Atmospheric axionlike particles at Super-Kamiokande

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Base on: Phys.Rev.D 106, 095029 (2022) 1, arXiv:2208.05111.

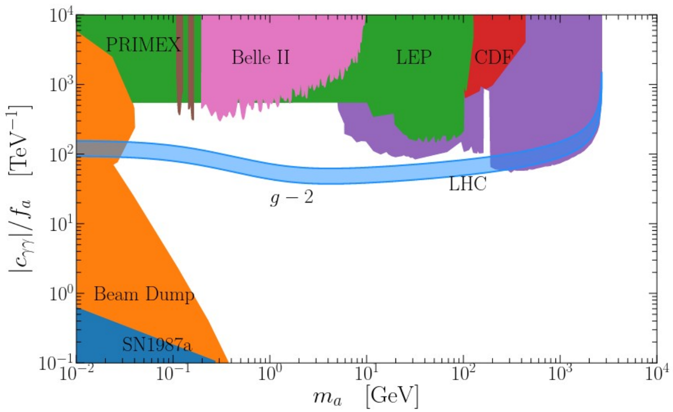
Saga-Yonsei Joint Workshop XIX, 16-19 Jan. 2023

Introduction

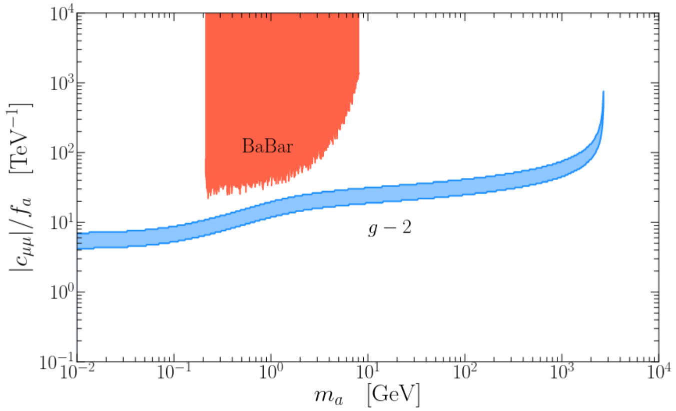
- **QCD axion**: solve strong CP problem.
- **Axionlike particle (ALP)**: is a psuedoscalar boson, its mass is not linear proportional to the couplings to SM particles.
- **ALP** remains one of the dark matter candidates.
- **ALP** can couple to photons, leptons, quarks, and gauge bosons.
- ALP-->di-photon searches at Belle II was discussed in *Sungjin Cho*'s talk.

Introduction

- ALP-photon coupling:



- ALP-muon coupling:



M.A.Buen-Abad, J.Fan, M. Reece, C.Sun,
JHEP09(2021)101

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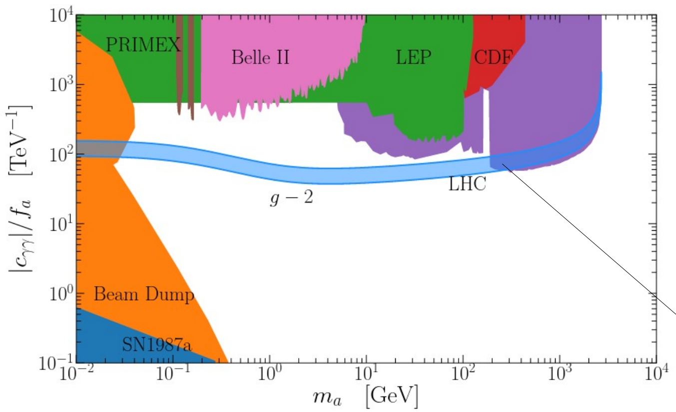

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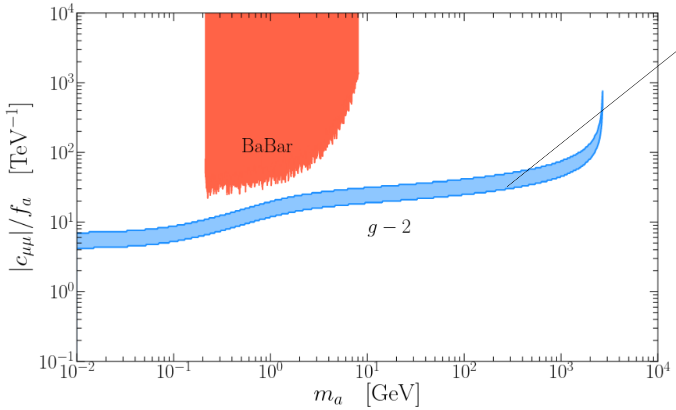

Require both couplings to explain muon g-2

M.A.Buen-Abad, J.Fan, M. Reece, C.Sun, JHEP09(2021)101

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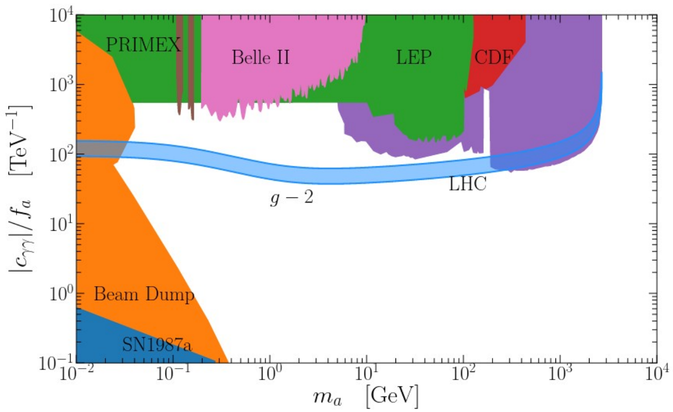

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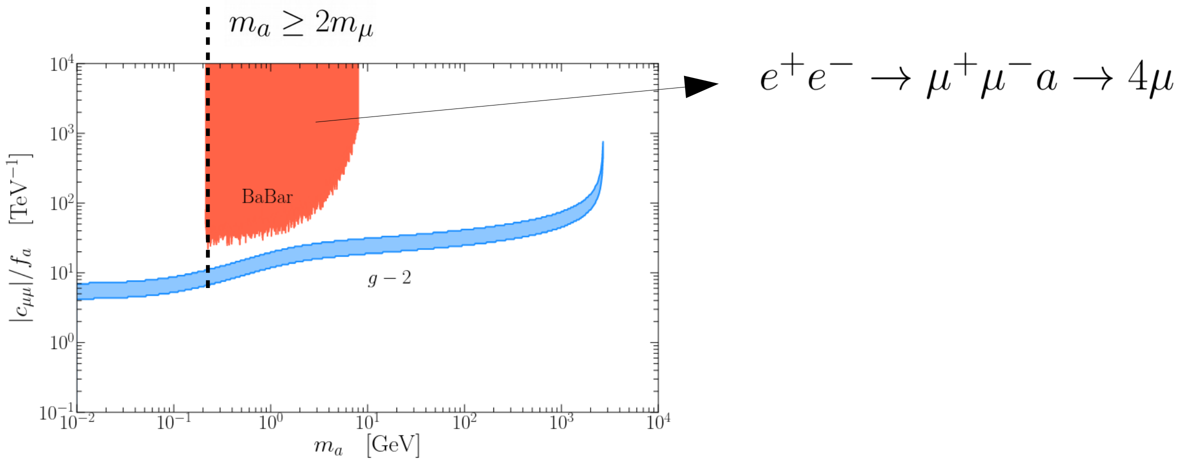

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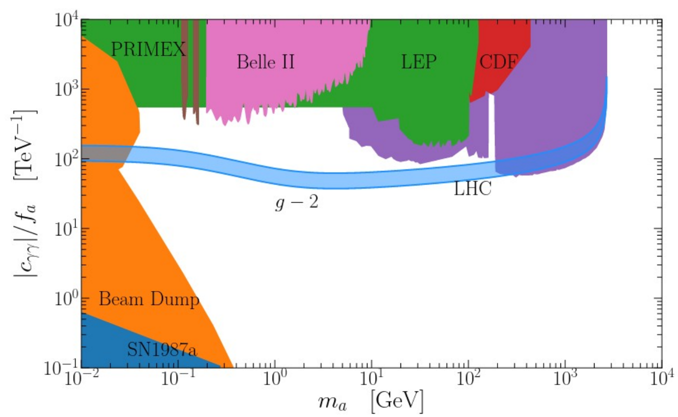

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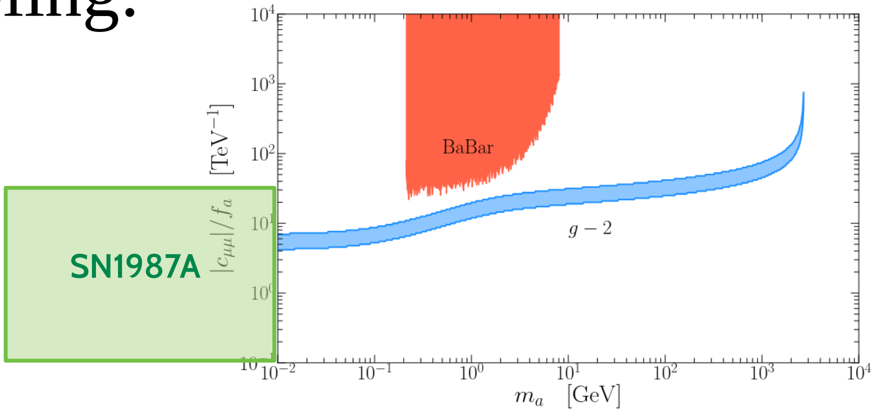

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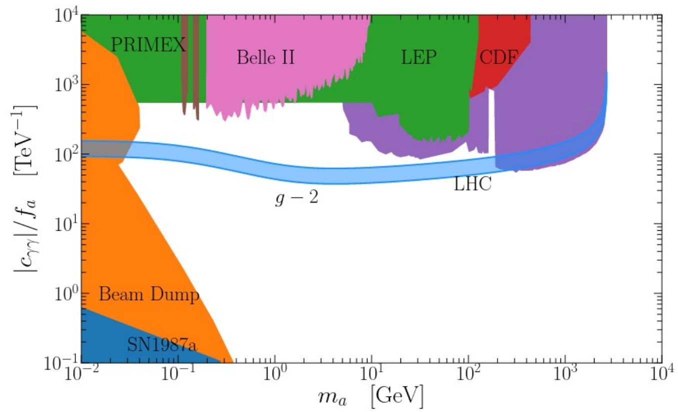

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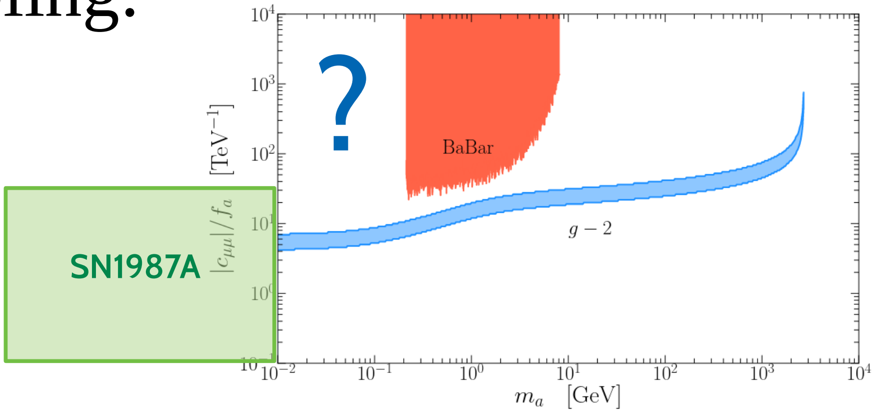
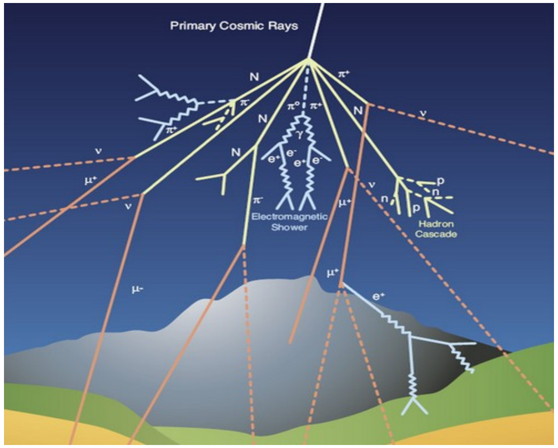


M.A.Buen-Abad, J.Fan, M. Reece, C.Sun,
JHEP09(2021)101

Introduction

- Cosmic rays reach Earth's atmosphere, produce large *air-showers* of pseudoscalar mesons, $\pi^0, \pi^\pm, K^0, K^\pm \cdots$.



Cosmic rays: particles from outer space | CERN

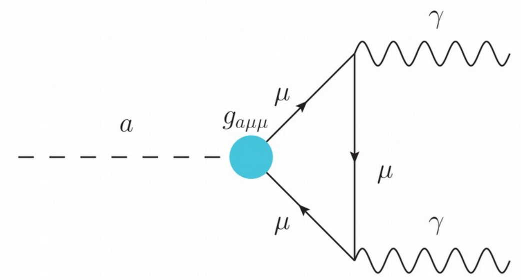
- Such pseudoscalar mesons decay to long-lived particals (**LLPs**), which potentially may decay in the neutrino experiments, i.e Super-Kamiokande (**SK**).

ALP-muon interaction

- In this work, we consider ALP-muon interaction

$$\mathcal{L} \supset -i g_{a\mu\mu} a \bar{\mu} \gamma_5 \mu$$

- For **ALP** mass $m_a < 2m_\mu$, **ALP** primarily decays into diphoton via the effective coupling:



$$\mathcal{L}_{\rm loop} \supset -\frac{1}{4} g^{\rm eff}_{a\gamma\gamma} a F^{\mu\nu} \tilde{F}_{\mu\nu}$$

$$g^{\rm eff}_{a\gamma\gamma} = \frac{g_{a\mu\mu}\alpha}{m_\mu \pi}\left[1 - \frac{4m_\mu^2}{m_a^2}\arcsin^2\left(\frac{m_a}{2m_\mu}\right)\right]$$

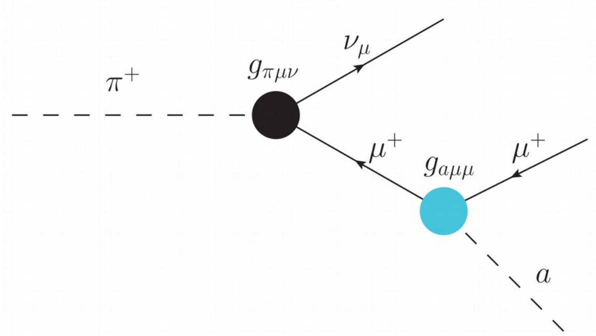
$$\tau_a = \Gamma^{-1}_{a\to\gamma\gamma} = \frac{64\pi}{(g^{\rm eff}_{a\gamma\gamma})^2 m_a^3}$$

M.Bauer, M.Neubert, A. Thamm, JHEP12(2017)044

- **ALP** can be long-lived due to the loop suppression.

ALP flux from airshower

- **ALP**s can be produced from charged meson decays $\pi^\pm \to \mu^\pm \nu a$ in air-showers with mass range $0 \leq m_a \leq m_\pi - m_\mu \simeq 33$ MeV .



K.Cheung, J.L.Kuo,P.Y.Tseng, Z.S. Wang, PRD106,095029(2022)

- Numerical code **MCEq** to compute the ALP flux at Earth's surface.
- The $g_{a\mu\mu}$ dictates the production rate, while $g_{a\gamma\gamma}^{\text{eff}}$ determines the decay length of ALP, $c\tau_a$.

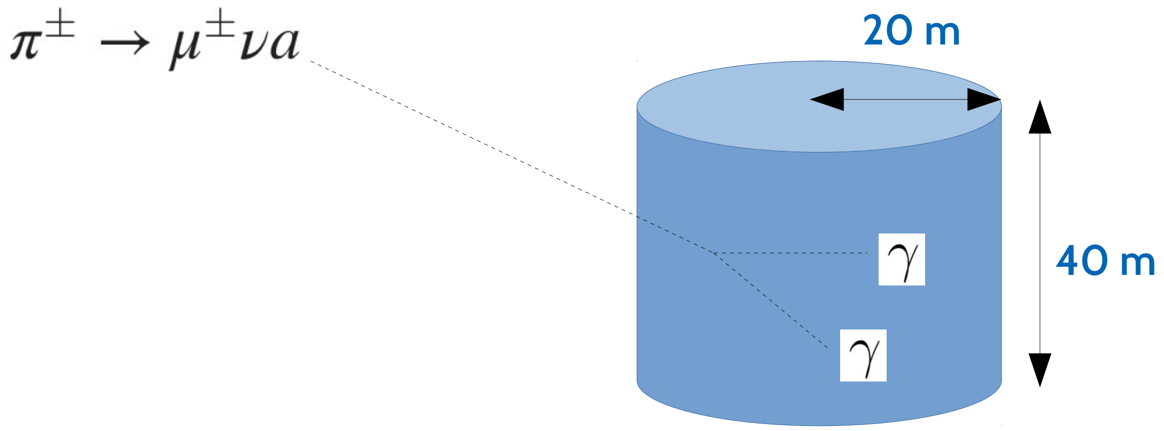
ALP detection on Earth

- At **SK**, the event distribution can be calculated by

$$\frac{d^2 N_{\text{event}}}{dT_a d\cos\theta} = \epsilon \Delta t A_{\text{eff}}(T_a, \cos\theta) \frac{d^2 \Phi_a}{dT_a d\cos\theta}$$

where we considered the detection efficiency and the detector geometry.

- The geometry of SK detector is a cylinder:



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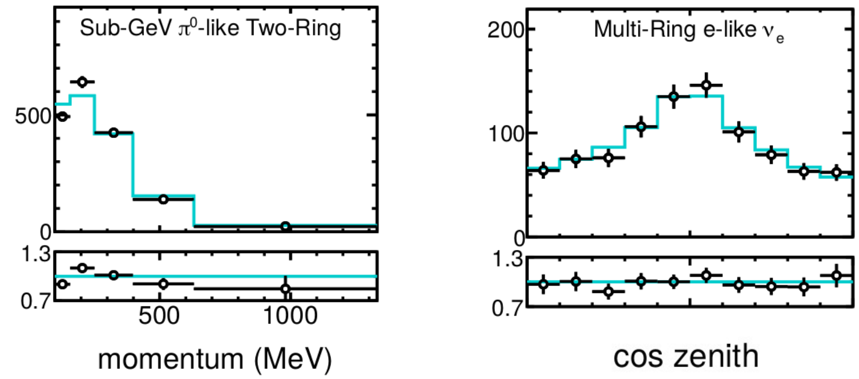
  where we considered the detection efficiency and the detector geometry.

- The SM backgrounds come from π^0 decay into *two-photon* and neutrino-induced electron-like events that create *multiple Cherenkov rings*.



Super-Kamiokande Collaboration, PRD97,072001(2018)

Constraint on the parameter space

- We perform χ^2 fit to the **SK** data

$$\chi_i^2 = 2\left\{N_{\rm sig}^i + N_{\rm bkg}^i - N_{\rm obs}^i\left[1 - \log\left(\frac{N_{\rm obs}^i}{N_{\rm sig}^i + N_{\rm bkg}^i}\right)\right]\right\}$$

where the expected **ALP** signal events is computed by

$$N_{\rm sig}^i = \int^i dT_a d\cos\theta \frac{d^2 N_{\rm event}}{dT_a d\cos\theta}$$

- The 90% C.L. constraint by requiring $\Delta\chi^2 \equiv \sum_i \chi_i^2 - \chi_0^2 \leq 4.865$.

Constraint on the parameter space

- The 90% C.L. constraint

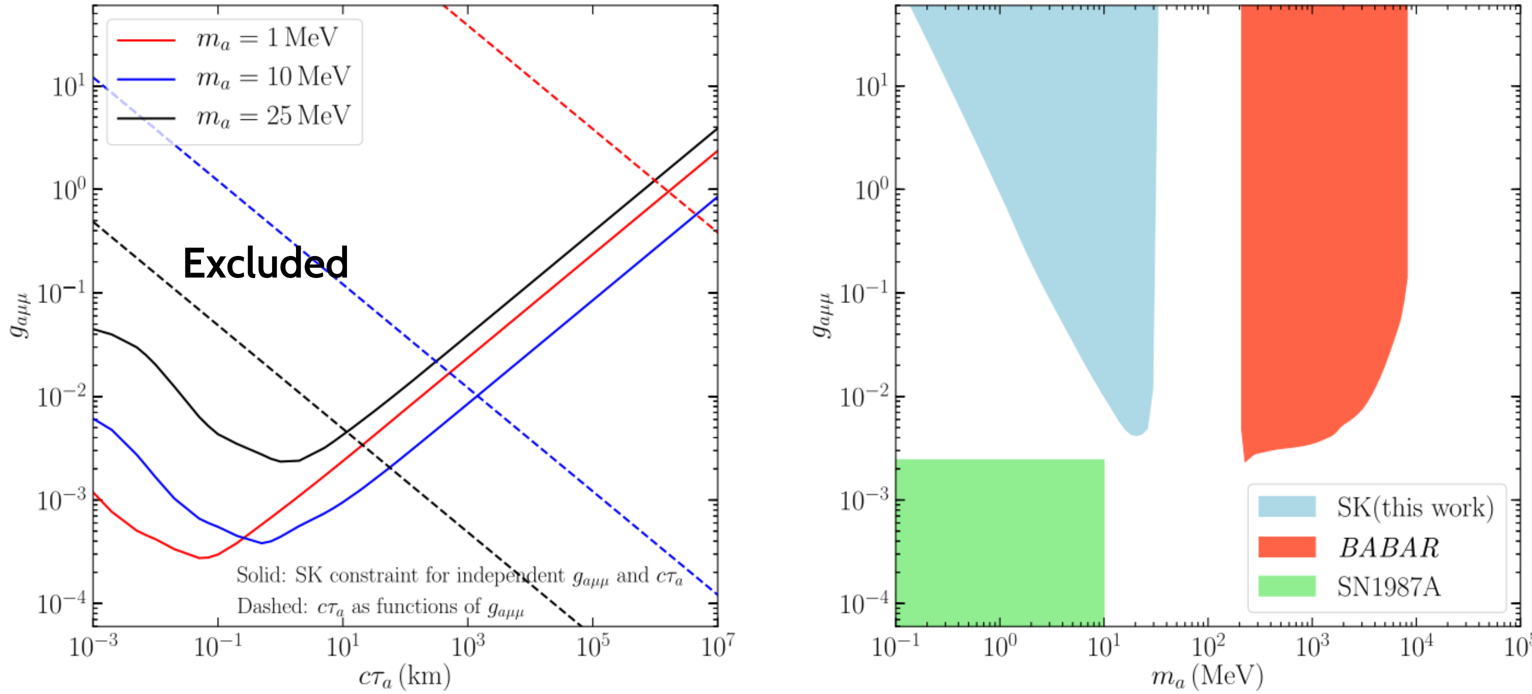


FIG. 2. Left panel: 90% C.L. sensitivity reach of SK to the muonphilic ALPs for independent $g_{a\mu\mu}$ and $c\tau_a$ (solid curves) and $c\tau_a$ as a function of $g_{a\mu\mu}$ according to Eq. (4) (dashed lines) in the $(c\tau_a, g_{a\mu\mu})$ plane, for three benchmark values of m_a: 1, 10, and 25 MeV. Right panel: constraints on $(m_a, g_{a\mu\mu})$ assuming $c\tau_a$ is proportional to $1/g_{a\mu\mu}^2$. Note that $g_{a\mu\mu}$ always induces the ALP production from the charged pion decays. For comparison, we also include the constraint from *BABAR*, which holds only for larger m_a [20], and the bounds from SN1987A, which cover $g_{a\mu\mu} \sim [10^{-10}, 2 \times 10^{-3}]$ for $m_a \leq 10$ MeV [50].

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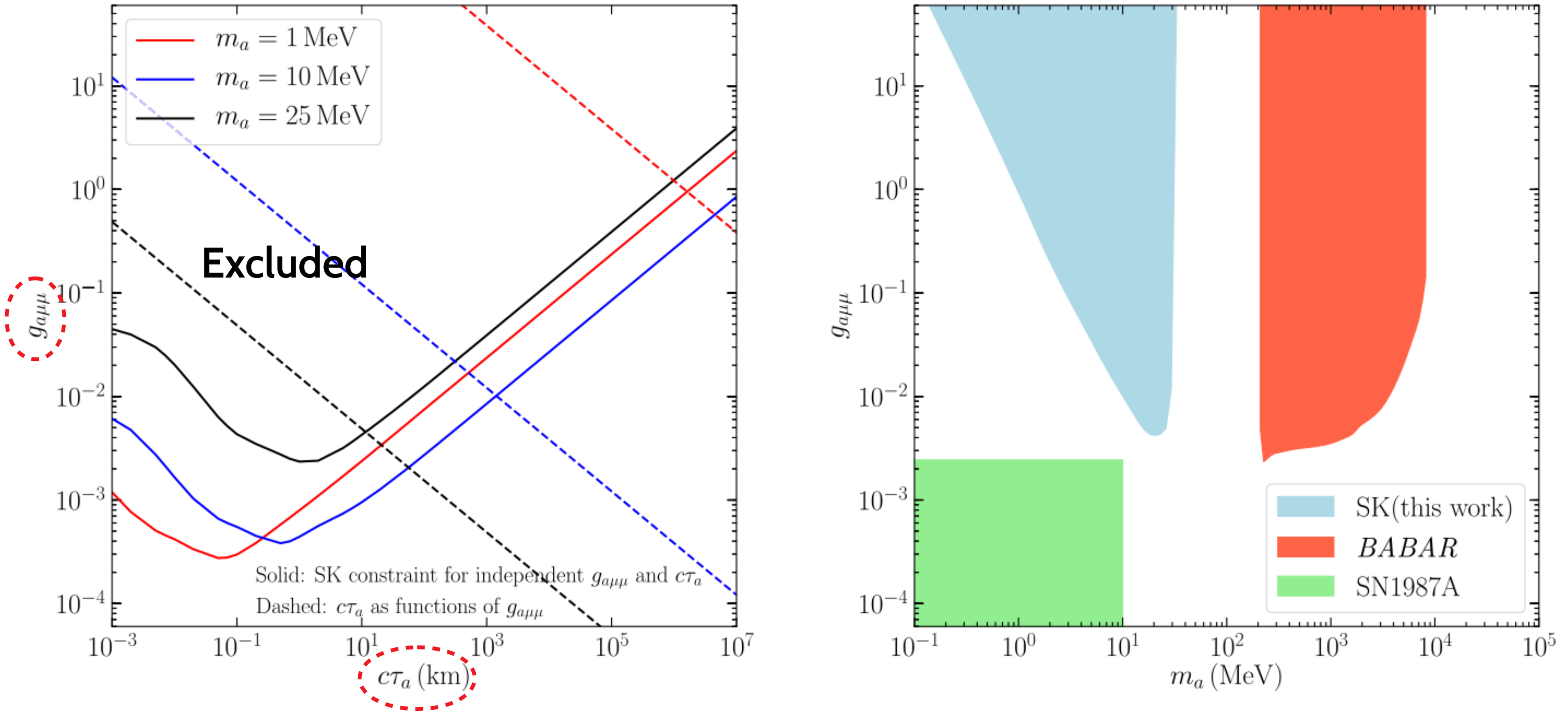

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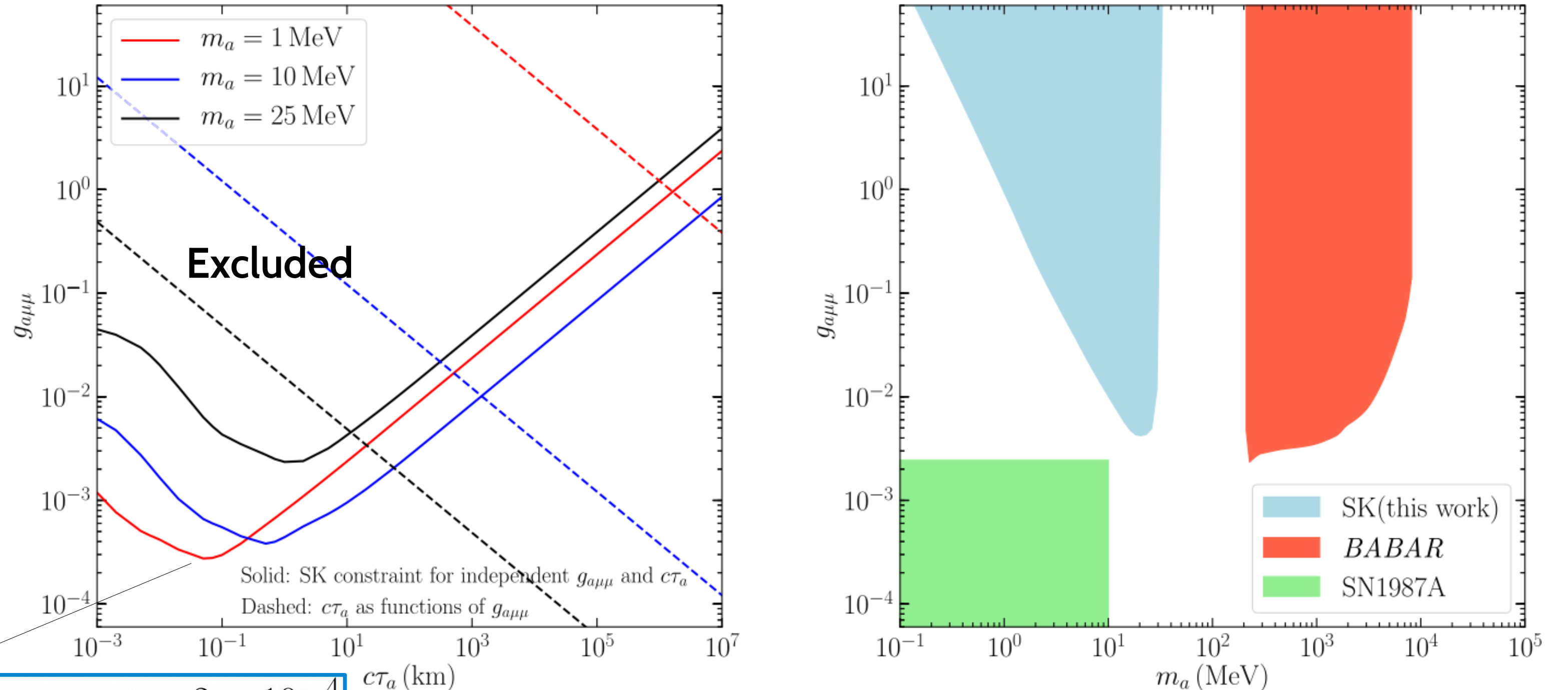

$c\tau_a = 8 \times 10^{-2}$ km, $g_{a\mu\mu} = 2 \times 10^{-4}$

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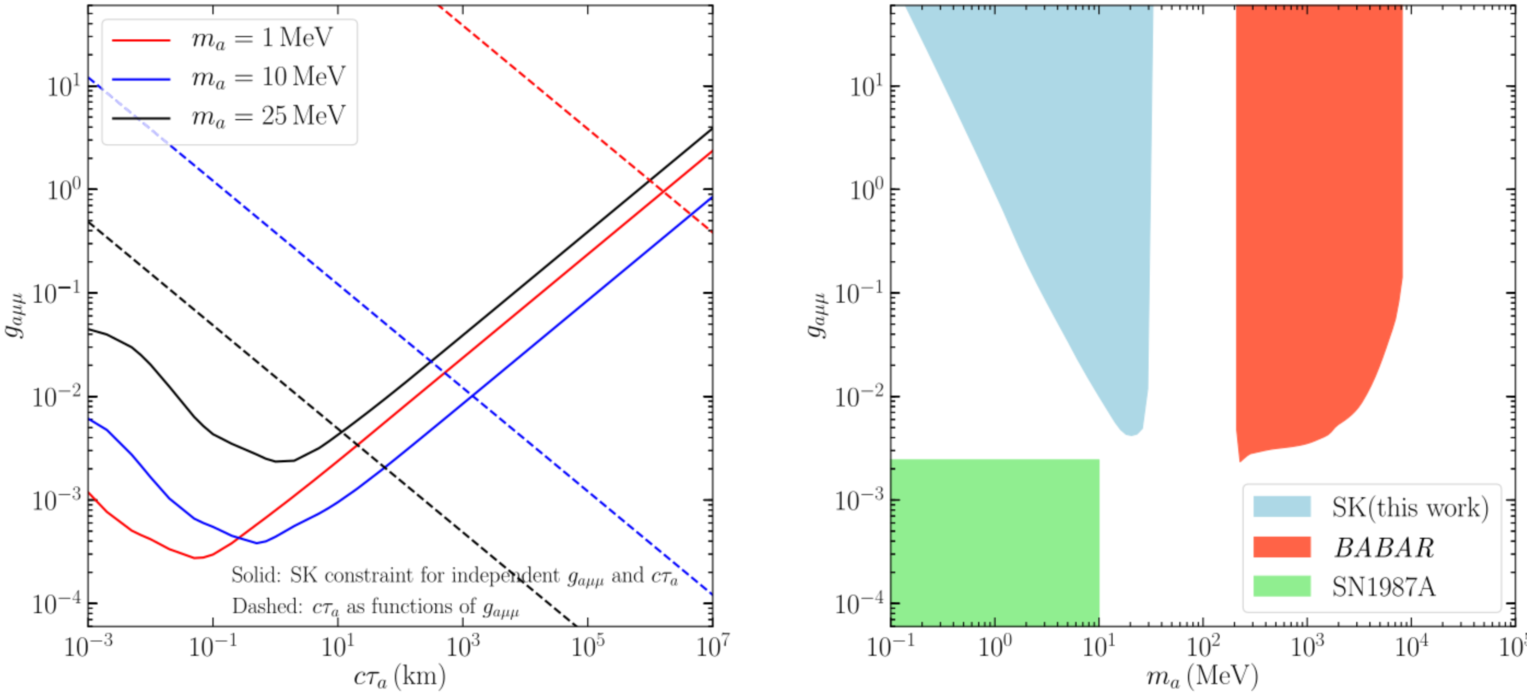

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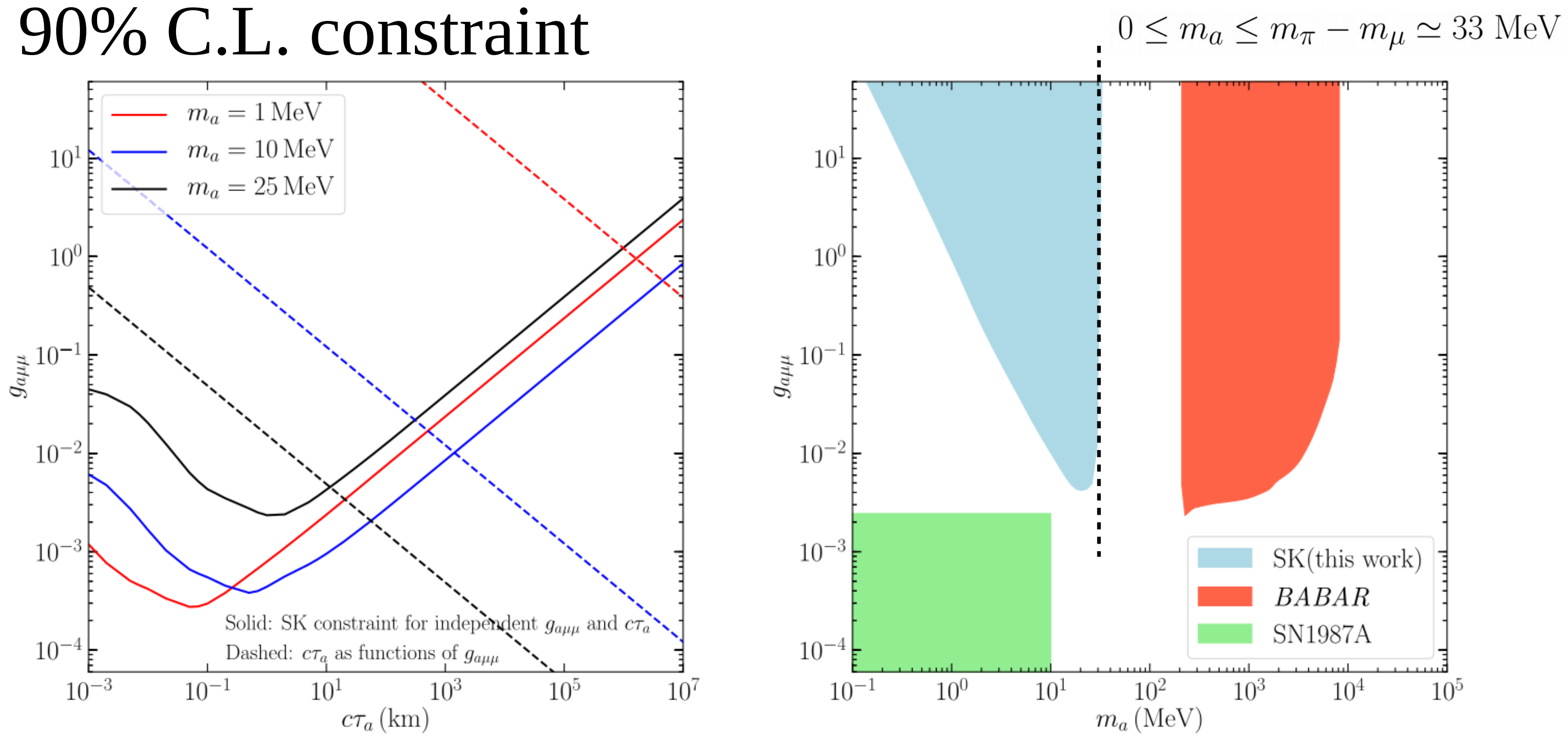

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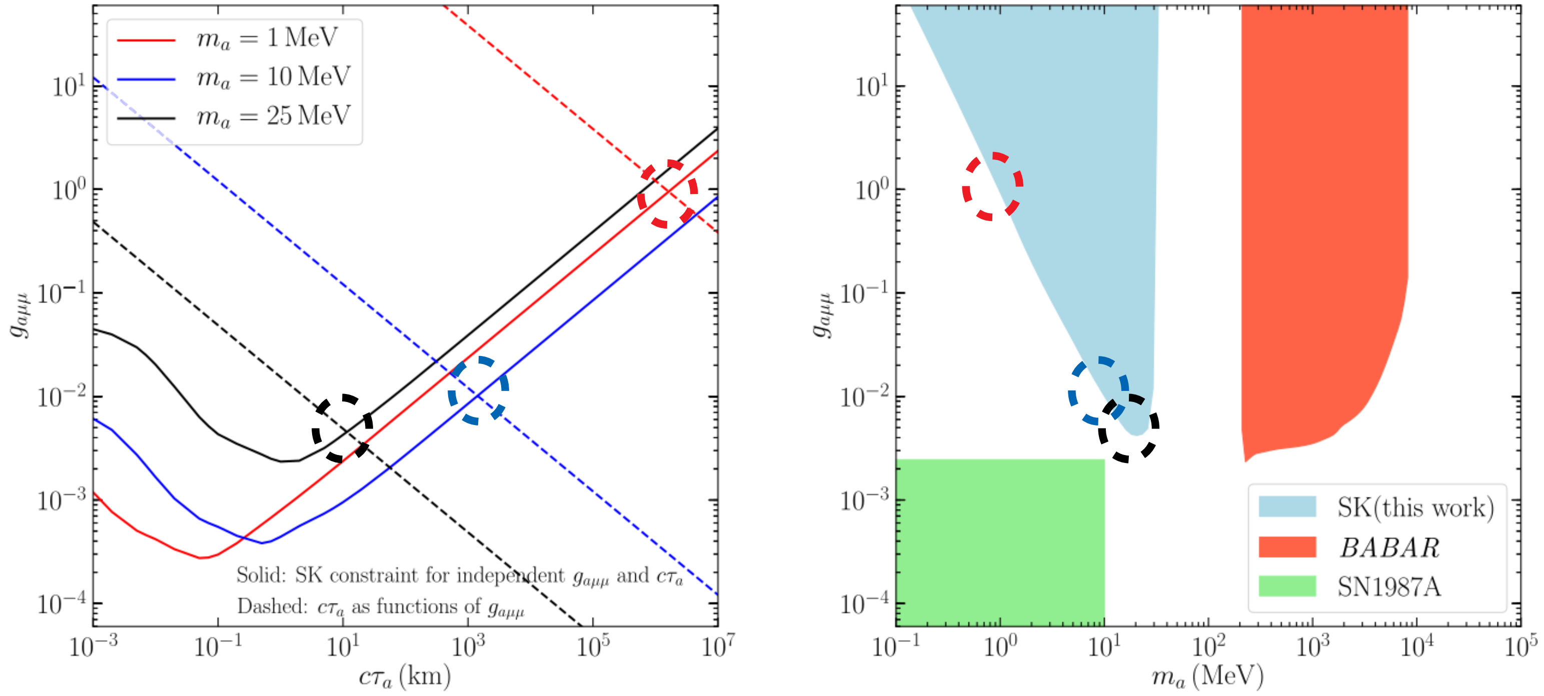

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BABAR collaboration PRD94,011102(2016)
A.Caputo,W.Raffelt,E.Vitagliano PRD105,035022(2022)

Discussion

- From the *air-shower*, require the $\pi^{\pm}$ decay before reach to the Earth surface, energy of $\pi^{\pm}$ should below 115 GeV. Therefore, we focus on **SK**, which has good resolution in sub-GeV and multi-GeV ranges.
- **ALP** couples to photons, can also be produced from *air-shower* of π^0 .
- But the lifetime of π^0 is too short, so that the ALP production branching ratio is too small.
- **IceCube** focuses on *ultrahigh energy*, therefore, sensitive to shorter decay length $c\tau_a \sim 5 \times 10^{-5}$ km for $m_a \sim 10$ MeV. We expect the constraint on $g_{a\mu\mu}$ will be weaker.

Summary

- We focus on **muonphilic** axionlike particle, which can radiatively couples to photons.
- **ALP**s are produced from $\pi^{\pm} \to \mu^{\pm}\nu a$ in the *air-shower*, when cosmic-rays hit the atmosphere.
- If consider $0 \leq m_a \leq m_\pi - m_\mu \simeq 33\ \mathrm{MeV}$, **ALP** decays $a \to \gamma\gamma$, instead of $a \to \mu^+\mu^-$, ALP becomes long-lived. It can reach Earth surface and decay inside **SK** detector.
- SK can probe $g_{a\mu\mu} \simeq 5 \times 10^{-3}$ and $m_a \simeq 20\ \mathrm{MeV}$, complementary to the limits from BABAR and SN1987A.

Thank you for your attention!

Back up

ALP detection on Earth

- At SK, the event distribution can be calculated by

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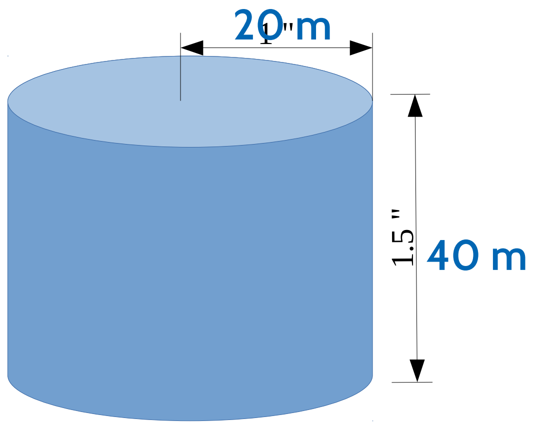

ALP detection on Earth

- The effective detection area:

$$A_{\text{eff}}(T_a, \cos\theta) = |\cos\theta| A_1(T_a, \cos\theta) + |\sin\theta| A_2(T_a, \cos\theta), \tag{B1}$$

where

$$A_1(T_a, \cos\theta) = \int_0^{R_{\text{SK}}} dr r \int_0^{2\pi} d\phi \left\{ 1 - \exp\left[-\frac{\Delta l_{\text{det},1}(r, \cos\theta, \phi)}{c\tau_a^{\text{lab}}(T_a)} \right] \right\}, \tag{B2}$$

$$A_2(T_a, \cos\theta) = R_{\text{SK}} \int_0^{H_{\text{SK}}} dh \int_{-\pi/2}^{\pi/2} d\phi \left\{ 1 - \exp\left[-\frac{\Delta l_{\text{det},2}(h, \cos\theta, \phi)}{c\tau_a^{\text{lab}}(T_a)} \right] \right\}, \tag{B3}$$

with $c\tau_a^{\text{lab}}$ being the ALP decay length in the lab frame. The ALP trajectories inside the detector are

$$\Delta l_{\text{det},1}(r, \cos\theta, \phi) \equiv \min\left[\frac{H_{\text{SK}}}{|\cos\theta|}, \frac{R_{\text{SK}}\sqrt{1 - (r^2/R_{\text{SK}}^2)\sin^2\phi} + r\cos\phi}{|\sin\theta|} \right] \quad \text{and} \tag{B4}$$

$$\Delta l_{\text{det},2}(r, \cos\theta, \phi) \equiv \min\left[\frac{H_{\text{SK}} - h}{|\cos\theta}, \frac{2R_{\text{SK}}\cos\phi}{|\sin\theta|} \right], \tag{B5}$$