Fully Testable Axion Dark Matter within a Minimal $SU(5)$ Unification Model*

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The Dark Side of the Universe - DSU2024
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*Stefan Antusch, I.D., Kevin Hinze, and Shaikh Saad, arXiv:2301.00808.

OUTLINE

- THE MODEL
- PECCEI-QUINN SYMMETRY
- PARAMETER SPACE ANALYSIS
- CONCLUSIONS

PRELUDE

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SU(5) and the Invisible Axion

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(Received 18 May 1981)

Dine, Fischler, and Srednicki have proposed a solution to the strong *CP* puzzle in which the mass and couplings of the axion are suppressed by an inverse power of a large mass. We construct an explicit SU(5) model in which this mass is the vacuum expectation value which breaks SU(5) down to SU(3)⊗SU(2)⊗U(1).

THE MODEL*

$SU(5)$	$SU(3)\times SU(2)\times U(1)$	$SU(5)$	$SU(3)\times SU(2)\times U(1)$
$5_H^{(\prime)} \equiv \Lambda^{(\prime)\,\alpha}$	$\Lambda_1^{(\prime)}\,\left(1,2,+\frac{1}{2}\right)$	$\overline{5}_{F\,i} \equiv F_{\alpha\,i}$	$L_i\,\left(1,2,-\frac{1}{2}\right)$
	$\Lambda_3^{(\prime)}\,\left(3,1,-\frac{1}{3}\right)$		$d_i^c\,\left(\overline{3},1,+\frac{1}{3}\right)$
$24_H \equiv \phi^\alpha_\beta$	$\phi_0\,(1,1,0)$	$10_{F\,i} \equiv T_i^{\alpha\beta}$	$Q_i\,\left(3,2,+\frac{1}{6}\right)$
	$\phi_1\,(1,3,0)$		$u_i^c\,\left(\overline{3},1,-\frac{2}{3}\right)$
	$\phi_3\,\left(3,2,-\frac{5}{6}\right)$		$e_i^c\,(1,1,+1)$
	$\phi_{\overline{3}}\,\left(\overline{3},2,+\frac{5}{6}\right)$	$\overline{15}_F \equiv \overline{\Sigma}_{\alpha\beta}$	$\overline{\Sigma}_1\,(1,3,-1)$
	$\phi_8\,(8,1,0)$		$\overline{\Sigma}_3\,\left(\overline{3},2,-\frac{1}{6}\right)$
$35_H \equiv \Phi_{\alpha\beta\gamma}$	$\Phi_1\,\left(1,4,-\frac{3}{2}\right)$		$\overline{\Sigma}_6\,\left(\overline{6},1,+\frac{2}{3}\right)$
	$\Phi_3\,\left(\overline{3},3,-\frac{2}{3}\right)$	$15_F \equiv \Sigma^{\alpha\beta}$	$\Sigma_1\,(1,3,+1)$
	$\Phi_6\,\left(\overline{6},2,+\frac{1}{6}\right)$		$\Sigma_3\,\left(3,2,+\frac{1}{6}\right)$
	$\Phi_{10}\,\left(\overline{10},1,+1\right)$		$\Sigma_6\,\left(6,1,-\frac{2}{3}\right)$

*I.D., Emina Džaferović-Mašić, Svjetlana Fajfer, and Shaikh Saad, arXiv:2401.16907.

*Stefan Antusch, I.D., Kevin Hinze, and Shaikh Saad, arXiv:2301.00808.

*I.D., Emina Džaferović-Mašić, and Shaikh Saad, arXiv:2105.01678.

*I.D. and Shaikh Saad, arXiv:1910.09008.

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$24_H \equiv \phi^\alpha_\beta$	$\phi_0\,(1,1,0)$ $\phi_1\,(1,3,0)$ $\phi_3\,(3,2,-\frac{5}{6})$ $\phi_{\overline{3}}\,(\overline{3},2,+\frac{5}{6})$ $\phi_8\,(8,1,0)$	$10_{F\,i} \equiv T_i^{\alpha\beta}$	$Q_i\,(3,2,+\frac{1}{6})$ $u_i^c\,(\overline{3},1,-\frac{2}{3})$ $e_i^c\,(1,1,+1)$
		$\overline{15}_F \equiv \overline{\Sigma}_{\alpha\beta}$	$\overline{\Sigma}_1\,(1,3,-1)$ $\overline{\Sigma}_3\,(\overline{3},2,-\frac{1}{6})$ $\overline{\Sigma}_6\,(\overline{6},1,+\frac{2}{3})$
$35_H \equiv \Phi_{\alpha\beta\gamma}$	$\Phi_1\,(1,4,-\frac{3}{2})$ $\Phi_3\,(\overline{3},3,-\frac{2}{3})$ $\Phi_6\,(\overline{6},2,+\frac{1}{6})$ $\Phi_{10}\,(\overline{10},1,+1)$	$15_F \equiv \Sigma^{\alpha\beta}$	$\Sigma_1\,(1,3,+1)$ $\Sigma_3\,(3,2,+\frac{1}{6})$ $\Sigma_6\,(6,1,-\frac{2}{3})$

$SU(5)$ irrep	$\overline{5}_{F\,i}$	$10_{F\,i}$	$\overline{15}_F$	15_F	5_H	$5'_H$	24_H	35_H	24_V
$U(1)_{\mathrm{PQ}}$ charge	$-\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{2}$	-1	$+1$	$+1$	-1	0

*Stefan Antusch, I.D., Kevin Hinze, and Shaikh Saad, arXiv:2301.00808.

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$24_H \equiv \phi^\alpha_\beta$	$\phi_0\,(1,1,0)$ $\phi_1\,(1,3,0)$ $\phi_3\,(3,2,-\frac{5}{6})$ $\phi_{\overline{3}}\,(\overline{3},2,+\frac{5}{6})$ $\phi_8\,(8,1,0)$	$10_{F\,i} \equiv T_i^{\alpha\beta}$	$Q_i\,(3,2,+\frac{1}{6})$ $u_i^c\,(\overline{3},1,-\frac{2}{3})$ $e_i^c\,(1,1,+1)$
		$\overline{15}_F \equiv \overline{\Sigma}_{\alpha\beta}$	$\overline{\Sigma}_1(1,3,-1)$ $\overline{\Sigma}_3\,(\overline{3},2,-\frac{1}{6})$ $\overline{\Sigma}_6\,(\overline{6},1,+\frac{2}{3})$
$35_H \equiv \Phi_{\alpha\beta\gamma}$	$\Phi_1\,(1,4,-\frac{3}{2})$ $\Phi_3\,(\overline{3},3,-\frac{2}{3})$ $\Phi_6\,(\overline{6},2,+\frac{1}{6})$ $\Phi_{10}\,(\overline{10},1,+1)$	$15_F \equiv \Sigma^{\alpha\beta}$	$\Sigma_1\,(1,3,+1)$ $\Sigma_3\,(3,2,+\frac{1}{6})$ $\Sigma_6\,(6,1,-\frac{2}{3})$

SCALAR SECTOR

GUT vacuum expectation value:

$$\mathcal{L} \supset -\mu^2 \phi^{*\beta}_{\alpha}\phi^{\alpha}_{\beta} + \xi_1(\phi^{*\beta}_{\alpha}\phi^{\alpha}_{\beta})^2 + \xi_2 \phi^{*\beta}_{\alpha}\phi^{\alpha}_{\gamma}\phi^{*\gamma}_{\delta}\phi^{\delta}_{\beta} + \xi_3 \phi^{*\beta}_{\alpha}\phi^{\delta}_{\gamma}\phi^{*\alpha}_{\beta}\phi^{\gamma}_{\delta} + \xi_4 \phi^{*\beta}_{\alpha}\phi^{\delta}_{\gamma}\phi^{*\alpha}_{\delta}\phi^{\gamma}_{\beta}$$

$$\langle\phi\rangle = \frac{v_\phi}{\sqrt{15}}\mathrm{diag}(-1,-1,-1,3/2,3/2)$$

multiplet	real part mass-squared	imaginary part mass-squared
$\phi_0\,(1,1,0)$	m_1^2	0
$\phi_1\,(1,3,0)$	m_3^2	$\frac{1}{4}m_3^2 + m_8^2$
$\phi_8\,(8,1,0)$	$\frac{1}{4}m_3^2$	m_8^2
$\phi_3\,\left(3,2,-\frac{5}{6}\right)$	0	$m_{5/6}^2$
$\phi_{\overline{3}}\,\left(\overline{3},2,+\frac{5}{6}\right)$	0	$m_{5/6}^2$

$$M_{\mathrm{GUT}}^2 = \frac{5\pi}{6}\alpha_{\mathrm{GUT}} v_\phi^2$$

SCALAR SECTOR

electroweak vacuum expectation value:

$$\mathcal{L} \supset -\frac{1}{2}\mu^2_{\Lambda^{(\prime)}}\Lambda^{(\prime)\dagger}\Lambda^{(\prime)} + \gamma_{\Lambda^{(\prime)}}\left(\Lambda^{(\prime)\dagger}\Lambda^{(\prime)}\right)^2 + \zeta_1\left(\Lambda^\dagger\Lambda\right)\left(\Lambda^{\prime\dagger}\Lambda^\prime\right) + \zeta_2\left(\Lambda^\dagger\Lambda^\prime\right)\left(\Lambda^{\prime\dagger}\Lambda\right)$$

$$\langle\Lambda^{(\prime)}\rangle = \begin{pmatrix}0 & 0 & 0 & 0 & v_{\Lambda^{(\prime)}}\end{pmatrix}^T$$

doublet-triplet splitting:

$$\begin{aligned}\mathcal{L} \supset\ & \lambda_{\Lambda^{(\prime)}}\Lambda^{(\prime)\dagger}\Lambda^{(\prime)}\phi^\dagger\phi + \Lambda^{(\prime)\dagger}\left(\alpha_{\Lambda^{(\prime)}}\phi^\dagger\phi + \beta_{\Lambda^{(\prime)}}\phi\phi^\dagger\right)\Lambda^{(\prime)} \\ & + \left\{\kappa_1\Lambda^{\prime\dagger}\phi^2\Lambda + \kappa_2\left(\Lambda^{\prime\dagger}\Lambda\right)\phi^2 + \text{h.c.}\right\}\end{aligned}$$

SCALAR SECTOR

35-dimensional scalar representation mass relation:

$$\mathcal{L} \supset \mu_{35}^2 \Phi\Phi^* + \lambda_0 \left(\Phi\Phi^*\right) \phi^*\phi + \lambda_1 \Phi_{\alpha\beta\gamma} (\Phi^*)^{\alpha\delta\epsilon} (\phi^*)_\delta^\beta \phi_\epsilon^\gamma + \lambda_2 \Phi_{\alpha\beta\epsilon} (\Phi^*)^{\alpha\beta\delta} (\phi^*)_\gamma^\epsilon \phi_\delta^\gamma$$

$$M_{\Phi_{10}}^2 = M_{\Phi_1}^2 - 3M_{\Phi_3}^2 + 3M_{\Phi_6}^2$$

lepton number breaking term:

$$\mathcal{L} \supset \lambda \Lambda^\alpha \Lambda'^\beta \Lambda'^\gamma \Phi_{\alpha\beta\gamma} + \text{h.c.}$$

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$24_H \equiv \phi_\beta^\alpha$	$\phi_0\,(1,1,0)$ $\phi_1\,(1,3,0)$ $\phi_3\,(3,2,-\frac{5}{6})$ $\phi_{\overline{3}}\,(\overline{3},2,+\frac{5}{6})$ $\phi_8\,(8,1,0)$	$10_{F\,i} \equiv T_i^{\alpha\beta}$ $\overline{15}_F \equiv \overline{\Sigma}_{\alpha\beta}$	$Q_i\,(3,2,+\frac{1}{6})$ $u_i^c\,(\overline{3},1,-\frac{2}{3})$ $e_i^c\,(1,1,+1)$ $\overline{\Sigma}_1(1,3,-1)$ $\overline{\Sigma}_3\,(\overline{3},2,-\frac{1}{6})$ $\overline{\Sigma}_6\,(\overline{6},1,+\frac{2}{3})$
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FERMION SECTOR

Yukawa couplings:

$$\mathcal{L} \supset Y^u_{ij}\ 10_{F\,i} 10_{F\,j} 5'_H + Y^d_{ij}\ 10_{F\,i} \overline{5}_{F\,j} 5^*_H + Y^a_i\ 15_F \overline{5}_{F\,i} 5^*_H$$
$$+ Y^b_i\ \overline{15}_F \overline{5}_{F\,i} 35^*_H + Y^c_i\ 10_{F\,i} \overline{15}_F 24_H + y\ \overline{15}_F 15_F 24_H + \text{h.c.}$$

$$Y^u_{ij} \equiv Y^u_{ji}, \quad Y^d_{ij} = Y^{d*}_{ij} \equiv \delta_{ij} Y^d_i, \quad Y^a_i, \quad Y^b_i, \quad Y^c_i, \quad y$$

15-dimensional fermion representation mass relation:

$$M_{\Sigma_1} = \frac{y}{2}\sqrt{\frac{3}{5}} v_\phi$$
$$M_{\Sigma_3} = \frac{y}{4\sqrt{15}} v_\phi$$
$$M_{\Sigma_6} = -\frac{y}{\sqrt{15}} v_\phi$$

FERMION SECTOR

charged fermion masses:

$$M_u = \left(1 + \delta^2\, Y^c Y^{c\dagger}\right)^{-\frac{1}{2}} 8 v_{\Lambda'} Y^u$$

$$M_d = \left(1 + \delta^2\, Y^c Y^{c\dagger}\right)^{-\frac{1}{2}} v_\Lambda \left(Y^d + \delta\, Y^c Y^a\right)$$

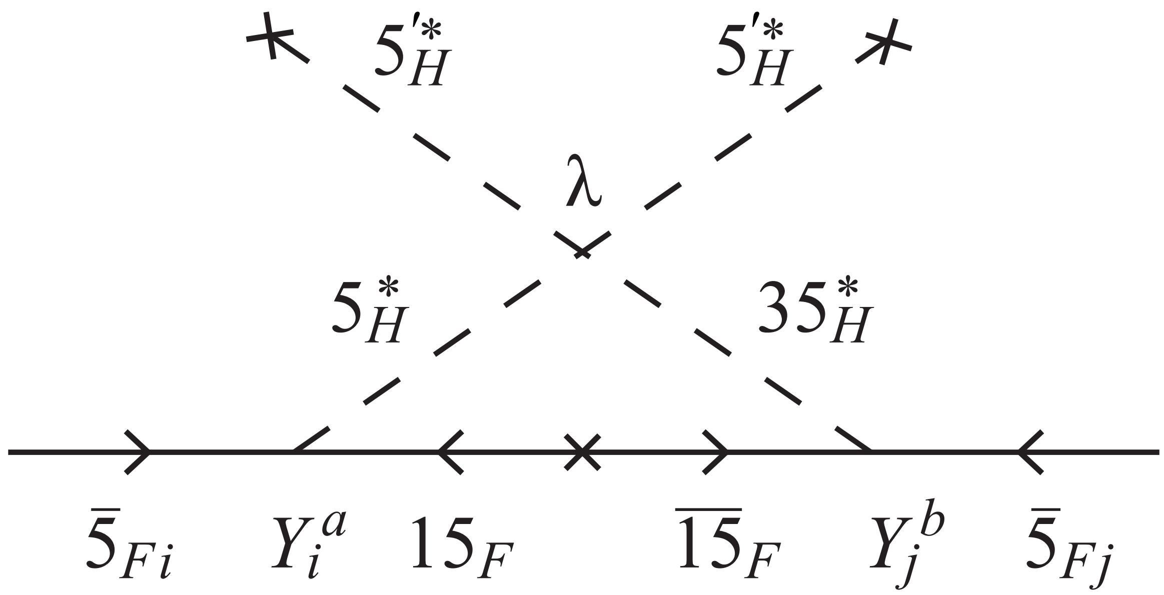
$$M_e = v_\Lambda Y^d$$

$$v'_\phi = -\frac{1}{4}\sqrt{\frac{5}{3}} v_\phi$$

$$\delta = -v'_\phi / M_{\Sigma_3}$$

$$v_\Lambda^2 + v_{\Lambda'}^2 = v^2$$

NEUTRINO MASS DIAGRAM[*]



[*]I.D. and Shaikh Saad, Phys.Rev.D 101 (2020) 1, 015009, arXiv:1910.09008.

FERMION SECTOR

neutrino masses:

$$(M_\nu)_{ij} \approx \frac{\lambda v_{\Lambda'}^2}{8\pi^2}(Y_i^a Y_j^b + Y_i^b Y_j^a)\frac{M_{\Sigma_1}}{M_{\Sigma_1}^2 - M_{\Phi_1}^2}\ln\left(\frac{M_{\Sigma_1}^2}{M_{\Phi_1}^2}\right)$$

$$\equiv m_0(Y_i^a Y_j^b + Y_i^b Y_j^a) = (N\ \mathrm{diag}(0, m_2, m_3)\ N^T)_{ij}$$

$$Y^{a\,T} = \frac{\xi}{\sqrt{2}}\begin{pmatrix} i\ r_2\ N_{12} + r_3\ N_{13} \\ i\ r_2\ N_{22} + r_3\ N_{23} \\ i\ r_2\ N_{32} + r_3\ N_{33} \end{pmatrix} \quad Y^{b\,T} = \frac{1}{\sqrt{2}\xi}\begin{pmatrix} -i\ r_2\ N_{12} + r_3\ N_{13} \\ -i\ r_2\ N_{22} + r_3\ N_{23} \\ -i\ r_2\ N_{32} + r_3\ N_{33} \end{pmatrix}$$ *

$$r_2 = \sqrt{m_2/m_0}$$

$$r_3 = \sqrt{m_3/m_0}$$

*I. Cordero-Carrión, M. Hirsch, and A. Vicente, arXiv:1812.03896.

PECCEI-QUINN SYMMETRY

$$\langle\phi\rangle = \frac{\hat{v}_\phi}{\sqrt{2}}\mathrm{diag}\left(\frac{-1}{\sqrt{15}}, \frac{-1}{\sqrt{15}}, \frac{-1}{\sqrt{15}}, \frac{3}{2\sqrt{15}}, \frac{3}{2\sqrt{15}}\right) e^{i a_\phi(x)/\hat{v}_\phi}, \quad \hat{v}_\phi \equiv \sqrt{2} v_\phi$$

$$\langle\Lambda'\rangle = \frac{\hat{v}_{\Lambda'}}{\sqrt{2}} e^{i\frac{a_{\Lambda'}}{\hat{v}_{\Lambda'}}}, \quad \langle\Lambda^*\rangle = \frac{\hat{v}_\Lambda}{\sqrt{2}} e^{i\frac{a_\Lambda}{\hat{v}_\Lambda}}, \quad \hat{v}_{\Lambda^{(\prime)}} \equiv \sqrt{2} v_{\Lambda^{(\prime)}}$$

$$a = \frac{x_{\Lambda'}\hat{v}_{\Lambda'}a_{\Lambda'} + x_\Lambda^* \hat{v}_\Lambda a_\Lambda + x_\phi \hat{v}_\phi a_\phi}{v_a}, \quad v_a^2 = x_{\Lambda'}^2 \hat{v}_{\Lambda'}^2 + x_\Lambda^2 \hat{v}_\Lambda^2 + x_\phi^2 \hat{v}_\phi^2$$

$$x_i^* = -x_i$$

$$\tan^2\beta = \frac{v_{\Lambda'}^2}{v_\Lambda^2} = \frac{x_\Lambda^*}{x_{\Lambda'}} \qquad\qquad v_\Lambda^2 + v_{\Lambda'}^2 = v^2$$

PECCEI-QUINN SYMMETRY

axion couplings:

$$\delta\mathcal{L}_{\rm eff} = \frac{\alpha_s}{8\pi}\frac{a}{f_a}G\widetilde{G} + \left(\frac{\alpha_{\rm em}}{2\pi f_a}\frac{E}{N}\right)\frac{a}{4}F\widetilde{F} \qquad E/N = 8/3$$

axion decay constant:

$$f_a = \frac{v_a}{2|N|} \approx \frac{\hat{v}_\phi}{2|N|} = \sqrt{\frac{3}{10\pi\alpha_{\rm GUT}}}\frac{M_{\rm GUT}}{|N|} \qquad |N| = 13/2$$

axion mass*:

$$m_a = 5.7\,{\rm neV}\left(\frac{10^{15}\,{\rm GeV}}{f_a}\right) = 5.7\,{\rm neV}\left(\frac{10^{15}\,{\rm GeV}}{M_{\rm GUT}}\right)|N|\sqrt{\frac{10\pi\alpha_{\rm GUT}}{3}}$$

*G. Grilli di Cortona, E. Hardy, J. Pardo Vega, and G. Villadoro, arXiv:1511.02867.
W. A. Bardeen, S. H. H. Tye, and J. A. M. Vermaseren,, Phys. Lett. B 76 (1978) 580–584.

PECCEI-QUINN SYMMETRY

axion mass:

$$m_a = 5.7\,\mathrm{neV}\,\left(\frac{10^{15}\,\mathrm{GeV}}{f_a}\right) = 5.7\,\mathrm{neV}\,\left(\frac{10^{15}\,\mathrm{GeV}}{M_{\mathrm{GUT}}}\right)|N|\sqrt{\frac{10\pi\alpha_{\mathrm{GUT}}}{3}}$$

m_a is in the [0.1, 4.7] neV range

PECCEI-QUINN SYMMETRY

axion coupling to the photons*:

$$\mathcal{L} \supset \underbrace{\frac{\alpha_{\rm em}}{2\pi f_a}\left(\frac{E}{N} - 1.92\right)}_{\equiv g_{a\gamma\gamma}} \frac{a}{4} F\widetilde{F}$$

axion coupling to nucleon n&:

$$\mathcal{L} \supset -\frac{i}{2} g_{aD}\, a\overline{\psi}_n \sigma_{\mu\nu}\gamma_5 \psi_n F^{\mu\nu}$$

$$d_n \approx a \underbrace{\frac{2.4 \times 10^{-16}}{f_a}}_{g_{aD}} e \cdot {\rm cm}$$

*G. Grilli di Cortona, E. Hardy, J. Pardo Vega, and G. Villadoro, arXiv:1511.02867.
&P. W. Graham and S. Rajendran, arXiv:1306.6088 [hep-ph].

PECCEI-QUINN SYMMETRY

axion dark matter contribution*:

$$\Omega h^2 \sim 0.12 \left(\frac{5\,\mathrm{neV}}{m_a}\right)^{1.17} \left(\frac{\theta_i}{1.53 \times 10^{-2}}\right)^2$$

$$\theta_i = a_i / f_a$$

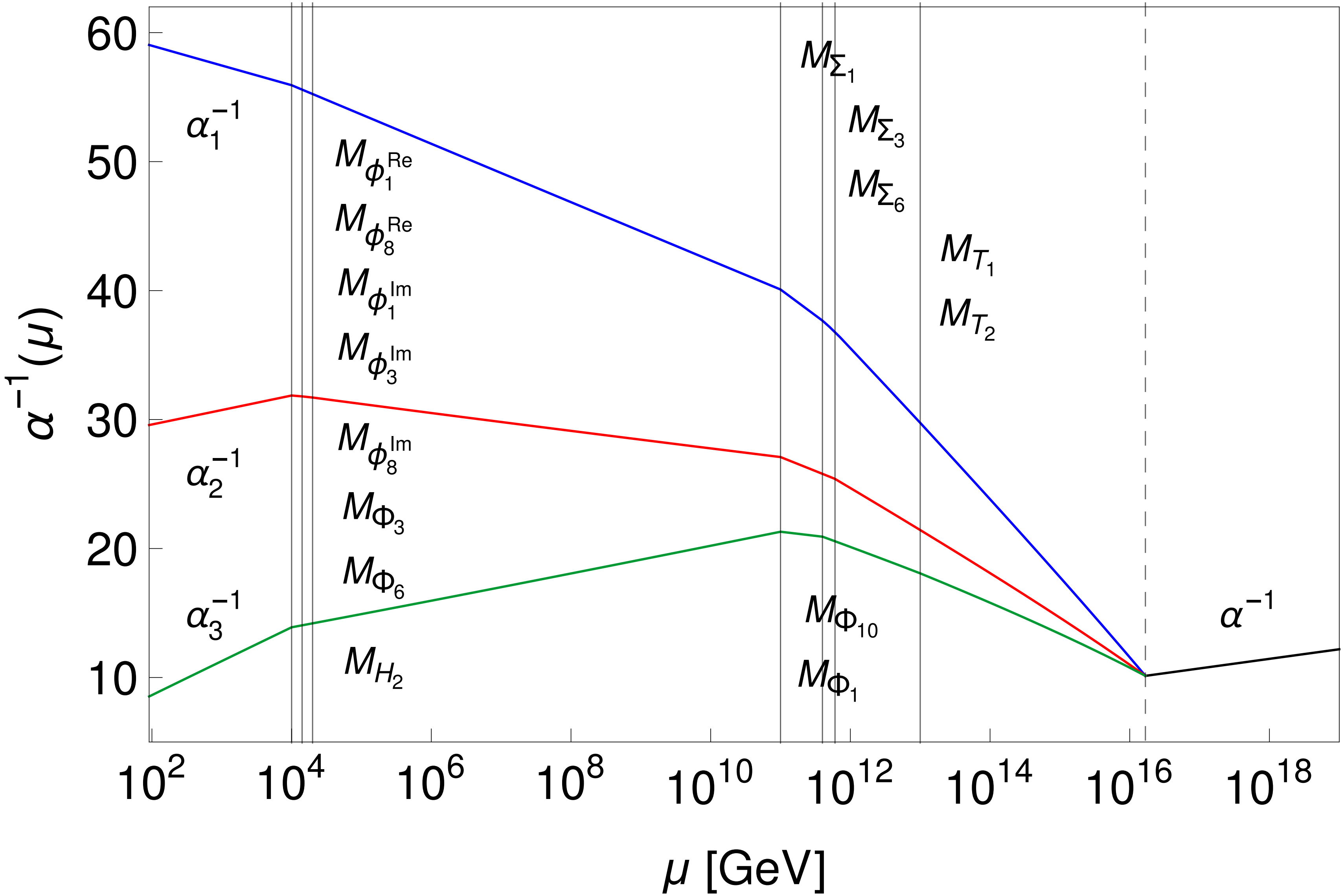
$$\Omega h^2 \sim 0.12 \pm 0.001$$

*G. Ballesteros, J. Redondo, A. Ringwald, and C. Tamarit, arXiv:1610.01639.

PARAMETER SPACE ANALYSIS

- gauge coupling analysis
- fermion mass fit
- proton partial decay lifetimes
- axion parameters

RESULTS



60
50
40
30
20
10
$\alpha^{-1}(\mu)$
10^2
10^4
10^6
10^8
10^{10}
10^{12}
10^{14}
10^{16}
10^{18}
μ [GeV]
α_1^{-1}
α_2^{-1}
α_3^{-1}
α^{-1}
$M_{\phi_1^{Re}}$
$M_{\phi_8^{Re}}$
$M_{\phi_1^{Im}}$
$M_{\phi_3^{Im}}$
$M_{\phi_8^{Im}}$
M_{Φ_3}
M_{Φ_6}
M_{H_2}
M_{Σ_1}
M_{Σ_3}
M_{Σ_6}
M_{T_1}
M_{T_2}
$M_{\Phi_{10}}$
M_{Φ_1}

RESULTS

$$Y^a = \Big(-0.120 + i\,0.00943,\;\; 0.513 + i\,0.200,\;\; 0.898\Big)$$

$$Y^b = \Big(0.109 + i\,0.150,\;\; 0.348 + i\,0.334,\;\; 0.195 - i\,0.0211\Big)$$

$$Y^c = \Big(0.00115 + i\,0.00198,\;\; -0.0532 + i\,0.0852,\;\; -2.781 - i\,0.743\Big) \times 10^{-6}$$

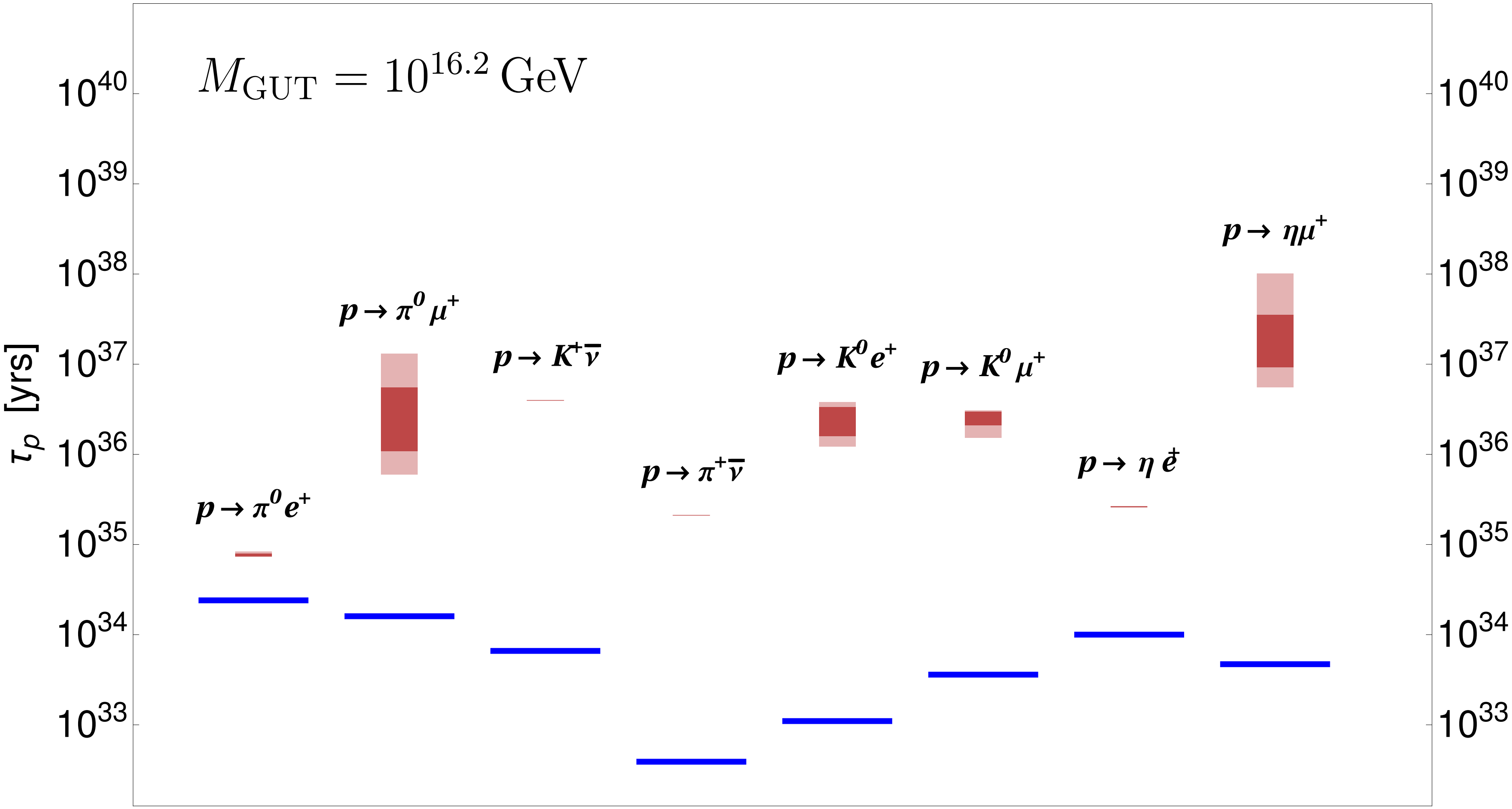
$M_{\mathrm{GUT}} = 10^{16.2}\,\mathrm{GeV}$, $m_{H_2} = 10^{3.77}\,\mathrm{GeV}$, $M_{T_1} = M_{T_2} = 10^{14.55}\,\mathrm{GeV}$, $M_{\phi_1^{\mathrm{Re}}} = 10^{4.39}\,\mathrm{GeV}$, $M_{\phi_1^{\mathrm{Im}}} = 10^{4.12}\,\mathrm{GeV}$, $M_{\phi_3^{\mathrm{Im}}} = 10^{4.40}\,\mathrm{GeV}$, $M_{\phi_8^{\mathrm{Re}}} = 10^{4.09}\,\mathrm{GeV}$, $M_{\phi_8^{\mathrm{Im}}} = 10^{3.71}\,\mathrm{GeV}$, $M_{\Sigma_1} = 10^{13.41}\,\mathrm{GeV}$, $M_{\Sigma_3} = 10^{12.63}\,\mathrm{GeV}$, $M_{\Sigma_3} = 10^{13.24}\,\mathrm{GeV}$, $M_{\Phi_1} = 10^{11.63}\,\mathrm{GeV}$, $M_{\Phi_3} = 10^{5.28}\,\mathrm{GeV}$, $M_{\Phi_6} = 10^{4.18}\,\mathrm{GeV}$, $M_{\Phi_{10}} = 10^{11.63}\,\mathrm{GeV}$, $\alpha_{\mathrm{GUT}}^{-1} = 15.62$, $\lambda = 1.00$, $\delta^\nu = -48.5^\circ$, $\beta^\nu = -71.3^\circ$

PROTON DECAY

decay channel	current bound τ_p [yrs]	future sensitivity τ_p [yrs]
$p \to \pi^0 \, e^+$	2.4×10^{34}	7.8×10^{34}
$p \to \pi^0 \, \mu^+$	1.6×10^{34}	7.7×10^{34}
$p \to \eta^0 \, e^+$	1.0×10^{34}	4.3×10^{34}
$p \to \eta^0 \, \mu^+$	4.7×10^{33}	4.9×10^{34}
$p \to K^0 \, e^+$	1.1×10^{33}	-
$p \to K^0 \, \mu^+$	3.6×10^{33}	-
$p \to \pi^+ \, \overline{\nu}$	3.9×10^{32}	-
$p \to K^+ \, \overline{\nu}$	6.6×10^{33}	3.2×10^{34}

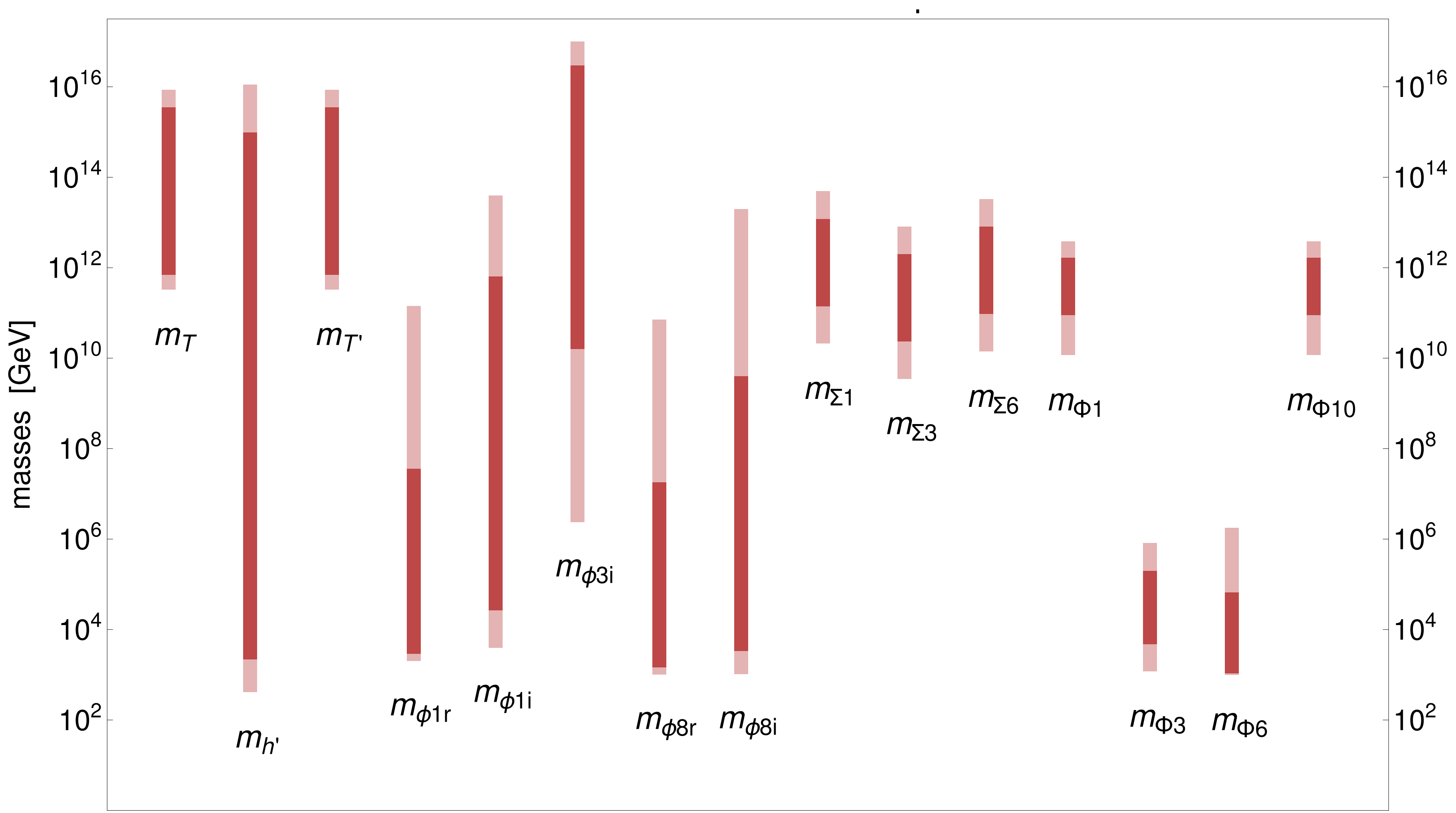
*Hyper-Kamiokande Collaboration, arXiv:1805.04163 [physics.ins-det].

RESULTS



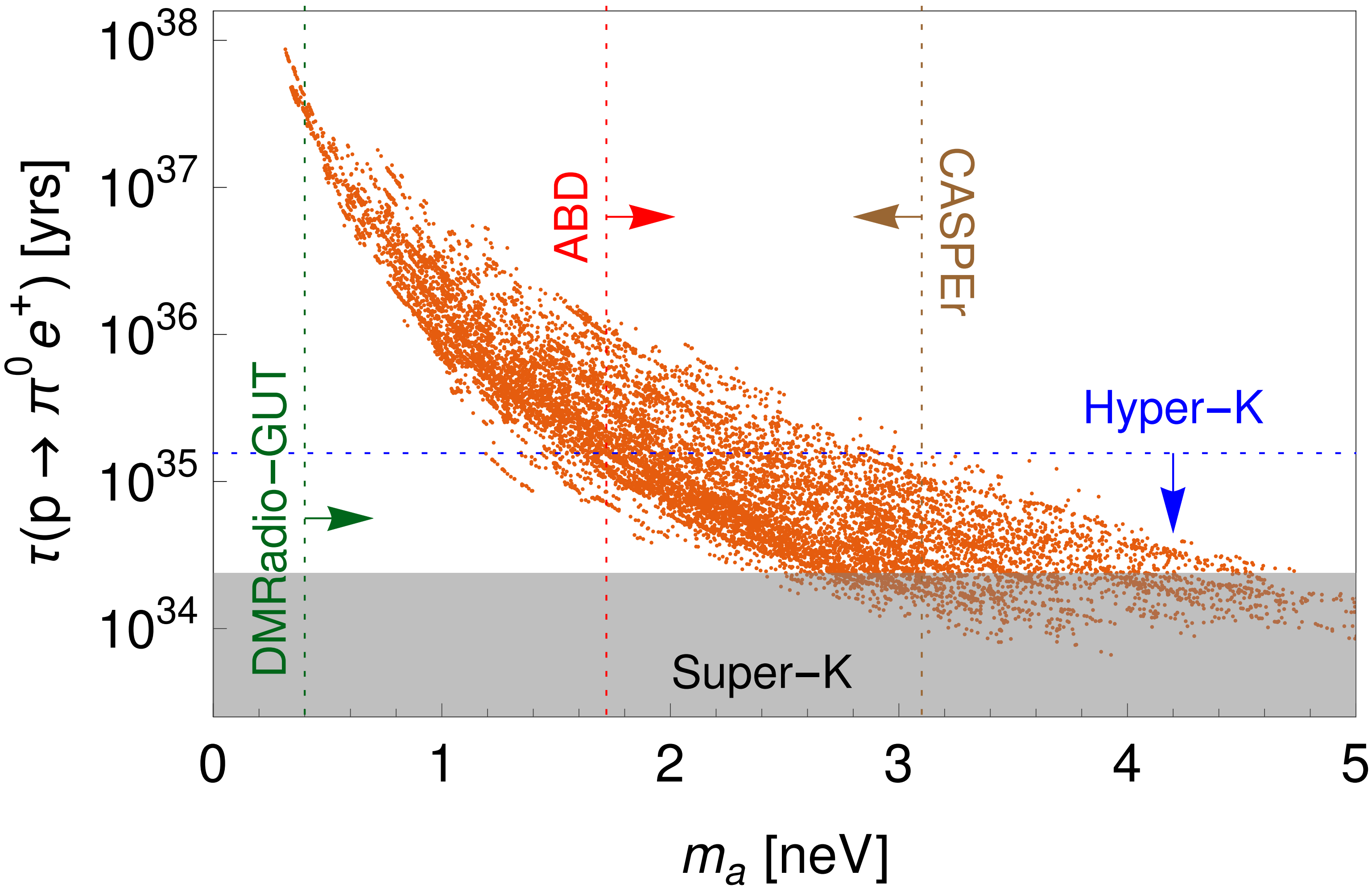
$M_{\rm GUT} = 10^{16.2}\,{\rm GeV}$
τ_p [yrs]
10^{33}
10^{34}
10^{35}
10^{36}
10^{37}
10^{38}
10^{39}
10^{40}
$p \to \pi^0 e^+$
$p \to \pi^0 \mu^+$
$p \to K^+ \overline{\nu}$
$p \to \pi^+ \overline{\nu}$
$p \to K^0 e^+$
$p \to K^0 \mu^+$
$p \to \eta e^+$
$p \to \eta \mu^+$

RESULTS



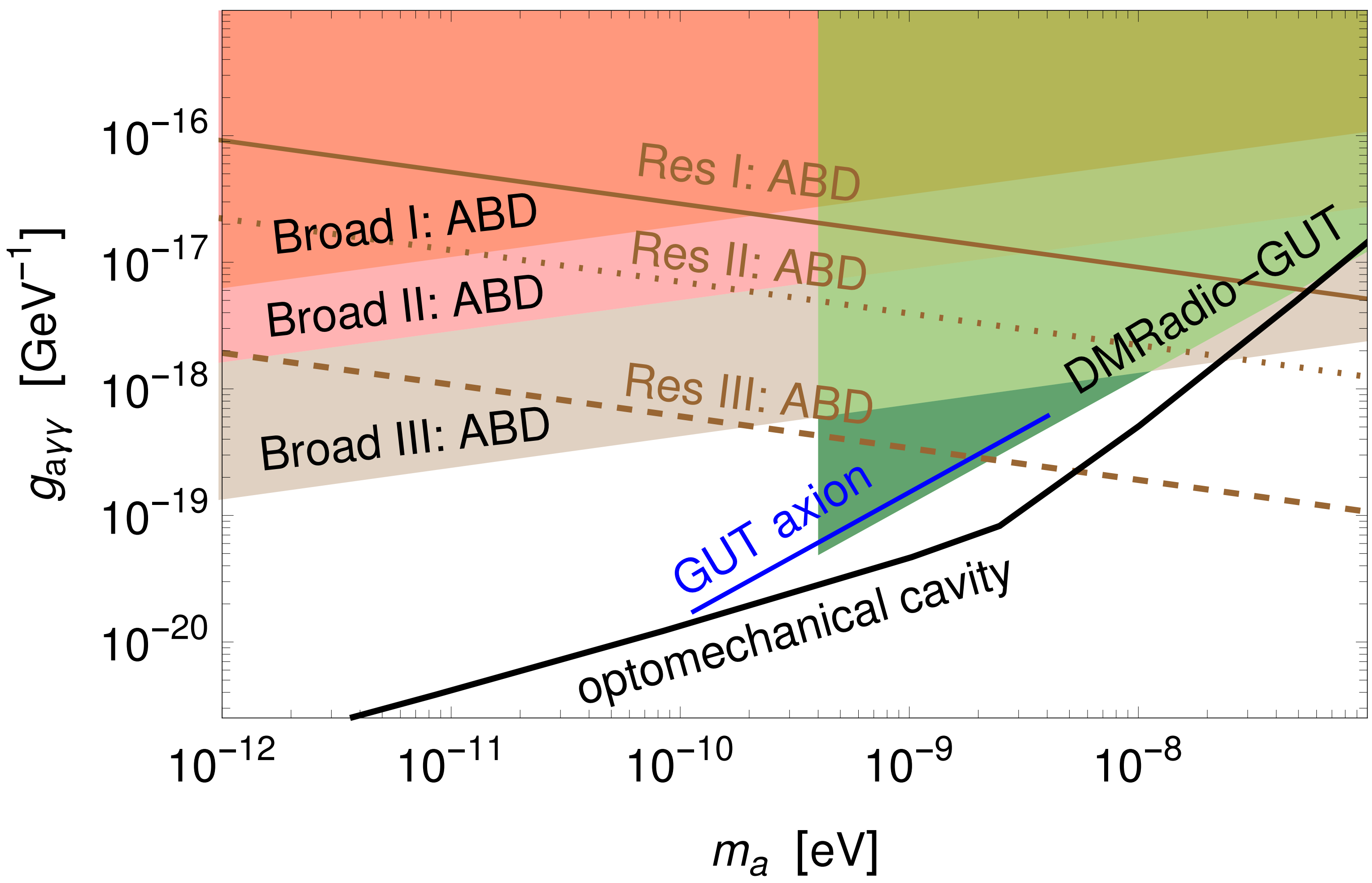
masses [GeV]
10^{16}
10^{14}
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
m_T
$m_{h'}$
$m_{T'}$
$m_{\phi 1r}$
$m_{\phi 1i}$
$m_{\phi 3i}$
$m_{\phi 8r}$
$m_{\phi 8i}$
$m_{\Sigma 1}$
$m_{\Sigma 3}$
$m_{\Sigma 6}$
$m_{\Phi 1}$
$m_{\Phi 3}$
$m_{\Phi 6}$
$m_{\Phi 10}$

RESULTS

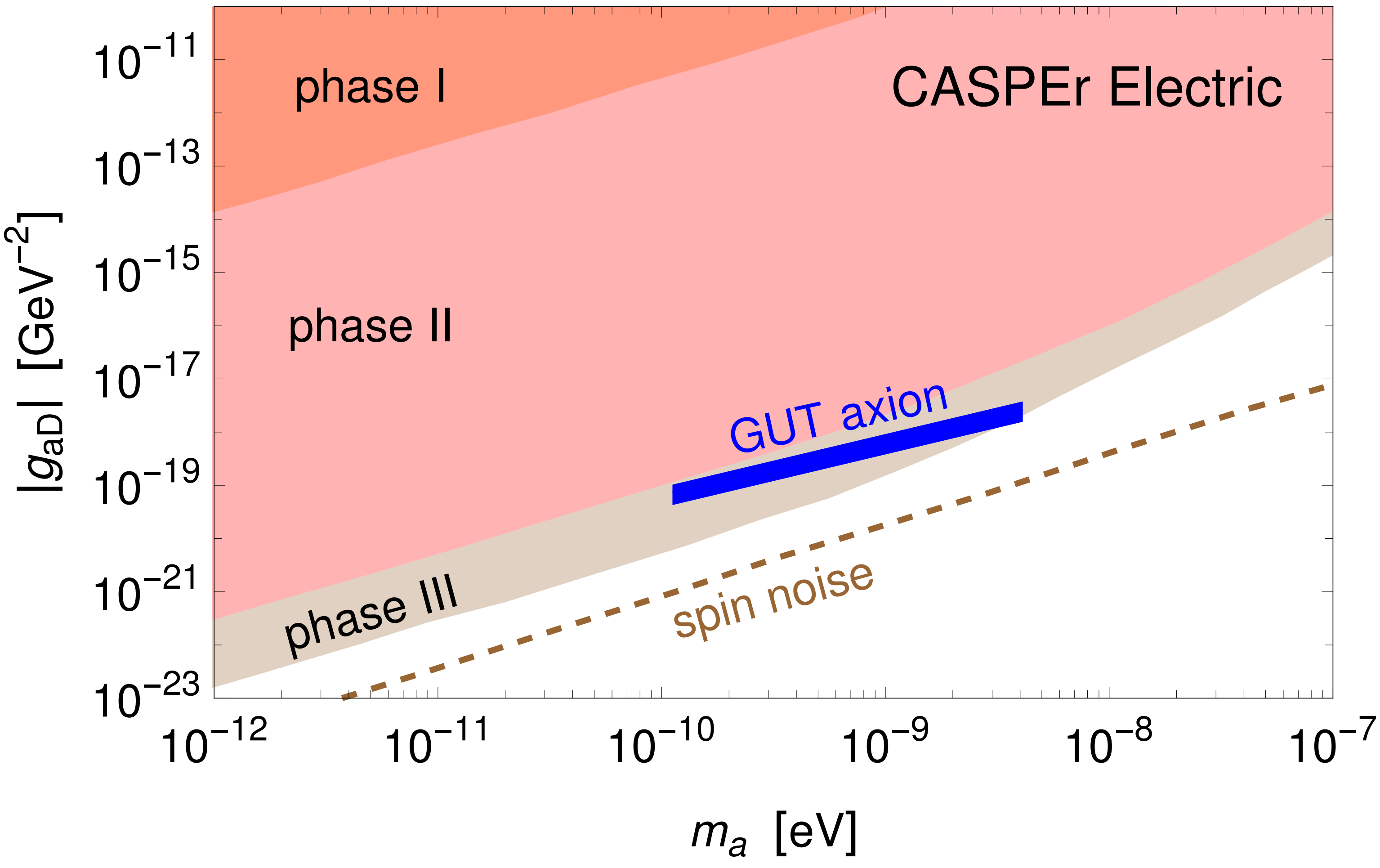


$\tau(p \to \pi^0 e^+)$ [yrs]
10^{38}
10^{37}
10^{36}
10^{35}
10^{34}
DMRadio−GUT
ABD
CASPEr
Hyper−K
Super−K
0
1
2
3
4
5
m_a [neV]

RESULTS


Res I: ABD
Broad I: ABD
Res II: ABD
Broad II: ABD
Res III: ABD
Broad III: ABD
DMRadio–GUT
GUT axion
optomechanical cavity
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
$g_{a\gamma\gamma}$ [GeV^{-1}]
10^{-12}
10^{-11}
10^{-10}
10^{-9}
10^{-8}
m_a [eV]

RESULTS



phase I
CASPEr Electric
phase II
GUT axion
phase III
spin noise
10^{-11}
10^{-13}
10^{-15}
10^{-17}
10^{-19}
10^{-21}
10^{-23}
$|g_{aD}|$ [GeV^{-2}]
10^{-12}
10^{-11}
10^{-10}
10^{-9}
10^{-8}
10^{-7}
m_a [eV]

RESULTS

neutrino Dirac CP phase:

$$\delta^\nu \in [-50.7^\circ, 55.6^\circ]$$

neutrinoless double beta decay parameter:

$$m_{\beta\beta} \in [1.46, 2.24]\,\mathrm{meV}$$

CONCLUSIONS

The $SU(5)\times U(1)_{PQ}$ model under consideration predicts existence of an ultralight axion dark matter within a narrow mass range of [0.1, 4.7] neV.

The entire parameter space of the proposal will be probed through a synergy between experiments that (will) look for proton decay (Hyper-Kamiokande), axion dark matter through axion-photon coupling (ABRACADABRA and DMRadio-GUT) and nucleon electric dipole moments (CASPEr Electric).

The model predicts neutrino Dirac CP phase to be $\delta^\nu \in [-50.7^\circ, 55.6^\circ]$

It also yields neutrinoless double beta decay parameter to be

$$m_{\beta\beta} \in [1.46, 2.24]\,\mathrm{meV}$$

The model requires normal hierarchy for neutrinos, where one neutrino is massless.

THANK YOU

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PARAMETER SPACE ANALYSIS

$$M_u = U_L \mathrm{diag}(m_u, m_c, m_t) U_L^T$$

$$U_L = D_L \mathrm{diag}(e^{i\beta_1^u}, e^{i\beta_2^u}, 1) V_{\mathrm{CKM}}^T \mathrm{diag}(e^{i\eta_1^u}, e^{i\eta_2^u}, e^{i\eta_3^u})$$

$$\eta_1^u = \eta_2^u = \eta_3^u = 0$$

$$M_e = M_e^{\mathrm{diag}} = \mathrm{diag}(m_e, m_\mu, m_\tau)$$

$$M_d = D_L M_d^{\mathrm{diag}} D_R^\dagger$$

$$N = (e^{i\eta_1^\nu}, e^{i\eta_2^\nu}, e^{i\eta_3^\nu}) V_{\mathrm{PMNS}}^*$$

PARAMETER SPACE ANALYSIS

$$Y^c = (y_1^c e^{i\eta_1^c}, y_2^c e^{i\eta_2^c}, y_3^c e^{i\eta_3^c})$$

$$Y^{a\,T} = \frac{\xi}{\sqrt{2}} \begin{pmatrix} i\, r_2\, N_{12} + r_3\, N_{13} \\ i\, r_2\, N_{22} + r_3\, N_{23} \\ i\, r_2\, N_{32} + r_3\, N_{33} \end{pmatrix} \quad Y^{b\,T} = \frac{1}{\sqrt{2}\xi} \begin{pmatrix} -i\, r_2\, N_{12} + r_3\, N_{13} \\ -i\, r_2\, N_{22} + r_3\, N_{23} \\ -i\, r_2\, N_{32} + r_3\, N_{33} \end{pmatrix}$$

NUMERICAL FIT FREE PARAMETERS:

GUT parameters: $\alpha_{\rm GUT},\ M_{\rm GUT}$

masses: $\phi_3^{\rm Im}, \phi_8^{\rm Re}, \phi_8^{\rm Im}, \Sigma_1, \Phi_1, \Phi_3, \Phi_6, T_1, T_2, H_2$

phases: $\beta_1^u, \beta_2^u, \delta^\nu, \beta^\nu, \eta_1^\nu, \eta_2^\nu, \eta_3^\nu, \eta_1^c, \eta_2^c, \eta_3^c$

dimensionless parameters: $y_1^c, y_2^c, y_3^c, \lambda, \xi$

PROTON DECAY

$$\Gamma(p \to \pi^0 e^+_\alpha) = \frac{m_p \pi}{2}\left(1 - \frac{m_\pi^2}{m_p^2}\right)^2 A_L^2 \frac{\alpha_{\rm GUT}^2}{M_{\rm GUT}^4}$$
$$\times \left(A_{SL}^2 |c(e^c_\alpha, d)\langle \pi^0|(ud)_L u_L|p\rangle|^2 + A_{SR}^2 |c(e_\alpha, d^c)\langle \pi^0|(ud)_R u_L|p\rangle|^2\right)$$

$$c(e^c_\alpha, d_\beta) = (U_R^\dagger U_L^*)_{11}(E_R^\dagger D_L^*)_{\alpha\beta} + (E_R^\dagger U_L^*)_{\alpha 1}(U_R^\dagger D_L^*)_{1\beta}$$
$$c(e_\alpha, d^c_\beta) = (U_R^\dagger U_L^*)_{11}(E_L^\dagger D_R^*)_{\alpha\beta}$$
$$c(\nu_l, d_\alpha, d^c_\beta) = (U_R^\dagger D_L^*)_{1\alpha}(D_R^\dagger N)_{\beta l}$$

$$M_u = U_L M_u^{\rm diag} U_R^\dagger \qquad M_d = D_L M_d^{\rm diag} D_R^\dagger$$
$$M_e = E_L M_e^{\rm diag} E_R^\dagger \qquad M_\nu = N M_\nu^{\rm diag} N^T$$

RESULTS

$$Y^a = \Big(-0.120 + i\,0.00943,\ \ 0.513 + i\,0.200,\ \ 0.898\Big)$$

$$Y^b = \Big(0.109 + i\,0.150,\ \ 0.348 + i\,0.334,\ \ 0.195 - i\,0.0211\Big)$$

$$Y^c = \Big(0.00115 + i\,0.00198,\ \ -0.0532 + i\,0.0852,\ \ -2.781 - i\,0.743\Big) \times 10^{-6}$$

$M_{\mathrm{GUT}} = 10^{16.2}\,\mathrm{GeV}$, $m_{H_2} = 10^{3.77}\,\mathrm{GeV}$, $M_{T_1} = M_{T_2} = 10^{14.55}\,\mathrm{GeV}$, $M_{\phi_1^{\mathrm{Re}}} = 10^{4.39}\,\mathrm{GeV}$, $M_{\phi_1^{\mathrm{Im}}} = 10^{4.12}\,\mathrm{GeV}$, $M_{\phi_3^{\mathrm{Im}}} = 10^{4.40}\,\mathrm{GeV}$, $M_{\phi_8^{\mathrm{Re}}} = 10^{4.09}\,\mathrm{GeV}$, $M_{\phi_8^{\mathrm{Im}}} = 10^{3.71}\,\mathrm{GeV}$, $M_{\Sigma_1} = 10^{13.41}\,\mathrm{GeV}$, $M_{\Sigma_3} = 10^{12.63}\,\mathrm{GeV}$, $M_{\Sigma_3} = 10^{13.24}\,\mathrm{GeV}$, $M_{\Phi_1} = 10^{11.63}\,\mathrm{GeV}$, $M_{\Phi_3} = 10^{5.28}\,\mathrm{GeV}$, $M_{\Phi_6} = 10^{4.18}\,\mathrm{GeV}$, $M_{\Phi_{10}} = 10^{11.63}\,\mathrm{GeV}$, $\alpha_{\mathrm{GUT}}^{-1} = 15.62$, $\lambda = 1.00$, $\delta^{\nu} = -48.5^{\circ}$, $\beta^{\nu} = -71.3^{\circ}$

…starting from a single benchmark point with a flat prior distribution a Markov-chain-Monte-Carlo (MCMC) analysis involving a Metropolis-Hasting algorithm is performed, giving us a total of 6×10^6 datapoints. We then use these points to calculate the highest posterior density regions of various quantities...