Searching for axion dark matter with magnons

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Refs: • T.Ikeda, AI, K.Miuchi, J.Soda, H.Kurashige, Y.Shikano (2021)

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Talk plan

1. QCD axion dark matter and axion-electron coupling

2. Magnon as collective (electronic) spin excitation

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

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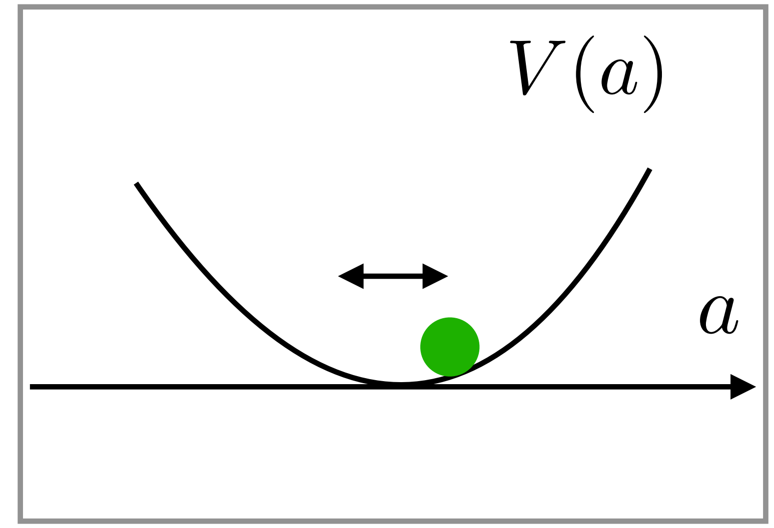
Axion DM

Axions can behave as a cold DM in the history of the universe if it oscillates around the bottom of the potential:

(The equation of state parameter $w = \frac{p}{\rho} = 0$)



$$a(x) = a_0 \cos(\omega t)$$

corresponding to the abundance of the axion DM (a_0)

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

(※ In the case of the QCD axion, the axion mass around $10\mu\mathrm{eV}$ is favored for DM.

$\because$ $\Omega_{\mathrm{DM}} \sim 0.3 \longrightarrow F_a \longrightarrow m_a$

$10\mu\mathrm{eV} \sim \mathrm{cm} \sim \mathrm{GHz}$ ← scale of tabletop size experiments)

Axion interactions

QCD axion couples to the SM particles like photons and electrons:

$$\mathcal{L}_{\text{photon}} = -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

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

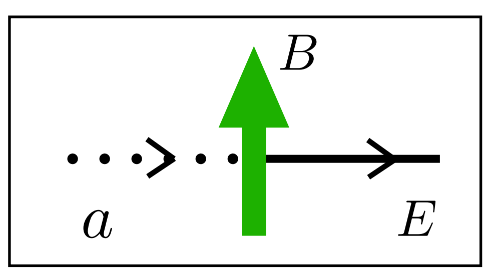
Theory

	Photon	Electron
KSVZ:	tree level	loop level
DFSZ:	tree level	tree level

important to distinguish the axion models

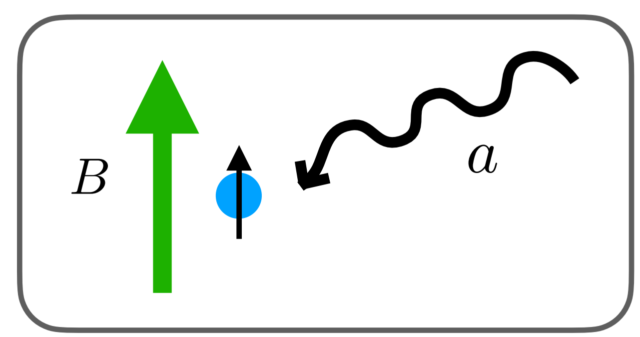
Experiments

axion to photon conversion



ex.) ADMX, ALPS, etc.

spin excitation by axion DM
(axion to magnon conversion)



Recently, several groups started experiments

ex.) QUAX, G. Flower, et al., T. Ikeda, et al.

Axion-electron interaction

An axion can interact with the electron as

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

(KSVZ: loop level
DFSZ: tree level)

In the non-relativistic limit for an electron, we have a Hamiltonian for the Schrodinger equation

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

effective magnetic field

Reflecting the nature and distribution of the axion DM

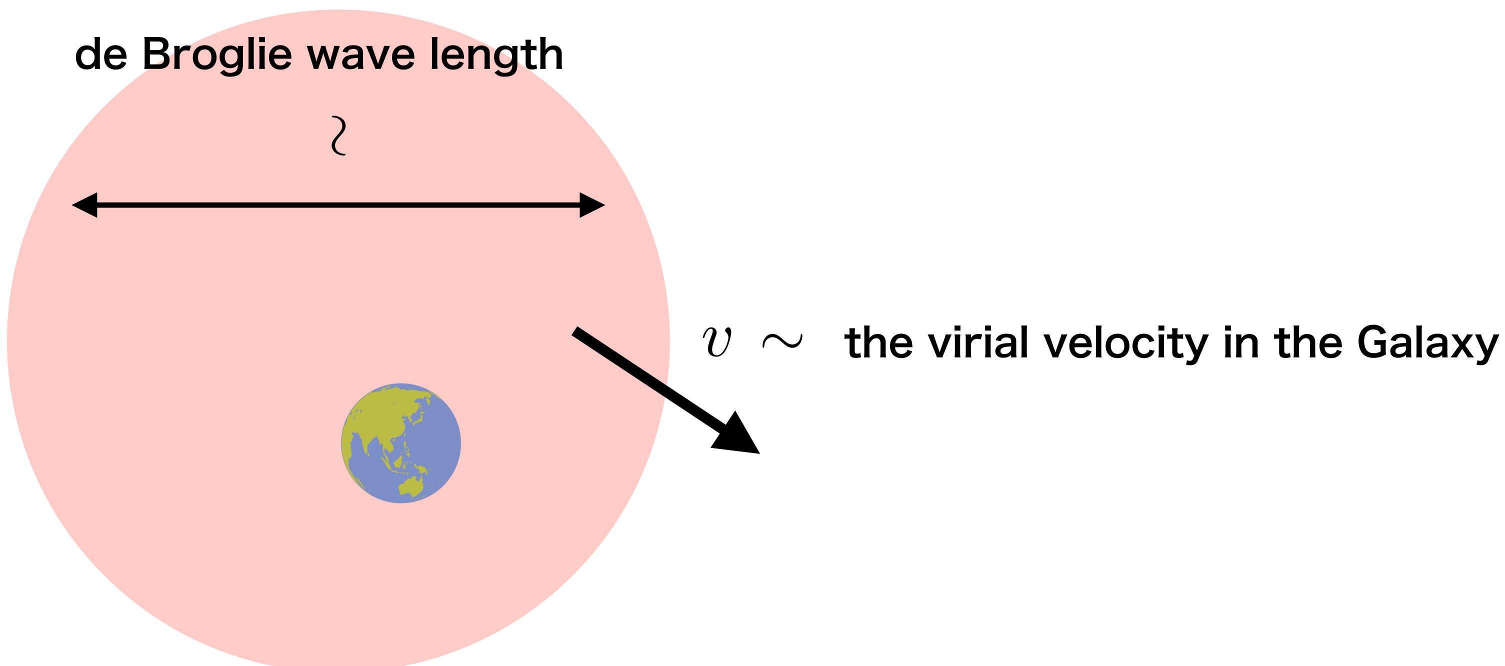
$\mu_B = \frac{|e|}{2m_e}$: Bohr magneton

$\hat{S}^i = \frac{\sigma^i}{2}$: spin of the electron

Effective magnetic field

The axion DM behaves as wave, which is coherently oscillating within the de Broglie wave length.

When the axion DM has a relative velocity to us,



then the gradient of the axion DM is $\nabla a \sim m_a v a$, therefore $$B_a = \frac{g_{aee}}{e} \nabla a \sim \frac{g_{aee}}{e} m_a v a$$

How large is the amplitude of the effective magnetic field?

Effective magnetic field

We can estimate the amplitude of the effective magnetic field as

$$B_a \simeq 4.4\times10^{-8}\times g_{aee}\left(\frac{\rho_{\rm ob}}{0.45\ {\rm GeV/cm^3}}\right)^{1/2}\left(\frac{v}{300\ {\rm km/s}}\right)[{\rm T}]$$

g_{aee} is tiny, then how can we detect such a small magnetic field?

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

R Barbieri, et al. (1985)

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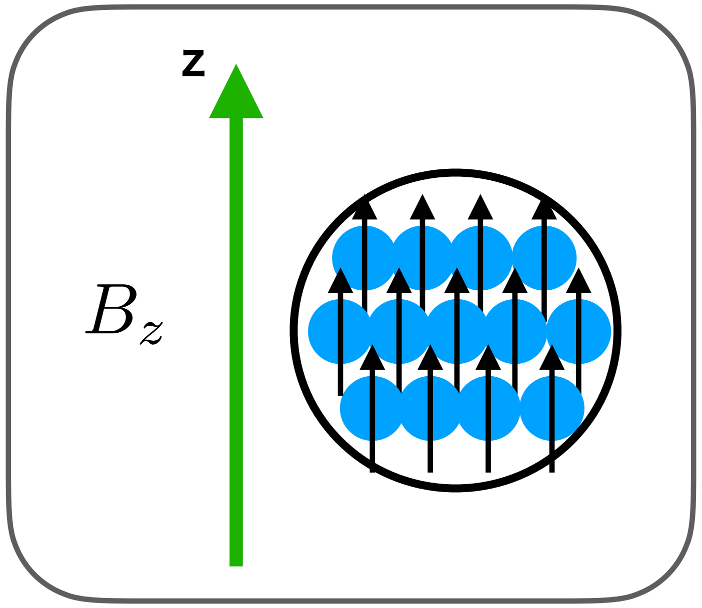
Collective spin system

We consider N electronic spins (e.g. a ferromagnetic crystal) in an external magnetic field B_z .



It is well described by the Heisenberg model:

$$\mathcal{H}_{mag} = -2\mu_B B_z \sum_i \hat{S}^z_{(i)} - \sum_{i,j} J_{ij} \hat{\boldsymbol{S}}_{(i)} \cdot \hat{\boldsymbol{S}}_{(j)}$$

$i = 1 \dots N$ specify the sites of spins.

J_{ij} : coupling constants between spins.

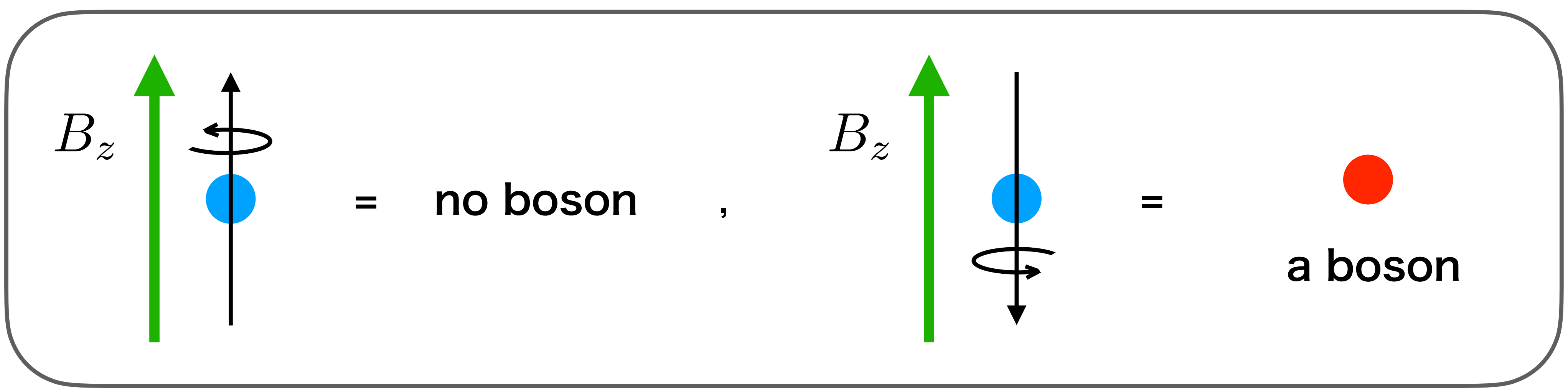
Holstein-Primakoff transformation

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

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

Actually the SU(2) algebra is satisfied, $[\hat{S}^a_{(i)}\,, \hat{S}^b_{(i)}] = i\epsilon_{abc}\hat{S}^c_{(i)}$.

In the case of an electron,



Next, let us study the case of N electrons system.

Collective spin system

$$\mathcal{H}_{mag} = -2\mu_B B_z \sum_i \hat{S}^z_{(i)} - \sum_{i,j} J_{ij} \hat{\boldsymbol{S}}_{(i)} \cdot \hat{\boldsymbol{S}}_{(j)}$$

Holstein-Primakoff transformation with $\hat{c}^\dagger_{\boldsymbol{k}} \hat{c}_{\boldsymbol{k}} \ll 1$

$$\mathcal{H}_{mag} = \sum_{\boldsymbol{k}} \hbar\omega_k \hat{c}^\dagger_{\boldsymbol{k}} \hat{c}_{\boldsymbol{k}}$$

quantized "spin wave"

=

magnon

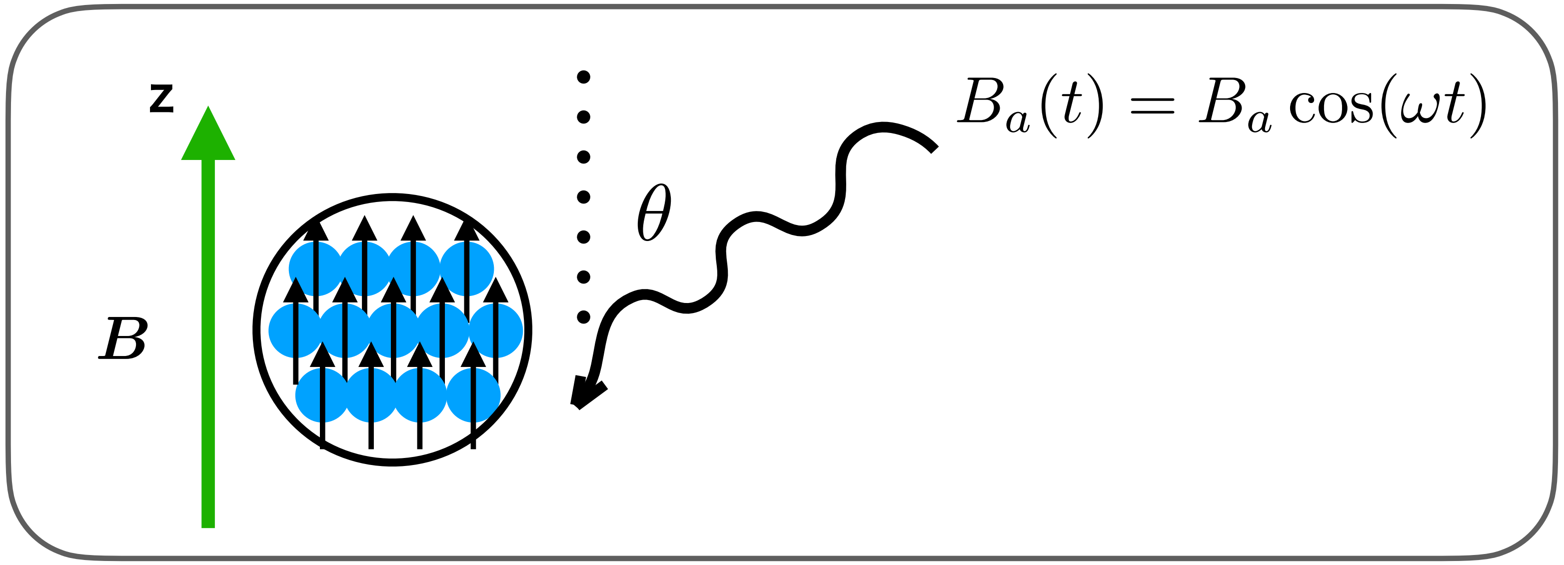
where the dispersion relation is given by

$$\hbar\omega_k = 2\mu_B B_z + \sqrt{N}\left(\tilde{J}(0) - \tilde{J}(\boldsymbol{k})\right)$$

(where $J(\boldsymbol{r}_j) = \sum_{\boldsymbol{k}} \frac{e^{-i\boldsymbol{k}\cdot\boldsymbol{r}_j}}{\sqrt{N}} \tilde{J}(\boldsymbol{k})$)

Axion-magnon resonance

We consider the effect of the axion DM on the N spin system



Then, the hamiltonian is given by

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

effective magnetic field from the axion DM

Magnon excitation

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

Holstein-Primakoff transformation

&

$$\boldsymbol{B}_a(t, \boldsymbol{x}) \simeq \boldsymbol{B}_a(t) = \frac{\boldsymbol{B}_a}{2}\left(e^{-iw_a t} + e^{iw_a t}\right)$$

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

- The coupling constant is effectively increased by $\sqrt{N} \sim \sqrt{10^{20}} \sim 10^{10}$.
- The axion DM can cause the resonance of the uniform mode $(k=0)$ of the magnon if $\omega_m = \omega_a$ $(\omega_m = 2\mu_B B_z)$.

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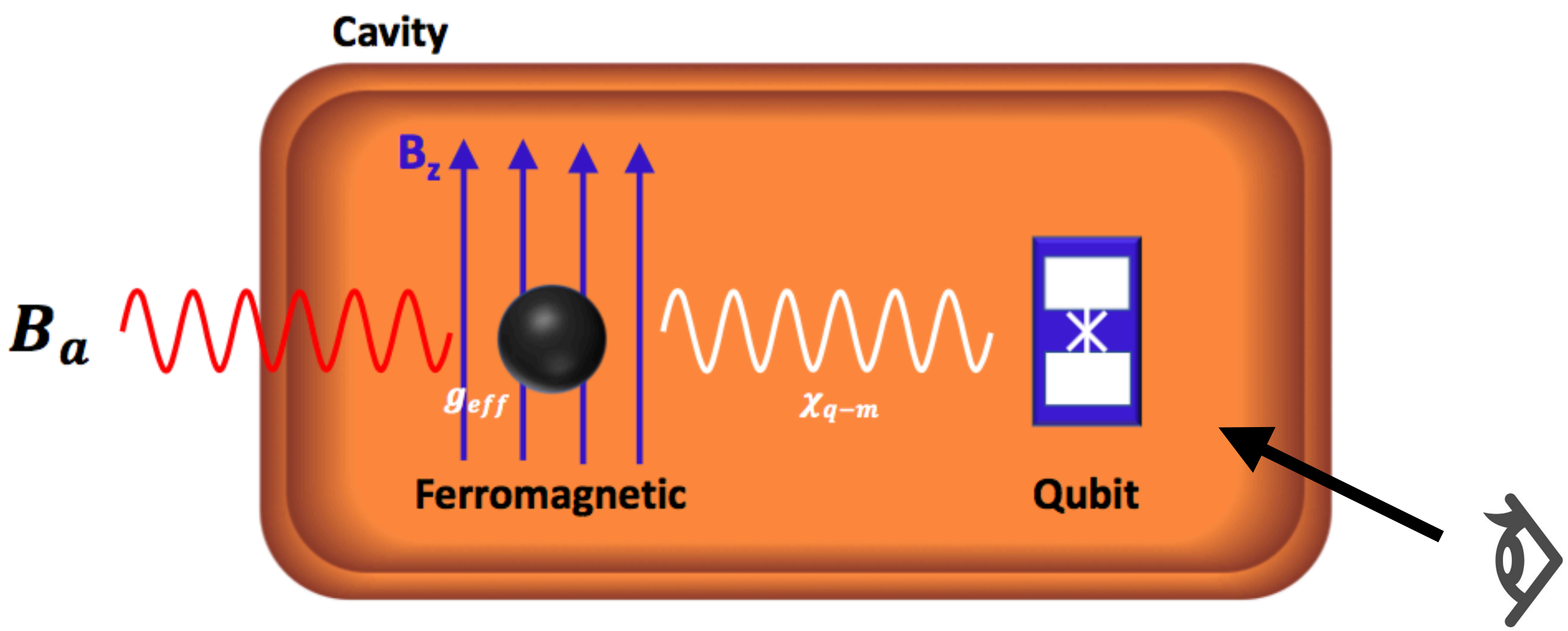
Experiment

We measured the quantum state of a magnon with qubit

(qubit: A two-state system)

(Tomonori. Ikeda, AI, Kentaro Miuchi, Jiro Soda,
Hisaya Kurashige, Yutaka Shikano, arXiv: 2102.08764 [hep-ex])



We can operate quantum nondemolition detection of the magnon by observing the qubit!

Upper limit

We reanalyzed data of a magnon experiment for other purpose (D. L-Quirion, et al, (2017)
and found no evidence of the axion DM

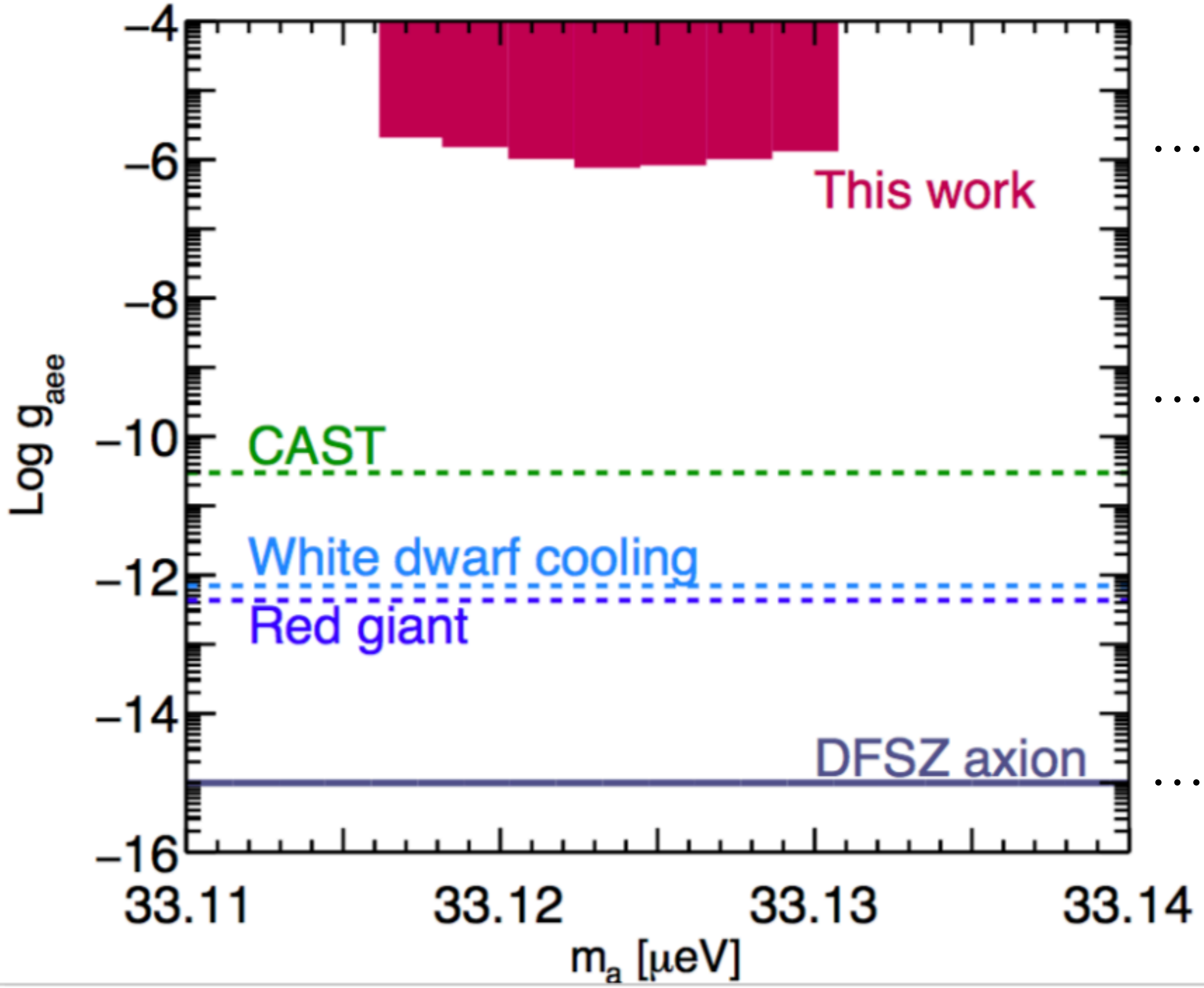
↓

Tomonori. Ikeda, AI, Kentaro Miuchi, Jiro Soda,
Hisaya Kurashige, Yutaka Shikano (2020)

$$B_a < 4.1 \times 10^{-14} \ [\mathrm{T}]$$ or $$g_{aee} < 1.3 \times 10^{-6}$$

at $m_a = 33$ μeV

Upper limit



statistically improvable by taking more data

- increase N
- decreasing noises

etc...

Summary

- QCD axion is a strong candidate for DM

- Interaction between an axion and a magnon, which is collective spin excitation of electrons, was studied

  - Axion-magnon coupling gets effective factor $\sqrt{N}$
  - Axion DM can excite magnons resonantly

- We reanalyzed data of a magnon experiment for other purpose and gave an upper limit $g_{aee} < 1.3 \times 10^{-6}$ at $m_a = 33$ μeV

- Further efforts are desired to reach the theoretical prediction of g_{aee}

  - increasing N
  - decreasing noises of experiments etc...