Flavor-Violating Axions: From the Lab to the Cosmos

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Introduction

Axions are well motivated theoretical particles that can explain the observed smallness of the neutron electric dipole moment through their CP-violating coupling to gluons. More generally, axion-like particles (ALPs) can couple to standard-model fermions, potentially giving rise to charged lepton flavor violation (CLFV). The most general ALP Lagrangian contains the terms

$$\mathcal{L}_{\mathrm{ALP}} \supset \frac{\partial_\alpha a}{2f_a}\bar{e}\gamma^\alpha\left(C^V_{e\mu} + C^A_{e\mu}\gamma_5\right)\mu$$

allowing, for example, a muon to decay to an electron + ALP (if kinematically allowed), as shown in Fig. 1 (a).

The theory is specified by 4 unknown parameters

- ALP mass m_a
- ALP decay constant f_a
- Vector $C^V_{e\mu}$ and axial $C^A_{e\mu}$ couplings

Depending on the ALP mass, different CLFV processes — in both laboratory and astrophysical settings — can be used to constrain the ALP parameters. We summarize and compare these limits.

Astrophysical Limits

- Axion production in stellar environments can lead to anomalous cooling
- Extreme electron degeneracy leads to significant muon populations in proto-neutron stars
- If $m_a < m_\mu + m_e$, muon can decay to ALP + electron
- For reasonable assumptions in SN1987A, energy loss rate ε is given by [1]

$$\varepsilon \approx 10^{19}\,\frac{\mathrm{erg}}{\mathrm{gs}}\left(\frac{BR(\mu\to ea)}{4\times10^{-3}}\right)$$

- Energy loss can be compared to Raffelt criterion [2] $\varepsilon \lesssim 10^{19}$ erg g^{-1} s^{-1} to constrain ALP parameters, as shown in Fig. 2.
- Bremsstrahlung process $\mu + p \to e + a + p$ can probe heavier ALPs, but is still highly suppressed for $m_a > m_\mu$ [3].

Laboratory Limits

Light ALPs ($m_a \lesssim m_\mu$)

- If $m_a \lesssim m_\mu$, then $\mu\to e+a$ is allowed and can be constrained by detecting the outgoing electrons
- Requires spin-polarized muons in order to distinguish from $\mu\to e+2\nu$ backgrounds
- Future CLFV experiments Mu3e and MEGII can be modified slightly to constrain this process [1]
- Resulting limits on f_a, shown in Fig. 2, are ≈ 2 orders of magnitude stronger than astrophysical constraints
- Sensitivity of lab experiments does depend on whether ALPS are right-handed $(C^V_{e\mu} = -C^A_{e\mu})$, left-handed $(C^V_{e\mu} = C^A_{e\mu})$, or isotropic $(C^V_{e\mu} = 0 \text{ or } C^A_{e\mu} = 0)$
- Branching ratios BR($\mu\to ea$)$\lesssim 7\times10^{-7}$, 7×10^{-8} for MEGII-fwd* and Mu3e-online, respectively.

Heavy ALPs ($m_a \gtrsim m_\mu$)

If $m_a > m_\mu$, kinematics forbid the decay $\mu\to e+a$, but we can obtain constraints from μ→e conversion mediated by a virtual ALP, as shown in Fig. 1(b). The ALP interaction with the nucleus can arise from either the CP-odd gluonic coupling or a coupling to light quarks

$$\mathcal{L}_{\mathrm{ALP}} \supset \frac{\alpha_s}{8\pi}\frac{1}{f_a}aG^a_{\mu\nu}\tilde{G}^{a\mu\nu} + \sum_{q=u,d,s} C^A_q\frac{\partial_\mu a}{2f_a}\bar{q}\gamma^\mu\gamma_5 q,$$

which introduces 3 new unknown couplings C^A_u, C^A_d, C^A_s

- Future experiments Mu2e and COMET could probe BR($\mu + A\to e + A$) $\lesssim 10^{-17}$ with ^{27}Al target
- Leading contribution couples to nuclear spin [4], requiring knowledge of nucleon pseudoscalar $F^{q/N}_P$ and gluonic $F^N_{\tilde{G}}$ form factors [5]
- Limits on f_a from μ→e conversion are much weaker than $\mu\to e+a$ because Fig. 1(b) is suppressed by $1/f_a^2$, compared to $1/f_a$ for Fig. 1(a)

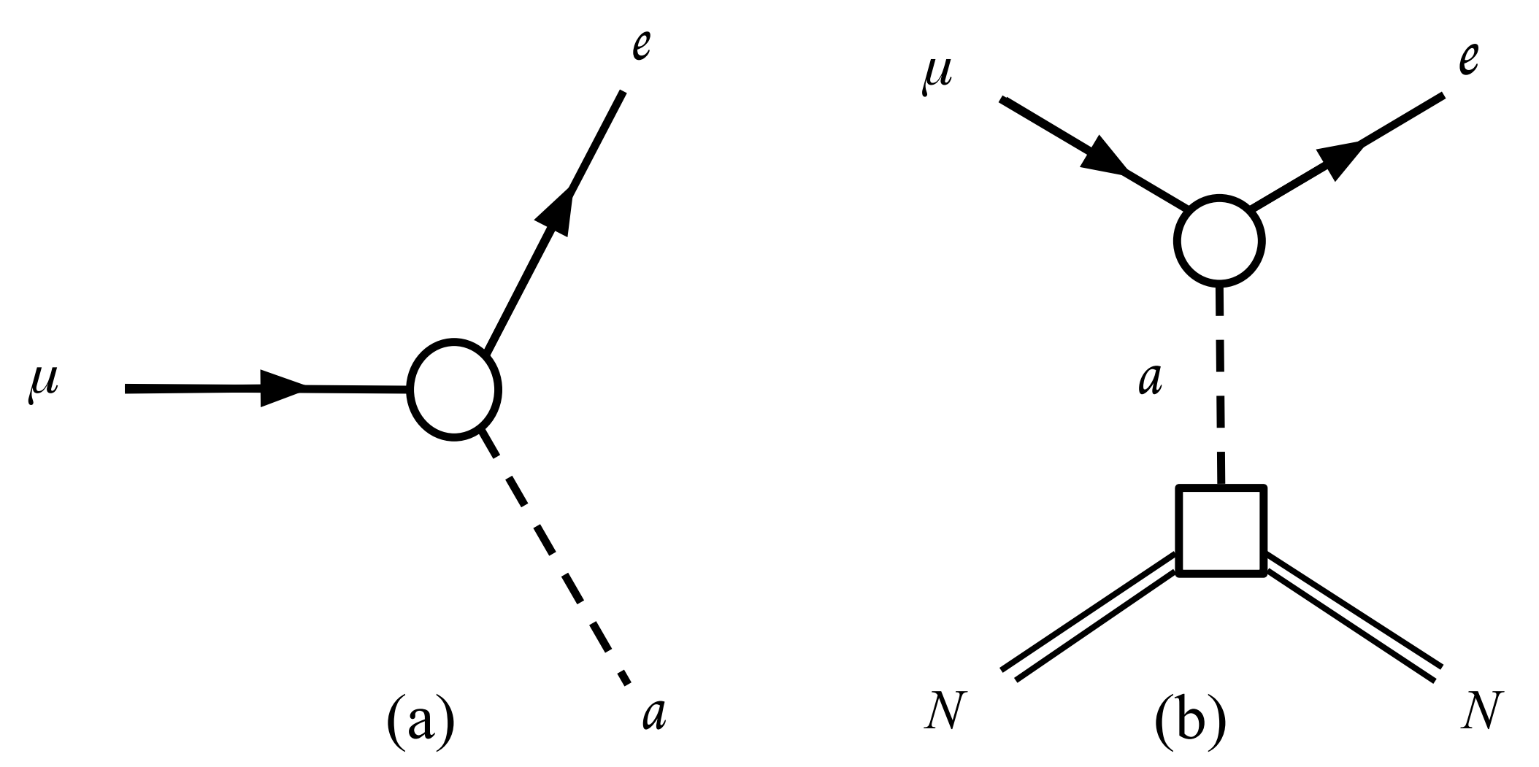

Figure 1: Feynman diagrams for (a) CLFV decay μ→e+a.
(b) Conversion process μ+(A,Z)→e+(A, Z)

Results

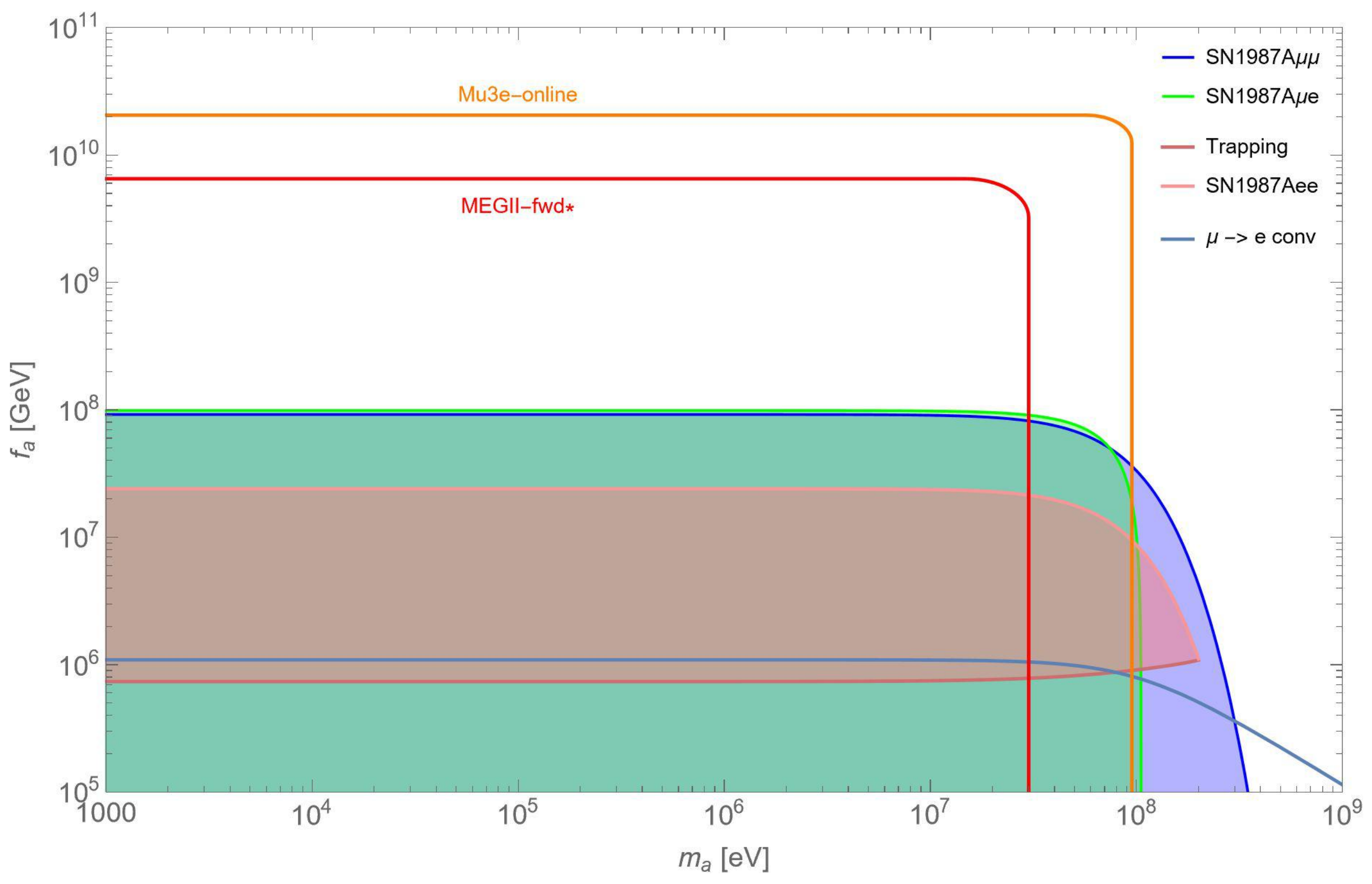

Figure 2: Limits on CLFV ALPs from astrophysics (SN1987A) and laboratory measurements (Mu3e-online, MEGII-fwd* and Mu2e/COMET).

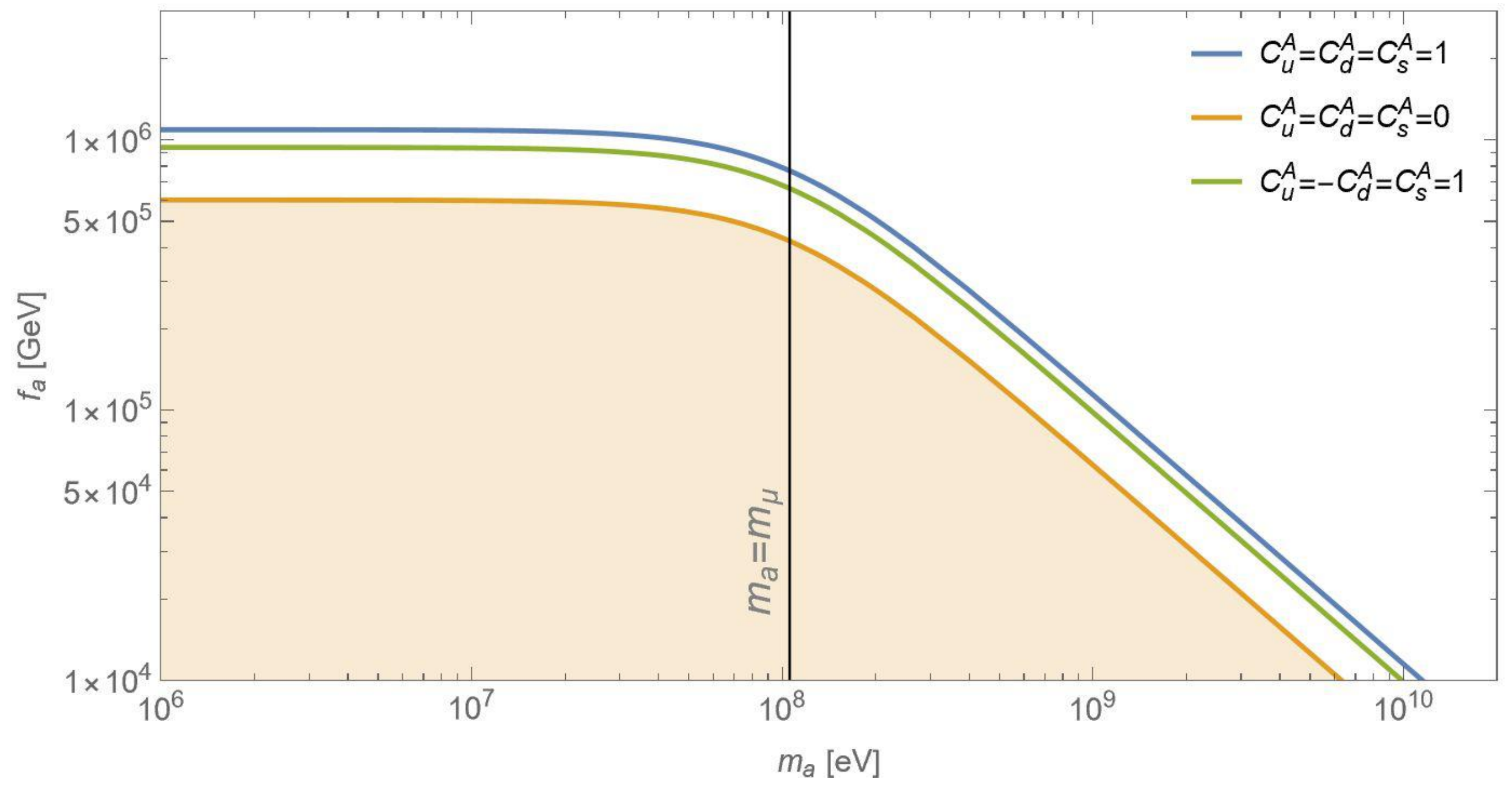

Figure 3: Limits on CLFV ALPs from μ→e conversion for three scenarios.

Conclusions

If axion-like particles exist in nature, they generically couple to standard-model leptons in a manner that violates flavor. The ideal probe for constraining such interactions depends on the mass of the axion. In all cases, laboratory constraints are more severe than astrophysical limits. For $m_a \lesssim m_\mu$, dedicated searches for the muon decay $\mu\to e+a$ can constrain $f_a \gtrsim 10^{10}$ GeV. For $m_a \gtrsim m_\mu$, the best limits are typically obtained from $\mu\to e$ conversion, but these constraints are sensitive to the ALP/quark couplings, including special cases where the conversion rate vanishes.

Acknowledgements

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