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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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

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

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))

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

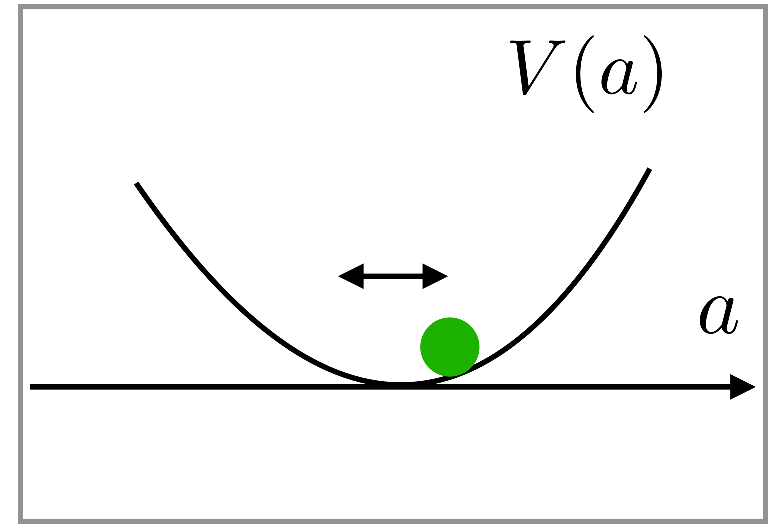
With a sufficiently large F_a , the QCD axion models are consistent with experiments.

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 (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.

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

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

Axion interactions

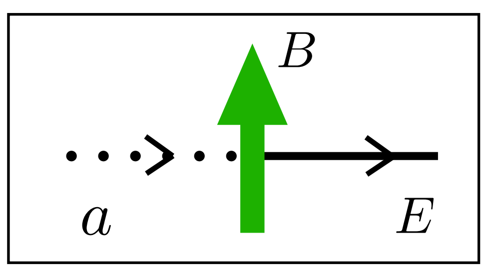
QCD axion couples to the SM particles like photons and electrons:

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

important to distinguish the axion models

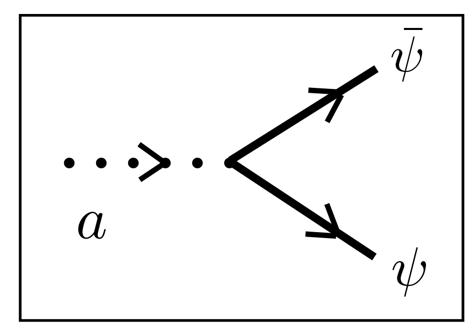
Experiments

axion to photon conversion



ex.) ADMX, ALPS, etc.

axion to electron (magnon) conversion (decay)



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

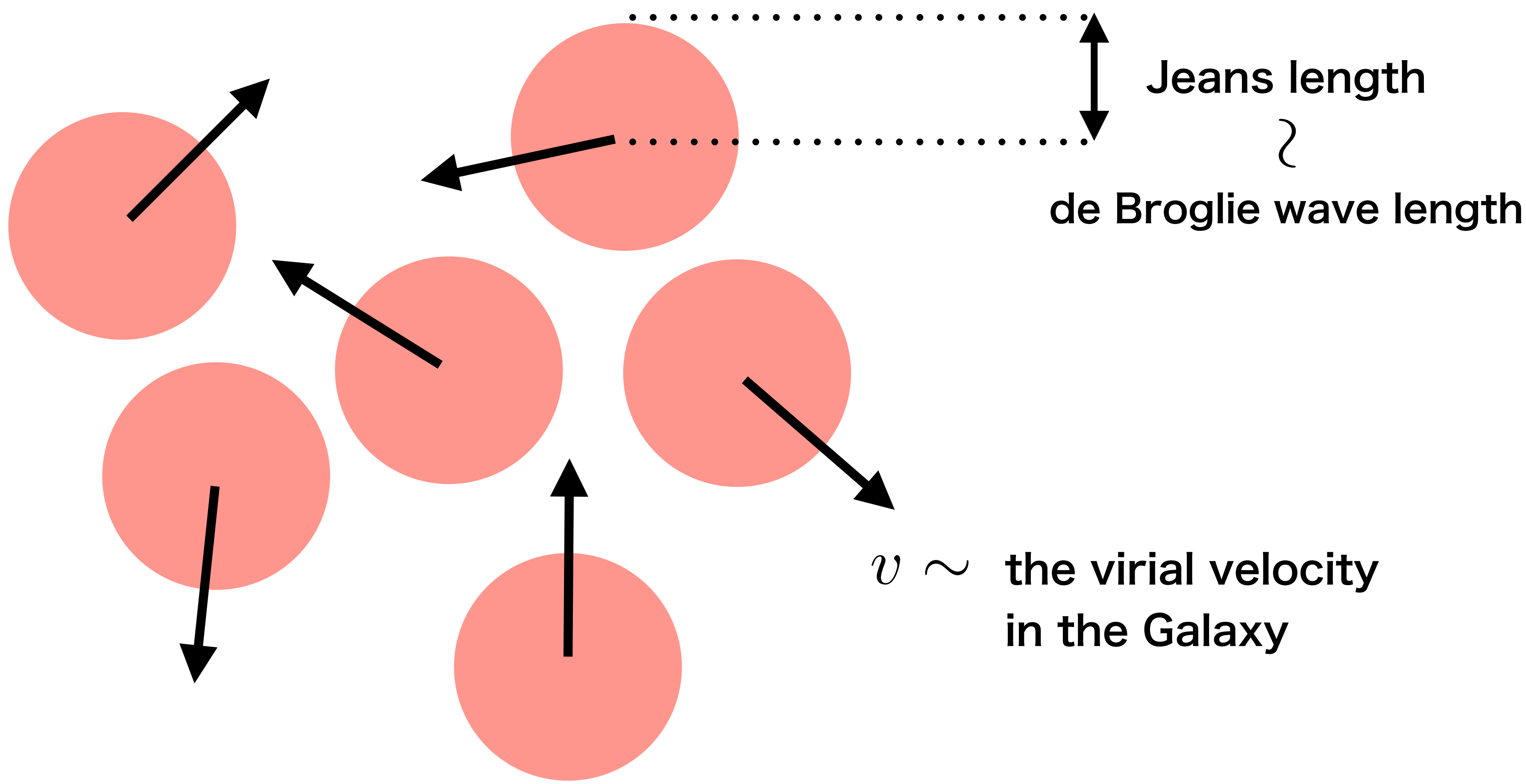
$$\hat{S}^i = \frac{\sigma^i}{2}$$: spin of the electron

Axion DM in the Galaxy

It is known 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)

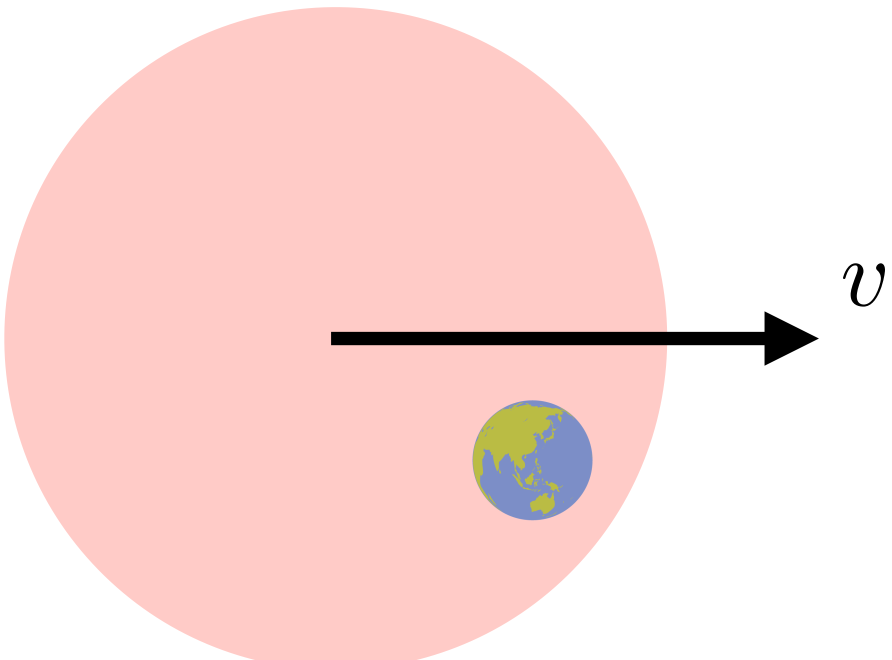
coherently oscillating & almost homogeneous



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

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

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

(D.J.E. Marsh (2015))

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

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

g_{aee} is tiny, 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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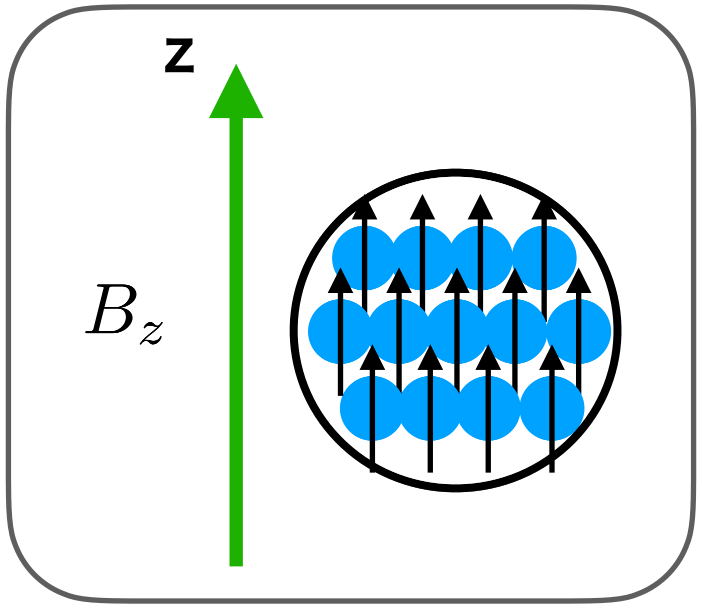
Collective spin system

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



It is well described by the Heisenberg model:

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

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

J_{ij} : coupling constants between spins

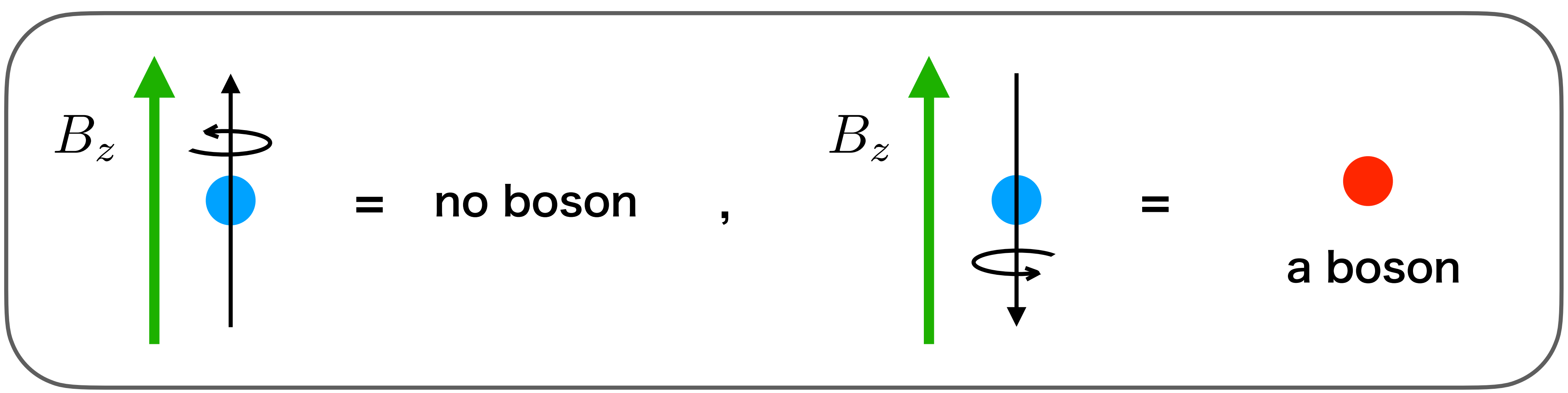
Holstein-Primakoff transformation

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

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

Using the Holstein-Primakoff transformation

$$\begin{cases} \hat{S}^z_{(i)} = \frac{1}{2} - \hat{C}^\dagger_i \hat{C}_i \ , \\ \hat{S}^+_{(i)} = \sqrt{1 - \hat{C}^\dagger_i \hat{C}_i}\ \hat{C}_i \ , \\ \hat{S}^-_{(i)} = \hat{C}^\dagger_i \sqrt{1 - \hat{C}^\dagger_i \hat{C}_i} \ , \end{cases}$$

$$-2\mu_B B_z \sum_i \hat{S}^z_{(i)} = -2\mu_B B_z \sum_i (\frac{1}{2} - \hat{C}^\dagger_i \hat{C}_i)$$

$$\rightarrow 2\mu_B B_z \sum_i \hat{C}^\dagger_i \hat{C}_i$$

Translating to the Fourier space as

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

$$= 2\mu_B B_z \sum_i \sum_{\boldsymbol{k}} \frac{e^{i\boldsymbol{k}\cdot\boldsymbol{r}_i}}{\sqrt{N}} \sum_{\boldsymbol{k}'} \frac{e^{-i\boldsymbol{k}'\cdot\boldsymbol{r}_i}}{\sqrt{N}} \hat{c}^\dagger_{\boldsymbol{k}} \hat{c}_{\boldsymbol{k}'}$$

$$= 2\mu_B B_z \sum_{\boldsymbol{k}} \sum_{\boldsymbol{k}'} \delta_{\boldsymbol{k}-\boldsymbol{k}'} \hat{c}^\dagger_{\boldsymbol{k}} \hat{c}_{\boldsymbol{k}'} \qquad (\because \sum_i e^{i(\boldsymbol{k}-\boldsymbol{k}')\cdot\boldsymbol{r}_i} = N\delta_{\boldsymbol{k}-\boldsymbol{k}'})$$

$$= 2\mu_B B_z \sum_{\boldsymbol{k}} \hat{c}^\dagger_{\boldsymbol{k}} \hat{c}_{\boldsymbol{k}}$$

Collective spin system

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

Now we have $$-2\mu_B B_z \sum_i \hat{S}^z_{(i)} = 2\mu_B B_z \sum_{\boldsymbol{k}} \hat{c}^\dagger_{\boldsymbol{k}} \hat{c}_{\boldsymbol{k}}$$

Doing similar calculation yields $$-\sum_{i,j} J_{ij} \hat{\boldsymbol{S}}_{(i)} \cdot \hat{\boldsymbol{S}}_{(j)} = \sqrt{N} \sum_{\boldsymbol{k}} \left(\tilde{J}(0) - \tilde{J}(\boldsymbol{k}) \right) \hat{c}^\dagger_{\boldsymbol{k}} \hat{c}_{\boldsymbol{k}}$$

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

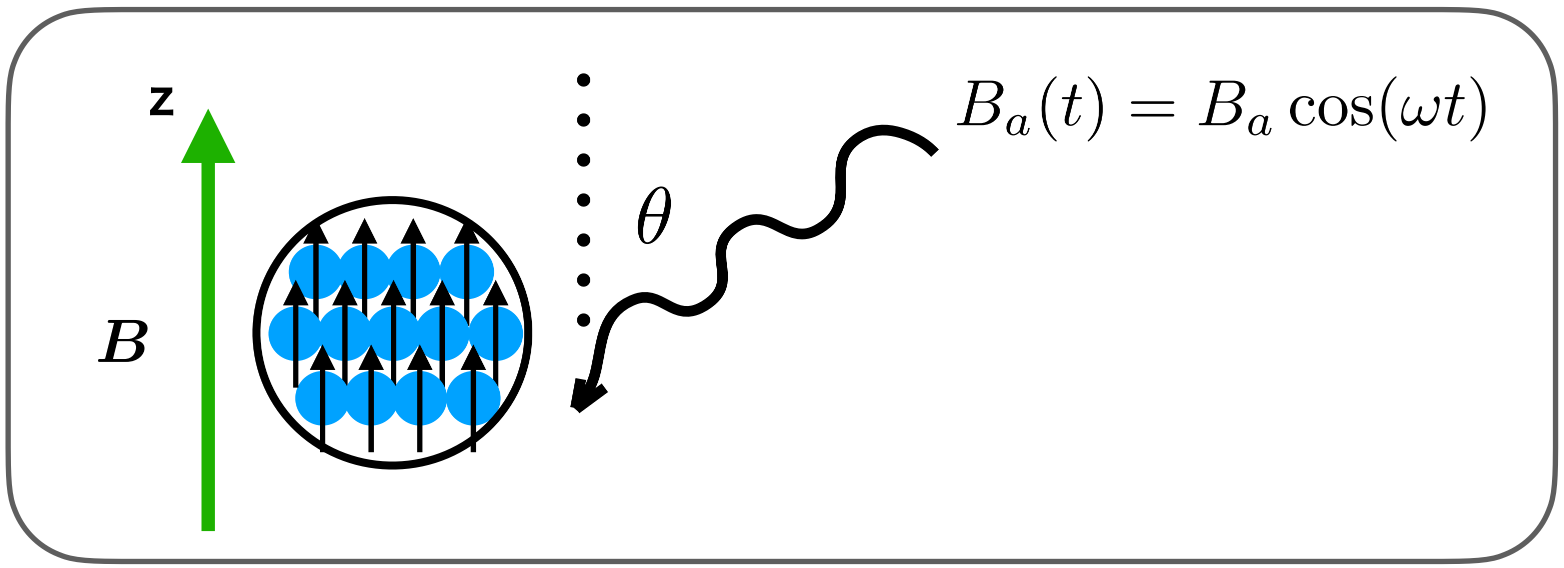
Therefore $$\mathcal{H}_{mag} = \sum_{\boldsymbol{k}} \hbar\omega_k \hat{c}^\dagger_{\boldsymbol{k}} \hat{c}_{\boldsymbol{k}}$$

← quantized "spin wave" = magnon

where the dispersion relation is given by $$\hbar\omega_k = 2\mu_B B_z + \sqrt{N} \left(\tilde{J}(0) - \tilde{J}(\boldsymbol{k}) \right)$$

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

&

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

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

$$+ \sum_{i=1..N} \mathcal{H}(\hat{c}_{k=i})$$

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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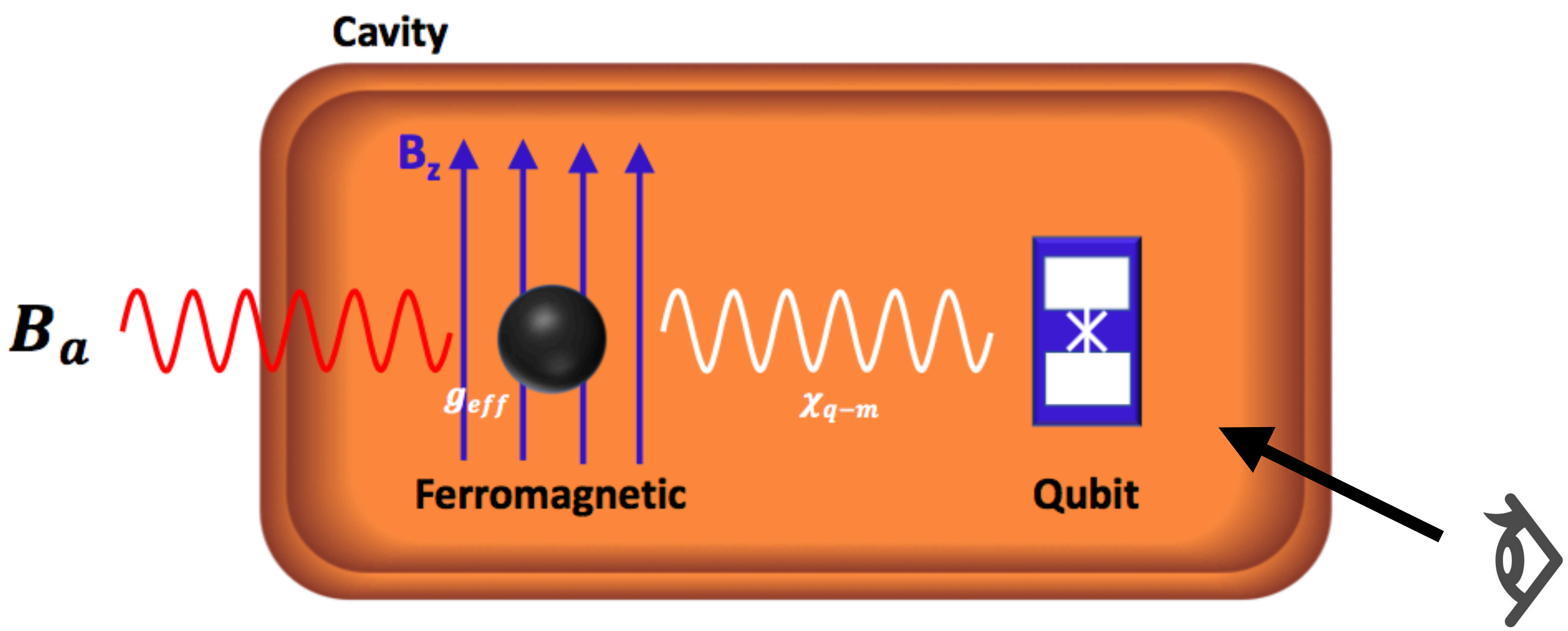
Experiment

We 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 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 for a density matrix of the system and we can calculate the qubit spectrum, which is the observable and depending on the magnon state.

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

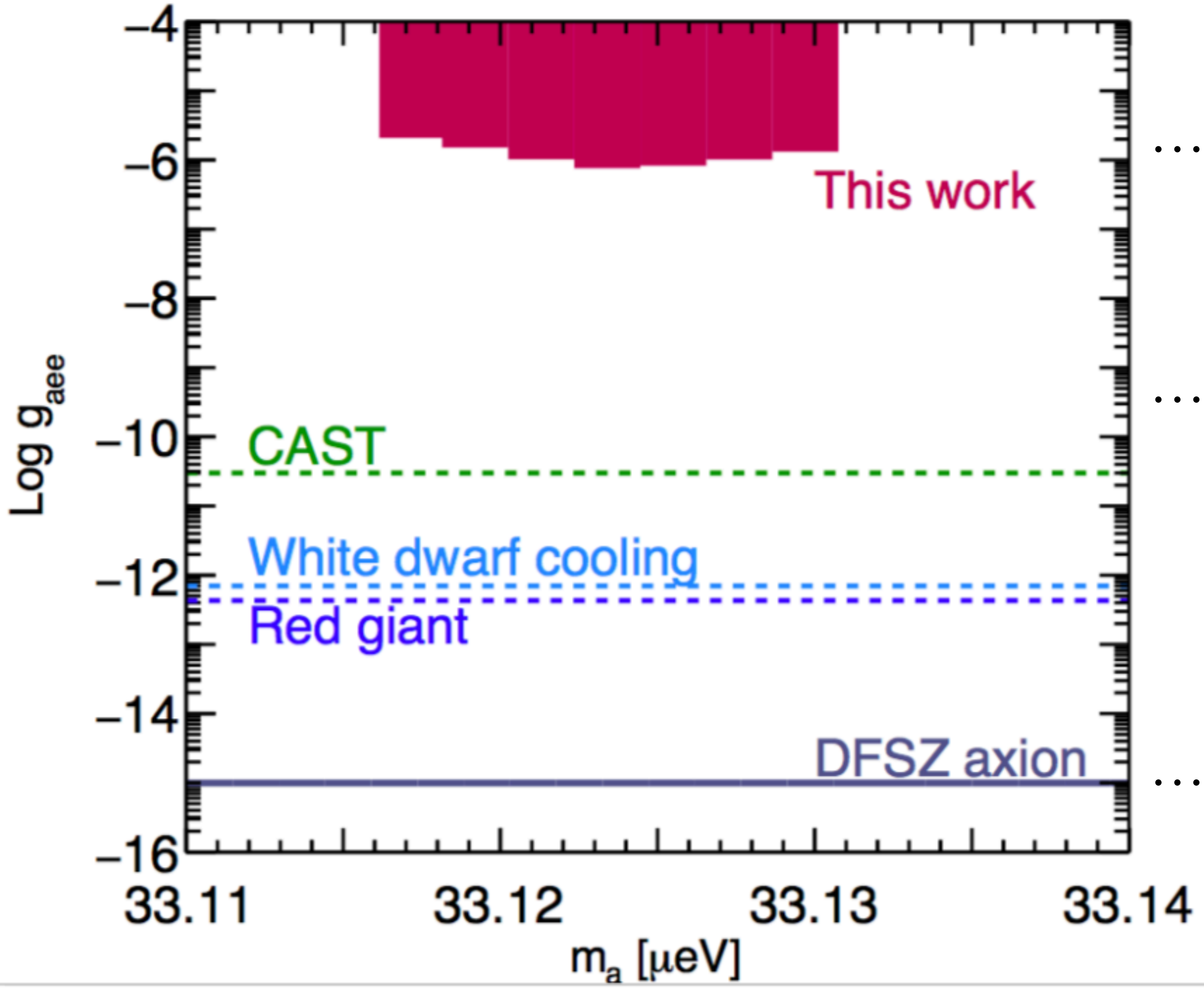
↓

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...