Flavored Universe dispatched via Axion and Neutrino

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Based on
arXiv: 1611.08359

Introduction

Now that the Higgs boson has been discovered at 126 GeV, assuming that it is indeed exactly the one predicted by the SM,

there are several theoretical problems

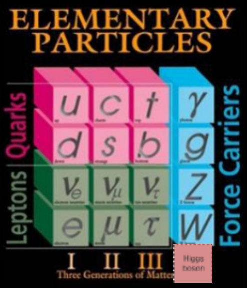
(inclusion of gravity, instability of the Higgs potential, neutrino masses and mixing angles with the CP violating phases, strong CP problem,…)

and cosmological issues

(dark matter, inflation, cosmological constant,…)

point toward the existence of physics beyond the SM

Why flavor physics ?



SM (19)

3 gauge couplings g_1, g_2, g_3
1 Higgs quartic coupling λ
1 Higgs mass-squared

Flavor universal (5)

6 quark masses
3 charged-lepton masses
4 quark mixing angles
Strong CP violating parameter

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Flavor dependent (23)

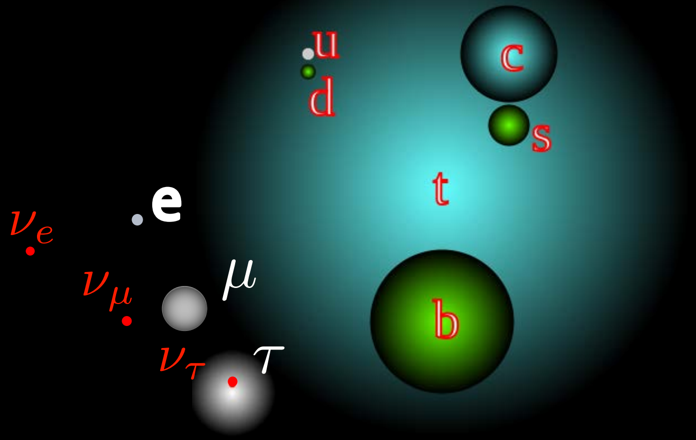
ν (9)

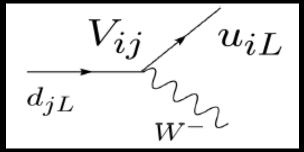
3 ν-masses
3 ν-mixing angles
3 CP-violating phases

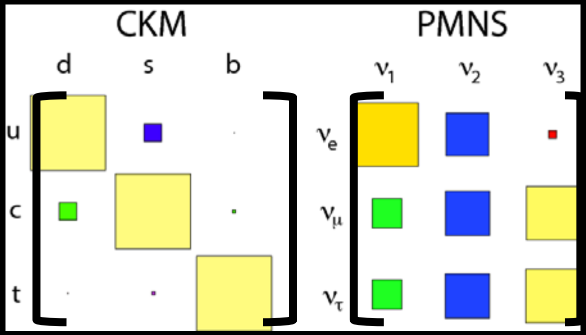
23 of the 28 parameters describe flavor physics in the νSM

What is the fundamental physics behind these parameters ?

Standard Model Puzzles







It does not look "accidental"

$$\mathcal{L}_{\rm QCD} = -\frac{1}{4} G^{a\mu\nu} G^a_{\mu\nu} + \vartheta \frac{\alpha_s}{8\pi} G^{a\mu\nu} \tilde{G}^a_{\mu\nu} + \bar{\psi}(i\gamma^\mu D_\mu - m_q\, e^{-i\gamma_5 \arg[\det m_q]})\psi$$

GLUON DYNAMICS

QCD vacuum; CP violating

KINETIC QUARK TERMS

QUARK MASSES

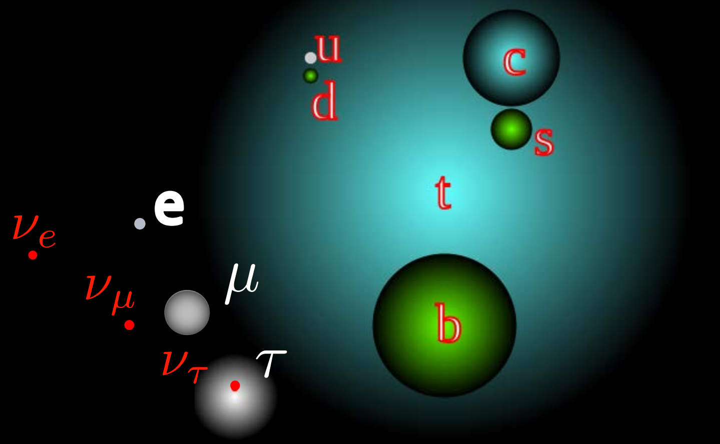
No neutron EDM found
$|\vartheta_{\rm eff}|<0.56 \times 10^{-10}$

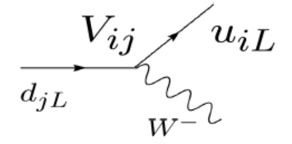
No CP violation in QCD

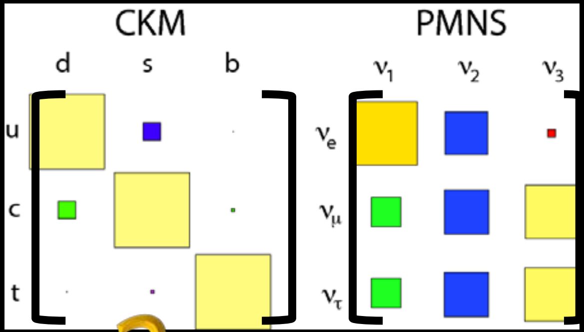
$$\mathcal{L}_\vartheta = \vartheta_{\rm eff} \frac{\alpha_s}{8\pi} G^{a\mu\nu} \tilde{G}^a_{\mu\nu}$$

Why is $\vartheta_{\rm eff}$ so small?

Standard Model Puzzles







It does not look "accidental"

New symmetry ?

beyond the SM gauge symmetry

$$\mathcal{L}_{\mathrm{QCD}} = -\frac{1}{4}G^{a\mu\nu}G^a_{\mu\nu} + \vartheta\frac{\alpha_s}{8\pi}G^{a\mu\nu}\tilde{G}^a_{\mu\nu} + \bar{\psi}(i\gamma^\mu D_\mu - m_q\, e^{-i\gamma_5 \arg[\det m_q]})\psi$$

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$$\mathcal{L}_\vartheta = \vartheta_{\mathrm{eff}}\frac{\alpha_s}{8\pi}G^{a\mu\nu}\tilde{G}^a_{\mu\nu}$$

Why is ϑ_{eff} so small ?

Goal and Motivations

The goal of this talk is to construct an explicit model for rather recent but fast growing issues of astro-particle physics and cosmology

By introducing an $U(1)$ symmetry,
in a way that the $U(1)_X$-$[\text{gravity}]^2$ anomaly-free condition
together with the SM flavor structure
demands additional sterile neutrinos as well as no axionic domain-wall problem

See details 1611.08359

A minimal and economic supersymmetric extension of SM for inflation, leptogenesis, and DM scenario can be realized within

$$G = SM \times U(1)_X \times A_4$$

non-Abelian discrete smallest group for 3 families

Goal and Motivations

flavored

$A_4 \times U(1)_X$

flavor puzzle ⇒ Mixing and Mass hierarchy

Symmetry of geometrical solid
(tetrahedral) ⇒ A_4 could be originated from superstring theory (supergravity)
K.S.Choi, et al

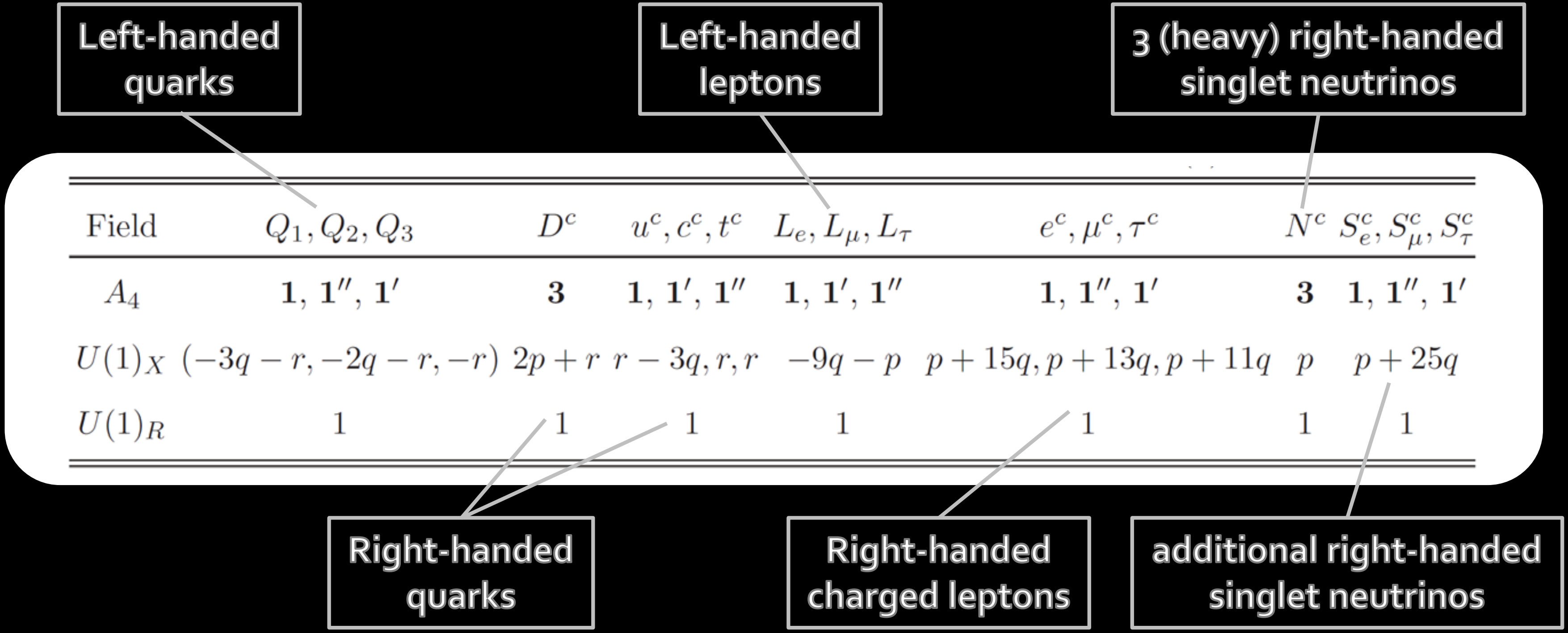
The spontaneous breakdown of anomalous $U(1)_X$ produces the QCD axion

In favor of such a new extension of the SM, Axions and Neutrinos could be powerful sources
for both theoretical and cosmological issues,

In that
They stand out as their convincing physics and the variety of experimental probes.

Many of the outstanding mysteries of astrophysics may be hidden from our sight at all wavelengths of the EM spectrum.

Tetrahedral A_4 & Flavored-PQ $U(1)_X$ Symmetry



Left-handed quarks

Left-handed leptons

3 (heavy) right-handed singlet neutrinos

Field	Q_1, Q_2, Q_3	D^c	u^c, c^c, t^c	L_e, L_μ, L_τ	e^c, μ^c, τ^c	N^c	S^c_e, S^c_μ, S^c_τ
A_4	$\mathbf{1}, \mathbf{1}'', \mathbf{1}'$	$\mathbf{3}$	$\mathbf{1}, \mathbf{1}', \mathbf{1}''$	$\mathbf{1}, \mathbf{1}', \mathbf{1}''$	$\mathbf{1}, \mathbf{1}'', \mathbf{1}'$	$\mathbf{3}$	$\mathbf{1}, \mathbf{1}'', \mathbf{1}'$
$U(1)_X$	$(-3q-r, -2q-r, -r)$	$2p+r$	$r-3q, r, r$	$-9q-p$	$p+15q, p+13q, p+11q$	p	$p+25q$
$U(1)_R$	1	1	1	1	1	1	1

Right-handed quarks

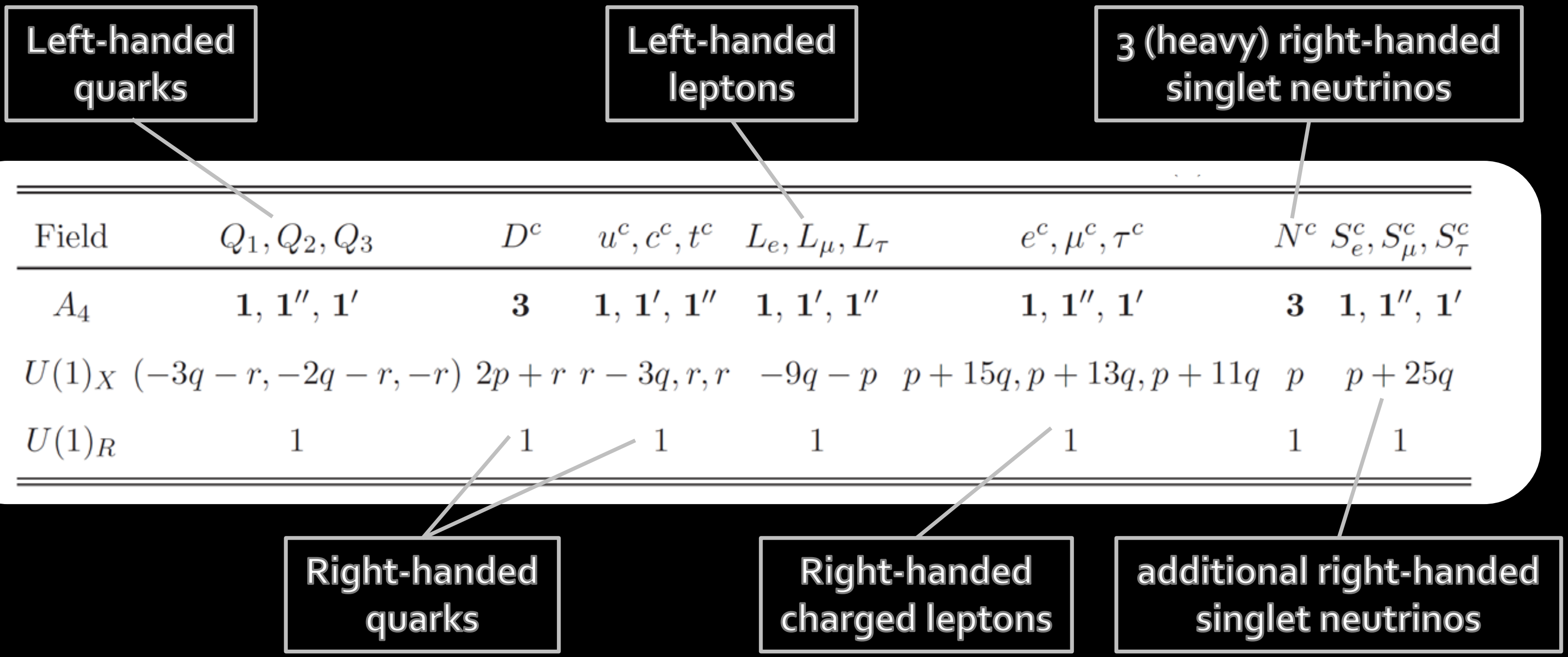
Right-handed charged leptons

additional right-handed singlet neutrinos

$U(1)_X$-[gravity]^2 anomaly-free condition together with the SM flavor structure demands additional sterile neutrinos

$U(1)_X$ quantum numbers of quark flavors are arranged in a way that no axionic domain-wall problem, which plays a crucial role in cosmology when the X-symmetry breaking occurs after inflation !!

Tetrahedral A_4 & Flavored-PQ $U(1)_X$ Symmetry



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A_4	$\mathbf{1}, \mathbf{1}'', \mathbf{1}'$	$\mathbf{3}$	$\mathbf{1}, \mathbf{1}', \mathbf{1}''$	$\mathbf{1}, \mathbf{1}', \mathbf{1}''$	$\mathbf{1}, \mathbf{1}'', \mathbf{1}'$	$\mathbf{3}$	$\mathbf{1}, \mathbf{1}'', \mathbf{1}'$
$U(1)_X$	$(-3q-r, -2q-r, -r)$	$2p+r$	$r-3q, r, r$	$-9q-p$	$p+15q, p+13q, p+11q$	p	$p+25q$
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Right-handed quarks

Right-handed charged leptons

additional right-handed singlet neutrinos

The $U(1)_X$ invariance forbids renormalizable Yukawa couplings for the light families, but would allow them through effective non-renormalizable couplings suppressed by **(flavon/Λ)**

And then the $U(1)_X$ charge assignments make them correspond to the measured fermion masses

The global $U(1)_X$ symmetry which is anomalous can provide a solution to the strong CP problem

Tetrahedral A_4 & Flavored-PQ $U(1)_X$ Symmetry

Field	Q_1, Q_2, Q_3	D^c	u^c, c^c, t^c	L_e, L_μ, L_τ	e^c, μ^c, τ^c	N^c	S^c_e, S^c_μ, S^c_τ
A_4	$\mathbf{1}, \mathbf{1}'', \mathbf{1}'$	$\mathbf{3}$	$\mathbf{1}, \mathbf{1}', \mathbf{1}''$	$\mathbf{1}, \mathbf{1}', \mathbf{1}''$	$\mathbf{1}, \mathbf{1}'', \mathbf{1}'$	$\mathbf{3}$	$\mathbf{1}, \mathbf{1}'', \mathbf{1}'$
$U(1)_X$	$(-3q-r, -2q-r, -r)$	$2p+r$	$r-3q, r, r$	$-9q-p$	$p+15q, p+13q, p+11q$	p	$p+25q$
$U(1)_R$	1	1	1	1	1	1	1

Different from KSVZ

Flavored-PQ symmetry

Anomaly-free $U(1)_X$-[gravity]^2 is correlated with the anomalous $U(1)_X$-$[SU(3)_C]^2$ through

Axionic domain wall number

Flavor structure

Tetrahedral A_4 & Flavored-PQ $U(1)_X$ Symmetry

Field	Q_1, Q_2, Q_3	D^c	u^c, c^c, t^c	L_e, L_μ, L_τ	e^c, μ^c, τ^c	N^c	S^c_e, S^c_μ, S^c_τ
A_4	$\mathbf{1}, \mathbf{1}'', \mathbf{1}'$	$\mathbf{3}$	$\mathbf{1}, \mathbf{1}', \mathbf{1}''$	$\mathbf{1}, \mathbf{1}', \mathbf{1}''$	$\mathbf{1}, \mathbf{1}'', \mathbf{1}'$	$\mathbf{3}$	$\mathbf{1}, \mathbf{1}'', \mathbf{1}'$
$U(1)_X$	$(-3q-r, -2q-r, -r)$	$2p+r$	$r-3q, r, r$	$-9q-p$	$p+15q, p+13q, p+11q$	p	$p+25q$
$U(1)_R$	1	1	1	1	1	1	1

anomalous

$U(1)_X$-$[SU(3)_C]^2$

$$\delta^{\rm GS}_k \delta^{ab} = 2 \sum X_{k\psi} {\rm Tr}[t^a t^b]$$

$$\delta_1^{GS} = 6 \text{ relative prime } \delta_2^{GS} = 13$$

Anomaly-free $U(1)_X$-$[\text{gravity}]^2$

$$0 = \{3 \cdot 2(-5q - 3r) + 3(6p + 3r) + 3(-3q + 3r)\}_{\rm quark}$$
$$+\{-2(27q + 3p) + (3p + 39q) + 3p + 3p + 75q\}_{\rm lepton}$$

Anomaly-free $[U(1)_X]^3$

$$0 = 3 \cdot 2\{(-3q-r)^3 + (-2q-r)^3 - r^3\} + 9(2p+r)^3 + 3\{(-3q+r)^3 + r^3 + r^3\}$$
$$+6(-9q-p)^3 + \{(p+15q)^3 + (p+13q)^3 + (p+11q)^3\} + 3p^3 + 3(p+25q)^3$$

Quantum number r only plays role in making the $[U(1)_X]^3$ anomaly-free

$$r = (-5 \pm \sqrt{367409})\, q/38$$

Irrational # ? !

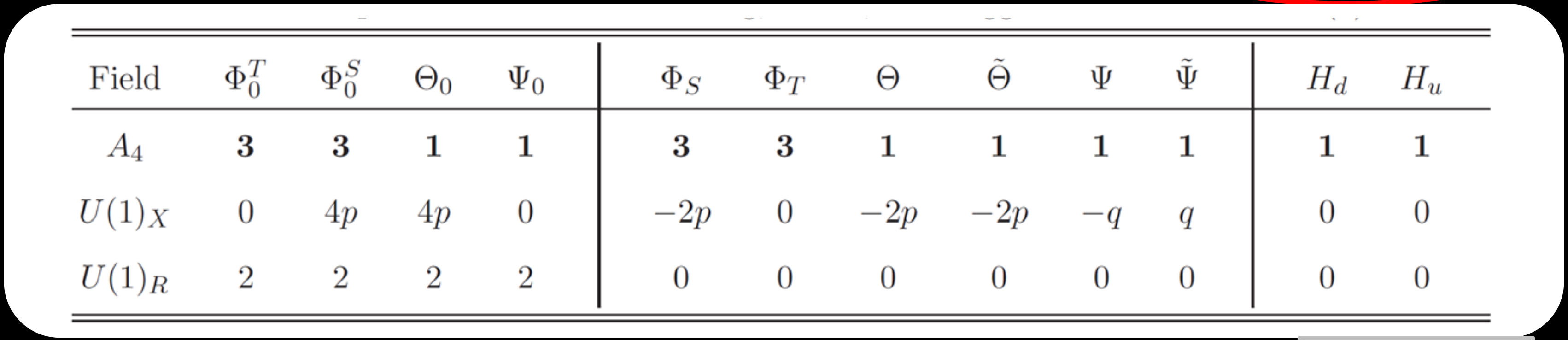
Tetrahedral A_4 & Flavored-PQ $U(1)_X$ Symmetry

to break the flavor group along required VEV directions and to allow the flavons to get VEVs, which only couple to the flavons (Driving field method, first, by Altarelli and Feruglio 2006)

Driving fields

Flavon fields

spontaneous breaking of the flavor symmetry



Field	Φ_0^T	Φ_0^S	Θ_0	Ψ_0	Φ_S	Φ_T	Θ	$\tilde{\Theta}$	Ψ	$\tilde{\Psi}$	H_d	H_u
A_4	**3**	**3**	**1**	**1**	**3**	**3**	**1**	**1**	**1**	**1**	**1**	**1**
$U(1)_X$	0	$4p$	$4p$	0	$-2p$	0	$-2p$	$-2p$	$-q$	q	0	0
$U(1)_R$	2	2	2	2	0	0	0	0	0	0	0	0

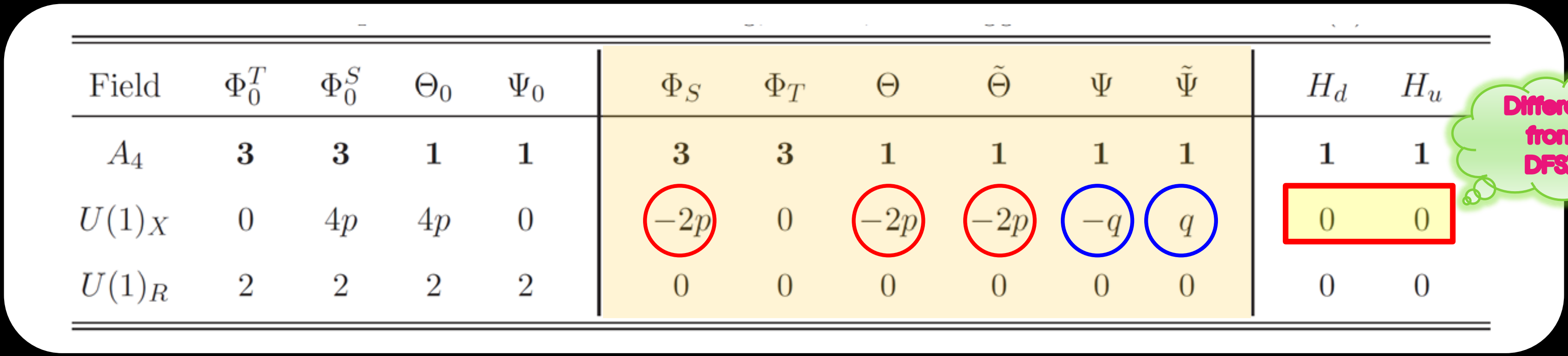
Higgs fields

Superpotential $\mu H_u H_d$ is not allowed, while the leading terms are allowed $g_{\Psi_0}\Psi_0 H_u H_d$ $+\frac{g_T}{\Lambda_{st}}(\Phi_0^T\Phi_T)_{\mathbf{1}}H_uH_d$ which promote the μ-term $\mu_{\rm eff}\equiv g_{\Psi_0}\langle\Psi_0\rangle+g_T\langle\Phi_0^T\rangle v_T/\Lambda_{st}$

The inflaton Ψ_0 can predominantly decay into Higgss (& Higgsinos) through the first term after inflation, which is important for inflation and leptogensis, while the second term is crucial for relating the sizable μ- term with low energy flavor physics

Tetrahedral A_4 & Flavored-PQ $U(1)_X$ Symmetry

Driving fields **Flavon fields** **Higgs fields**



Field	Φ_0^T	Φ_0^S	Θ_0	Ψ_0	Φ_S	Φ_T	Θ	$\tilde{\Theta}$	Ψ	$\tilde{\Psi}$	H_d	H_u
A_4	**3**	**3**	**1**	**1**	**3**	**3**	**1**	**1**	**1**	**1**	**1**	**1**
$U(1)_X$	0	$4p$	$4p$	0	$-2p$	0	$-2p$	$-2p$	$-q$	q	0	0
$U(1)_R$	2	2	2	2	0	0	0	0	0	0	0	0

Different from DFSZ

Since the flavon fields are the SM gauge singlets,
a direct coupling to ordinary quarks and leptons is possible via Yukawa interactions

Anomalous global
$U(1)_X = U(1)_{X_1} \times U(1)_{X_2}$

Hierarchy of the SM fermions

Vacuum configuration

Axion as a solution to strong CP problem and $N_{DW} = 1$

Connection between strings and the low energy flavor world
(See, 1604.01255)

Tetrahedral A_4 & Flavored-PQ $U(1)_X$ Symmetry

The most general superpotential linear in the driving fields

$$W_v = \Phi_0^T \left(\tilde{\mu}\,\Phi_T + \tilde{g}\,\Phi_T\Phi_T\right) + \Phi_0^S \left(g_1\,\Phi_S\Phi_S + g_2\,\tilde{\Theta}\Phi_S\right) + \Theta_0 \left(g_3\,\Phi_S\Phi_S + g_4\,\Theta\Theta + g_5\,\Theta\tilde{\Theta} + g_6\,\tilde{\Theta}\tilde{\Theta}\right) + g_7\,\Psi_0\left(\Psi\tilde{\Psi} - \mu_\Psi^2\right)$$

Non-trivial Supersymmetric Mimima for flavor physics

$$\langle\Phi_T\rangle = \frac{1}{\sqrt{2}}\left(v_T, 0, 0\right), \quad \langle\Phi_S\rangle = \frac{1}{\sqrt{2}}\left(v_S, v_S, v_S\right), \quad \langle\Theta\rangle = \frac{v_\Theta}{\sqrt{2}}, \quad \langle\tilde{\Theta}\rangle = 0, \quad \langle\Psi\rangle = \langle\tilde{\Psi}\rangle = \frac{v_\Psi}{\sqrt{2}}$$

$$v_T = -\sqrt{\frac{3}{2}\frac{\tilde{\mu}}{\tilde{g}}}, \qquad v_\Theta = v_S\sqrt{-3\frac{g_3}{g_4}}, \qquad v_\Psi = \mu_\Psi\sqrt{\frac{-2}{g_7}}$$

SPONTANEOUSLY

$A4 \times U(1)_X$

- The scalar supersymmetric $W(\Phi_T\,\Phi_S)$ terms are absent ⇨ TBM-like pattern
- In SUSY limit, Flat directions in the flavon potential (Unstable)
- After flavon and driving fields receiving corrections, from NLO terms in the scalar potential, from deviations of canonical kahler potential, from SUSY breaking effects, and from radiative effects ⇨ Absolute minima

Leptonic tetrahedral A_4 & flavored-PQ $U(1)_X$ Symmetry

Yukawa couplings of Dirac neutrino are a function of flavon field $\mathbf{\Psi}$
$y_i^s = y_i^s(\mathbf{\Psi})$

Yukawa couplings between RH neutrinos $S^c_{e,\mu,\tau}$ are functions of flavon $\mathbf{\Theta}$ and $\mathbf{\Psi}$
$y_i^{ss} = y_i^{ss}(\mathbf{\Psi}, \mathbf{\Theta})$

$$\begin{aligned} W_{\ell\nu} \;=\;& y_1^s\, L_e\, S_e^c\, H_u + y_2^s\, L_\mu\, S_\mu^c\, H_u + y_3^s\, L_\tau\, S_\tau^c\, H_u \\ +\;& \frac{1}{2}\left(y_1^{ss}\, S_e^c S_e^c + y_2^{ss}\, S_\mu^c\, S_\tau^c + y_3^{ss}\, S_\tau^c\, S_\mu^c\right)\tilde{\Psi} \\ +\;& y_1^\nu\, L_e (N^c \Phi_T)_{\mathbf{1}} \frac{H_u}{\Lambda} + y_2^\nu\, L_\mu (N^c \Phi_T)_{\mathbf{1}''} \frac{H_u}{\Lambda} + y_3^\nu\, L_\tau (N^c \Phi_T)_{\mathbf{1}'} \frac{H_u}{\Lambda} \\ +\;& \frac{1}{2}(\hat{y}_\Theta\, \Theta + \hat{y}_{\tilde{\Theta}}\, \tilde{\Theta})(N^c N^c)_{\mathbf{1}} + \frac{\hat{y}_R}{2}(N^c N^c)_{\mathbf{3}_s} \Phi_S \\ +\;& y_e\, L_e\, e^c\, H_d + y_\mu\, L_\mu\, \mu^c\, H_d + y_\tau\, L_\tau\, \tau^c\, H_d\,. \end{aligned}$$

Yukawa couplings of Dirac neutrino are a function of flavon $\tilde{\mathbf{\Psi}}$
$y_i^\nu = y_i^\nu(\tilde{\mathbf{\Psi}})$;
$\mathbf{\Phi}_T$ appears in Yukawa terms coupling LH-leptons to RH neutrinos N^c

Yukawa couplings of charged leptons are a function of flavon field $\mathbf{\Psi}$
$y_{e,\mu,\tau} = y_{e,\mu,\tau}(\mathbf{\Psi})$

$\mathbf{\Theta}$ and $\mathbf{\Phi}_S$ appears in Yukawa terms between RH neutrinos N^c

Leptonic tetrahedral A_4 & flavored-PQ $U(1)_X$ Symmetry

$$y_i^s = \hat{y}_i^s \left(\frac{\Psi}{\Lambda}\right)^{16}$$

$$\frac{\langle\Theta\rangle}{\Lambda} \sim \lambda^2 \ll \frac{\langle\Psi\rangle}{\Lambda} = \frac{\langle\tilde{\Psi}\rangle}{\Lambda} \equiv \lambda$$

Cabbibo angle

$$y_i^{ss} = \hat{y}_i^{ss} \left(\frac{\Psi}{\Lambda}\right)^{51} \frac{\Theta}{\Lambda}$$

$$\begin{aligned} W_{\ell\nu} =\ & y_1^s\, L_e\, S_e^c\, H_u + y_2^s\, L_\mu\, S_\mu^c\, H_u + y_3^s\, L_\tau\, S_\tau^c\, H_u \\ &+ \frac{1}{2}\left(y_1^{ss}\, S_e^c S_e^c + y_2^{ss}\, S_\mu^c\, S_\tau^c + y_3^{ss}\, S_\tau^c\, S_\mu^c\right)\tilde{\Psi} \\ &+ y_1^\nu\, L_e (N^c\Phi_T)_{\mathbf{1}} \frac{H_u}{\Lambda} + y_2^\nu\, L_\mu (N^c\Phi_T)_{\mathbf{1}''} \frac{H_u}{\Lambda} + y_3^\nu\, L_\tau (N^c\Phi_T)_{\mathbf{1}'} \frac{H_u}{\Lambda} \\ &+ \frac{1}{2}(\hat{y}_\Theta\, \Theta + \hat{y}_{\tilde{\Theta}}\, \tilde{\Theta})(N^c N^c)_{\mathbf{1}} + \frac{\hat{y}_R}{2}(N^c N^c)_{\mathbf{3}_s}\, \Phi_S \\ &+ y_e\, L_e\, e^c\, H_d + y_\mu\, L_\mu\, \mu^c\, H_d + y_\tau\, L_\tau\, \tau^c\, H_d\,. \end{aligned}$$

$$y_i^\nu = \hat{y}_i^\nu \left(\frac{\tilde{\Psi}}{\Lambda}\right)^{9}$$

$$y_e = \hat{y}_e \left(\frac{\Psi}{\Lambda}\right)^6, \quad y_\mu = \hat{y}_\mu \left(\frac{\Psi}{\Lambda}\right)^4, \quad y_\tau = \hat{y}_\tau \left(\frac{\Psi}{\Lambda}\right)^2$$

$$\hat{y}_\Theta \approx \hat{y}_{\tilde{\Theta}} \approx \hat{y}_R \approx \mathcal{O}(1)$$

Leptonic tetrahedral A_4 & flavored-PQ $U(1)_X$ Symmetry

Through these Yukawa couplings, the ordinary SM leptons interact with SM gauge singlet flavon $\Psi(\tilde{\Psi})$ or Θ

Anomalous current
$J^X_\mu = X_e\, \bar{e}\, \gamma_\mu \gamma_5\, e + \cdots$

Lepton family $L_{e,\mu,\tau}$, $S^c_{e,\mu,\tau}$, e^c, μ^c, τ^c singlets under A4

Hermitian matrix is automatically diagonal

$$\begin{aligned}
W_{\ell\nu} \;=\;& y^s_1\, L_e\, S^c_e\, H_u + y^s_2\, L_\mu\, S^c_\mu\, H_u + y^s_3\, L_\tau\, S^c_\tau\, H_u \\
&+ \frac{1}{2}\left(y^{ss}_1\, S^c_e S^c_e + y^{ss}_2\, S^c_\mu\, S^c_\tau + y^{ss}_3\, S^c_\tau\, S^c_\mu\right)\tilde{\Psi} \\
&+ y^\nu_1\, L_e (N^c\Phi_T)_{\mathbf{1}}\frac{H_u}{\Lambda} + y^\nu_2\, L_\mu (N^c\Phi_T)_{\mathbf{1}''}\frac{H_u}{\Lambda} + y^\nu_3\, L_\tau (N^c\Phi_T)_{\mathbf{1}'}\frac{H_u}{\Lambda} \\
&+ \underline{\frac{1}{2}(\hat{y}_\Theta\, \Theta + \hat{y}_{\tilde{\Theta}}\, \tilde{\Theta})(N^cN^c)_{\mathbf{1}} + \frac{\hat{y}_R}{2}(N^cN^c)_{\mathbf{3}_s}}\Phi_S \\
&+ y_e\, L_e\, e^c\, H_d + y_\mu\, L_\mu\, \mu^c\, H_d + y_\tau\, L_\tau\, \tau^c\, H_d\,.
\end{aligned}$$

Higher dim. operators induced by Φ_T, but, kept small enough

No Residual symmetry → No domain wall problem

Quark tetrahedral A_4 & flavored-PQ $U(1)_X$ Symmetry

$Q_1(u^c)\sim 1$, $Q_2(t^c)\sim 1''$, $Q_3(c^c)\sim 1'$, up-type quark mass matrix automatically diagonal

A4 triplet :
Non-diagonal entries, But
only 6 physical parameters
CKM ?

$$\begin{aligned} W_q^u &= y_u\, Q_1 u^c\, H_u + y_c\, Q_2\, c^c\, H_u + y_t\, Q_3\, t^c\, H_u\,, \\ W_q^d &= y_d\, Q_1 (D^c \Phi_S)_{\mathbf{1}} \frac{H_d}{\Lambda} + y_s\, Q_2 (D^c \Phi_S)_{\mathbf{1}'} \frac{H_d}{\Lambda} + y_b\, Q_3 (D^c \Phi_S)_{\mathbf{1}''} \frac{H_d}{\Lambda} \end{aligned}$$

Yukawa couplings
are a function of flavon $\tilde{\Psi}$

$$y_u = \hat{y}_u \left(\frac{\tilde{\Psi}}{\Lambda}\right)^6, \qquad y_c = \hat{y}_c \left(\frac{\tilde{\Psi}}{\Lambda}\right)^2, \qquad y_t = \hat{y}_t$$

$$y_d = \hat{y}_d \left(\frac{\tilde{\Psi}}{\Lambda}\right)^3, \qquad y_s = \hat{y}_s \left(\frac{\tilde{\Psi}}{\Lambda}\right)^2, \qquad y_b = \hat{y}_b\,.$$

Quark tetrahedral A_4 & flavored-PQ $U(1)_X$ Symmetry

$Q_1(u^c)\sim 1$, $Q_2(t^c)\sim 1''$, $Q_3(c^c)\sim 1'$, up-type quark mass matrix automatically diagonal

Non-trivial next-leading order terms driven by Θ and Φ_T provide the correct CKM matrix

$$
\begin{aligned}
W_q^u &= y_u\, Q_1 u^c\, H_u + y_c\, Q_2\, c^c\, H_u + y_t\, Q_3\, t^c\, H_u\,, \\
W_q^d &= y_d\, Q_1 (D^c\Phi_S)_{\mathbf{1}} \frac{H_d}{\Lambda} + y_s\, Q_2 (D^c\Phi_S)_{\mathbf{1}'} \frac{H_d}{\Lambda} + y_b\, Q_3 (D^c\Phi_S)_{\mathbf{1}''} \frac{H_d}{\Lambda} \\
&+ x_d\, Q_1 (D^c\Phi_T)_{\mathbf{1}} \frac{\Theta}{\Lambda^2} H_d + x_s\, Q_2 (D^c\Phi_T)_{\mathbf{1}'} \frac{\Theta}{\Lambda^2} H_d + x_b\, Q_3 (D^c\Phi_T)_{\mathbf{1}''} \frac{\Theta}{\Lambda^2} H_d \\
&+ x_d^{as}\, Q_1 (D^c\Phi_T\Phi_S)_{\mathbf{1}} \frac{H_d}{\Lambda^2} + x_s^{as}\, Q_2 (D^c\Phi_T\Phi_S)_{\mathbf{1}'} \frac{H_d}{\Lambda^2} + x_b^{as}\, Q_3 (D^c\Phi_T\Phi_S)_{\mathbf{1}''} \frac{H_d}{\Lambda^2}
\end{aligned}
$$

Through these Yukawa couplings, the ordinary SM quarks interact with SM gauge singlet flavon $\tilde{\Psi}$ or Θ

Anomalous current $J^X_\mu = \cdots + X_u\, \bar{u}\, \gamma_\mu \gamma_5\, u + X_d\, \bar{d}\, \gamma_\mu \gamma_5\, d\, + \cdots$

flavored-PQ symmetry A4 X U(1)$_X$

After EW & flavor symmetry breaking, the mass terms

CKM mixing

$$-\mathcal{L}_Y = \overline{q^u_R}\,\mathcal{M}_u\,q^u_L + e^{i\frac{A_1}{v_{\mathcal{F}}}}\,\overline{q^d_R}\,\mathcal{M}_d\,q^d_L + \overline{\ell_R}\,\mathcal{M}_\ell\,\ell_L$$

⇨ Charged quarks and leptons

$$+\frac{1}{2}\begin{pmatrix}\overline{\nu^c_L} & \overline{S_R} & \overline{N_R}\end{pmatrix}\begin{pmatrix} 0 & e^{16i\frac{A_2}{v_g}}\,m^T_{DS} & e^{-9i\frac{A_2}{v_g}}\,m^T_D \\ e^{16i\frac{A_2}{v_g}}\,m_{DS} & e^{i(50\frac{A_2}{v_g}+\frac{A_1}{v_{\mathcal{F}}})}\,M_S & 0 \\ e^{-9i\frac{A_2}{v_g}}\,m_D & 0 & e^{i\frac{A_1}{v_{\mathcal{F}}}}\,M_R \end{pmatrix}\begin{pmatrix}\nu_L \\ S^c_R \\ N^c_R\end{pmatrix} + \text{h.c.}$$

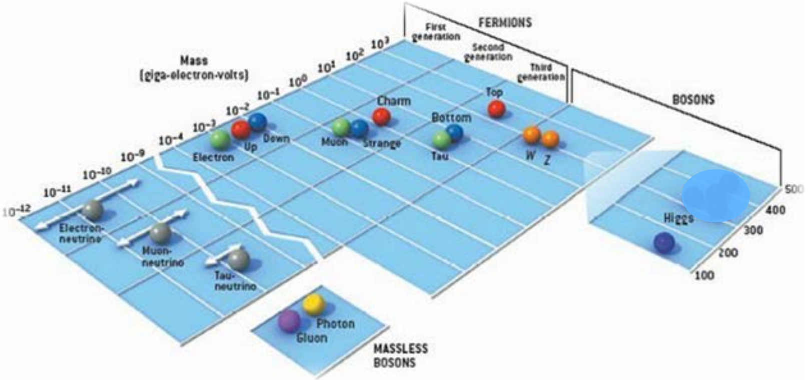
⇨ Neutrinos

The observed mass hierarchies for Charged quarks and leptons

$$y_u = \hat{y}_u\left(\frac{\tilde{\Psi}}{\Lambda}\right)^6, \quad y_c = \hat{y}_c\left(\frac{\tilde{\Psi}}{\Lambda}\right)^2, \quad y_t = \hat{y}_t$$

$$y_d = \hat{y}_d\left(\frac{\tilde{\Psi}}{\Lambda}\right)^3, \quad y_s = \hat{y}_s\left(\frac{\tilde{\Psi}}{\Lambda}\right)^2, \quad y_b = \hat{y}_b\,.$$

$$y_e = \hat{y}_e\left(\frac{\Psi}{\Lambda}\right)^6, \quad y_\mu = \hat{y}_\mu\left(\frac{\Psi}{\Lambda}\right)^4, \quad y_\tau = \hat{y}_\tau\left(\frac{\Psi}{\Lambda}\right)^2$$



flavored-PQ symmetry A4 X $U(1)_X$

$$-\mathcal{L}_Y = \overline{q^u_R}\,\mathcal{M}_u\,q^u_L + e^{i\frac{A_1}{v_\mathcal{F}}}\,\overline{q^d_R}\,\mathcal{M}_d\,q^d_L + \overline{\ell_R}\,\mathcal{M}_\ell\,\ell_L$$

$$+\frac{1}{2}\left(\overline{\nu^c_L}\;\overline{S_R}\;\overline{N_R}\right)\begin{pmatrix} 0 & e^{16i\frac{A_2}{v_g}}\,m^T_{DS} & e^{-9i\frac{A_2}{v_g}}\,m^T_D \\ e^{16i\frac{A_2}{v_g}}\,m_{DS} & e^{i(50\frac{A_2}{v_g}+\frac{A_1}{v_\mathcal{F}})}\,M_S & 0 \\ e^{-9i\frac{A_2}{v_g}}\,m_D & 0 & e^{i\frac{A_1}{v_\mathcal{F}}}\,M_R \end{pmatrix}\begin{pmatrix}\nu_L \\ S^c_R \\ N^c_R\end{pmatrix} + \text{h.c.}$$

Different Yukawa couplings

Exact TBM mixing

$$M_R \gg m_D \gg m_{DS} \gg M_S$$

$$\hat{y}_\Theta \approx \hat{y}_{\tilde{\Theta}} \approx \hat{y}_R \approx O(1) \gg y^\nu_i = \hat{y}^\nu_i\left(\frac{\tilde{\Psi}}{\Lambda}\right)^9 \gg y^s_i = \hat{y}^s_i\left(\frac{\Psi}{\Lambda}\right)^{16} \gg y^{ss}_i = \hat{y}^{ss}_i\left(\frac{\Psi}{\Lambda}\right)^{51}\frac{\Theta}{\Lambda}$$

$$-\mathcal{L}^{a-\nu}_W \simeq \frac{1}{2}\left(\overline{\nu^c_L}\;\overline{S_R}\right)\mathcal{M}_\nu\begin{pmatrix}\nu_L \\ S^c_R\end{pmatrix} + \frac{1}{2}\overline{N_R}\,M_R\,N^c_R + \frac{g}{\sqrt{2}}W^-_\mu\overline{\ell_L}\gamma^\mu\,\nu_L + \text{h.c.}$$

$$-\frac{X_1}{2}\frac{A_1}{f_{a1}}\,M_i\overline{N}_i\,i\gamma_5\,N^c_i - \left\{\frac{X_1}{2}\frac{A_1}{f_{a1}} - 25\,X_2\frac{A_2}{f_{a2}}\right\}m_{s_i}\overline{S}_i\,i\gamma_5\,S_i$$

$$-\left\{\frac{X_1}{2}\frac{A_1}{f_{a1}} - 9X_2\frac{A_2}{f_{a2}}\right\}m_{\nu_i}\overline{\nu}_i\,i\gamma_5\,\nu_i - \frac{1}{2}\overline{N}_i\,i\partial\!\!\!/\,N_i - \frac{1}{2}\overline{S}_i\,i\partial\!\!\!/\,S_i - \frac{1}{2}\overline{\nu}_i\,i\partial\!\!\!/\,\nu_i$$

$$\mathcal{M}_\nu = \begin{pmatrix} -m^T_D M^{-1}_R m_D & m^T_{DS} \\ m_{DS} & M_S \end{pmatrix}$$

Pseudo-Dirac Neutrino !!

flavored-PQ symmetry A4 X $U(1)_X$

The low energy effective light neutrinos become pseudo-Dirac particles !!

$$\hat{M} = U_R^T\, m_{DS}\, U_L$$
$$= \text{diag}\,(m_1, m_2, m_3)$$

Diagonalization of Hermitian matrix

$$W_\nu^T \mathcal{M}_\nu \mathcal{M}_\nu^\dagger W_\nu^* = \begin{array}{c} \begin{array}{cc} \nu & S \end{array} \\ \begin{pmatrix} |\hat{M}|^2 + |\hat{M}||\delta| & 0 \\ 0 & |\hat{M}|^2 - |\hat{M}||\delta| \end{pmatrix} \end{array}$$
$$\equiv \text{diag}(m_{\nu_1}^2, m_{\nu_2}^2, m_{\nu_3}^2, m_{s_1}^2, m_{s_2}^2 m_{s_3}^2)\,.$$

Pseudo-Dirac Mass splitting

$$\delta \simeq \hat{M}_{\nu\nu}$$
$$= U_L^T\, M_{\nu\nu}\, U_L$$

$-m_D^T M_R^{-1} m_D$

Mass splitting $\Delta m_k^2 \equiv m_{\nu_k}^2 - m_{S_k}^2 = 2\, m_k\, |\delta_k| \ll m_{\nu_k}^2$ in the k-th pair

The pseudo-Dirac mass splittings will manifest themselves through very long wavelength oscillations

Due to the fact that $|\Delta m_{Atm}^2| \equiv |m_{\nu_3}^2 - (m_{\nu_1}^2 + m_{\nu_2}^2)/2| \gg \Delta m_{Sol}^2 \equiv m_{\nu_2}^2 - m_{\nu_1}^2 \gg \Delta m_k^2$

NO : $m_{\nu_1}^2 < m_{\nu_2}^2 < m_{\nu_3}^2$, $m_{S_1}^2 < m_{S_2}^2 < m_{S_3}^2$

IO : $m_{\nu_3}^2 < m_{\nu_1}^2 < m_{\nu_2}^2$, $m_{S_3}^2 < m_{S_1}^2 < m_{S_2}^2$

Two possible Mass orderings

flavored-PQ symmetry A4 X U(1)$_X$

The mass splittings are constrained by

$$6\times10^{-16}\,eV^2 \;\leq\; \Delta\mathrm{m}_\mathrm{k}^2 \;\leq 1.8\times10^{-12}\,eV^2$$

Solar neutrino oscillations (arXiv: 0906.1611)

BBN constraints (NPB373,498; astro-ph/9307027)

Neutrino mass hierarchy in oscillation data

for $m_{\nu_k}\sim 0.01\;eV$, from the leptogenesis and inflationary scenario,

if we set the initial minima of AD fields to the (almost) Planck scale, the ratios $\mathbf{m_i}/\boldsymbol{\Delta}\mathbf{m_i^2}$ could be fixed as

$$\frac{1}{\delta_i}=\frac{2m_i}{\Delta\mathrm{m}_\mathrm{i}^2}\leq\frac{M_P^2}{H_I v^2\sin^2\beta}\left(\frac{3}{\tilde{c}_H}\right)^{1/2}$$

Using $H_I\simeq10^{10}GeV$, sin$\beta\simeq1$, and $\tilde{c}_H\simeq1$, we obtain $\delta_i\geq2.95\times10^{-14}eV$

The charged WK interaction for the neutrino production and detection

$$-\mathcal{L}_{\rm c.c.}=\frac{g}{\sqrt{2}}W_\mu^-\overline{\ell_\alpha}\frac{1+\gamma_5}{2}\gamma^\mu\,U_{\alpha k}\,\xi_k+{\rm h.c.}$$

$$U\equiv U_L$$

$$\nu_\alpha=U_{\alpha k}\,\xi_k\quad\text{with}\quad\xi_k=\frac{1}{\sqrt{2}}\begin{pmatrix}1 & i\end{pmatrix}\begin{pmatrix}\nu_k\\ S_k^c\end{pmatrix}$$

$$\boldsymbol{\delta}\simeq\widehat{M}_{\nu\nu}=U_{PMNS}^TM_{\nu\nu}U_{PMNS}$$

flavored-PQ symmetry A4 X U(1)$_X$

The seesaw mass matrix responsible for very long wavelength oscillations

In the limit $y_2 = y_3 \to 1$

$$\sin^2\theta_{12} = \frac{1}{3}, \sin^2\theta_{23} = \frac{1}{2}, \sin\theta_{13} = 0$$

$$|\delta_1| = 3m_0|F|, |\delta_2| = 3m_0, |\delta_3| = 3m_0|G|$$

$$\begin{aligned} M_{\nu\nu} &= m_0\, e^{i\pi} \begin{pmatrix} 1+2F & (1-F)\,y_2 & (1-F)\,y_3 \\ (1-F)\,y_2 & \left(1+\frac{F+3G}{2}\right) y_2^2 & \left(1+\frac{F-3G}{2}\right) y_2\, y_3 \\ (1-F)\,y_3 & \left(1+\frac{F-3G}{2}\right) y_2\, y_3 & \left(1+\frac{F+3G}{2}\right) y_3^2 \end{pmatrix} \\ &= U^*_{\rm PMNS} \hat{M}_{\nu\nu} U^\dagger_{\rm PMNS}\,, \end{aligned}$$

$$m_0 \equiv \left|\frac{\hat{y}_1^{\nu 2} v_u^2}{3M}\right| \left(\frac{v_T}{\sqrt{2}\Lambda}\right)^2 \left(\frac{v_\Psi}{\sqrt{2}\Lambda}\right)^{18}, \quad F = \left(\tilde{\kappa}\, e^{i\phi}+1\right)^{-1}, \quad G = \left(\tilde{\kappa}\, e^{i\phi}-1\right)^{-1}$$

stars are employed to place constraints on the decay constant of the NG mode A_2 (QCD axion A) through the A_2 to electron interaction (axion A to photon and neutron interactions)

$$M = |\hat{y}_\Theta| \times 2.75^{+1.50}_{-1.25} \times 10^9\ GeV$$

$$|\delta_2| \simeq 2.94\times 10^{-11}\left(\frac{4.24\times 10^9 GeV}{M}\right)\left|\hat{y}_1^\nu \frac{v_T}{\sqrt{2}\,\Lambda}\right|^2 \sin^2\beta\ \ eV \simeq 1.50\times 10^{-14}\left|\hat{y}_1^\nu\right|^2 eV$$

$$|\delta_1| \simeq |\delta_2| \simeq |\delta_3| \simeq \mathcal{O}(m_0)$$

flavored-PQ symmetry A4 X U(1)$_X$

Once the mass splittings Δm_k^2 are constrained by astronomical-scale baseline experiments, such as IceCube, $(\theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP})$ and $|\delta_k|$ are well constrained through

$$\Delta m_k^2 = 2\, m_k\, |\delta_k|$$

Seesaw formula
(fixed by the axion decay constants)

Pseudo-Dirac m_{DS} (or y_i^s)
(constrained by the neutrino oscillation
and the cosmological data
$0.06 \le \sum_k m_{\nu_k} < 0.194\ eV$)

at 95% CL, Planck Collaboration (2015)

For the baseline, $4\pi E\ /\ \Delta \mathrm{m}^2_{\mathrm{Sol,Atm}} \ll L$, the probability of neutrino flavor conversion reads

If $\Delta \mathrm{m}_\mathrm{k}^2$ are fixed via model,
ν-flight-length L
could be determined

Mass splitting

Flight length

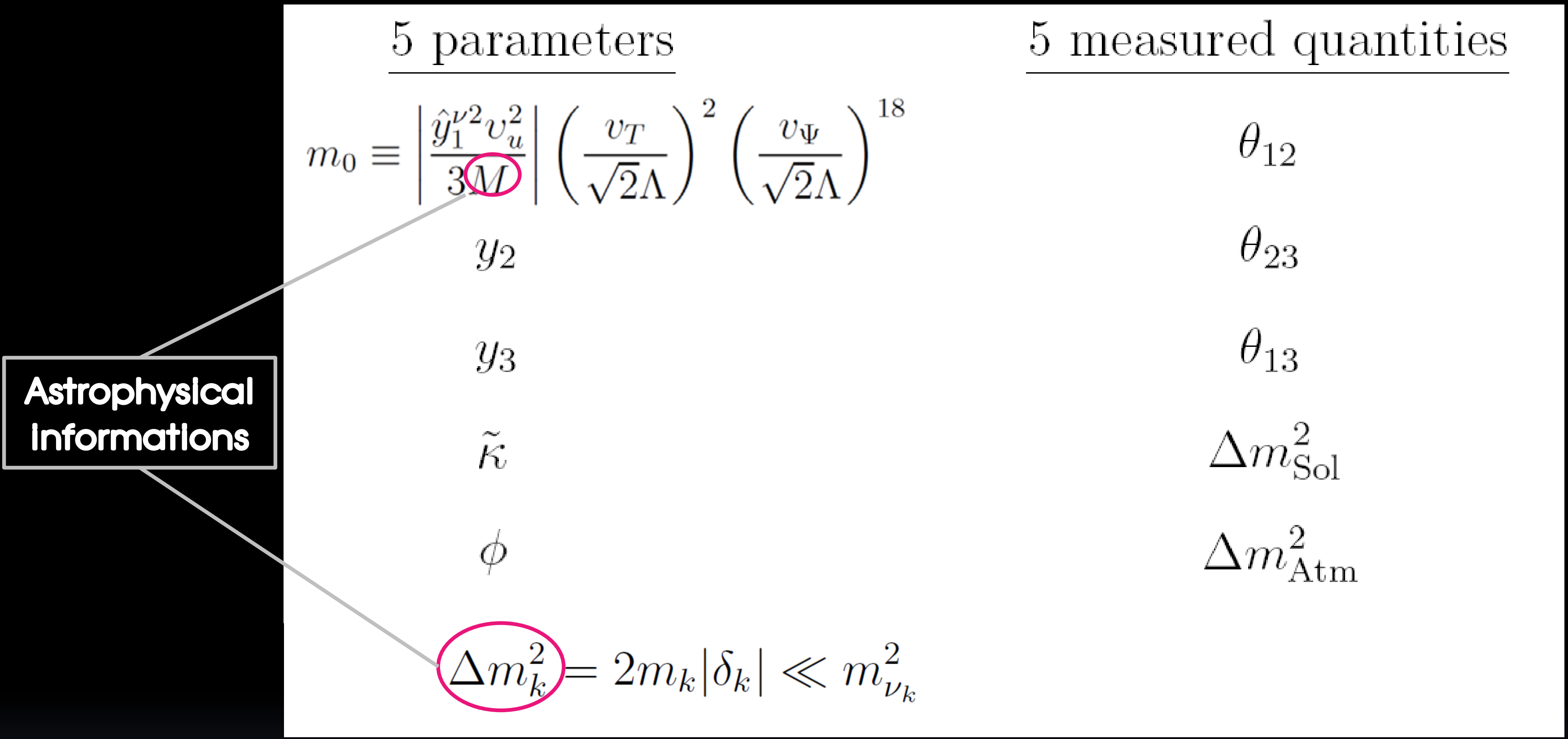
$$P_{\nu_\alpha \to \nu_\beta} = \sum_{k=1-3} |U_{\alpha k}|^2 |U_{\beta k}|^2 \cos^2\left(\frac{\Delta \mathrm{m}_\mathrm{k}^2\ \mathrm{L}}{4\ E}\right)$$

PMNS

ν - Energy

IceCube
N_T / N_S

Phenomenology of light neutrino



5 parameters	5 measured quantities
$m_0 \equiv \left\lvert\frac{\hat{y}_1^{\nu 2} v_u^2}{3M}\right\rvert \left(\frac{v_T}{\sqrt{2}\Lambda}\right)^2 \left(\frac{v_\Psi}{\sqrt{2}\Lambda}\right)^{18}$	θ_{12}
y_2	θ_{23}
y_3	θ_{13}
$\tilde{\kappa}$	$\Delta m^2_{\rm Sol}$
ϕ	$\Delta m^2_{\rm Atm}$
$\Delta m_k^2 = 2m_k\lvert\delta_k\rvert \ll m_{\nu_k}^2$	

Model prediction: + 4 observables

Axion interaction to Quarks & charged-Leptons

A4 X U(1)$_X$ spontaneously broken

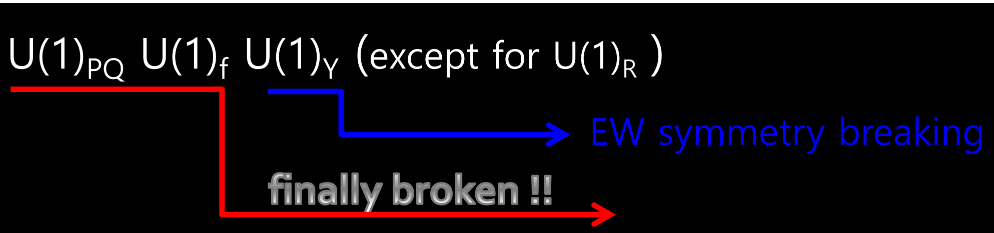
$$\Phi_{Si} = \frac{e^{i\frac{\phi_S}{v_S}}}{\sqrt{2}}(v_S + h_S)\ , \qquad \Theta = \frac{e^{i\frac{\phi_\theta}{v_\Theta}}}{\sqrt{2}}(v_\Theta + h_\Theta)\ ,$$

$$\Psi = \frac{v_\Psi}{\sqrt{2}} e^{i\frac{\phi_\Psi}{v_g}}\left(1 + \frac{h_\Psi}{v_g}\right)\ , \qquad \tilde{\Psi} = \frac{v_{\tilde{\Psi}}}{\sqrt{2}} e^{-i\frac{\phi_\Psi}{v_g}}\left(1 + \frac{h_\Psi}{v_g}\right)$$

Massless NG modes

$$A_1 = \frac{v_S\,\phi_S + v_\Theta\,\phi_\theta}{\sqrt{v_S^2 + v_\Theta^2}}$$

$$A_2 = \phi_\Psi$$



Three U(1) symmetries : U(1)$_{PQ}$ U(1)$_f$ U(1)$_Y$ (except for U(1)$_R$)

EW symmetry breaking

finally broken !!

$$U(1)_X = U(1)_{X_1}\ X\ U(1)_{X_2} = U(1)_{\tilde{X}} \times U(1)_f$$

anomalous **Anomaly-free**

They couple to ordinary charged fermions

$$\begin{aligned}
-\mathcal{L}^{a-q} \simeq\ & \frac{\partial_\mu A_1}{2f_{a1}}\{X_{1d}\,\bar{d}\gamma^\mu\gamma_5 d + X_{1s}\,\bar{s}\gamma^\mu\gamma_5 s + X_{1b}\,\bar{b}\gamma^\mu\gamma_5 b\} \\
&+ \frac{\partial_\mu A_2}{2f_{a2}}\{X_u\,\bar{u}\gamma^\mu\gamma_5 u + X_c\,\bar{c}\gamma^\mu\gamma_5 c + X_{2d}\,\bar{d}\gamma^\mu\gamma_5 d + X_{2s}\,\bar{s}\gamma^\mu\gamma_5 s\} \\
&+ m_u\,\bar{u}u + m_c\,\bar{c}c + m_t\,\bar{t}t + m_d\,\bar{d}d + m_s\,\bar{s}s + m_b\,\bar{b}b - \bar{q}\,i\partial\!\!\!/\,q, \\
-\mathcal{L}^{a-\ell} \simeq\ & \frac{\partial_\mu A_2}{2f_{a2}}\{X_e\,\bar{e}\,\gamma^\mu\gamma_5\,e + X_\mu\,\bar{\mu}\,\gamma^\mu\gamma_5\,\mu + X_\tau\,\bar{\tau}\,\gamma^\mu\gamma_5\,\tau\} \\
&+ m_e\,\bar{e}e + m_\mu\,\bar{\mu}\mu + m_\tau\,\bar{\tau}\tau - \bar{\ell}\,i\partial\!\!\!/\,\ell,
\end{aligned}$$

So, detecting them would provide a window to physics far beyond what can be probed at accelerators

Axion and Astro-Particle Constraints-I

Since the weakly coupled NG modes (the QCD axion)
could carry away a large amount of energy from the interior of stars $\sim 1/f_a$,
the couplings should be bounded with electrons.

Astrophysical lower bounds on f_a can be inferred from axion coupling to electrons

$$\alpha_{Aee} < 1.5 \times 10^{-26} \; (95\% \; CL)$$

red giant of globular clusters (arXiv: 1311.1669)

$$\alpha_{Aee} < 6 \times 10^{-27}$$

White-Dwarf (arXiv: 1311.1669)

$$g_{Aee} < 7.7 \times 10^{-12} \; (90\% \; CL)$$

Sun from XENON100 (arXiv: 1404.1455)

$$\begin{aligned} f_{a_2} &\gtrsim (3.98 \times 10^{8} - 1.23 \times 10^{10})\,\mathrm{GeV}\,, && \mathrm{FA} \\ f_{\mathrm{K}} &\gtrsim (1.02 \times 10^{4} - 3.15 \times 10^{5})\,\mathrm{GeV}\,, && \mathrm{KSVZ} \\ f_{\mathrm{D}} &\gtrsim (6.64 \times 10^{7} - 2.04 \times 10^{9})\ \tan\beta\,\mathrm{GeV}\,, && \mathrm{DFSZ} \end{aligned}$$

Longstanding anomaly in the cooling of WDs might be explained by axions

$$4.1 \times 10^{-28} \lesssim \alpha_{Aee} \lesssim 3.7 \times 10^{-27} \;\Leftrightarrow\; \begin{cases} f_{a_2} = (1.4 - 4.3) \times 10^{10}\,\mathrm{GeV}\,, & \mathrm{FA} \\ f_{\mathrm{K}} = (3.7 - 11.0) \times 10^{5}\,\mathrm{GeV}\,, & \mathrm{KSVZ} \\ f_{\mathrm{D}} = (2.4 - 7.1) \times 10^{9}\ \tan\beta\,\mathrm{GeV}\,, & \mathrm{DFSZ} \end{cases}$$

arXiv:1406.7712, 1210.0263,…etc

Axion and Strong CP invariance

The NG interactions arise only via derivative couplings ➡ non-linearly realized global symmetry

$$U(1)_f : \qquad G \to G + \Upsilon(\text{constant})$$

Axion

$$A = \frac{A_1\,\delta_1^{\rm GS}\,f_{a_2} + A_2\,\delta_2^{\rm GS}\,f_{a_1}}{\sqrt{(\delta_2^{\rm GS}\,f_{a_1})^2 + (\delta_1^{\rm GS}\,f_{a_2})^2}}\,, \qquad G = \frac{A_2\,\delta_1^{\rm GS}\,f_{a_2} - A_1\,\delta_2^{\rm GS}\,f_{a_1}}{\sqrt{(\delta_2^{\rm GS}\,f_{a_1})^2 + (\delta_1^{\rm GS}\,f_{a_2})^2}}$$

True NG boson

$$\langle 0|J_\mu^{\tilde X}(x)|A(p)\rangle = ip_\mu\, f_A\, e^{-ip\cdot x} \qquad\qquad \langle 0|J_\mu^{\tilde X}(x)|G\rangle = 0$$

Decay constant

$$f_A = \left\{\left(\frac{1}{2f_{a1}\delta_2^{\rm GS}}\right)^2 + \left(\frac{1}{2f_{a2}\delta_1^{\rm GS}}\right)^2\right\}^{-\frac{1}{2}}$$

$$\left(\tilde X_1 v_{\mathcal F}\right)^2 = \left(\tilde X_2 v_g\right)^2$$

Scale relation

$$f_A = \sqrt{2}\,\delta_2^{\rm GS}\,f_{a1} = \sqrt{2}\,\delta_1^{\rm GS}\,f_{a2}$$

Under the $U(1)_{\tilde X}$ transformation, the axion field A translates with the decay constant F_A

$$\boldsymbol{A \to A + F_A\,\alpha}$$ **with** $F_A \equiv f_A/N$ and $N = 2\delta_1^{\rm GS}\delta_2^{\rm GS}$

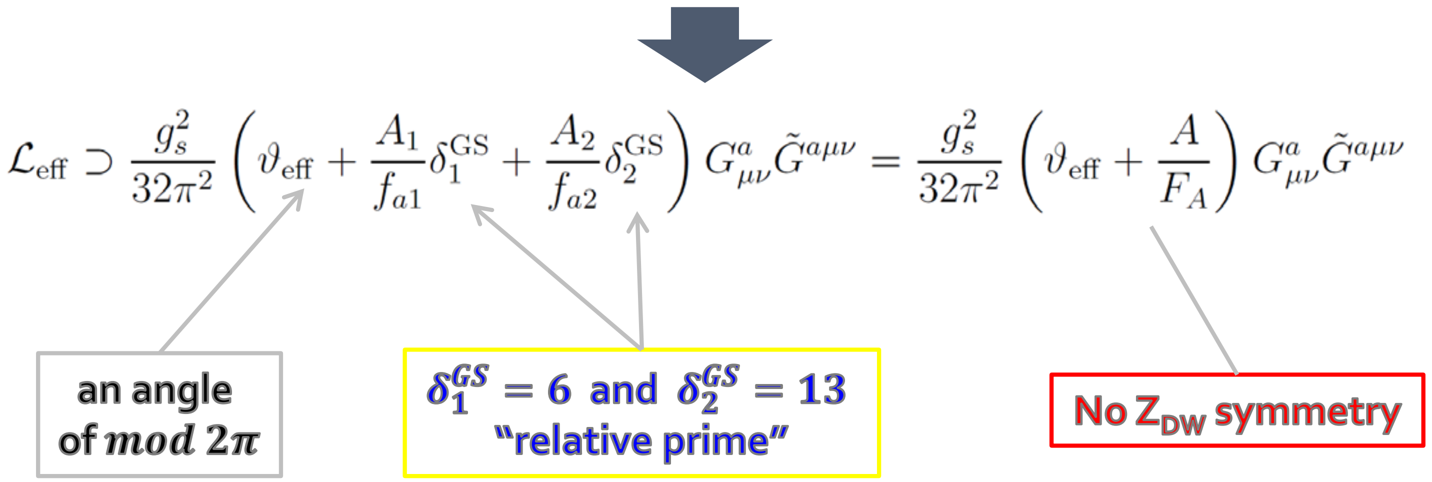
If N were large, then F_A can be lowered significantly compared to the symmetry breaking scale

Axion and Strong CP invariance

No Axionic Domain-wall Problem

The current $J_\mu^{X_i}$ is anomalous, i.e., it is violated at one-loop by the triangle anomaly

$$\partial_\mu J^\mu_{X_i} = \frac{\delta_i^{\rm GS}}{16\pi^2}{\rm Tr}(G^{\mu\nu}\tilde{G}_{\mu\nu})$$



$$\mathcal{L}_{\rm eff} \supset \frac{g_s^2}{32\pi^2}\left(\vartheta_{\rm eff} + \frac{A_1}{f_{a1}}\delta_1^{\rm GS} + \frac{A_2}{f_{a2}}\delta_2^{\rm GS}\right) G^a_{\mu\nu}\tilde{G}^{a\mu\nu} = \frac{g_s^2}{32\pi^2}\left(\vartheta_{\rm eff} + \frac{A}{F_A}\right) G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

an angle of $mod\ 2\pi$

$\delta_1^{GS} = 6$ and $\delta_2^{GS} = 13$
"relative prime"

No Z_{DW} symmetry

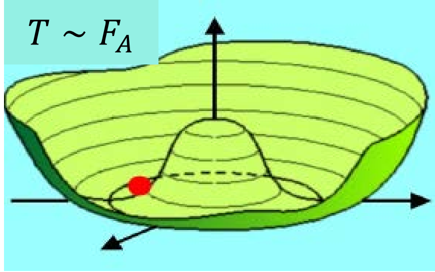
At low energies A will get a VEV, at "$\langle A\rangle = -\vartheta_{eff}\, F_A$" **CP invariance** eliminating the constant ϑ_{eff} term

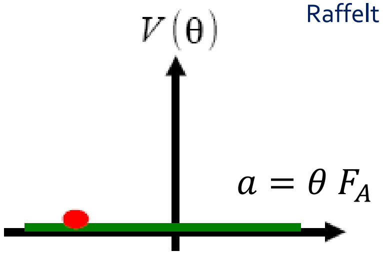
Axion and Strong CP invariance

Physical axion "a" = A-<A> is the excitation
with the vacuum expectation removed

At energies far below f_A

$$\mathcal{L} \supset \frac{1}{2}(\partial_\mu a)^2 - \frac{\partial_\mu a}{2f_A}\sum_\psi \tilde{X}_\psi \bar{\psi}\gamma^\mu\gamma_5\psi + \frac{g_s^2}{32\pi^2}\frac{a}{F_A}G^a_{\mu\nu}\tilde{G}^{a\mu\nu} + \frac{e^2}{32\pi^2}\left(\frac{E}{N}\right)\frac{a}{F_A}F_{\mu\nu}\tilde{F}^{\mu\nu}$$



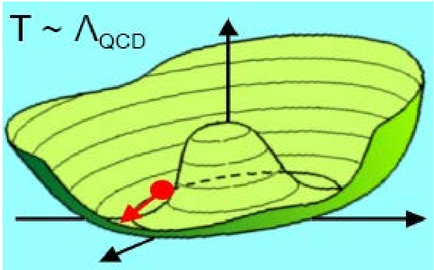


Raffelt

Since the SM fields have $U(1)_{EM}$ charges,
the axion coupling to photon is appeared through a chiral rotation,
which survive to the QCD scale

Axion and Strong CP invariance

Below QCD scale, where the light quarks have hadronized into mesons

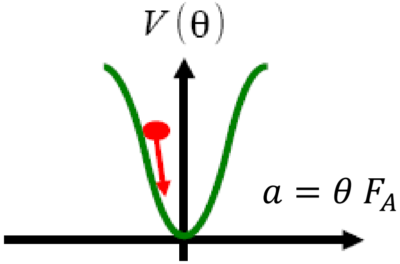


Raffelt

Non-perturbative effects induce a potential for "A" whose minimum is at "$\langle A\rangle = -\vartheta_{eff}\, F_A$"

$$-\mathcal{L}_A = \overbrace{\left(\sum_{q=u,d,s} m_q \bar{q}_L e^{-i\alpha_q} q_R + \text{h.c.}\right)} - \frac{e^2}{32\pi^2}\left(\frac{E}{N} - \frac{2}{3}\frac{4+z+w}{1+z+w}\right)\frac{a}{F_A}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$+ \frac{\partial_\mu a}{2F_A} X_{\psi_N}\overline{\psi}_N\, \gamma_\mu \gamma^5\, \psi_N$$



Axion mass ∝ curvature of the effective potential induced by the anomaly

$$m_a^2 = \left\langle \frac{\partial^2 V(A)}{\partial a^2} \right\rangle_{\langle A\rangle = -\vartheta_{\rm eff} F_A} = \frac{f_\pi^2}{F_A^2}\frac{\mu m_u}{1+z+w}. \Rightarrow \quad m_a = 4.34\,\text{meV}\left(\frac{1.3\times 10^9\,\text{GeV}}{F_A}\right)$$

Axion and Astro-Particle Constraints-II

Below the chiral symmetry breaking scale, the axion-hadron interactions are meaningful for the axion production rate in the core of a star
where the temperature is not as high as 1 GeV

$$-\mathcal{L}_A = \left(\sum_{q=u,d,s} m_q \bar{q}_L e^{-i\alpha_q} q_R + \text{h.c.}\right) - \frac{e^2}{32\pi^2}\left(\frac{E}{N} - \frac{2}{3}\frac{4+z+w}{1+z+w}\right)\frac{a}{F_A}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$+ \boxed{\frac{\partial_\mu a}{2F_A} X_{\psi_N}\overline{\psi}_N \gamma_\mu \gamma^5 \psi_N}$$

Nucleon doublet
$\boldsymbol{\psi_N = (p,n)^T}$

QCD axion coupling to neutron $g_{Ann} = \dfrac{X_n\, m_n}{F_A}$

$$X_n = \left(\frac{4}{\delta_2^{\rm GS}} - \eta\right)\Delta d + \left(\frac{3}{2\delta_2^{\rm GS}} + \frac{1}{2\delta_1^{\rm GS}} - \eta z\right)\Delta u + \left(\frac{1}{\delta_2^{\rm GS}} + \frac{1}{2\delta_1^{\rm GS}} - \eta\omega\right)\Delta s$$

A hint for extra cooling from the neutron star in the supernova remnant "Cassiopeia A" by axion neutron bremstrahlung (arXiv:1405.6873)

$$g_{Ann} = (3.8 \pm 3) \times 10^{-10} \Leftrightarrow 7.66 \times 10^7 \lesssim F_A/\text{GeV} \lesssim 1.95 \times 10^9$$

Combining with the Constraints-I ⇨

$$f_{a_1} = 1.1^{+0.6}_{-0.5} \times 10^{10}\,\text{GeV}\,, \qquad f_{a_2} = 2.4^{+1.2}_{-1.0} \times 10^{10}\,\text{GeV}$$

$$\underline{F_A = 1.30^{+0.66}_{-0.54} \times 10^9\,\text{GeV}}$$

Axion and Astro-Particle Constraints-II

$$-\mathcal{L}_A = \left(\sum_{q=u,d,s} m_q \bar{q}_L e^{-i\alpha_q} q_R + \text{h.c.}\right) - \frac{e^2}{32\pi^2}\left(\frac{E}{N} - \frac{2}{3}\frac{4+z+w}{1+z+w}\right)\frac{a}{F_A} F_{\mu\nu}\tilde{F}^{\mu\nu}$$
$$+ \frac{\partial_\mu a}{2F_A} X_{\psi_N} \overline{\psi}_N \gamma_\mu \gamma^5 \psi_N$$

$$\mathbf{\frac{14}{39}}$$

After integrating out the heavy π^0 and η at low energies

$$\mathcal{L}_{a\gamma\gamma} = \frac{1}{4} g_{a\gamma\gamma}\, a_{\text{phys}}\, F^{\mu\nu}\tilde{F}_{\mu\nu} = -g_{a\gamma\gamma}\, a_{\text{phys}}\, \vec{E}\cdot\vec{B}$$

axion-photon coupling $g_{A\gamma\gamma} = \frac{\alpha_{em}}{2\pi}\frac{m_a}{f_\pi m_{\pi^0}}\frac{\alpha_{em}}{\sqrt{F(z,w)}}\left(\frac{E}{N} - \frac{2}{3}\frac{4+z+w}{1+z+w}\right)$

Recent analysis of the HB stars in galactic GCs

(arXiv:1406.6053)

$$|g_{a\gamma\gamma}| < 6.6\times 10^{-11}\,\text{GeV}^{-1}\ (95\%\,\text{CL}) \Leftrightarrow F_A \gtrsim \left\{\begin{array}{lll} & & m_a \\ 2.57\times 10^7\,\text{GeV} & \text{FA} & < 0.22\ eV \\ 3.20\times 10^7\,\text{GeV}, & \text{KSVZ} & < 0.18\ eV \\ 1.50\times 10^7\,\text{GeV}, & \text{DFSZ} & < 0.38\ eV \end{array}\right.$$

Axion and Astro-Particle Constraints

From the Constraint-I, longstanding anomaly in the cooling of WDs

$$4.1\times10^{-28}\lesssim\alpha_{Aee}\lesssim3.7\times10^{-27}\Leftrightarrow\begin{cases} f_{a_2}=(1.4-4.3)\times10^{10}\,\mathrm{GeV}\,, & \mathrm{FA}\\ f_{\mathrm{K}}=(3.7-11.0)\times10^{5}\,\mathrm{GeV}\,, & \mathrm{KSVZ}\\ f_{\mathrm{D}}=(2.4-7.1)\times10^{9}\,\tan\beta\,\mathrm{GeV}\,, & \mathrm{DFSZ}\end{cases}$$

From the Constraint-I, axion to electron interactions

$$\begin{aligned} &f_{a_2}\gtrsim(3.98\times10^{8}-1.23\times10^{10})\,\mathrm{GeV}\,, && \mathrm{FA}\\ &f_{\mathrm{K}}\gtrsim(1.02\times10^{4}-3.15\times10^{5})\,\mathrm{GeV}\,, && \mathrm{KSVZ}\\ &f_{\mathrm{D}}\gtrsim(6.64\times10^{7}-2.04\times10^{9})\,\tan\beta\,\mathrm{GeV}\,, && \mathrm{DFSZ}\end{aligned}$$

From the Constraints-II

$$|g_{a\gamma\gamma}|<6.6\times10^{-11}\,\mathrm{GeV}^{-1}\ (95\%\,\mathrm{CL})\Leftrightarrow F_A\gtrsim\begin{cases} 2.57\times10^{7}\,\mathrm{GeV} & \mathrm{FA}\\ 3.20\times10^{7}\,\mathrm{GeV}, & \mathrm{KSVZ}\\ 1.50\times10^{7}\,\mathrm{GeV}, & \mathrm{DFSZ}\end{cases}$$

KSVZ model might be excluded

⇨ DFSZ model is disfavored if $F_D=\mathrm{f_D}/\mathrm{N}<H_I/2\pi$ with $N=N_g\left(\tan\beta+\frac{1}{\tan\beta}\right)$ due to $N_{DW}=6$

Prediction

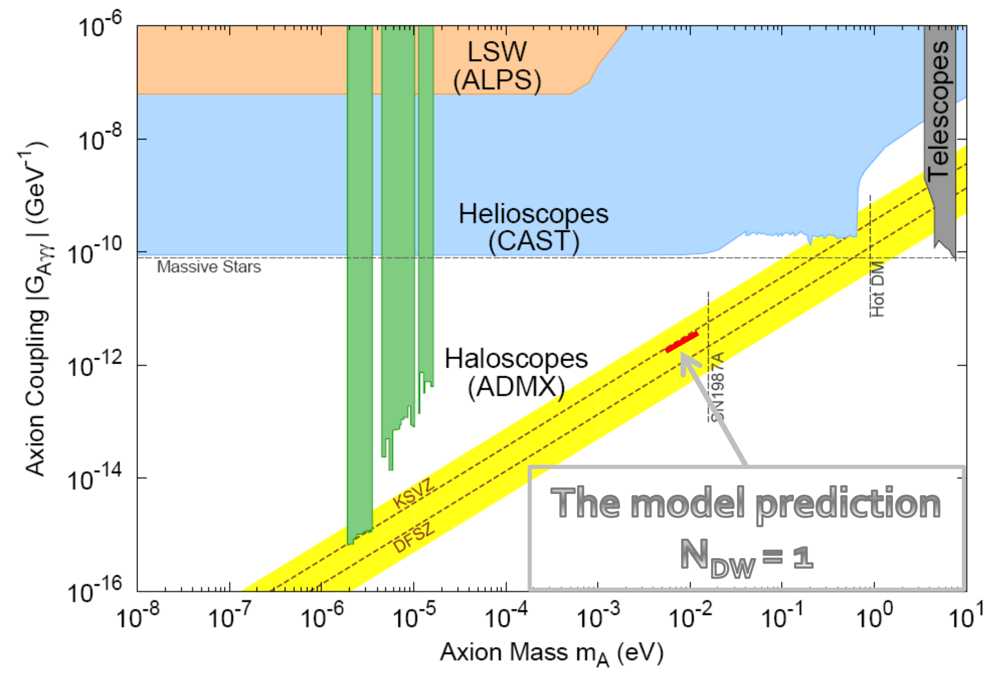
$$F_A=1.30^{+0.66}_{-0.54}\times10^{9}\,\mathrm{GeV}$$

$$m_a=4.34^{+3.37}_{-1.49}\,\mathrm{meV}\Leftrightarrow|g_{a\gamma\gamma}|=1.30^{+1.01}_{-0.45}\times10^{-12}\,\mathrm{GeV}^{-1}$$

$$\lambda_a=2.86^{+1.50}_{-1.25}\times10^{-2}\,\mathrm{cm}$$

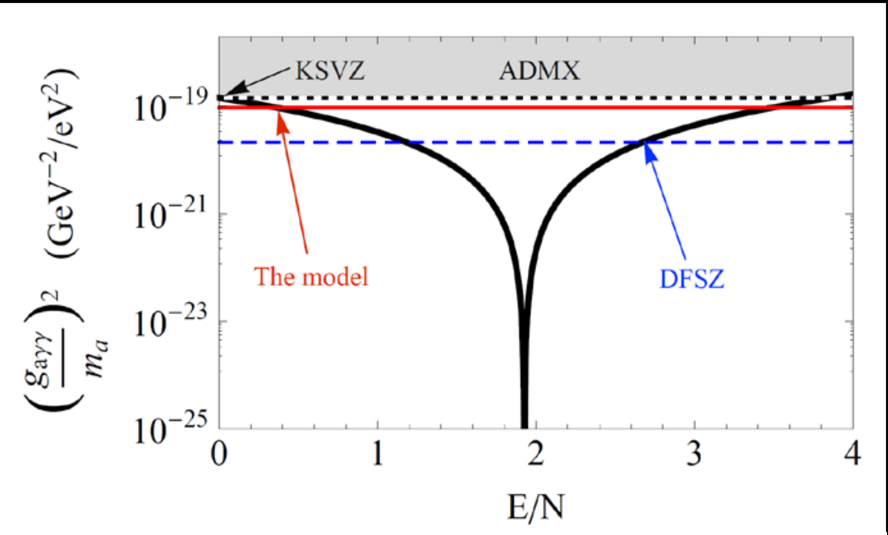
Flavored-Axion : arXiv 1410.1634 / 1611.08359

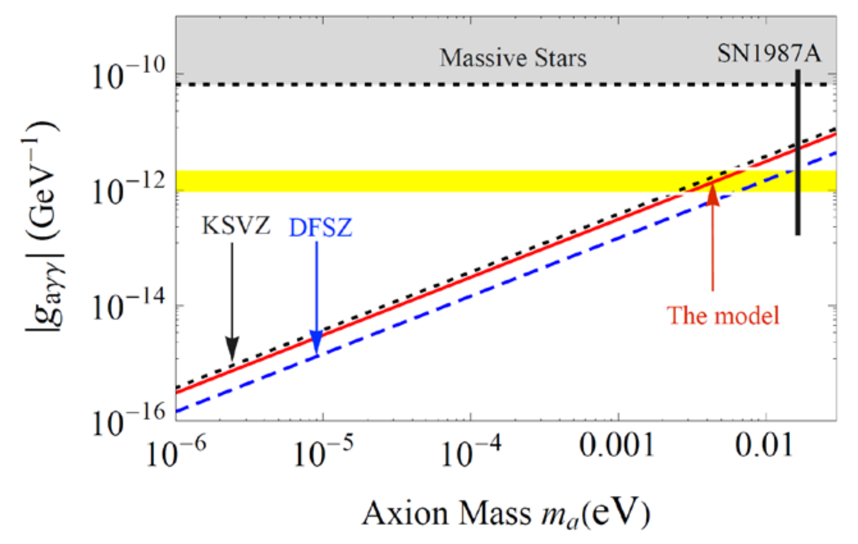
Background from Particle Data Group



The model prediction

$N_{DW} = 1$





KSVZ : $N_{DW} = 1$, $E/N = 0$

Kim (79); Shifman, Vainshtein & Zakharov (80)

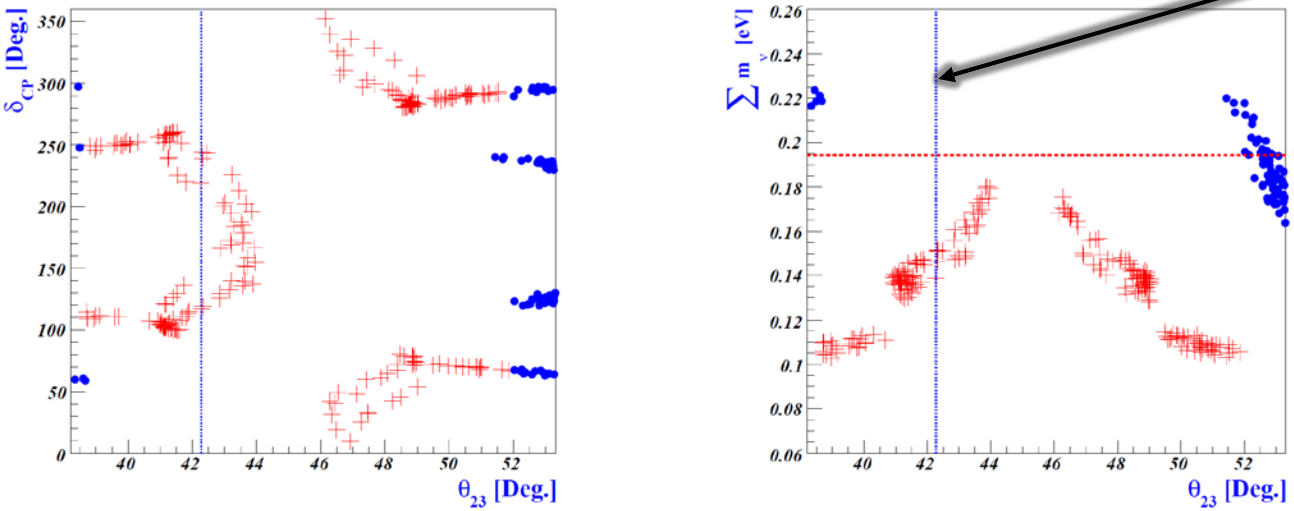
DFSZ : $N_{DW} = 6$, $E/N = 8/3$

Dine, Fischler & Srednicki (81); Zhitnitsky (80)

Flavored-Axion : $N_{DW} = 1$, $E/N = 14/39$

flavored-PQ symmetry A4 X U(1)$_X$

Normal mass Ordering



Best-fit value
1512.06856

Planck Collaboration
2015

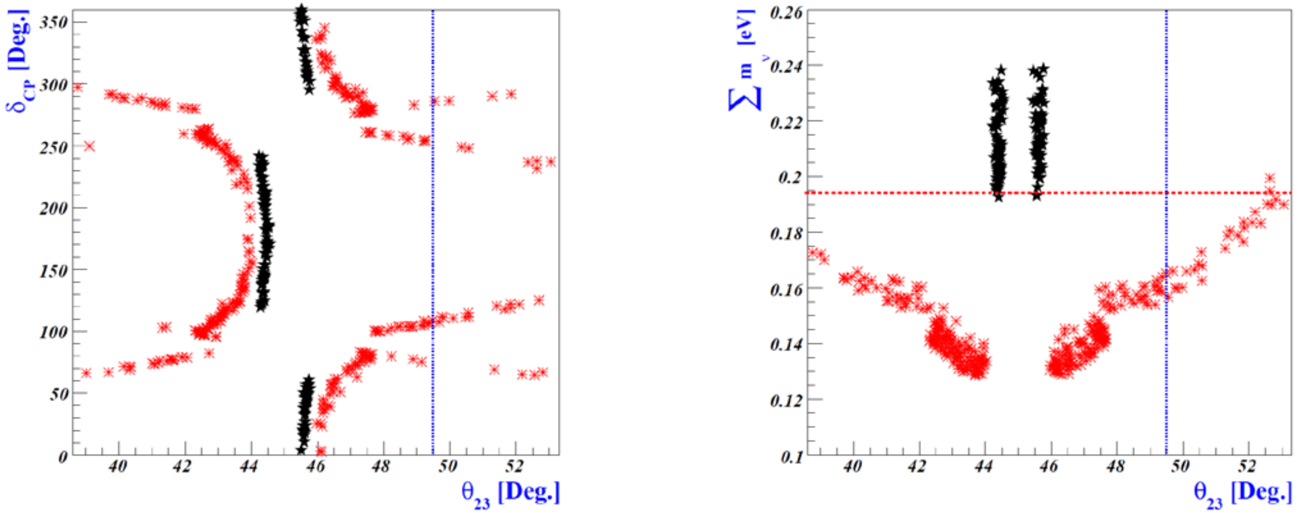
$\sum_k m_{\nu_k} < 0.194\,eV$

● $\Delta m_1^2 = \Delta m_2^2 = \Delta m_3^2 = 5\times10^{-15} eV^2 \quad \rightarrow \quad |\theta_{23} - 45°| \sim 7°$

+ $\Delta m_1^2 = \Delta m_2^2 = 2.7\times10^{-15} eV^2 < \Delta m_3^2 = 5\times10^{-15} eV^2$

flavored-PQ symmetry A4 X U(1)$_X$

Inverted mass Ordering

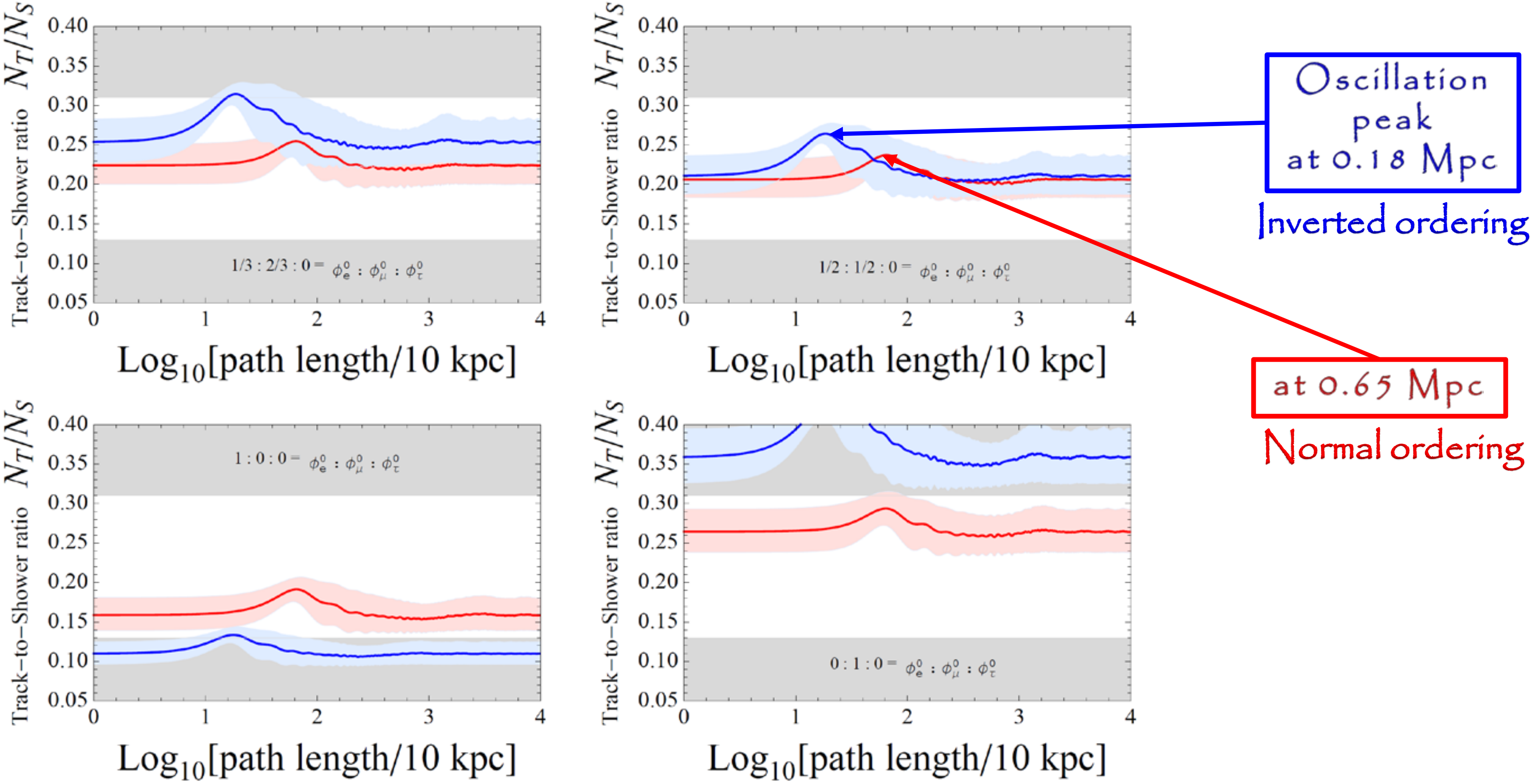


★ $\Delta m_1^2 = \Delta m_2^2 = \Delta m_3^2 = 5 \times 10^{-14} eV^2 \rightarrow |\theta_{23} - 45°| \sim 0.5°$

✱ $\Delta m_1^2 = \Delta m_2^2 = 10^{-14} eV^2 > \Delta m_3^2 = 5.5 \times 10^{-15} eV^2$

$60\,TeV \le E_\nu \le 3\,PeV$ @ IceCube

High energy ν-events at IceCube are analyzed in Ref. 1502.02923 $\frac{N_T}{N_S} = 0.18^{+0.13}_{-0.05}$



Oscillation peak at 0.18 Mpc

Inverted ordering

at 0.65 Mpc

Normal ordering

Blue-curved line $\Delta m_1^2 = \Delta m_2^2 = 10^{-14}\,eV^2 > \Delta m_3^2 = 5.5 \times 10^{-15}\,eV^2$

Red-curved line $\Delta m_1^2 = \Delta m_2^2 = 2.7 \times 10^{-15}\,eV^2 < \Delta m_3^2 = 5 \times 10^{-15}\,eV^2$

Conclusion

Motivated by the flavored Peccei-Quinn symmetry model
for unifying flavor physics and string theory (1604.0125),
we constructed an explicit model by introducing an $U(1)_X$ symmetry
for rather recent but fast growing issues of astro-particle physics and cosmology,
in a way that the $U(1)_X$-[gravity]^2 anomaly-free condition with the SM flavor structure
demands additional sterile neutrinos as well as no axionic domain wall problem.

The QCD axion decay constant, through its connection to the astrophysical constraints of stellar evolution and the SM fermion masses, is shown to be fixed at

$$F_A = 1.30^{+0.66}_{-0.54} \times 10^9 GeV$$

(consequently, $m_a = 4.34^{+3.37}_{-1.49}\ meV$ and $|g_{a\gamma\gamma}| = 1.30^{+1.01}_{-0.45} \times 10^{-12} GeV^{-1}$).

We showed that,
how neutrino oscillations at low energies could be connected to new oscillations available on high energy neutrinos.