The 26th LHC Mini-Workshop

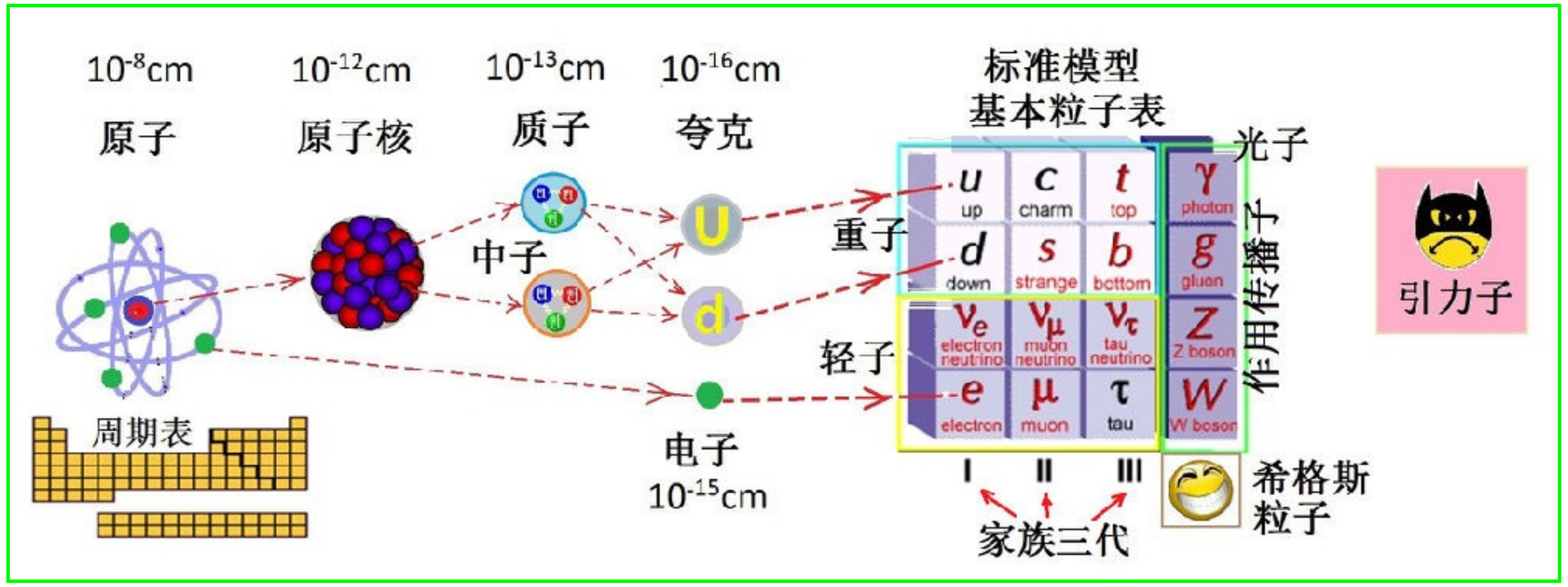
Majoron DM from type-II seesaw

WEI CHAO (Beijing Normal University) **2022.10.29**

Based on arXiv:2210.13233, with Ying-quan Peng, Hai-jun Li and Mingjie Jin

New Physics beyond the SM?

标准模型是描述基本粒子之间强相互作用、弱相互作用和电磁相互作用这三种基本力的理论



黑格斯粒子导致弱电对称性自发破缺
2012年被LHC发现，2013 诺贝尔奖

$SU(3)_C \times SU(2)_L \times U(1)_Y$

黑格斯机制

$SU(3)_C \times U(1)em$

物理学中的乌云

引领20世纪物理学的发展的乌云

量子力学
广义相对论

- 黑体辐射
- 迈克逊-莫雷实验

具有确凿试验证据的超出标准模型的新物理

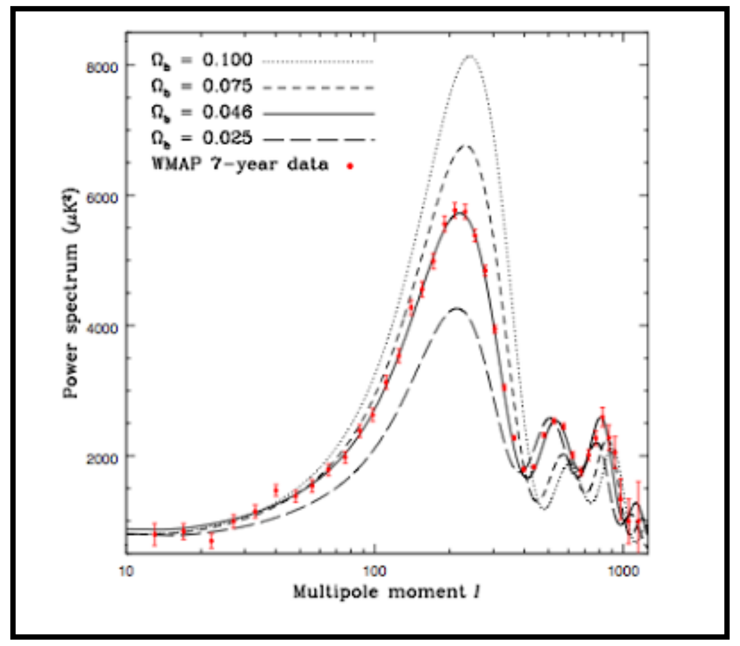
NP!

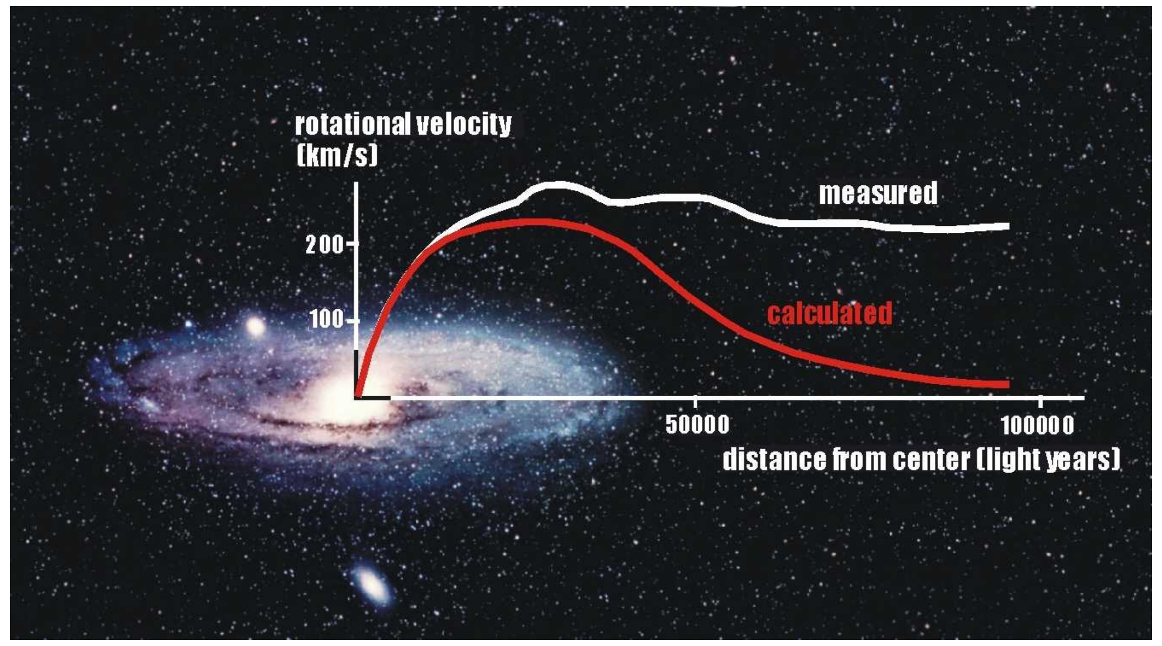
- 中微子;
- 暗物质;
- 重子数不对称;

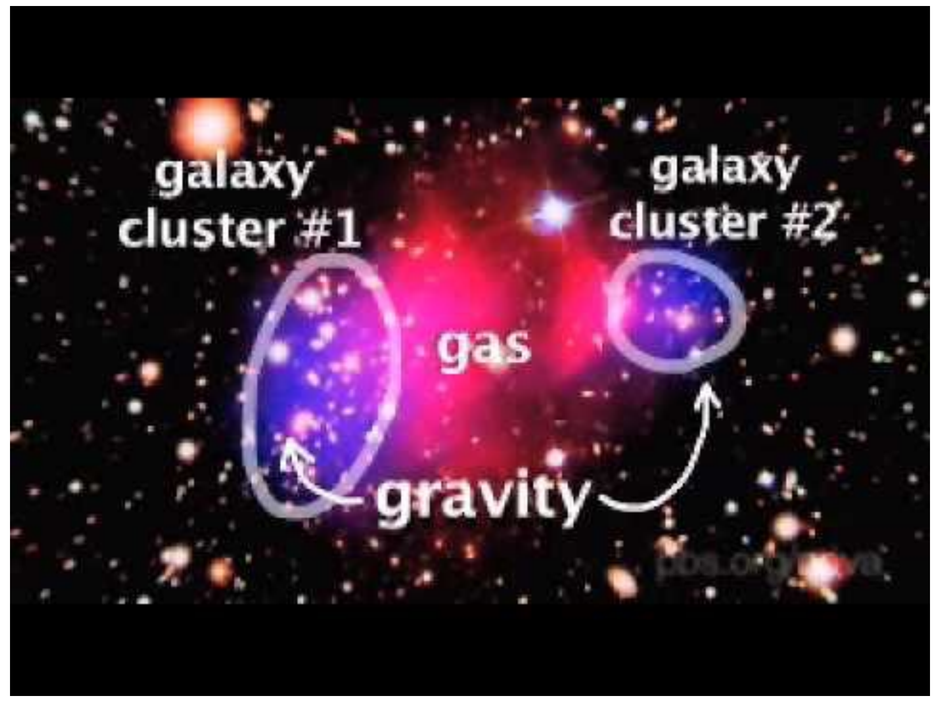
- Muon g-2?
- W-mass anomaly

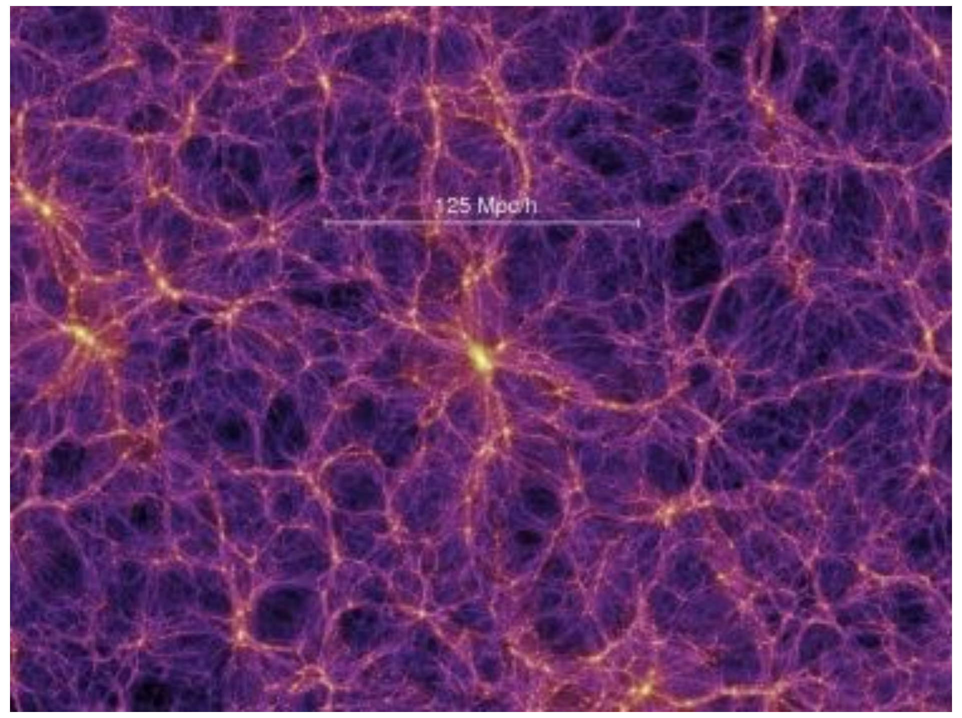
What is dark matter?

在各个尺度上都有暗物质存在的证据







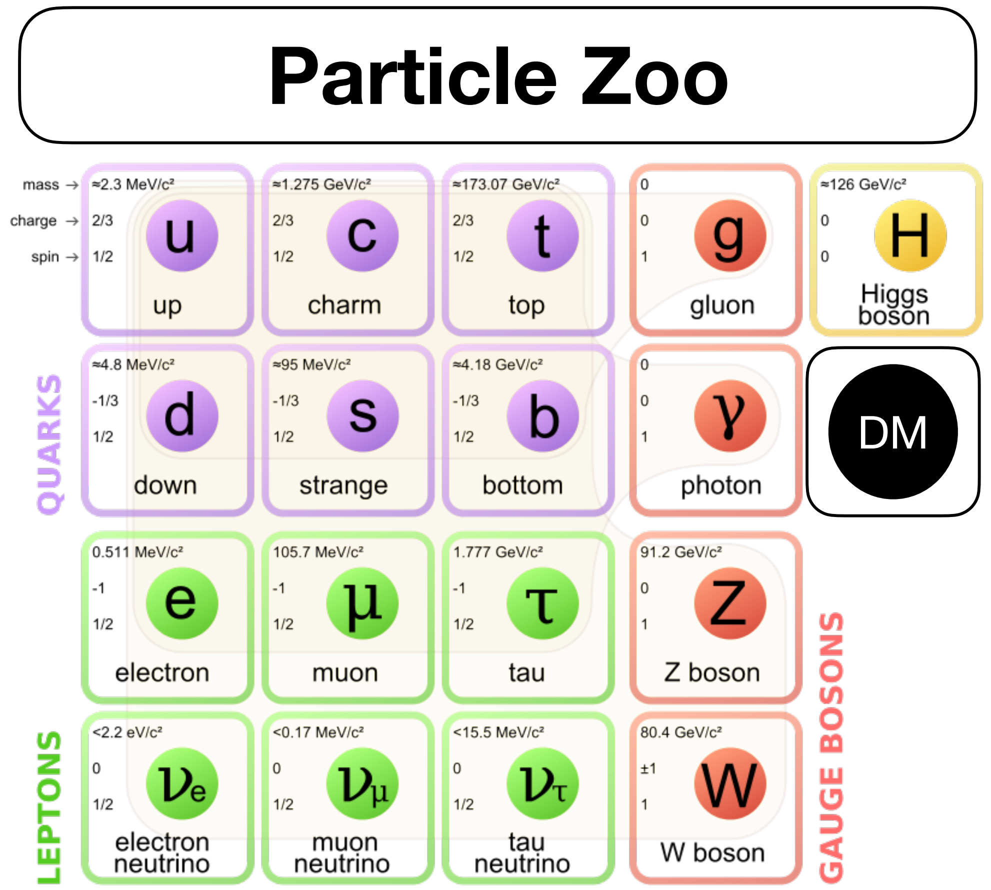


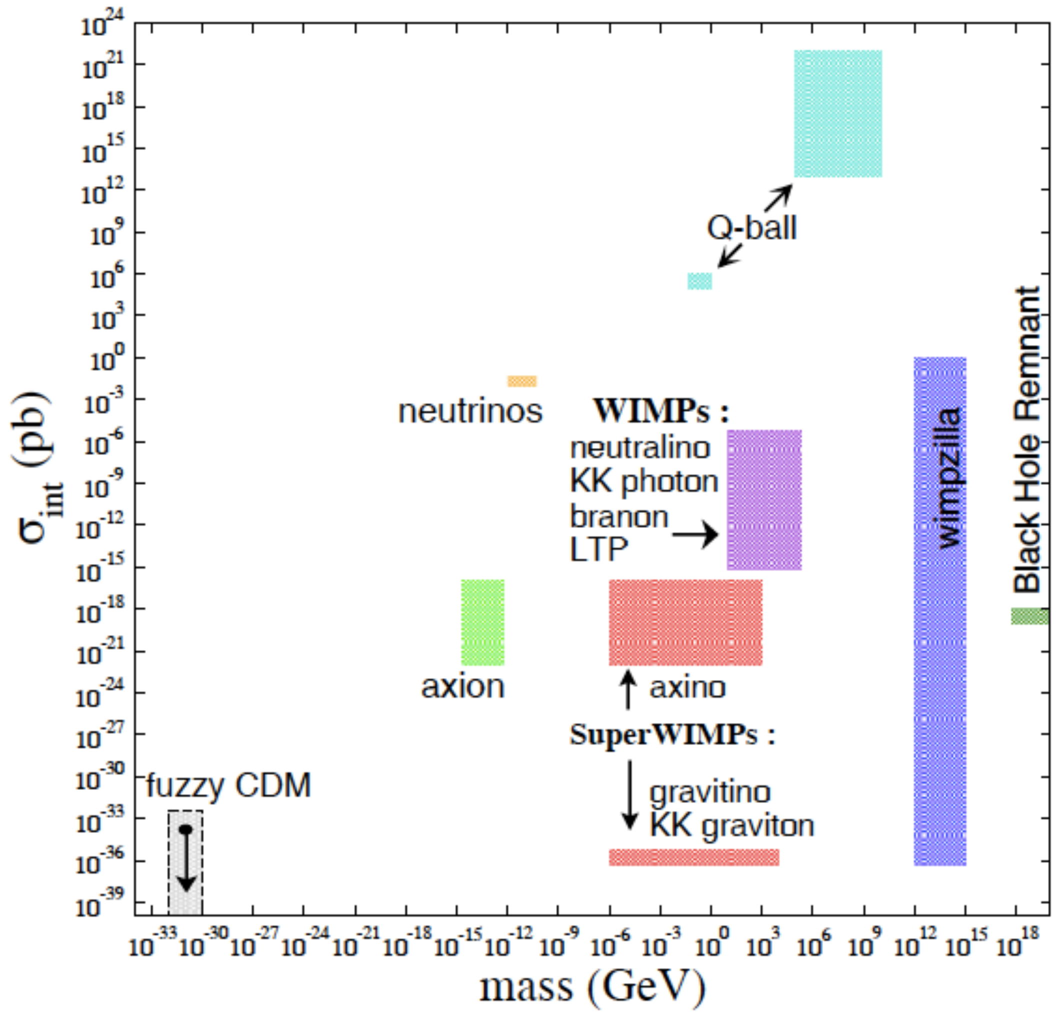
暗物质是什么?

答： 不知道!

~~Mass~~ ~~Spin~~ ~~Interactions~~

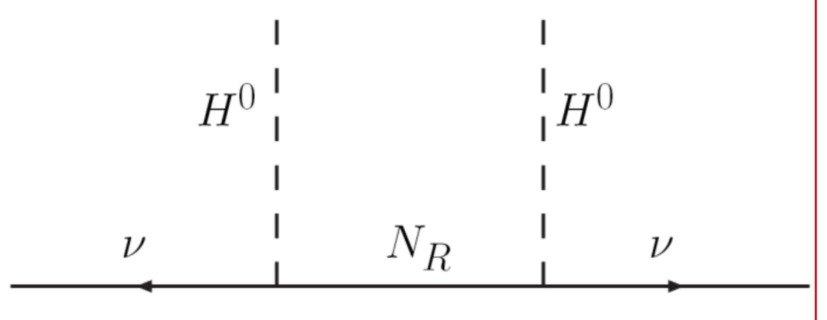
Neutral, non-baryonic, weakly interacting particle!





Neutrino mass generations

Old History： Majorana neutrino mass from the dim-5 Weinberg operator $\kappa_{\alpha\beta}\overline{\ell_L^{\alpha}}\tilde{H}\tilde{H}^T\ell_L^{\beta C}$



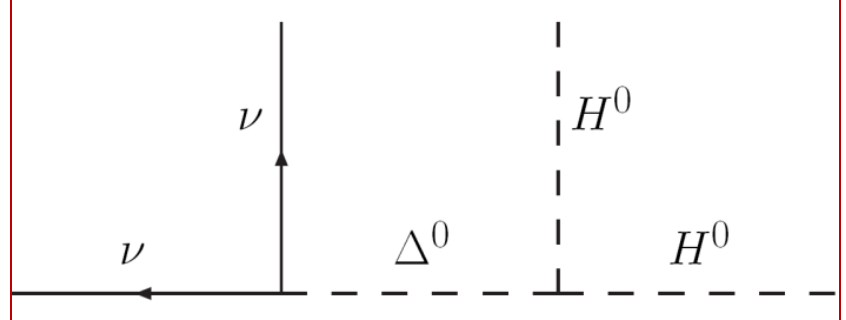
(a)

$$-\mathcal{L} = \overline{\ell_L} Y_\nu N_R \tilde{H} + \frac{1}{2}\overline{N_R^{\rm C}} M_R N_R + {\rm h.c.}$$

SU(2)_L 费米子单态

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

Minkowski（77）



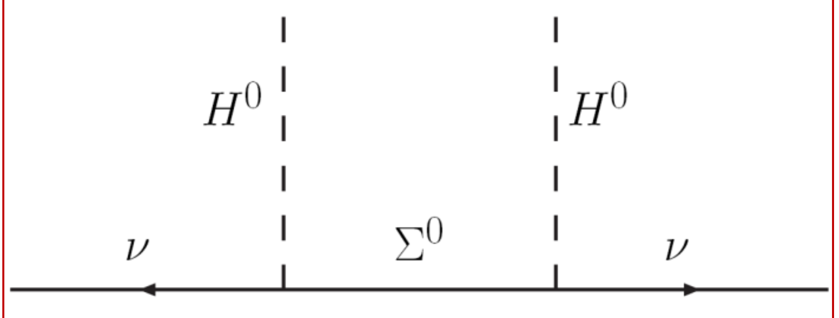
(b)

$$-\mathcal{L} = \frac{1}{2}\overline{\ell_L} Y_\Delta \Delta \varepsilon \ell_L^{\rm C} - \lambda_\Delta M_\Delta H^T \varepsilon \Delta H + {\rm h.c.}$$

SU(2)_L 标量场三重态

$$M_\nu = Y_\Delta v_\Delta$$

Magg， Wetterich（80）



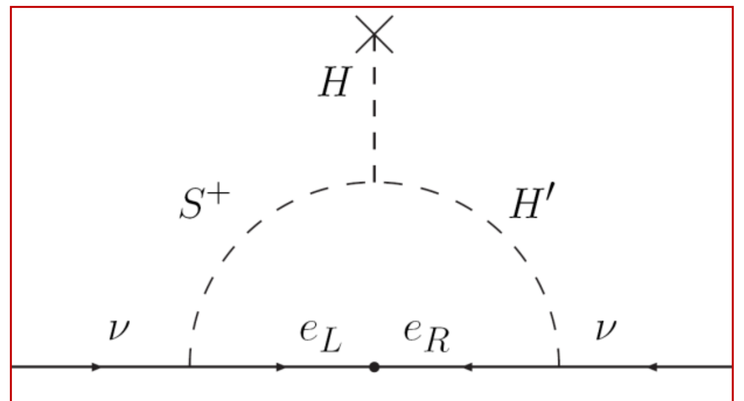
(c)

$$-\mathcal{L} = \frac{1}{2}{\rm Tr}\left[\Sigma M_\Sigma \Sigma^{\rm C}\right] + \sqrt{2}\overline{\ell_L} Y_\Sigma \Sigma \tilde{H} + {\rm h.c.}$$

SU(2)_L 费米场三重态

$$M_\nu = -M_D M_\Sigma^{-1} M_D^T$$

Foot，Lew， He，Joshi（89）



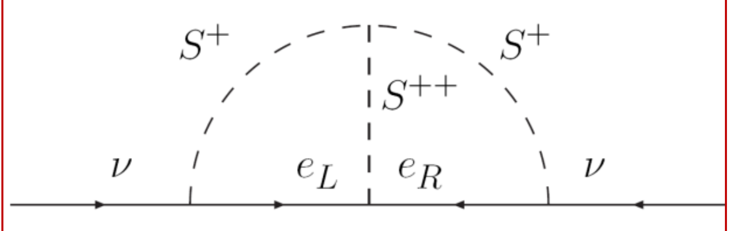
(a)

$$-\mathcal{L} = \ell_L^T Y_S \varepsilon \ell_L S^+ - \mu H^T \varepsilon H' S^- + {\rm h.c.}$$

$$(M_\nu)_{\alpha\beta} = A\,(Y_S)_{\alpha\beta}\,(m_\alpha^2 - m_\beta^2)$$

Zee（80）

标量场单态+标量场二重态



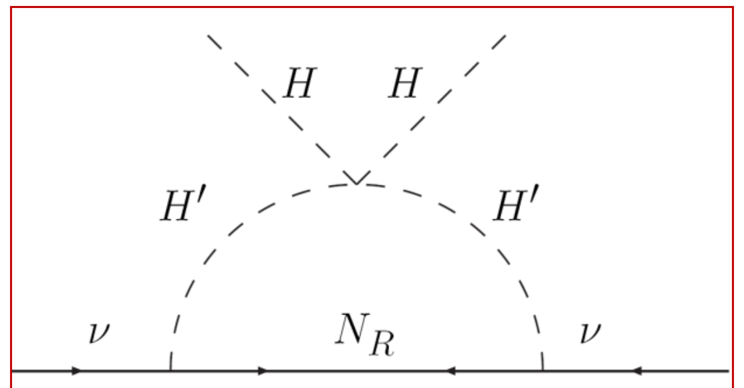
(b)

$$-\mathcal{L} = \ell_L^T Y_S \varepsilon \ell_L S^+ + e_R^T F_S e_R S^{++} + \mu S^- S^- S^{++} + {\rm h.c.}$$

$$(M_\nu)_{\alpha\beta} = 8\mu \sum_{\kappa\lambda} m_\kappa m_\lambda (Y_S)_{\alpha\kappa} (F_S)_{\kappa\lambda} (Y_S)_{\lambda\beta} I_{\kappa\lambda}$$

Babu（88）

两个标量场单态



(c)

$$-\mathcal{L} = \overline{\ell_L} Y_\nu N_R \tilde{H}' + \frac{1}{2}\overline{N_R^{\rm C}} M_R N_R + \frac{1}{2}\lambda_5 (H^\dagger H')^2 + {\rm h.c.}$$

$$(M_\nu)_{\alpha\beta} = \sum_i (Y_\nu)_{\alpha i} M_i^{-1} (Y_\nu)_{\beta i} I(M_i^2/m_0^2)$$

Ma （98）

标量场二重态+右手Majorana中微子+Z_2分立对称性

● ● ●

Y. Cai, T. Han, T. Li, 1711.02180

Neutrino mass generations

Neutrino mass from higher dimensional effective operators

(F. Bonnet et al, 2009; Y. Liao, 2011)

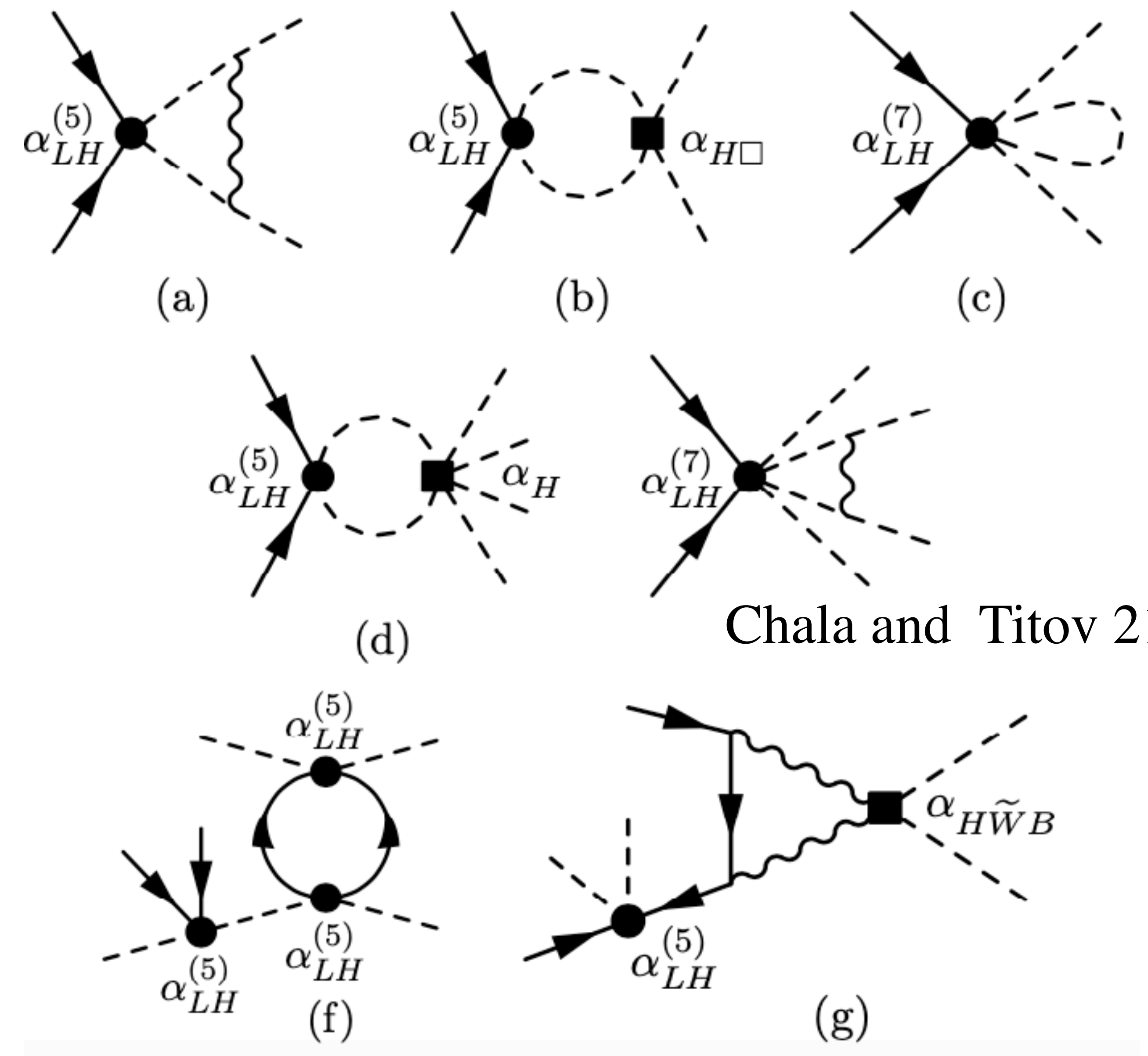
Majorana neutrino mass the tree-level:

The unique operator of dim 2n+5, that can give neutrino masses at the tree level is

$$\mathcal{O}^{2n+5} = \mathcal{O}_{\text{weinberg}} \times \frac{(H^\dagger H)^n}{\Lambda^{2n}}$$

Neutrino mass from loop corrections:

- *Dimension-5: Weinberg operator for neutrino-masses (S. Weinberg 1979)*
- *Dimension-6: W. Buchmuller and D. Wyler, 1986; B. Grzadkowski et al, 2010; ……*
- *Dimension-7: L. Lehman, 2014; Y. Liao and X.D. Ma, 2016; ……*
  Dimension-8: C.W. Murphy, 2020; H.L. Li et al., 2020; … …
- *Dimension-9: Y. Liao and X.D. Ma, 2020; H.L. Li et al, 2020, 2021; … …*



Chala and Titov 2104.08248

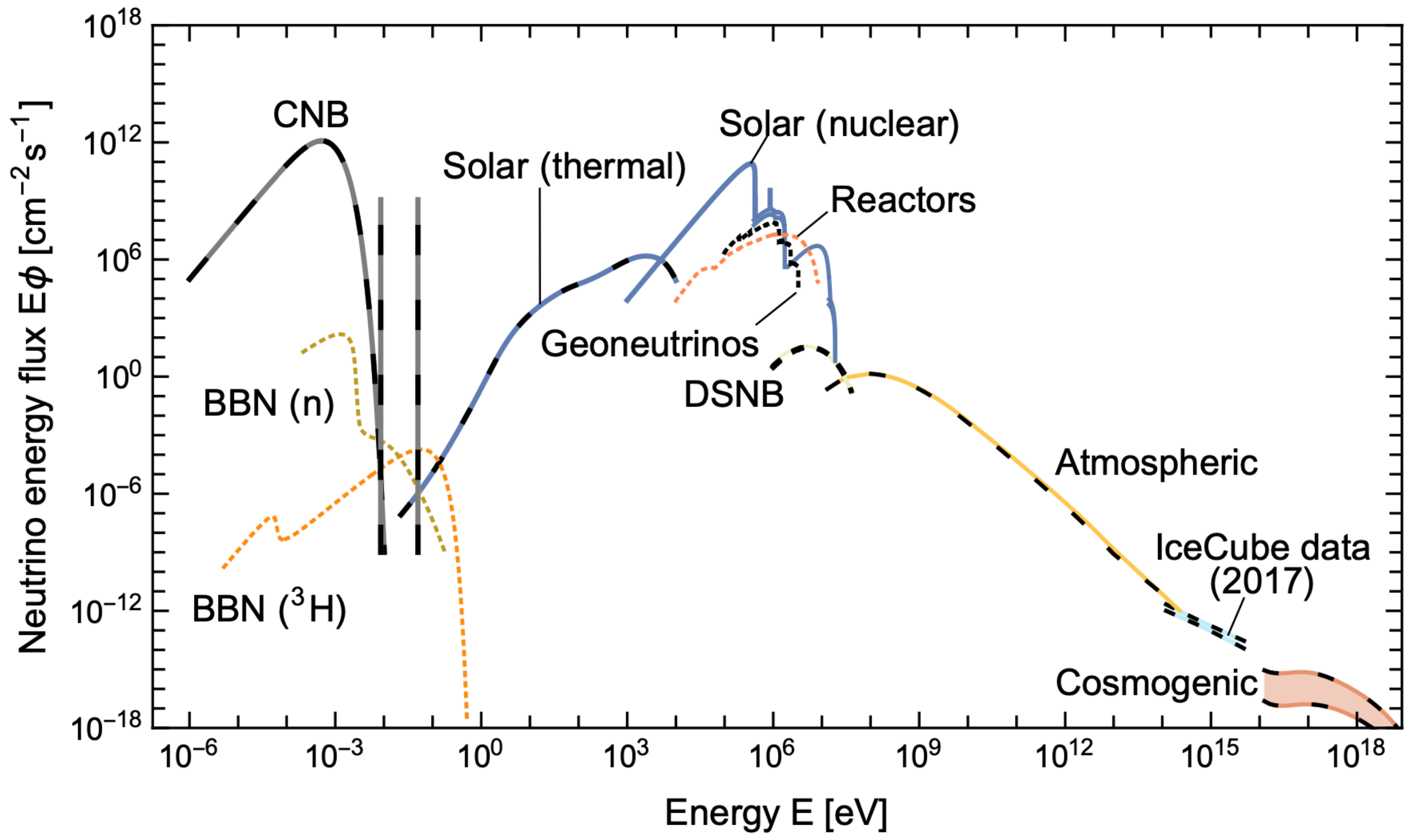
$\mathcal{O}_{2B}$	$-\frac{1}{2}(\partial_\mu B^{\mu\nu})(\partial^\rho B_{\rho\nu})$
$\mathcal{O}_{2W}$	$-\frac{1}{2}(D_\mu W^{I\mu\nu})(D^\rho W^I_{\rho\nu})$
$\mathcal{O}_{BDH}$	$\partial_\nu B^{\mu\nu}(H^\dagger i\overleftrightarrow{D}_\mu H)$
$\mathcal{O}_{WDH}$	$D_\nu W^{I\mu\nu}(H^\dagger i\overleftrightarrow{D}^I_\mu H)$
$\mathcal{O}_{DH}$	$(D_\mu D^\mu H)^\dagger (D_\nu D^\nu H)$
$\mathcal{O}'_{HD}$	$(H^\dagger H)(D_\mu H)^\dagger (D^\mu H)$
$\mathcal{O}''_{HD}$	$(H^\dagger H) D_\mu (H^\dagger i\overleftrightarrow{D}^\mu H)$
$\mathcal{O}_{LD}$	$\frac{i}{2}\overline{L}\{D_\mu D^\mu, \not{D}\} L$
$\mathcal{O}'^{(1)}_{HL}$	$(H^\dagger H)(\overline{L} i\overleftrightarrow{\not{D}} L)$
$\mathcal{O}''^{(1)}_{HL}$	$\partial_\mu (H^\dagger H)(\overline{L}\gamma^\mu L)$
$\mathcal{O}'^{(3)}_{HL}$	$(H^\dagger \sigma^I H)(\overline{L} i\overleftrightarrow{\not{D}}^I L)$
$\mathcal{O}''^{(3)}_{HL}$	$D_\mu (H^\dagger \sigma^I H)(\overline{L}\gamma^\mu \sigma^I L)$
$\mathcal{O}^{(R)}_{LHD}$	$\epsilon_{ij}\epsilon_{mn} L^i C L^m H^j \square H^n$

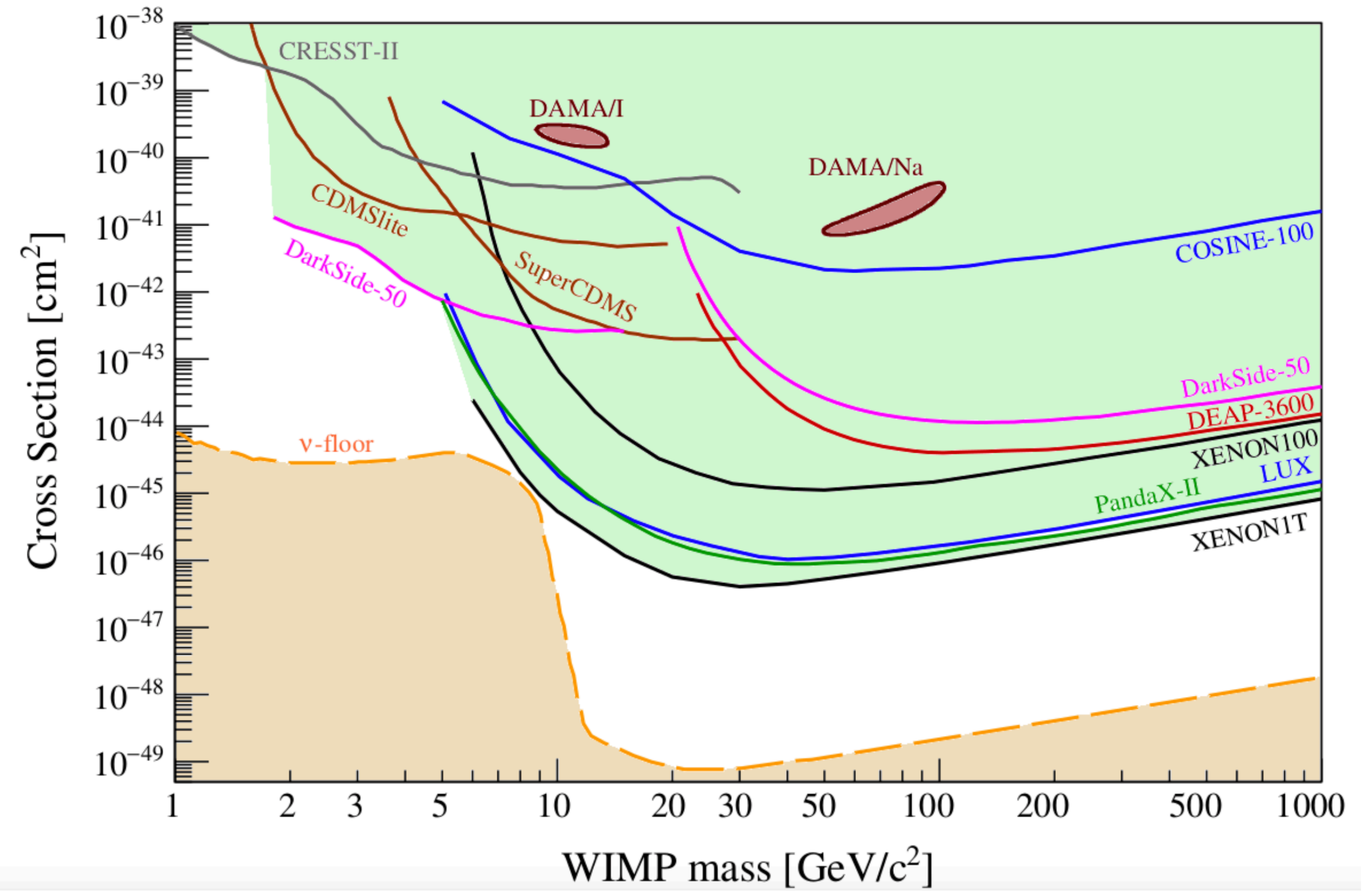
Is neutrino correlated with DM?

Yes!

- Properties of neutrinos are similar to these of dark matter
- Neutrino is a **hot** dark matter candidate
- Sterile neutrino is typical **warm/cold** dark matter candidate
- The signal of neutrino in direct detection experiments is similar to that of DM

Question:
Are new physics relevant to neutrinos and dark matter related with each other?
Hope so!





Generating DM & neutrino mass via seesaw

Type-II seesaw + spontaneous breaking U(1)_L

$$V(S,\Phi,\Delta) = V(\Phi,\Delta) - \mu_S^2 (S^\dagger S) + \lambda_6 (S^\dagger S)^2$$
$$+\lambda_7 (S^\dagger S)(\Phi^\dagger \Phi) + \lambda_8 (S^\dagger S)\mathrm{Tr}(\Delta^\dagger \Delta) + \mu \Phi^T i\tau_2 \Delta^\dagger \Phi + \lambda S \Phi^T i\tau_2 \Delta^\dagger \Phi + \mathrm{h.c.},$$

$$\Phi = \begin{pmatrix} \phi^+ \\ \frac{v_\phi + \phi + i\chi}{\sqrt{2}} \end{pmatrix} \qquad \Delta = \begin{pmatrix} \frac{\Delta^+}{\sqrt{2}} & \Delta^{++} \\ \frac{v_\Delta + \delta + i\xi}{\sqrt{2}} & \frac{\Delta^+}{\sqrt{2}} \end{pmatrix} \qquad S = \frac{v_s + \tilde{s} + i\tilde{a}}{\sqrt{2}}$$

$\tilde{a}$: **Majoron**

Majoron massive! **Majoron massless!**

Neutrino massive

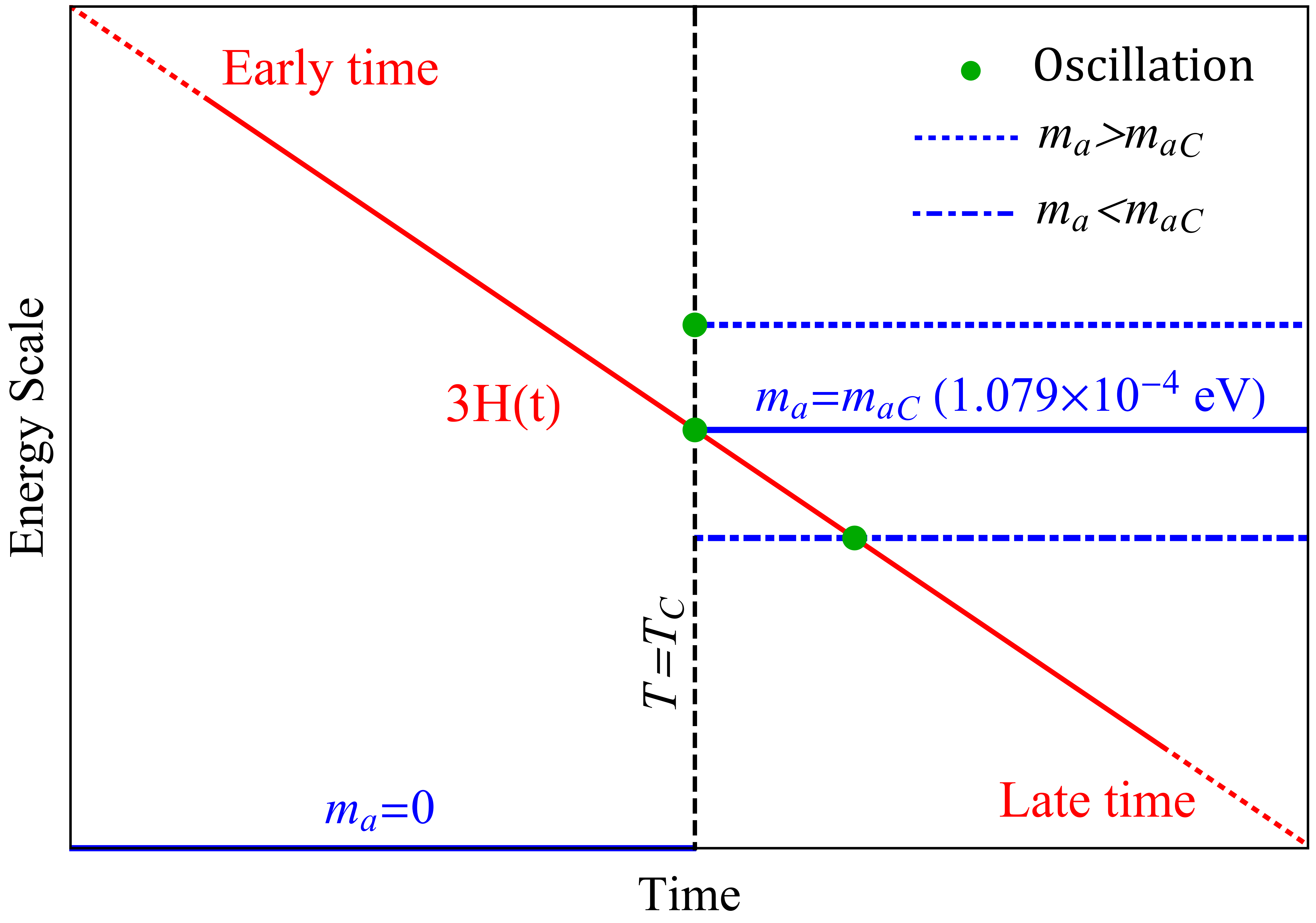
EWSB scale **fa** $\cancel{U}(1)_L$ **T**

Majoron dark matter

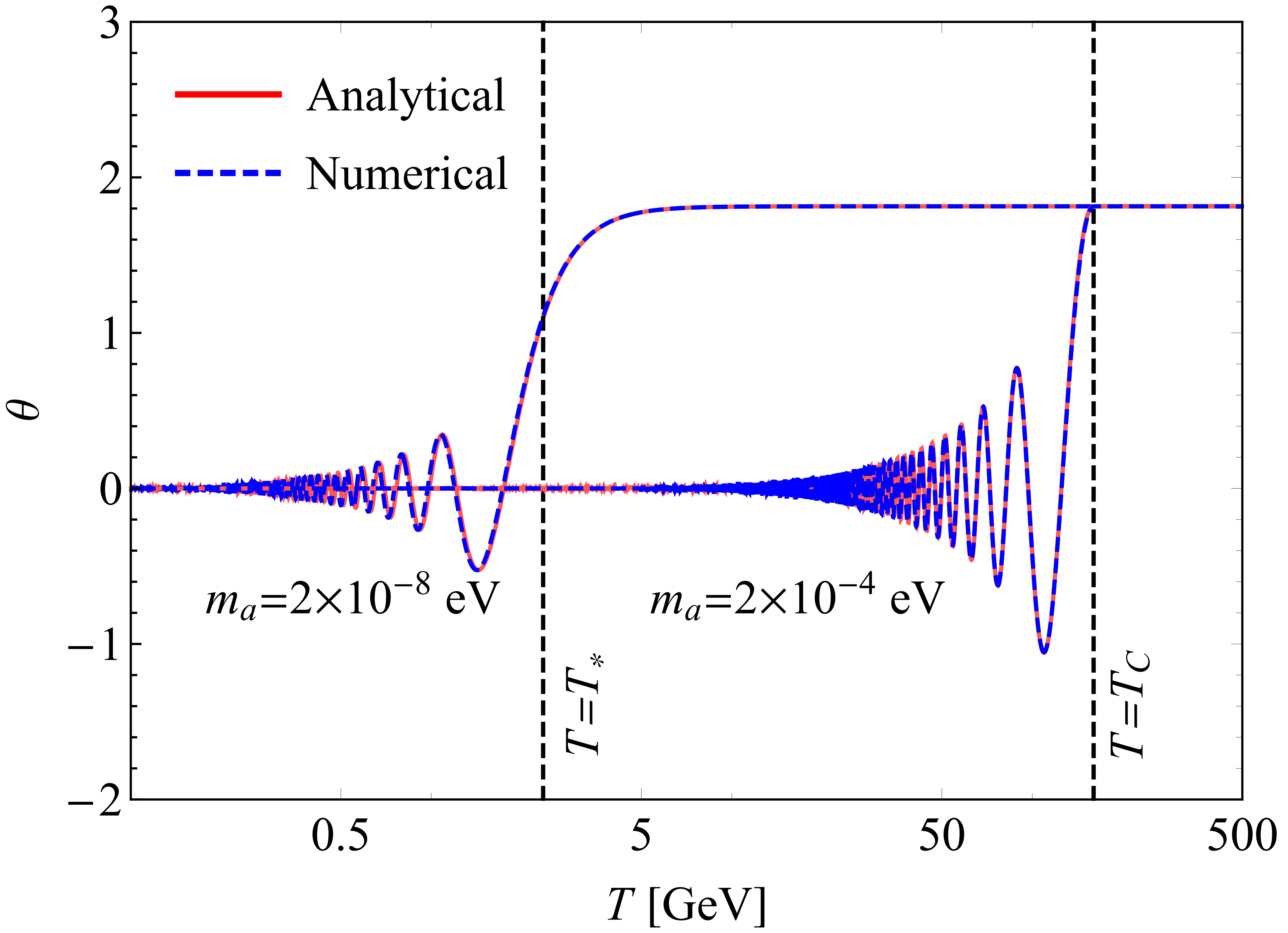
$$m_a^2(T) = \begin{cases} \dfrac{\mu v_\phi^2(T) v_\Delta(T)}{\sqrt{2} f_a^2}, & T \le T_\mathrm{C} \\ 0\,, & T > T_\mathrm{C} \end{cases}$$

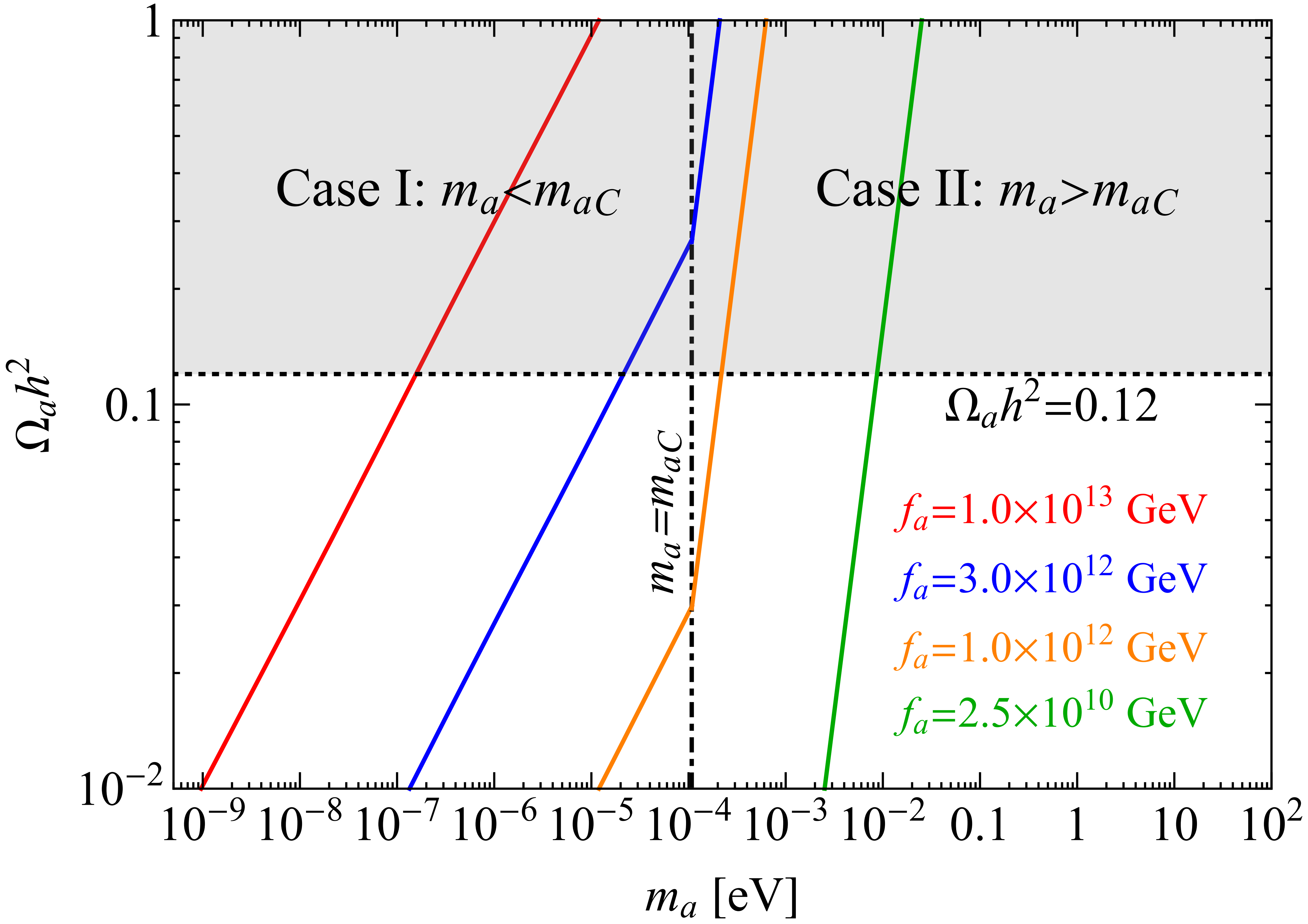
$$T_\mathrm{osc} = \begin{cases} T_*\,, & m_a < m_{a\mathrm{C}} \\ T_\mathrm{C}\,, & m_a \ge m_{a\mathrm{C}} \end{cases}$$

$$m_{a\mathrm{C}} = 1.079 \times 10^{-4}\,\mathrm{eV}$$



Majoron dark matter





Majoron interactions

Vertices	Coefficients
a^4	$\frac{1}{4}\lambda_1 V_{13}^4 + \frac{1}{4}\lambda_4 V_{13}^2 V_{23}^2 + \frac{1}{4}\lambda_5 V_{13}^2 V_{23}^2 + \frac{1}{2}\lambda V_{13}^2 V_{23} V_{33} + \frac{1}{4}\lambda_2 V_{23}^4 + \frac{1}{4}\lambda_3 V_{23}^4 + \frac{1}{4}\lambda_6 V_{33}^4$
a^3G	$\lambda_1 V_{11} V_{13}^3 + \frac{1}{2}\lambda_4 V_{11} V_{13} V_{23}^2 + \frac{1}{2}\lambda_5 V_{11} V_{13} V_{23}^2 + \lambda V_{11} V_{13} V_{23} V_{33} + \frac{1}{2}\lambda_4 V_{13}^2 V_{21} V_{23}$ $+\frac{1}{2}\lambda_5 V_{13}^2 V_{21} V_{23} + \frac{1}{2}\lambda V_{13}^2 V_{21} V_{33} + \frac{1}{2}\lambda V_{13}^2 V_{23} V_{31} + \lambda_2 V_{21} V_{23}^3 + \lambda_3 V_{21} V_{23}^3 + \lambda_6 V_{31} V_{33}^3$
a^2h^2	$\frac{1}{2}\lambda_1 U_{11}^2 V_{13}^2 + \frac{1}{4}\lambda_4 U_{11}^2 V_{23}^2 + \frac{1}{4}\lambda_5 U_{11}^2 V_{23}^2 - \frac{1}{2}\lambda U_{11}^2 V_{23} V_{33} + \lambda U_{11} U_{21} V_{13} V_{33}$ $-\lambda U_{11} U_{31} V_{13} V_{23} + \frac{1}{4}\lambda_4 U_{21}^2 V_{13}^2 + \frac{1}{4}\lambda_5 U_{21}^2 V_{13}^2 + \frac{1}{2}\lambda_2 U_{21}^2 V_{23}^2 + \frac{1}{2}\lambda_3 U_{21}^2 V_{23}^2 + \frac{1}{2}\lambda U_{21} U_{31} V_{13}^2 + \frac{1}{2}\lambda_6 U_{31}^2 V_{33}^2$
a^2h	$\lambda_1 U_{11} v_\phi V_{13}^2 + \frac{1}{2}\lambda_4 U_{11} v_\phi V_{23}^2 + \frac{1}{2}\lambda_5 U_{11} v_\phi V_{23}^2 - \lambda U_{11} v_\phi V_{23} V_{33} - \sqrt{2}\mu U_{11} V_{13} V_{23}$ $-\lambda U_{11} V_{13} V_{23} v_s + \lambda U_{11} V_{13} V_{33} v_\Delta + \lambda U_{21} v_\phi V_{13} V_{33} + \frac{1}{\sqrt{2}}\mu U_{21} V_{13}^2 + \frac{1}{2}\lambda_4 U_{21} V_{13}^2 v_\Delta + \frac{1}{2}\lambda_5 U_{21} V_{13}^2 v_\Delta$ $+\frac{1}{2}\lambda U_{21} V_{13}^2 v_s + \lambda_2 U_{21} V_{23}^2 v_\Delta + \lambda_3 U_{21} V_{23}^2 v_\Delta - \lambda U_{31} v_\phi V_{13} V_{23} + \frac{1}{2}\lambda U_{31} V_{13}^2 v_\Delta + \lambda_6 U_{31} V_{33}^2 v_s$
a^2G^2	$\frac{3}{2}\lambda_1 V_{11}^2 V_{13}^2 + \frac{1}{4}\lambda_4 V_{11}^2 V_{23}^2 + \frac{1}{4}\lambda_5 V_{11}^2 V_{23}^2 + \frac{1}{2}\lambda V_{11}^2 V_{23} V_{33} + \lambda_4 V_{11} V_{13} V_{21} V_{23} + \lambda_5 V_{11} V_{13} V_{21} V_{23}$ $+\lambda V_{11} V_{13} V_{21} V_{33} + \lambda V_{11} V_{13} V_{23} V_{31} + \frac{1}{4}\lambda_4 V_{13}^2 V_{21}^2 + \frac{1}{4}\lambda_5 V_{13}^2 V_{21}^2 + \frac{1}{2}\lambda V_{13}^2 V_{21} V_{31} + \frac{3}{2}\lambda_2 V_{21}^2 V_{23}^2 + \frac{3}{2}\lambda_3 V_{21}^2 V_{23}^2 + \frac{3}{2}\lambda_6 V_{31}^2 V_{33}^2$
$a^2G^+G^-$	$\lambda_1 V_{13}^2 \cos^2\beta + \frac{1}{2}\lambda_4 V_{13}^2 \sin^2\beta + \frac{1}{4}\lambda_5 V_{13}^2 \sin^2\beta + \frac{1}{\sqrt{2}}\lambda_5 V_{13} V_{23} \sin\beta\cos\beta$ $+\sqrt{2}\lambda V_{13} V_{33} \sin\beta\cos\beta + \lambda_2 V_{23}^2 \sin^2\beta + \frac{1}{2}\lambda_3 V_{23}^2 \sin^2\beta + \frac{1}{2}\lambda_4 V_{23}^2 \cos^2\beta$
aG^3	$\lambda_1 V_{11}^3 V_{13} + \frac{1}{2}\lambda_4 V_{11}^2 V_{21} V_{23} + \frac{1}{2}\lambda_5 V_{11}^2 V_{21} V_{23} + \frac{1}{2}\lambda V_{11}^2 V_{21} V_{33} + \frac{1}{2}\lambda V_{11}^2 V_{23} V_{31}$ $+\frac{1}{2}\lambda_4 V_{11} V_{13} V_{21}^2 + \frac{1}{2}\lambda_5 V_{11} V_{13} V_{21}^2 + \lambda V_{11} V_{13} V_{21} V_{31} + \lambda_2 V_{21}^3 V_{23} + \lambda_3 V_{21}^3 V_{23} + \lambda_6 V_{31}^3 V_{33}$
ah^2G	$\lambda_1 U_{11}^2 V_{11} V_{13} + \frac{1}{2}\lambda_4 U_{11}^2 V_{21} V_{23} + \frac{1}{2}\lambda_5 U_{11}^2 V_{21} V_{23} - \frac{1}{2}\lambda U_{11}^2 V_{21} V_{33} - \frac{1}{2}\lambda U_{11}^2 V_{23} V_{31}$ $+\lambda U_{11} U_{21} V_{11} V_{33} + \lambda U_{11} U_{21} V_{13} V_{31} - \lambda U_{11} U_{31} V_{11} V_{23} - \lambda U_{11} U_{31} V_{13} V_{21} + \frac{1}{2}\lambda_4 U_{21}^2 V_{11} V_{13}$ $+\frac{1}{2}\lambda_5 U_{21}^2 V_{11} V_{13} + \lambda_2 U_{21}^2 V_{21} V_{23} + \lambda_3 U_{21}^2 V_{21} V_{23} + \lambda U_{21} U_{31} V_{11} V_{13} + \lambda_6 U_{31}^2 V_{31} V_{33}$
$a\bar{\nu}\nu$	$V_{23} m_\nu / v_\Delta$

TWO IMPORTANT INTERACTIONS

$$\lambda_{haa} haa$$

$$\overline{\nu_L^C} i a \lambda_{a\bar{\nu}\nu} \nu_L + \mathrm{h.c.}$$

$$\lambda_{haa} : -\lambda U_{11} V_{13} V_{23} f_a + \frac{1}{2}\lambda U_{21} V_{13}^2 f_a$$

$$\lambda_{a\bar{\nu}\nu} : V_{23} m_\nu / v_\Delta ,$$

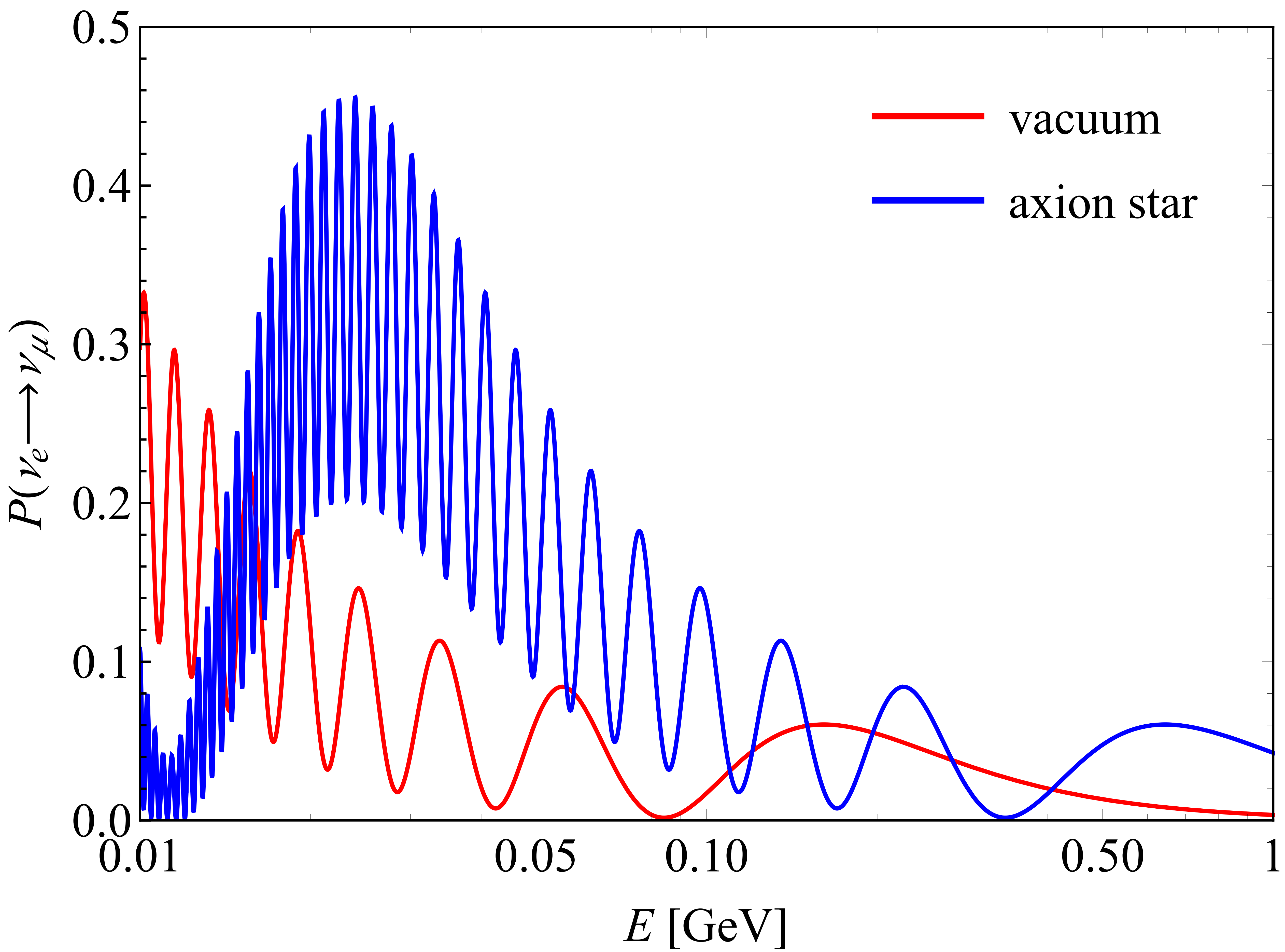
Neutrino oscillation in Majoron star

Effective potential

$$V_{\text{eff}} = i\sqrt{2\rho_a} V_{23} m_a^{-1} v_\Delta^{-1} \cos(m_a t) \overline{\nu_L^C} m_\nu \nu_L + \text{h.c.}$$

Amplitude:

$$A_{\alpha\to\beta} = \sum_i \widehat{U}_{\beta i} \widehat{U}^*_{\alpha i} \exp\left[-i\frac{m_i^2 x}{2E}\left(1+\frac{\rho_a V_{23}^2}{m_a^2 v_\Delta^2}+\frac{\rho_a V_{23}^2 \cos 2m_a x}{2x m_a^3 v_\Delta^2}\right)\right]$$



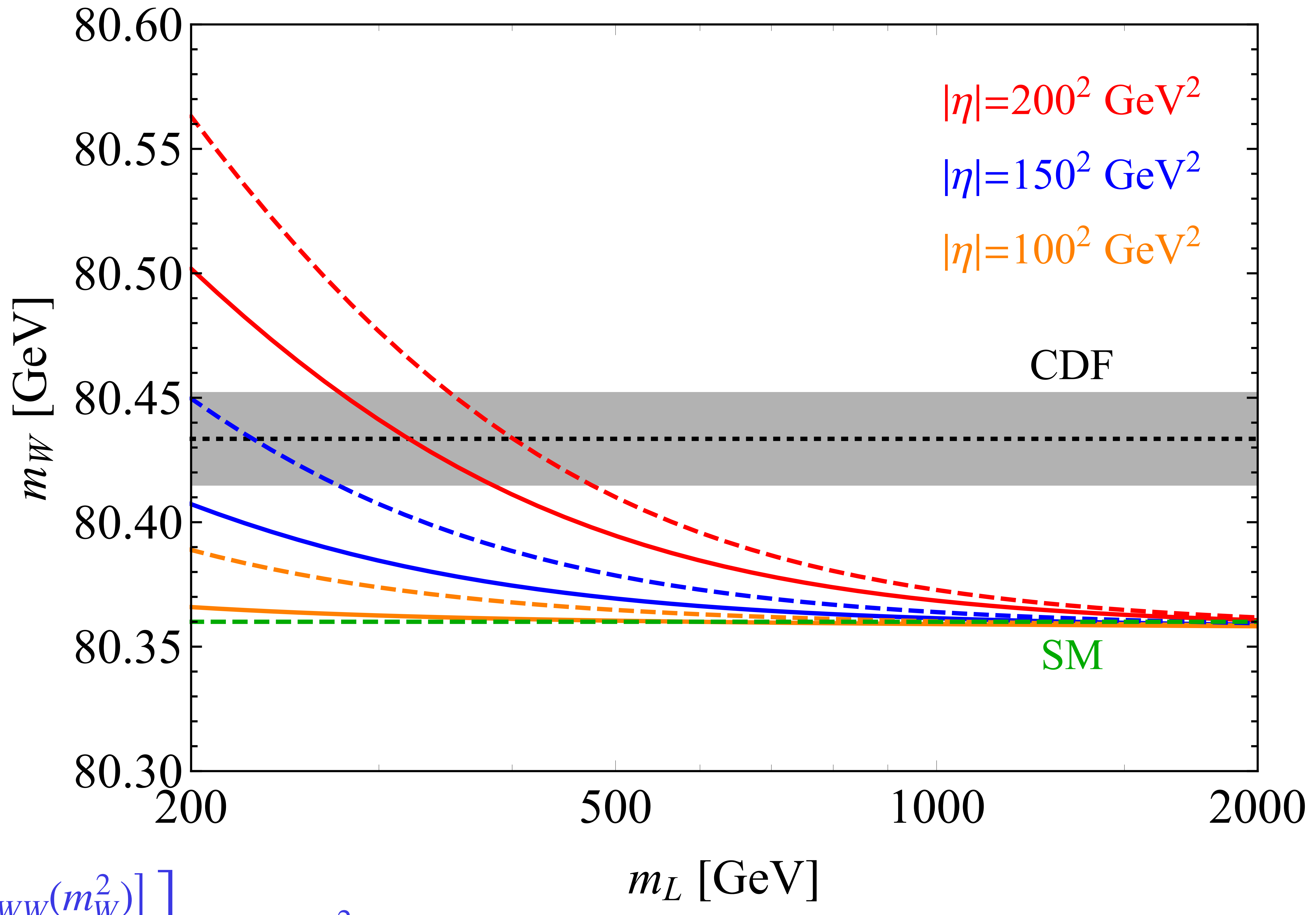
W-boson mass anomaly

$$m_W^2 = \frac{m_Z^2}{2}\left[1+\sqrt{1-\frac{4\pi\alpha_{\rm em}}{\sqrt{2}G_F m_Z^2}(1+\Delta r)}\,\right],$$

$$\Delta r = \Delta\alpha_{\rm em} - c_W^2/s_W^2\Delta\rho_{\rm loop} + \Delta r_{\rm rem}$$

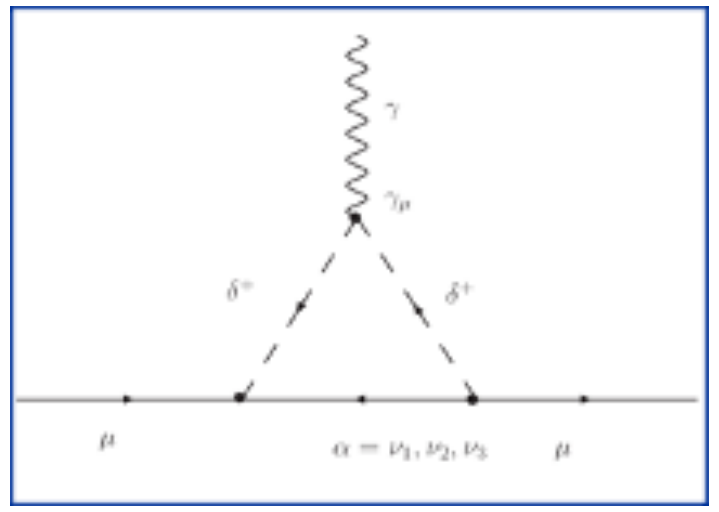
$$\Delta\alpha_{\rm em} = \Pi'_{\gamma\gamma}(0) - \Pi'_{\gamma\gamma}(m_Z^2)\,,$$

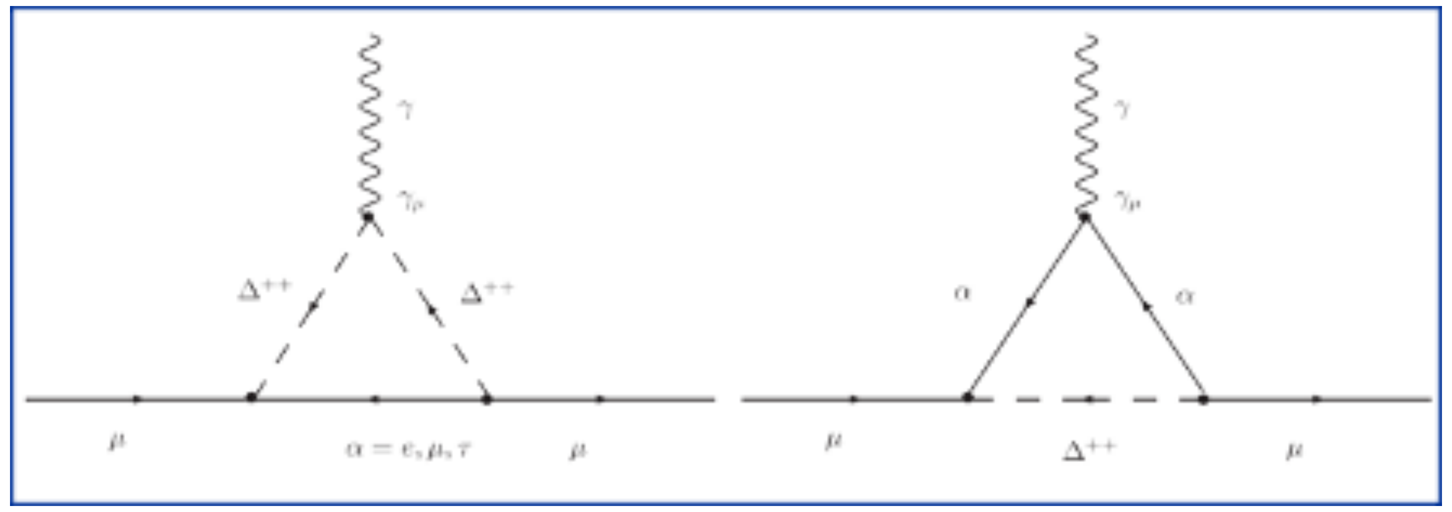
$$\Delta\rho_{\rm loop} = \frac{\Pi_{ZZ}(0)}{m_Z^2} - \frac{\Pi_{WW}(0)}{m_W^2} + \frac{2s_W}{c_W}\frac{\Pi_{Z\gamma}(0)}{m_Z^2}\,,$$



$$\Delta r_{\rm rem} = \frac{c_W^2}{s_W^2}\left[\frac{\Pi_{ZZ}(0)}{m_Z^2} - \frac{{\rm Re}\left[\Pi_{ZZ}(m_Z^2)\right]}{m_Z^2}\right] + \left(1-\frac{c_W^2}{s_W^2}\right)\left[\frac{\Pi_{WW}(0)}{m_W^2} - \frac{{\rm Re}\left[\Pi_{WW}(m_W^2)\right]}{m_W^2}\right] + \Pi'_{\gamma\gamma}(m_Z^2) + \delta_{\rm VB}\,.$$

Summary





Type-II seesaw

Neutrino mass

Axion-like DM

W-Mass

g-2

Thank you!