Probing axion dark matter with magnon

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Talk plan

1. Axion : axion DM, axion-electron interaction

2. Magnon as collective spin excitation of electrons

3. Experimental upper limit on the axion-electron coupling constant

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Axion

QCD axion : a Nambu-Goldstone boson of the broken Peccei-Quinn symmetry (for resolving the strong CP problem)

Invisible axion models

- The KSVZ model — J.E.Kim (1979), M.A.Shifman, A.Vainshtein, V.I.Zakharov (1980)
- The DFSZ model — M.Dine, W.Fischler, M.Srednicki (1981), A.Zhitnitsky (1980)

(QCD) axion is a strong candidate for dark matter.

How can we detect ?

Axion-electron interaction

An axion can interact with the electron: (KSVZ: loop level, DFSZ: tree level)

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

$$\left(\tilde{g}_{aee} (\partial_\mu a) \bar{\psi} \gamma^\mu \gamma_5 \psi(x) \,, \quad \tilde{g}_{aee} = \frac{g_{aee}}{2m_e} \right)$$

In the non-relativistic limit, $\left(\mu_B = \frac{|e|}{2m}\right.$: Bohr magneton , $\left. \hat{S}^i = \frac{\sigma^i}{2} \right.$: spin $\left. \right)$

$$\mathcal{H}_{\rm int} \simeq -\frac{g_{aee}\hbar}{2m_e} \hat{\boldsymbol{\sigma}} \cdot \boldsymbol{\nabla} a = -2\mu_B \hat{\boldsymbol{S}} \cdot \left(\frac{g_{aee}}{e} \boldsymbol{\nabla} a \right)$$

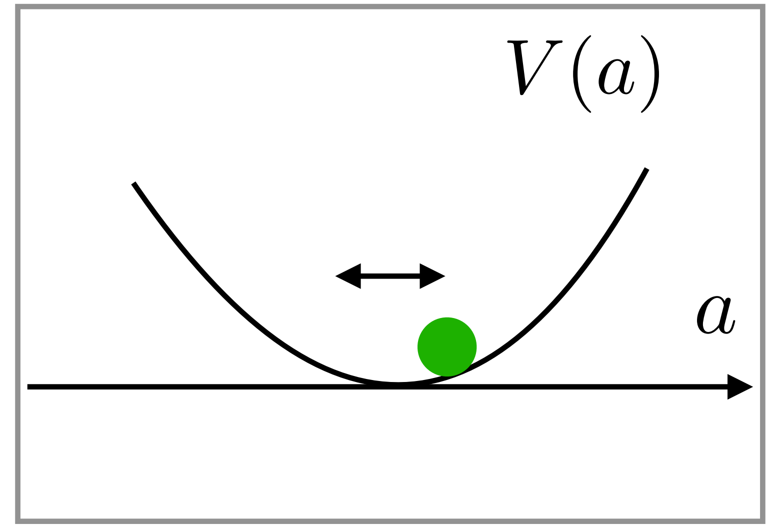
effective magnetic field

Reflecting the nature and distribution of the axion DM

Axion DM

Axions can behave as DM if it oscillates around the bottom of the potential :

(The equation of state parameter $w = 0$)



$$a(x) = a_0 \cos(\omega t - \boldsymbol{k}\boldsymbol{x})$$

a_0: corresponding to the abundance of the axion DM

ω: determined by the axion mass ($\omega = m_a$)

※ In the case of the QCD axion, the axion mass around μeV is favored for DM.

$$m_a \sim \mu\mathrm{eV}$$

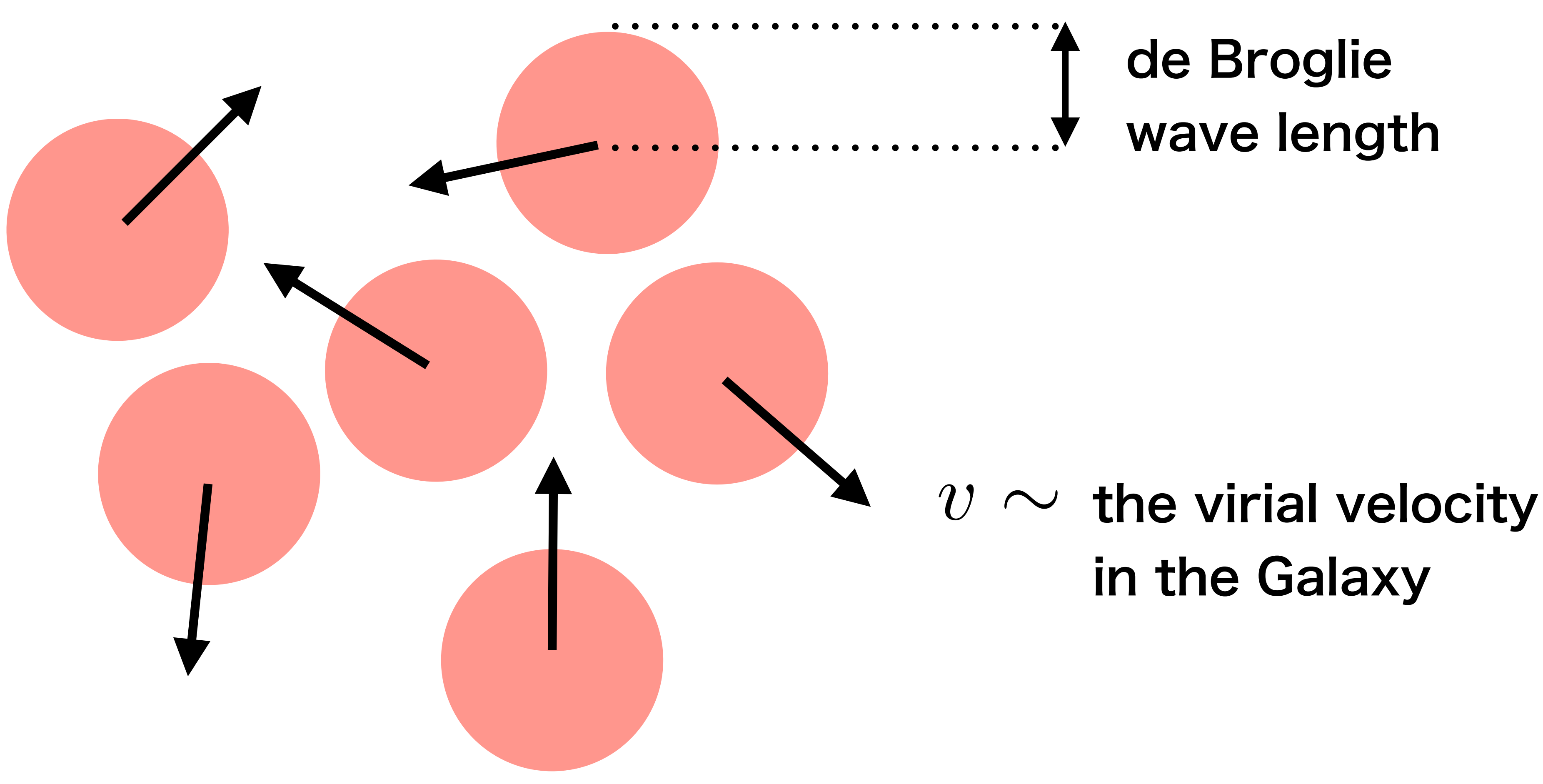
← scale of cavity experiments (cm, GHz)

Effective magnetic field

$$\boldsymbol{B}_a = \frac{g_{aee}}{e}\boldsymbol{\nabla} a$$

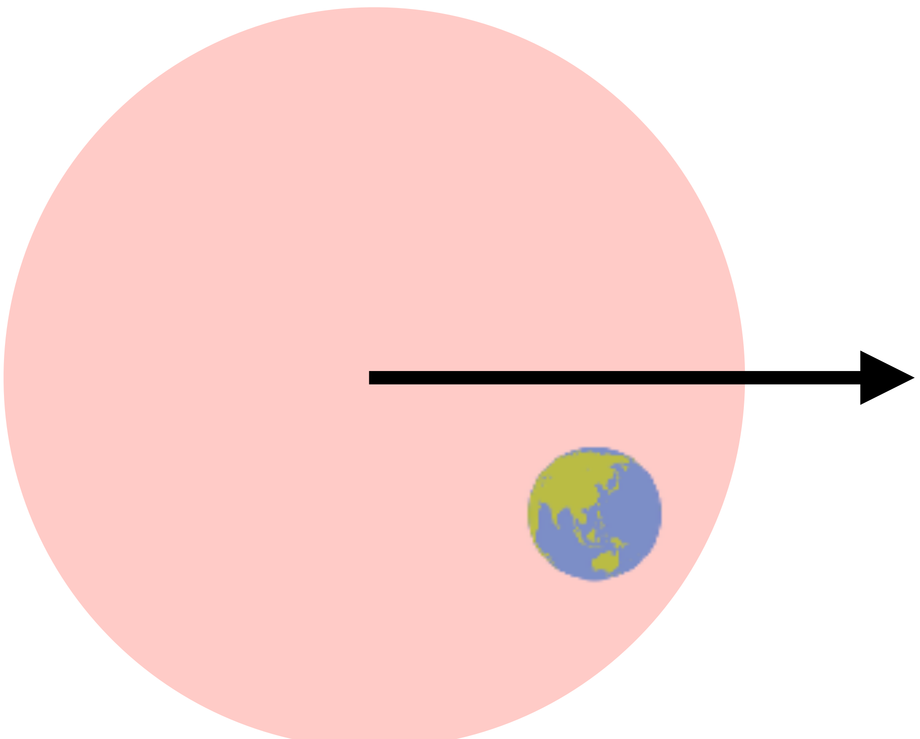
If gradient of the axion DM is non-zero, it acts as magnetic fields.

We assume that the axion DM forms clumps in the Galaxy
as a stable solution of the Shrodinger-Poisson equation.



Effective magnetic field

When a clump of axion DM is going through us, we feel "axion-wind"



Then $\nabla a \sim m_a v a$ and the coherence time is

$$t_{\rm ob} \sim \frac{r_{\rm ob}}{v}$$
$$= 2.3 \times 10^6 \times \left(\frac{1.0\mu eV}{m_a}\right)^{1/2} \left(\frac{0.45\ {\rm GeV/cm^3}}{\rho_{\rm ob}}\right)^{1/4} \left(\frac{300\ {\rm km/s}}{v}\right) [{\rm s}]$$

Effective magnetic field

We can estimate the amplitude of the effective magnetic field as

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

g_{aee} is tiny, how can we measure such small magnetic field?

- Axion-electron resonance caused by coherent oscillation of axion DM
- Use so many electrons (magnon)

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2. **Magnon as collective spin excitation of electrons**

3. Experimental upper limit on the axion-electron coupling constant

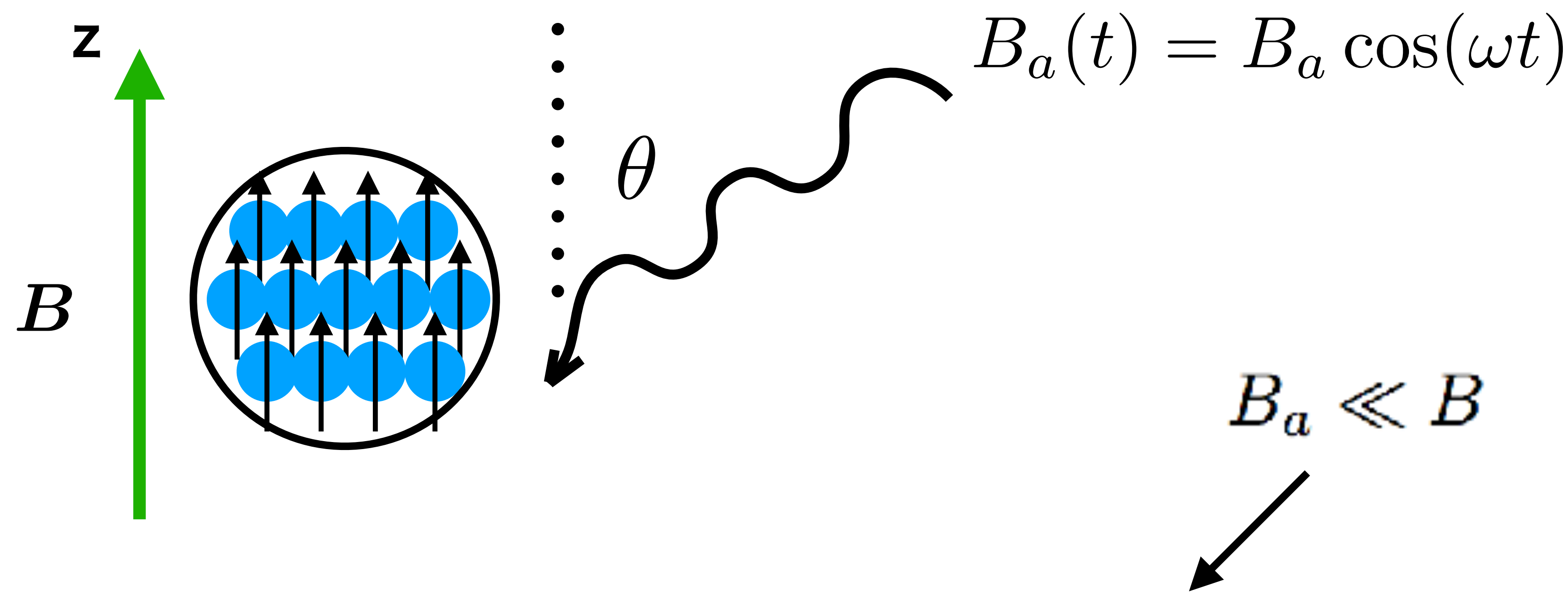
Magnon

We consider a ferromagnetic sample which has N electronic spins in an external magnetic field B.

It is well described by the Heisenberg model:

$$\mathcal{H} = -2\mu_B \sum_i \hat{\boldsymbol{S}}_i \cdot (\boldsymbol{B} + \boldsymbol{B}_a) - \sum_{i,j} J_{ij} \hat{\boldsymbol{S}}_i \cdot \hat{\boldsymbol{S}}_j$$

$i = 1 \ldots N$ specify the sites of electrons.



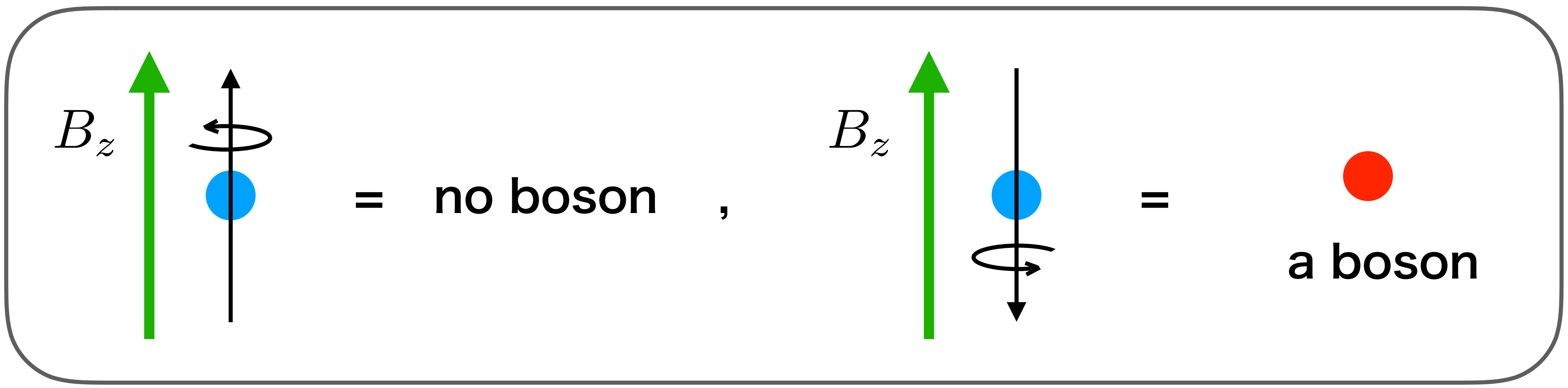
$\boldsymbol{B} = (0, 0, B_z)$, $\boldsymbol{B}_a = (B_a \sin\theta, 0, B_a \cos\theta) \simeq (B_a \sin\theta, 0, 0)$

Holstein-Primakoff transformation

Spin operators can be rewritten in terms of bosonic operators by using the Holstein-Primakoff transformation:

$$\begin{cases} \hat{S}^z_{(i)} = \frac{1}{2} - \hat{C}^\dagger_i \hat{C}_i \,, \\ \hat{S}^+_{(i)} = \sqrt{1 - \hat{C}^\dagger_i \hat{C}_i}\; \hat{C}_i \,, \\ \hat{S}^-_{(i)} = \hat{C}^\dagger_i \sqrt{1 - \hat{C}^\dagger_i \hat{C}_i} \,, \end{cases} \quad \text{where} \quad [\hat{C}_i, \hat{C}^\dagger_j] = \delta_{ij}$$

A spin flip corresponds to creation of a boson.



Furthermore, we can move on to Fourier space :

$$\hat{C}_i = \sum_{\boldsymbol{k}} \frac{e^{-i\boldsymbol{k}\cdot\boldsymbol{r}_i}}{\sqrt{N}} \hat{c}_k$$

A bosonic operator of "spin wave"
=
Magnon

Magnon

$$\mathcal{H} = -2\mu_B \sum_i \hat{\boldsymbol{S}}_i \cdot (\boldsymbol{B} + \boldsymbol{B}_a) - \sum_{i,j} J_{ij} \hat{\boldsymbol{S}}_i \cdot \hat{\boldsymbol{S}}_j$$

Holstein-Primakoff transformation

$$\mathcal{H} \simeq 2\mu_B B_z \hat{c}^\dagger_{k=0} \hat{c}_{k=0} + 2\mu_B \frac{B_a \sin\theta}{4} \sqrt{N} \left(\hat{c}^\dagger_{k=0} e^{-i\omega_a t} + \hat{c}_{k=0} e^{i\omega_a t} \right) + \sum_{i=1..N} \mathcal{H}(\hat{c}_{k=i})$$

The coupling constant is effectively increased by $\sqrt{N}$.
Typically, $\sqrt{N} \sim \sqrt{10^{20}} \sim 10^{10}$.

The axion DM excites the uniform mode of the magnon!

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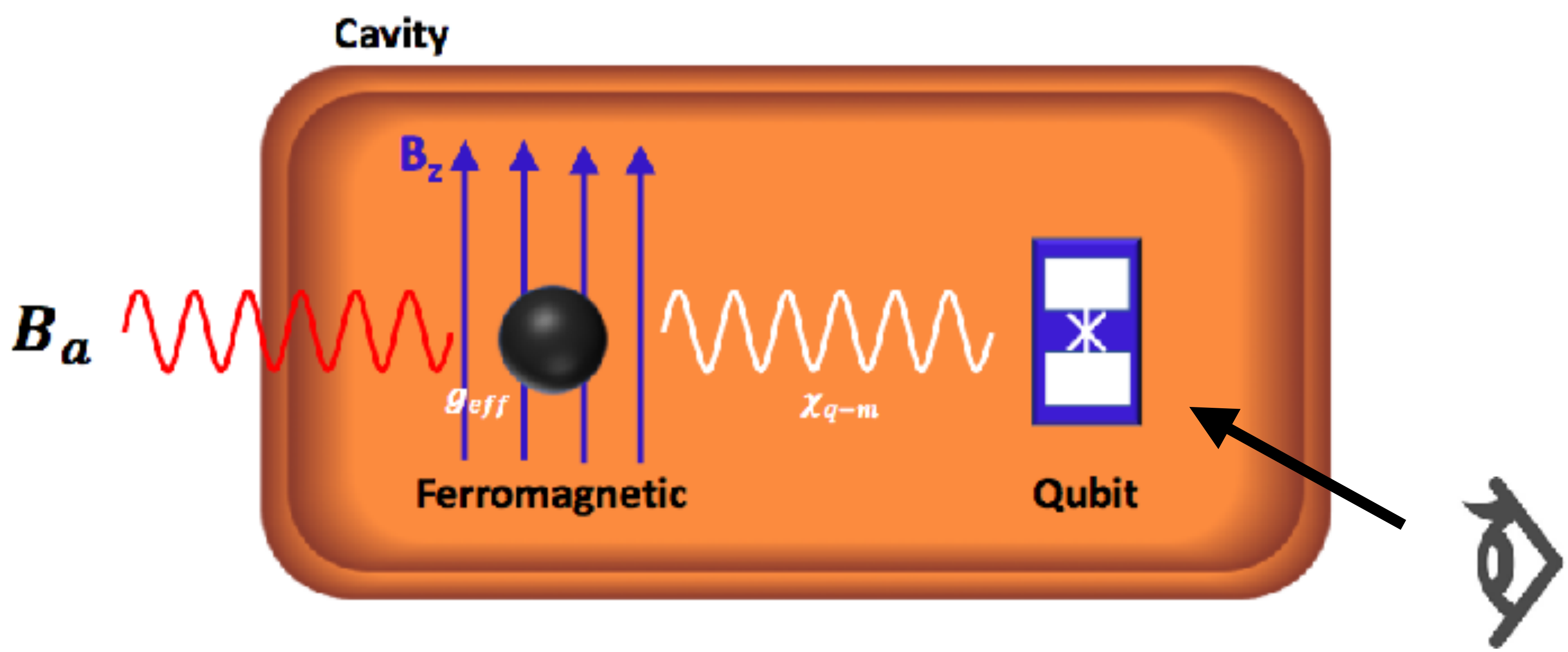
Experiment

We measured the quantum state of a magnon with qubit

(qubit: A two-state system)



We can see the quantum state of the magnon by observing qubit spectrum!

Qubit spectrum

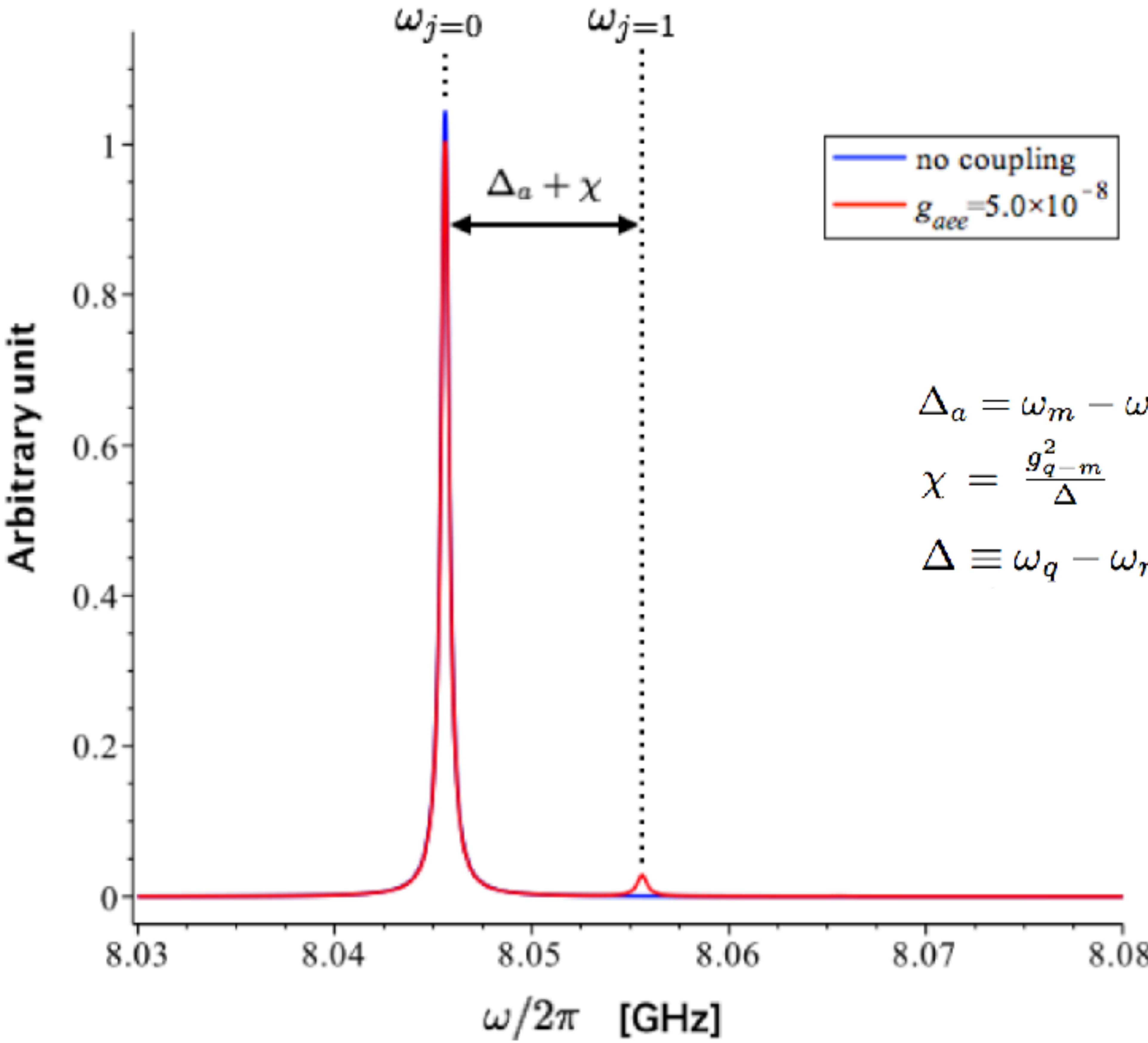
$$\mathcal{H}_{\rm tot} = \hbar\omega_m \hat{c}^\dagger \hat{c} + \frac{\hbar\omega_q}{2}\hat{\sigma}_z + \hbar g_{q-m}(\hat{c}^\dagger\hat{\sigma}_- + \hat{\sigma}_+\hat{c})$$
$$+g_{eff}\left(\hat{c}^\dagger e^{-i\omega_a t} + \hat{c}e^{i\omega_a t}\right)$$
$$+\mathcal{H}_{\rm noise}$$

- ω_m : magnon frequency
- ω_q : qubit frequency
- g_{q-m} : magnon-qubit coupling constant
- g_{eff} : magnon-axion coupling constant

This system is approximately solvable and we can obtain the qubit spectrum:

$$S(\omega) = \mathrm{Re}\left[\frac{1}{\sqrt{2\pi}}\int_0^\infty \mathrm{dt} < \hat{\sigma}_-(\mathrm{t})\hat{\sigma}_+(0) > \mathrm{e}^{\mathrm{i}\omega \mathrm{t}}\right]$$

Magnon state and qubit spectrum



$$\Delta_a = \omega_m - \omega_a$$

$$\chi = \frac{g_{q-m}^2}{\Delta}$$

$$\Delta \equiv \omega_q - \omega_m$$

Upper limit

We observed the qubit spectrum and found no evidence of the axion DM.

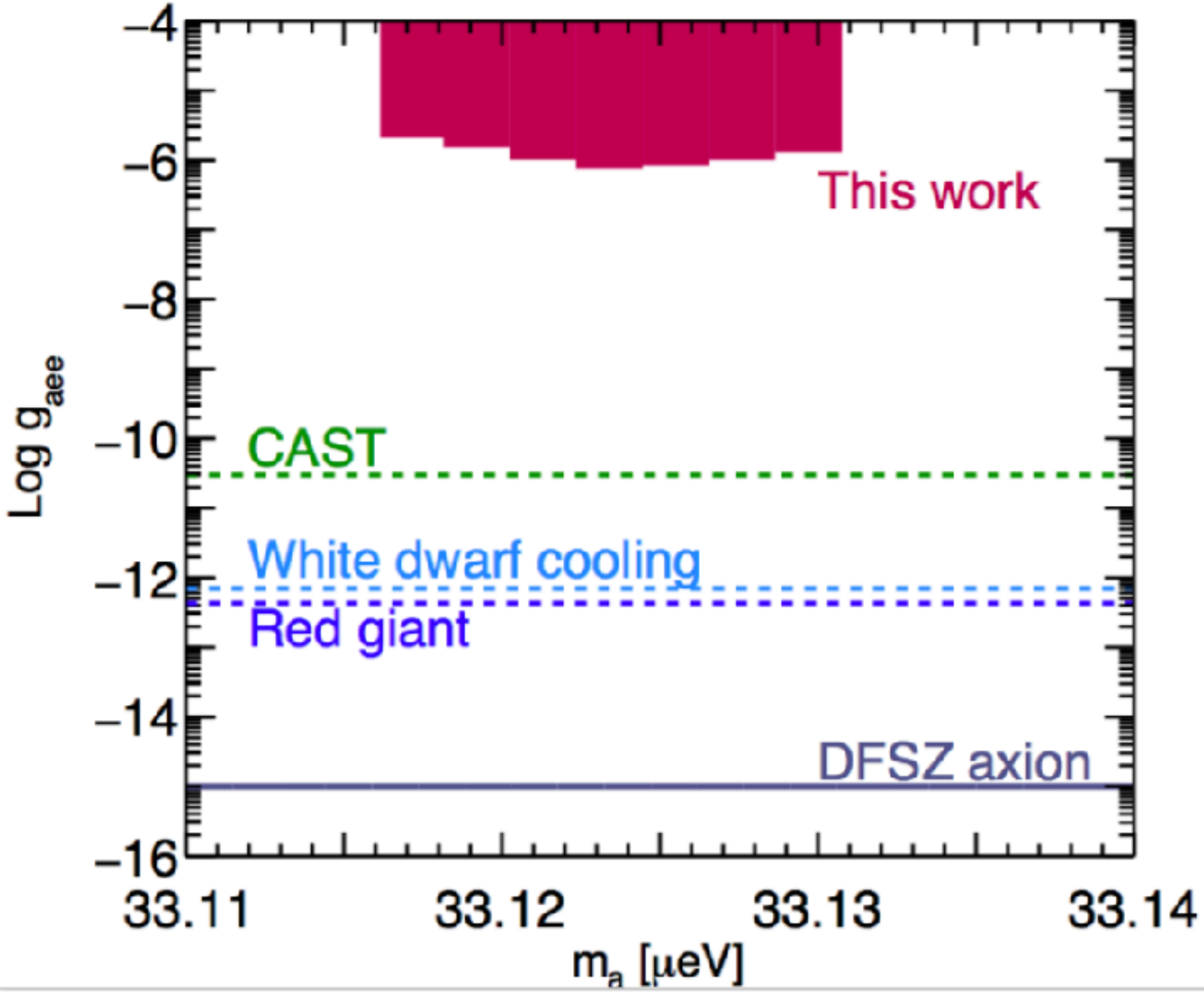
$$B_a < 4.1 \times 10^{-14} \text{ [T]}$$

or

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

at $m_a = 33$ μeV

Upper limit



This work
CAST
White dwarf cooling
Red giant
DFSZ axion
−4
−6
−8
−10
−12
−14
−16
Log g_aee
33.11
33.12
33.13
33.14
m_a [μeV]

Summary

- Axion is a strong candidate for DM
- Axion DM can induce resonant spin precession of electrons
- Axion-magnon coupling get effective factor $\sqrt{N} \sim \sqrt{10^{20}} \sim 10^{10}$
- We measured the quantum state of a magnon and gave an upper limit $g_{aee} < 1.3 \times 10^{-6}$ at $m_a = 33$ μeV