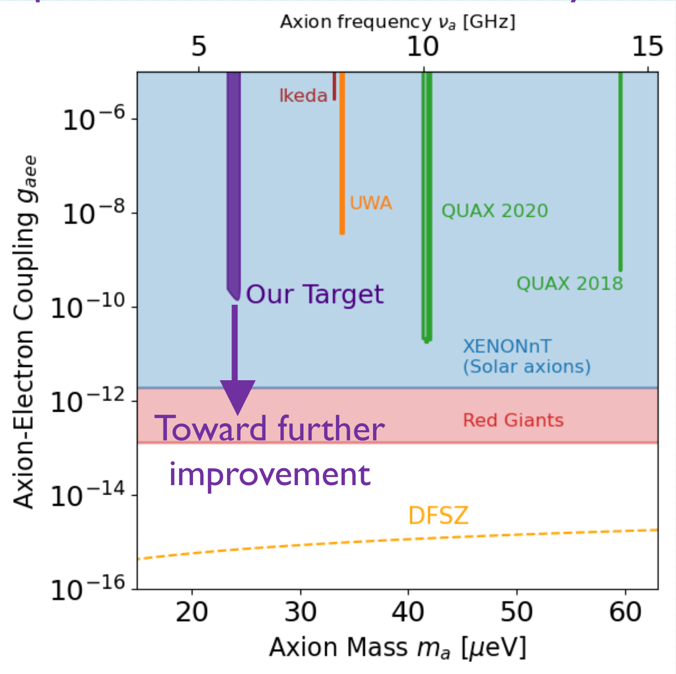
Workshop week

3. Qubit spectroscopy

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 to achieve beyond SQL sensitivity

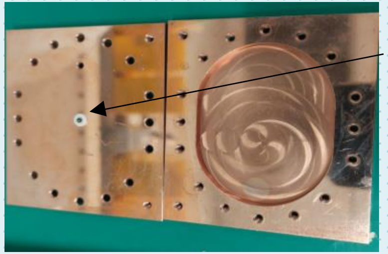
Larger YIG
Optimized Kittel mode - Qubit hybrid

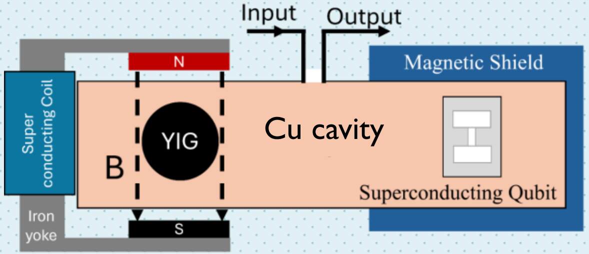


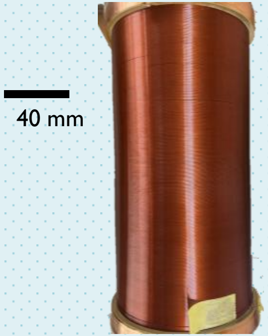
GOALS

Initial target:

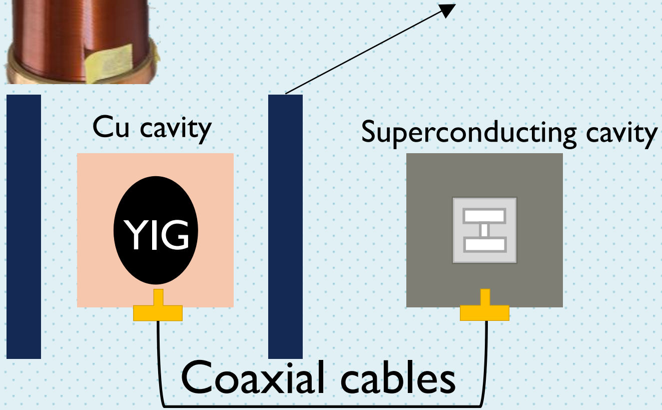
Qubit-Kittel mode hybrid with 2 mm YIG







Superconducting solenoid magnet (0.5 T) (ϕ86 mm) (designed and manufactured by the CRC, UTokyo group)



Future design:

- Solenoid magnet has better uniformity allows YIG with larger volume
- Separate SC cavity for qubit allows better coherence.
- Multiple qubit for increased sensitivity

THANK YOU!

Acknowledgements :

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