Searching for axion dark matter with magnons

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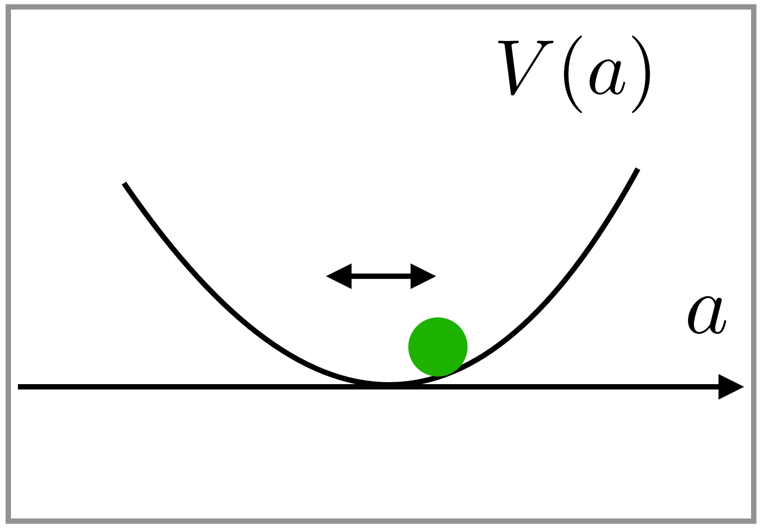
Refs: T.Ikeda, AI, K.Miuchi, J.Soda, H.Kurashige, Y.Shikano (2021)

2022 7/19 at MPA

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 $w = \frac{p}{\rho} = 0$)



$$\Rightarrow \quad \boxed{a(x) = a_0 \cos(\omega t)}$$

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 $10\mu\text{eV}$ is favored for DM.

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

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

Axion-electron interaction

An axion can interact with an electron as

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

$$\left(\begin{array}{c} \text{KSVZ: loop level} \\ \text{DFSZ: tree level} \end{array} \right)$$

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

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

effective magnetic field

↑

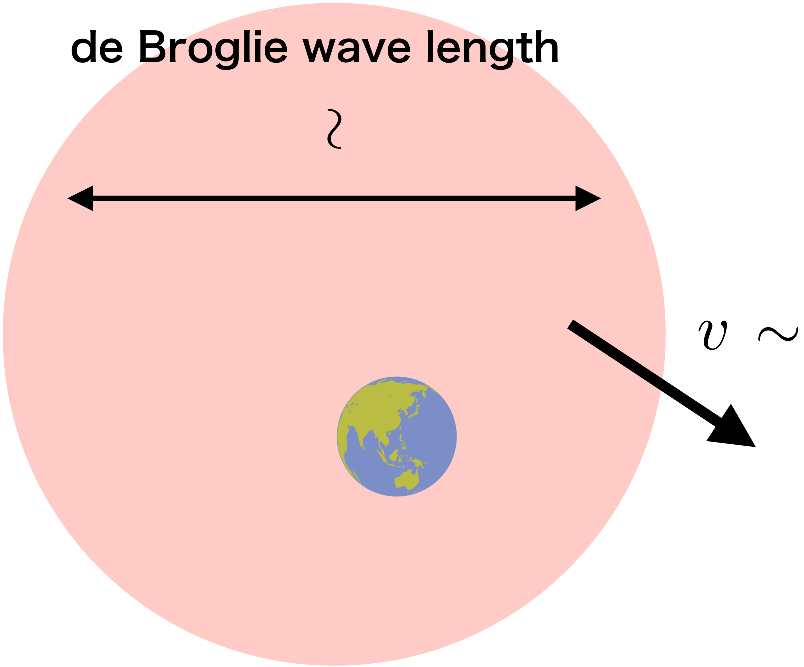
Reflecting the nature and distribution of the axion DM

$$\left(\begin{array}{ll} \mu_B = \dfrac{|e|}{2m_e} & \text{: Bohr magneton} \\ \hat{S}^i = \dfrac{\sigma^i}{2} & \text{: spin of the electron} \end{array} \right)$$

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,



$v \sim$ the virial velocity in the Galaxy

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

How large is the amplitude of the effective magnetic field?

Effective magnetic field

We can estimate the amplitude of the effective magnetic field as

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

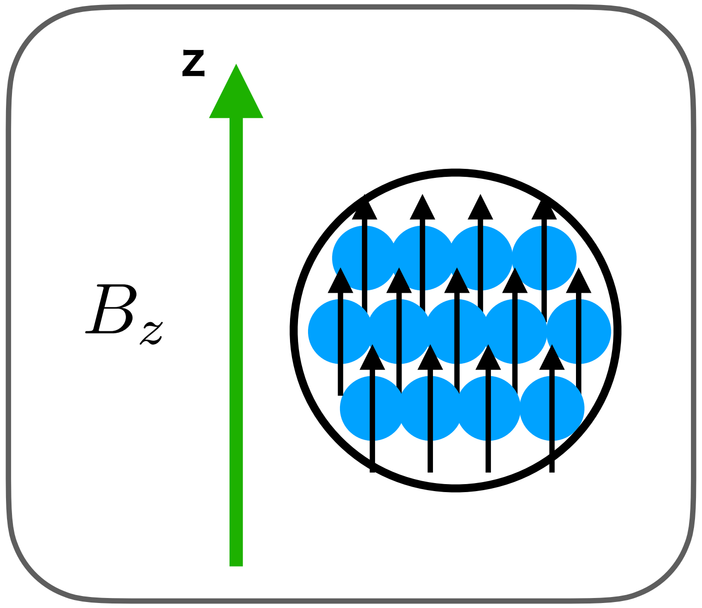
g_{aee} is tiny, then how can we detect such a small magnetic field?

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

R Barbieri, et al. (1985)

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:

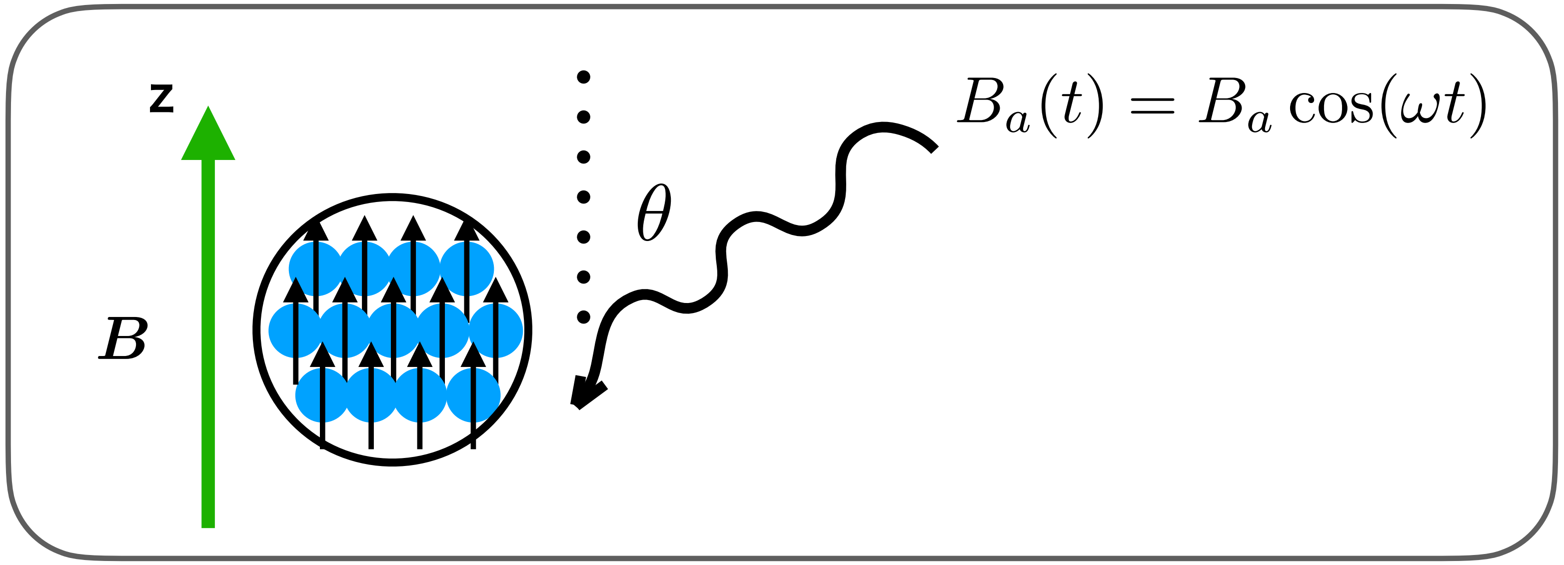
$$\boxed{\mathcal{H}_{mag} = -2\mu_B B_z \sum_i \hat{S}^z_{(i)} - \sum_{i,j} J_{ij} \hat{\boldsymbol{S}}_{(i)} \cdot \hat{\boldsymbol{S}}_{(j)}}$$

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

J_{ij} : coupling constants between spins.

Axion-magnon resonance

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



Then, the hamiltonian is given by

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

effective magnetic field from the axion DM

Magnon excitation

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

Holstein-Primakoff transformation

&

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

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

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

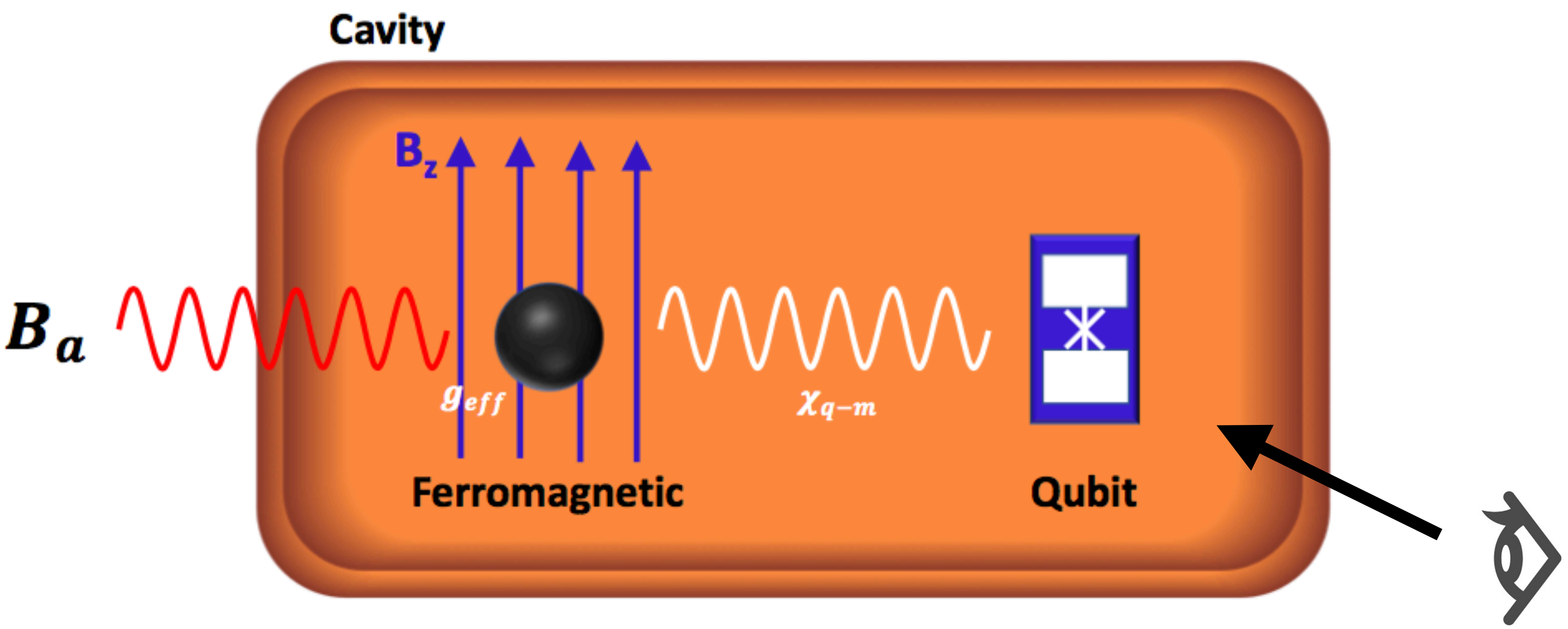
- The axion DM can cause the resonance of the uniform mode $(k = 0)$ of the magnon if $\omega_m = \omega_a$ $(\omega_m = 2\mu_B B_z)$.

Experiment

We tried to measure 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])



This detection method enables us to operate quantum nondemolition detection of the magnon with the qubit!

Upper limit

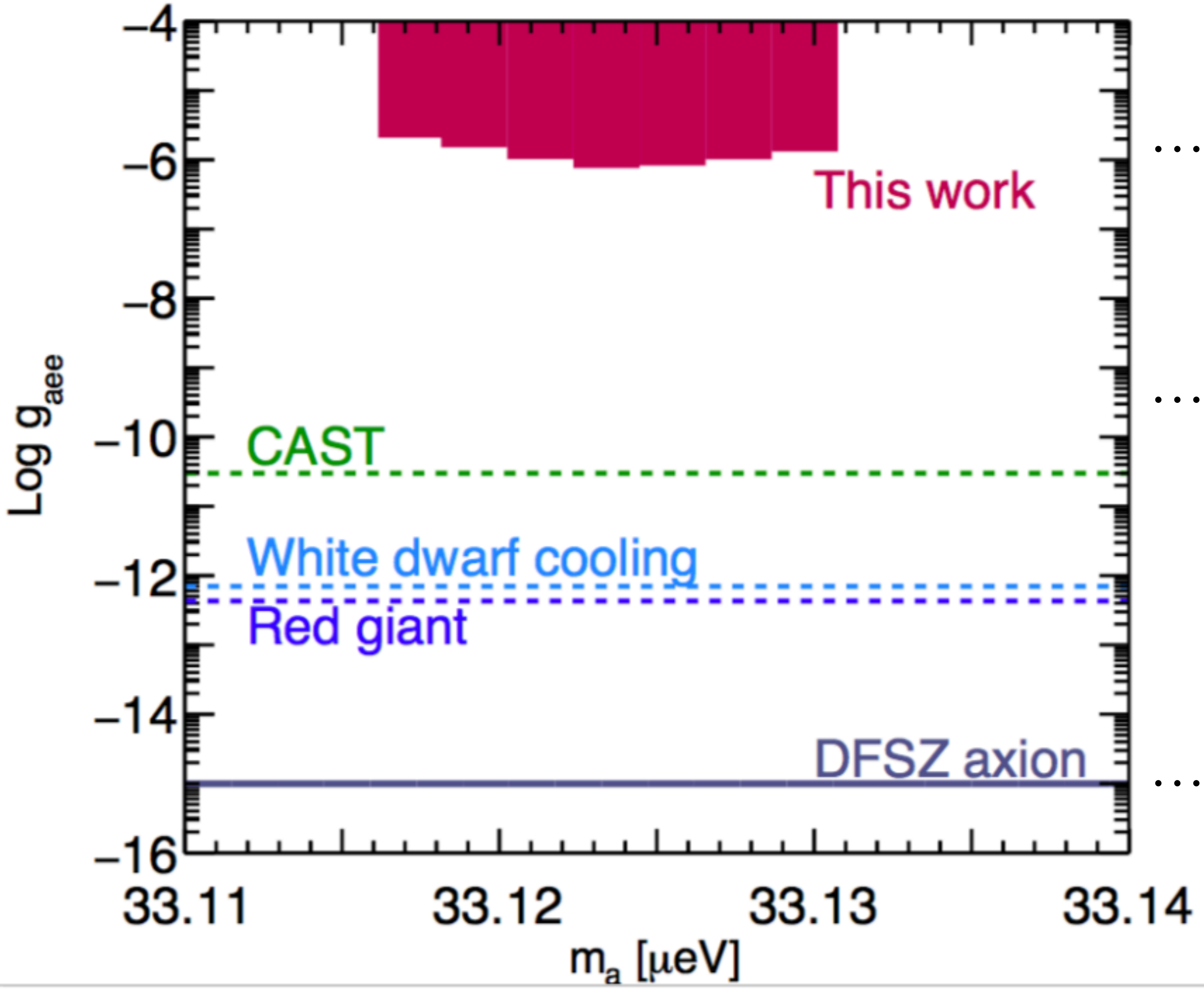
We reanalyzed data of a magnon experiment for other purpose (D. L-Quirion, et al, (2017)
and found no evidence of the axion DM

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...