An anomaly-free leptophilic axion-like particle and its flavour violating tests

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Based on 2007.08834 with Maria López-Ibáñez, Aurora Melis, Oscar Vives, Jin Min Yang

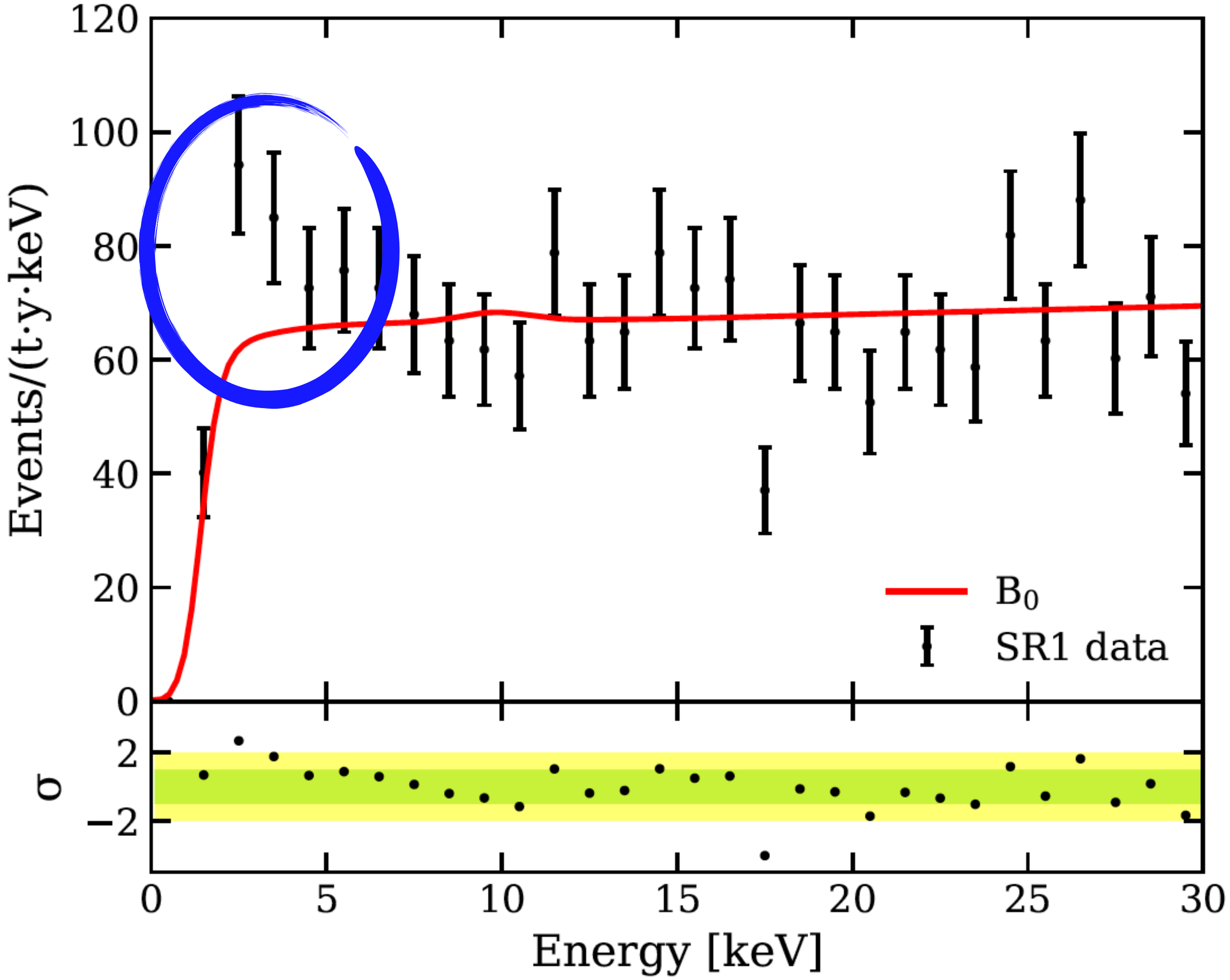
Mini-workshop: Low Energy Recoils from Deep Underground 2020.9.26

Location of SYSU

Campus of SYSU

Wecome to visit!

Electron recoil events in XENON1T(arXiv:2006.09721)



Possible explanations by new physics

- Solar axions
- Neutrino magnetic moment
- KeV-scale bosonic DM
  1. ALP
  2. Dark photon
- Boosted dark matter
- Others

Details of other explanations see talks later!

What is axion-like-particle(ALP)?

- Axion-like particles (ALPs) are pseudo Nambu-Goldstone bosons of spontaneously broken global symmetries

- If it solves the strong CP problem, usually call it axion

- It can be very light due to the existence of the shift symmetry

- If it is dark matter candidate, life time need to be long enough and can be produced both by misalignment mechanism or thermal production in the early universe

ALP hinted by Xenon1T

F. Takahashi, M. Yamada, W. Yin, 2006.10035

- Coupling with electron

$$-\mathcal{L} = m_e \bar{e}_R e_L e^{i q_e \frac{a}{f}}$$

U(1) Charge difference

$$q_e = q_{e_R} - q_{e_L}$$

- No U(1)-U(1)e-U(1)e anomaly

Too large coupling with electromagnetic field excluded by X-ray search

- No U(1)-SU(3)c-SU(3)c anomaly (can not solve the strong CP problem)

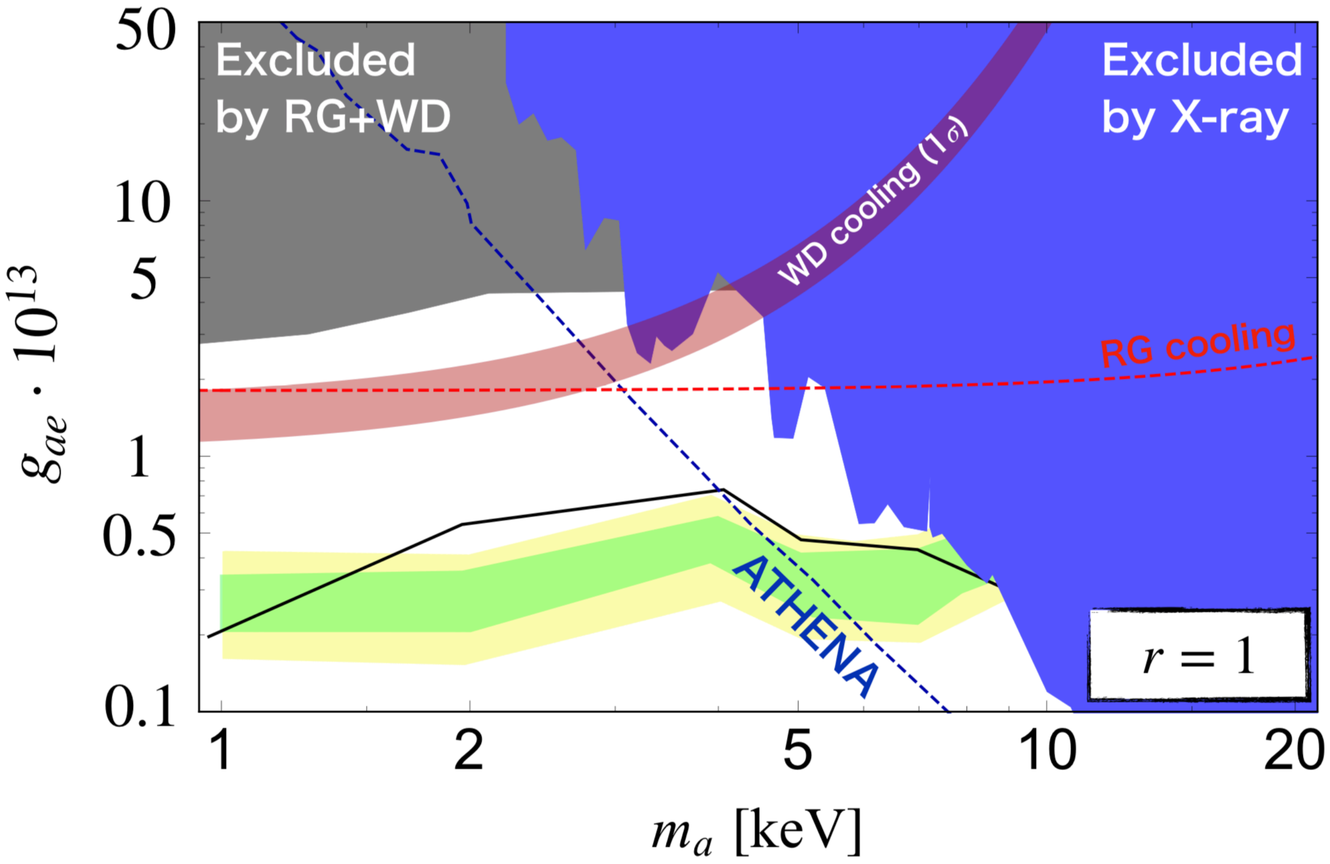
Mixing with pion induce too large coupling with electromagnetic field

ALP hinted by Xenon1T

- Suppressed coupling with photon

$$\frac{\alpha}{48\pi}\frac{q_e}{f_a}\boxed{\frac{m_a^2}{m_e^2}}aF_{\mu\nu}\tilde{F}^{\mu\nu}$$

K. Nakayama, F. Takahashi, T. T. Yanagida, arXiv:1403.7390



F. Takahashi, M. Yamada, W. Yin, 2006.10035

$$g_{ae} = q_e m_e / f_a$$

$$f_a / q_e \sim 3 \times 10^9 \mathrm{GeV}$$

Few keV

An anomaly-free ALP!

Flavor universal global symmetry?

Considering the model SM+3N

- Tiny neutrino mass via see-saw
- Baryon asymmetry from leptogenesis

Most simple possibility is U(1)B-L/U(1)L

Adding another scalar field $\Phi(+2)$

- Spontaneously breaking the global symmetry

$$\Phi = \frac{1}{\sqrt{2}}(s+f)e^{\underline{ia}/f} \qquad \text{(majoron)}$$

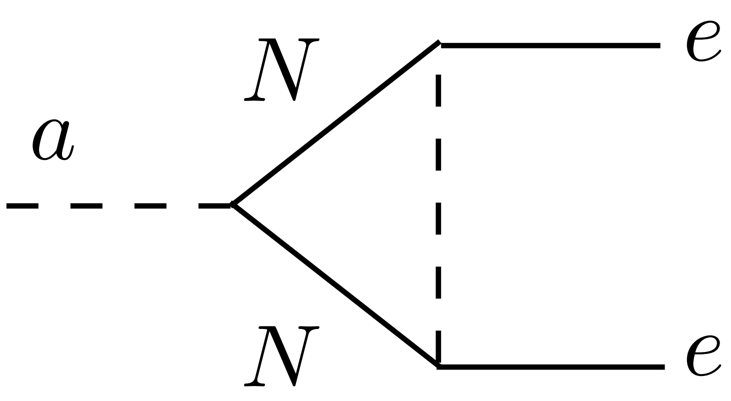
- Generate the majorana mass for the right-handed neutrino

$$y_N \bar{L} H N + y \Phi \bar{N}^c N$$

Flavor universal global symmetry?

No tree level coupling with electron!

Generated at one loop



$$C^A_{e_i e_j} = \frac{1}{16\pi^2}\left[\frac{\delta_{ij}}{2}\,\mathrm{Tr}\left(y_N y_N^\dagger\right) - (y_N y_N^\dagger)_{ij}\right]$$

Already flavor violation by loop

From see-saw mechanism,

$$m_\nu \sim 0.1\mathrm{eV}$$

$$m_\nu \sim \frac{y_N^2 v^2}{m_N} \Rightarrow y_N^2 \sim \frac{m_\nu m_N}{v^2}$$

$$f/C_e \sim \frac{16\pi^2 f}{y_N^2} = \frac{16\pi^2 v^2}{m_\nu}\frac{f}{m_N} > 10^{16}\mathrm{GeV}$$

Too weak interaction with electron!

The global symmetry should be flavor non-universal!

LFV induced by a flavor non-universal ALP

For the mass matrix and charge

$$U_L^{e\,\dagger}\,M_e\,U_R^e = \mathrm{Diag}(m_e, m_\mu, m_\tau)$$

$$x_L = \mathrm{Diag}\{q_{L_1}, q_{L_2}, q_{L_3}\} \qquad x_R = \mathrm{Diag}\{q_{e_1}, q_{e_2}, q_{e_3}\}$$

Flavor non-universal coupling:

$$-\mathcal{L}_{ae} = i\frac{\partial_\mu a}{2f_a}\,\bar{e}_i\,\gamma^\mu\left(V_{ij}^e + \gamma^5 A_{ij}^e\right)e_j,$$

$$V_{ij}^e = \frac{1}{2}\left(U_R^{e\,\dagger}x_R U_R^e + U_L^{e\,\dagger}x_L U_L^e\right)$$

$$A_{ij}^e = \frac{1}{2}\left(U_R^{e\,\dagger}x_R U_R^e - U_L^{e\,\dagger}x_L U_L^e\right)$$

Prediction of lepton flavor violation $l_i \to l_j a$

We will show that such lepton flavor violation could be probed in near future

Model I: ALP identified as Flaxion/Axiflavon

Y. Ema, K. Hamaguchi, T. Moroi and K. Nakayama, arXiv:1612.05492

L. Calibbi, F. Goertz, D. Redigolo, R. Ziegler and J. Zupan, arXiv:1612.08040

At the same time to explain the fermion mass hierarchy and mixing via Froggatt-Nielsen mechanism

$$\begin{aligned} -\mathcal{L} = {} & y^d_{ij} \left(\frac{\phi}{M}\right)^{n^d_{ij}} \overline{Q}_i H d_{Rj} + y^u_{ij} \left(\frac{\phi}{M}\right)^{n^u_{ij}} \overline{Q}_i \widetilde{H} u_{Rj} \\ & + y^l_{ij} \left(\frac{\phi}{M}\right)^{n^l_{ij}} \overline{L}_i H l_{Rj} + y^\nu_{i\alpha} \left(\frac{\phi}{M}\right)^{n^\nu_{i\alpha}} \overline{L}_i \widetilde{H} N_{R\alpha} \\ & + \frac{1}{2} y^N_{\alpha\beta} \left(\frac{\phi}{M}\right)^{n^N_{\alpha\beta}} M \overline{N^c_{R\alpha}} N_{R\beta} + \text{h.c.}\,, \end{aligned}$$

$$\epsilon \equiv \frac{v_\phi}{M}$$

$$\begin{aligned} n^u_{ij} &= q_{Q_i} - q_{u_j}\,, \\ n^d_{ij} &= q_{Q_i} - q_{d_j}\,, \\ n^l_{ij} &= q_{L_i} - q_{l_j}\,, \\ n^\nu_{i\alpha} &= q_{L_i} - q_{N_\alpha} \\ n^N_{\alpha\beta} &= -q_{N_\alpha} - q_{N_\beta}\,. \end{aligned}$$

The difference here is the flavor symmetry should be anomaly free.

Model I: ALP identified as Flaxion/Axiflavon

Not easy to cancel U(1)-SU(3)c-SU(3)c anomaly,
Only considering the lepton sector: U(1) and a Z2 symmetry

$$H_1(\underline{0}),\ \boxed{H_2(q_{H_2})},\ \phi(1)$$

$$L(q_{L_1}, q_{L_2}, q_{L_3}),\ \boxed{e(q_{e_1}, q_{e_2}, q_{e_3}),\ N_R(0,0,0)}$$

$$\mathcal{L}_Y \supset \boxed{Y_u\,\bar{Q}\widetilde{H}_1 u \ + \ Y_d\,\bar{Q}H_1 d} + \boxed{c^e_{ij}\,\epsilon^{n^e_{ij}}\,\bar{L}_i\,\widetilde{H}_2\,e_j}$$
$$+ \boxed{c^\nu_{ij}\,\epsilon^{n^\nu_{ij}}\,\bar{L}_i\,H_2\,N_j} + \ (M_R)_{ij}\ \bar{N}_{R_i}\,N^c_{R_j},$$

$$\epsilon = |v_\phi/\Lambda|$$

$$n^e_{ij} = q_{L_i} - q_{e_j} + q_{H_2}, n^\nu_{ij} = q_{L_i} - q_{N_{R,j}} - q_{H_2}$$

$$|U^e_L|_{ij} = |U^e_R|_{ij} \approx \delta_{ij} + \epsilon^{n^e_{ij}}/\epsilon^{n^e_{jj}} \quad \text{with } i \le j\,.$$

Model I: ALP identified as Flaxion/Axiflavon

Sufficient conditions for anomaly free

$$\sum_i Q_{L_i} = 0, \quad \sum_i Q_{e_i} = 0$$

As a typical example

$$H_1(0),\ H_2(2),\ \phi(1)$$
$$L(1,0,-1),\ e(-1,0,1),\ N_R(0,0,0)$$

$$n^e_{ij} = \begin{pmatrix} 4 & 3 & 2 \\ 3 & 2 & 1 \\ 2 & 1 & \boxed{0} \end{pmatrix}, \qquad n^\nu_{ij} = \begin{pmatrix} 1 & 1 & 1 \\ 2 & 2 & 2 \\ 3 & 3 & 3 \end{pmatrix}.$$

$$v_{H_2} \sim 10^{-2} v_{\rm EW}$$

$$\epsilon = 0.1$$

Model I: ALP identified as Flaxion/Axiflavon

With $\epsilon = 0.1$ $\quad c^e_{ij} = \begin{pmatrix} 1.0 & 1.6 & 1.0 \\ 1.6 & 1.0 & -2.7 \\ 1.0 & -2.7 & 1.0 \end{pmatrix}$.

We can reproduce the lepton masses

$$|U^e_L|_{ij} = |U^e_R|_{ij} \approx \delta_{ij} + \epsilon^{n^e_{ij}}/\epsilon^{n^e_{jj}} \quad \text{with } i \leq j\,.$$

$$e - \mu \text{ mixing is } \mathcal{O}(\epsilon) \sim 0.1$$

Model I: ALP identified as Flaxion/Axiflavon

Scalar potential:

$$V(H_1,H_2,\phi)=m_1^2H_1^\dagger H_1+m_2^2H_2^\dagger H_2+\lambda_1(H_1^\dagger H_1)^2+\lambda_2(H_2^\dagger H_2)^2$$
$$+\lambda_3(H_1^\dagger H_1)(H_2^\dagger H_2)+\lambda_4|H_1\cdot H_2|^2+\boxed{m^2H_1\cdot H_2}+\lambda(\phi^\dagger\phi-v_\phi^2)^2$$

Soft breaking of the U(1) and Z2, giving mass to the ALP

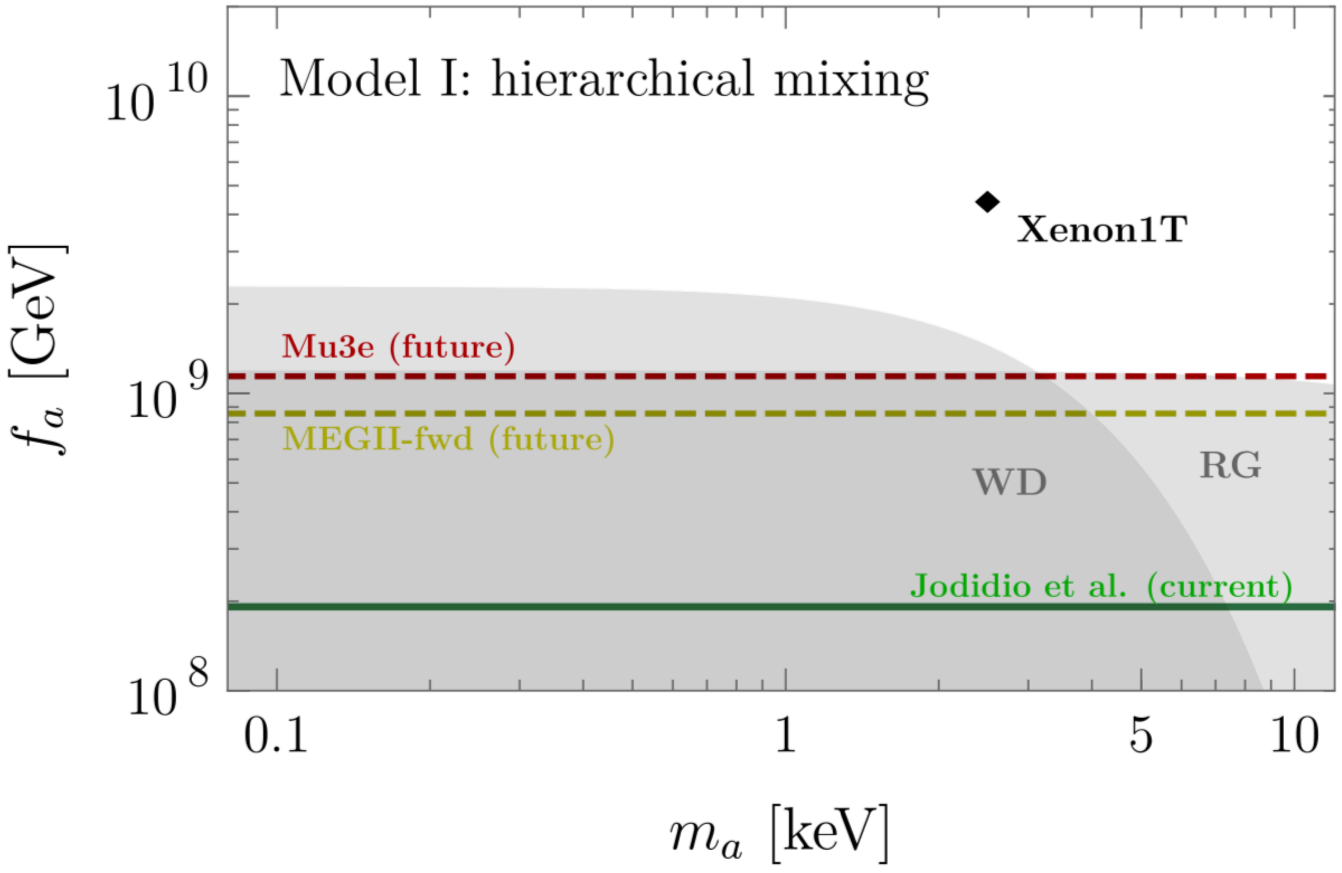
- For m around few hundreds GeV to predict mass around keV
- Extra Higgses are good targets for LHC and lepton collider
- LHC limit is weak because of suppressed coupling with quarks

Model I: ALP identified as Flaxion/Axiflavon

$$\mathrm{BR}\left(\ell_i \to \ell_j a\right) = \frac{m_{\ell_i}^3}{16\pi\Gamma(\ell_j)} \frac{\left|C_{ij}^e\right|^2}{4\, f_a^2} \left(1 - \frac{m_a^2}{\ell_i^2}\right)^2$$

$$\left|C_{ij}^e\right|^2 = \left|V_{ij}^e\right|^2 + \left|A_{ij}^e\right|^2$$

Lepton decay	**BR limit**	**Experiment**
$\mathrm{BR}\,(\mu \to e\,a)$	$< 2.6 \cdot 10^{-6}$	`Jodidio et al.`
	$< 2.1 \cdot 10^{-5}$	`TWIST`
	$< 1.3 \cdot 10^{-7}$	MEGII-fwd $*$
	$< 7.3 \cdot 10^{-8}$	`Mu3e` $*$
$\mathrm{BR}\,(\mu \to e\,a\,\gamma)$	$< 1.1 \cdot 10^{-9}$	`Crystal Box`
$\mathrm{BR}\,(\tau \to e\,a)$	$< 2.7 \cdot 10^{-3}$	`ARGUS`
	$< 8.4 \cdot 10^{-6}$	`Belle-II`
$\mathrm{BR}\,(\tau \to \mu\,a)$	$< 4.5 \cdot 10^{-3}$	`ARGUS`
	$< 1.6 \cdot 10^{-5}$	`Belle-II`



Model II: general mixing

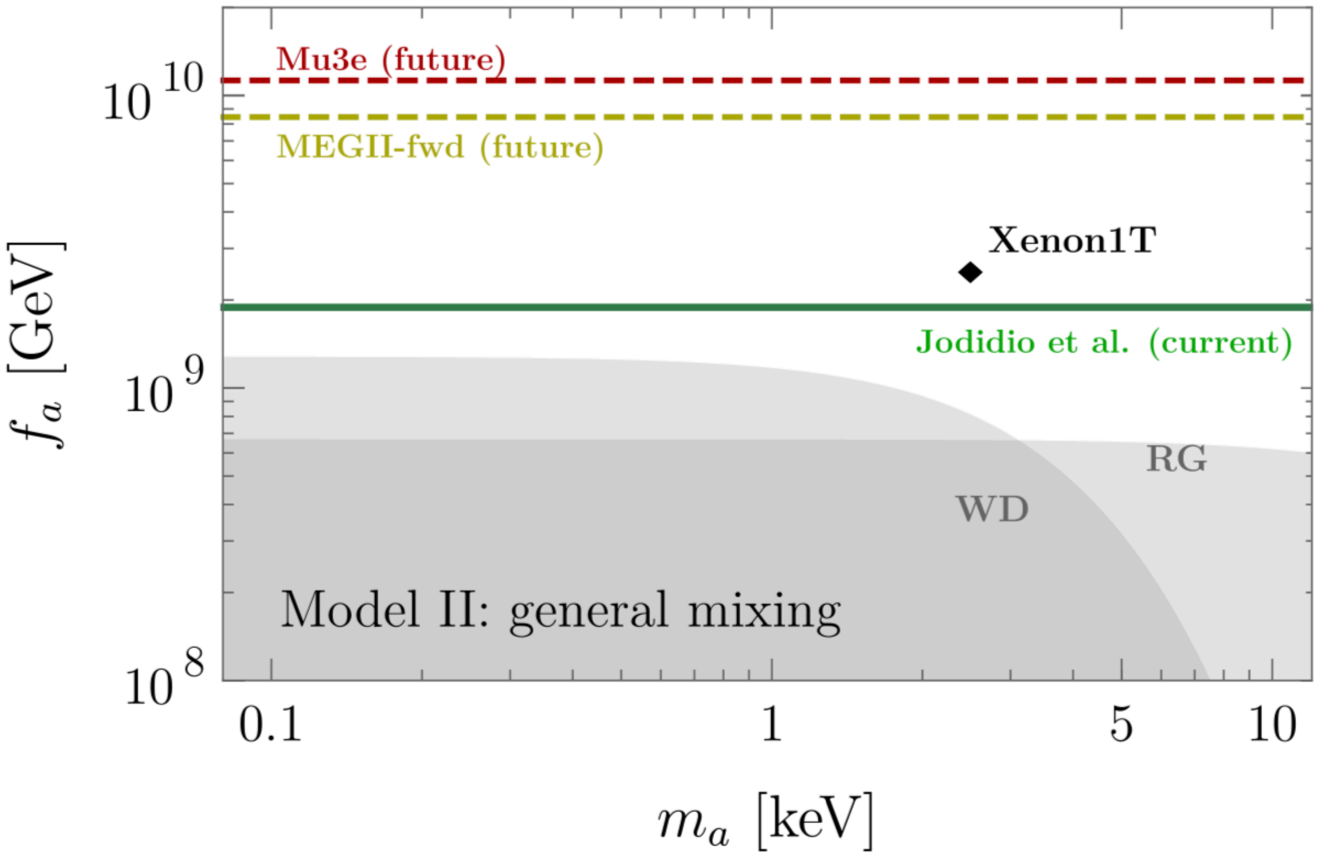
$U(1) \subset \mathcal{F}$ Determine the Yukawa structure

Masses and mixings are not fixed by the U(1) charges

For example, same charge assignment without all coupling order 1 and $v_\phi/\Lambda \simeq \mathcal{O}(1)$

If we take the PMNS matrix totally from charged lepton sector

$$V^e_{ij},\, A^e_{ij} = \frac{1}{2}\, U^{e\,\dagger}_{\rm PMNS} \left(x_R \,\pm\, x_L\right) U^e_{\rm PMNS}.$$



Summary and conclusion

- The Xenon1T result may indicate an anomaly-free ALP
- The origin of such anomaly-free ALP is still mysteries
- It may related to the fermion mass structure
- Once it is confirmed by future experiment data, it would be very interesting to see whether we can test it by other experiments