
Light ALPs and Lepton Flavor Violation in Muonic Atoms

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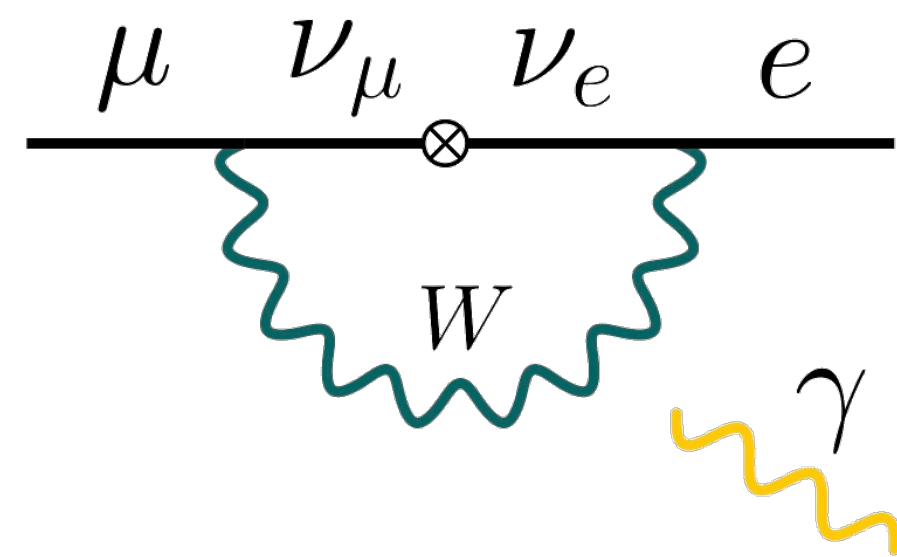
Ref.: [arXiv:2604.07481](https://arxiv.org/abs/2604.07481) with Alexey Petrov

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Charged LFV is a clean NP signal

- Neutrino oscillations show that lepton flavor is not conserved.
- But charged-lepton flavor violation is essentially absent in the SM.



$$\mathcal{B}(\mu \rightarrow e\gamma) \sim 10^{-54}$$

- Detection would be definite signal of new physics

Active experimental Landscape

- Current best limit on charged LFV

$$\mathcal{B}(\mu \rightarrow e\gamma) \leq 1.5 \times 10^{-13} \text{ (90\% CL)}$$

MEG II (2025)

- Most progress in upcoming $\mu \rightarrow 3e$ and stopped-muon experiments

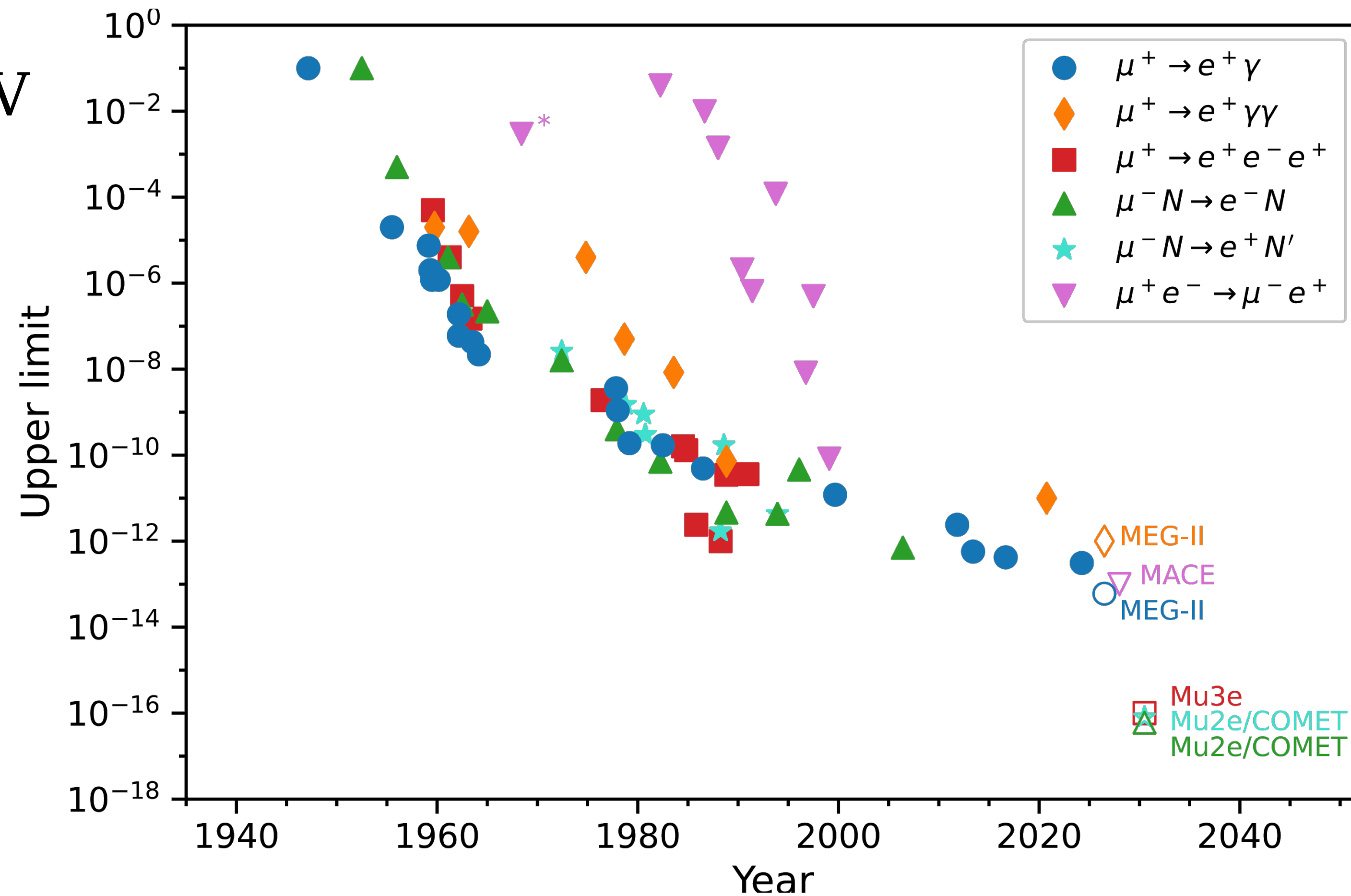
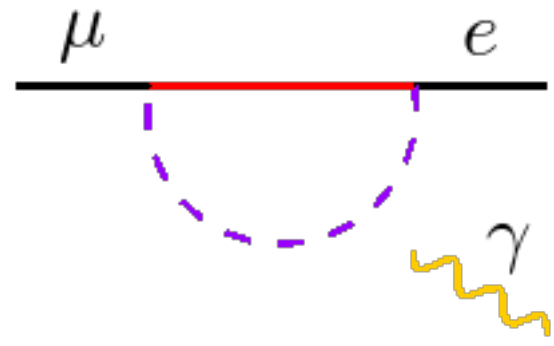
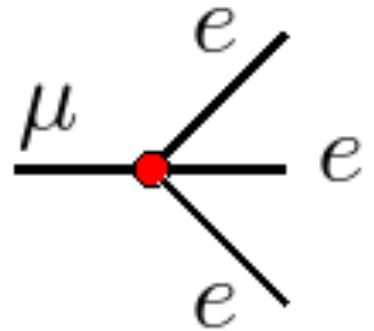
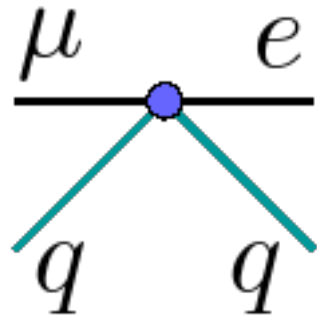


FIGURE FROM ECHENARD, PETROV, ARXIV: 2602.12442

Many LFV probes, different new-physics directions

Different LFV channels probe complementary pieces of new physics.

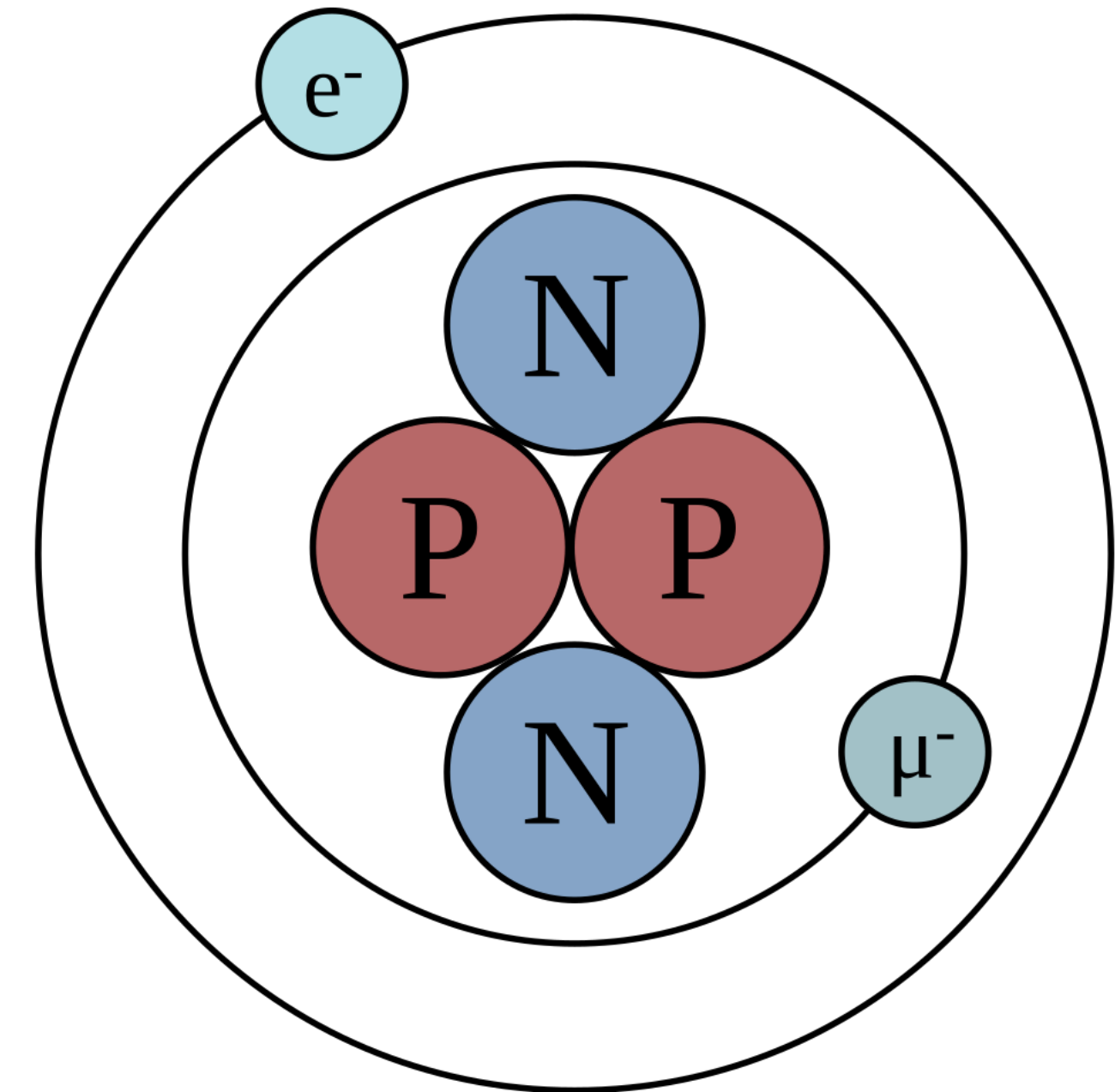
$\mu \rightarrow e\gamma$	dipole operators	
$\mu \rightarrow 3e$	four-lepton interactions dipole operators	
$\mu \rightarrow e$ conversion	quark / nuclear couplings dipole operators	

Muonic atoms give another LFV opportunity

- A captured negative muon replaces an atomic electron to form a muonic atom.
- It can then interact with a bound electron:



- This gives a charged-particle-only LFV signal in the same environment as $\mu \rightarrow e$ conversion.



CREDIT: WIKIPEDIA

Why look for $\mu^- e^- \rightarrow e^- e^-$

- two charged electrons, no photon
- larger phase space than $\mu \rightarrow 3e$
- μ and e wave-function overlap increases in heavy muonic atoms
- sensitive to both short- or long-lived light particles

Heavy vs. light new physics

- Heavy new physics frameworks

$$\frac{1}{\Lambda^2} (\bar{e} \Gamma \mu) (\bar{e} \Gamma e) \begin{array}{l} \nearrow \mu \rightarrow 3e \\ \searrow \mu e \rightarrow ee \end{array}$$

- Always related to $\mu \rightarrow 3e$
- A light NP mediator can change this expectation

$$\mu \rightarrow e\phi, \phi \rightarrow ee$$

- If ϕ is long-lived \Rightarrow may escape detection in $\mu \rightarrow 3e$ exp.

ALP model

- We consider a simplified ALP interaction with charged leptons:

$$\mathcal{L}_{al\ell} \supset a \bar{e} \left(g_{e\mu}^S + g_{e\mu}^P \gamma_5 \right) \mu + a \bar{e} g_{ee}^P \gamma_5 e + \text{h.c.}$$

- Contains both flavor violating and flavor-conserving couplings
- We also consider (optionally) ALP decay to a dark sector via $a \bar{\chi} \gamma_5 \chi$

Calculation details

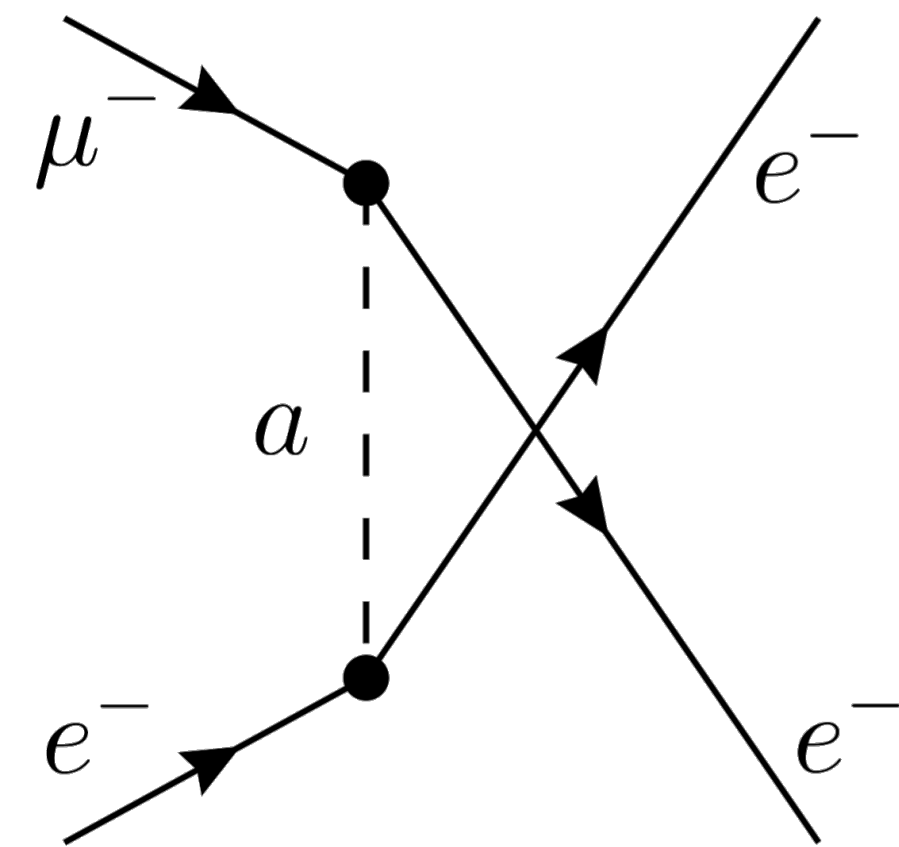
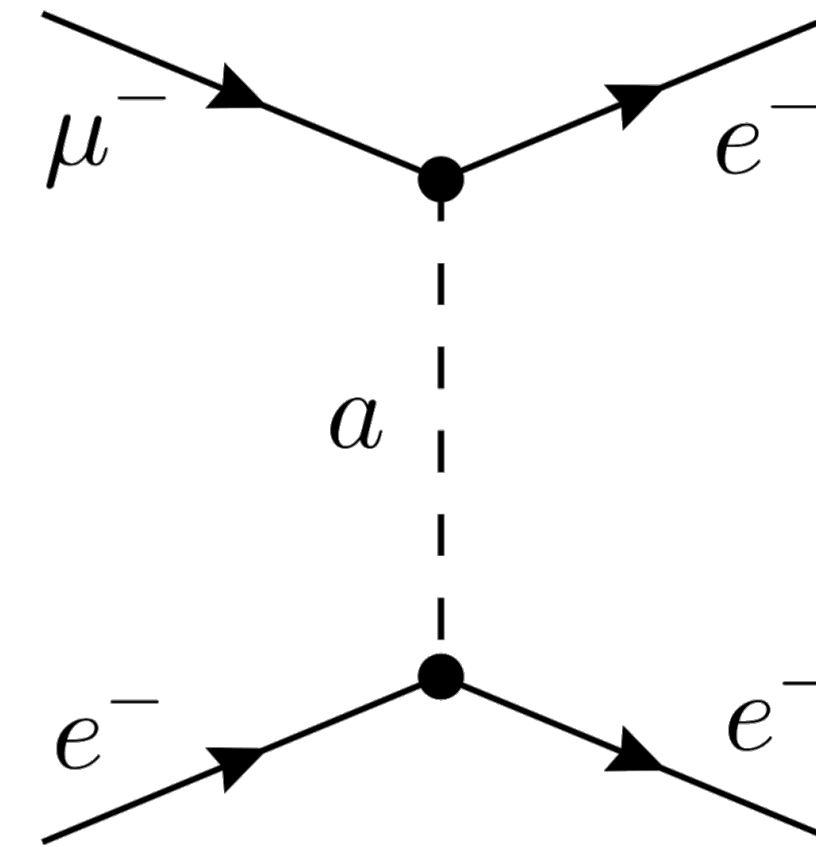
- ALP mediates at tree-level

$$\mathcal{M} \sim g_{e\mu} g_{ee} \times \frac{1}{q^2 - m_a^2} \times \text{atomic overlap}$$

- Approximations:

- 3-momenta of initial states ignored
- $Z\alpha_e \ll 1$

- Transition Rate = $2 |\psi_e(0)|^2 \sigma |\vec{v}_1 - \vec{v}_2|$



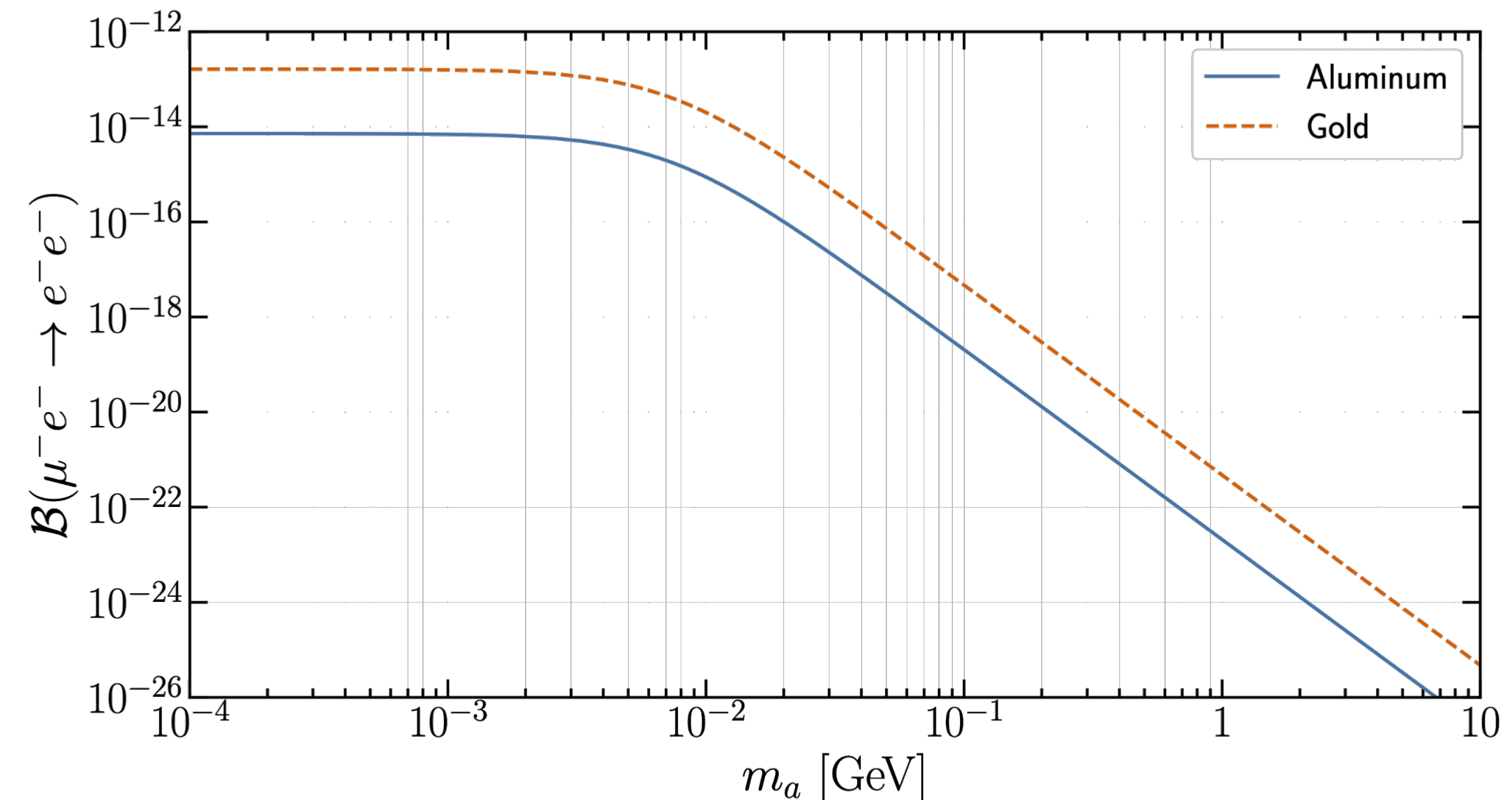
$$\psi_e(r) = \frac{e^{-r/a_e}}{\sqrt{\pi a_e^3}}$$

Heavier muonic atoms are better

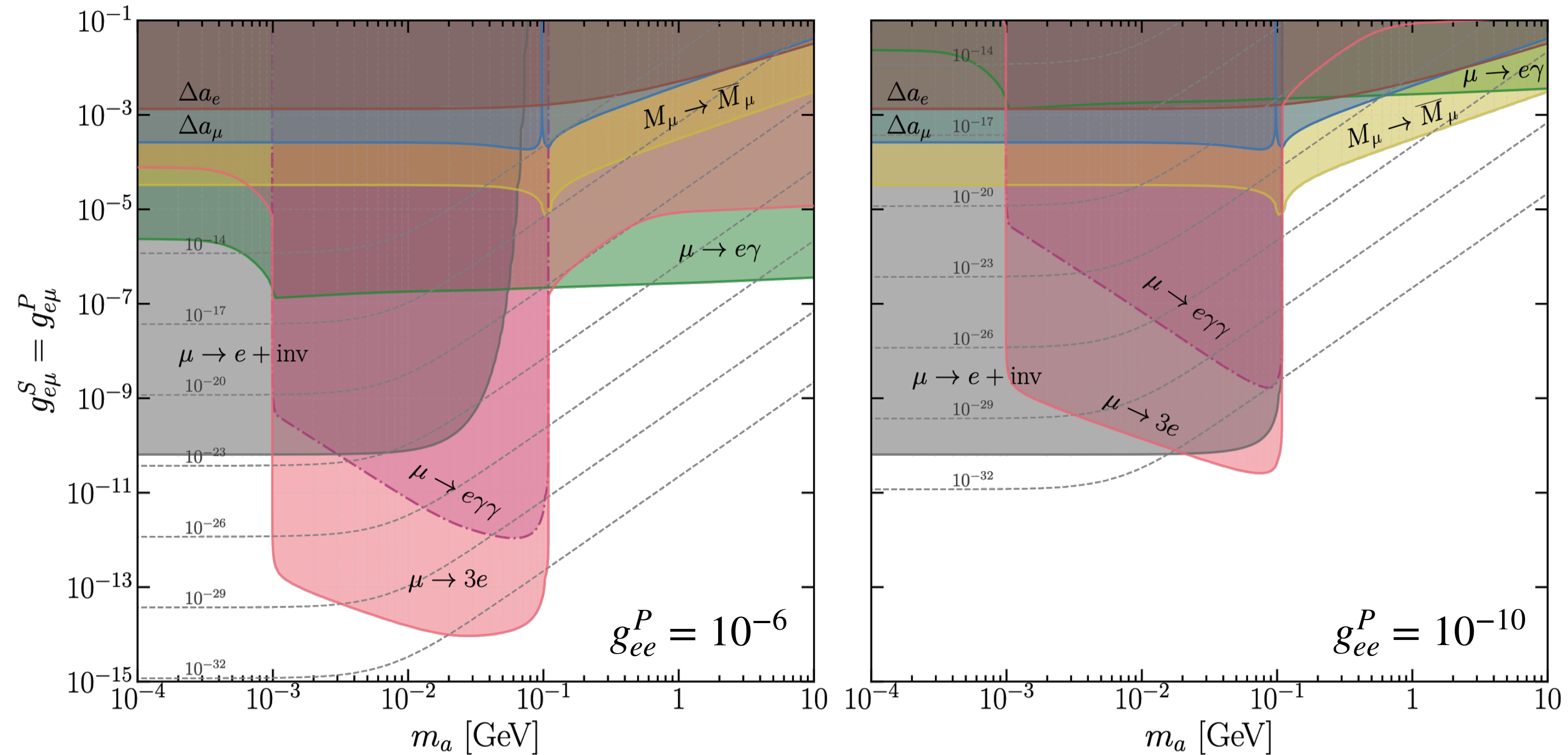
- Larger nuclear charge increases the wavefunctions overlap of bound leptons

$$\text{Transition rate} \propto (Z - 1)^3$$

- Lifetime of muonic atom also changes
 - Hydrogen: $\tilde{\tau}_\mu \sim 2.2 \mu\text{s}$
 - Aluminum: $\tilde{\tau}_\mu \sim 0.9 \mu\text{s}$
 - Gold: $\tilde{\tau}_\mu \sim 0.07 \mu\text{s}$

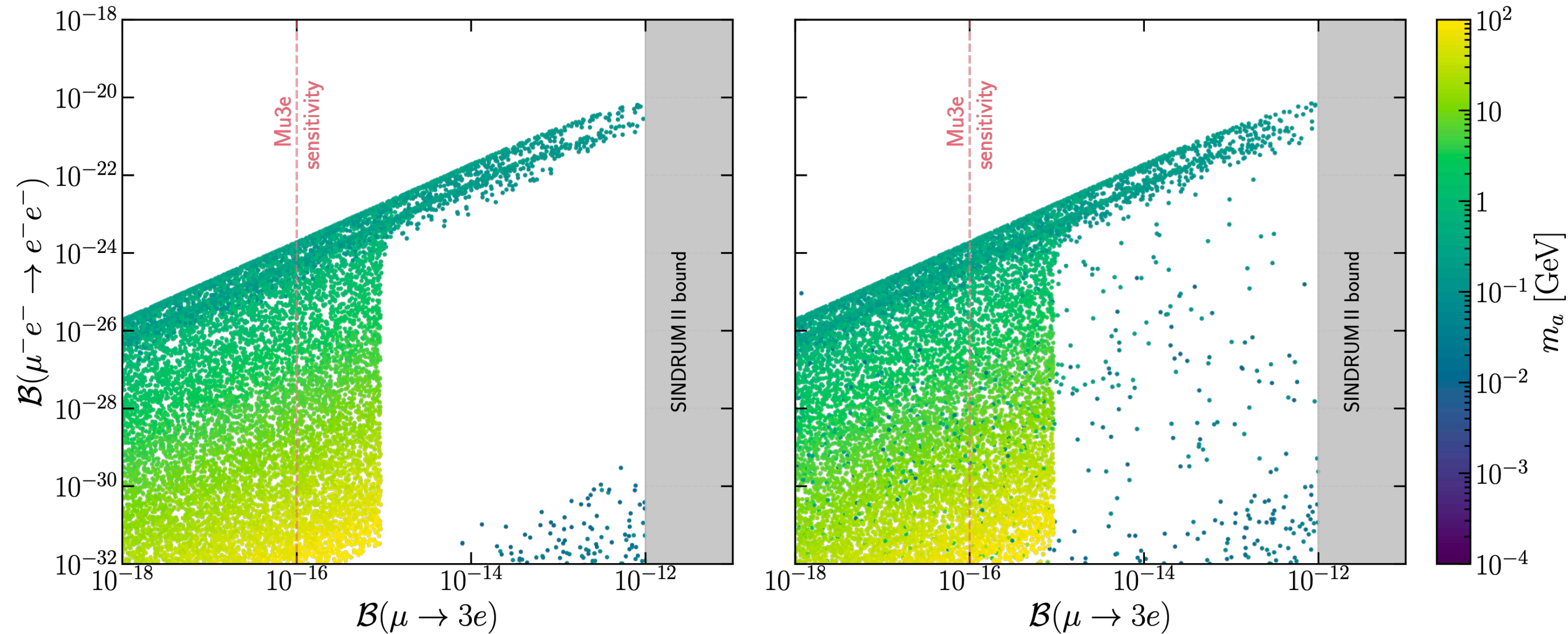


Light ALP mass region is strongly constrained



- Signal contours grow toward small m_a
- Existing LFV bounds remove much of this region.

Parameter scan: how large can the rate be?



- After applying LFV, Δa_ℓ , astrophysical, beam-dump constraints:
 $\mathcal{B}(\mu^- e^- \rightarrow e^- e^-)_{AI} \lesssim 10^{-20}$
- Largest rates occur near the current $\mu \rightarrow 3e$ current bound
- Invisible ALP decays do not significantly change this conclusion.

Summary

- Muonic atoms provide a complementary LFV channel $\mu^- e^- \rightarrow e^- e^-$.
- Light ALPs can enhance the transition rate.
- Existing constraints strongly limit the allowed parameter space.
- For aluminum, we find branching ratio $\mathcal{O}(10^{-20})$.
- The largest rates are correlated with $\mu \rightarrow 3e$.