g-2 from MeV ALPs

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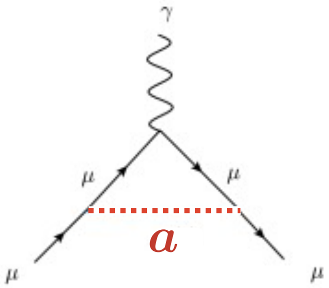
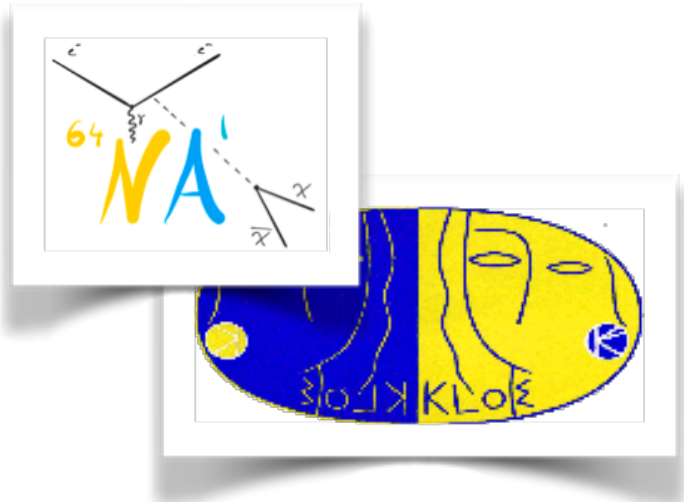




based on

arXiv:2011.08919 with D. Buttazzo, P. Panci and D. Teresi

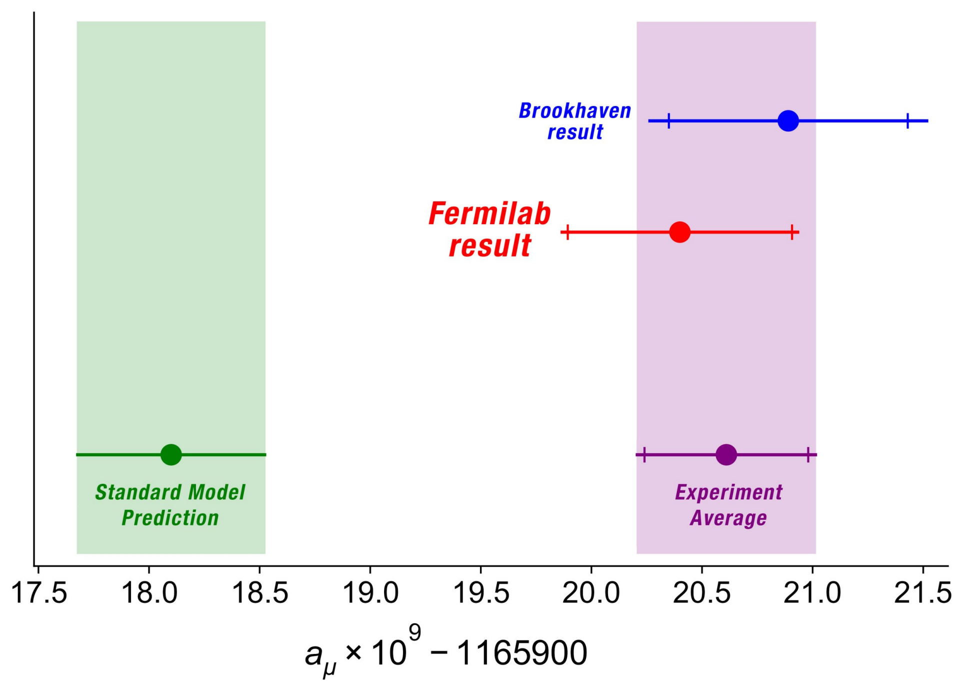
+ work in progress

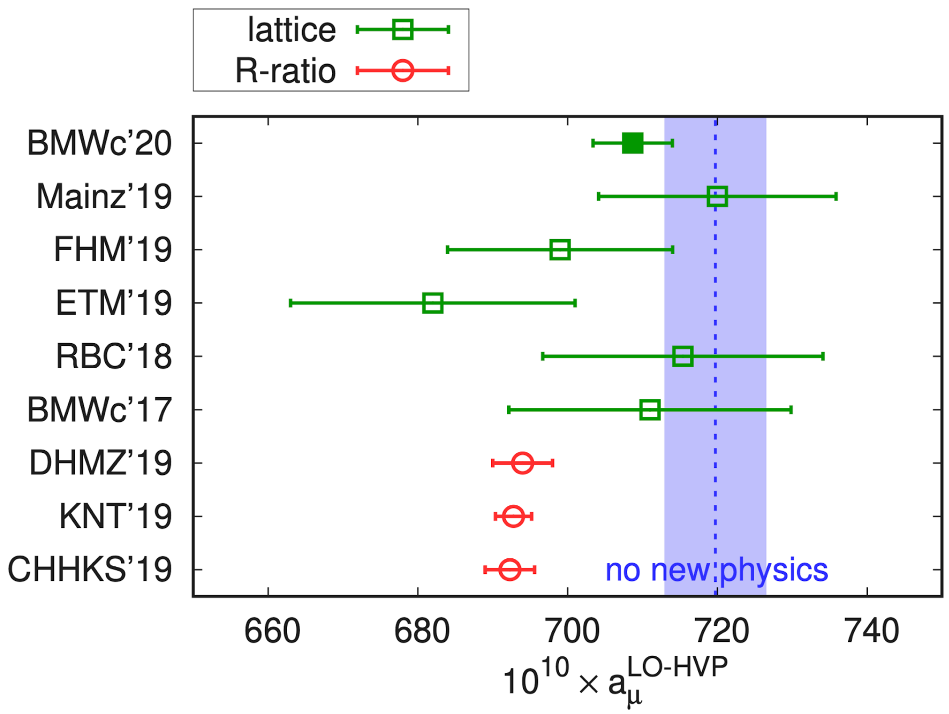
Portorož 2021

Karlsruher Institut für Technologie

The (g-2)$_\mu$ Anomaly

- New (g-2)$_\mu$ world average has 4.2σ tension with SM prediction, but disagreement between lattice vs. dispersive result for non-PT input





- Can be easily explained by new particles around electroweak scale

<u>In this talk</u>: MeV axion with electroweak decay constant

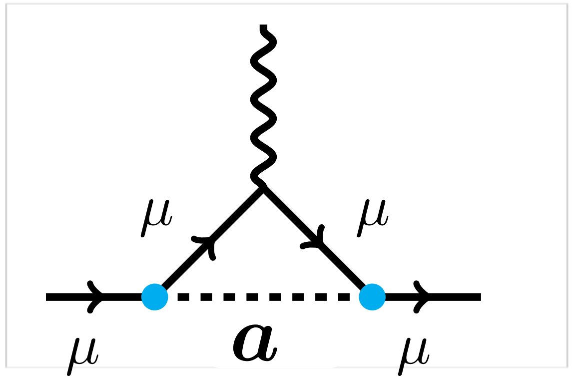
Axion couplings to Muons

- Consider axion couplings to pseudo-scalar muon current

$$\mathcal{L}_\mu = -i\frac{c_{\mu a}}{f_a} m_\mu a \bar{\mu}\gamma_5\mu = \frac{c_{\mu a}}{f_a}\frac{\partial_\mu a}{2}\bar{\mu}\gamma^\mu\gamma_5\mu - \frac{c_{\mu a}}{f_a}\frac{\alpha}{4\pi} aF\tilde{F}$$

axion-dependent chiral field redefinition
= EOM with anomaly term

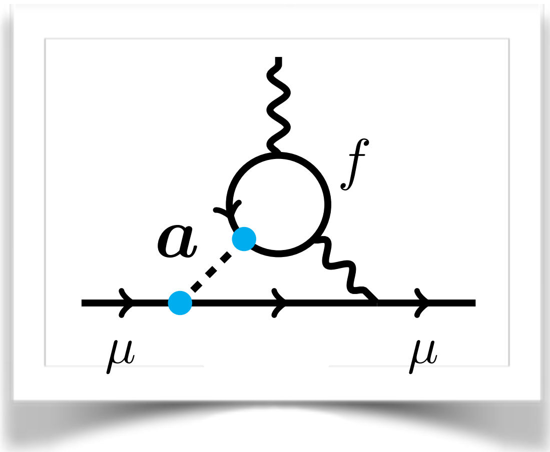
- Gives one-loop contribution to $(g\text{-}2)_\mu$ with wrong sign



$$\Delta a_\mu^{1-\text{loop}} = -\frac{m_\mu^2 c_{\mu a}^2}{64\pi^2 f_a^2} h_1\left(\frac{m_a^2}{m_\mu^2}\right) \quad \begin{cases} h_1(x \ll 1) = 1 \\ h_1(x \gg 1) \sim \log x/x \end{cases}$$

Axion couplings to Photons

- Consider also 2-loop Barr-Zee contributions from other fermions



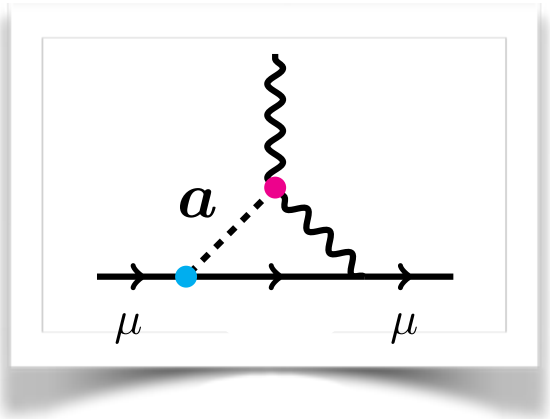
$$\Delta a_\mu^{2-\text{loop}} = N_c \frac{m_\mu^2 c_{\mu a} c_{fa}}{8\pi^2 f_a^2} \frac{\alpha}{\pi} g\left(\frac{m_a^2}{m_\mu^2}, \frac{m_a^2}{m_f^2}\right)$$

$$g(u,v) =: \int_0^1 dx dy dz \frac{ux}{u\bar{x} + uvxyz\bar{z} + vz\bar{z}x^2\bar{y}^2}$$

$$\xrightarrow{m_a \ll m_f, m_\mu} 3 + \log m_f^2/m_\mu^2$$

Get right sign when axion coupled to fermions with $c_{\mu a} \ll c_{fa}$

- Induce effective axion couplings to photons



✦ general IR result $(c_{\gamma a}, c_{\mu a})$ depends on cutoff

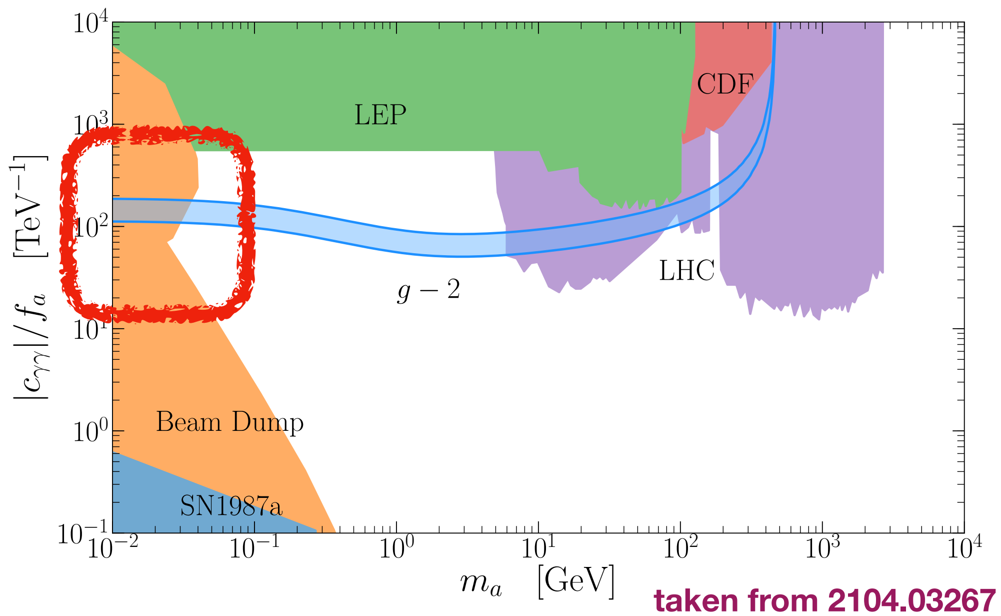
Marciano et al. ’17, Bauer et al, ’18, Buen-Abad et al. ‘21

✦ result for pseudoscalar couplings must be finite

Chang et al. ’00, generalized in 2011.08919

Axion couplings to Electrons

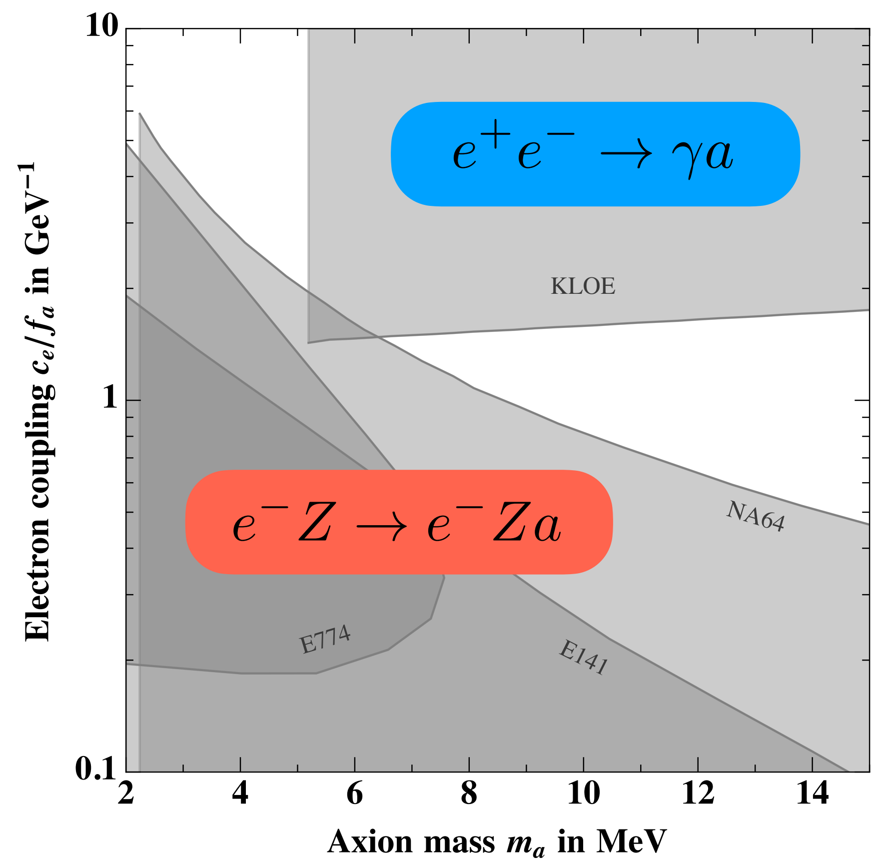
- Photon couplings of MeV axions are strongly constrained



taken from 2104.03267

…only if long-lived!

bounds disappear when axion decays promptly to electrons



- **Need sizable axion couplings to electrons** to avoid constraints from KLOE and beam dumps

Axion couplings to Taus

- Get 1-loop contribution to (g-2)$_e$ that is factor ~100 too large

$$\Delta a_e^{1-\text{loop}} = -\frac{m_e^2 c_{ea}^2}{64\pi^2 f_a^2} h_1\left(\frac{m_a^2}{m_e^2}\right) \quad \begin{cases} h_1(x \ll 1) = 1 \\ h_1(x \gg 1) \sim \log x / x \end{cases} \leftarrow$$

…but can tune against Barr-Zee contribution needed for (g-2)$_\mu$

$$\Delta a_e^{2-\text{loop}} = N_c \frac{m_e^2 c_{ea} c_{fa}}{8\pi^2 f_a^2}\frac{\alpha}{\pi} g\left(\frac{m_a^2}{m_e^2}, \frac{m_a^2}{m_f^2}\right) \xrightarrow{m_e \ll m_a \ll m_f} 2 + \log m_f^2/m_a^2$$

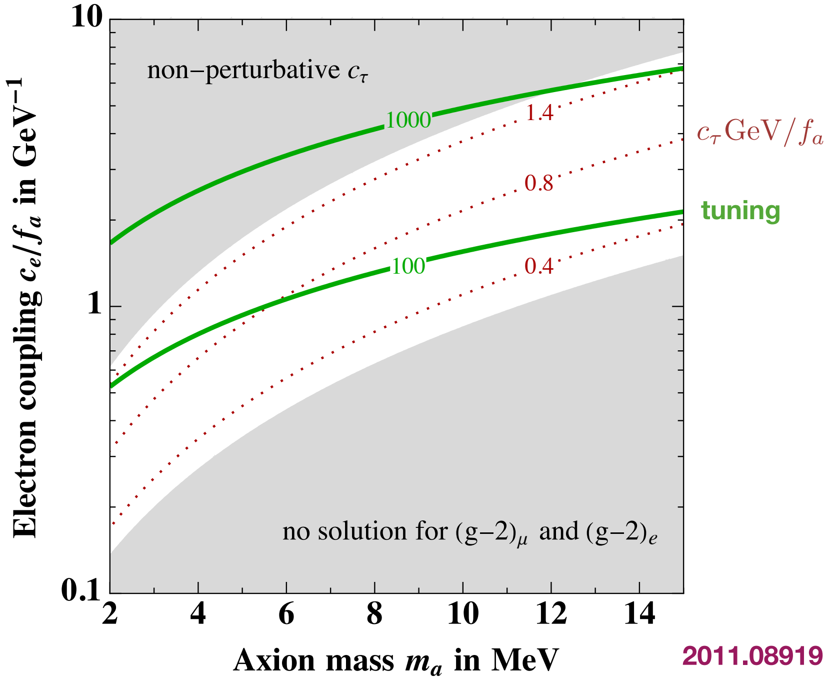
- 4-parameter model with couplings to all leptons

mu+tau couplings fixed to reproduce (g-2)$_{\mu,e}$

with single tuning of 1%, not always possible

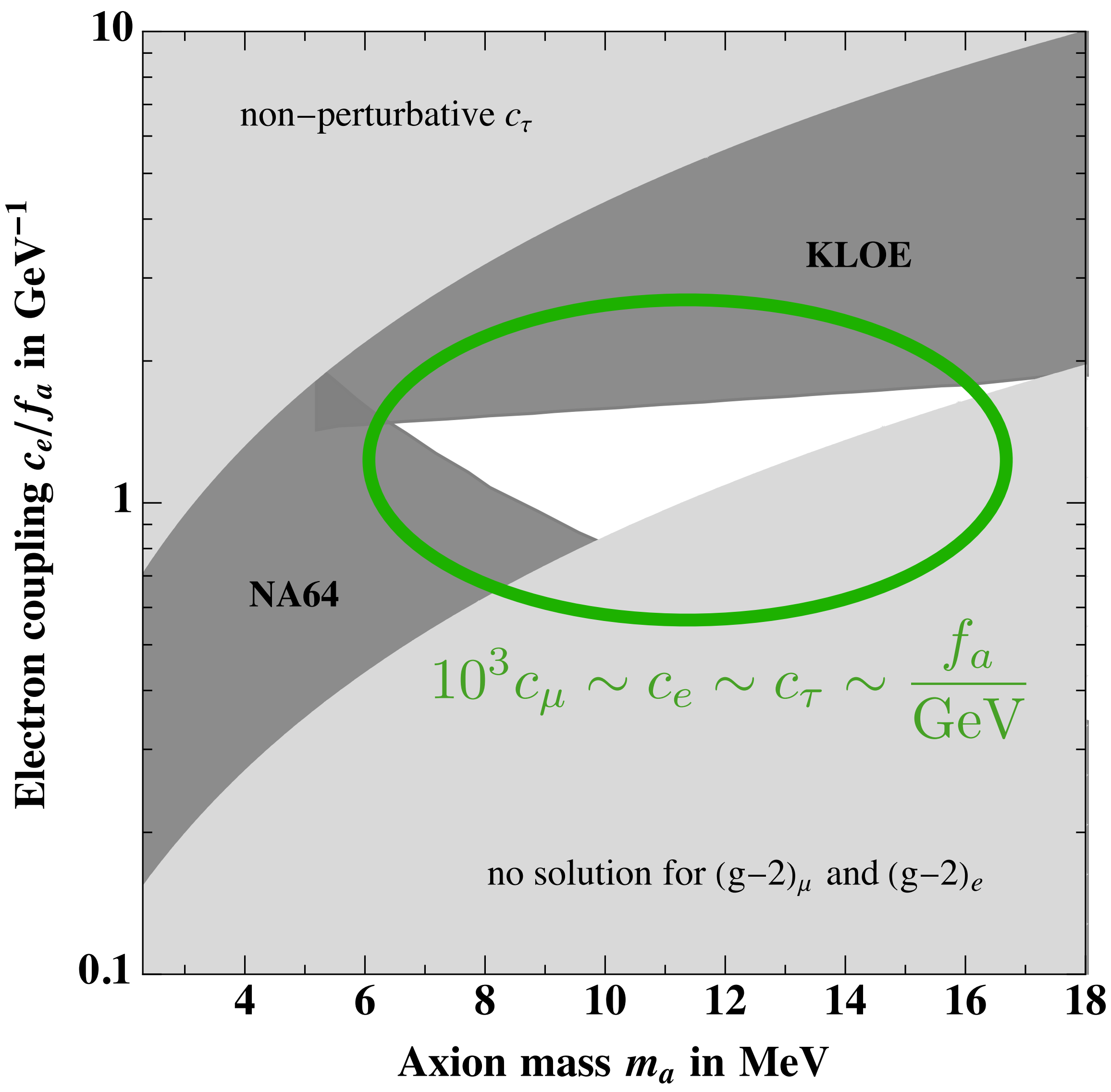
Need sizable tau couplings ~ electron couplings

constrained by perturbativity



2011.08919

A sweet spot in the multi-MeV region

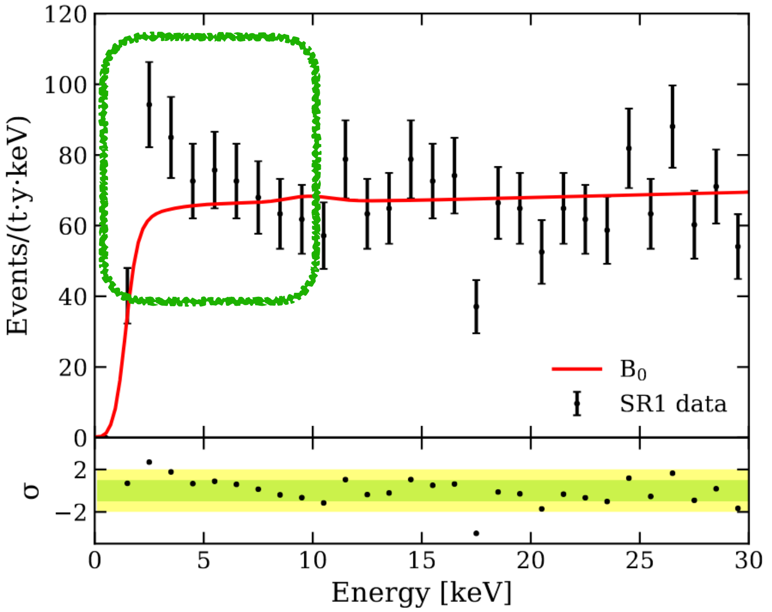


allows to explain XENON1T excess & can be visible QCD axion

Connection to the XENON1T Excess

- Xenon1T saw excess in electron recoils with significance ~3.5σ

- Can be addressed when axion has large coupling to DM fermion 2011.08919

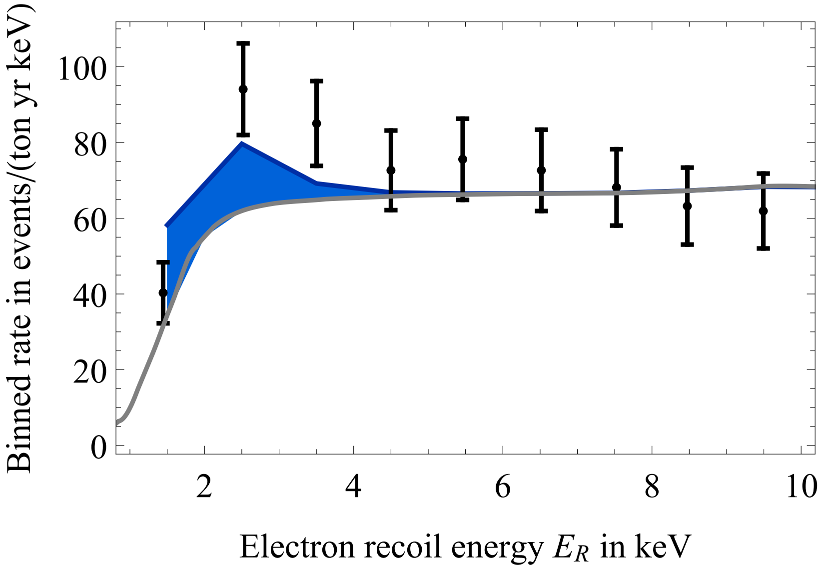


$$\mathcal{L} = -ia\left(g_\chi \bar{\chi}\gamma_5\chi + g_e\bar{e}\gamma_5 e\right)$$

pseudoscalar structure gives steeply falling recoil spectrum that can improve fit because excess is close to exp. threshold at few keV

large annihilation cross-section of few GeV DM to axions: **natural asymmetric DM scenario**

m_χ = 2.6 GeV, m_a = 8 MeV, g_e/m_e =1.3 GeV^{-1}



Connection to the QCD Axion

- Need axion with mass ~few MeV and decay constant ~GeV

perfectly fits QCD Axion relation!

$$m_a = 6\,\mu\text{eV}\,\frac{10^{12}\text{GeV}}{f_a} = 6\,\text{MeV}\,\frac{\text{GeV}}{f_a}$$

- Such a heavy QCD axion is actually **not experimentally excluded!**

[and gives nice solution to PQ quality problem!] **1710.03764** by D. Alves & N. Weiner

a) $J/\psi, \Upsilon \to \gamma a$ —fix by→ **small axion couplings = PQ charges of b,c**

b) $K^+ \to \pi^+ a_{\text{invis}}$ —fix by→ **prompt decay to e's & small axion-pion mixing**

$$\text{Br}(K^+ \to \pi^+ a)_{\text{invis}} \sim \theta_{a\pi}^2 < 10^{-10}$$

$$\theta_{a\pi} \sim \frac{c_u m_u - c_d m_d}{m_u + m_d} f_\pi / f_a \sim 0.1 \frac{\text{GeV}}{f_a}$$

→ $\text{Br}(K^+ \to \pi^+ (a \to e^+ e^-)) \lesssim 10^{-6}$

$c_u \approx 2 c_d$ → $\theta_{a\pi} \sim 10^{-3} \frac{\text{GeV}}{f_a}$

Towards a complete model

- UV-complete model with couplings only to first generation fermions

2102.10118 by C. Wagner et al.

  - DFSZ-like model: add doublet + singlet scalars charged under PQ

$$\mathcal{L}_{\rm PQ}^{\rm Yuk} \supset -\sum_{i=1,2,3}\left(\bar{Q}^i Y_u^{i1} H_u u_R^1 + \bar{Q}^i Y_d^{i1} H_d d_R^1 + \bar{L}^i Y_e^{i1} H_e e_R^1\right)$$
$$\mathcal{L}_{\rm SM}^{\rm Yuk} \supset -\sum_{i=1,2,3}\sum_{j=2,3}\left(\bar{Q}^i Y_u^{ij} \tilde{H} u_R^j + \bar{Q}^i Y_d^{ij} H d_R^j + \bar{L}^i Y_e^{ij} H e_R^j\right)$$

$$V_{\rm PQ} = \left(A_u \phi_u^* H \cdot H_u + A_d \phi_d^* H^\dagger H_d + A_e \phi_e^* H^\dagger H_e + A_\phi \phi_u^* \phi_d^2 + B_\phi \phi_d^* \phi_e^n\right)$$
$$V_{\rm dia} = \sum -\mu_\Phi^2 \Phi^\dagger \Phi + \lambda_\Phi \left(\Phi^\dagger \Phi\right)^2,$$

  - PQ invariance + orthogonality of axion on Goldstone eaten by Z fixes all PQ charges in terms of Higgs vevs

$$0 = X_H v_H^2 + X_{H_i} v_{H_i}^2$$

  - Axion mass and all its couplings determined by small doublet + singlet vevs

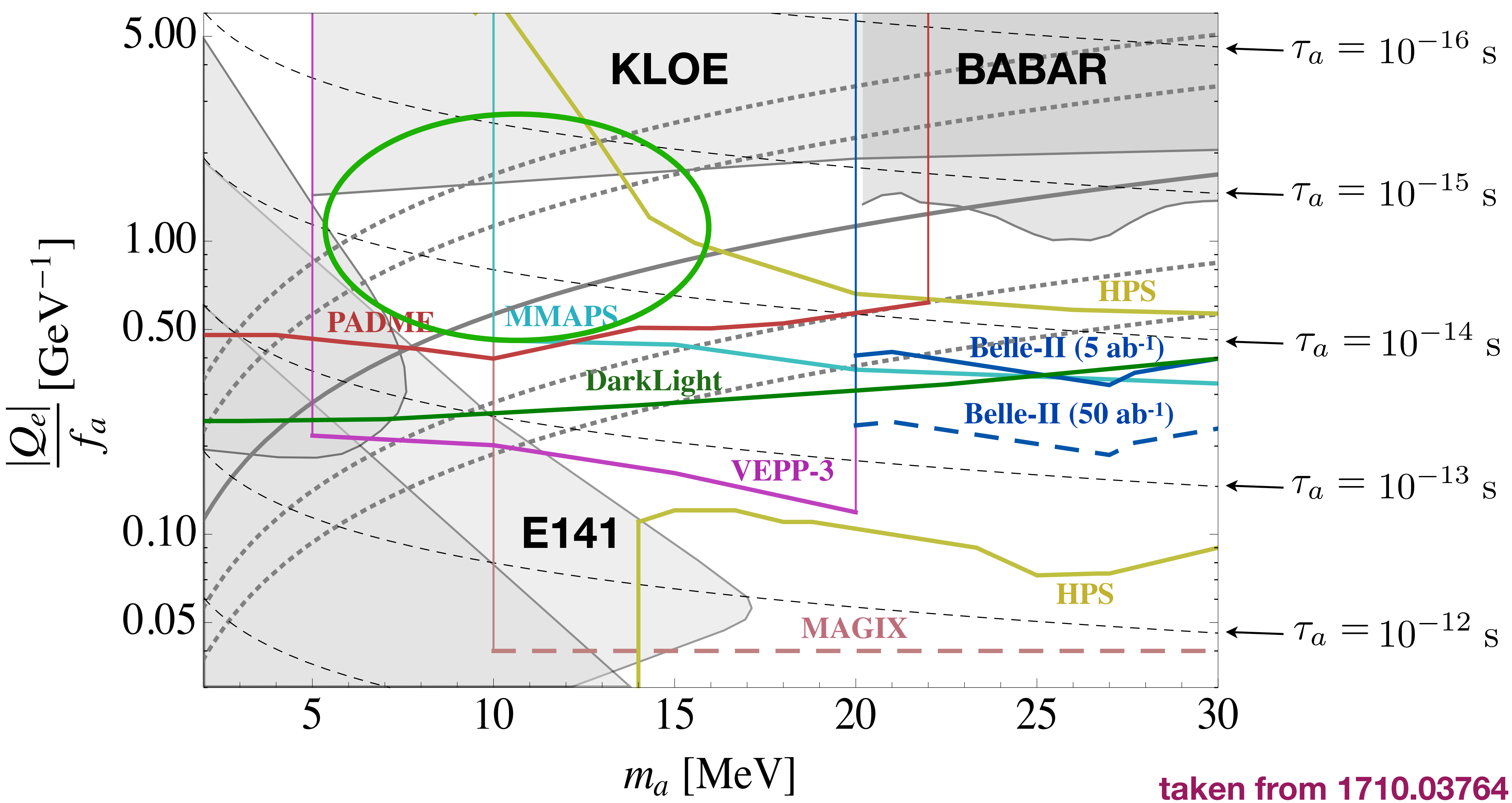
$$m_a = \frac{5.7\,\mathrm{MeV}}{\eta\, 246},\; c_u = \frac{2}{3},\; c_d = \frac{1}{3},\; c_e = \frac{1}{3n},\; c_{\rm rest} \propto \epsilon^2$$

$$\epsilon \equiv \frac{v_{H_i}}{v_H} \approx \frac{v_{H_i}}{v} \ll \eta \equiv \frac{v_{\phi_i}}{v}$$

  - Can make scalar sector sufficiently heavy with large A-terms

Experimental Prospects

Sweet spot will be covered by next-generation experiments



taken from 1710.03764

Summary

★ Can address $(g\text{-}2)_\mu$ with 7-17 MeV ALP that couples to all charged leptons [need 1% tuning to satisfy $(g\text{-}2)_e$]

★ Beam dump constraints are avoided since axion promptly decays to electrons

★ Also accounts for XENON1T excess in electron recoils when axion coupled to DM fermion [that can be ADM]

★ ALP can be QCD axion when coupled also to first generation quarks such that pion-phobic [new contribs to g-2 are small]