Majoron as the QCD axion in a radiative seesaw model

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Based on [1] Phys. Rev. D 96, 075039
with Ernest Ma (UC Riverside)
and Koji Tsumura (Kyoto U.)

Our research's purpose

- Strong CP problem
- Dark matter
- (small) Neutrino mass
- Baryon number asymmetry

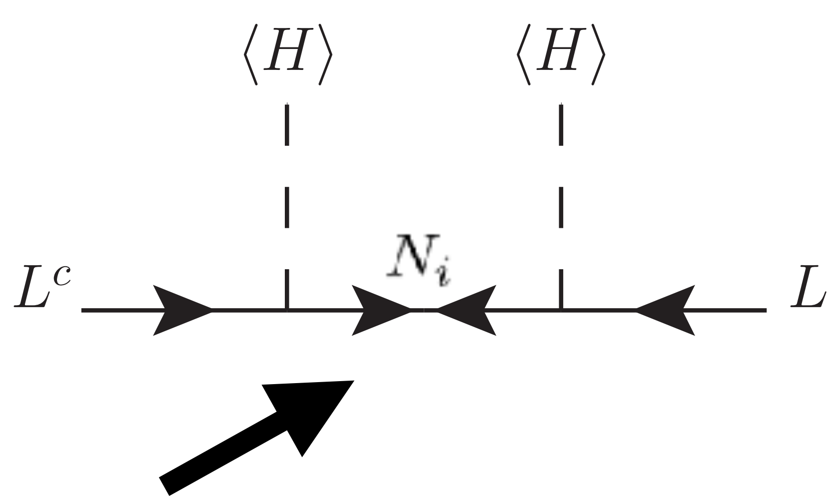
How to explain small neutrino mass

SM+ heavy particle :

$$\frac{c_{\alpha\beta}}{\Lambda}\left(\overline{\tilde{L}_\alpha} H\right)\left(\tilde{H}^\dagger L_\beta\right) + \mathrm{H.c.}$$ [4]

ex) Type I Seesaw [5]

- Heavy right-hand neutrino $N_{iR},\ (i = 1, \cdots, n_N)$ is added.
- After integrating out N_{iR}, neutrino Majorana mass is created.



Heavier than weak scale !

$$\mathcal{M}_{\nu ij} = \sum_k \frac{h_{ik} h_{jk} v^2}{2M_{\mathrm{M}k}}$$

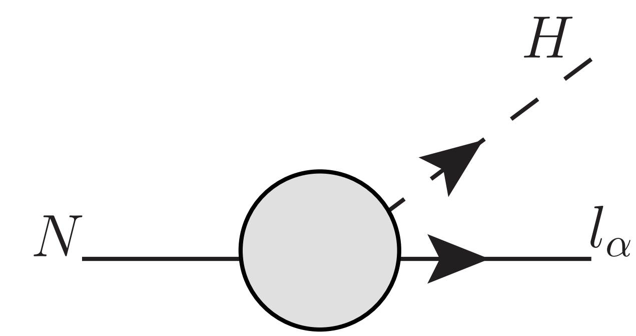
	Ψ_R
$SU(3)_C$	1
$SU(2)_L$	1
$U(1)_Y$	0
spin	1/2

Leptogenesis

[6]

Seesaw model can generate baryon number asymmetry.

- N_R is far from equilibrium at reheating scale.
- The decay process: $N_R \to LH(\mathrm{or}\,\overline{L}H^\dagger)$ breaks B-L and CP.



➡ **Lepton number asymmetry is generated.**

- Lepton asymmetry becomes baryon asymmetry by sphaleron process.

$$Y_B = \frac{12}{37} Y_{B-L}$$

[7]

➡ **Baryon number asymmetry is generated.**

$$Y_B = \frac{n_B}{s} \sim 10^{-10}$$

Dark Matter

- There are many evidence of Dark matter (DM):
  - The flatness of galaxy rotation curve
  - The mass distribution among bullet cluster measured by gravitational lensing
  - The formation of large-scale structure
  - Cosmic microwave background (CMB) observation
  - etc…

$$\Omega_{\rm DM} h^2 \sim 0.12$$ [8,9]

- In the standard model of particle physics (SM), there are no candidate of DM, naively.

➡ **DM may be New particle.**

- WIMP dark matter [10] (Symmetry stabilizes dark matter)
- invisible QCD axion [11,12] (the coupling to SM is very small)
- etc…

Strong CP problem

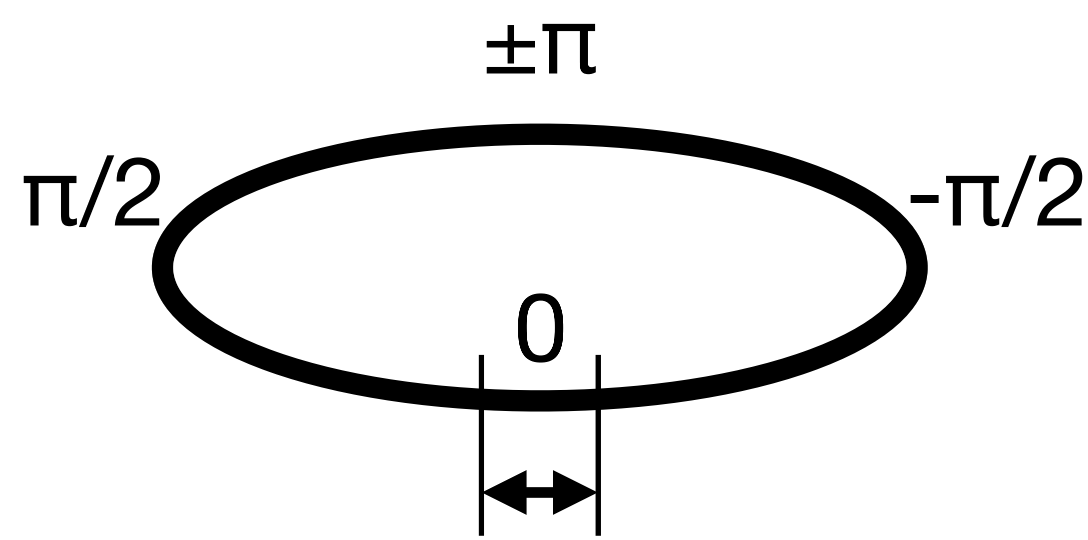
- QCD θ term is allowed in SM:

$$\mathcal{L}_\theta = + \frac{\theta g_3^2}{32\pi^2} \tilde{G}^A_{\mu\nu} G^{A\mu\nu} \quad (-\pi < \theta < \pi)$$

- This θ's range is -π to π. Naively, θ has a random value in the range.

- However θ is very small.
(the measurement of neutron electric dipole moment)

- What mechanism makes θ small ?



$$\theta \lesssim 10^{-11}$$

[13]

Strong CP problem (2)

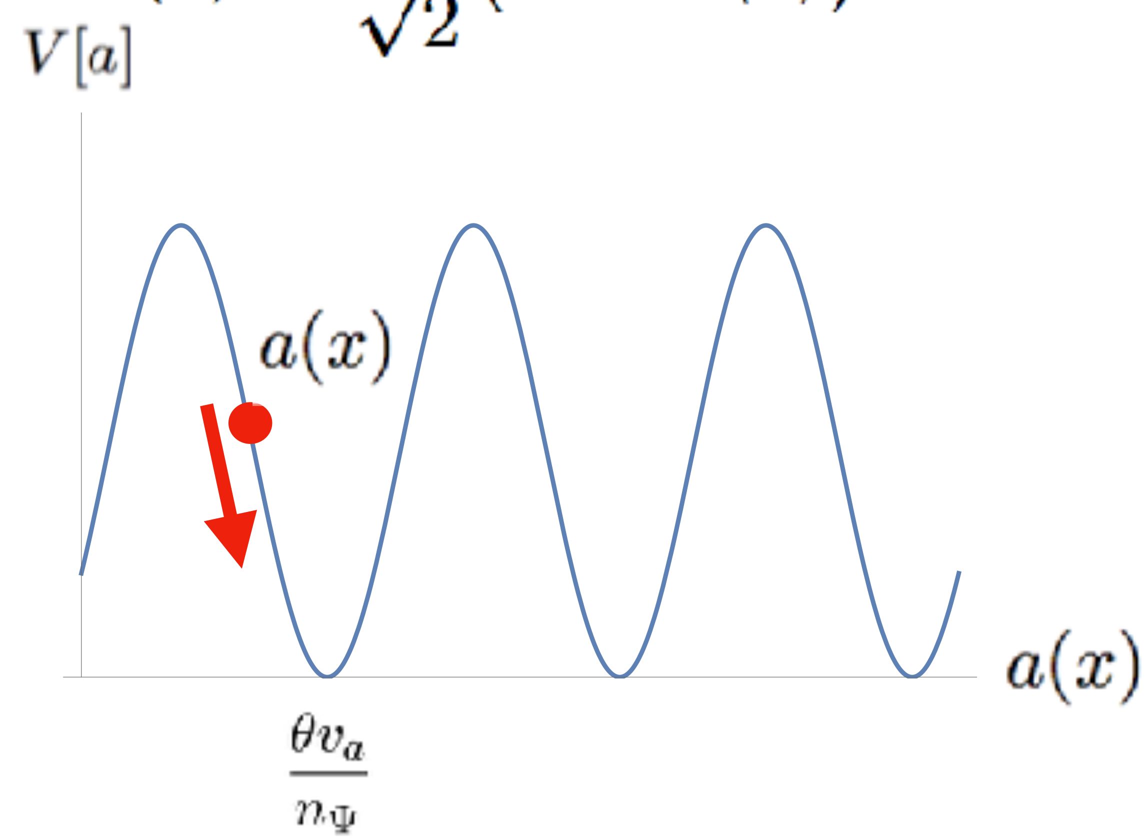
QCD axion model [11,12,14,15]

ex) KSVZ axion model

- colored fermion Ψ
- complex scalar S with wine bottle potential
- Additional Chiral symmetry (Peccei Quinn (PQ) symmetry)
- PQ symmetry is broken by S, and its pseudo NG-boson is axion a.

	S	Ψ_R	Ψ_L
$SU(3)_C$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{3}$
$SU(2)_L$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$U(1)_Y$	0	$-1/3$	$-1/3$
$U(1)_{\rm PQ}$	-2	1	-1
spin	0	$1/2$	$1/2$

$$S(x) = \frac{1}{\sqrt{2}}\left(v_a + \sigma(x)\right)e^{i\,a(x)/v_a}$$



QCD θ term becomes small by axion dynamical effect:

$$\mathcal{L}_\theta = +\frac{g_3^2}{32\pi^2}\left(\theta - \frac{n_\Psi a(x)}{v_a}\right)\tilde{G}^A_{\mu\nu}G^{A\mu\nu}$$

$\rightarrow 0$ **solution of the strong CP problem**

Our research

Our research is

The unification of Seesaw model and Axion model:

- mediator in seesaw = colored fermion in axion model
- Lepton symmetry breaking = PQ (spontaneous) symmetry breaking

[16]

$$\frac{M_i}{2}\overline{N^c_{iR}}N_{iR} + \mathrm{H.c.} \qquad - y^i_\Psi \langle S \rangle \overline{\Psi_{iL}}\Psi_{iR} + \mathrm{H.c.}$$

Majoron = Axion

→ It explains Dark matter, neutrino mass, the baryon number asymmetry and strong CP problem.

I explain it below…

Additional fields & their representation

	S	Ψ_R^A	Φ^A
$SU(3)_C$	$\mathbf{1}$	$\mathbf{8}$	$\mathbf{8}$
$SU(2)_L$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$
$U(1)_Y$	0	0	1/2
$U(1)_{\rm PQ} = U(1)_{\mathbb{L}}$	-2	1	0
spin	0	1/2	0

- S : Complex scalar with **wine bottle potential**.
- Ψ_{iR}^A : **Color octet** right-handed fermion ($i = 1, \cdots, n_\Psi$).
- Φ^A : Complex scalar field in $(\mathbf{8}, \mathbf{2})_{1/2}$.
- Additional Symmetry: $U(1)_{\rm PQ} = U(1)_{\rm Lepton\ \#}$
  - S, Ψ_{iR}^A and Φ^A behave as (radiative) seesaw model.
  - S and Ψ_{iR}^A behave as invisible axion model.
  - After PQ breaking, Ψ_{iR}^A 's Majorana mass is generated: $-\frac{1}{2} y_\Psi^i \langle S \rangle \overline{(\Psi_{iR}^A)^c} \Psi_{iR}^A + \text{H.c.}$

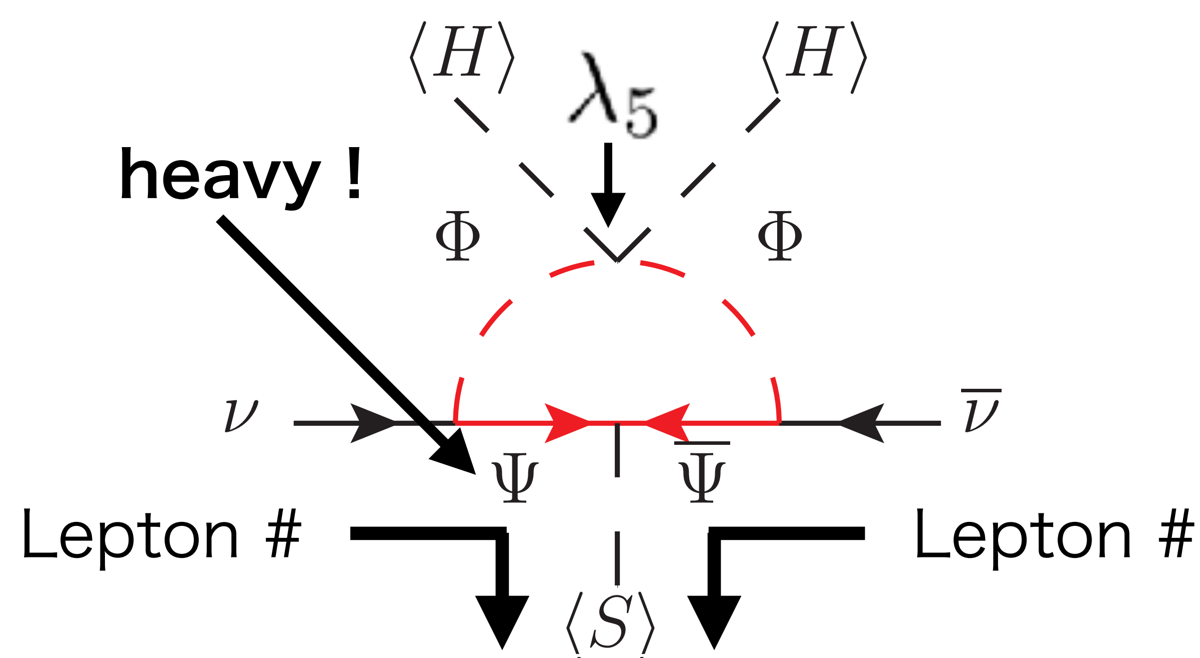
I assumed that $\mathcal{O}(10^4)\text{TeV} \lesssim M_\Phi \ll M_{\Psi_1} \lesssim 10^{12}\text{GeV}$ in my analysis.

neutrino mass

Neutrinos gain mass through radiative correction:

$$(\mathcal{M}_\nu)_{ij} \simeq \frac{1}{4\pi^2}\lambda_5 v^2 \sum_k h_\Psi^{ik} h_\Psi^{jk} M_{\Psi k} \frac{M_{\Psi k}^2 \ln \frac{M_{\Psi k}^2}{m_0^2} - M_{\Psi k}^2 + m_0^2}{(M_{\Psi k}^2 - m_0^2)^2}.$$

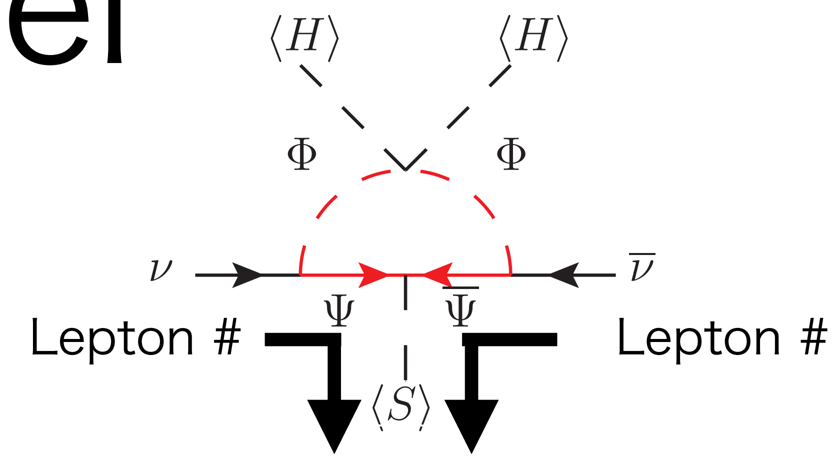
$$2\lambda_5 v^2 \ll m_0^2 \equiv \frac{M_{\mathrm{Re}\Phi^0} + M_{\mathrm{Im}\Phi^0}}{2}$$



Lepton number's breaking is occurred by S ,

the mediator Ψ_{iR}^A 's mass comes from PQ scale.

As axion model



The fields which work as axion model:

- Colored fermion Ψ^{A}_{iR}
- Complex scalar S
- PQ number = Lepton number $\mathbb{L}(\Psi^{A}_{R}) = 1,\ \mathbb{L}(S) = -2$

$$\mathcal{L}_\theta = + \frac{g_3^2}{32\pi^2}\left(\theta - \frac{a(x)}{v_a/(3n_\Psi)}\right)\tilde{G}^{A}_{\mu\nu}G^{A\mu\nu}$$

$$\to 0$$

Strong CP problem is solved.

$$\Omega_a h^2 \sim 0.18\theta_a^2\left(\frac{v_a/(3n_\Psi)}{10^{12}\ \mathrm{GeV}}\right)^{1.19}$$

[17,18]

Axion behaves as DM.

Leptogenesis

(preliminary)

the picture of Leptogenesis in our model

- Ψ_{iR}^{A} is far from equilibrium at the reheating scale.
- After reheating, the process $\Psi_1^A \rightarrow \Phi^{A(\dagger)} L^{(\dagger)}$ creates Lepton number asymmetry.
- Ψ_{iR}^{A} is colored particle. Ψ_{iR}^{A}'s thermalization in our model is faster than the one of right-handed neutrino N_{iR} in the type I Seesaw model.

Parameter setting from DM and neutrino data

- PQ scale $v_a \leftarrow$ determined by DM relic density

$$\Omega_{\rm DM} h^2 \simeq 0.18 \theta_i^2 \left(\frac{v_a/(3n_\Psi)}{10^{12}\ {\rm GeV}} \right)^{1.19},\ n_\Psi = 3, \theta_i = \mathcal{O}(1)$$

$$\to v_a \simeq 7.1 \times 10^{11}\ {\rm GeV}$$

- coupling $h_\Psi^{ik} \leftarrow$ determined by Neutrino Mass Matrix

$$(\mathcal{M}_\nu)_{ij} \simeq \frac{\lambda_5 v^2}{4\pi} \sum_k \frac{h_\Psi^{ik} h_\Psi^{jk}}{M_{\Psi_k}}\ \ (M_\Phi \ll M_\Psi)$$

$$\mathcal{L}_{L\Phi\Psi_R} = h_\Psi^{ij} \widetilde{\Phi}^{A\dagger} \overline{\Psi_{jR}^A} L_i + {\rm H.c.}$$

$$h_\Psi^{ik} \to \frac{2\pi}{\sqrt{\lambda_5} v} U_{\rm PMNS}^* \sqrt{m_\nu^{\rm diag}} R^{\rm T} \sqrt{M_\Psi^{\rm diag}}$$

(R: complex orthogonal matrix)

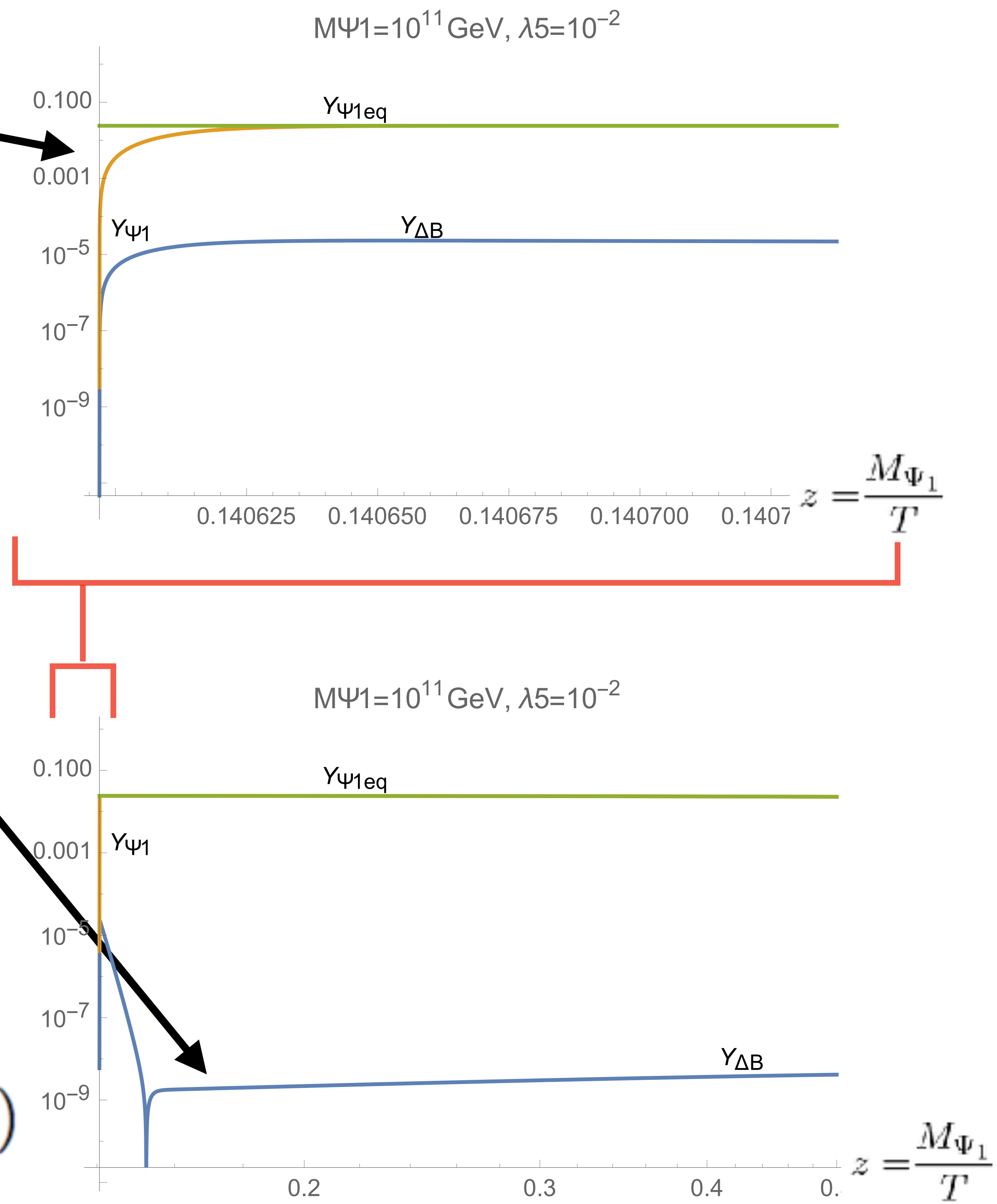
(I assumed Normal Hierarchy in my analysis.)

λ_5 : $(H^\dagger \Phi^A)^2$'s coupling

numerical solution of Boltzmann equation

- After reheating , Ψ_{iR}^{A} is thermalized quickly. During it, Lepton number asymmetry is created.
- After generating and washout of Lepton asymmetry are balanced, Lepton asymmetry becomes stabilized.
- In order to create sufficient baryon number: $Y_B = \frac{n_B}{s} \sim 10^{-10}$, the lightest Ψ_{iR}^{A} 's mass is:

$$M_{\Psi_1} \gtrsim 2 \times 10^{10}\mathrm{GeV}$$
$$(\lambda_5 = 10^{-2}, M_{\Psi_1} \simeq 10^{-2} M_{\Psi_{2,3}})$$



The prediction of reheating temperature

In order to explain baryon number asymmetry, the reheating temperature is bounded:

$$2 \times 10^{10}\mathrm{GeV} \lesssim M_{\Psi_1} \lesssim T_{\mathrm{reheat}} \lesssim v_a \quad .$$

- The lower bound comes from the baryon number asymmetry.
- The upper bound comes from the Domain wall problem.

Summary

- Our model can explain DM, strong CP problem, neutrino mass and baryon number asymmetry.
- In our model, the mediator in seesaw model becomes colored fermion in axion model. This mediator's mass comes from PQ scale.
- Based on the leptogenesis, our model can predict the reheating temperature: $2 \times 10^{10}\mathrm{GeV} \lesssim M_{\Psi_1} \lesssim T_{\mathrm{reheat}} \lesssim v_a$.

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Backup

Flavor Changing Neutral Current (FCNC)

$$\mathcal{L}_{Q\Phi q_R} = g_u^{ij}\,\overline{Q_i}\,\widetilde{\Phi^A}\,T^A\,u_{jR} + g_d^{ij}\,\overline{Q_i}\,\Phi^A\,T^A\,d_{jR} + \mathrm{H.c.}$$

Δm_K is the mass difference in $K^0 - \overline{K^0}$ mixing.

$$\frac{\Delta m_K^{\Phi^A}}{\Delta m_K^{\mathrm{exp}}} \sim \frac{g_{u,d}^2 \Lambda_{\mathrm{QCD}}^3}{M_\Phi^2 \Delta m_K^{\mathrm{exp}}}$$

$$\Delta m_K^{\mathrm{exp}} = (3.484 \pm 0.006) \times 10^{-15}\mathrm{GeV}$$ [8]

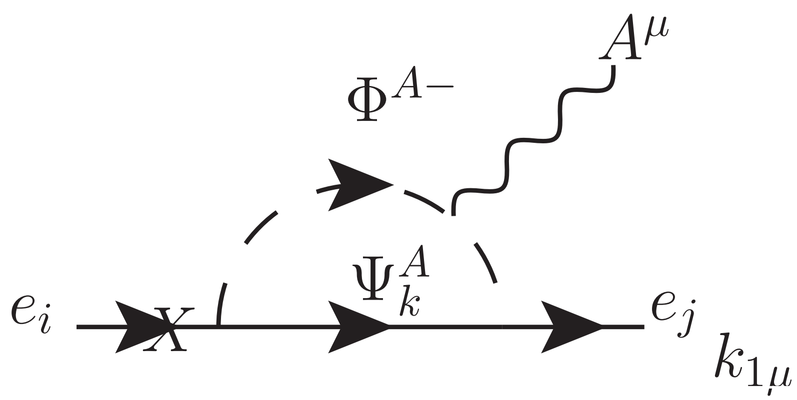
Assuming that Φ^A's contribution to Δm_K is in the error and $g_{u,d} \sim \mathcal{O}(1)$,

$$M_\Phi \gtrsim \mathcal{O}(10^4)\mathrm{TeV}\ .$$

LFV process

Based on leptogenesis, Ψ_{iR}^{A} is heavy.

So, LFV process in our model meets the experimental limit.



$$\mathrm{Br}(\ell_i \to \ell_j \gamma) = \frac{3\alpha}{\pi M_{\Phi_\pm}^4 G_F^2} |h_\Psi^{ik} F_2(M_{\Psi_k}^2 / M_{\Phi_\pm^2}) h_\Psi^{\dagger kj}|^2$$

$$F_2(x) = \frac{1 - 6x + 3x^2 + 2x^3 - 6x^2 \ln x}{6(1-x)^4}$$

$$\underset{\substack{10^7\mathrm{GeV} < M_{\Psi_1} < 10^{12}\mathrm{GeV},\ 10^{-6} < \lambda_5 < 1, \\ 10^3\mathrm{GeV} < M_{\Phi_\pm} < 10^7\mathrm{GeV},\ M_{\Phi_\pm} < 10^{-2} M_{\Psi_1}}}{\mathrm{Max}} \frac{\mathrm{Br}(\mu \to e\gamma)}{(\mathrm{Br}(\mu \to e\gamma))_{\mathrm{limit}}} \sim 10^{-27}$$

New Yukawa coupling

$$\mathcal{L}_{Q\Phi q_R} = g_u^{ij}\,\overline{Q_i}\,\widetilde{\Phi^A}\,T^A\,u_{jR} + g_d^{ij}\,\overline{Q_i}\,\Phi^A\,T^A\,d_{jR} + \mathrm{H.c.}$$

$$\mathcal{L}_{L\Phi\Psi_R} = h_\Psi^{ij}\,\overline{L_i}\,\widetilde{\Phi^A}\,\Psi_{jR}^A + \mathrm{H.c.}$$

$$\mathcal{L}_{S\Psi_R\Psi_R} = -\frac{1}{2}\,y_\Psi^i\,S\,\overline{(\Psi_{iR}^A)^c}\Psi_{iR} + \mathrm{H.c.}$$

Boltzmann equation

$$s\frac{dY_{\Delta L}}{dt} \simeq \frac{g_{\Psi_1^A} M_{\Psi_1}^3}{2\pi^2 z} K_1(z)\Gamma(\Psi_1^A \to 2)\left[\epsilon \frac{Y_{\Psi_1^A} - Y_{\Psi_1^A}^{\rm eq}}{Y_{\Psi_1^A}^{\rm eq}} - \frac{1}{6}\frac{Y_{\Delta L}}{Y_{\ell_\alpha}^{\rm eq}}\right]$$

$$s\frac{dY_{\Psi_1^A}}{dt} \simeq - \frac{Y_{\Psi_1^A} - Y_{\Psi_1^A}^{\rm eq}}{Y_{\Psi_1^A}^{\rm eq}} \frac{g_{\Psi_1^A} M_{\Psi_3}^3}{2\pi^2 z} K_1(z)\Gamma(\Psi_1^A \to 2)$$

$$+ 2\gamma^{XX\Psi_1\Psi_1} - 2\left(\frac{Y_{\Psi_1}}{Y_{\Psi_1}^{\rm eq}}\right)^2 \gamma^{\Psi_1\Psi_1 XX}$$

$$\gamma^{\Psi_1\Psi_1 XX} = \frac{1}{8\pi^4}\left(\frac{M_{\Psi_1}}{z}\right)^4 \left(\frac{3\times 4}{\pi} + \frac{1}{2}\frac{36}{\pi} + \frac{6}{\pi}\right) \times \left\{4\pi\alpha_s(T = M_{\Psi_1}/z)\right\}^2$$

$$\gamma^{XX\Psi_1\Psi_1} = \frac{1}{2}\frac{1}{8\pi^4}\left(\frac{M_{\Psi_1}}{z}\right)^4 \left(\frac{3\times 4}{\pi} + \frac{36}{\pi} + \frac{12}{\pi}\right) \times \left\{4\pi\alpha_s(T = M_{\Psi_1}/z)\right\}^2$$

$$\Gamma(\Psi_1^A \to 2) = \frac{8 \times [h_\Psi^\dagger h_\Psi]_{11} M_{\Psi_1}}{4\pi g_{\Psi_1^A}}$$

$$\epsilon = \frac{1}{8\pi} \frac{\sum_{k=2,3} {\rm Im}(h_\Psi^{i1} h_\Psi^{ik*} [h_\Psi^\dagger h_\Psi]_{k1}) \{f(\xi_k) + g(\xi_k)\}}{[h_\Psi^\dagger h_\Psi]_{11}}$$

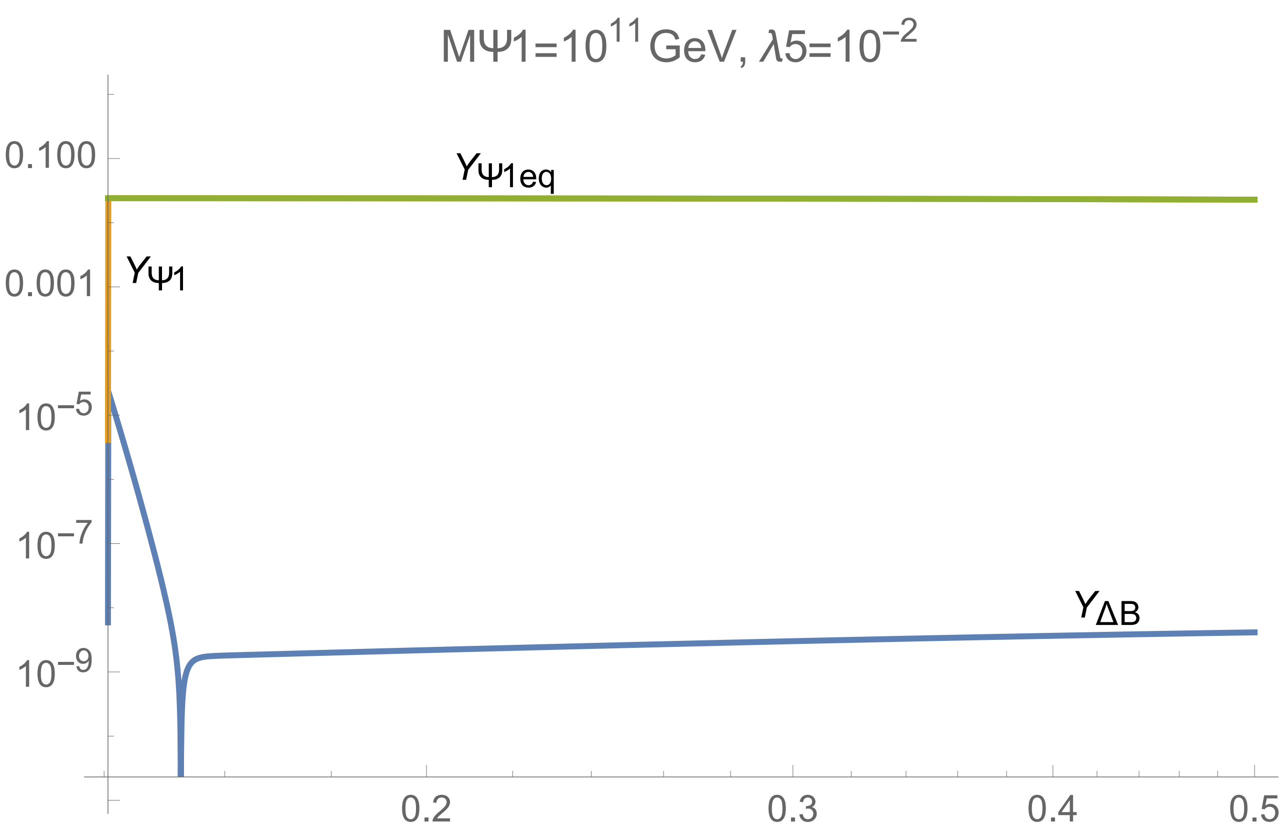
$$f(\xi) = \sqrt{\xi}\left\{1 - (1+\xi)\ln\frac{1+\xi}{\xi}\right\},\ g(\xi) = \frac{\sqrt{\xi}}{1-\xi}$$

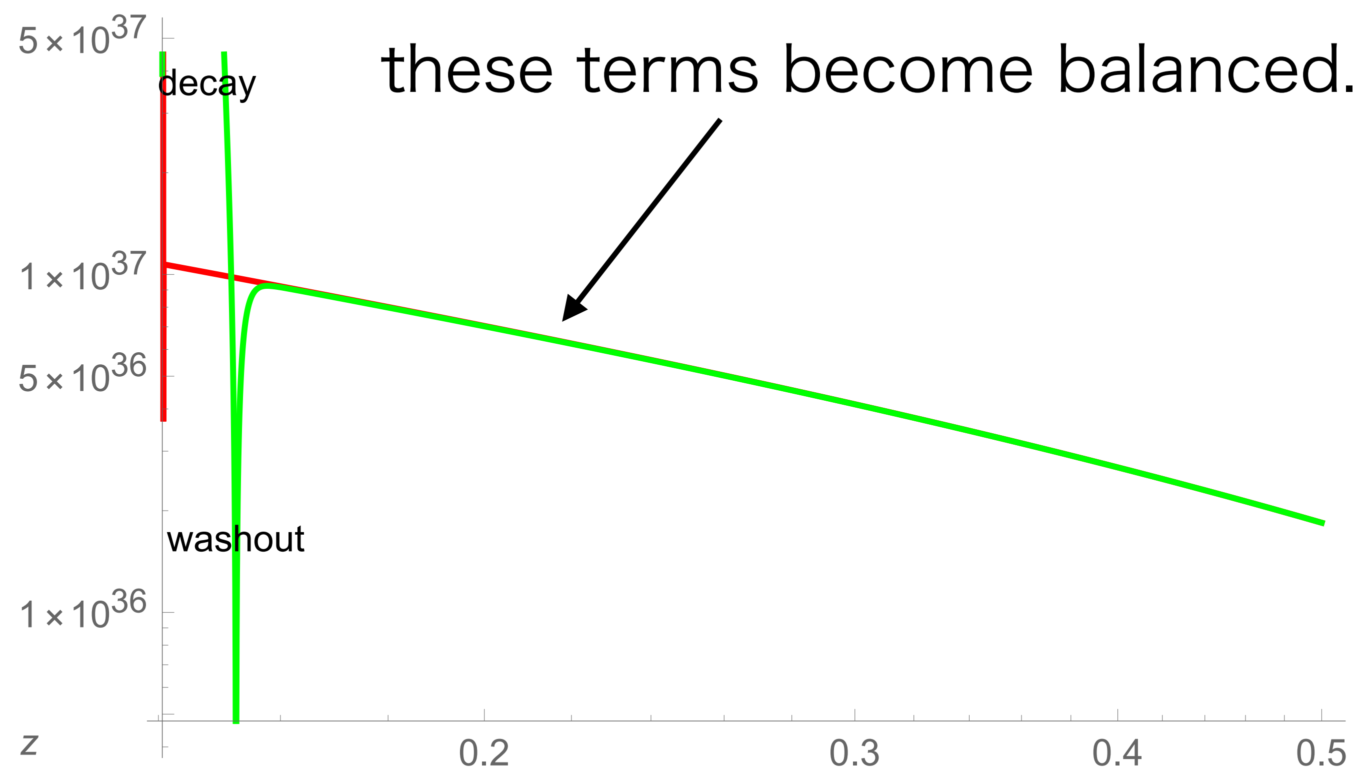
$$\xi_k = \frac{M_{\Psi_k^2}}{M_{\Psi_1}^2},\ g_{\Psi_1^A} = 2\times 8,\ g_{\ell_\alpha} = 2\times 2$$

The balance between Ψ_{iR}^{A}'s decay and lepton asymmetry's washout.

$$s\frac{dY_{\Delta L}}{dt} \simeq \frac{g_{\Psi_1^A} M_{\Psi_1}^3}{2\pi^2 z} K_1(z)\Gamma(\Psi_1^A \to 2)\left[\epsilon\frac{Y_{\Psi_1^A} - Y_{\Psi_1^A}^{\mathrm{eq}}}{Y_{\Psi_1^A}^{\mathrm{eq}}} - \frac{1}{6}\frac{Y_{\Delta L}}{Y_{\ell_\alpha}^{\mathrm{eq}}}\right]$$

The first term in RHS is Ψ_{iR}^{A} decay term,
and the second term is washout term.



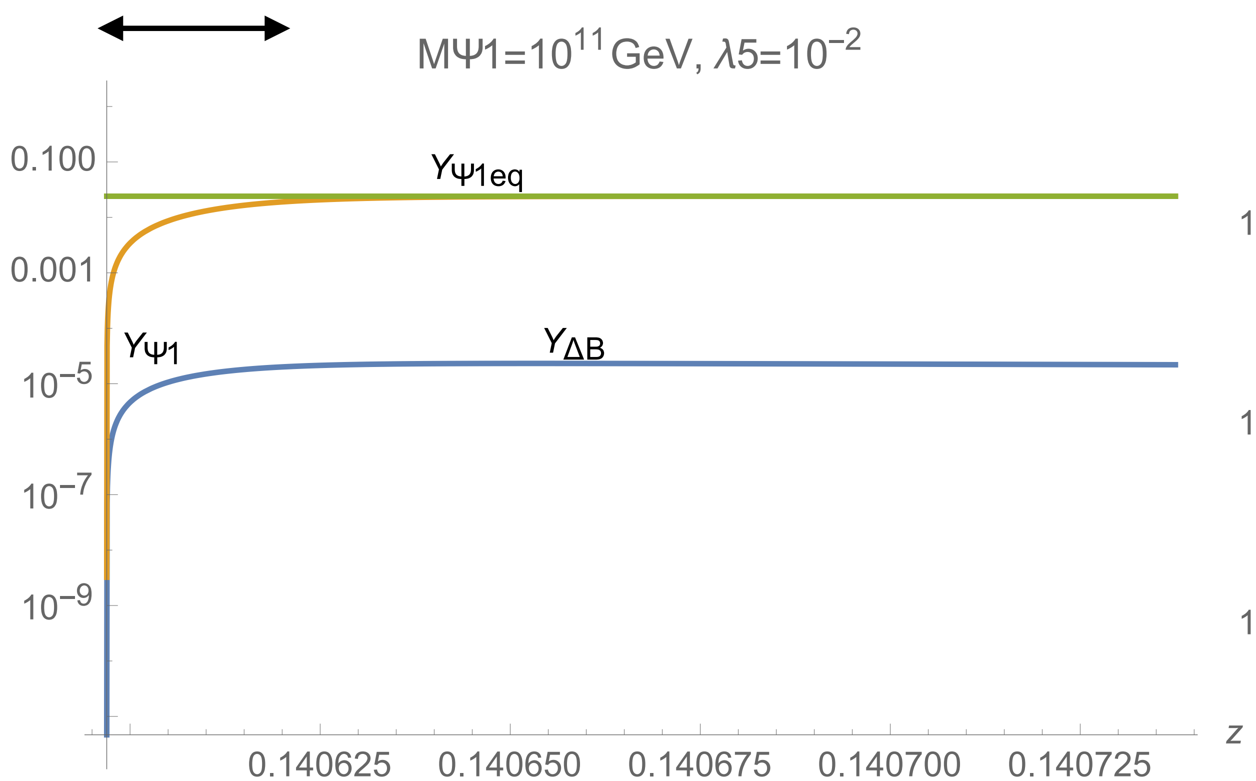


Ψ1's thermalization is fast due to its QCD process.

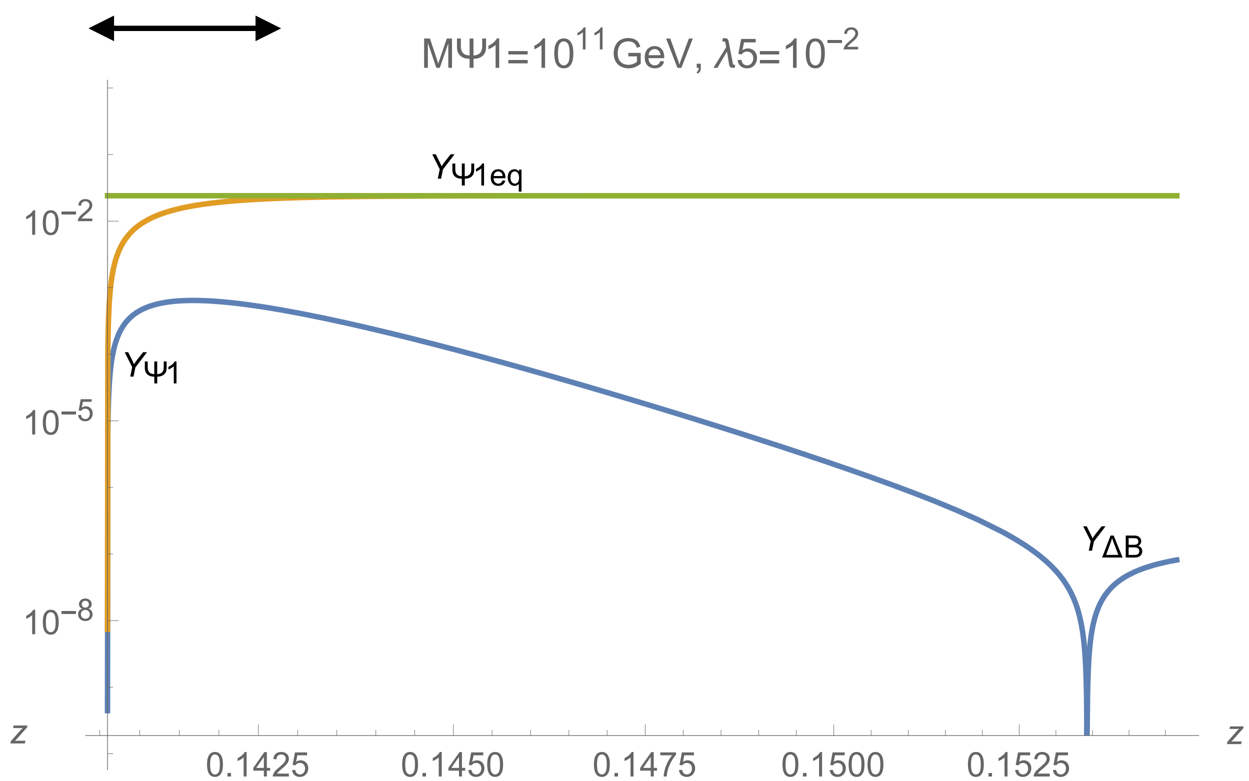
The analysis with Ψ1's QCD process in our model.

The analysis without Ψ1's QCD process in our model.

$\Delta z \sim \mathcal{O}(10^{-5})$



$\Delta z \sim \mathcal{O}(10^{-3})$



Axion coupling with SM particle

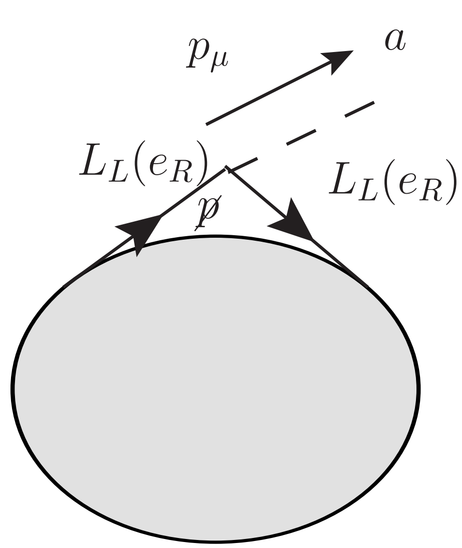
Axion (Majoron) in our model couples with Lepton.
Especially, it couples with a charged lepton's **vector** current.

$$\frac{\partial_\mu a}{2v_a}(\overline{L_L}\gamma^\mu L_L + \overline{e_R}\gamma^\mu e_R)$$

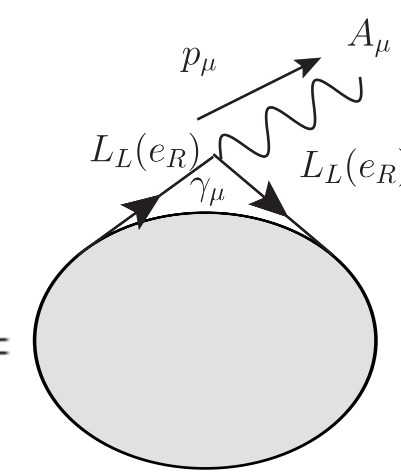
(Other coupling with SM particle is same as KSVZ-like axion.)

However, when axion is on-shell, this coupling becomes zero.

$$i\mathcal{M}_a = p_\mu \mathcal{M}^\mu =$$



$$i\mathcal{M}_A = -ie\epsilon^*_\mu(p)\mathcal{M}^\mu =$$



These $\mathcal{M}^\mu$ are same,
so $i\mathcal{M}_a = 0$ due to Ward Takahashi identity.