

Constraints on MeV Axions from Kaon Decays

(On going work)

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MeV mass range Axion

- QCD axion is a dynamical solution of strong CP problem
- Axion mass

$$m_a^2 \approx \frac{m_u m_d}{(m_u + m_d)^2} \frac{m_\pi^2 f_\pi^2}{f_a^2}$$

f_a : axion decay constant

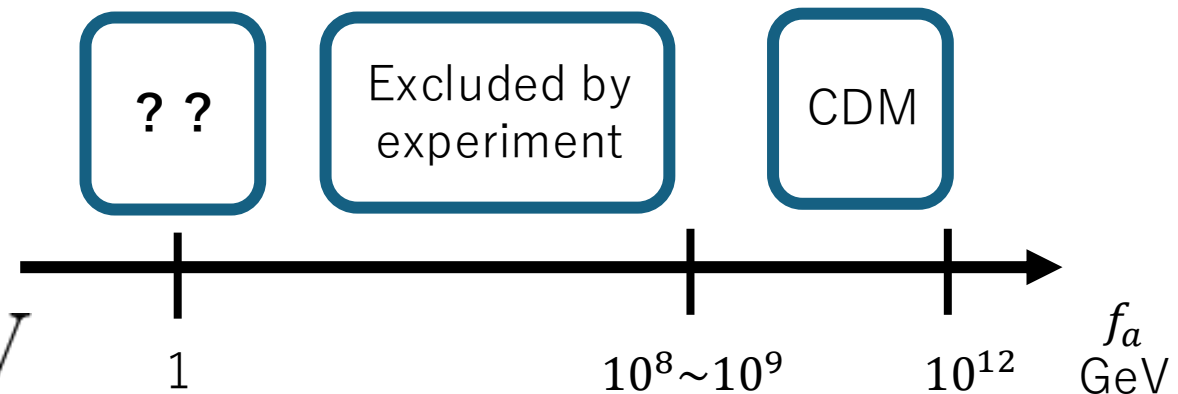
f_π : pion decay constant

Many studies

$$10^9 \text{ GeV} \leq f_a \leq 10^{12} \text{ GeV}$$

Recently

$$f_a \sim 1 \text{ GeV} \quad m_a \sim 10 \text{ MeV}$$



MeV axion model

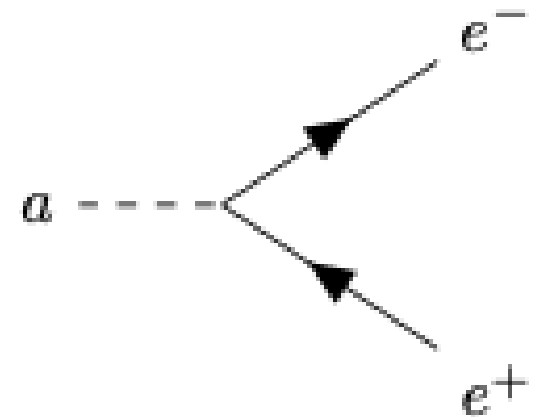
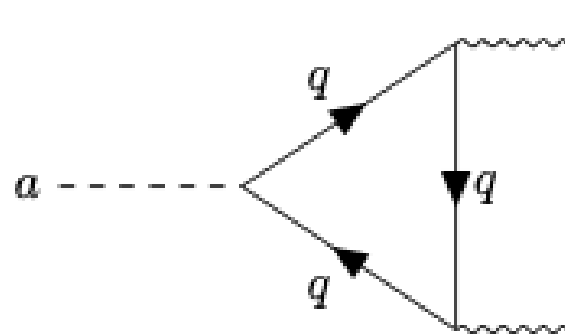
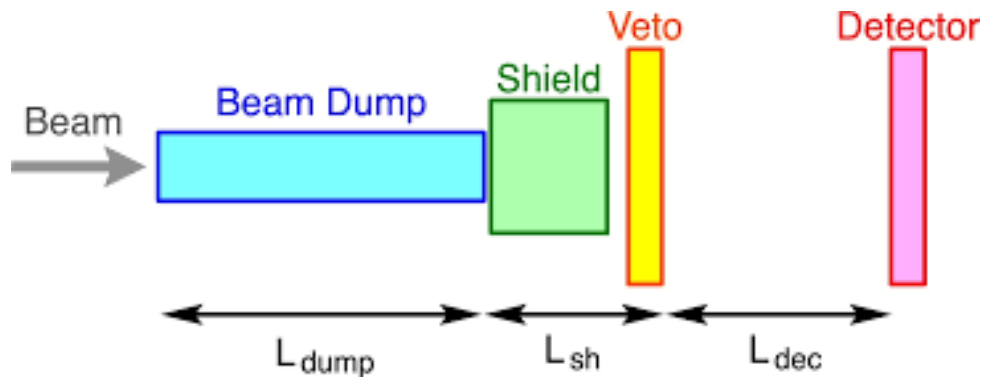
MeV Axion Model

Proton beam dump experiment

$$\text{Br}(K^+ \rightarrow \pi^+ (a \rightarrow \text{invisible})) \lesssim 4.5 \times 10^{-11} \quad (\text{E787 Collaboration})$$

MeV axion model

$$\text{Br}(K^+ \rightarrow \pi^+ a) \sim 10^{-4} \times \left(\frac{f_a}{1 \text{ GeV}} \right)^{-1}$$



➡ Axion couples to e^-

MeV Axion Model

Quarkonia Decay

Muon $g - 2$



Axion couples to only
first generation fermions

The rare decay process $\pi^+ \rightarrow e^+ \nu_e a$

$$\theta_{a\pi} \lesssim (0.5 - 0.7) \times 10^{-4} \quad \text{SINDRUM collaboration}$$

$$\theta_{a\pi} \sim - \left(\frac{Q_u m_u - Q_d m_d}{m_u + m_d} \right) \frac{f_\pi}{f_a}$$

Quarkonia Decay

Muon $g - 2$



Axion couples to only first generation fermions

The rare decay process

$$\mathcal{O}(10^{-2}) \times \left(\frac{Q_u}{Q_d} - \frac{m_d}{m_u} \right)$$

$$\theta_{a\pi} \sim - \left(\frac{Q_u m_u - Q_d m_d}{m_u + m_d} \right) \frac{f_\pi}{f_a}$$

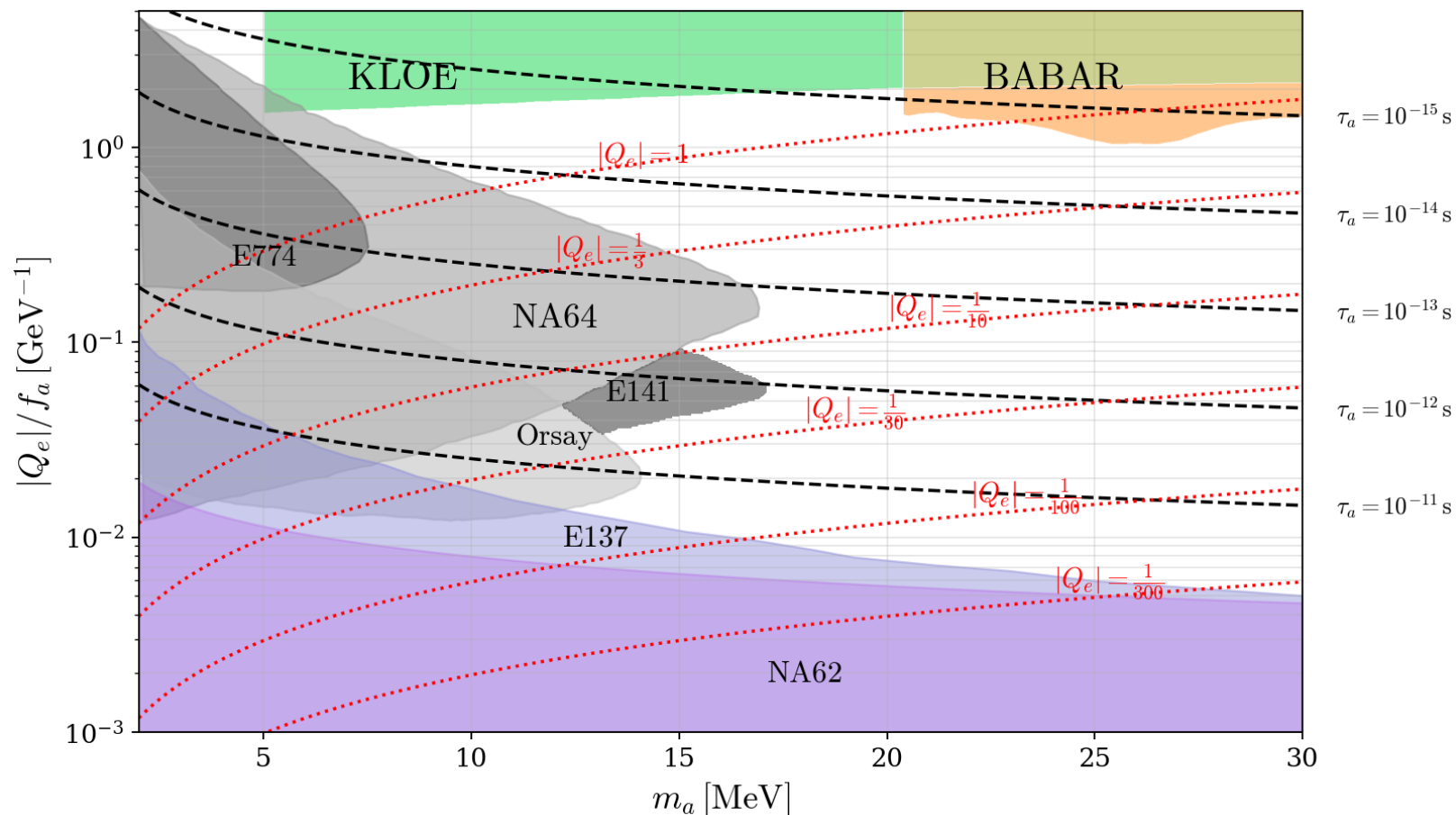
$$\theta_{a\pi} \lesssim (0.5 - 0.7) \times 10^{-4}$$

SINDRUM collaboration

$$\frac{m_u}{m_d} = 0.462 \pm 0.020 \quad (\text{PDG 2024})$$

if $\frac{Q_u}{Q_d} = 2 \rightarrow \theta_{a\pi} \sim 0$

Current Experimental Bound



Beam dump Experiments



$$8 \text{ MeV} \lesssim m_a \lesssim 30 \text{ MeV}$$



B Meson Decays

S. Nakagawa et.al.(2024)
JHEP 10, 153 (2024)

$K_L \rightarrow \pi^0 \pi^0 e^+ e^-$ at KTeV

Branch of $K_L \rightarrow \pi^0 \pi^0 (a \rightarrow e^+ e^-)$

$$\text{Br}(K_L \rightarrow \pi^0 \pi^0 e^+ e^-) \lesssim 6.6 \times 10^{-9}$$

KTeV Collaboration

Surprisingly, despite the stringent KTeV bound, this constraint has been overlooked!!

$$\text{Br}(K_L \rightarrow \pi^0 \pi^0 a) \simeq 0.75 \left(\theta_{a\eta_{ud}} + \sqrt{2} \theta_{a\eta_s} \right)^2$$

D. S. M. Alves
Phys. Rev. D **103**, 055018

Leading order estimation

$$\text{Br}(K_L \rightarrow \pi^0 \pi^0 (a \rightarrow e^+ e^-)) \simeq 6 \times 10^{-6} \times \left(\frac{m_a}{10 \text{ MeV}} \right)^2$$

Branch of $K_L \rightarrow \pi^0 \pi^0 a$

$$\text{Br}(K_L \rightarrow \pi^0 \pi^0 e^+ e^-) \lesssim 6.6 \times 10^{-9} \quad \text{KTeV Collaboration}$$

This constraint cannot be applied directly

Information Obtained
from the Experiment



Upper Limit on
the Total Number of Events

$$\text{Number of incoming } K_L \times \text{Branching ratio} \times \text{Efficiency} = \text{Total Number of Events}$$

Efficiency

SM $\approx 0.2\%$

MeV Axion Model ???



Let's determine **the efficiency in the MeV Axion Model**
using a Monte Carlo simulation!

Simulation Flow

1. Simulate 3-body decay of K_L in rest frame



2. Inject K_L with given energy spectrum



3. Boost simulated decay products to lab frame

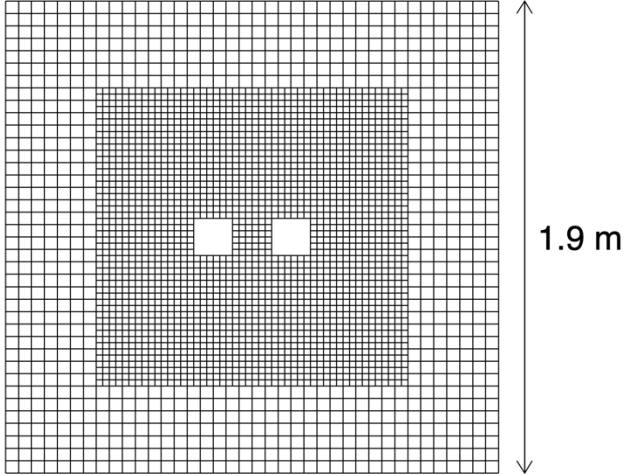
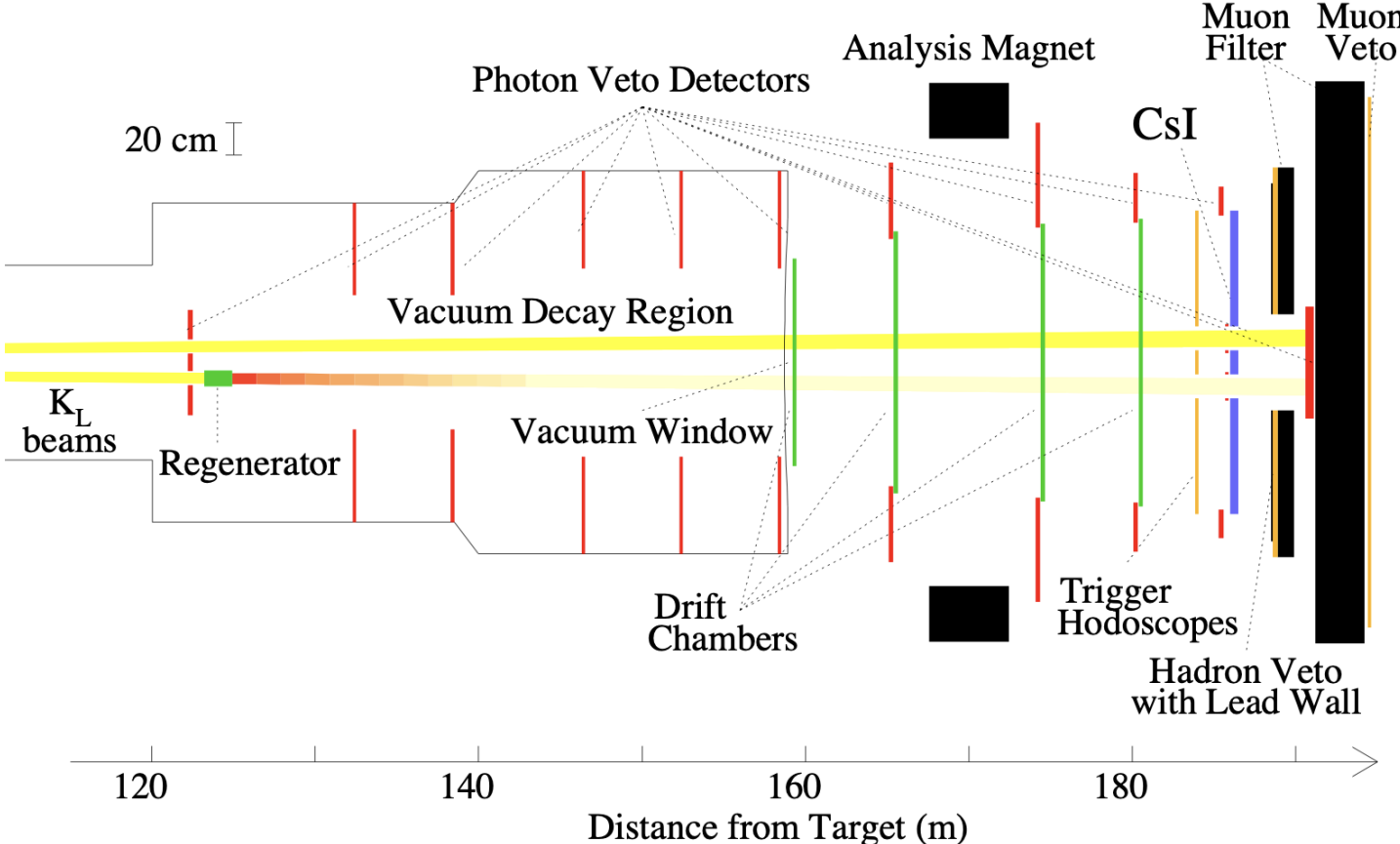


4. Simulate secondary decays: $\pi^0 \rightarrow \gamma\gamma$ $a \rightarrow e^+e^-$



5. Simulate detector hits of decay products

KTeV Experiment

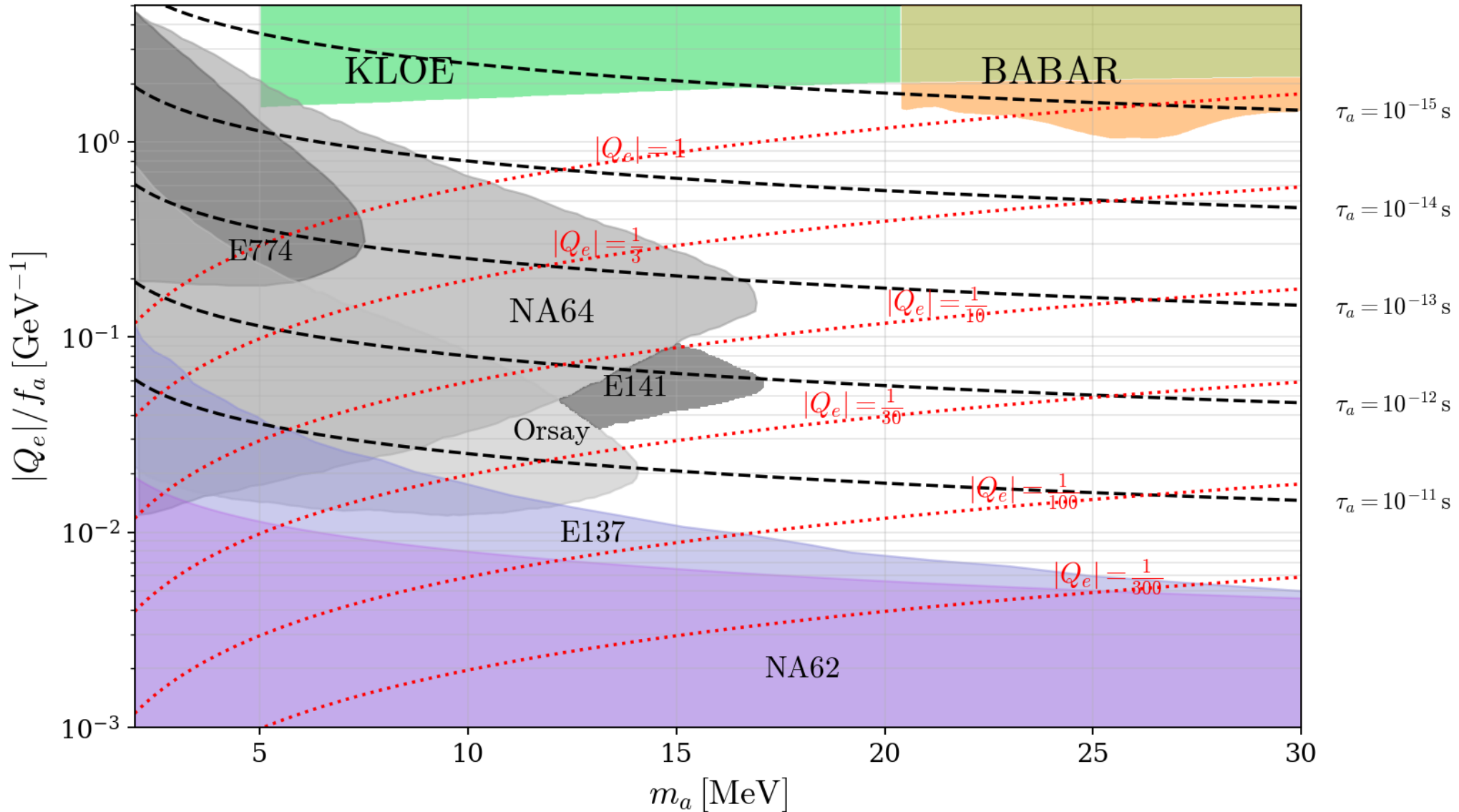


Step	Selection / Processing	Event count
1	Total number of incident K_L	1,000,000
2	Number of hit events	5,812
3	After applying cuts: $0.493 \leq M_{\pi^0\pi^0e^+e^-} \leq 0.501$, $p_x^2 + p_y^2 \leq 1.5 \times 10^{-4}$	5,561
4	Removal of $K_L \rightarrow \pi^0\pi^0(\pi^0 \rightarrow e^+e^-e^+e^-)$ background Apply cut $M_{ee} > 0.10 \text{ GeV}/c^2$	5,561
5	Removal of $K_L \rightarrow \pi^0\pi^0(\pi^0 \rightarrow e^+e^-\gamma)$ background Apply cut $M_{ee} > 0.045 \text{ GeV}/c^2$	3,119
6	Removal of $K_L \rightarrow \pi^0\pi^0(\pi^0 \rightarrow \gamma(\gamma \rightarrow e^+e^-))$ background Apply cut on $M_{e\gamma}$ within $0.115\text{--}0.145 \text{ GeV}/c^2$, and require remaining $\gamma\gamma$ to satisfy $m_{\pi^0} \pm 3 \text{ MeV}/c^2$	2,648
—	Final number of events	2,648

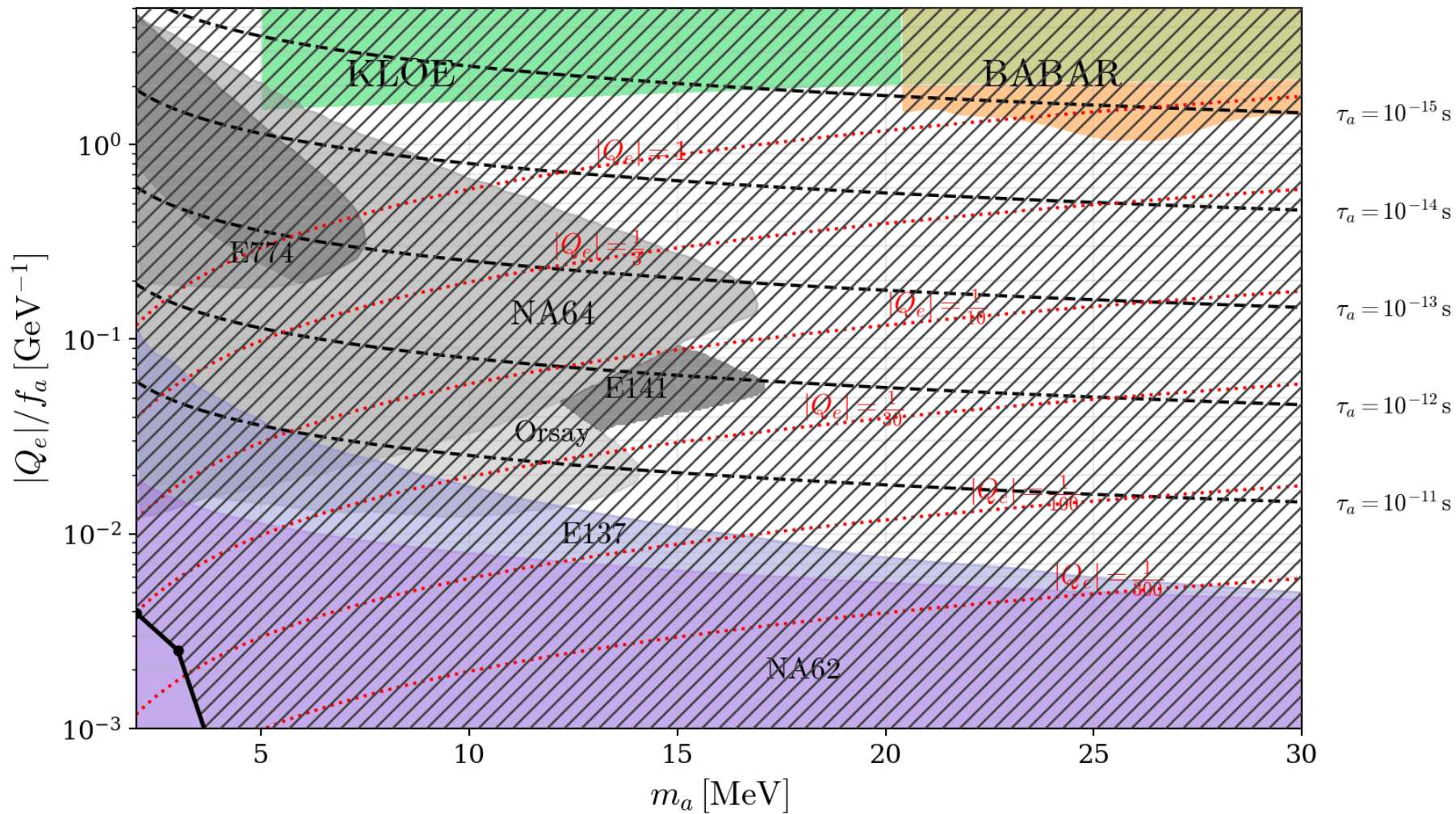
➔ **Efficiency(MeV Axion) $\approx 0.26\%$**

Efficiency(SM) $\approx 0.18\%$

Result

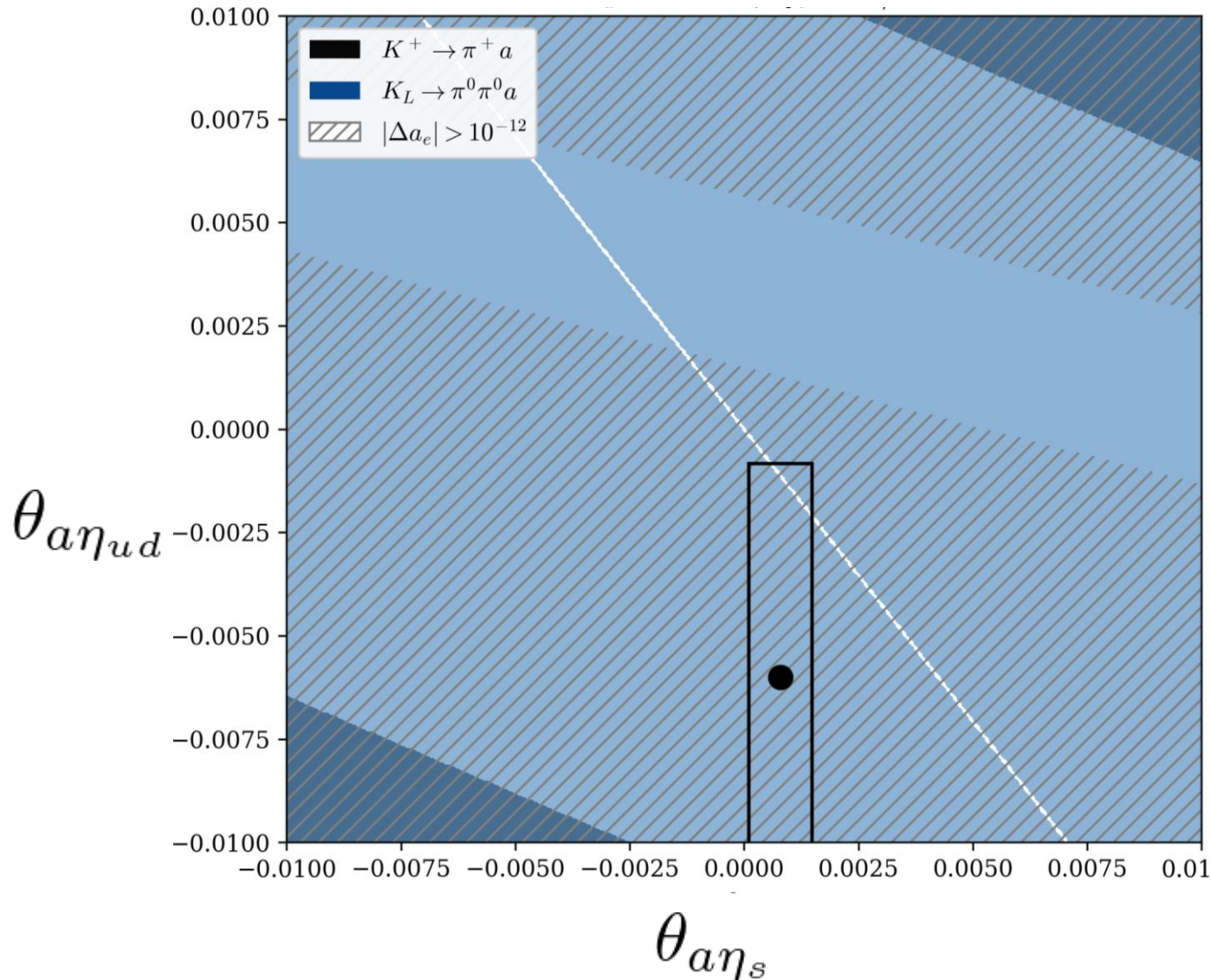


Result



All region is excluded!

Result



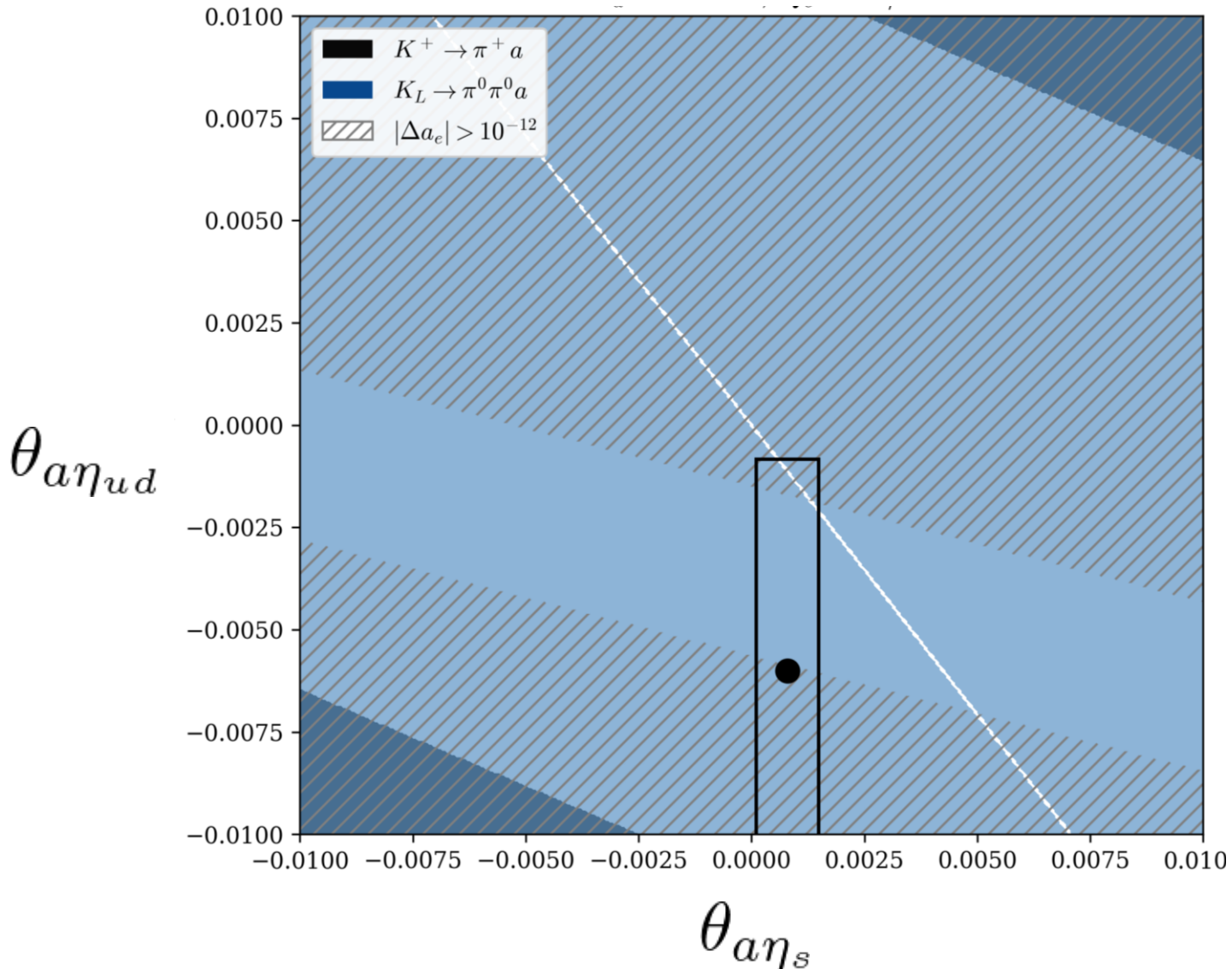
$$m_a = 17 \text{ MeV}$$

$$Q_e = \frac{1}{3}$$

$$\text{Br}(K_L \rightarrow \pi^0 \pi^0 a) \simeq 0.75 (\theta_{a\eta_{ud}} + \sqrt{2} \theta_{a\eta_s})^2$$

$$\text{Box: } \frac{2m_K}{\Lambda}$$

Result



$$m_a = 17 \text{ MeV}$$

$$Q_e = -\frac{1}{3}$$

$$\text{Br}(K_L \rightarrow \pi^0 \pi^0 a) \simeq 0.75 (\theta_{a\eta_{ud}} + \sqrt{2} \theta_{a\eta_s})^2$$

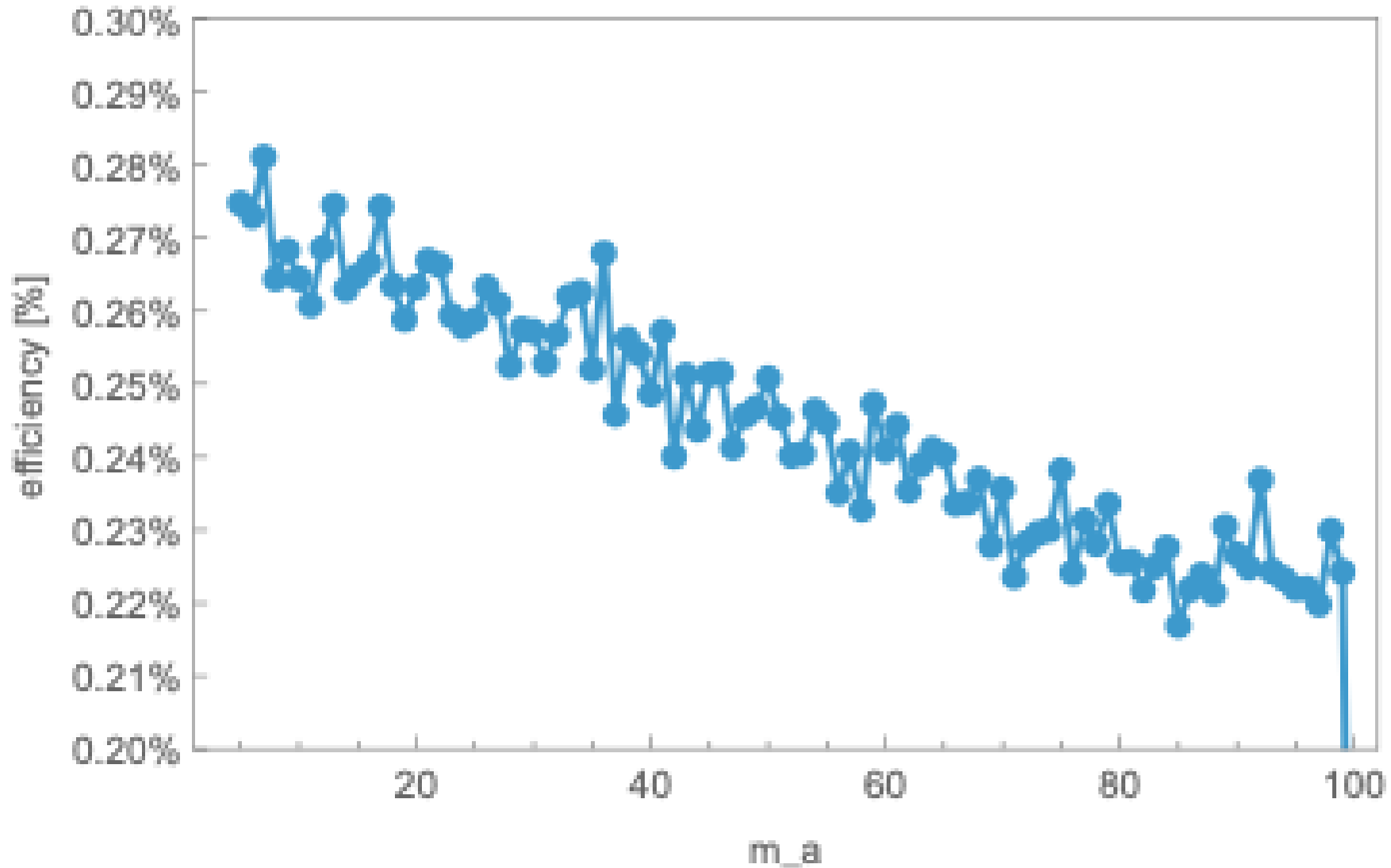
$$\text{Box: } \frac{2m_K}{\Lambda}$$

Summary

- The KTeV experiment places strong constraint on MeV axion model
- In LO estimation, we obtained the efficiency sufficient to exclude the MeV axion model.
- Even after taking into account the uncertainties of χ^2_{PT} , an extreme tuning is required.

Back up

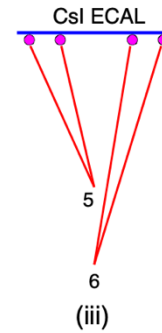
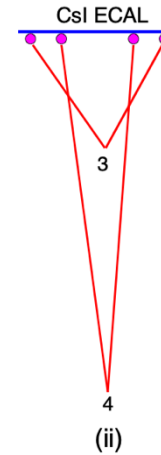
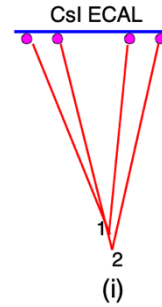
Efficiency plot



$$\chi^2 = \chi_{trac}^2 + \chi_{cal}^2$$

$$\chi_{trac}^2 = \sum_{i=1,2} \sum_{DC=1,2} \left(\frac{[x_{DC}^i - s_x^i(z_{DC}^i - z_v)]^2}{\sigma_x^2} + \frac{[y_{DC}^i - s_y^i(z_{DC}^i - z_v)]^2}{\sigma_y^2} \right)$$

$$\chi_{cal}^2 = \frac{(z_A - z_v)^2}{\sigma_A^2} + \frac{(z_B - z_v)^2}{\sigma_B^2}$$



$$K_L \rightarrow \pi^0 \pi^0 a$$

$$d\Phi_3 = \frac{1}{(2\pi)^9} \prod_{i=1}^3 \frac{d^3 p_i}{2E_i} \delta^4(P - p_1 - p_2 - p_3)$$

$$d\Phi_3 = (2\pi)^3 \int ds_{12} d\Phi_2(P \rightarrow q, p_3) d\Phi_2(q \rightarrow p_1, p_2)$$

Chiral Lagrangian

$$\mathcal{L}_a^{\text{eff}} = m_u e^{iQ_u^{PQ} a/f_a} u u^c + m_d e^{iQ_d^{PQ} a/f_a} d d^c + m_e e^{iQ_e^{PQ} a/f_a} e e^c$$

Chiral Lagrangian

$$\mathcal{L}_\chi^{(0)} = \frac{f_\pi^2}{4} \text{Tr}[2BM_q(a)U + h.c.] - \frac{1}{2} M_0^2 \eta_0^2$$

$$M_q(a) \equiv \begin{pmatrix} m_u e^{iQ_u^{PQ} a/f_a} & & \\ & m_d e^{iQ_d^{PQ} a/f_a} & \\ & & m_s \end{pmatrix}$$

$$U \equiv \exp\left(i \frac{\sqrt{2}}{f_\pi} \Sigma\right)$$

$$\Sigma \equiv \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta_8}{\sqrt{6}} + \frac{\eta_0}{\sqrt{3}} & & \pi^+ & K^+ \\ & \pi^+ & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta_8}{\sqrt{6}} + \frac{\eta_0}{\sqrt{3}} & K^0 \\ & K^- & \overline{K^0} & -\frac{\eta_8}{\sqrt{3/2}} + \frac{\eta_0}{\sqrt{3}} \end{pmatrix}$$

Constraint of decays of Kaon

Existing bound

$$\text{Br}(K^+ \rightarrow \pi^+ a \rightarrow \pi^+ e^+ e^-) \leq 10^{-6} - 10^{-5} \quad \text{D. S. M. Alves et.al. JHEP 07, 092 (2018)}$$

$$\text{Br}(K^+ \rightarrow \pi^+ a) \Big|_{a-\pi \text{ mixing}} = \theta_{a\pi}^2 \text{Br}(K^+ \rightarrow \pi^+ \pi^0) \approx 10^{-9}$$

Pion Phobia

 **$a - \eta_{8,0}$ mixing is main contribution**

$$\mathcal{M}(K^+ \rightarrow \pi^+ a) \Big|_{a-\eta_{8,0} \text{ mixing}} = \theta_{a\eta_8} \mathcal{M}(K^+ \rightarrow \pi^+ \eta_8) + \theta_{a\eta_0} \mathcal{M}(K^+ \rightarrow \pi^+ \eta_0)$$

Octet enhancement

$$\mathcal{L}_\chi^{\Delta S=1} \Big|_{\mathcal{O}(p^2)} = g_8 f_\pi^2 \text{Tr}[\lambda_{ds} \partial_\mu U \partial^\mu U^\dagger] + g_{27} f_\pi^2 C_{ab} \text{Tr}[\lambda_a \partial_\mu U U^\dagger \lambda_b \partial^\mu U U^\dagger] + h.c.$$

$$\frac{\Gamma(K_S^0 \rightarrow \pi\pi)}{\Gamma(K^+ \rightarrow \pi^+\pi^0)} \approx 668 \quad \frac{g_8}{g_{27}} \cong 31.2$$



If we consider $\mathcal{O}(p^4)$ expansion

$$|\theta_{a\eta_{ud}}|_{\text{octet enh.}} \leq (1.7 - 5.3) \times 10^{-4}$$

$$\mathcal{L}_\chi^{\Delta S=1} \Big|_{\mathcal{O}(p^4)} \supset g'_8 \frac{f_\pi^2}{\Lambda^2} \text{Tr}[\lambda_{ds} M_q U] \text{Tr}[\partial_\mu U \partial^\mu U^\dagger] + h.c.$$

$$\frac{g_8}{g_{27}} \sim \mathcal{O}(1) \quad \frac{g'_8}{g_{27}} \sim \mathcal{O}(100)$$

$$|\theta_{a\eta_{ud}}|_{\text{not octet enh.}} \leq (0.5 - 1.6) \times 10^{-2}$$