Axion dark matter search with magnons

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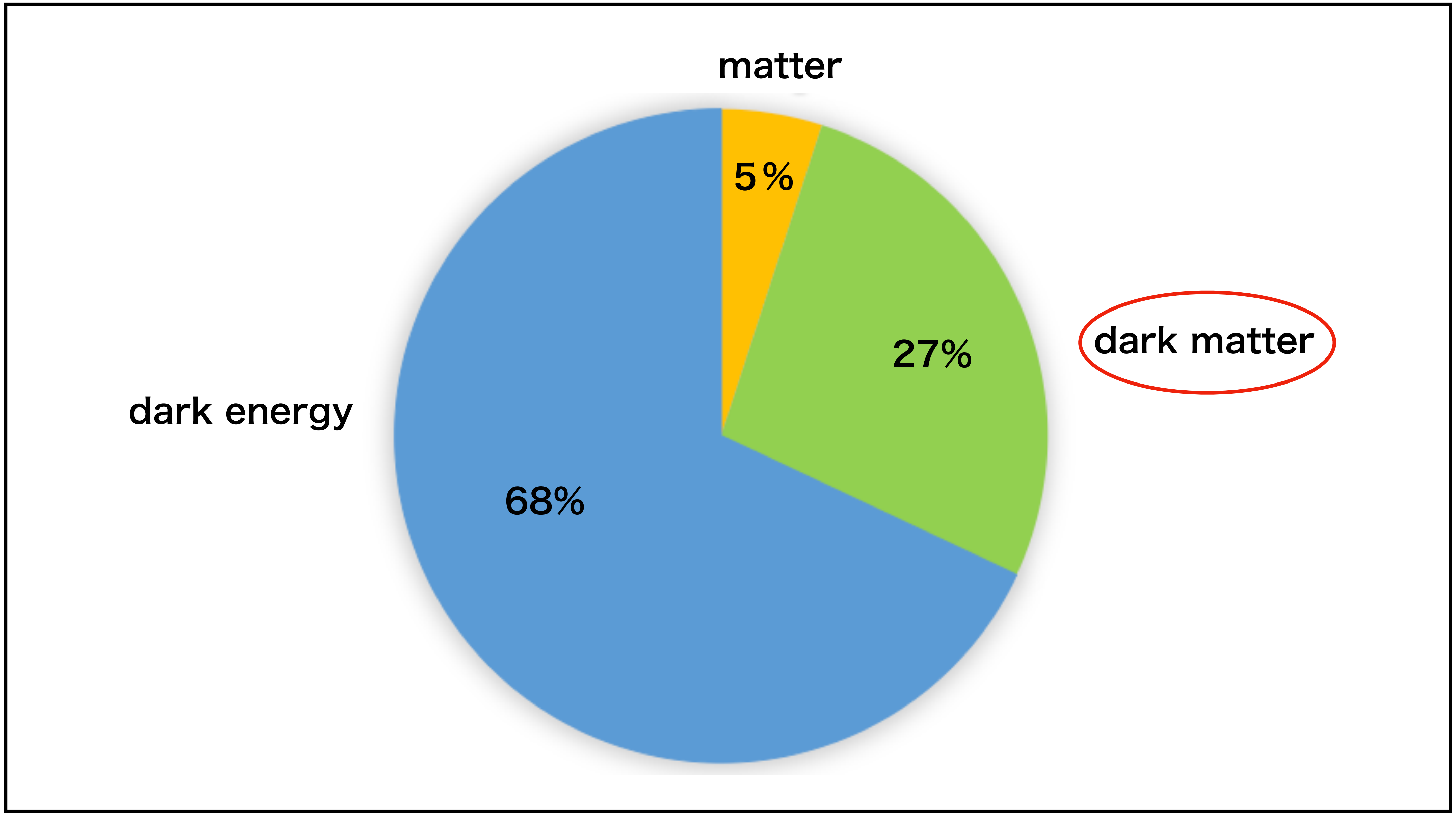
Introduction



what is the dark matter?

- WIMP
- (QCD) axion ← How do we detect it?
- Primordial black holes

Talk plan

1. QCD axion as a dark matter candidate

2. Magnon as collective electron spin excitation

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

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QCD Axion

Peccei-Quinn mechanism (Peccei, Quinn (1977))

In order to resolve the strong CP problem, we consider a Peccei-Quinn field which breaks an $U(1)_{\rm PQ}$ symmetry at an energy scale $\sim F_a$

→ The Nambu-Goldstone boson, the QCD axion, dynamically make a CP violated term vanish in the QCD sector

Two invisible axion models (consistent with experiments)

- 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))

Axion mass and coupling constants in the models are (M. Sivertz, et al. (1982))

$$m_a \sim 6 \times 10^{-6}\mathrm{eV} \left(\frac{10^{12}\mathrm{GeV}}{F_a}\right), \quad g_i \propto \frac{1}{F_a}$$

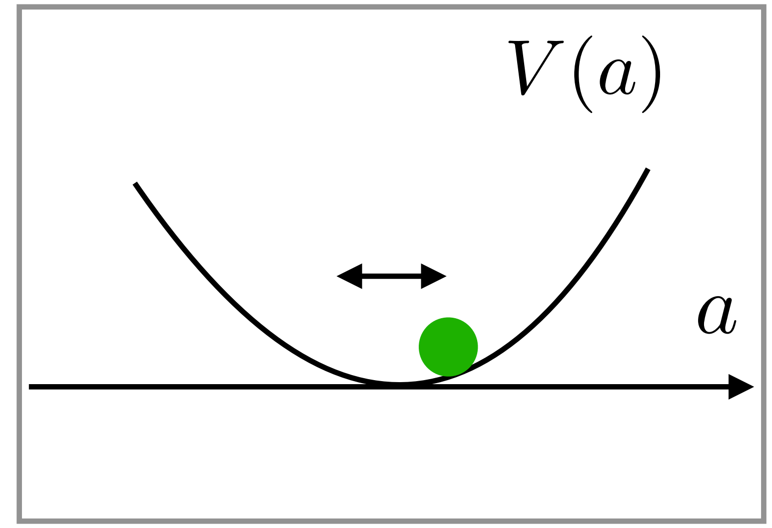
With a sufficiently large F_a , the QCD axion models are consistent with experiments.

Also, the QCD axion can be a dark matter!

Axion DM

Axions can behave as a cold DM in the evolution 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

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.

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

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

Axion interactions

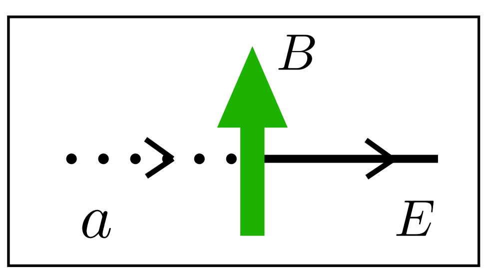
QCD axion couples to the SM particles like photons and electrons:

	Photon	Electron
Lagrangian	$\mathcal{L}_{\rm photon} = g_{a\gamma\gamma} a(x) F_{\mu\nu} \tilde{F}^{\mu\nu}$	$\mathcal{L}_{\rm electron} = -i g_{aee} a(x) \bar{\psi}(x) \gamma_5 \psi(x)$
Theory KSVZ:	tree level	loop level
DFSZ:	tree level	tree level

important to distinguish models

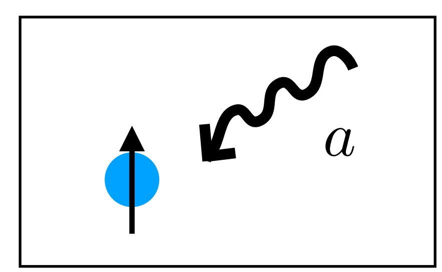
Experiments

axion to photon conversion



ex.) ADMX, CAST, ALPS, **TASEH**

excitation of electrons (magnons) by axion



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 non-relativistic Hamiltonian:

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

effective magnetic field

Reflecting the nature and distribution of the axion DM

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

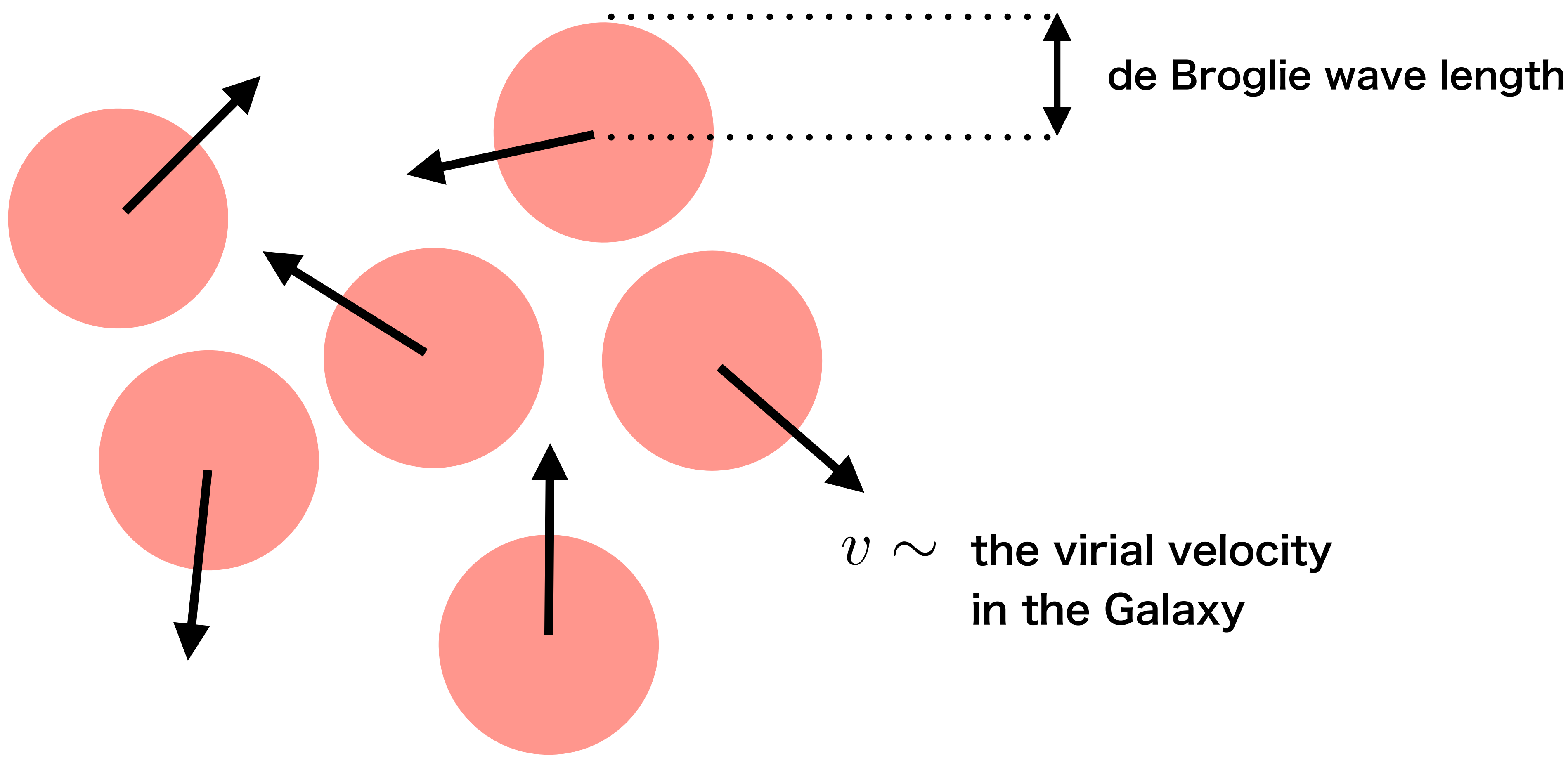
$\hat{S}^i = \frac{\sigma^i}{2}$: spin of the electron

Axion DM in the Galaxy

It is often assumed that the axion DM forms clumps in the Galaxy
as a stable solution of the Schrodinger-Poisson equation.

(L. Hui, et al. (2017) and references therein)

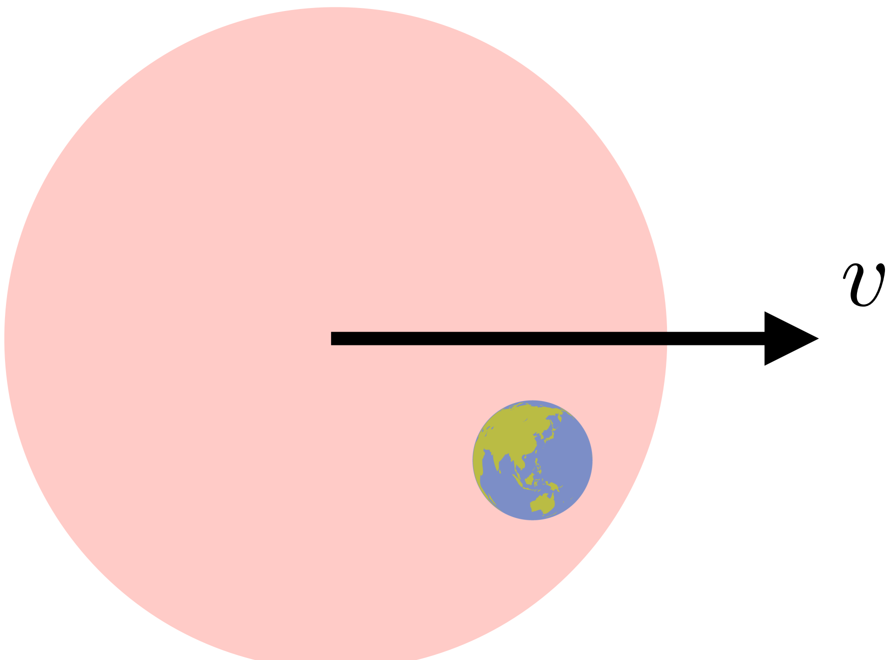
coherently oscillating & almost homogeneous



Effective magnetic field

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

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



Then the gradient of the axion DM is $\nabla a \sim m_a v a$

- What is the typical size of a clump?
- How large is the amplitude of the effective magnetic field?

Coherence length & time

size of a clump ← roughly given by the de Broglie wave length

$$r_{\rm ob} \sim 6.8 \times 10^{11} \left(\frac{1.0\mu{\rm eV}}{m_a}\right)^{1/2} \left(\frac{0.45\ {\rm GeV/cm^3}}{\rho_{\rm ob}}\right)^{1/4} [{\rm m}]$$

coherence time

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

→ Notably, the coherence time is long enough for axion to magnon conversion experiments

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 detect such a small magnetic field?

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

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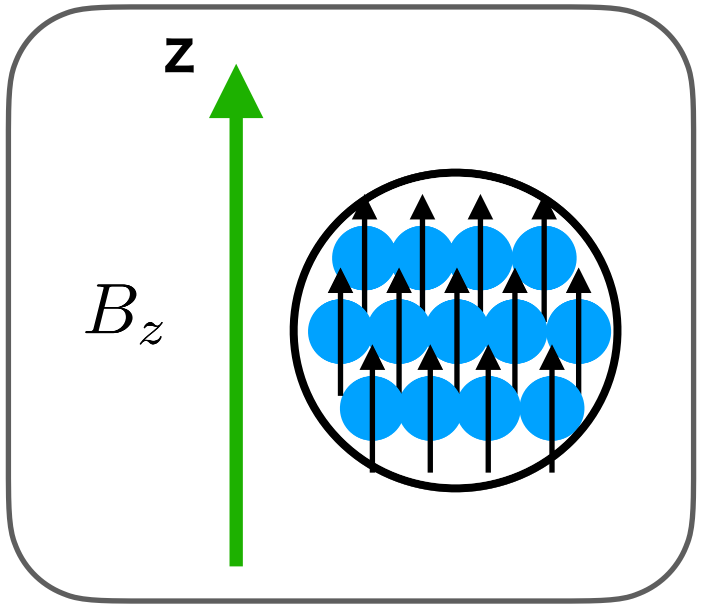
Collective spin system

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



It is well described by the Heisenberg model:

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

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

J_{ij} : coupling constants between spins

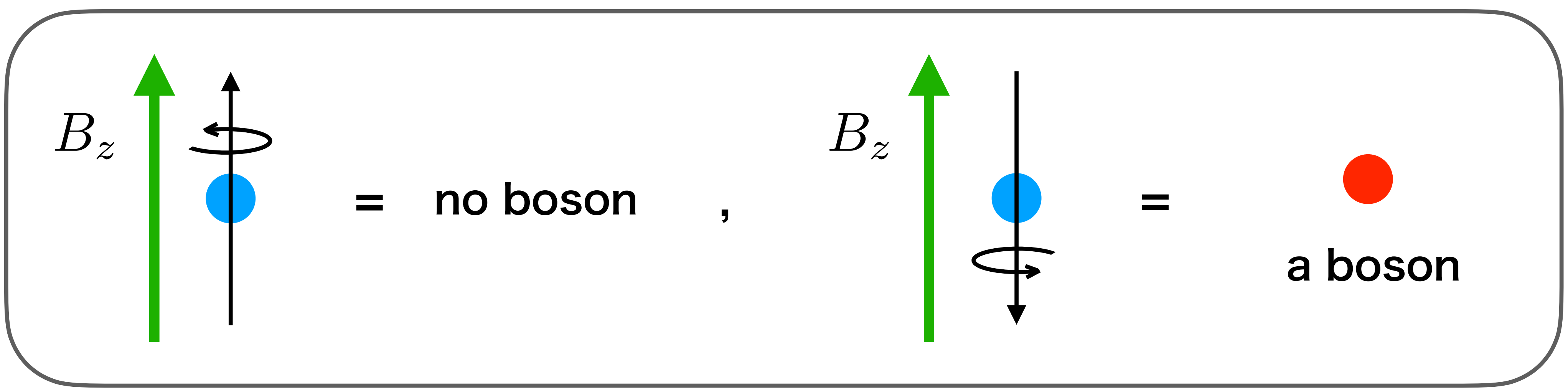
Holstein-Primakoff transformation

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

Therefore

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

quantized "spin wave"

II

magnon

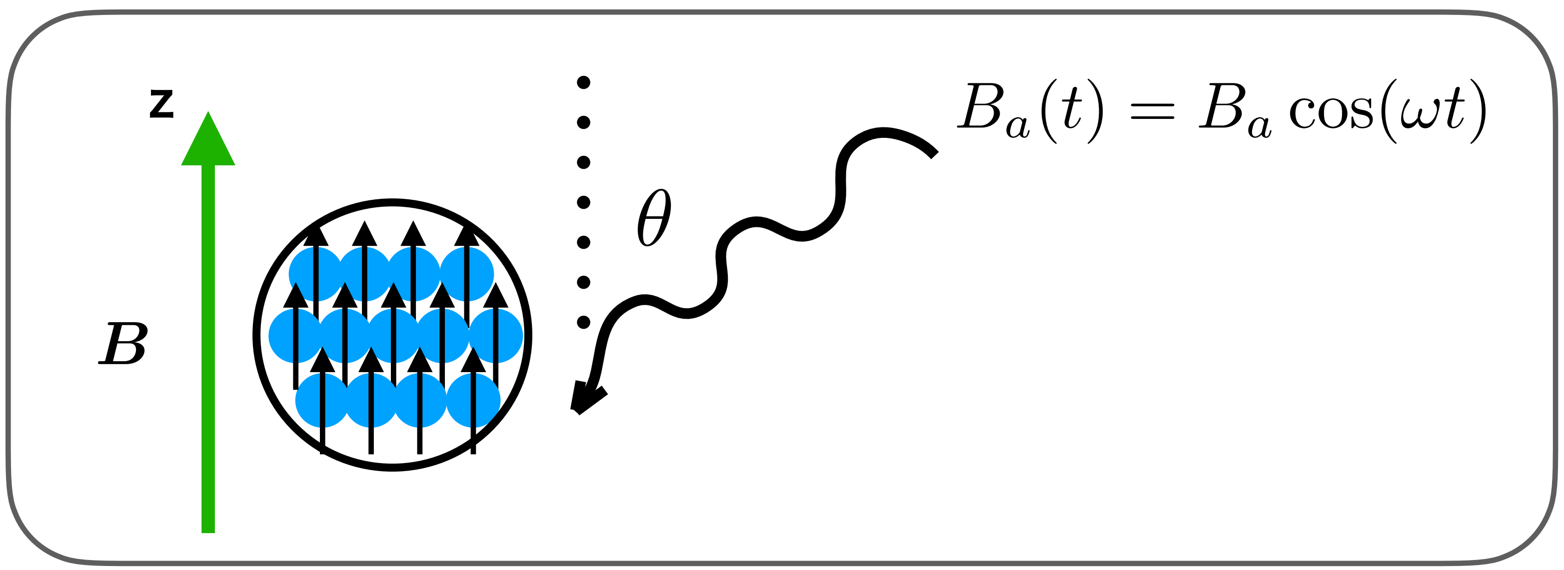
where the dispersion relation is given by

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

(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

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

effective magnetic field from the axion DM

Magnon

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

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 $\omega_m = \omega_a \quad (\omega_m = 2\mu_B B_z)$.

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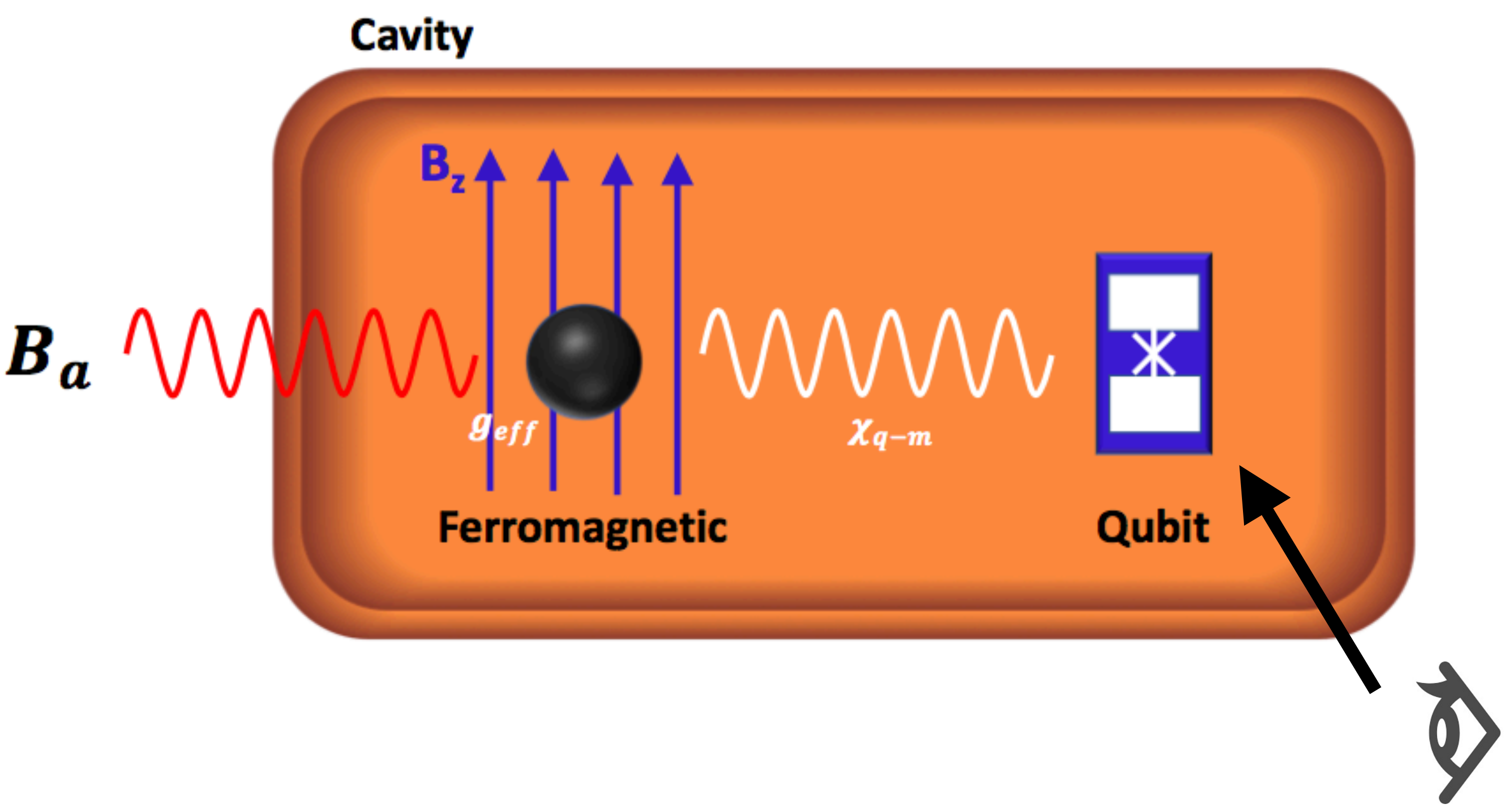
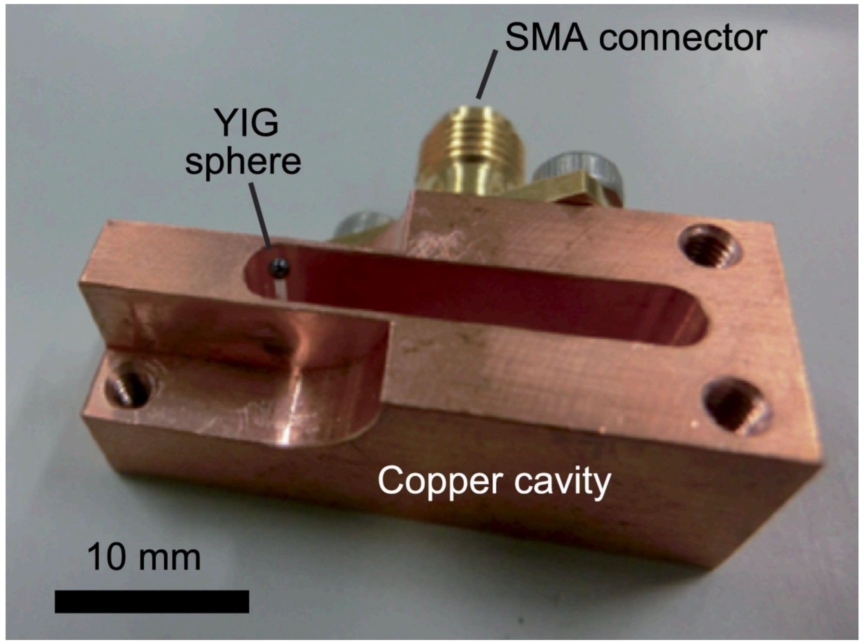
Experiment

We utilized an experiment for measuring the quantum state of a magnon with qubit

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





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

Qubit spectrum

The Hamiltonian of the system is given by

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

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

The system is approximately solvable for a density matrix of the system and we can calculate the qubit spectrum, which is the observable and depending on the magnon number.

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

Upper limit

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

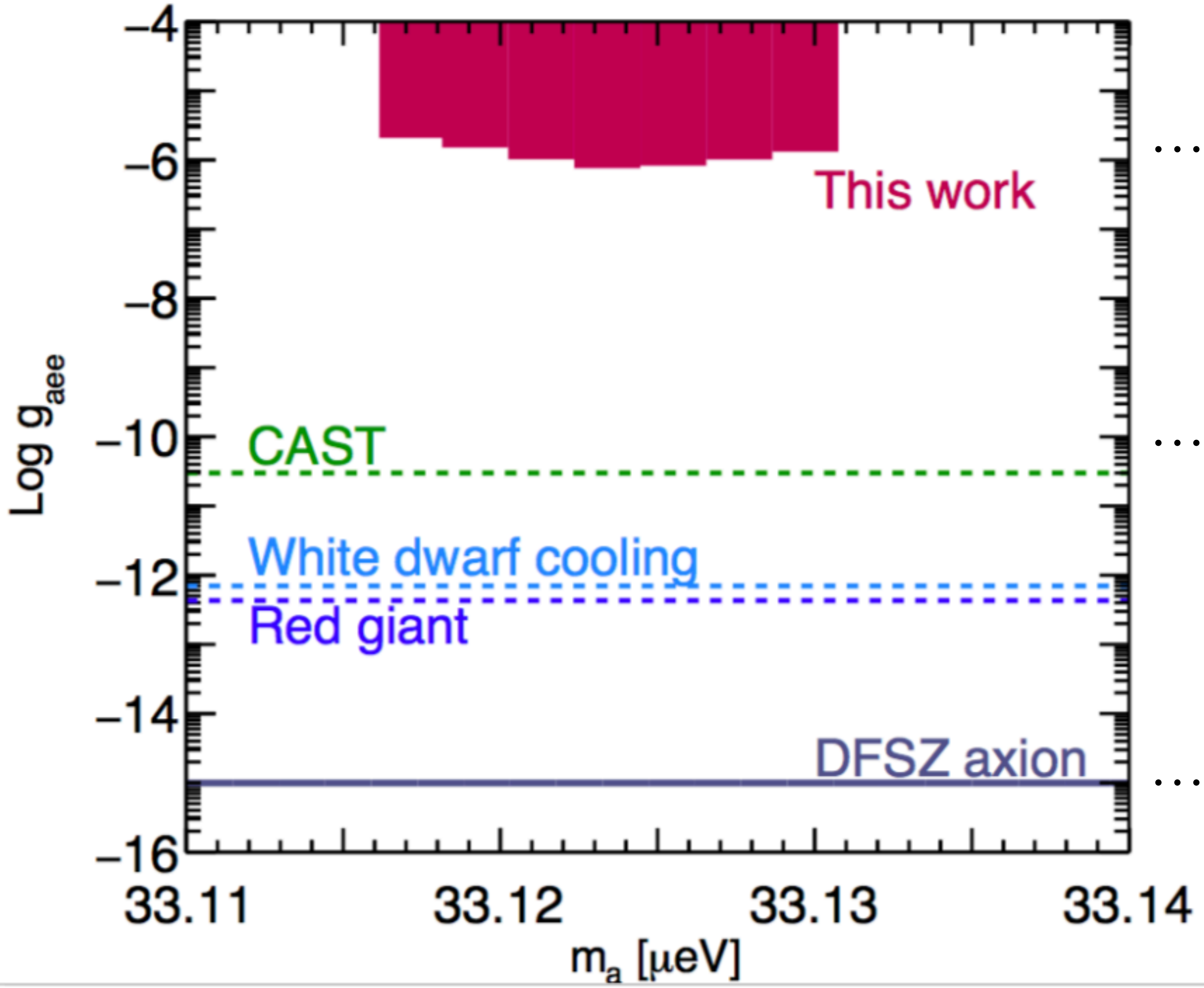
↓

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

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

at $m_a = 33$ μeV

Upper limit



statistically improvable by taking more datas

- 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 a 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}

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