Axion dark matter detection with magnon

Kentaro Miuchi
(Kobe University, connecting from Gran Sasso, Italy)

QUP workshop toward project

2022 Nov 7th

based on PRD **105**, 102004

Axion search with quantum nondemolition detection of magnons

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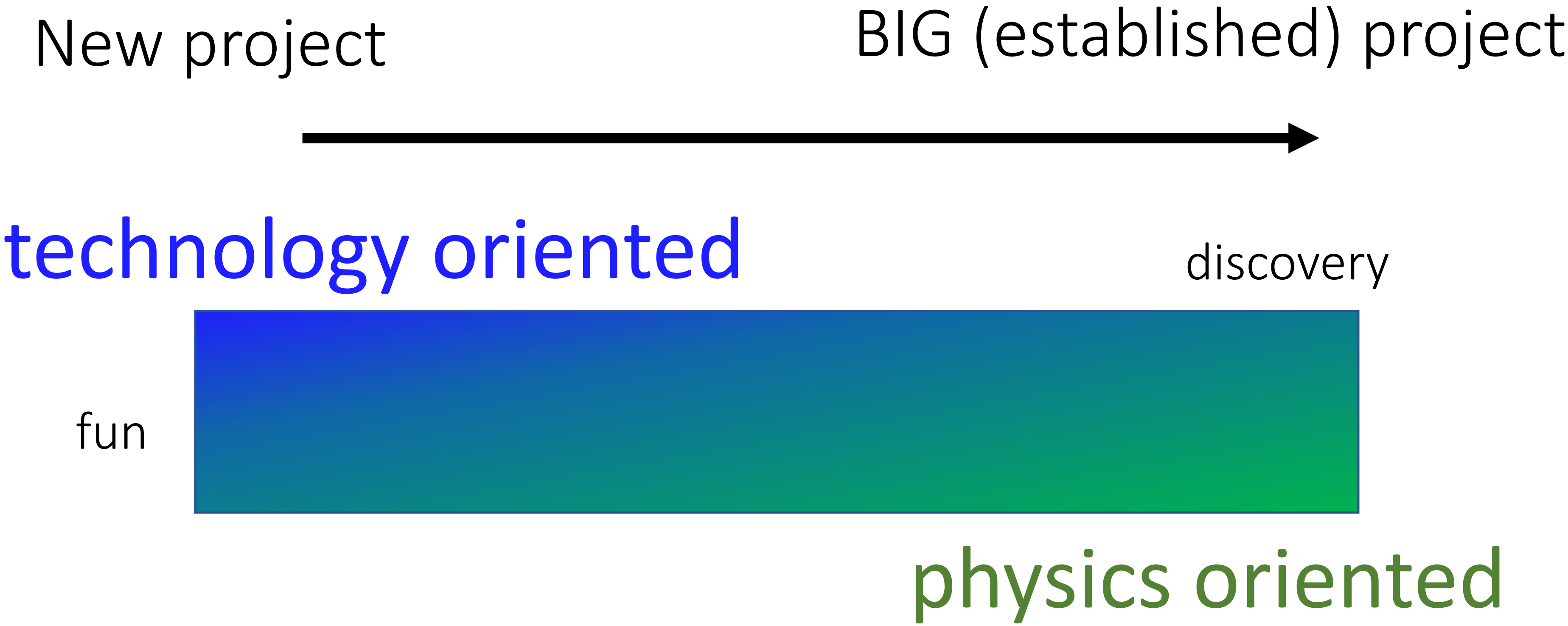
Yutaka Shikano[||]

enough queue for project Q
Let's enjoy the collecions.

Project



balance in community, person

I am looking forward to seeing the “chosen one”.

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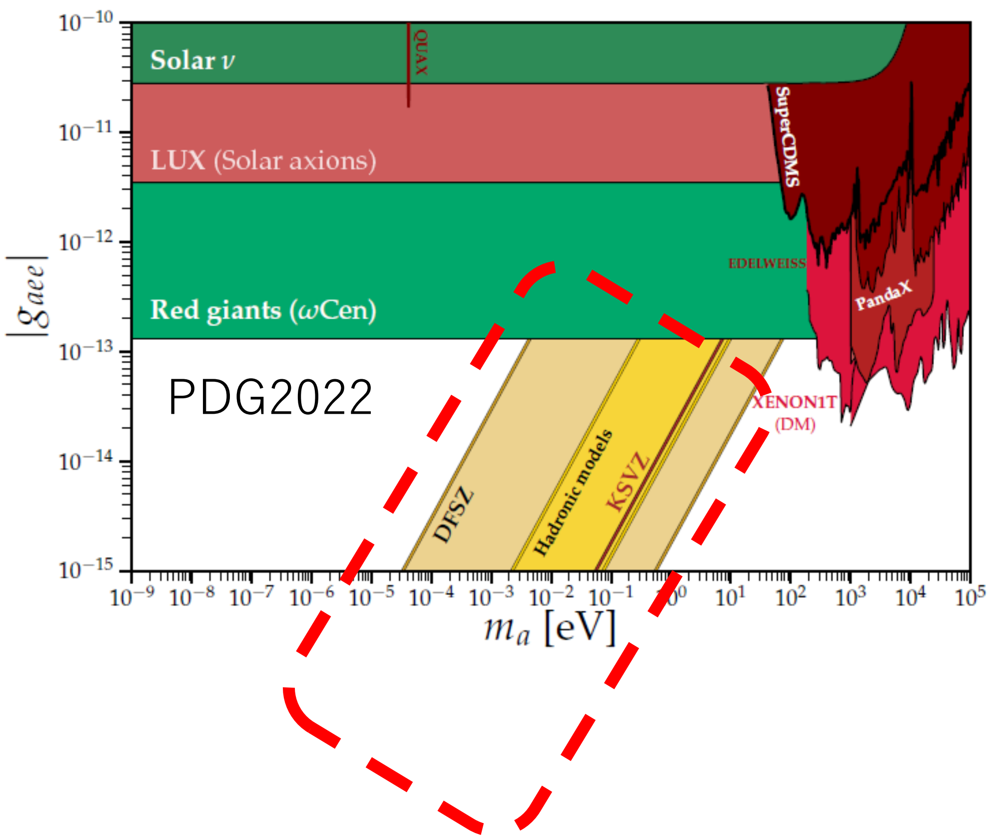
Motivations

- Physics motivation: dark matter halo axion
  - g_{aee}(axion-electron coupling)

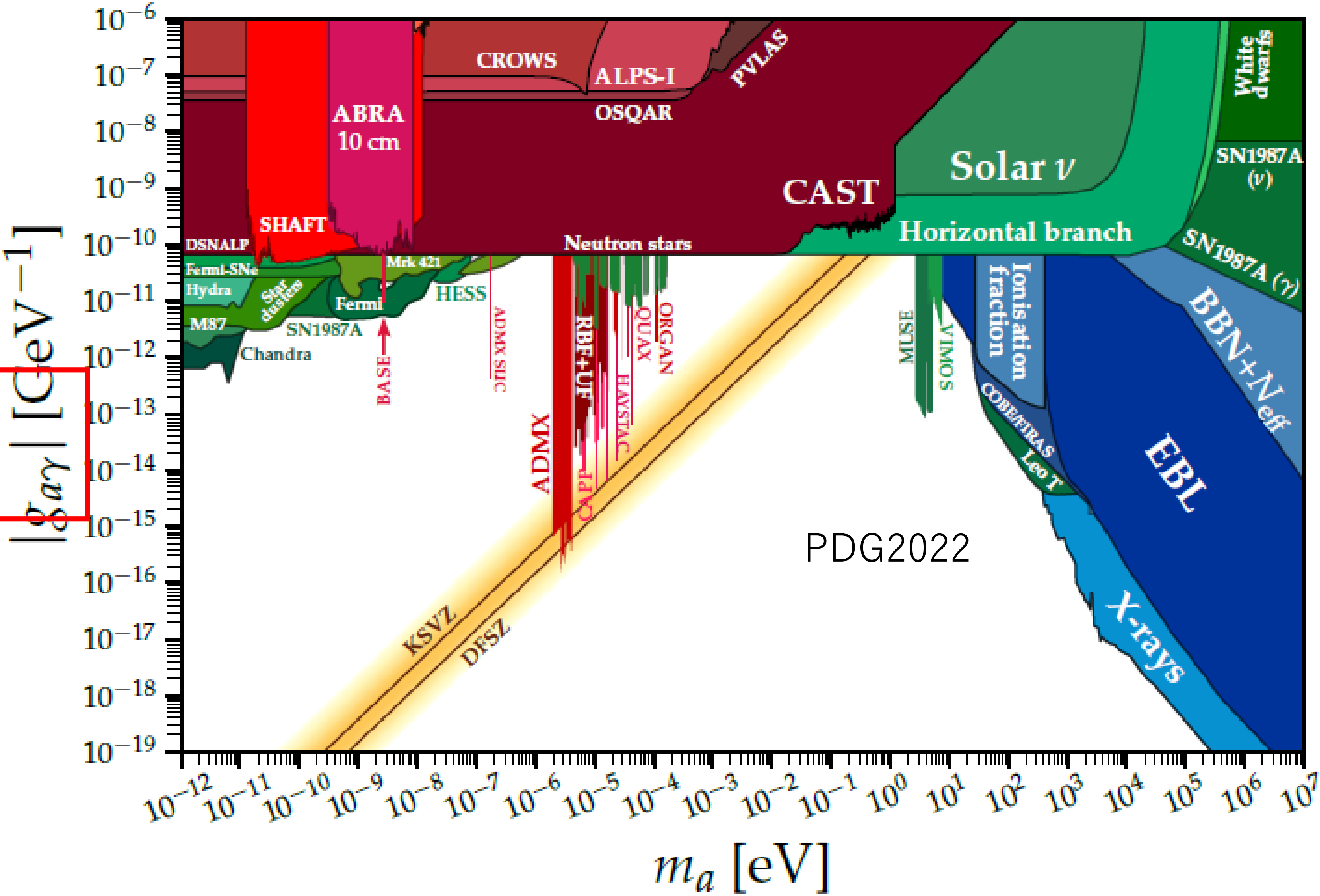


1μeV～1meV
⇔ 1GHZ～1THz range

$$f_a = \frac{\omega_a}{2\pi} = \frac{m_a c^2}{h} \simeq 0.24 \left(\frac{m_a}{1.0\ \mu\text{eV}} \right) \text{GHz.} \qquad (1)$$

- Technology motivation: quantum technology

axion search main stream: axion-gamma coupling

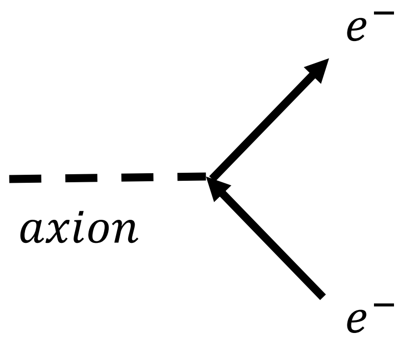


Detection Principles

axion−electron interaction

- ✓ axion-electron coupling

$$\mathcal{L}_{\rm int} = -i g_{aee} a(x)\bar{\psi}(x)\gamma_5\psi(x),$$



a: axion filed,ψ: electron field

- ✓ Interaction term for non-relativistic DM halo

$$-\frac{g_{aee}\hbar}{2m}\hat{\sigma}\cdot\nabla a = -2\left(\frac{e\hbar}{2m}\right)\left(\frac{1}{2}\hat{\sigma}\right)\cdot\left(\frac{g_{aee}}{e}\nabla a\right)$$

m:electron mass

μ_B:Bohr magneton

S: elctron spin

B_a: magnetic field by axions

- ✓ magnetic field by axion

$$B_a \simeq 4.4\times 10^{-8} g_{aee}\left(\frac{\rho_{\rm DM}}{0.45\ {\rm GeV/cm^3}}\right)^{1/2}\left(\frac{v_{\rm tot}}{300\ {\rm km/s}}\right)\ {\rm T},$$

ρ_{DM}: local halo density

v_{tot}: axion velocity @ earth

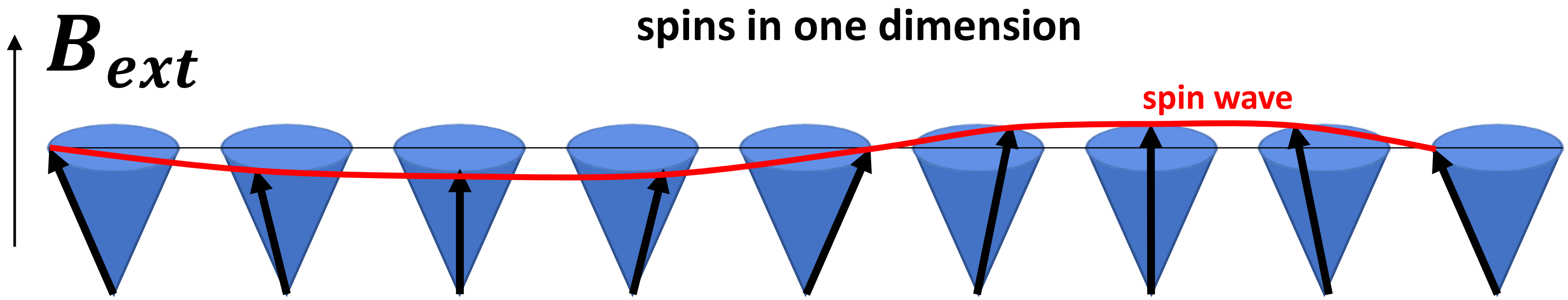
✓CAVEAT: Super tiny for one electron

Magnon: elections' collective spin

✓ spin behaviors in ferromagnet with external magnetic field

$$\hat{\mathcal{H}} = -g\mu_{\mathrm{B}} B_z \sum_i \hat{S}_i^z - 2J \sum_{\langle i,j \rangle} \hat{\mathbf{S}}_i \cdot \hat{\mathbf{S}}_j,$$

from external field　　　　interaction of neighboring spins



➢ collective excitation of spins can be described as spin wave : Magnon

✓ Magnon-axion coupling

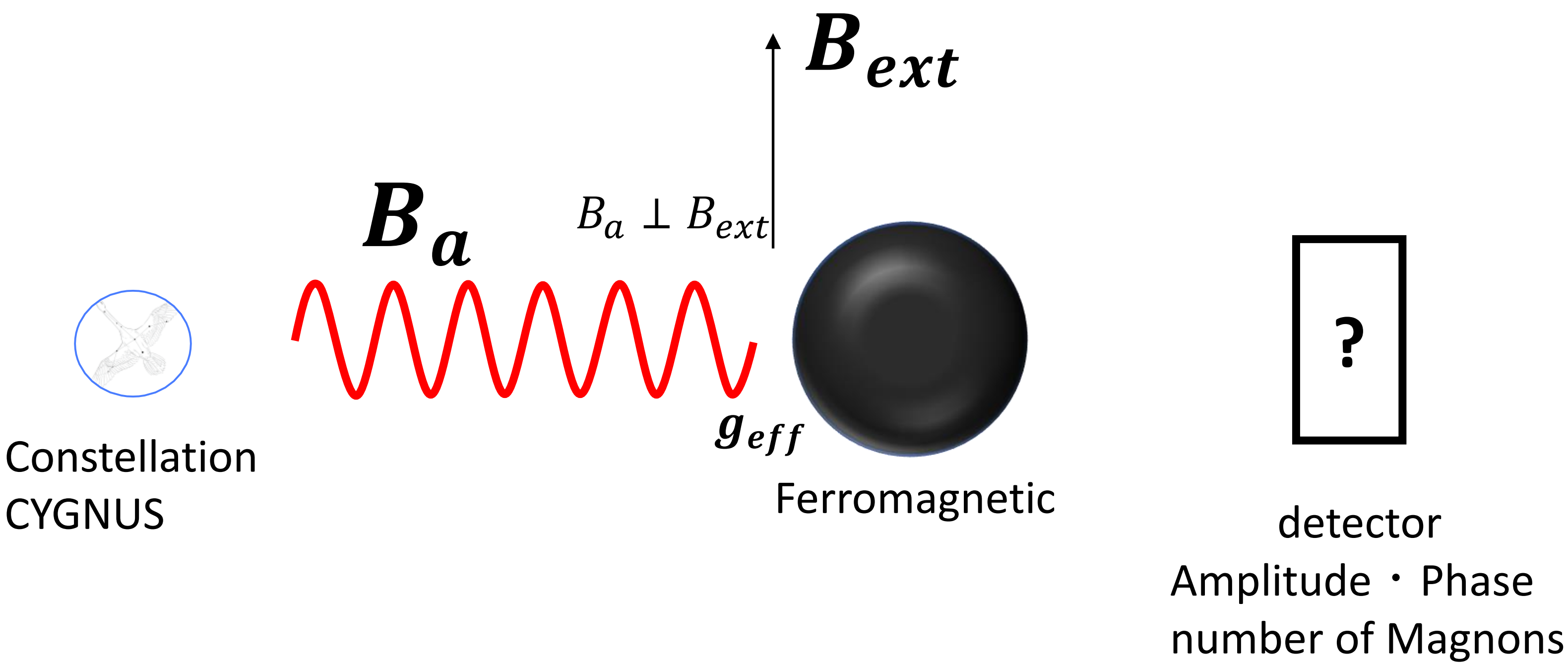
$$\mathcal{H}_{int} = \hbar g_{eff} (\hat{a}^\dagger \hat{c} + \hat{a} \hat{c}^\dagger), \quad g_{eff} \equiv \frac{g\mu_B B_a}{2\hbar} \sqrt{2sN},$$

$\sqrt{N}$ enhancement
N: number of spins

HALO Axion detection

axion (B*a*) gives a kick to one electron

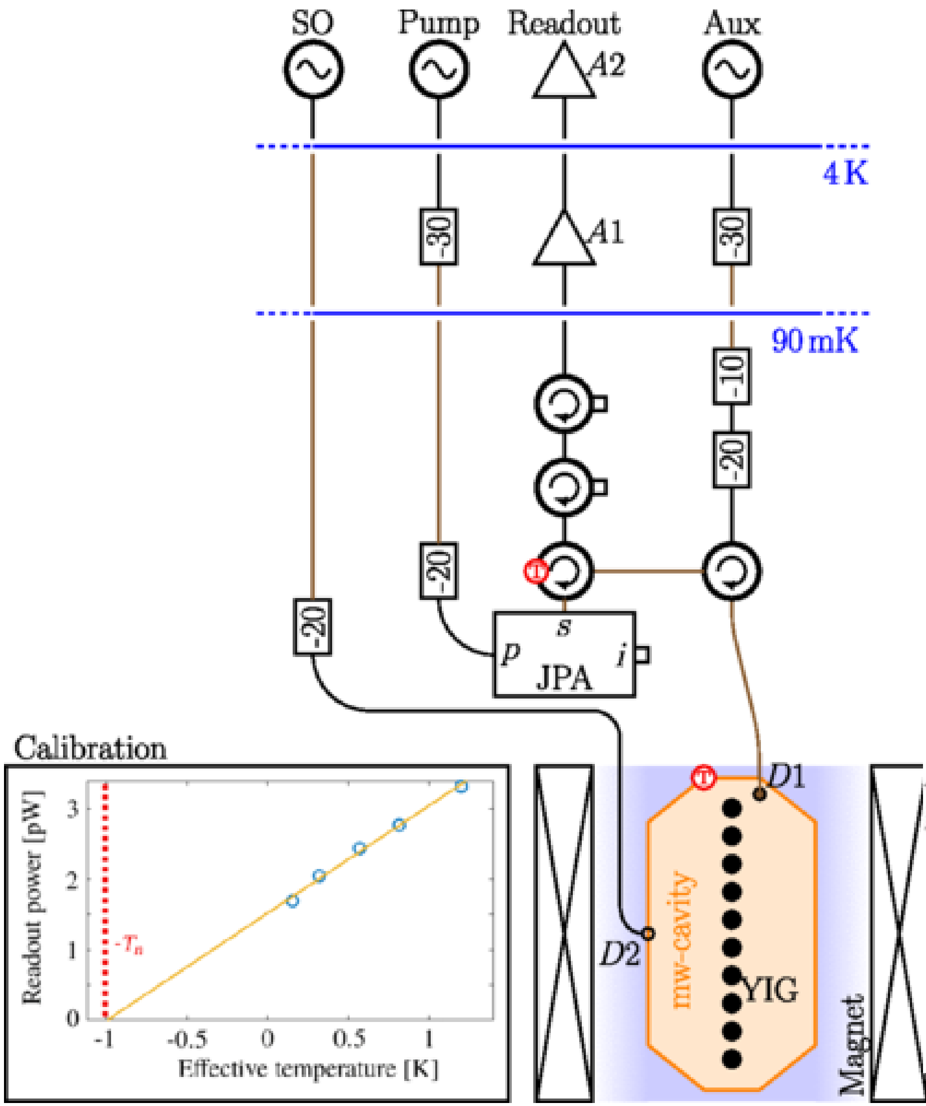
→ Magnon made by B*ext*

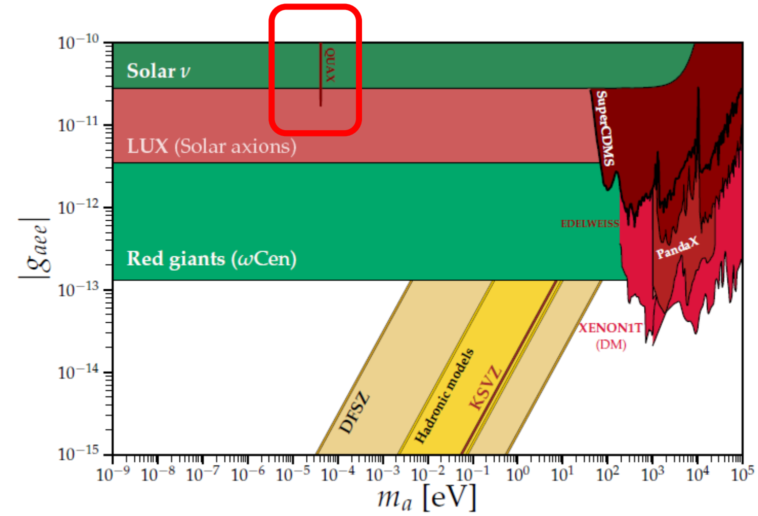


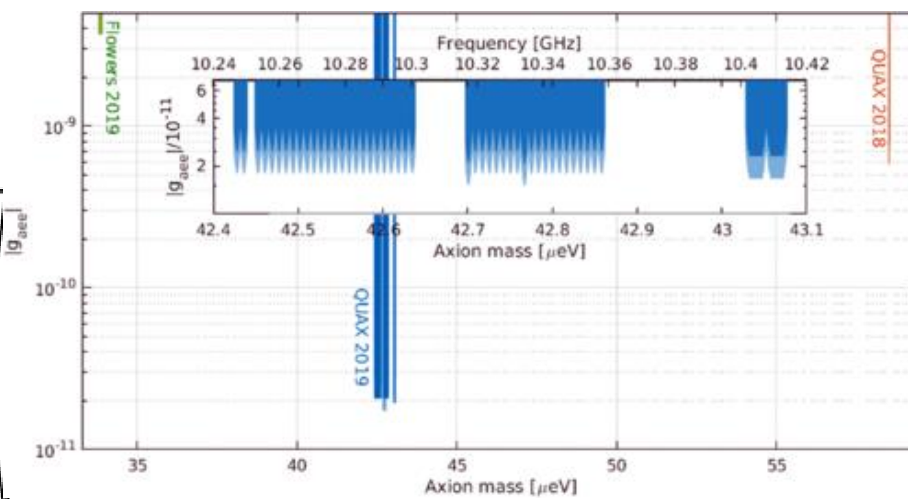
→Measure the Magnons!

QUAX: the pioneer

magnon measurement by cavity-antenna



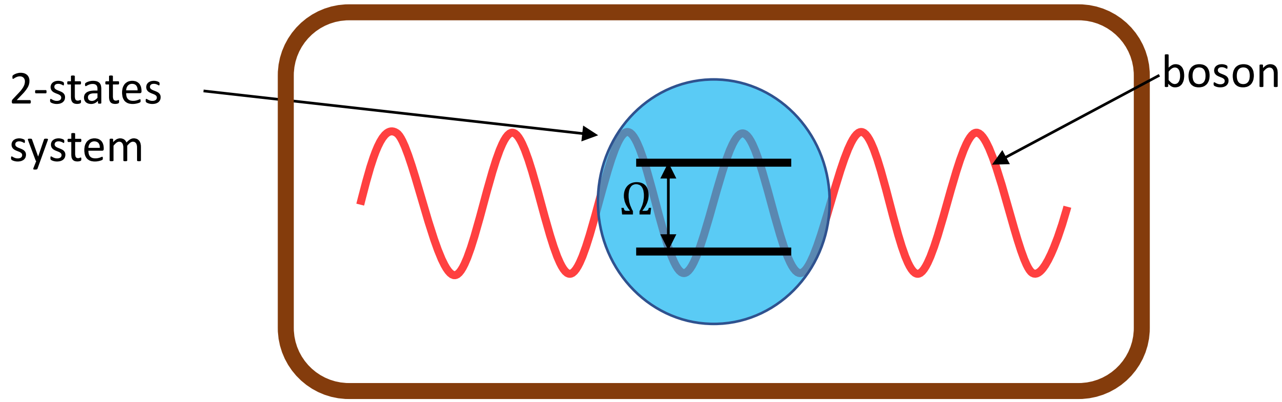




Phys. Rev. Lett. **124**, 171801 (2020)

Phys. Rev. Lett. **124**, 171801 (2020)

Make it QUP !
Quantum non demolition measurement



✓ Hamiltonian

ac-Stark shift   Lamb shift

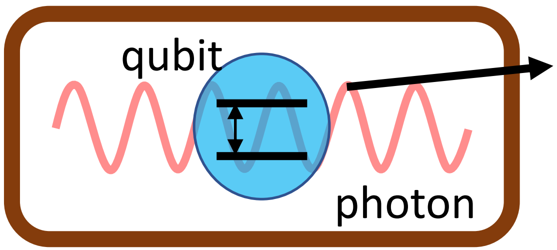
$$H = \hbar\omega_r\left(a^\dagger a + \frac{1}{2}\right) + \frac{\hbar}{2}\left(\Omega + \frac{2g^2}{\Delta}a^\dagger a + \frac{g^2}{\Delta}\right)\sigma^z \quad \text{, with } \Delta = \omega_r - \Omega$$

Wave length of the states transition depends on the number of Bosons.

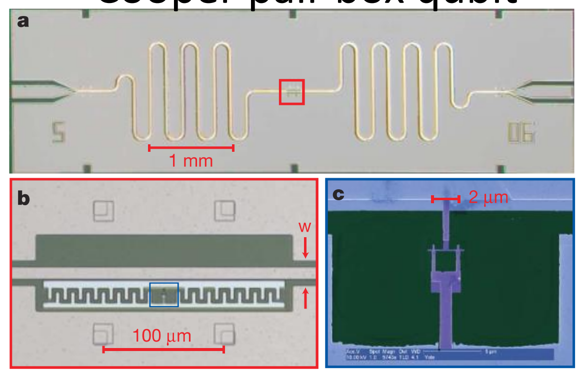
➢ **Boson numbers can be known by measuring the transition wave length. (QND measurement)**

photon counting by Qubit

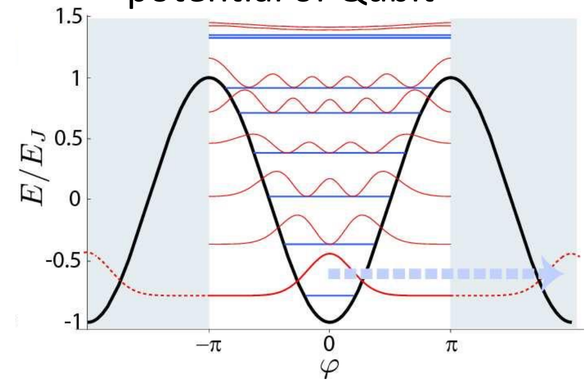
✓ Ridberg's atom → artificial atom (Qubit) **D.I.Schuster, et.al., Nature 445 515(2007)**



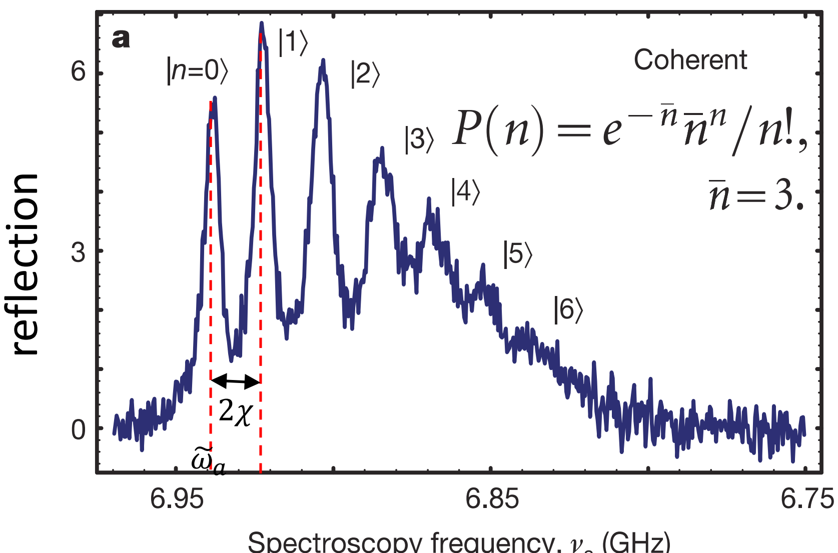
Cooper pair box qubit



potential of Qubit



J.Koch, et.al, Phys.Rev.A76,042319(2007



$$H_{eff} = \hbar\omega_r \hat{a}^\dagger \hat{a} + \frac{\hbar}{2}\left(\tilde{\omega}_a + 2\chi \hat{a}^\dagger \hat{a}\right)\hat{\sigma}_z$$

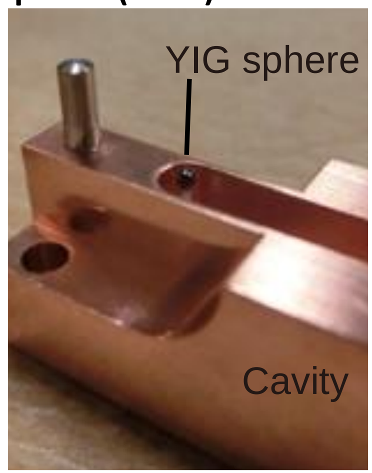
➢ **photon number is known by the frequency given to Qubit**

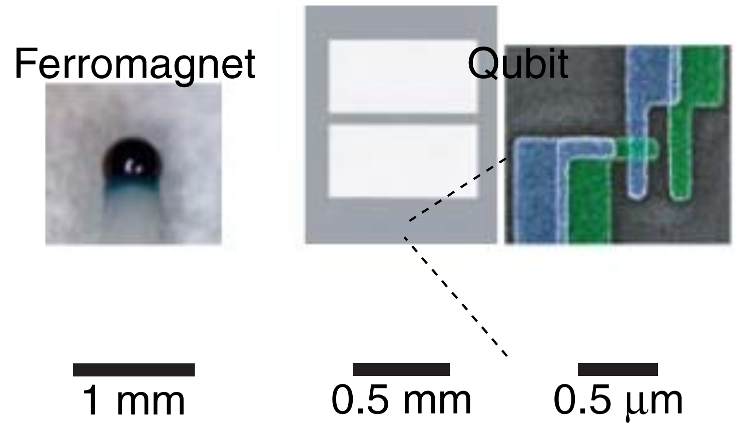
Magnon measurement with qubit

D.Lachance-Quirion, et.al., Sci.Adv. 2017;3:e1603150

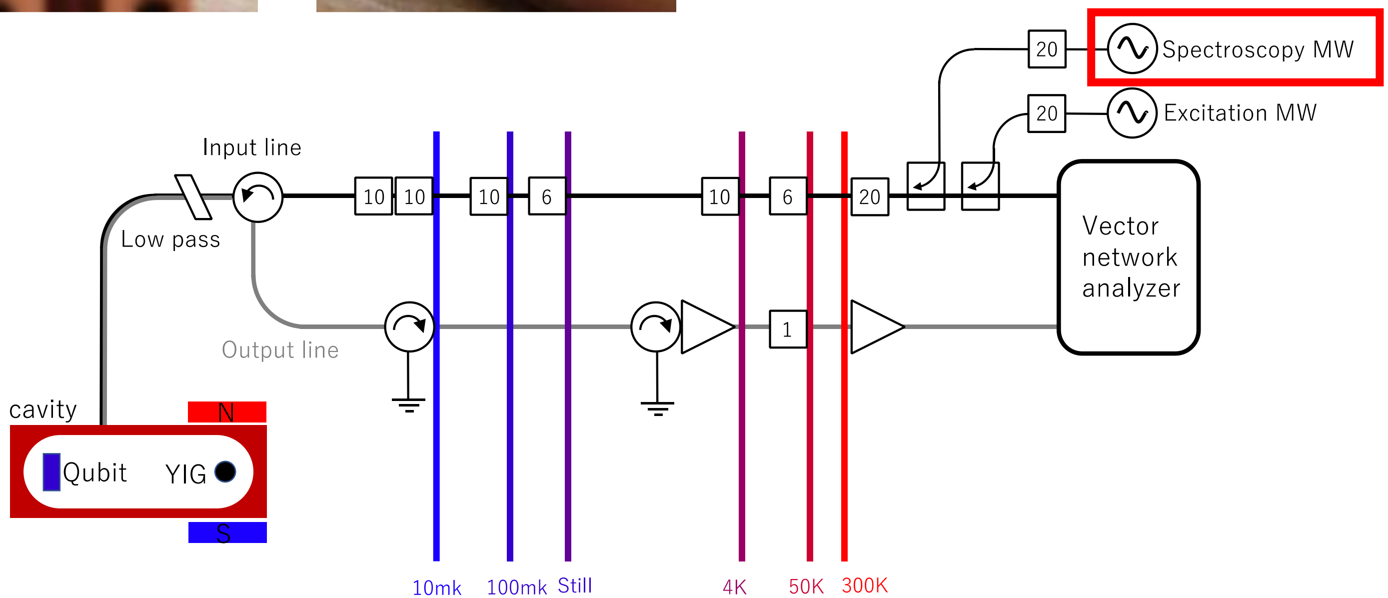
✓ Setup@ Nakamura lab T. Tokyo

C. R. Physique 17 (2016) 729–739



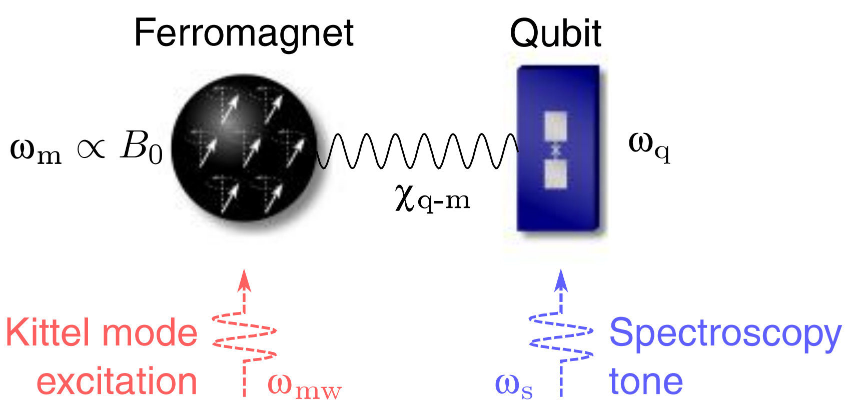


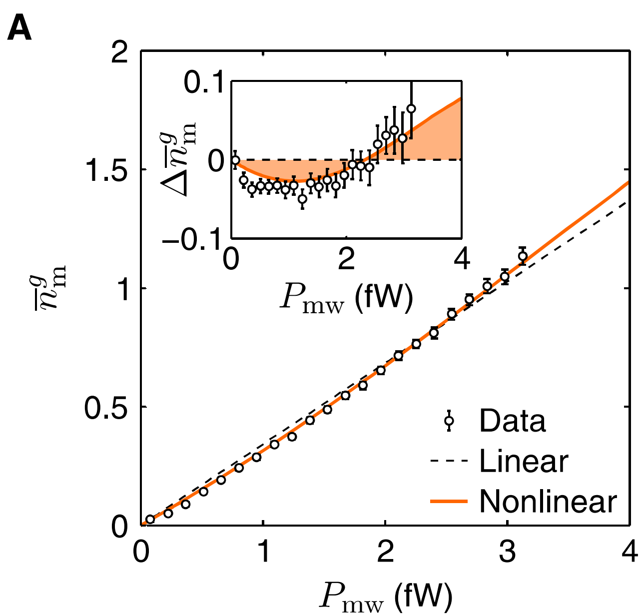
scan

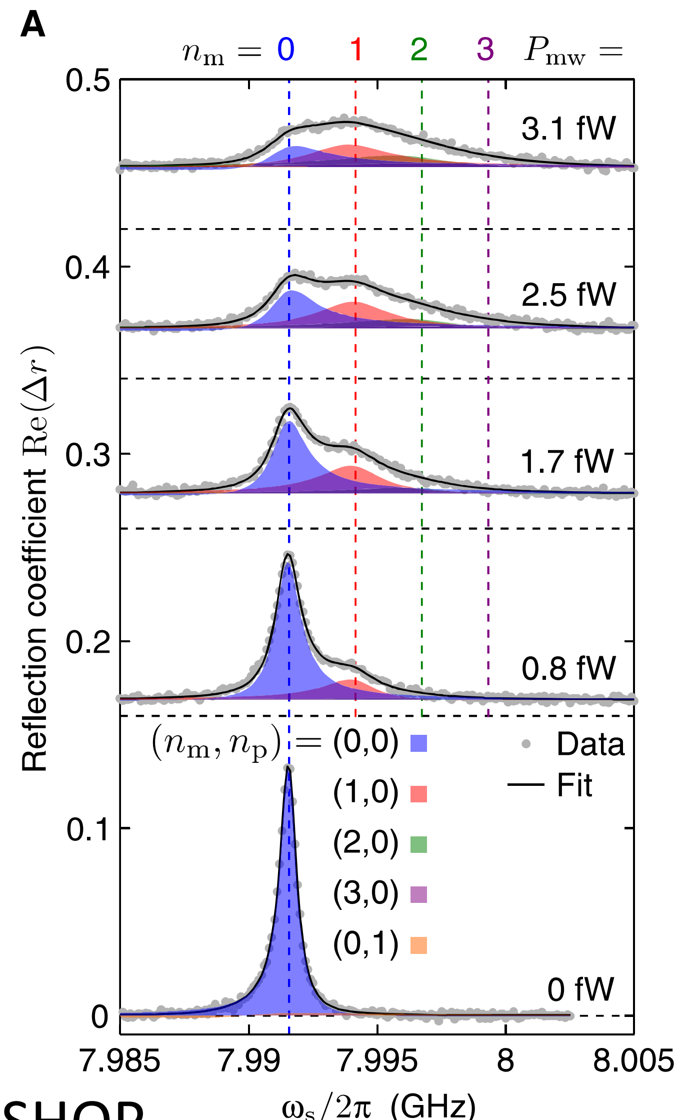


Demonstration of magnon detection (= calibration for axion search)

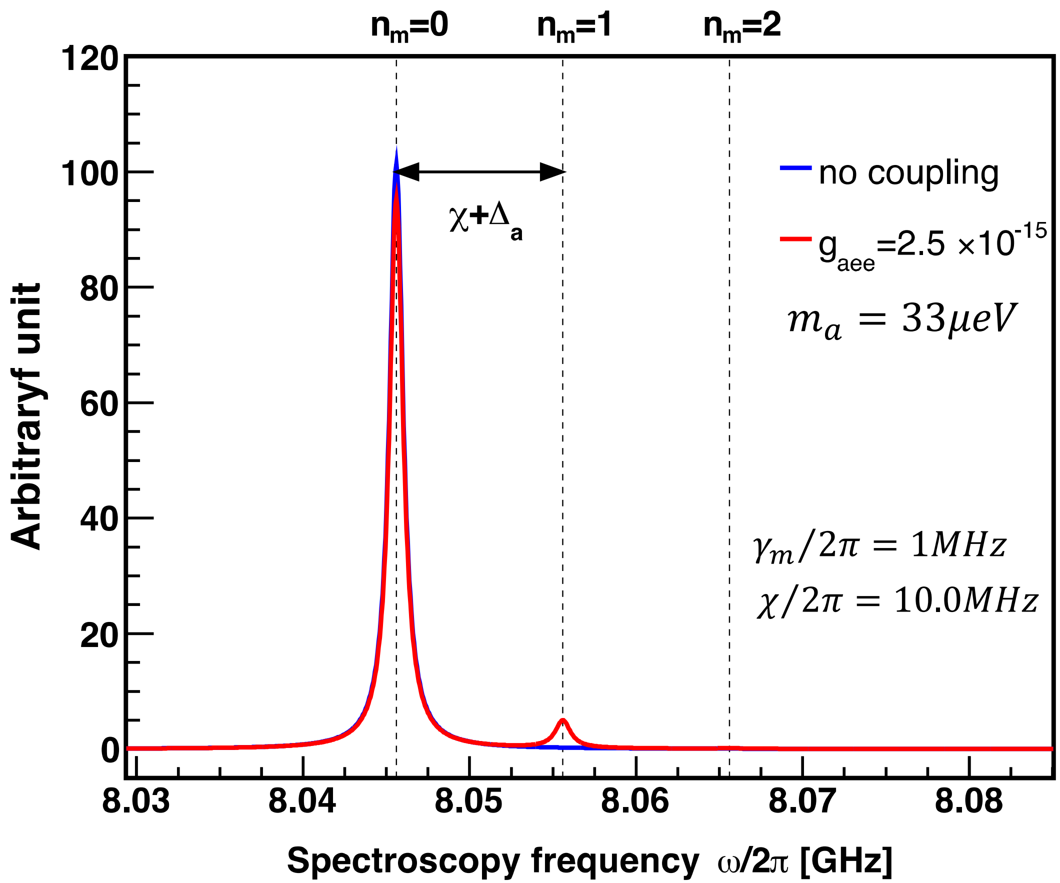
D.Lachance-Quirion, et.al., Sci.Adv. 2017;3:e1603150

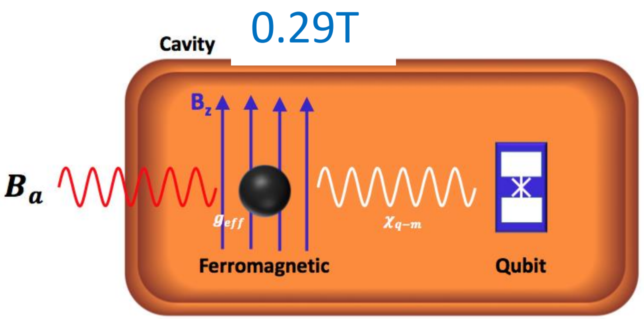






Expected signal by axion–Magnon interactions





- ✓ Axion-Magnon couplings

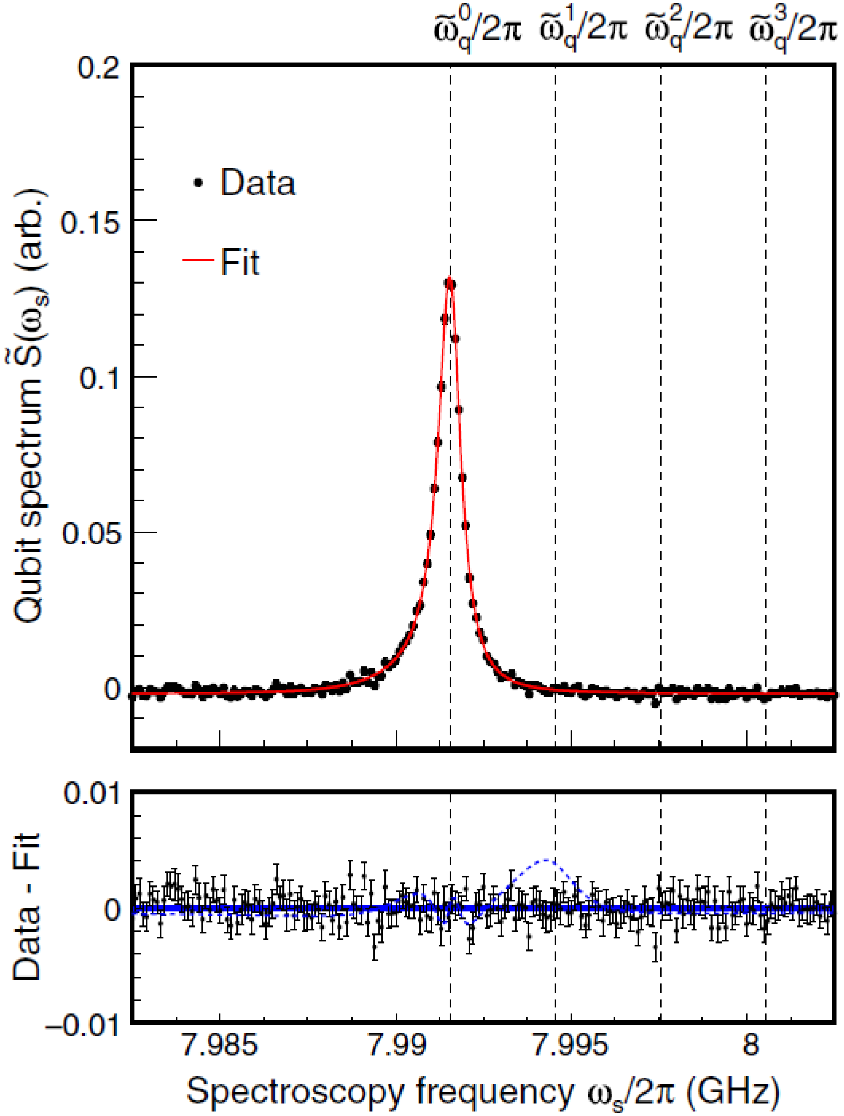
$$g_{eff} \equiv \frac{g\mu_B B_a}{2\hbar}\sqrt{2sN},$$

- ✓ Average Magnon numbers

$$\bar{n}^m_{\pm} = \frac{g^2_{eff}}{\gamma^2_m/4 + (\Delta_a \pm \chi)^2},$$

➢ **A peak is expected at $f_{n=1}$ in the QBIT excitation spectrum**

DM RUN (or BG run for U.Tokyo group)

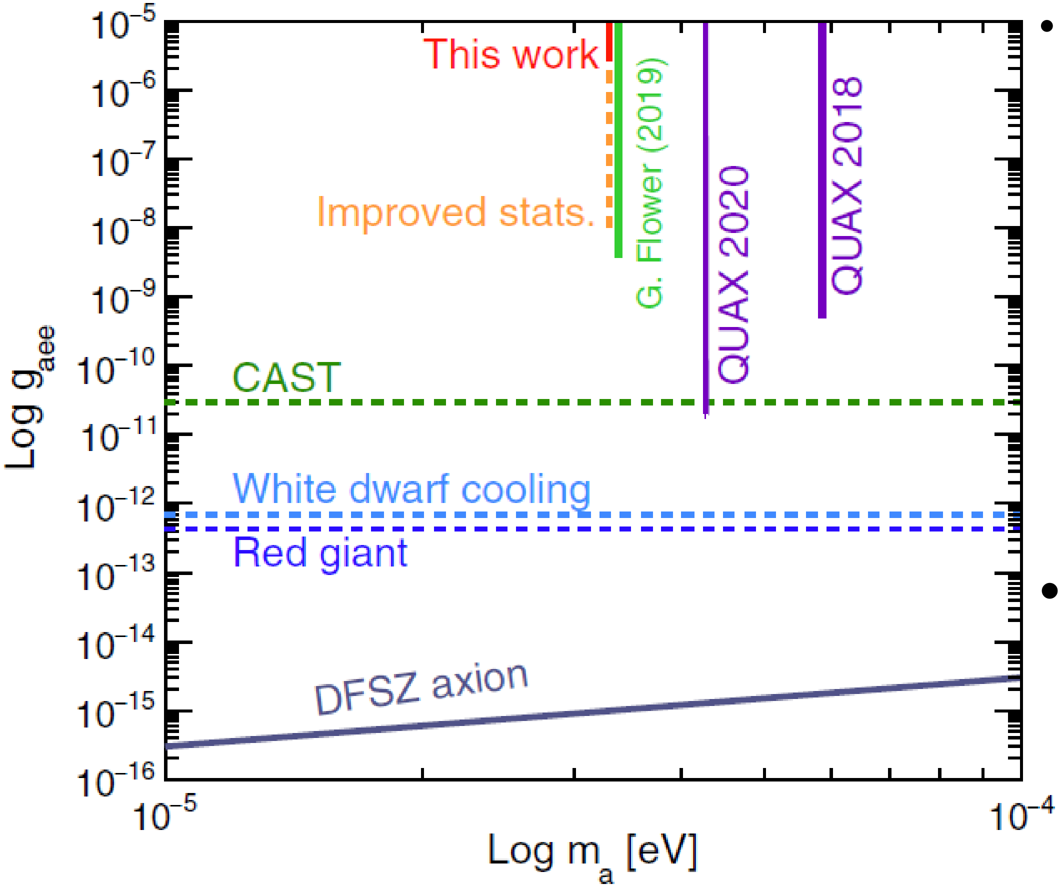


- 0.5mm diameter YIG
  spin density : $\sim 2.1 \times 10^{22}\ \mathrm{cm}^{-3}$
- 4 hours' data in August 2015
- scan 200 frequency-bins

➢ **No significant peak was found at f=1**

Reuslts

95%C.L. limits



- First limit for ma=33μeV axions

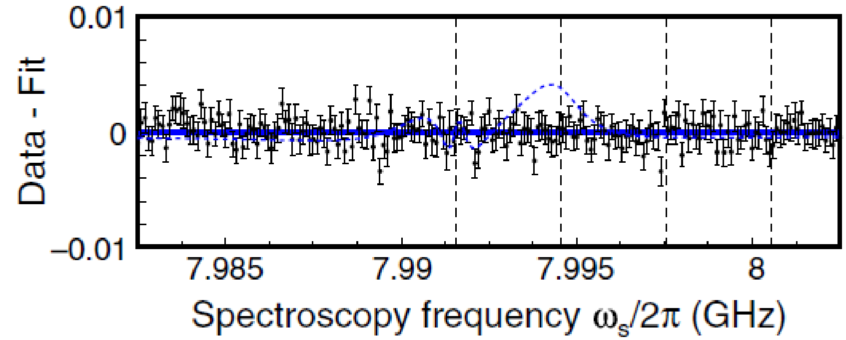
$$B_a < 4.1 \times 10^{-14}\ [\mathrm{T}].$$

$$g_{aee} < 1.3 \times 10^{-6}$$

QUAX, G.Flowers : YIG + cavity

- AXION search by QUBIT: principle is EXPERIMENTALLY shown!

For improvements
(see also Kusaka-san’ s talk)



- statistics increase: × 100
  - (200bins in 4hours → 100 bins in 1week)
  - → × 10 in sensitivity
- Magnon number increase
  - G. Flower et. al. uses Φ 2.1mm in contrast to Φ 0.5mm (this work)
  - Magnon number × 64 → × 8 sensitivity
- magnon-width improvements (Q-value of YIG (~1000)) :
  - would give a further × O(10) statistic improvements made by “pencil” search

$$\bar{n}^m_\pm = \frac{g_{eff}^2}{\gamma_m^2/4 + (\Delta_a \pm \chi)^2},$$

Conclusions

- DM axion search was performed by Magnon counting method
- Fisrt limit for ma=33μeV $g_{aee} < 1.3 \times 10^{-6}$ (95% C.L.)
- A lot of room for improvement