# Research and development towards an axion search experiment using quantum sensing of magnons

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JSR Fellowship

FoPM

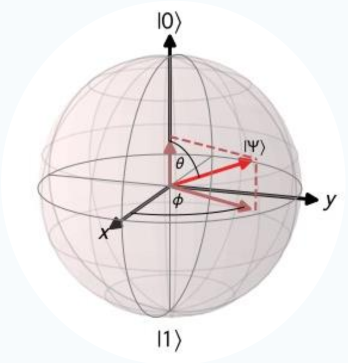
THE UNIVERSITY OF TOKYO


excite

Magnon

which is readout with

Superconducting Qubit




## Goal
Axion DM search

## Strategy
Quantum sensing of magnon

## Uniqueness
Magnon counting with SC qubit

## Motivation
Beyond SQL measurement

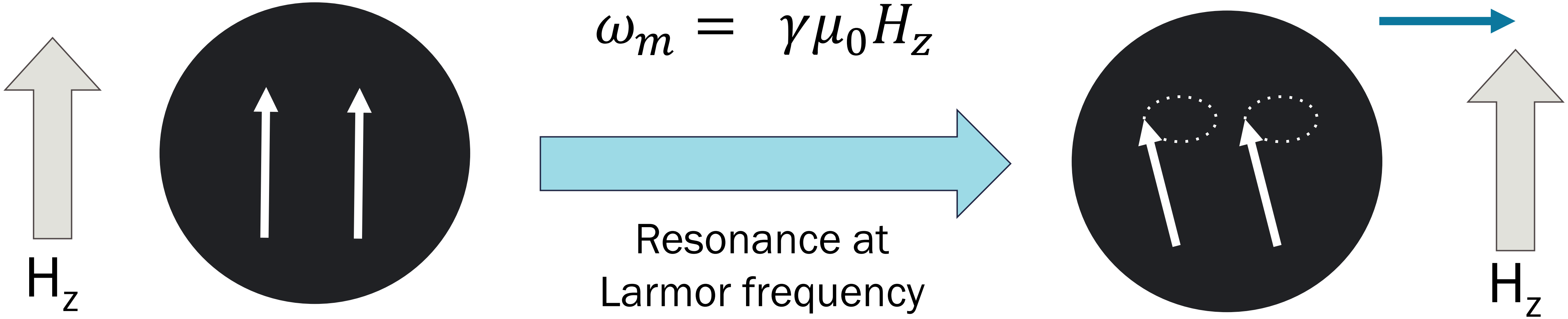
# What are magnons?
# Quanta of collective spin excitation

Uniformly oscillating magnetic field, $h_x$

Ground state

Excited state

$$\omega_m = \gamma\mu_0 H_z$$

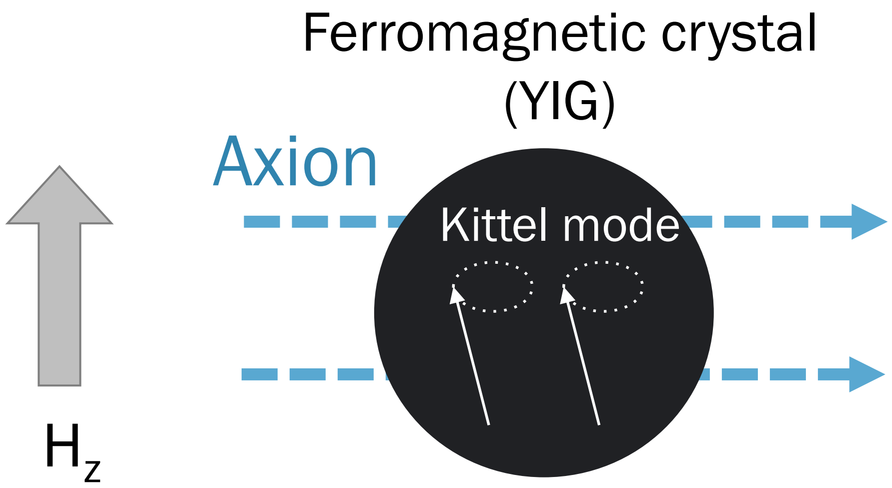



Resonance at Larmor frequency

Ferromagnetic crystal (YIG),
Spins aligned along external magnetic field

Kittel mode
(Uniformly precessing spins)
Single quanta: Magnon

# AXION (DARK MATTER) AS EFFECTIVE MAGNETIC FIELD




Our expected target:

$m_a$ : 5~10 GHz → 20~30 μeV

Axions excite magnon under resonance,

$$\omega_a = \omega_m = \gamma \mu_0 H_z$$

## Axions ~ Effective magnetic field $(B_a)$

(DFSZ axion etc.)

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

$$P = \gamma^2 \hbar \omega_a n_s B_a^2 \cdot \frac{\boldsymbol{V_s}}{\boldsymbol{2\kappa_m}}$$

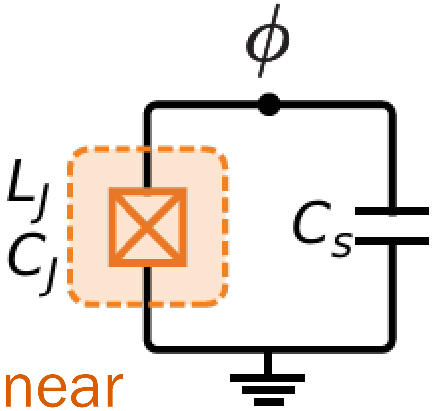
Large signal requires:

1. Large crystal volume, $V_s$
2. Small Kittel mode linewidth, $\kappa_m$

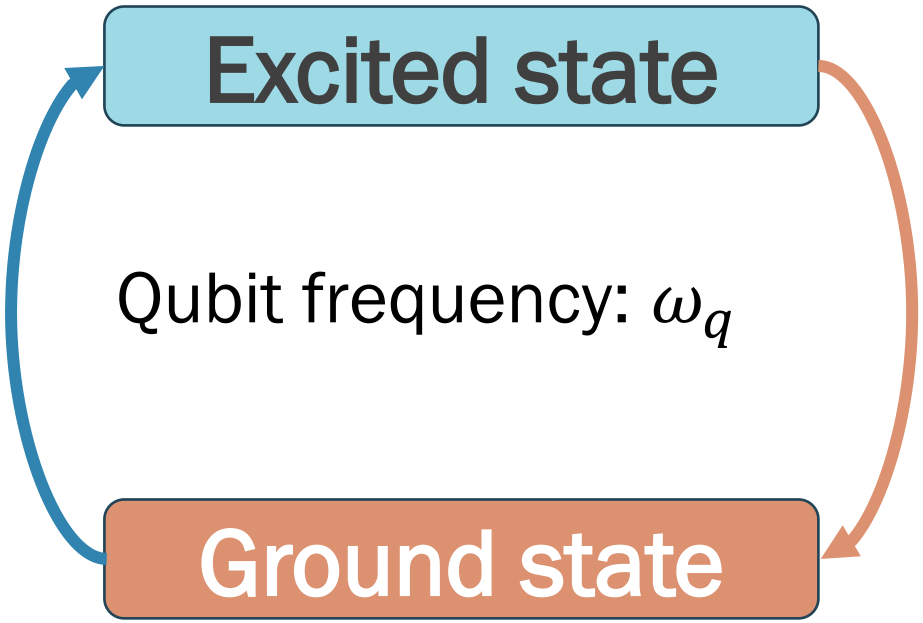
$g_{aee}$ : Axion-electron coupling
$n_s$ : Spin density in YIG
$\nabla a$ : Axion field gradient
$\omega_a$ : Axion frequency
$\gamma$ : Gyromagnetic ratio

# Qubit: Effective two - level system

**Superconducting qubits:**
Effective two - level system created using non-linearity in superconducting circuits.




Non-linear element




Computational space confined to two levels

# Qubit: Effective two - level system

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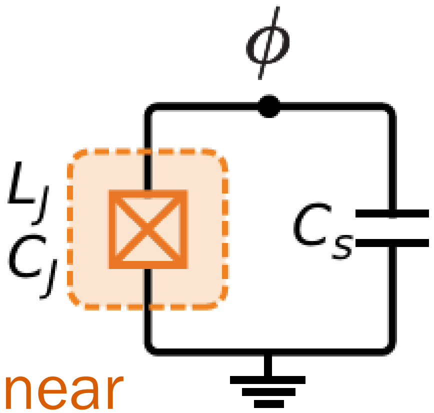



Non-linear element

Excited state

Qubit frequency: $\omega_q$

Ground state

Computational space confined to two levels

Strong coupling

Cavity Resonator

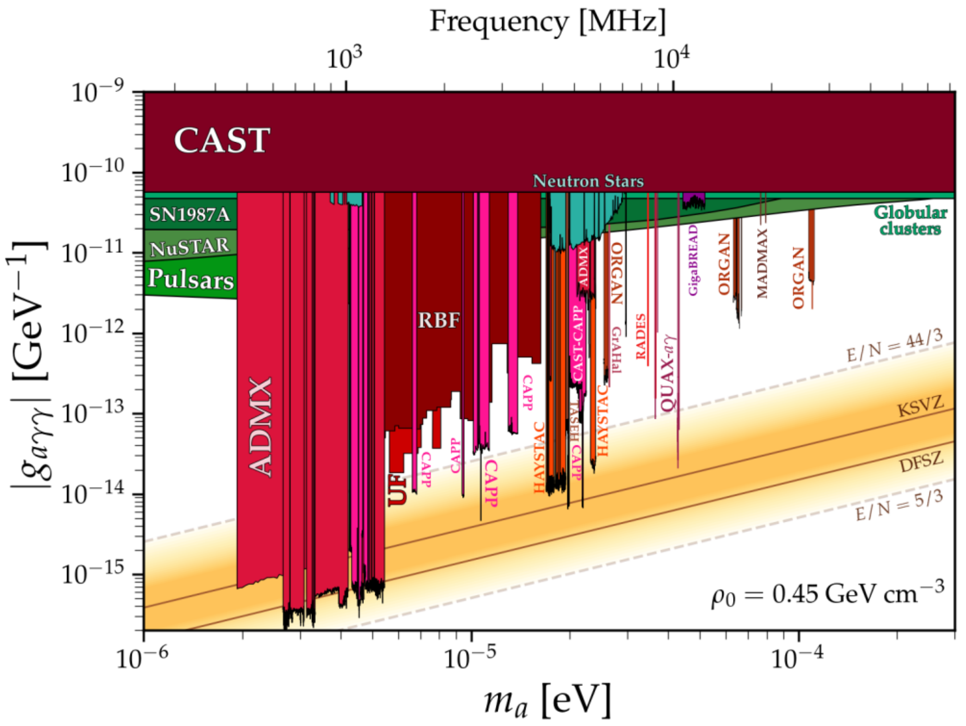
Which intermediates coupling with Kittel mode

# Background of axion search using magnons

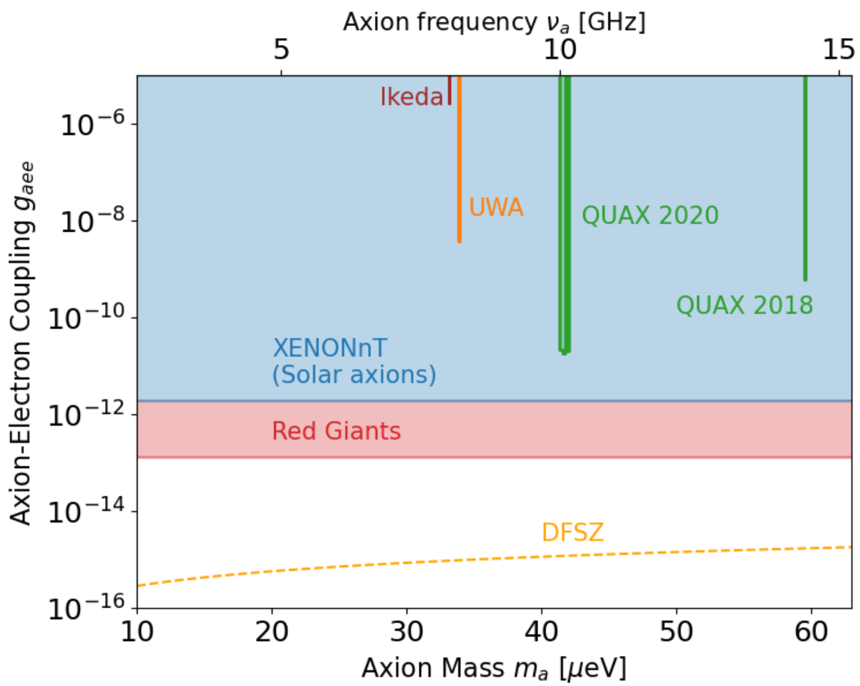
# Haloscope based experiments

Ciaran O'Hare

**Axion-photon coupling parameter space**




**Axion-electron coupling parameter space**




Relatively unscanned

Several Cavity based haloscope underway
Eg ADMX, HAYSTACK , QUAX, CAPP etc.

**Our Goal**

*Search axion with magnons*

# Axion search with magnons:
*Current state*

Larger Signal

Axis not in scale (for illustration)

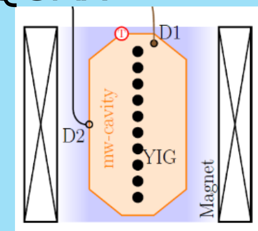
Cavity 0 | 0.05 | 5 | 50 | 1600 Volume of YIG ($mm^3$)

Amplifier based readout

Flower *et al.* (2019)

YIG sphere $\phi$ 2 mm

Crescini *et al.* (2021) QUAX




10 x YIG sphere $\phi$ 2.1 mm

Noise temperature ~ 1 K, Quantum limited

Qubit Readout

Avoid SQL

# Axion search with magnons:
### *Current state*

Larger Signal

Axis not in scale
(for illustration)

Cavity 0 0.05 5 50 1600 Volume of YIG ($mm^3$)

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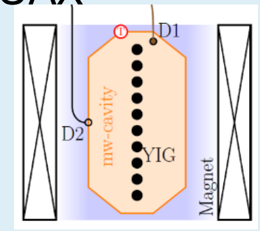
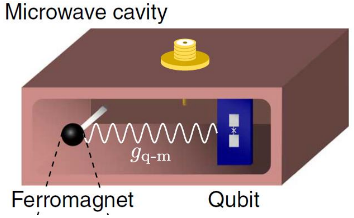



10 x YIG sphere $\phi$ 2.1 mm

Qubit Readout

Avoid SQL




Lachance-Quiron *et al.* (2017)
YIG sphere $\phi$ 0.5 mm
@Nakamura lab

Not optimized for axion search (*not beyond SQL*)

# Axion search with magnons:
***Current state***

Larger Signal

Axis not in scale
(for illustration)

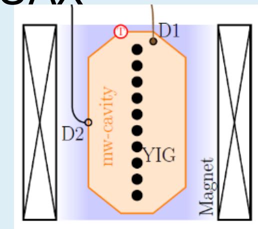
Cavity 0 0.05 5 50 1600 Volume of YIG ($mm^3$)

Amplifier based readout

Flower *et al.* (2019)

YIG sphere $\phi$ 2 mm

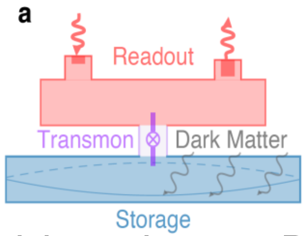
Crescini *et al.* (2021)
QUAX




10 x YIG sphere $\phi$ 2.1 mm

Qubit
Reado

Avoid S


- Dispersive interaction
- No magnetic field,
- R=1300 times faster than SQL

Hidden photon, Dixit et al. (2020)

# Axion search with magnons:

***Current state***

Larger Signal

Axis not in scale
(for illustration)

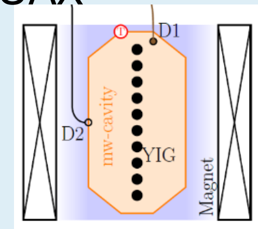
Cavity | 0 | 0.05 | 5 | 50 | 1600 | Volume of YIG ($mm^3$)

Amplifier based readout

Flower *et al.* (2019)

YIG sphere $\phi$ 2 mm

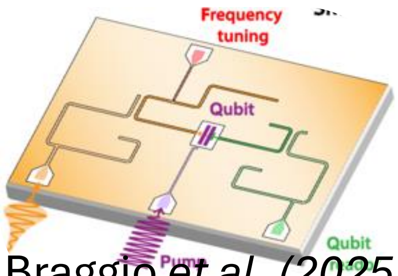
Crescini *et al.* (2021)
QUAX




10 x YIG sphere $\phi$ 2.1 mm

Qubi
Reado

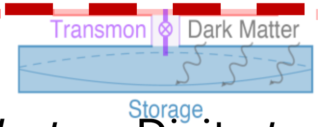
Avoid S




Braggio *et al. (2025)*
*QUAX*

- **SMPD:** using 4-wave mixing,
- SC Cavity in magnetic field,
- <u>*R=20*</u> times faster than SQL,

YIG sphere $\phi$ 0.5 mm




*<u>Hidden photon,</u>* Dixit *et al. (2020)*

# Axion search with magnons:
## *Current state*

Larger Signal

Axis not in scale (for illustration)

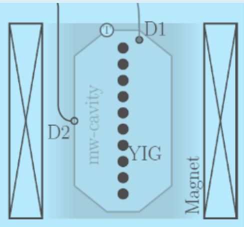
Cavity 0 0.05 5 50 1600 Volume of YIG ($mm^3$)

Amplifier based readout

Flower *et al.* (2019)

sphere $\phi$ 2 mm

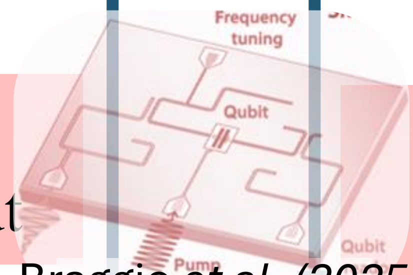
Crescini *et al.* (2021) QUAX



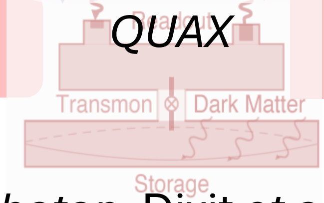

10 x YIG sphere $\phi$ 2.1 mm

Qubit Readout

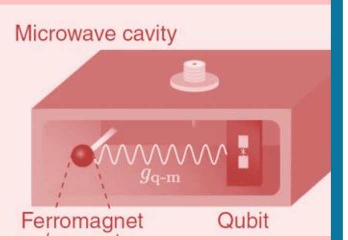
Avoid SQL



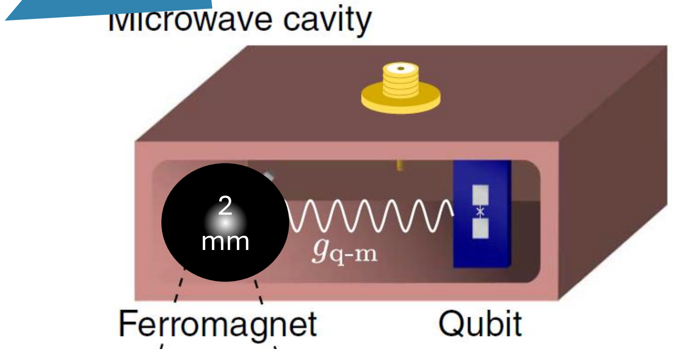

Braggio *et al. (2025)* *QUAX*




*Hidden photon,* Dixit *et al. (2020)*

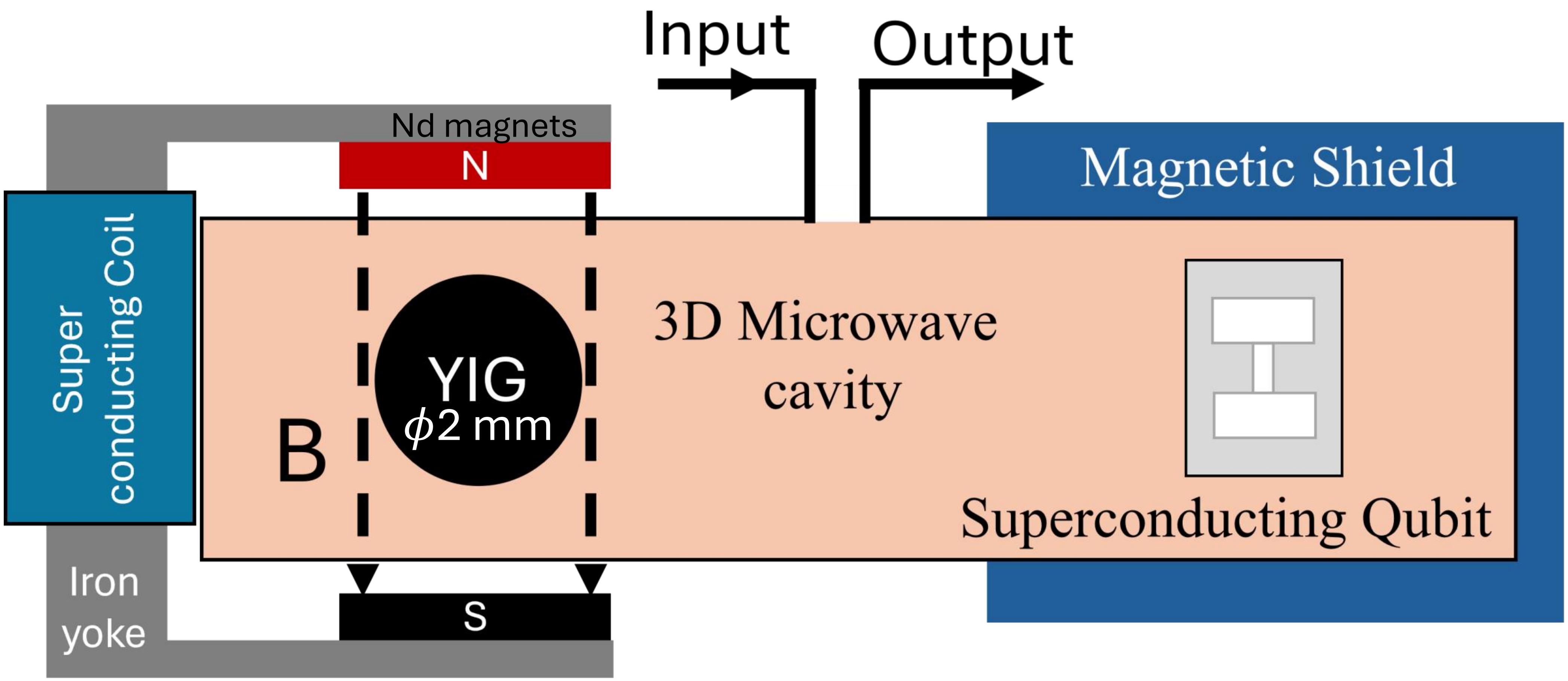



Lachance-Quir...
YIG sphere...




**Goal:**
Perform axion search beyond SQL using qubit readout for large YIG

# Our Planned Axion Detector



# Outline

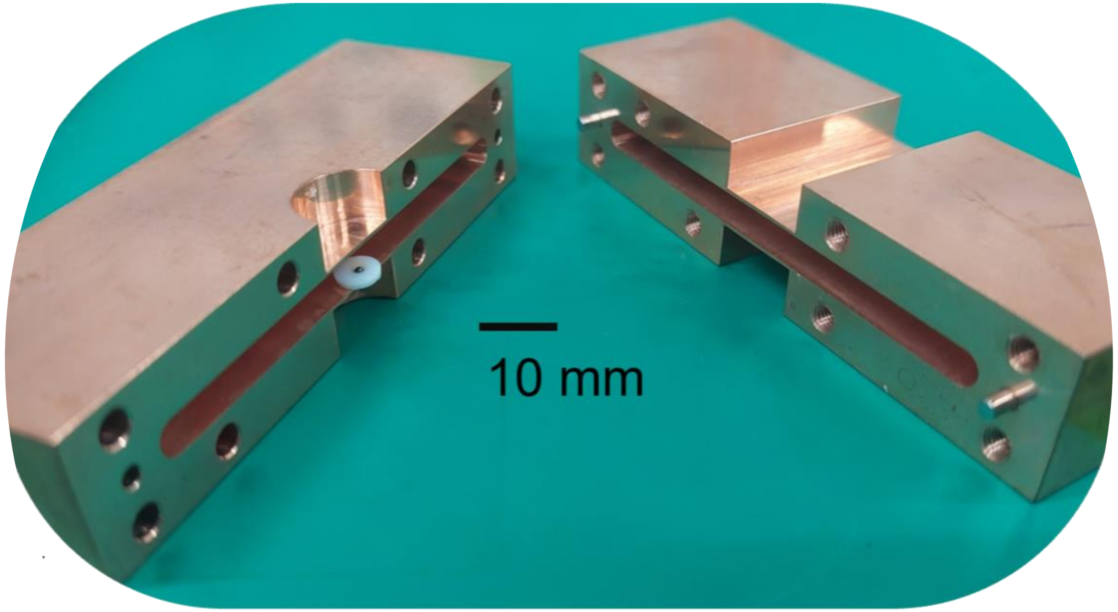
Building a cavity-Kittel mode hybrid

Increasing volume of YIG

Quantum sensing using dispersive interaction with qubit

Entanglement based protocol

Dissipation based protocol



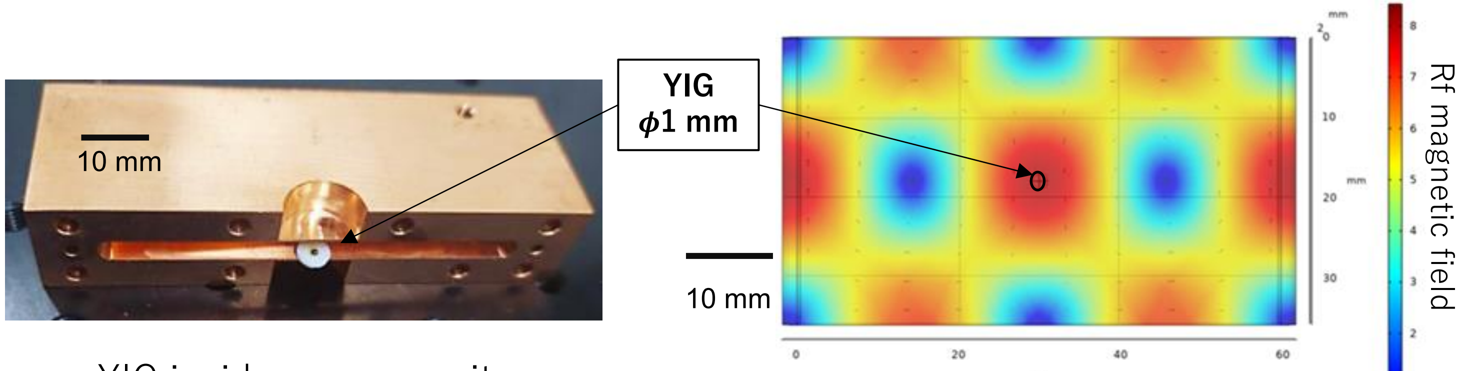

# Building cavity – Kittel mode hybrid

Goal: Increase volume of YIG

# Characterization of cavity-Kittel Mode Hybrid System

Setup

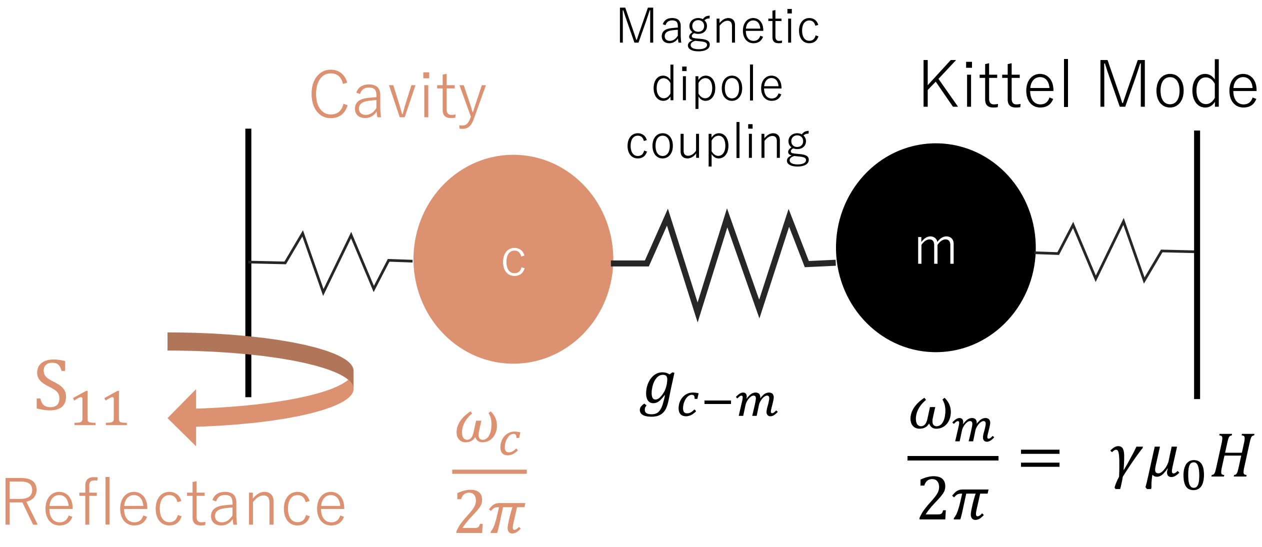
RF simulation



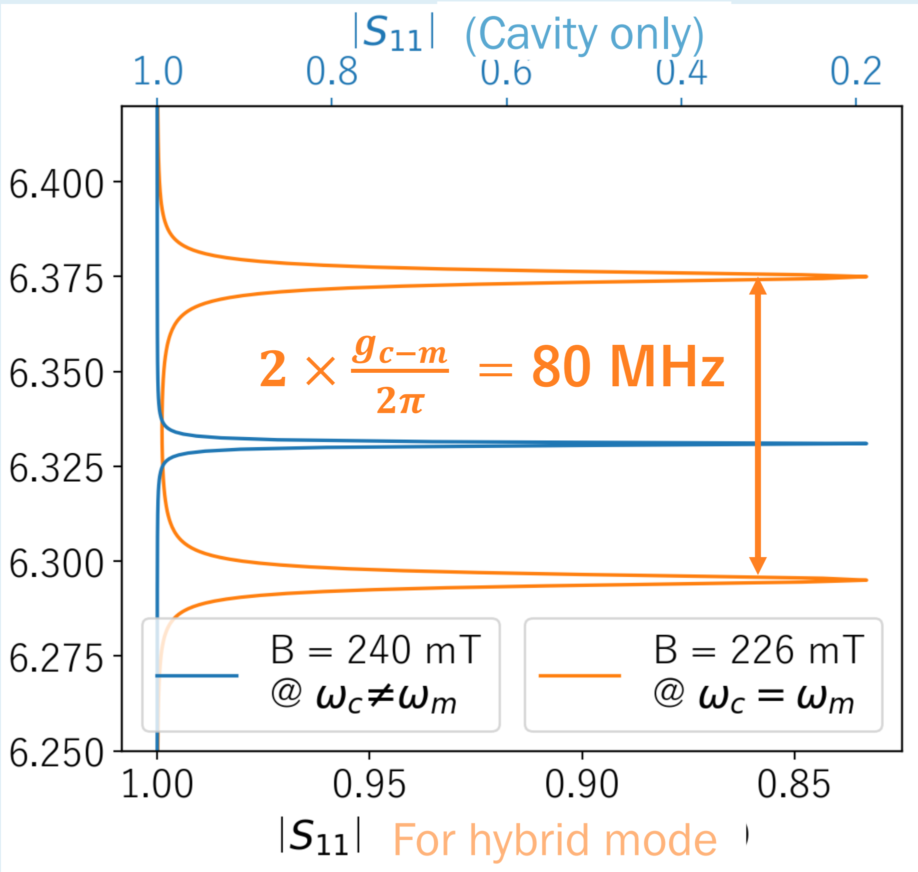

YIG inside copper cavity

RF magnetic field of cavity

## Two coupled harmonic oscillators




## Simulation of hybrid spectrum




@ $\omega_c = \omega_m$,

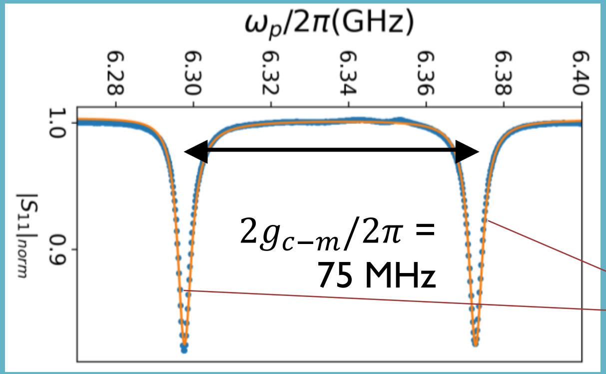
Two hybrid peaks

# KITTEL MODE –CAVITY HYBRID

YIG SPHERE, $\phi$ = 1 MM

Reflectance of cavity measured with VNA

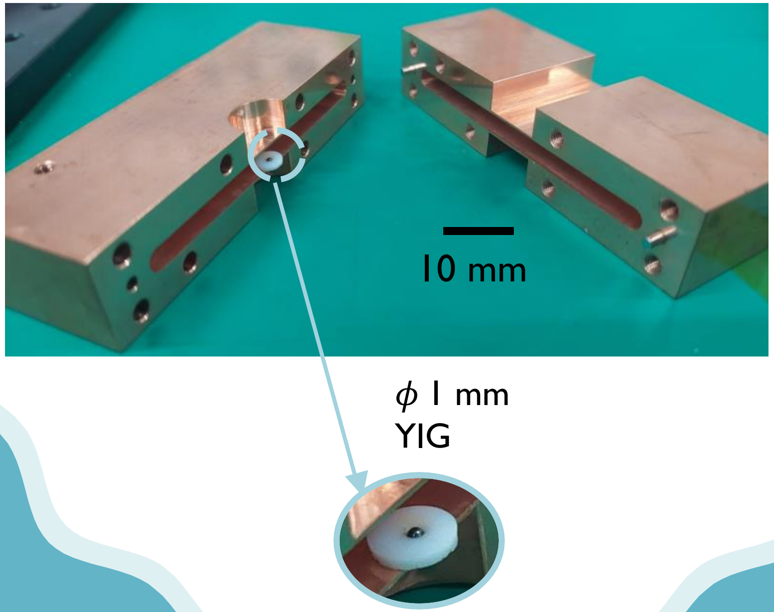
- *Two peaks* of cavity – Kittel mode hybrid system.
  - (single cavity peak in absence of hybridization)




@60 mK

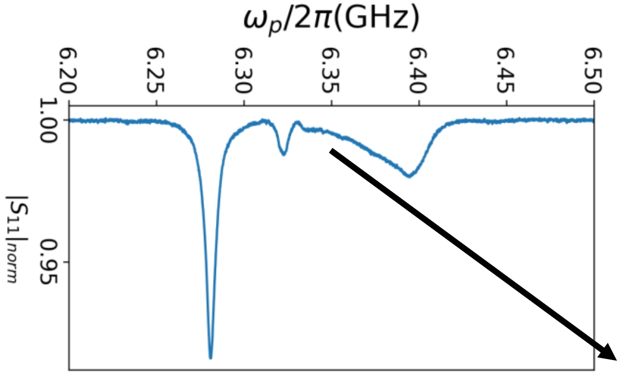
$\kappa_m$: $2\pi\times$3.87 MHz

Double peak as expected



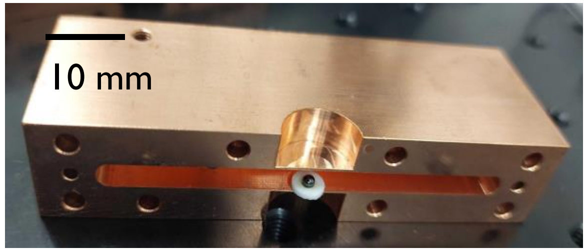

# INCREASE VOLUME OF YIG, $\phi$ = 2 MM

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




@100 mK

coupling with higher modes



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YIG SPHERE, $\phi$ = 1 MM

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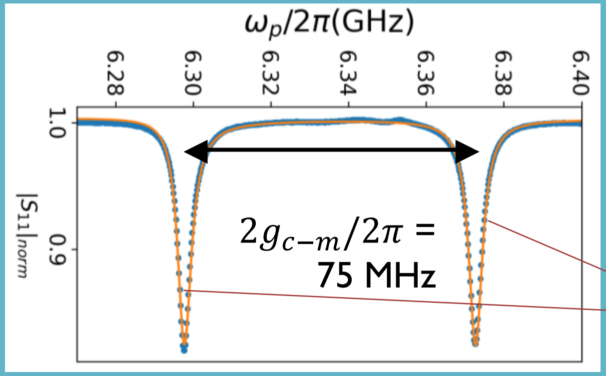


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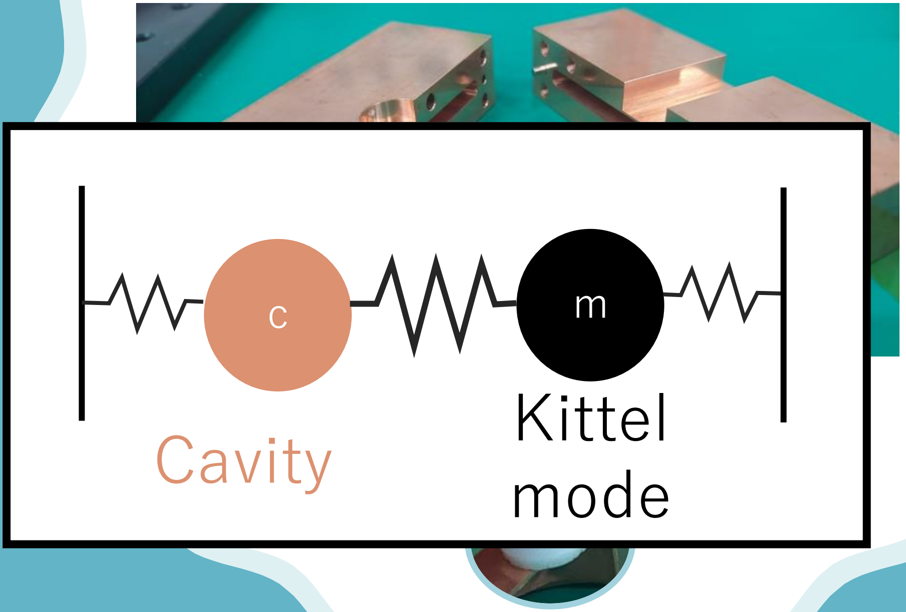


# INCREASE VOLUME OF YIG, $\phi$ = 2 MM

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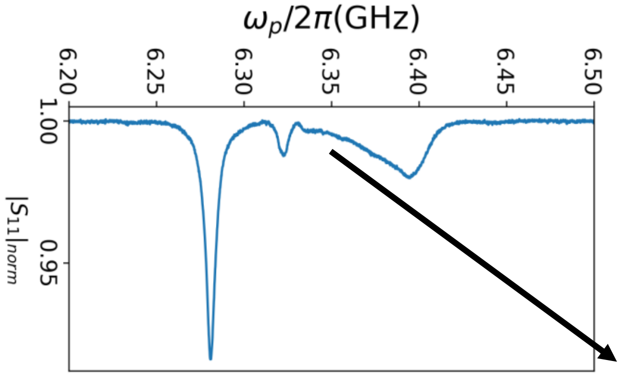
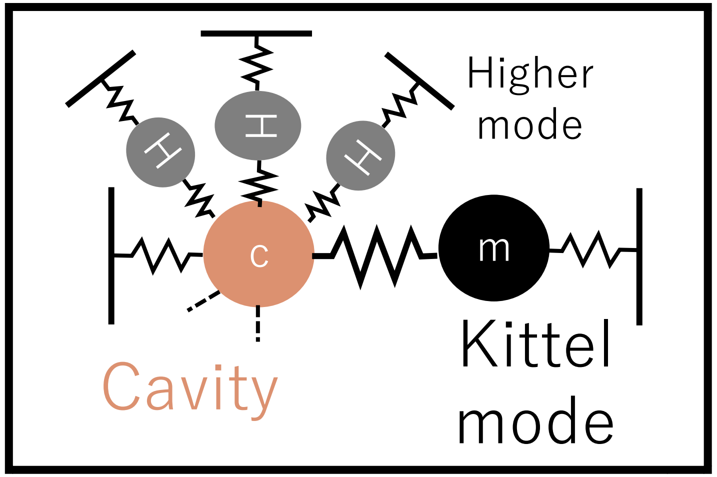


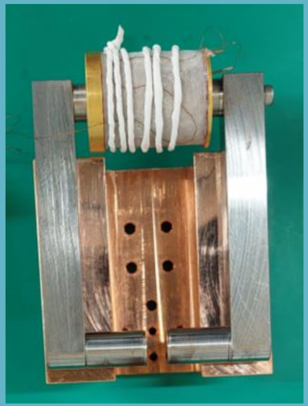

@100 mK

coupling with higher modes

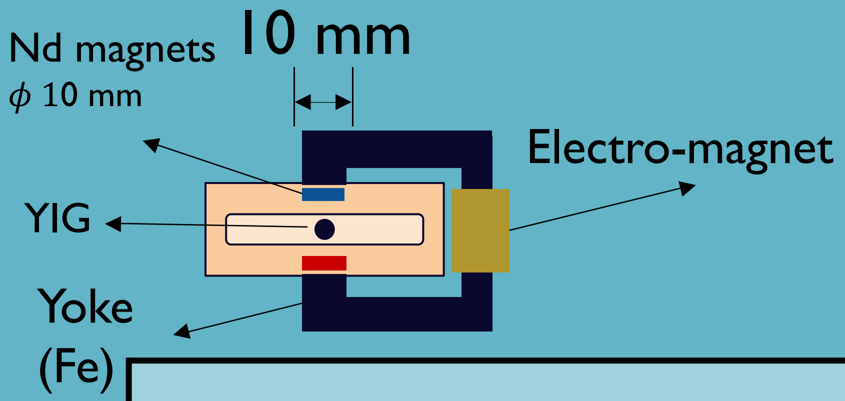


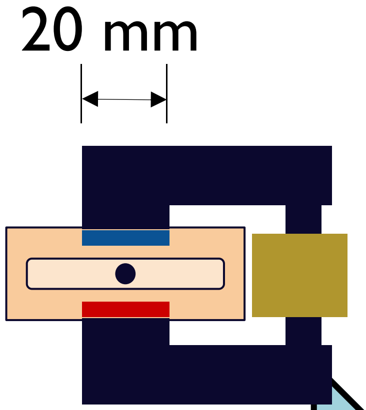
# IMPROVED FIELD UNIFORMITY FOR LARGER YIG

Setup with 10 mm yoke

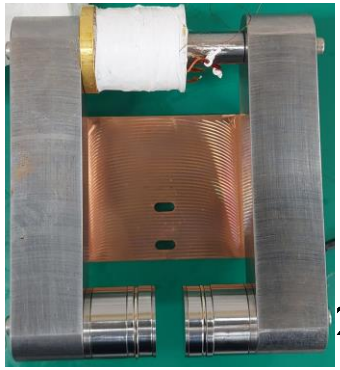


10 mm



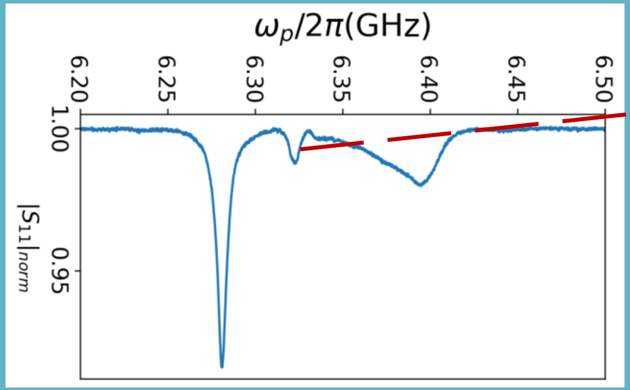

Setup with 20 mm yoke



20 mm

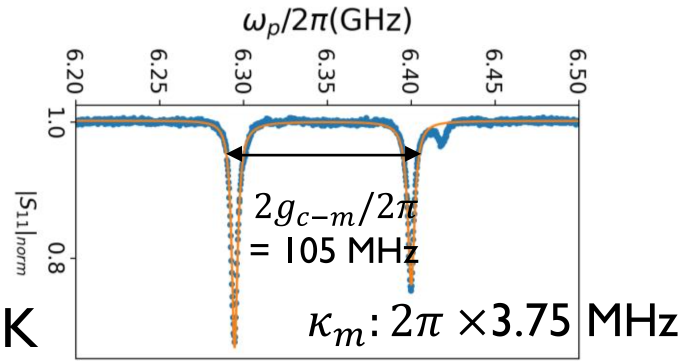
Larger Magnetic Yoke

Elimination of undesirable higher mode




Undesirable higher modes due to non-uniform magnetic field

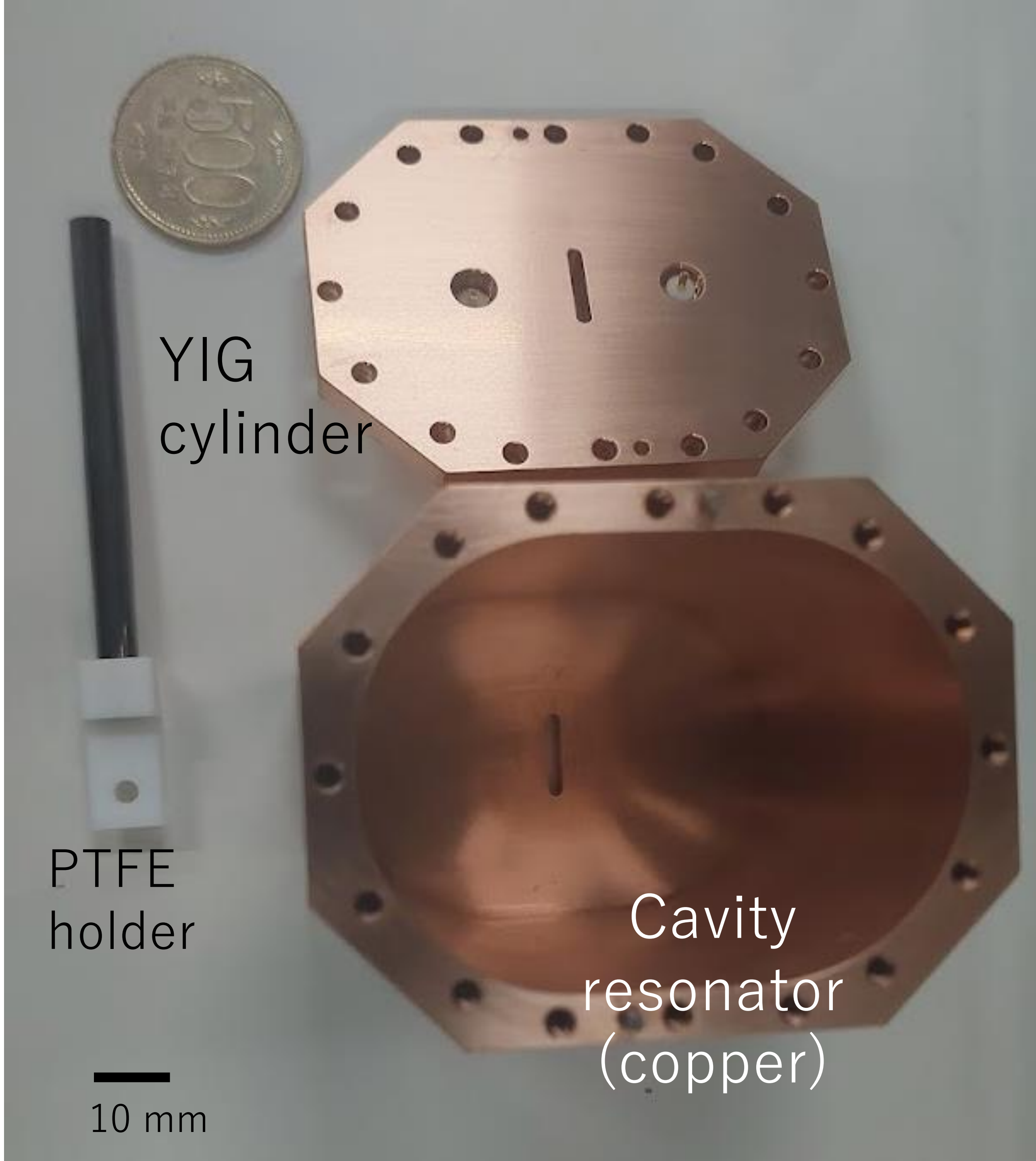
@100 mK




@100 mK

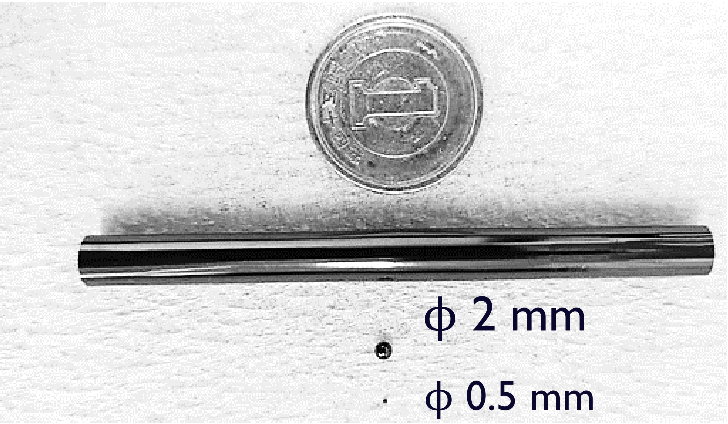
# Cavity-Kittel Mode Hybrid

YIG Cylindrical
Diameter: 5.6 mm
Length: 67 mm



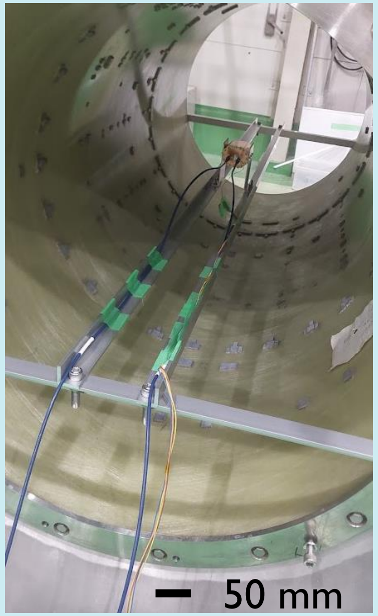
# LARGE CYLINDRICAL YIG

YIG CYLINDRICAL
DIAMETER: 5.6 MM
LENGTH: 67 MM




Increase in volume by ~400 compared to $\phi$ 2 mm sphere

Experimental setup at KEK



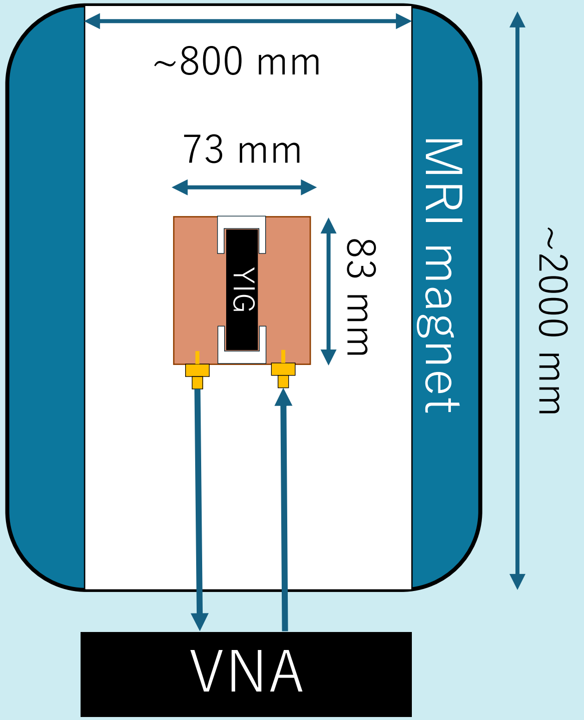
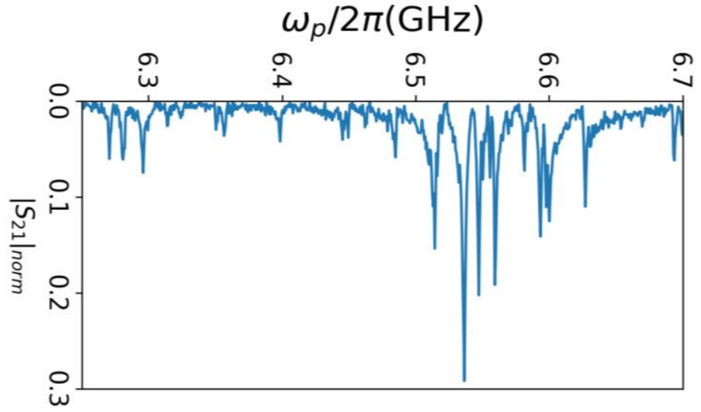



Diagram not in scale

**Result at room temperature**

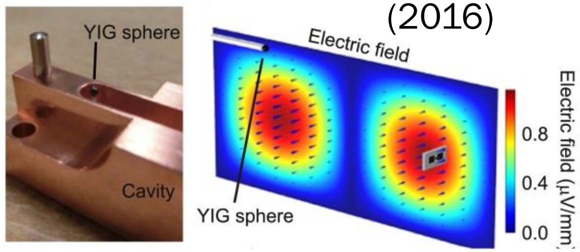



Non-uniformity in demagnetizing field due to *cylindrical shape* cause many higher order modes

# Summary: Improvement in YIG volume

**Past research using qubit @ Nakamura lab**
YIG sphere : $\phi$0.5 mm

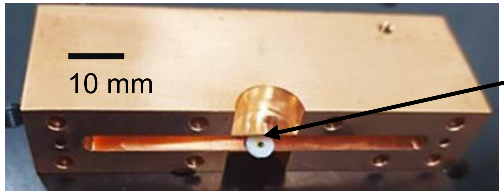
Tabuchi *et al.* (2016)




Qubit and Kittel mode coupling

Strong coupling :
$g_{c-m} >> \kappa_m$

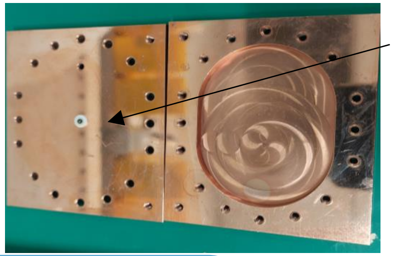
**YIG sphere: $\phi$1 mm**
$g_{c-m}$: $2\pi$ ×37.5 MHz
$\kappa_m$: $2\pi$ ×3.87 MHz




YIG $\phi$ 1 mm

Strong coupling:
$g_{c-m} >> \kappa_m$

**YIG sphere: $\phi$2 mm**
$g_{c-m}$: $2\pi$ ×52.4 MHz
$\kappa_m$: $2\pi$ ×3.75 MHz



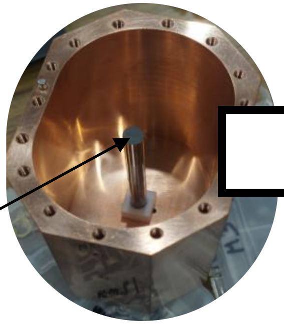
YIG $\phi$ 2 mm

10 mm

Cavity–Kittel mode coupling implemented

**YIG Cylinder**
Higher-order mode excitation

10 mm



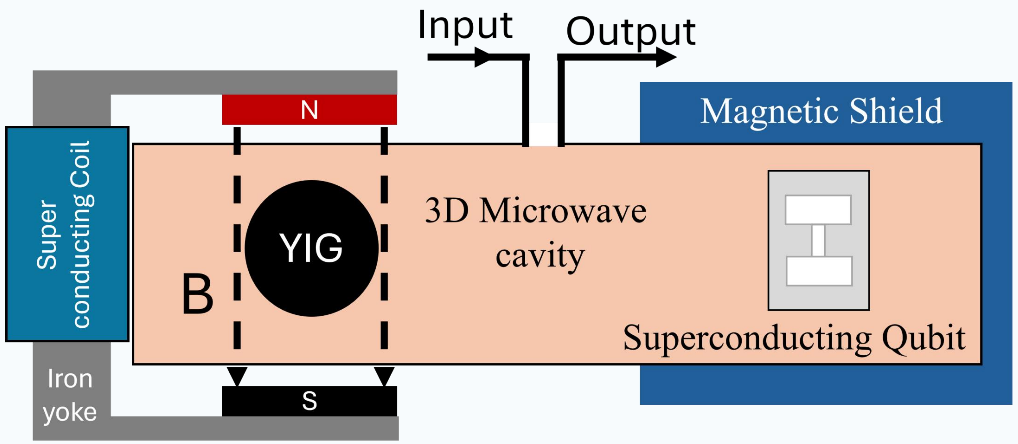
YIG cylinder

Next targets

**Towards axion search with Larger YIG**

**Coupling with Qubit**
Reduced noise with quantum sensing

Reduce higher modes using elliptical crystal

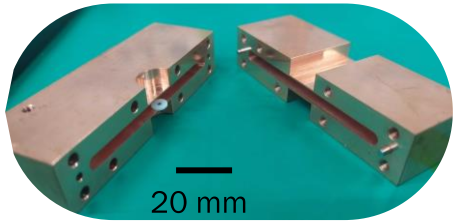



# Magnon counter with a superconducting qubit

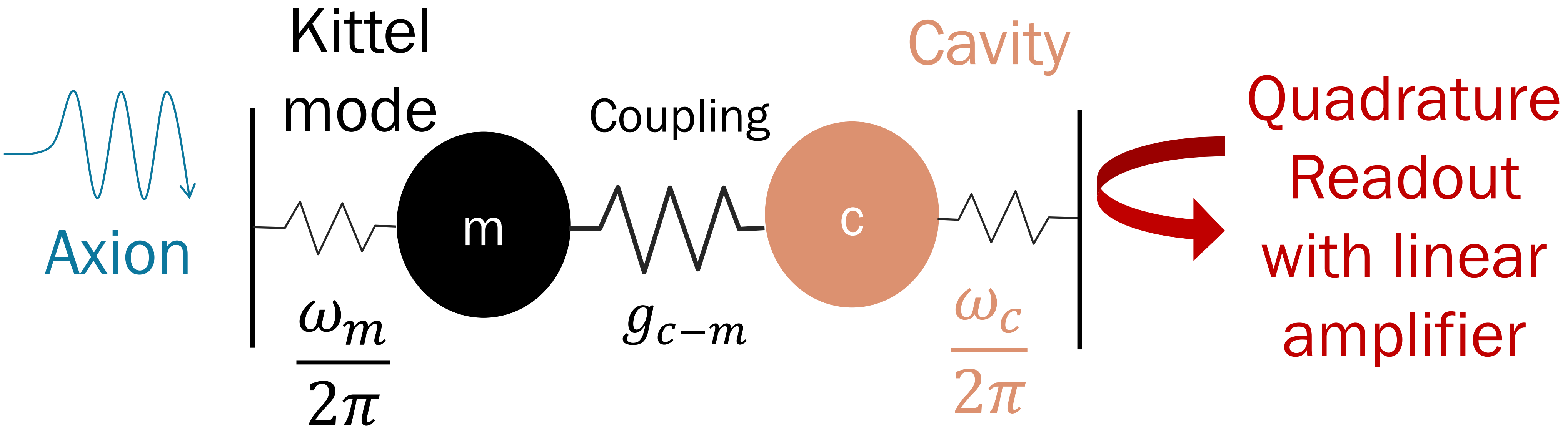
**Prospects and challenges to overcome SQL**

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

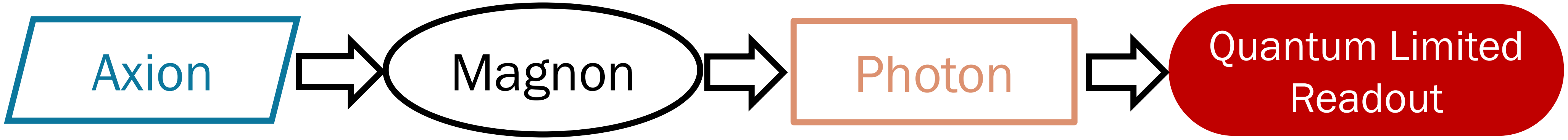
# Quantum limited axion search
## (with cavity-Kittel mode hybrid)




Coupled Harmonic Resonator Model for cavity – Kittel mode hybrid

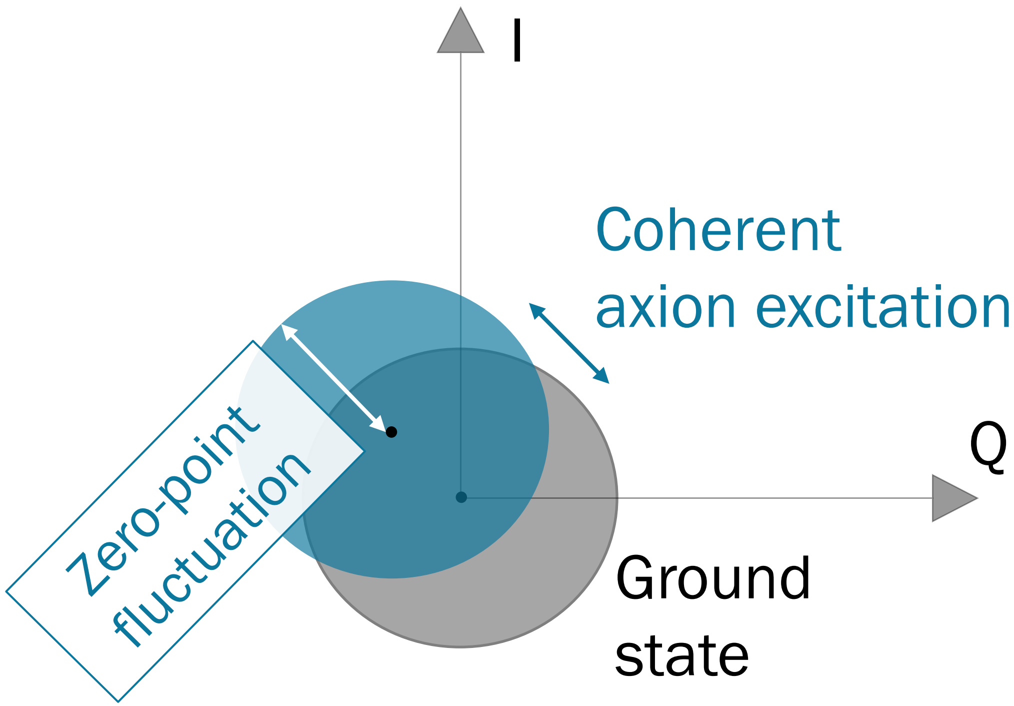



### Detection scheme



# Overcoming standard Quantum Limit (SQL)

## Readout in quadrature basis

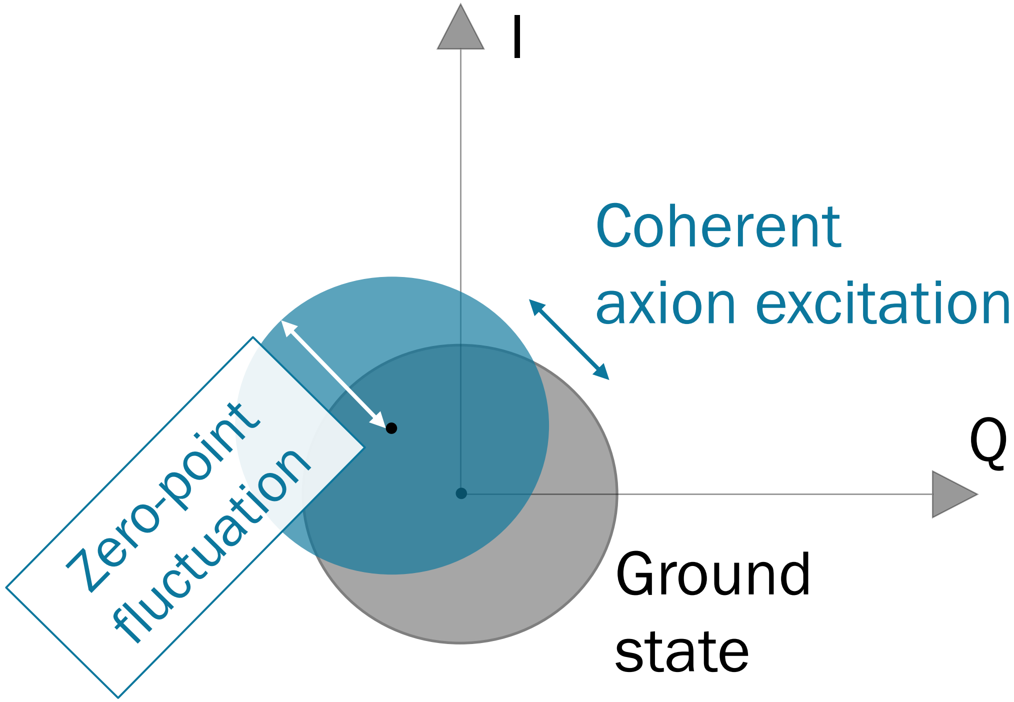



$$\Delta I \cdot \Delta Q \geq 1$$

- 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 $\omega$ 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)

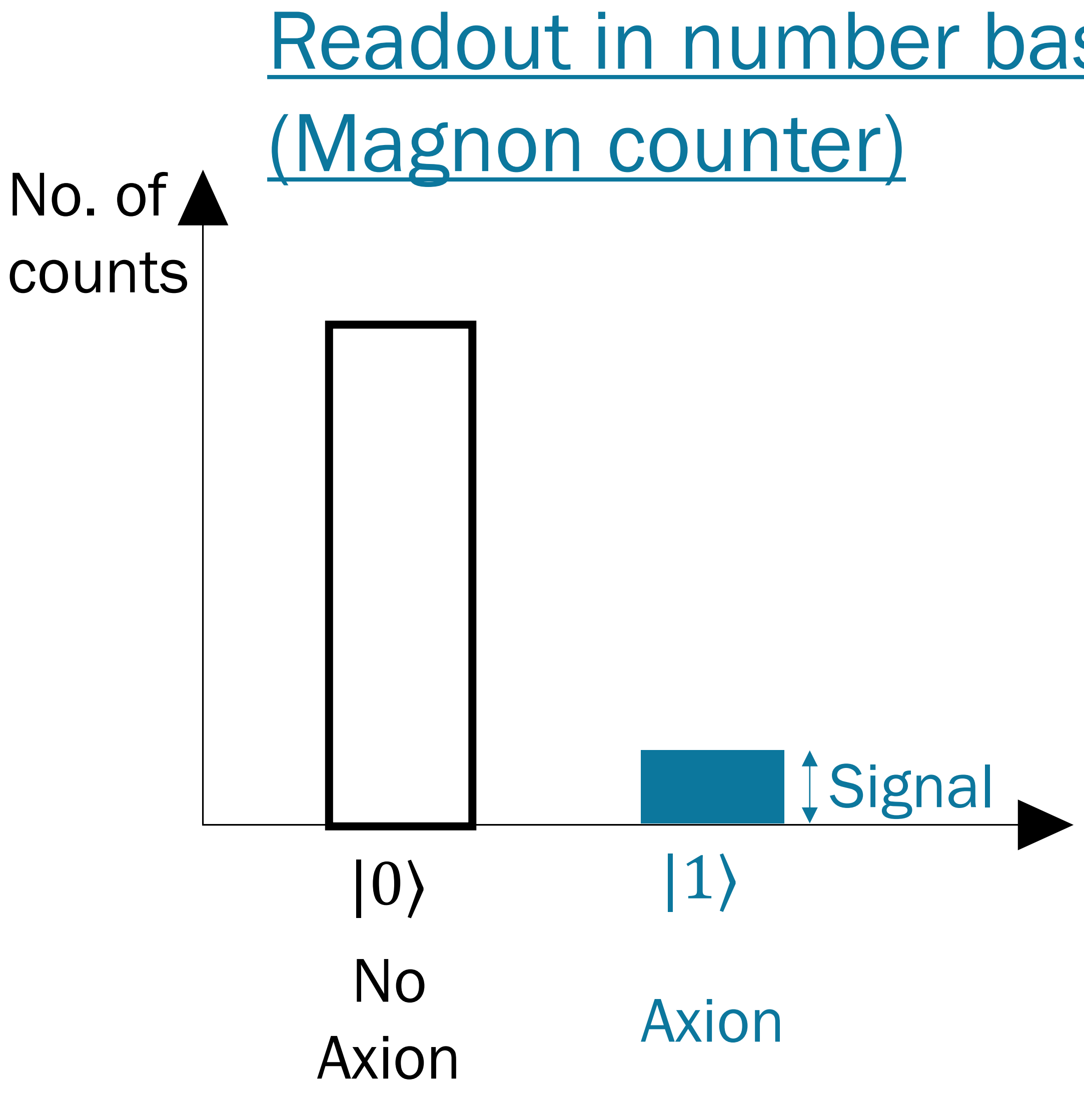
Readout in quadrature basis




$$\Delta I \cdot \Delta Q \geq 1$$

- 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**).

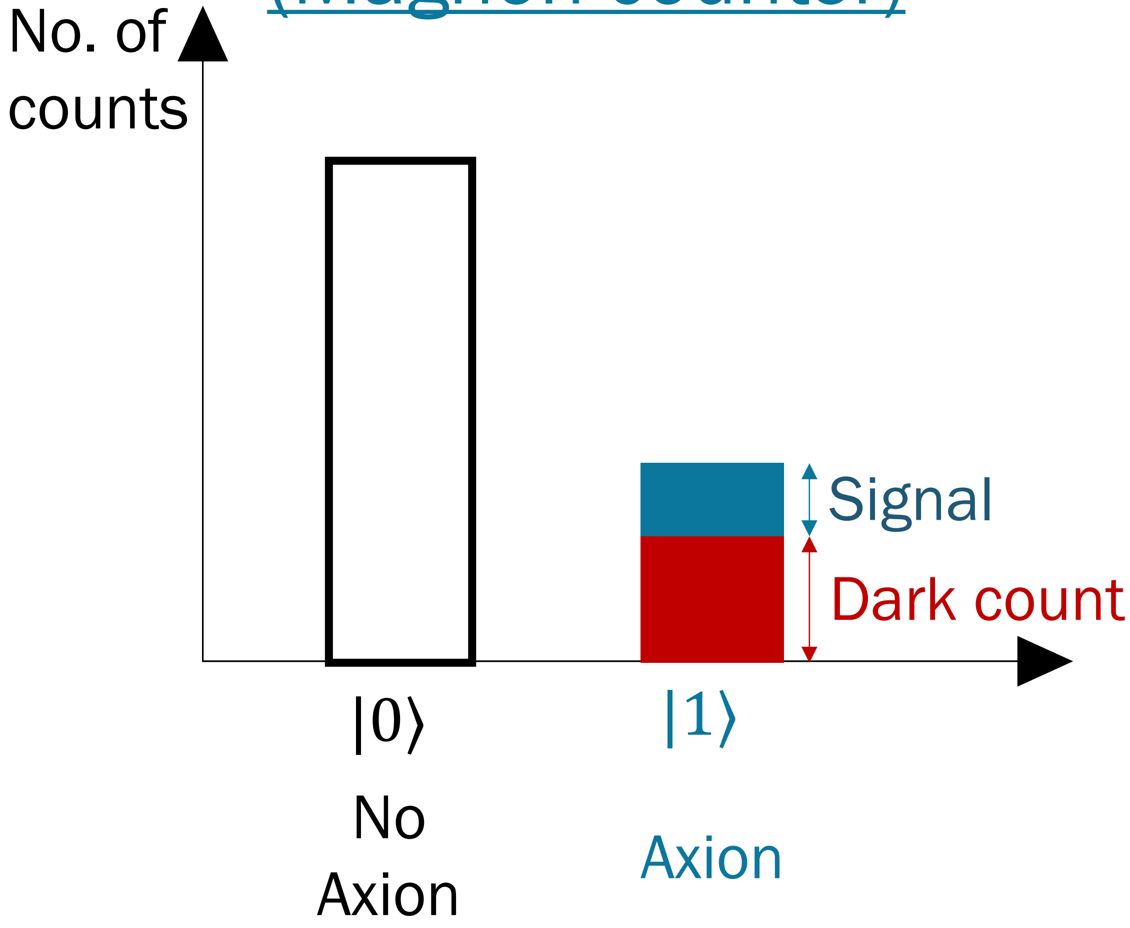
# Overcoming standard Quantum Limit (SQL)




- 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)



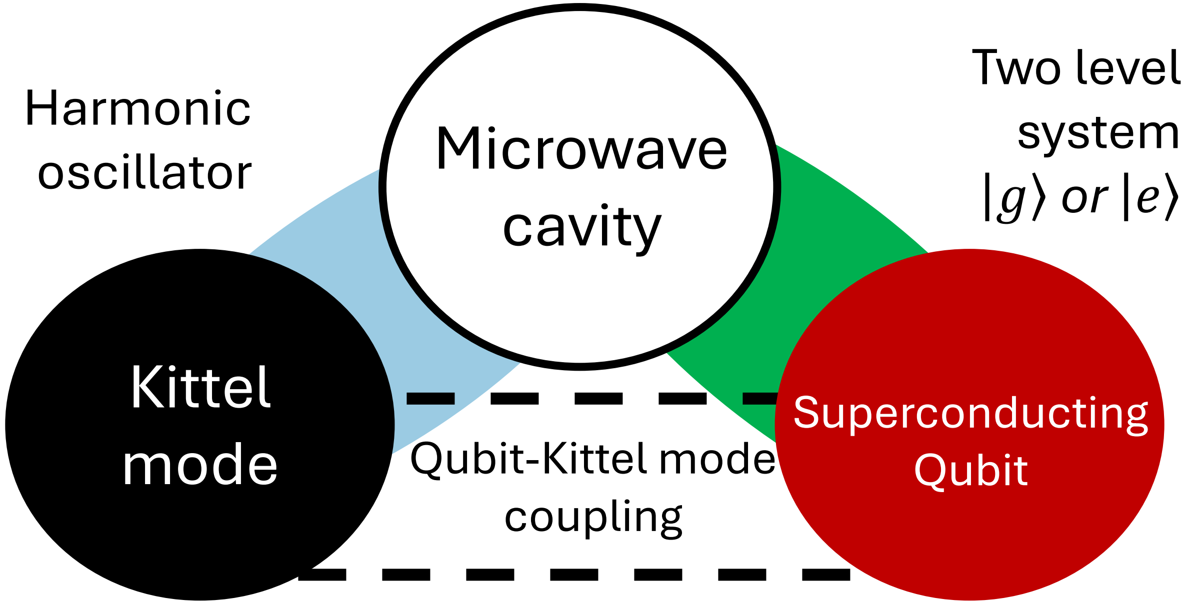

- Dark count still present in magnon counter
  - Error in magnon counter readout
  - Temperature dependent thermal noise
- **Sensitivity beyond SQL** possible by ***reducing dark count***

# Superconducting qubit: Magnon counter

$\hat{b}$ : Annihilation operator for Kittel mode
$\widehat{\sigma_z}$ : Pauli Z operator for Qubit

Lachance-Quirion *et al.* (2019)

**Qubit-Kittel mode hybrid**




Strong dispersive regime
$(|\omega_m - \omega_q| \gg g_{\mathrm{q-m}})$

Dispersive Hamiltonian

$$H/\hbar = \boxed{(\omega_q + 2\chi_{q-m}\hat{b}^{+}\hat{b})}\widehat{\sigma_z} + \omega_m \widehat{b^{+}}\hat{b}$$

Magnon no. ($\mathrm{n_m} = \hat{b}^{+}\hat{b}$) dependent Qubit frequency

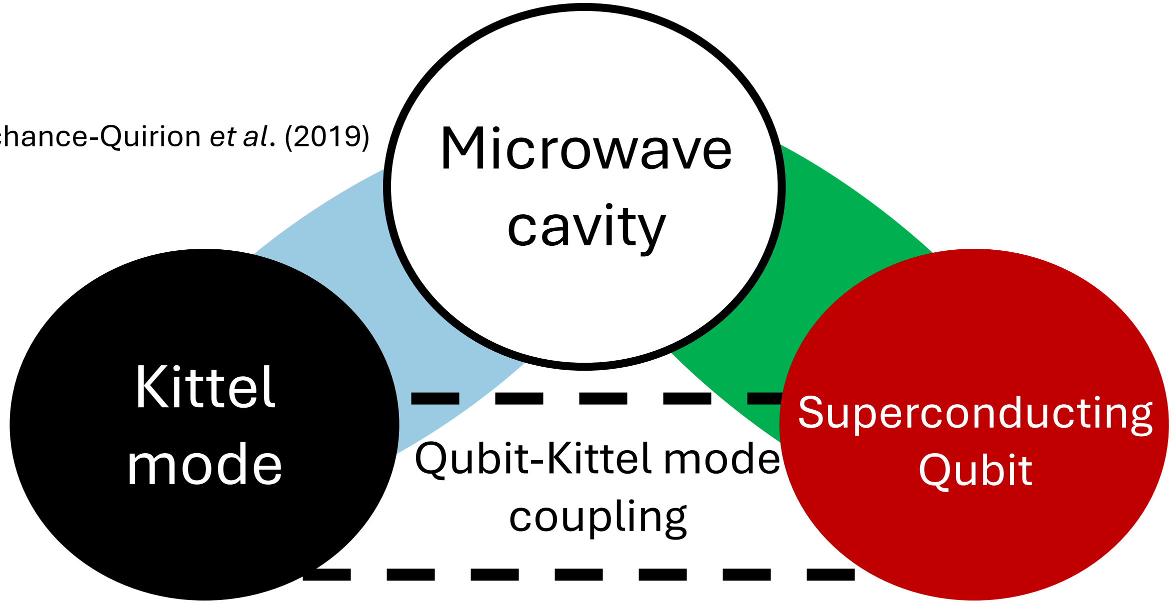
- No phase, $\phi_m$ information $\Delta n_m \cdot \Delta\phi_m \gtrsim 1$
- Magnon counting unconstrained by Standard Quantum Limit (SQL)

$\chi_{\mathrm{q-m}}$: Qubit - Kittel mode dispersive shift
$g_{\mathrm{q-m}}$: Qubit - Kittel mode coupling strength

# Superconducting qubit as magnon counter: Dispersive Interaction

## Qubit-Kittel mode hybrid

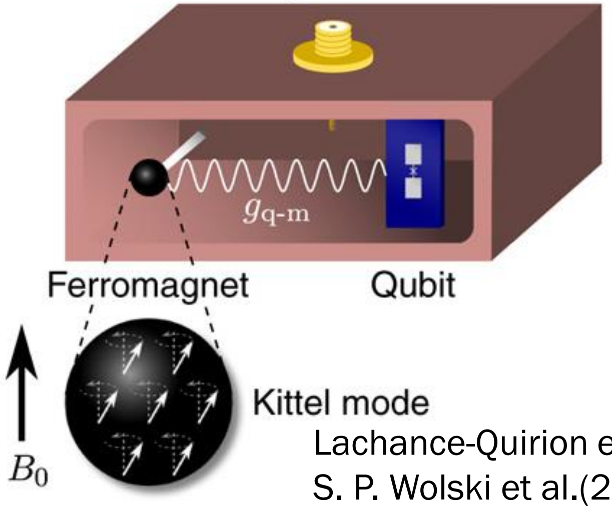
Lachance-Quirion *et al*. (2019)




Strong dispersive regime

$(|\omega_m - \omega_q| \gg g_{\mathrm{q-m}})$

## Experimental setup




Kittel mode-Qubit hybrid implemented with <u>*0.5 mm YIG*</u> at Nakamura lab

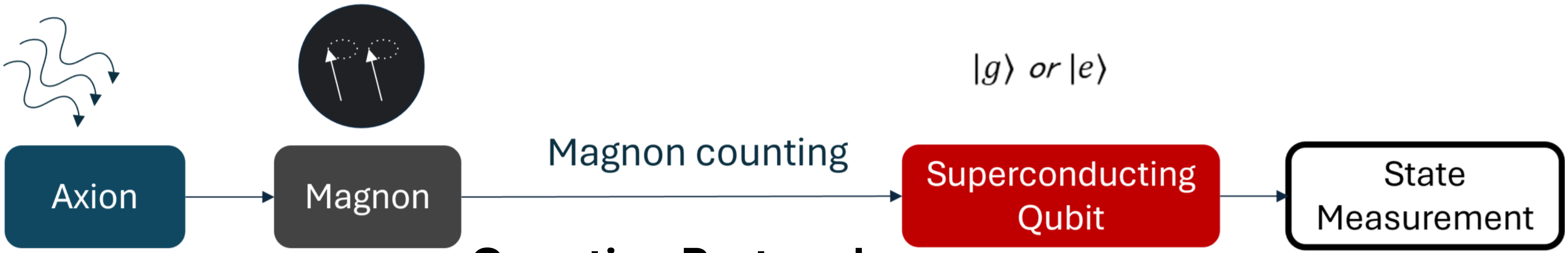
Lachance-Quirion et al. (2017,2020)
S. P. Wolski et al.(2020)

$\chi_{\mathrm{q-m}}$: Qubit - Kittel mode dispersive shift
$g_{\mathrm{q-m}}$: Qubit - Kittel mode coupling strength

Magnon number dependent Qubit frequency: $\widetilde{\omega_q^{n_m}} = (\omega_q + 2\chi_{\mathrm{q-m}} n_m)$

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

# Quantum sensing of magnon with SC qubit




**Counting Protocols**

1. Entanglement based protocol

   (D. Lachance-Quirion *et al.* (2020))

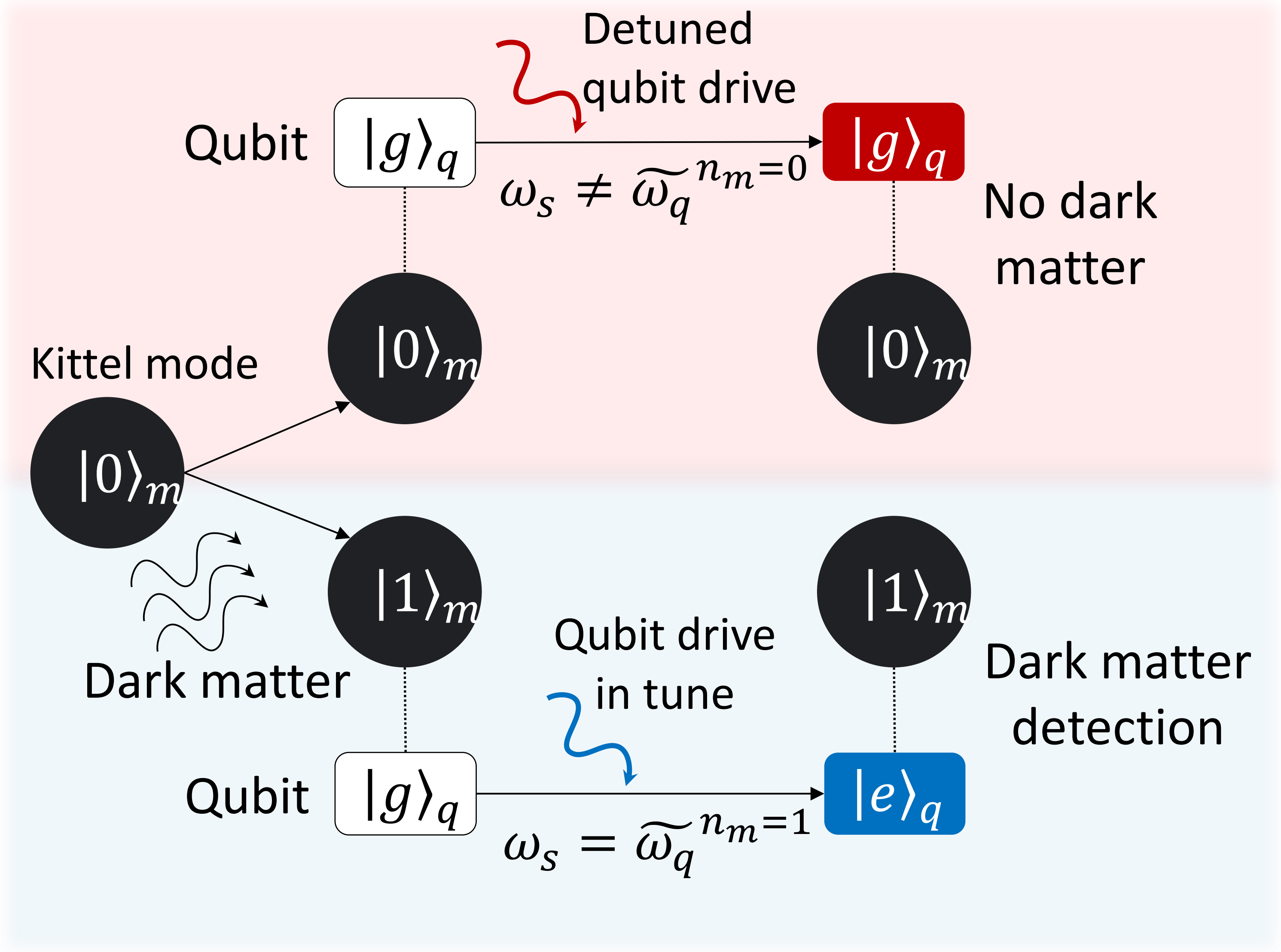
2. Dissipation based protocol

   (S. P. Wolski *et al.*(2020))

3. Spectroscopy based protocol

   ( D. Lachance-Quirion *et al.* (2016))

# ENTANGLEMENT BASED PROTOCOL




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

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

# SCHEMATIC OF QUBIT-KITTEL MODE HYBRID

$\kappa_i$: Internal decay rate of cavity

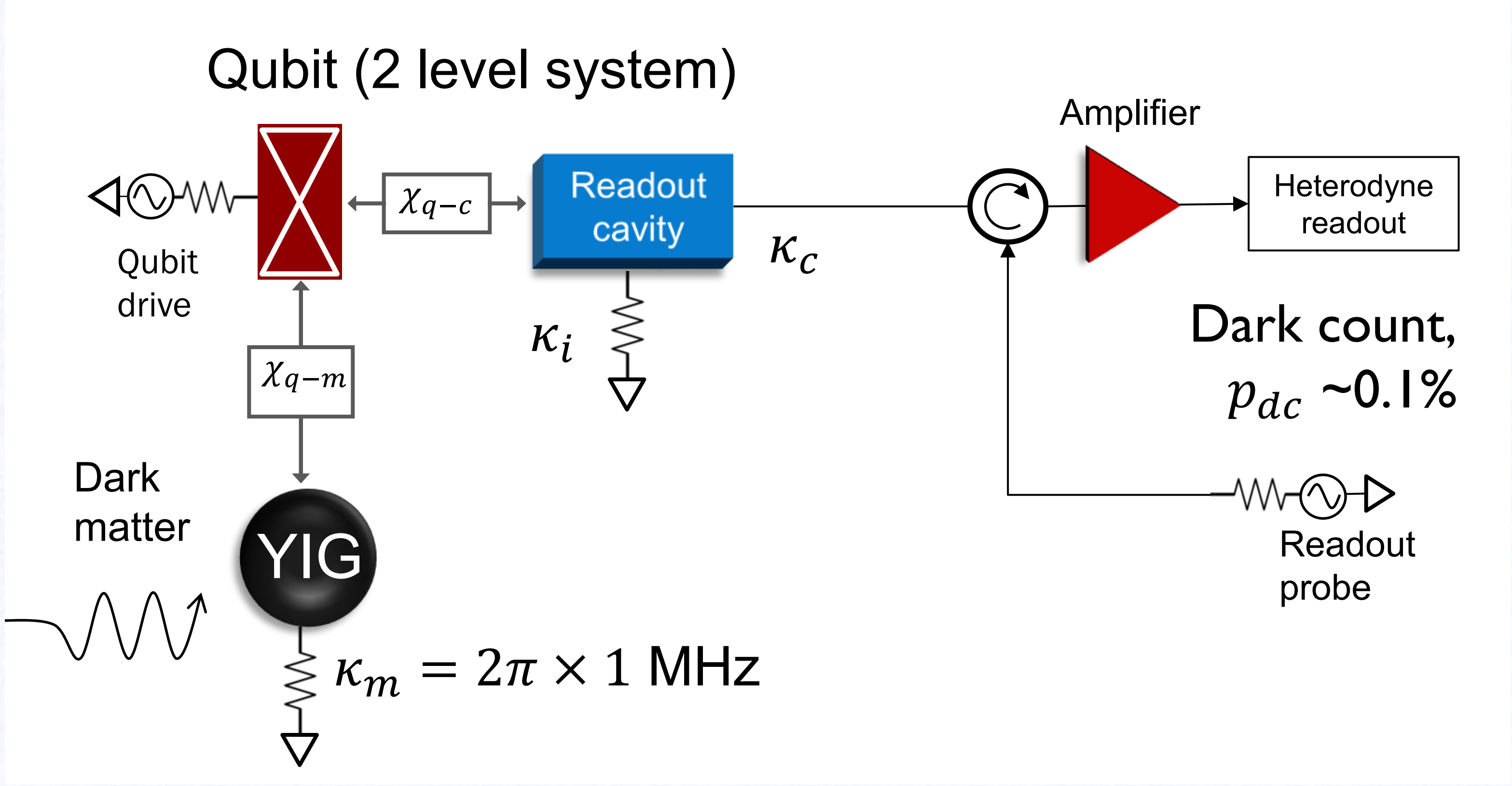
$\kappa_c$: External coupling rate of readout cavity

$\kappa_m$ : Kittel mode linewidth

$\chi_{q-c}$: Dispersive shift between qubit and cavity

$\chi_{q-m}$: Dispersive shift between qubit and Kittel mode

$\Delta\nu_a$: Axion linewidth




Ideally,

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

Sensitivity limited by

1. Qubit readout dark count, $p_{dc}$
2. Kittel mode linewidth, $\kappa_m$

# LOSS OF EFFICIENCY DUE TO DECOHERENCE

Qubit decoherence causes loss of efficiency

At optimal configuration

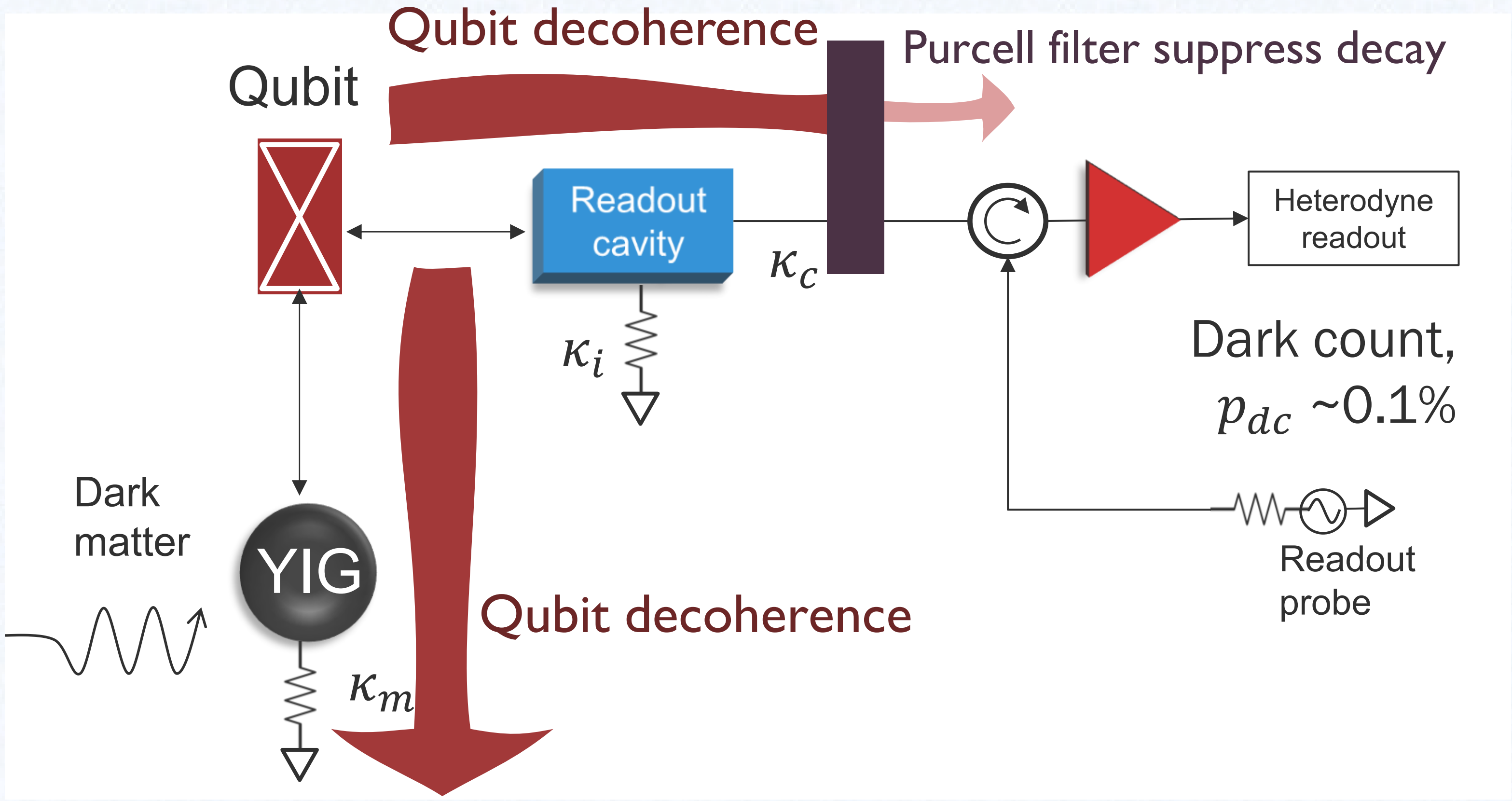
$$R = 0.07 \times 0.8 \times 1.6$$

$R^{ideal}$

Kittel mode induced inefficiency

Readout cavity induced inefficiency

Optimized with Purcell filter




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

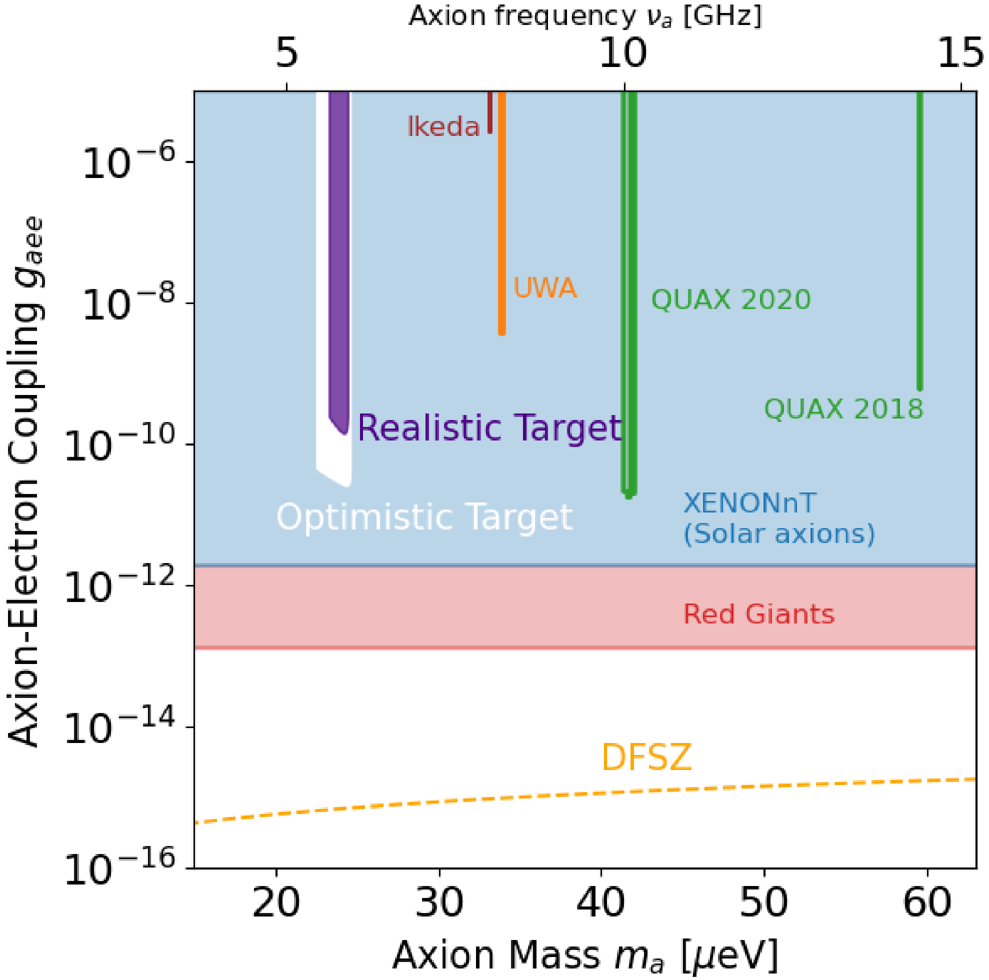
Still below SQL

To achieve sensitivity beyond SQL:

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

# Entanglement based Protocol
## Optimistic Estimation

$R = \frac{\tau_{SQL}}{\tau_{ent}}$, shows how fast scan rate is compared to quantum limited axion search




**Assumptions:**

Dark count, $p_{dc}$ ~0.1%

Purcell filter enhancement factor: 100

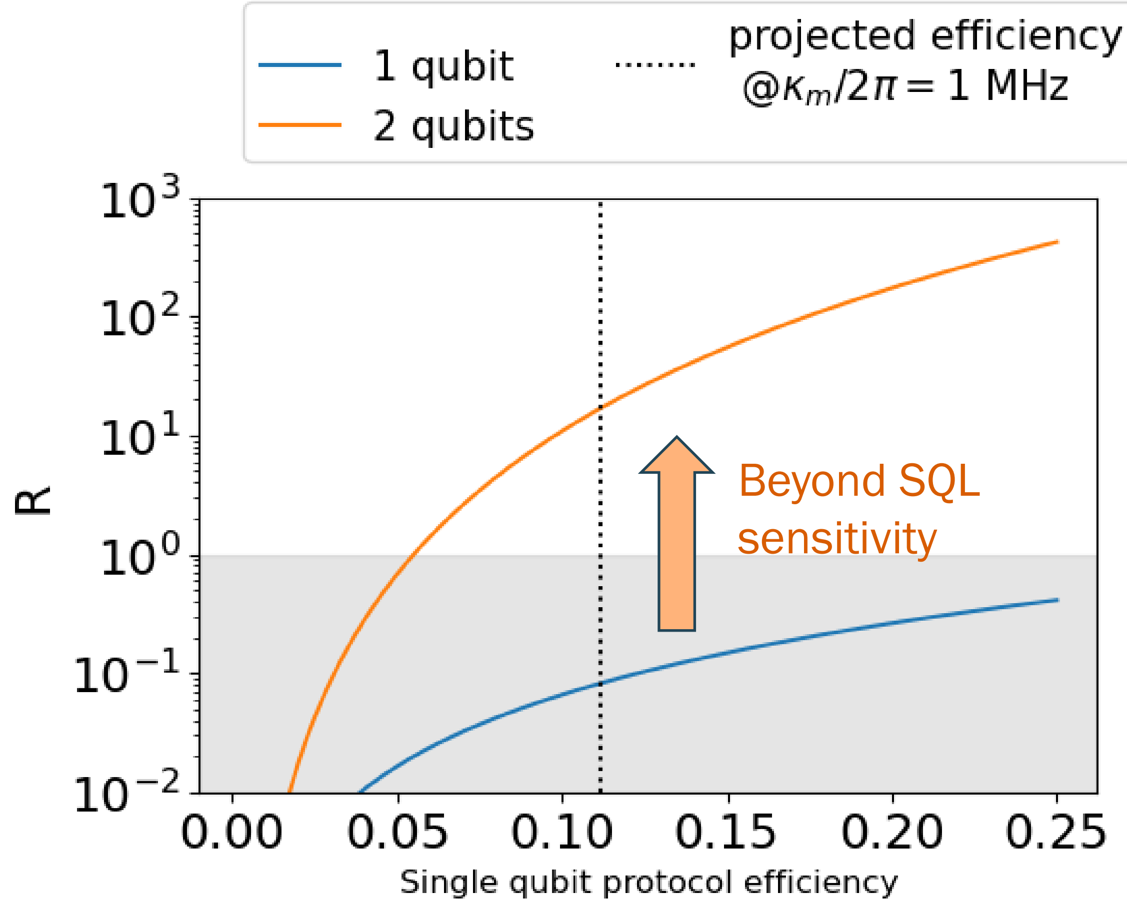
Qubit as pure two-level system

Single YIG sphere of diameter 2 mm

| | $\kappa_m/2\pi$ | $R_{ideal}$ | $R$ (with inefficiencies) |
|---|---|---|---|
| Realistic | 1 MHz | 1.6 | 0.1 (below SQL) |
| Optimistic | 0.2 MHz | 8.2 | 3.5 (beyond SQL) |

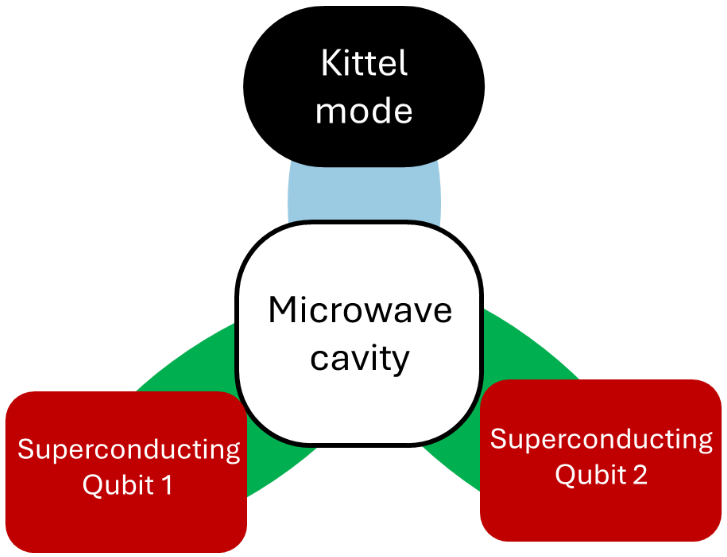
*Improvement in Kittel mode linewidth* necessary to overcome SQL

# Reduced dark count: Multiple qubits




**Assumptions:**
Single qubit dark count, $p_{dc}$ ~0.1%
Identical efficiency and dark count for both qubits

**Two Qubit-Kittel mode hybrid**

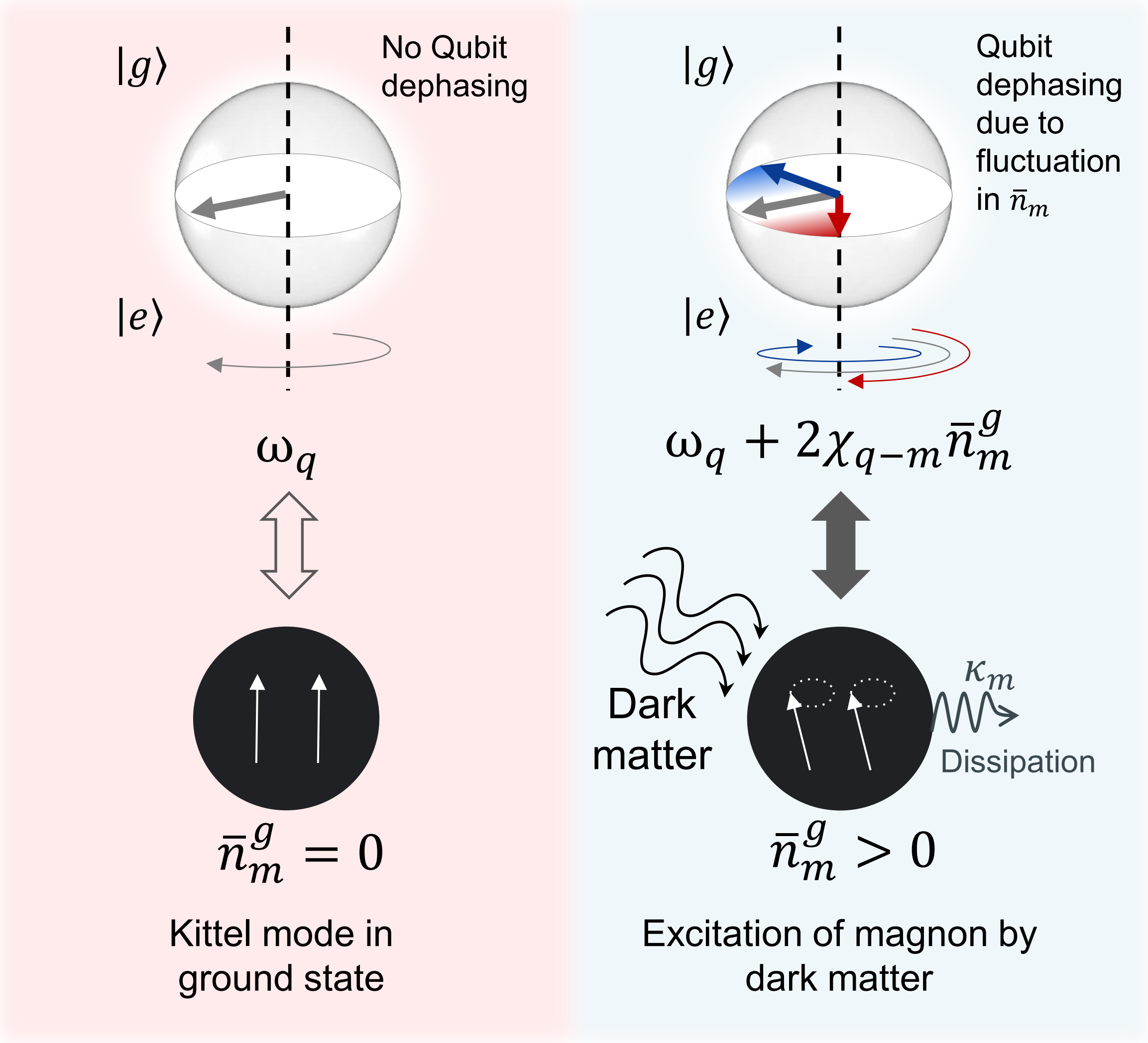



Multiple qubit allows suppression of qubit dark count rate:

**Effective dark count =** $p_{dc}^2$

For *large enough protocol efficiency*, multiple qubit can allow beyond SQL sensitivity

# DISSIPATION BASED PROTOCOL




In presence of dark matter induced magnon, decoherence rate of qubit is accelerated which can be measured with *Ramsey protocol*

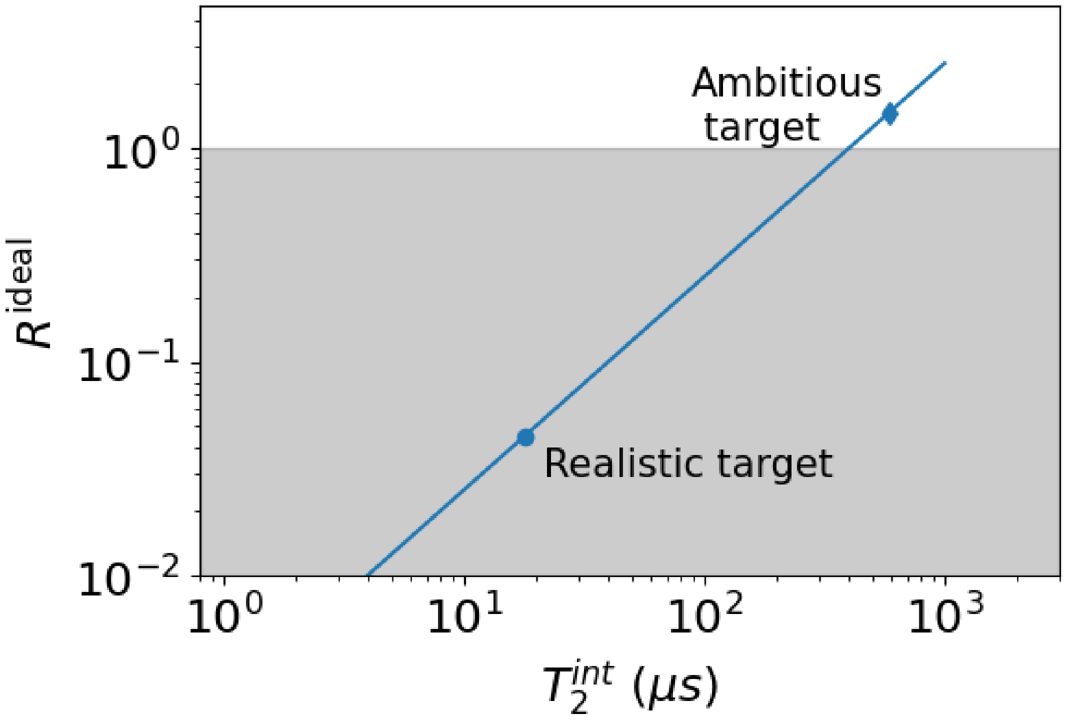
$$\frac{1}{T_2^q} \propto \bar{n}_m^g$$

$T_2^q$: Qubit coherence time
$\bar{n}_m^g$: Average magnon number induced by dark matter

# Limitation to sensitivity of Dissipation protocol

$$R^{ideal} = \frac{\tau_{SQL}}{\tau_{diss}} = \frac{\mathrm{T}_2^{int} \Delta\nu_a}{2},$$

where $\mathrm{T}_2^{int}$ is the qubit coherence time in absence of magnons




Qubit decoherence in absence of magnon through

- Purcell decay of qubit through cavity and Kittel mode
- Dephasing from thermal photons

act as *primary background noise* to dissipation protocol

| | $\mathrm{T}_2^{int}$ | $R^{ideal}$ |
|---|---|---|
| Realistic | ~20 $\mu s$<br>(with copper cavity and $\kappa_m/2\pi = 1$ MHz) | 0.05 |
| Ambitious | ~600 $\mu s$<br>(require SC cavity and $\kappa_m/2\pi < 0.2$ MHz) | 1.5 |

# Limitation to sensitivity of Dissipation protocol

Dissipation protocol requires *large qubit coherence time $T_2$* to achieve sensitivity beyond SQL which poses significant experimental challenge for Kittel mode - qubit hybrid

Intri

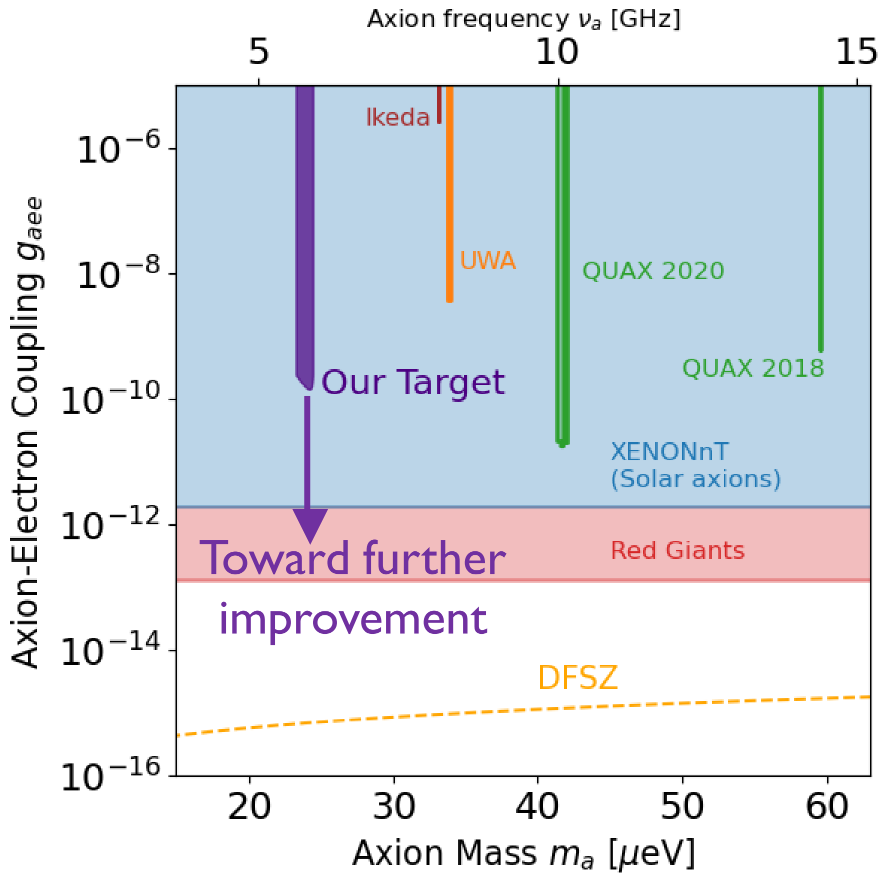
act as primary background noise to dissipation protocol

| | | |
|---|---|---|
| Realistic | ~20 $\mu s$ (with copper cavity and $\kappa_m/2\pi = 1$ MHz) | 0.05 |
| Ambitious | ~600 $\mu s$ (require SC cavity and $\kappa_m/2\pi$ < 0.2 MHz) | 1.5 |

# 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

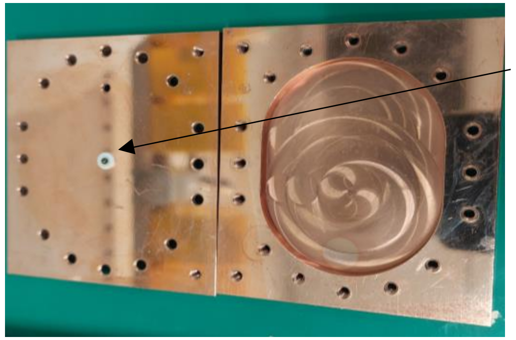
Larger YIG
Optimized Kittel mode - Qubit hybrid



# GOALS

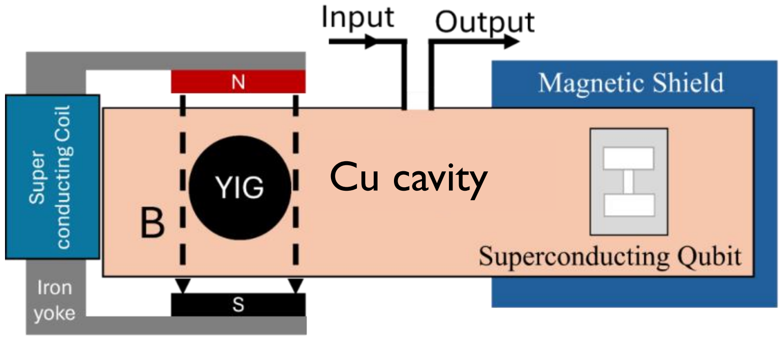
## Initial target:

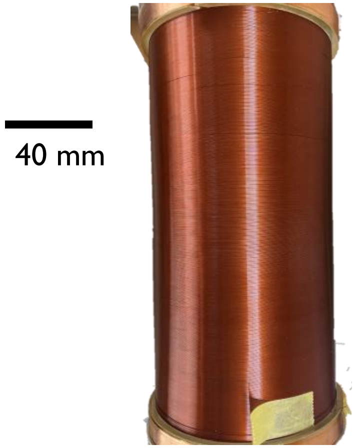
Qubit-Kittel mode hybrid with
2 mm YIG



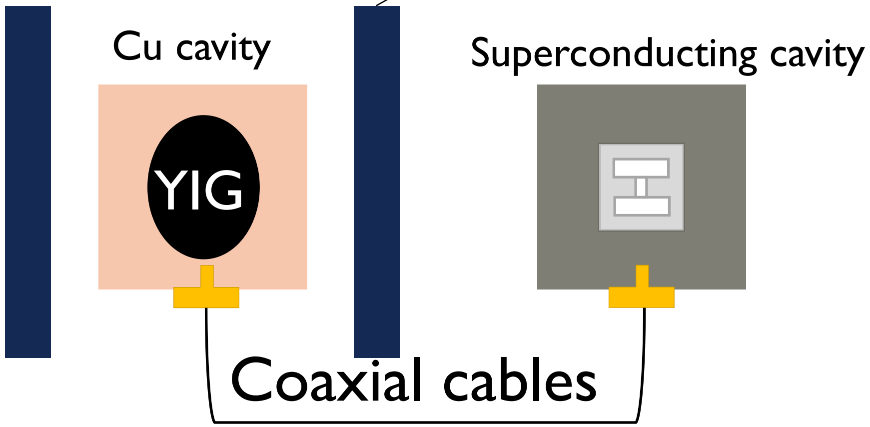
YIG sphere
$\phi$ 2 mm

10 mm




**Superconducting solenoid magnet (0.5 T)** ($\phi$86 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 :**
- Experiments in this talk were performed at Kusaka lab UTokyo, CRC UTokyo, and KEK Cryogenics Science Center.
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