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

INTERNATIONAL WORKSHOP ON MULTI-PROBE APPROACH TO WAVY DARK MATTERS
DECEMBER 2

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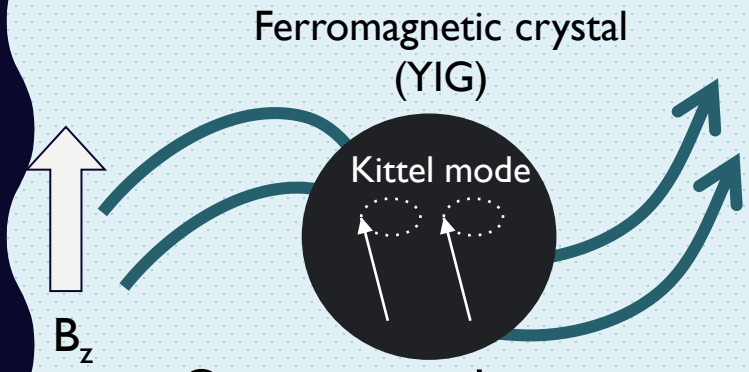
FoPM

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 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.)

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

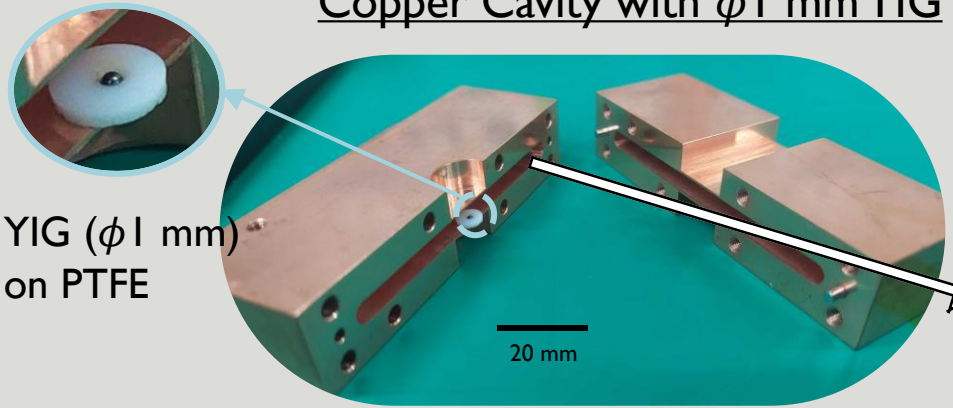
Increase in YIG volume → Increased signal

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

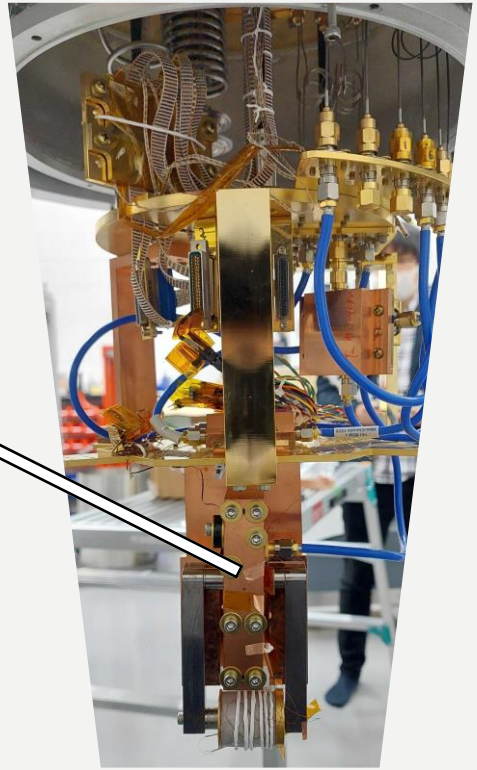
g_{aee} : Axion-election coupling
N : No. of spins in YIG
∇a : Axion field gradient
ω_a : Axion frequency

MAGNON READOUT WITH CAVITY-KITTEL MODE HYBRID

Copper Cavity with ϕ1 mm YIG



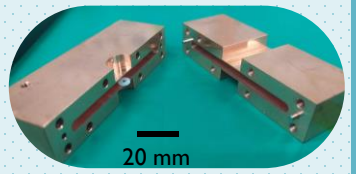
Cavity-magnon hybrid
@ Kusaka lab DR



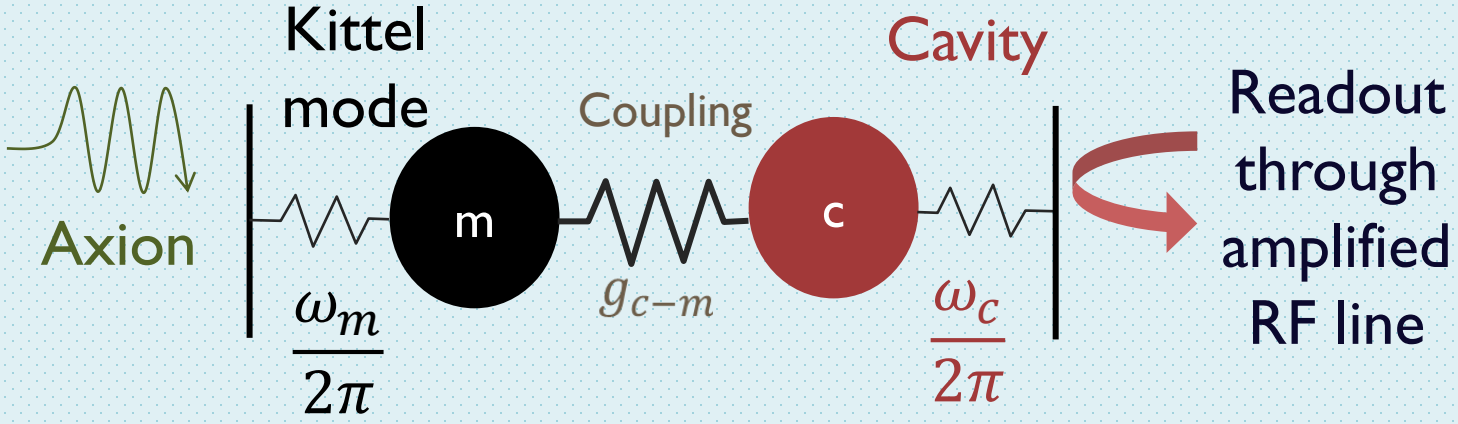
Cryogenic readout of magnon

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

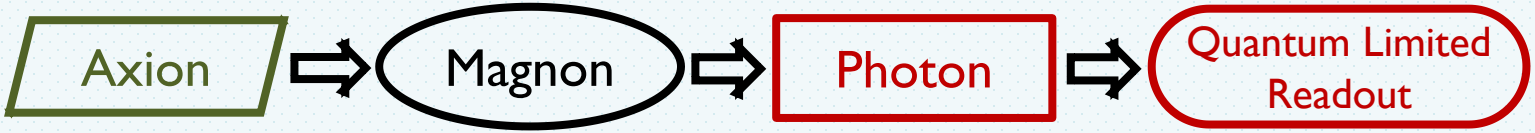
CONVENTIONAL AXION SEARCH
(WITH CAVITY-KITTEL MODE HYBRID)



Coupled Harmonic Resonator Model for cavity – Kittel mode hybrid



Detection scheme



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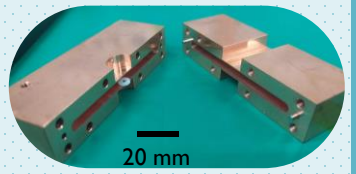

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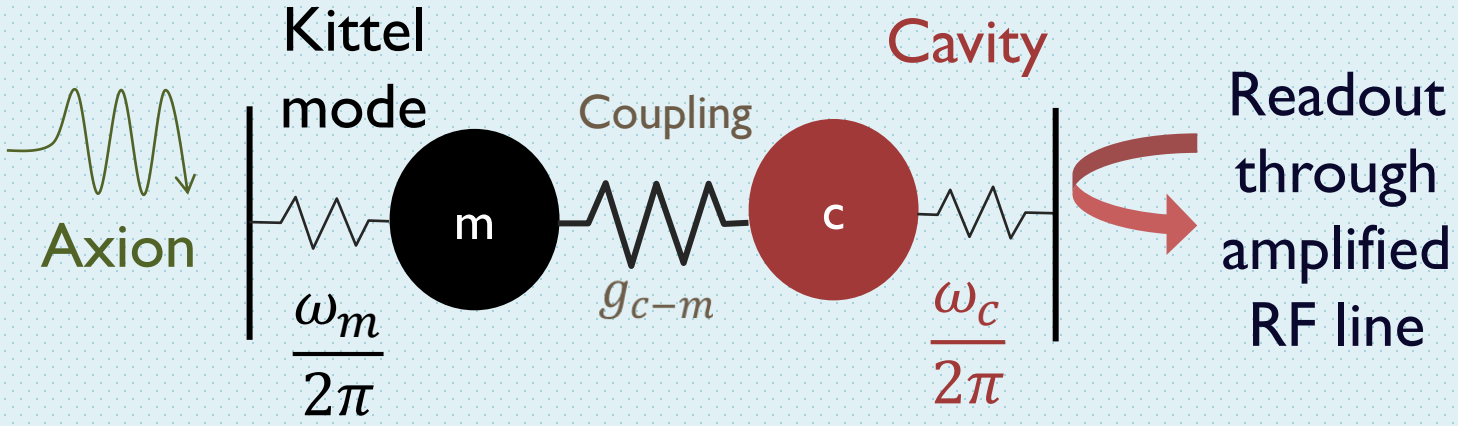

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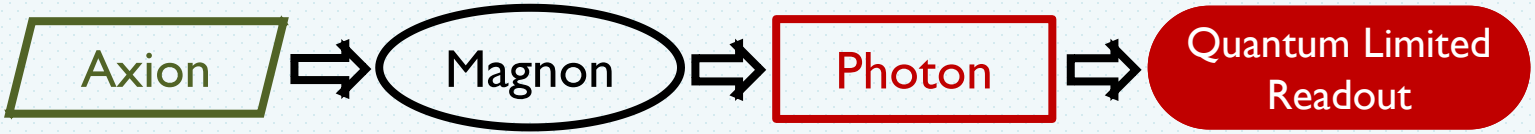
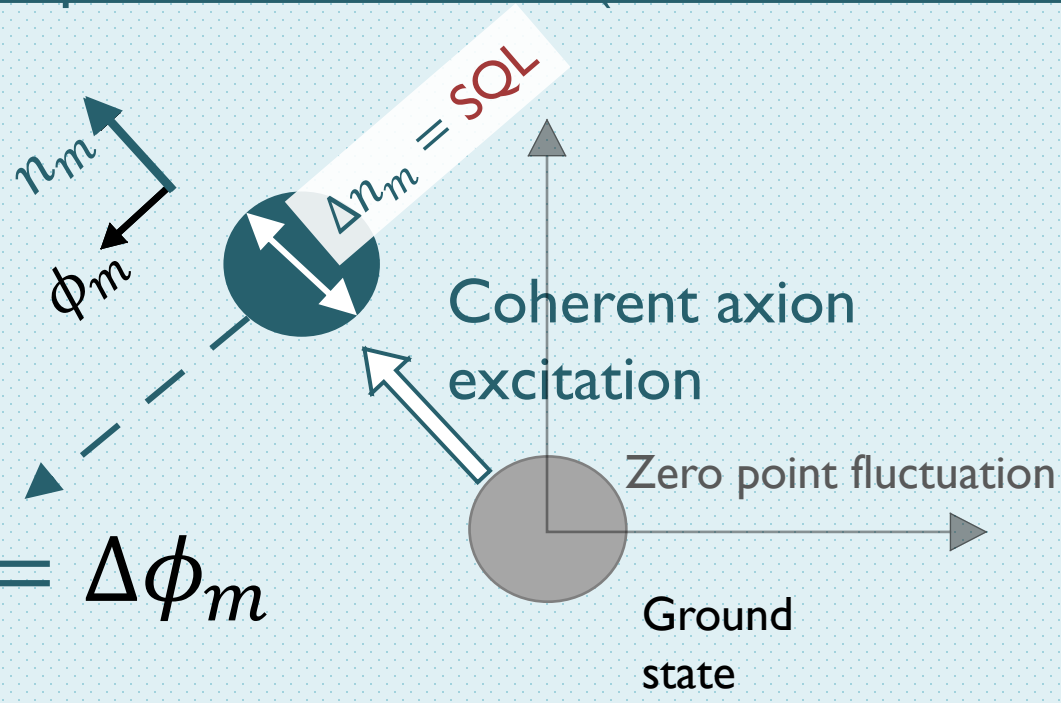


OVERCOMING STANDARD QUANTUM LIMIT (SQL)

Phase space of Kittel mode (Harmonic oscillator)



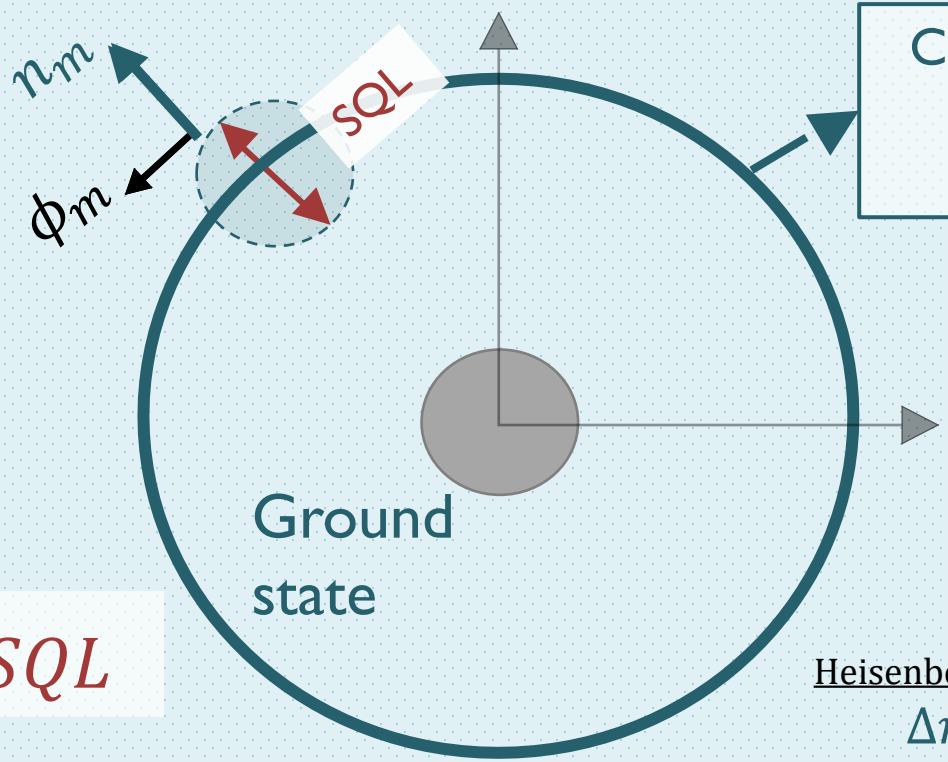
$$\Delta n_m = \Delta \phi_m$$

Heisenberg uncertainty principle

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

Δn_m: Uncertainty in magnon no.
$\Delta \phi_m$: Uncertainty in phase

OVERCOMING STANDARD QUANTUM LIMIT (SQL)



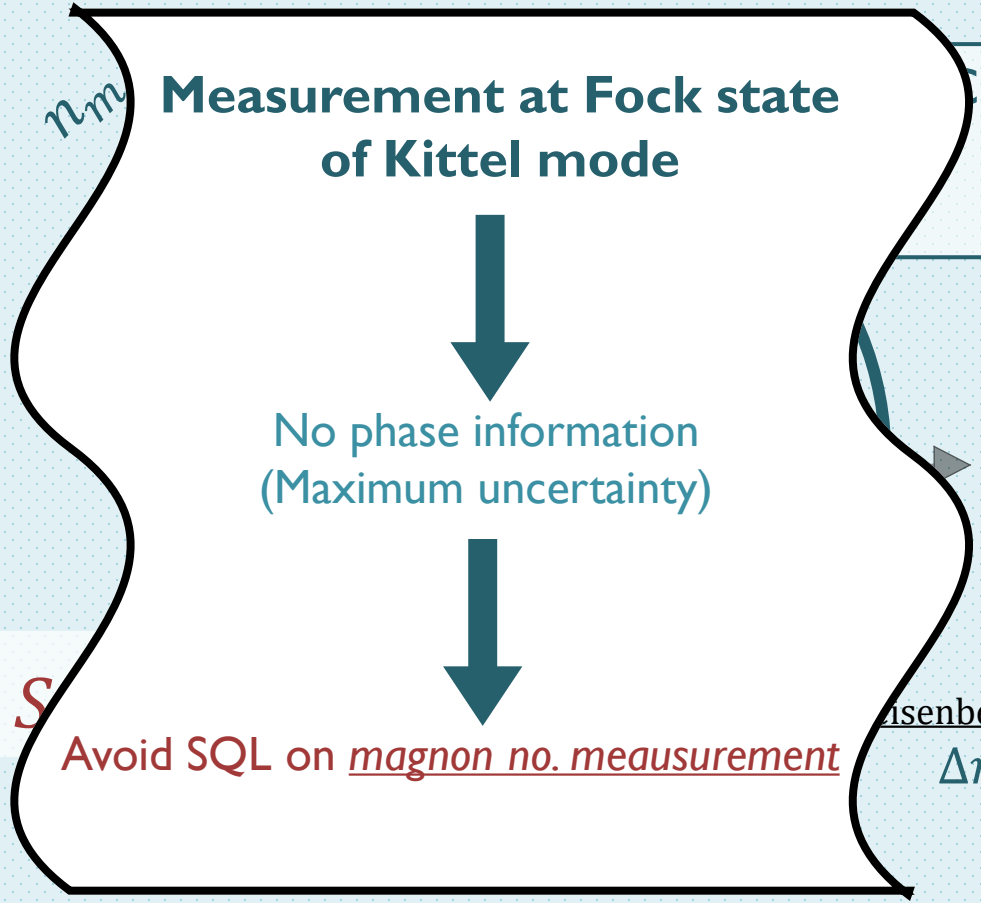
$$\Delta n_m^{fock} < SQL$$

Heisenberg uncertainty principle

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

Fig. Phase space of Kittel mode

OVERCOMING STANDARD QUANTUM LIMIT (SQL)



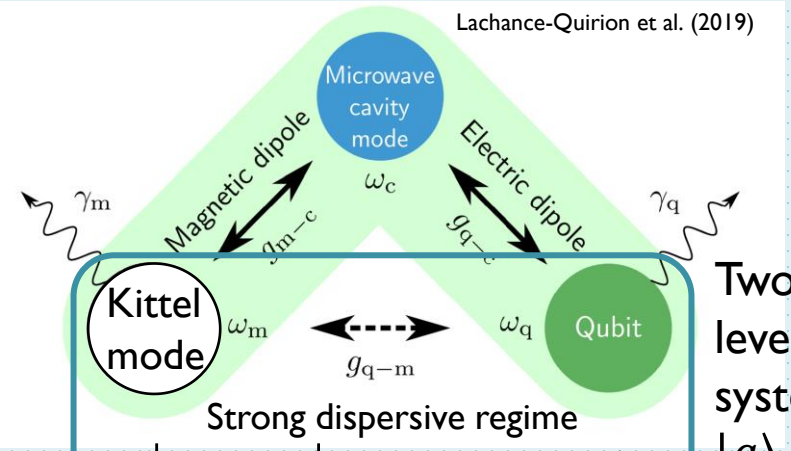
$\Delta n_m^{fock} < S$

Heisenberg uncertainty principle

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

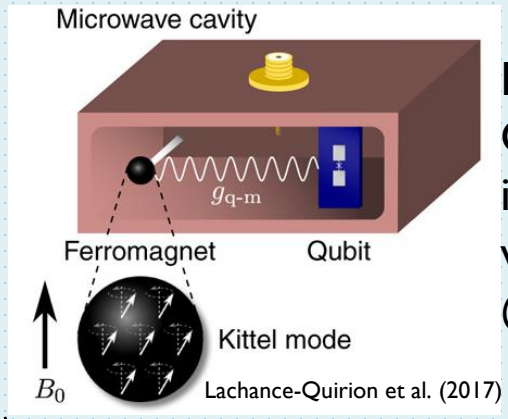
SUPERCONDUCTING QUBIT AS MAGNON COUNTER

Qubit-Kittel mode hybrid



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

Experimental setup



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

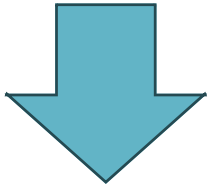
χ_{q-m}: Qubit - Kittel mode dispersive shift
g_{q-m}: Qubit - Kittel mode coupling strength

Magnon no. 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



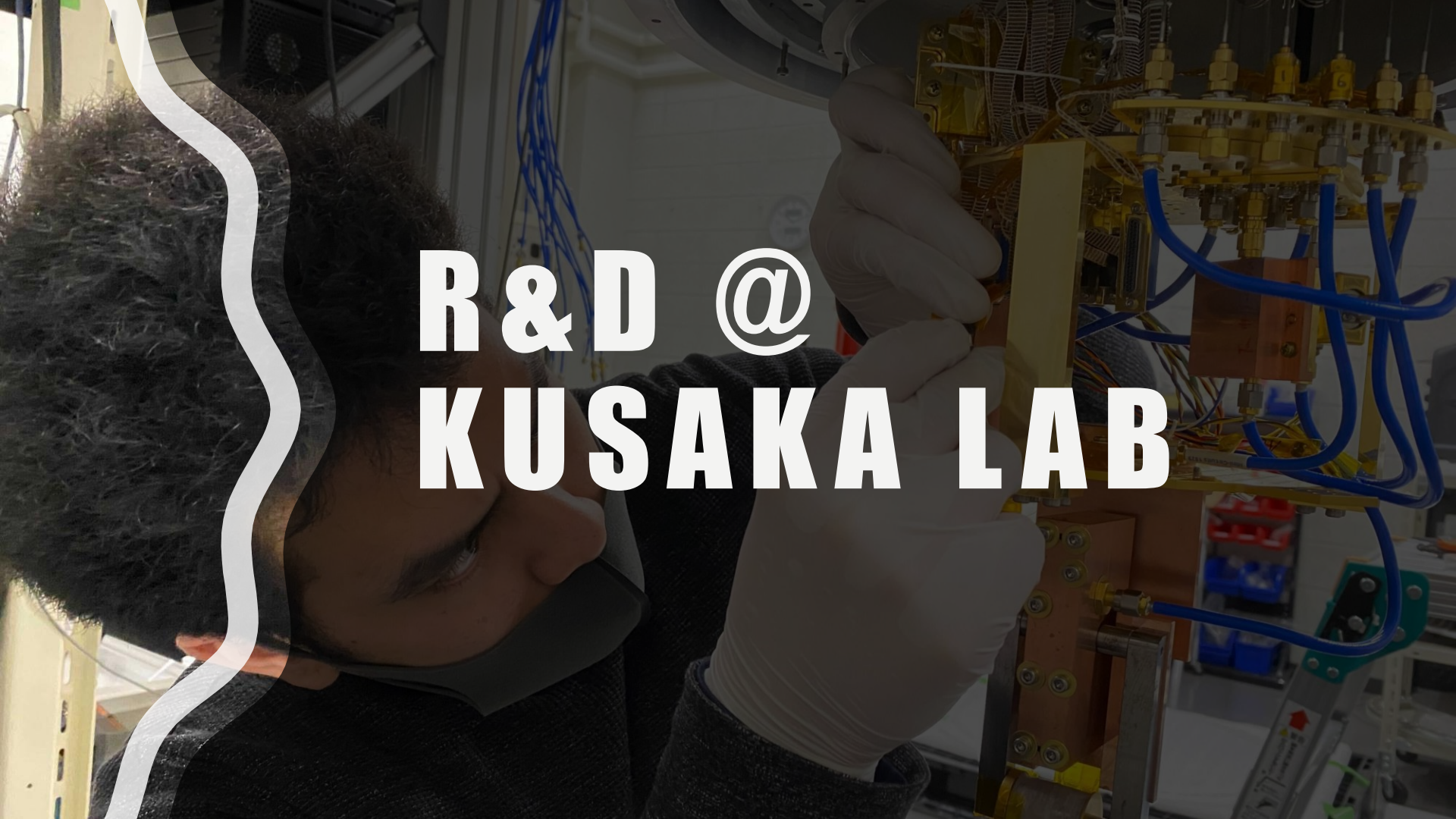
Unconstrained by SQL

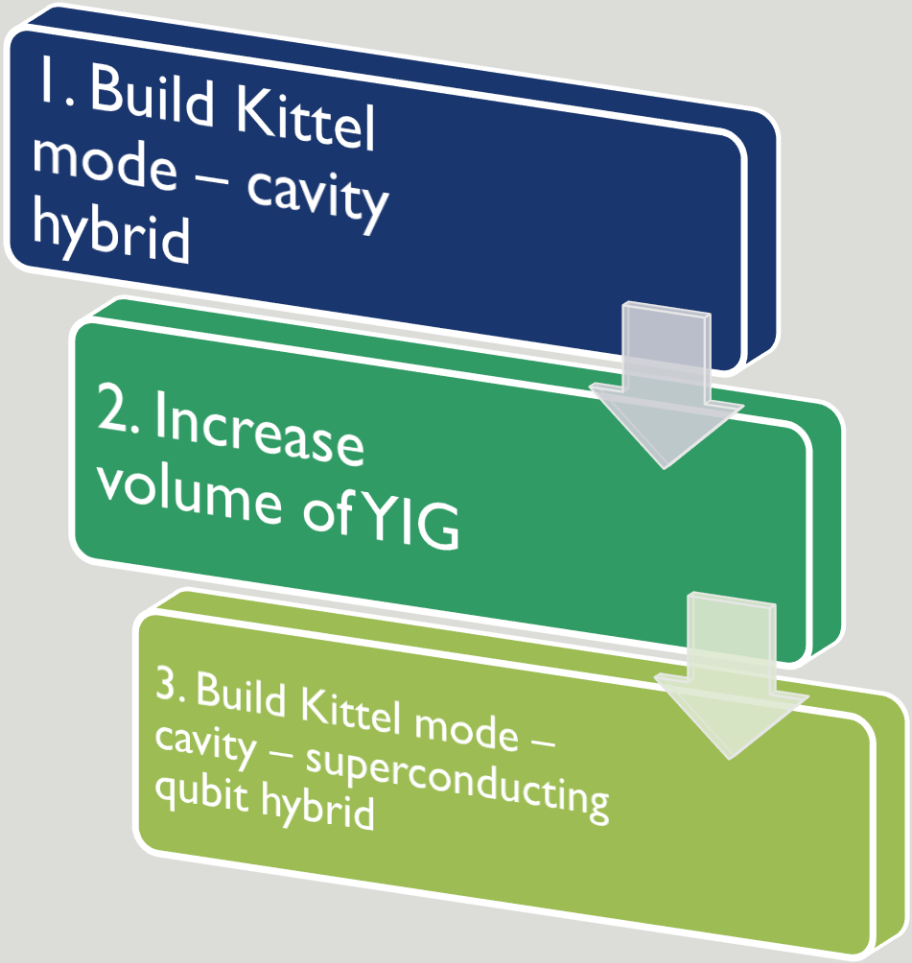
Magnon no. dependent Qubit frequency: $\omega_q^{n_m} = \left(\omega_q + 2\chi_{\mathrm{q-m}} n_m\right)$

IMPROVING AXION SENSITIVITY

INCREASE YIG VOLUME

OVERCOME STANDARD QUANTUM LIMIT WITH QUBITS


R&D @
KUSAKA LAB



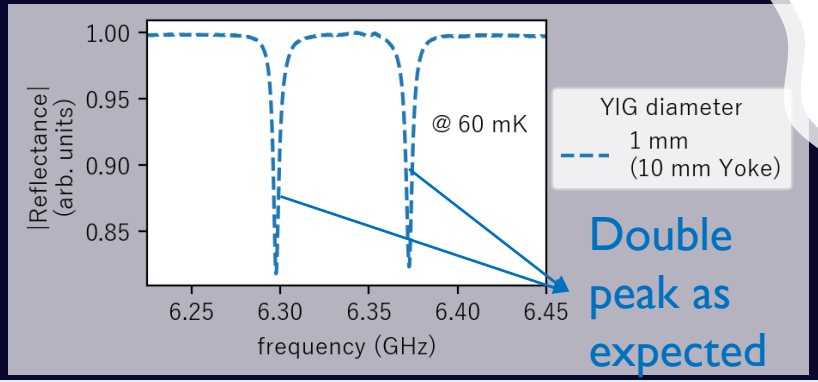
OUR R&D GOALS

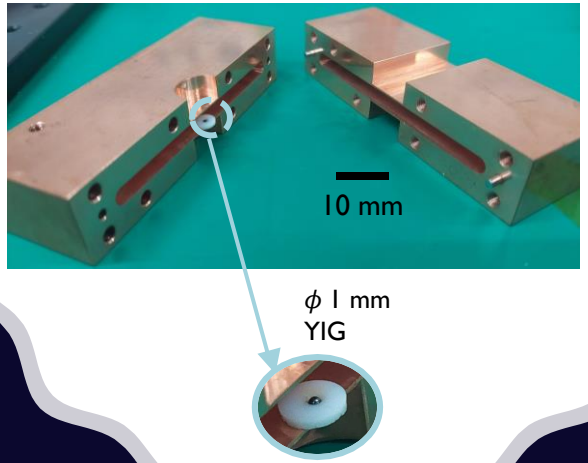
We are working with *Nakamura group* to optimize their Kittel mode – superconducting qubit hybrid system for BSM particle (axions, hidden photons, gravitons) search.

1. BUILD KITTEL MODE –CAVITY HYBRID

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

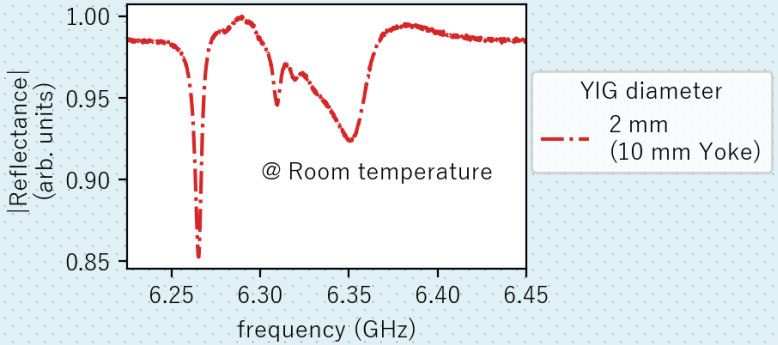
Reflectance of cavity measured with VNA

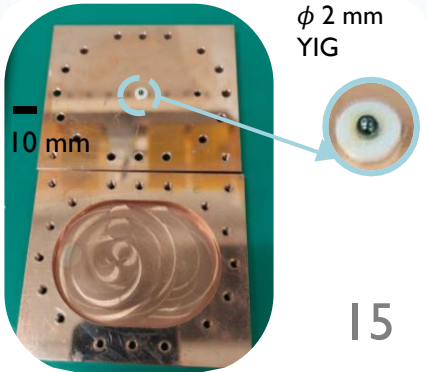




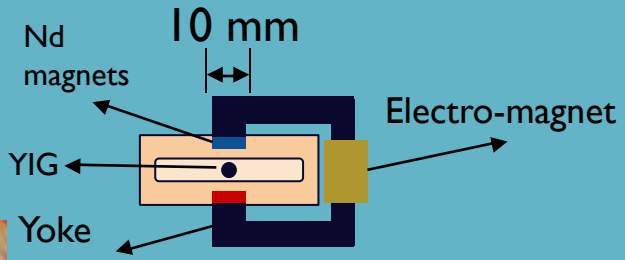
2. INCREASE VOLUME OF YIG

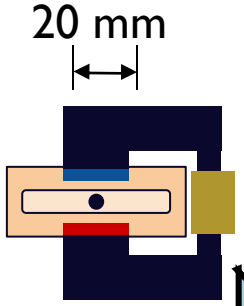
- Appearance of undesirable higher modes due to non-uniform magnetic field



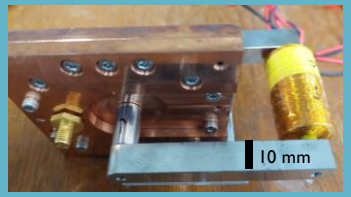


2. IMPROVED FIELD UNIFORMITY FOR LARGER YIG

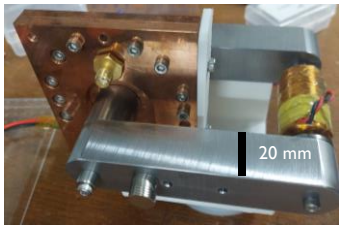




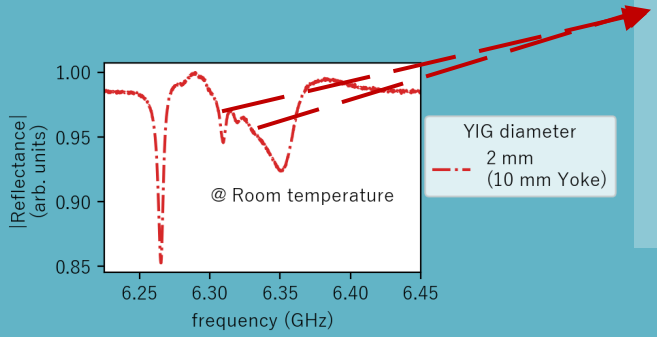
Setup with 10 mm yoke



Setup with 20 mm yoke

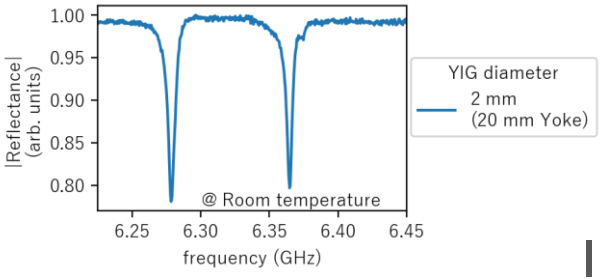


Larger Magnetic Yoke



Undesirable higher modes due to non-uniform magnetic field

Elimination of undesirable higher mode



1. Build Kittel mode – cavity hybrid (Done)

2. Increase volume of YIG (Done)

3. Build Kittel mode – cavity – superconducting qubit hybrid

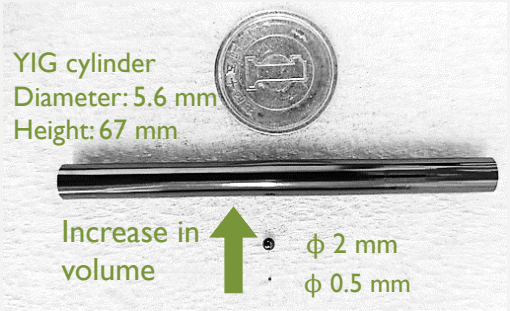
4. Further improvement in volume

NEXT STEPS

→ Cavity – Superconducting Qubit hybrid with ***2 mm YIG***

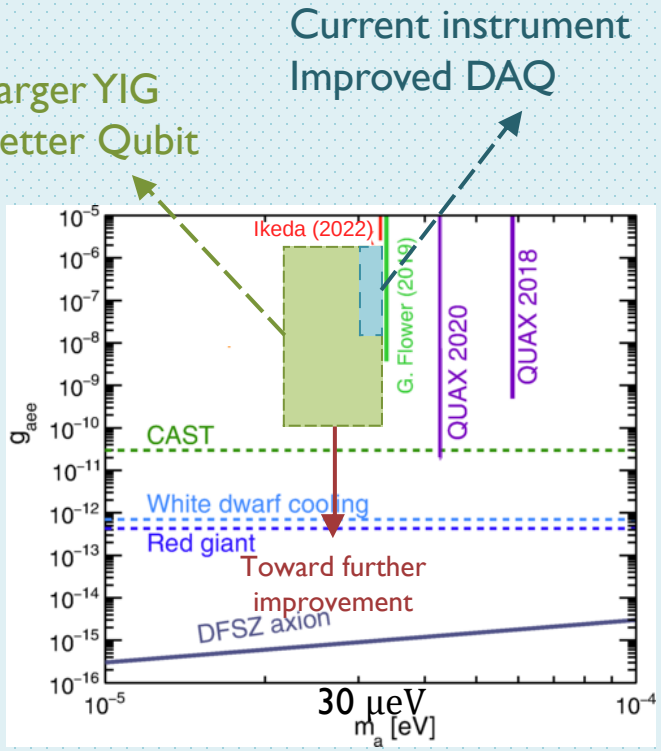
- cf. current design @ Nakamura lab has 0.5 mm YIG

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.



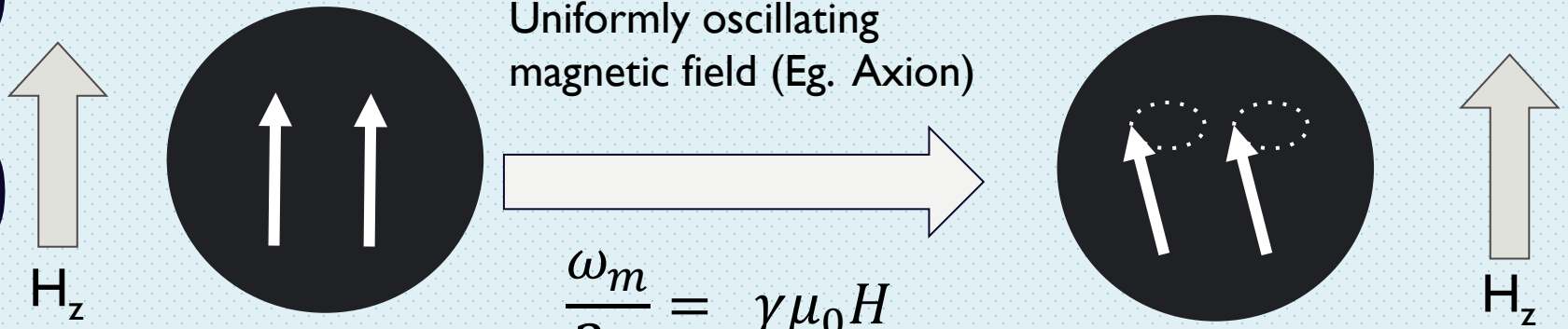
THANK YOU!

BACK UP SLIDES

WHAT ARE MAGNONS? → SPIN WAVE QUANTA

Ground state

Excited state



$$\frac{\omega_m}{2\pi} = \gamma \mu_0 H$$

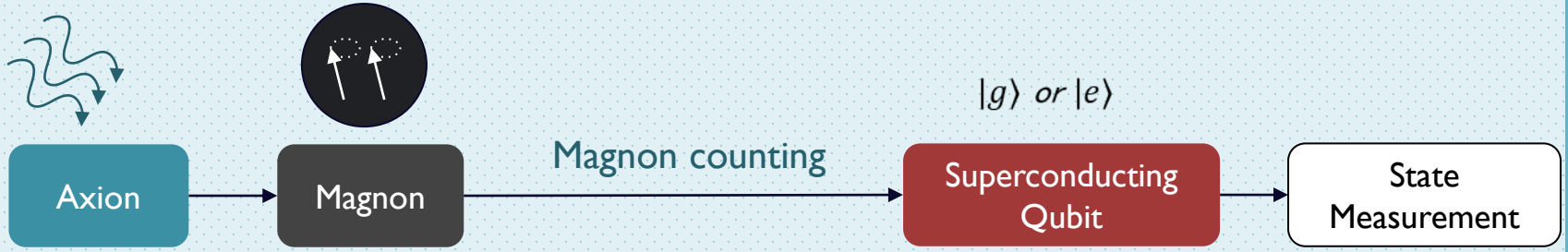
Ferromagnetic crystal (YIG)

Kittel mode
(Uniformly precessing spins)

Spins are aligned in presence of external magnetic field

Quantum Harmonic Oscillator
(Single Quantum is a Magnon)

MAGNON COUNTING PROTOCOL USING SUPERCONDUCTING QUBIT



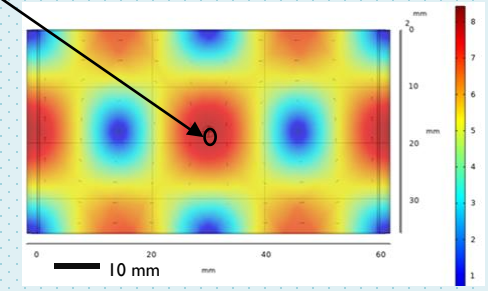
Magnon Counting protocol

1. *Qubit spectroscopy* : Number splitting of qubit spectrum
   (D. Lachance-Quirion *et al.* (2017)) → Axion search by Ikeda et al. (2022)
2. *Entanglement based protocol* : Entanglement of qubit and magnon no. state
   (D. Lachance-Quirion *et al.* (2020))
3. *Dissipation based protocol* : Magnon no. dependent qubit dephasing
   (S. P. Wolski et al.(2020))

MAGNON READOUT WITH CAVITY-KITTEL MODE HYBRID

YIG ϕ1 mm @ maximum of magnetic field

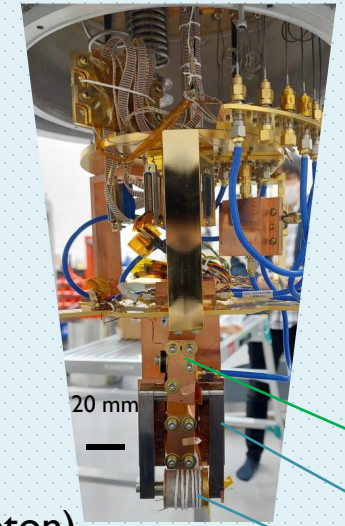
Simulation of RF Magnetic field

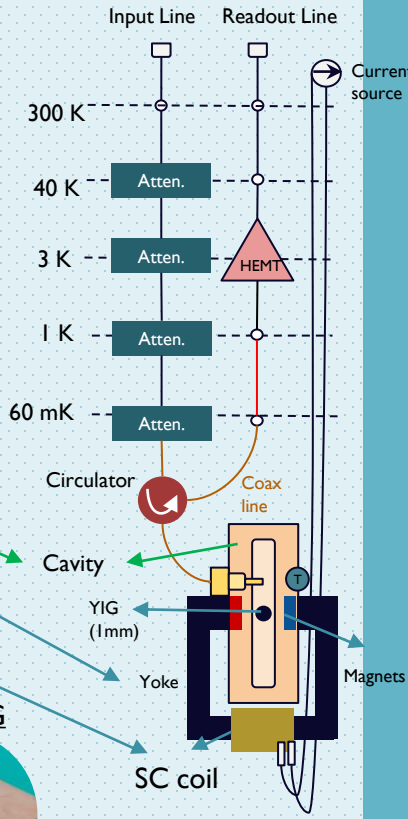


Cavity (photon) and Kittel mode (magnon) coupled through magnetic dipole

Typical RF readout line in Dilution Refrigerator

Cavity-magnon hybrid @ Kusaka lab DR





Cryogenic readout of magnon

- Kittel mode (magnon) readout via microwave cavity (photon)
- DR-cooled below 100 mK → reduce thermal noise
- Microwave amplification by HEMT amplifier (noise: ~4 K)

Cu Cavity with 1mm YIG