Axion and FIMP Dark Matter in a U(1) extension of the Standard Model

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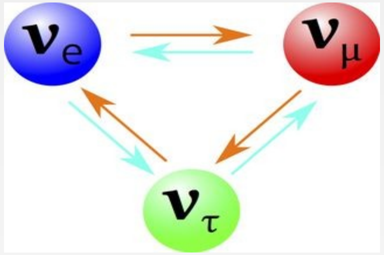
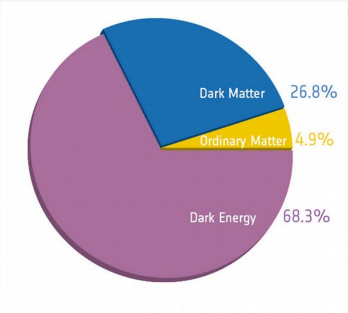
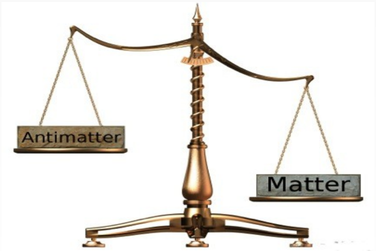
Problems in the SM

- SM fails to explain neutrino mass and mixings.
- SM doesn't have a DM candidate.
- SM can not explain the observed baryon asymmetry.
- The origin of smallness of the θ-parameter.







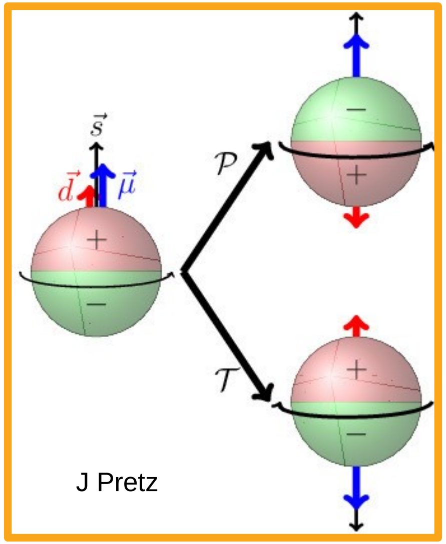
Strong CP Problem

nEDM → $H = -d_n E.\hat{S}$

nEDM → $L = -d_n \frac{i}{2} \bar{n} \sigma_{\mu\nu} \gamma_5 n F^{\mu\nu}$

- The measurement of nEDM d_n will imply P, CP violation and could be related to the early matter-antimatter asymmetry.
- nEDM puts bound on $\mathrm{d_n}$ *i.e.* $|\mathrm{d_n}| < 1.5 \times 10^{-12} \mathrm{e\,GeV^{-1}}$ Abel et al, PRL 20
- $\mathrm{L}_\theta = \theta \frac{\mathrm{g_s^2}}{32\pi^2} \mathrm{G}\tilde{\mathrm{G}}$ contribution to nEDM which comes out as $\mathrm{d_n} \sim 1.2 \times 10^{-2} \theta \mathrm{e\,GeV^{-1}}$

  Pospelov, Ritz '99
- Comparing theoretical and the experimental values of nEDM, we obtain $\theta < 10^{-10}$
- The problem arises why the θ parameter is so small



Gauge group and Particle content

Accidental Symmetry

Complete gauge group → $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_X \times U(1)_{PQ} \times \mathbb{Z}_2$

Gauge Group	Baryon Fields			Lepton Fields						Scalar Fields
	Q_L^i	u_R^i	d_R^i	L_L^e	L_L^μ	L_L^τ	e_R	μ_R	τ_R	ϕ_h
$\mathrm{SU(2)_L}$	2	1	1	2	2	2	1	1	1	2
$\mathrm{U(1)_Y}$	1/6	2/3	−1/3	−1/2	−1/2	−1/2	−1	−1	−1	1/2
$U(1)_X$	m	m	m	n_e	n	n	n_e	n	n	0
$U(1)_{PQ}$	0	0	0	$-2a$	0	0	$-2a$	0	0	0

Gauge Group	Fermions							Scalars	
	N_1	N_2	N_3	ψ_L	ψ_R	χ_L	χ_R	ϕ_1	ϕ_2
$\mathrm{SU(3)_c, SU(2)_L}$	$(1,1)$	$(1,1)$	$(1,1)$	$(3,1)$	$(3,1)$	$(3,1)$	$(3,1)$	1	1
$U(1)_X$	n_e	n	n	α_L	α_R	β_L	β_R	$\alpha_L - \alpha_R$	$\beta_L - \beta_R$
$U(1)_{PQ}$	$-2a$	0	0	$-a$	a	a	$-a$	$-2a$	$2a$
$\mathbb{Z}_2$	−1	1	1	1	1	−1	−1	1	1
No. of flavors	1	1	1	N_ψ	N_ψ	N_χ	N_χ	1	1

- KSVZ type axion model has been considered
- $\mathbb{Z}_2$-symmetry forbids mixing among the exotic quarks and also stabilise the FIMP DM
- We have two DM namely axion and right handed neutrino which is odd under $\mathbb{Z}_2$
- $U(1)_{\mathrm{PQ}}$ symmetry is accidental and extracted from $U(1)_X$ gauge symmetry

Gauge anomaly will put bound on the additional abelian gauge group charges

Lagrangian

Full Lagrangian → $\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_N^{Yuk} + \mathcal{L}_{BSM}^{Yuk}$

Yukawa for RHN

SM Lagrangian

Yukawa for EQ

Lagrangian associated with the right handed neutrinos:

$$\mathcal{L}_N^{Yuk} = y_{\mu 2}\bar{L}_\mu \phi_h N_2 + y_{\mu 3}\bar{L}_\mu \phi_h N_3 + y_{\tau 2}\bar{L}_\tau \phi_h N_2 + y_{\tau 3}\bar{L}_\tau \phi_h N_3 + y_{e2}\bar{L}_e \phi_h N_2 \frac{\phi_1}{M_{PL}}$$

→ Dirac mass terms

$$+ y_{e3}\bar{L}_e \phi_h N_3 \frac{\phi_1}{M_{PL}} + y_{22} N_2 N_2 \frac{\phi_1\phi_2}{M_{PL}} + y_{23} N_2 N_3 \frac{\phi_1\phi_2}{M_{PL}} + y_{33} N_3 N_3 \frac{\phi_1\phi_2}{M_{PL}} + h.c..$$

→ RHN mass terms

Terms associated with the exotic quarks: $\mathcal{L}_{BSM}^{Yuk} = \sum_{i,j=1}^{N_\psi 0} \lambda_{ij}\, \bar{\psi}_L^i \psi_R^j \phi_1 + \sum_{i,j=1}^{N_\chi} y_{ij} \bar{\chi}_L^i \chi_R^j \phi_2 + h.c..$

Redefining the fields: $\psi_L \to e^{i\frac{a_1}{2v_1}},\ \psi_R \to e^{-i\frac{a_1}{2v_1}},\ \chi_L \to e^{i\frac{a_2}{2v_2}},\ \chi_R \to e^{-i\frac{a_2}{2v_2}}$

Axion gluon coupling:

$$\mathcal{L}_{AGG} = \left(\frac{N_\psi a_1}{v_1} + \frac{N_\chi a_2}{v_2}\right)\frac{g_s^2}{32\pi^2} G_{\mu\nu}\tilde{G^{\mu\nu}} = N_\psi \frac{A}{F_a}\frac{g_s^2}{32\pi^2} G_{\mu\nu}\tilde{G^{\mu\nu}},$$

$$A = \frac{v_2 a_1 + n_\chi v_1 a_2}{\sqrt{n_\chi^2 v_1^2 + v_2^2}} \qquad F_a = \frac{v_1 v_2}{\sqrt{n_\chi^2 v_1^2 + v_2^2}}$$

Choice of α_L and β_L

$U(1)_\chi^3$ and $[Gravity]^2 \times U(1)_X$ → $(n_\chi^2 - 1)y^2 + 3(n_\chi - z)y + 3(1 - z^2) = 0$

where $z = \frac{\beta_L}{\alpha_R}$, $n_\chi = \frac{N_\chi}{N_\psi}$ and $y = \frac{\beta_R - \beta_L}{\alpha_R} = \frac{\Delta\beta}{\alpha_R}$

Roots and condition for real eigenvalues →

$$y_\pm = \frac{-3(n_\chi - z) \pm \sqrt{9(n_\chi - z)^2 - 12(n_\chi^2 - 1)(1 - z^2)}}{2(n_\chi^2 - 1)}$$

$$z_\pm = \frac{3n_\chi \pm 2|n_\chi^2 - 1|}{(4n_\chi^2 - 1)}$$

Sets of Allowed Charge assignments →

n_χ	z	y	α_L	β_L	β_R	$\alpha_L - \alpha_R$	$\beta_L - \beta_R$	n_e	n	m
10	1	$-\frac{3}{11}$	$-\frac{19}{11}\alpha_R$	α_R	$\frac{8}{11}\alpha_R$	$-\frac{30}{11}\alpha_R$	$\frac{3}{11}\alpha_R$	$-\frac{3}{2}\alpha_R$	$\frac{27}{22}\alpha_R$	$-\frac{7}{66}\alpha_R$
10	-1	$-\frac{1}{3}$	$-\frac{7}{3}\alpha_R$	$-\alpha_R$	$-\frac{4}{3}\alpha_R$	$-\frac{10}{3}\alpha_R$	$\frac{1}{3}\alpha_R$	$-\frac{11}{6}\alpha_R$	$\frac{3}{2}\alpha_R$	$-\frac{7}{54}\alpha_R$
11	1	$-\frac{1}{4}$	$-\frac{7}{4}\alpha_R$	α_R	$\frac{3}{4}\alpha_R$	$-\frac{11}{4}\alpha_R$	$\frac{1}{4}\alpha_R$	$-\frac{3}{2}\alpha_R$	$\frac{5}{4}\alpha_R$	$-\frac{1}{9}\alpha_R$
11	-1	$-\frac{3}{10}$	$-\frac{23}{10}\alpha_R$	$-\alpha_R$	$-\frac{13}{10}\alpha_R$	$-\frac{33}{10}\alpha_R$	$\frac{3}{10}\alpha_R$	$-\frac{9}{5}\alpha_R$	$\frac{3}{2}\alpha_R$	$-\frac{2}{15}\alpha_R$

$$n_e = -\frac{1 + n_\chi}{2}(\beta_L - \beta_R),\ n = \frac{n_\chi - 1}{2}(\beta_L - \beta_R) \text{ and } m = -\frac{n_e + 2n}{9}$$

Gravitational Effect in axion Potential

$g = |g| e^{i\delta}$

PQ breaking higher dimensional operator at the Planck scale

$$\mathcal{V}_{PL}(\Phi_1, \Phi_2) = \frac{g}{N_\psi! N_\chi!} \frac{\Phi_1^{N_\psi} \Phi_2^{N_\chi}}{M_{PL}^{N_\psi + N_\chi - 4}} + h.c.$$

$$r_g = \frac{(M_A^g)^2}{(M_A)^2}$$

Total axion potential

$$V(\bar{\theta}_a) = F_a^2 M_a^2 \left[(1 - \cos \bar{\theta}_a) + r_g \left(1 - \cos(p\, \bar{\theta}_a + \delta)\right) \right]$$

Kamionkowski et al, 92

$$(\mathrm{M}_A^g)^2 = \frac{|g|}{N_\psi! N_\chi!} \frac{\langle \Phi_1 \rangle^{N_\psi} \langle \Phi_2 \rangle^{N_\chi}}{(\sqrt{2})^{N_\psi + N_\chi} M_{PL}^{N_\psi + N_\chi - 4} F_A^2}$$

quantum-gravitational induced axion mass

Extra potential term shift the minima from $\theta = 0$ by an amount

$$\Delta\theta = \frac{r_g |p \sin \delta|}{\left[1 + p^4 r_g^2 + 2 p^2 r_g \cos \delta\right]^{1/2}}$$

$r_g \ll 1$ and $|p \sin \delta| \sim 1$

$$\Delta\theta \sim r_g = \frac{|g|}{N_\psi! N_\chi! \, (\sqrt{2})^{N_\psi + N_\chi}} \frac{v_1^{N_\psi} v_2^{N_\chi}}{M_{PL}^{N_\psi + N_\chi - 4} (f_\pi m_\pi)^2} \frac{(m_u + m_d)^4}{m_u^2 m_d^2}$$

Analytical Estimate of $\Delta\theta$

$v_1 = v_2$ and $|g| \sim 1$ → $$\Delta\theta \sim \frac{1}{n_\chi!}\left[\frac{1+n_\chi^2}{2}\right]^{\frac{1+n_\chi}{2}}\left[\frac{F_a^2}{f_\pi m_\pi}\right]^2\left[\frac{F_a}{M_{PL}}\right]^{n_\chi-3}\frac{(m_u+m_d)^4}{m_u^2 m_d^2}$$

Stirling's formula for $n_\chi \gg 1$

$n_\chi\left(1+\ln\frac{F_a}{M_{PL}}\right) < 0$

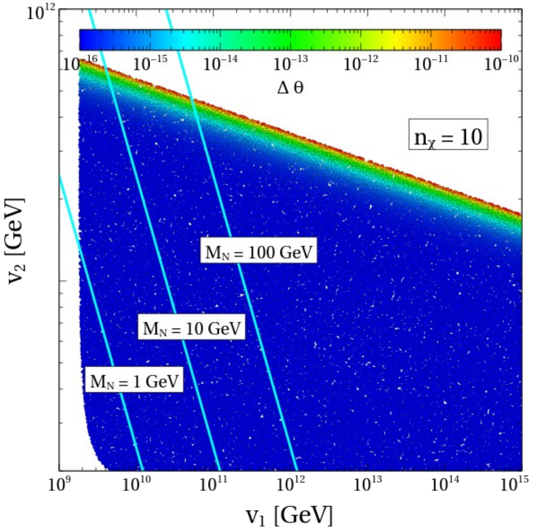
$$\Delta\theta \sim \frac{e^{n_\chi}}{(\sqrt{2})^{1+n_\chi}}\left[1+\frac{1}{n_\chi^2}\right]^{\frac{1+n_\chi}{2}}\sqrt{\frac{n_\chi}{2\pi}}\left[\frac{F_a^2}{f_\pi m_\pi}\right]^2\left[\frac{F_a}{M_{PL}}\right]^{n_\chi-3}\frac{(m_u+m_d)^4}{m_u^2 m_d^2}$$

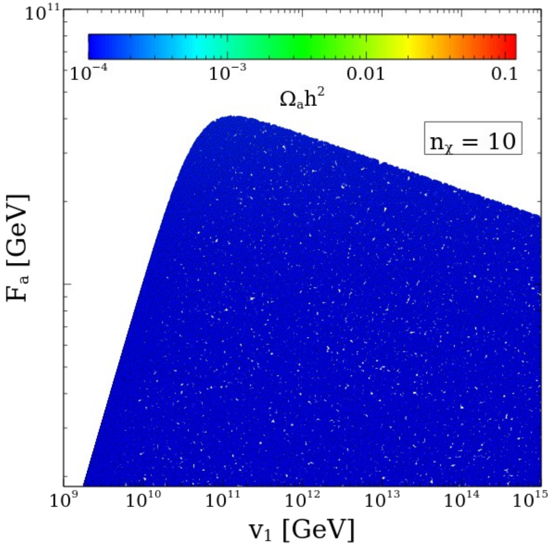
Ruled out by nEDM

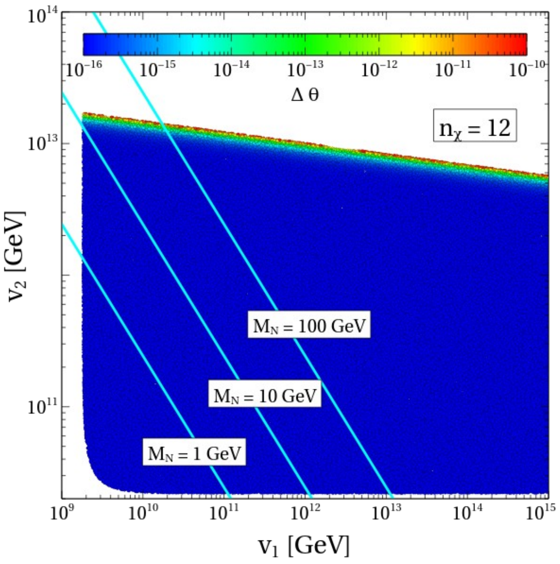
$n_\chi \leq 8$ → $\Delta\theta \geq 10^{-10}$

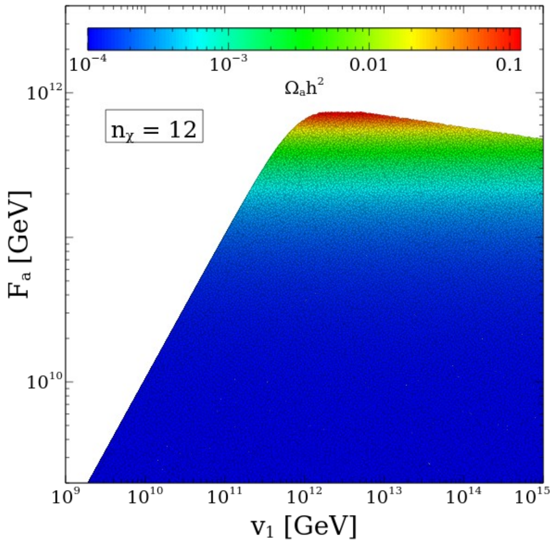
$n_\chi = 9$ → $\Delta\theta \sim 29.41 \times 10^{-10}\left[\frac{F_a}{10^{10}\mathrm{GeV}}\right]^{10}$

Running of SU(3) coupling above the EQ mass scale → $\beta_3(\alpha_3) = -\frac{\alpha_3^2}{2\pi}\left[7-\frac{2(N_\psi+N_\chi)}{3}\right]$ → $N_\psi + N_\chi \leq 10$









Axion relic density using misalignment:

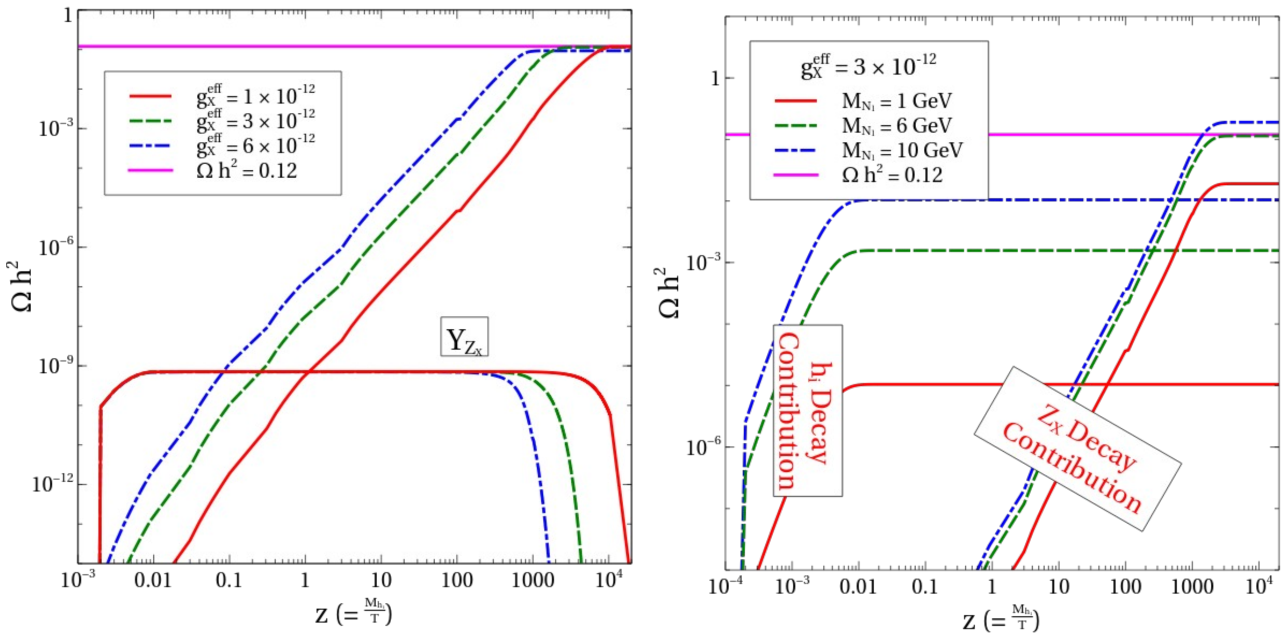
$$\Omega_a h^2 \simeq 0.18\,\theta_i^2 \left(\frac{F_a}{10^{12}\,\mathrm{GeV}}\right)^{1.19}$$

Turner et al '85

- $n_\chi = 10$ can not give us total amount for dark matter although not true for higher n_χ values.
- $n_\chi = 12$ Can give right relic density for part of the parameter space.
- From the asymptotic freedom we can not take high value of n_χ.
- We need a second component to fill the gap to the total DM relic density.

N_1 as FIMP

- In the present work, we can consider one of the RHN as DM which is odd under $\mathbb{Z}_2$
- Lagrangian for the DM candidate N_1: $\mathcal{L}_{N_1} = \frac{i}{2}\bar{N}_1\gamma^\mu\left(\partial_\mu - i\, g_X^{eff} Z_X\right)N_1 + \lambda \bar{N}_1^c N_1 \frac{\phi_1^\dagger \phi_2}{M_{Pl}} + h.c.$



- FIMP is produced from the decay of h_i and Z_X
- Z_X never reaches thermal equilibrium so we have determined its distribution function.

Analytical estimate of FIMP DM

$h_i \to N_1 N_1$ decays contribute to the FIMP DM :

$$\Omega^{FIMP}_{N_1} h^2 \sim \frac{2.038 \times 10^{27}}{g_s \sqrt{g_\rho}} \sum_i \frac{M^3_{N_1}}{16\pi M_{h_i}\, F_a^2 (n_\chi^2 + 1)}$$

$h_i \to Z_X Z_X \to N_1 N_1$ decays contribute to the FIMP DM :

$$(\Omega^{SF}_{N_1} h^2) \sim \frac{2.038 \times 10^{27}}{g_s \sqrt{g_\rho}} 2BR_{Z_X \to N_1 N_1} \sum_i \frac{M_{N_1} q_i^2 M_{h_i}}{32\pi q_2^2 (n_\chi^2 + 1)^2 F_a^2}$$

$Z_X \to N_1 N_1$ branching analytically can be approximated as

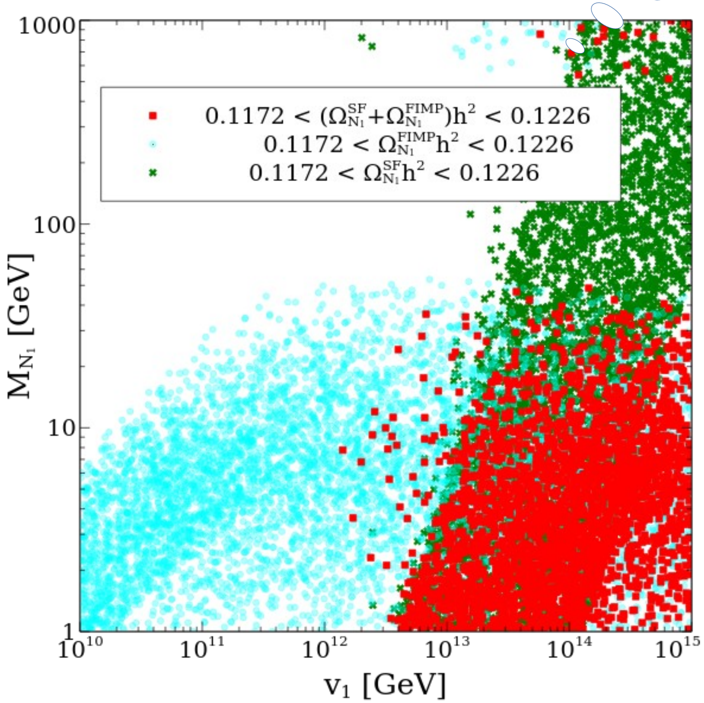
$$2BR_{Z_X \to N_1 N_1} = \frac{2}{24} \frac{(n_\chi + 1)^2}{n_\chi^2 - 8n_\chi + 28/3} \to \frac{1}{12}, \quad \text{for } n_\chi \gg 1$$

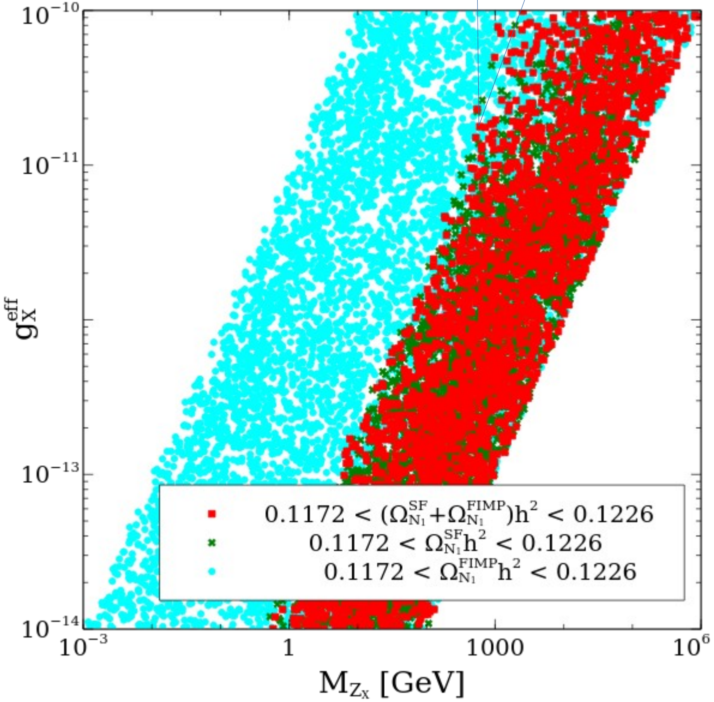
→ In the DM scatter plots, we have considered contribution both axion and FIMP DM

Scatter Plots

Points due to PS Suppression

$M_{Z_X} \propto g_X^2 \sqrt{n_\chi^2 v_1^2 + v_2^2}$





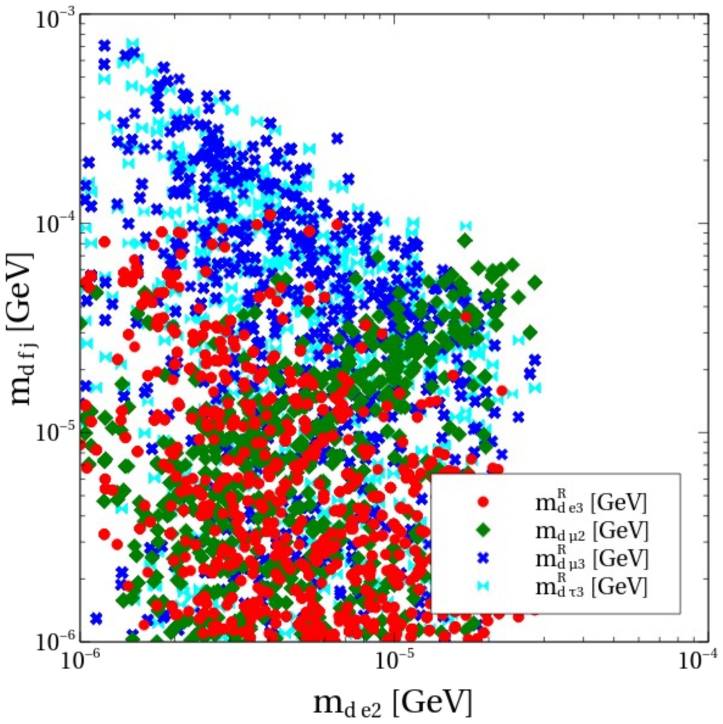
- Cyan region is from the higgses decay.
- Green region is from additional gauge boson decay.
- Red region is the total contribution.

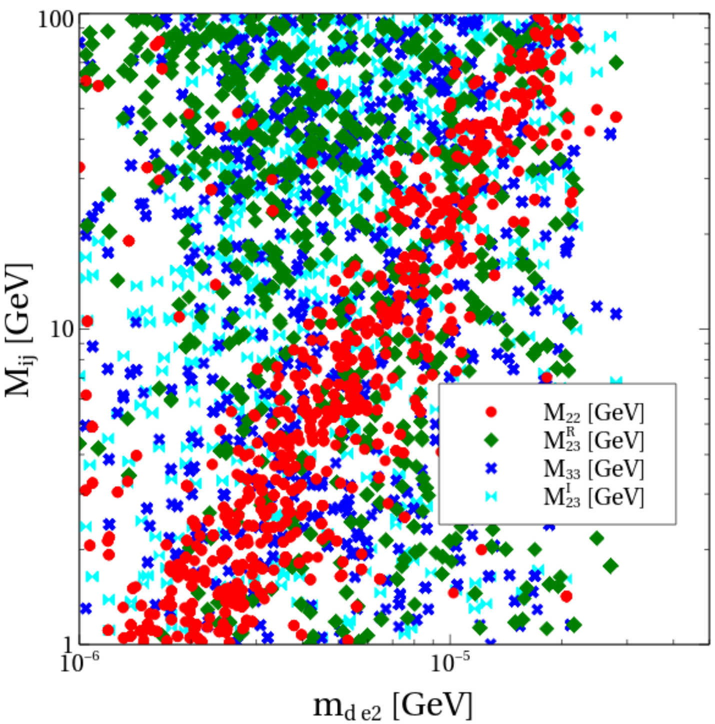
→ Higher values of FIMP DM mass are ruled out due to over production of DM

Neutrino mass

Neutrino mass is generated by Type-I Seesaw

$$m_\nu = -m_D^T M_R^{-1} M_D$$





Model parameters have the correlations as shown in the two plots

- Present model can generate oscillation parameters in the correct range by varying the model parameters
- The lightest **eigenvalue** among the active neutrinos **is zero** since the mixing involves only two RHN

Conclusion

- Present model can accommodate neutrino mass with the allowed range of the neutrino oscillation parameters.
- It also explain the smallness of the θ-parameter and solves the strong CP problem naturally.
- With asymptotic freedom, we could have a not so small contribution to θ which corresponds to small F_a and may be measured in near future experiments.
- Unless we choose very high value of n_χ (≥ 12)which might ruin the asymptotic freedom of QCD coupling, axion can not accommodate whole amount of DM relic density.
- ADMX, MADMAX, babyIAXO can explore the present model for axion mass range from $\mu\mathrm{eV}$ and above, even if axion is not the total DM density.
- One of the right handed neutrino can be a FIMP DM and fill the deficit in the total DM relic density.
- RH FIMP DM is produced from the decay of thermal Higgses and non-thermal gauge boson.

Thank you for your attention

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