第十七届TeV工作组学术会议（2023.12.15-19，南京）

Majorana Majoron and the BAU

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Based on arXiv: 231106469, with Ying-quan Peng

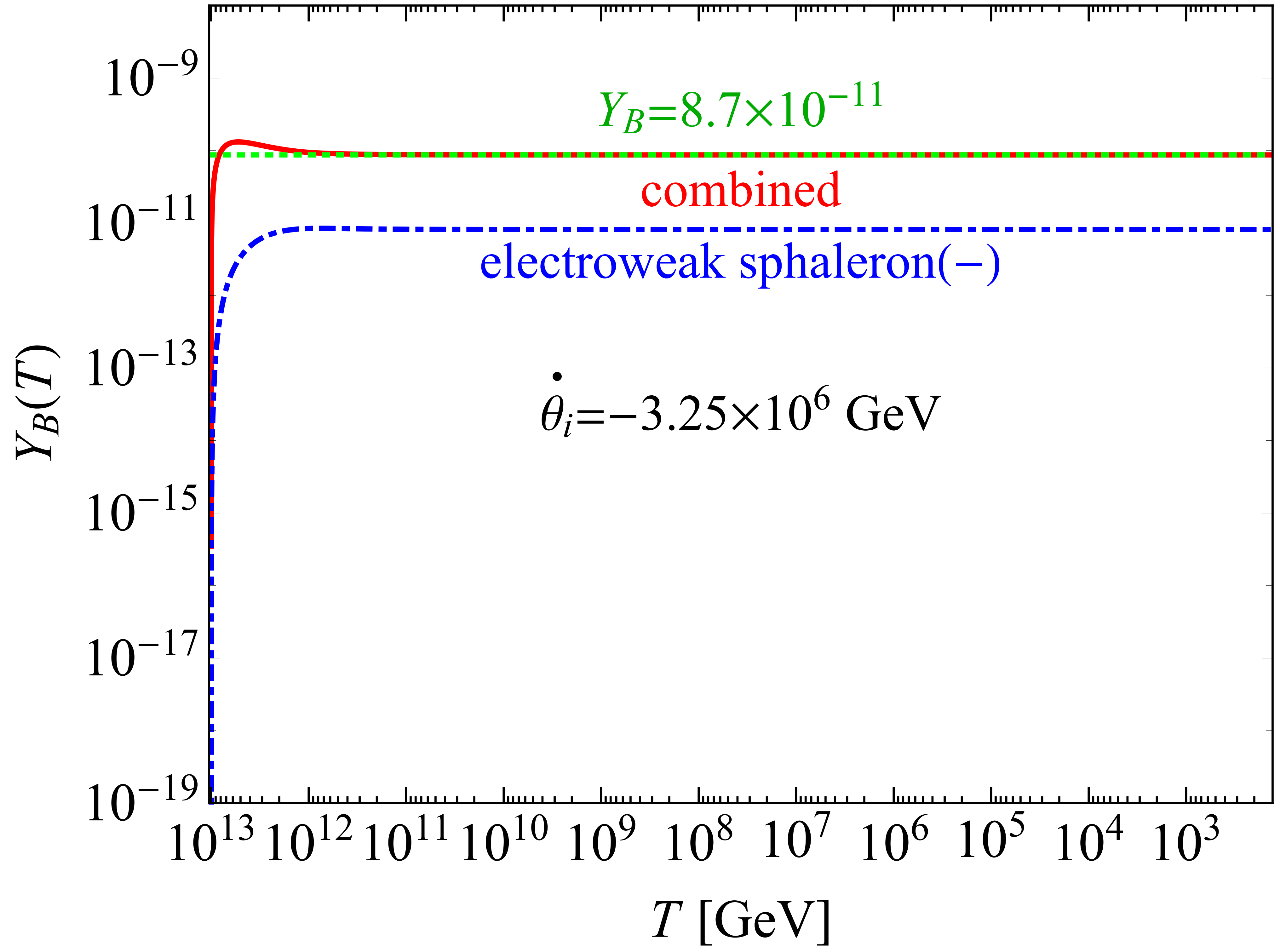
Preview

I: The origin of the ALP mass

There is no well-known mechanism for the mass generation of ALP, except the QCD axion.

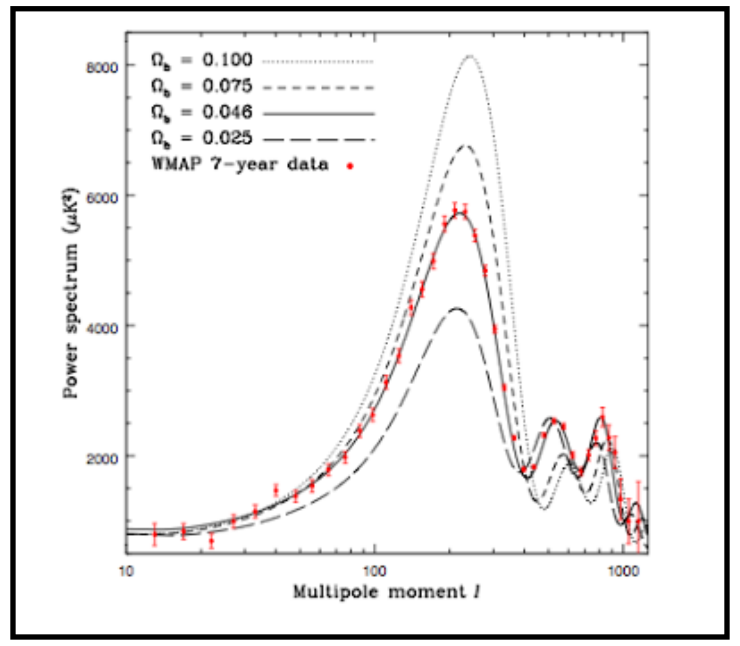
We present a mechanism for the mass generation of Majoron via the type-I and the type-II seesaw mechanism.

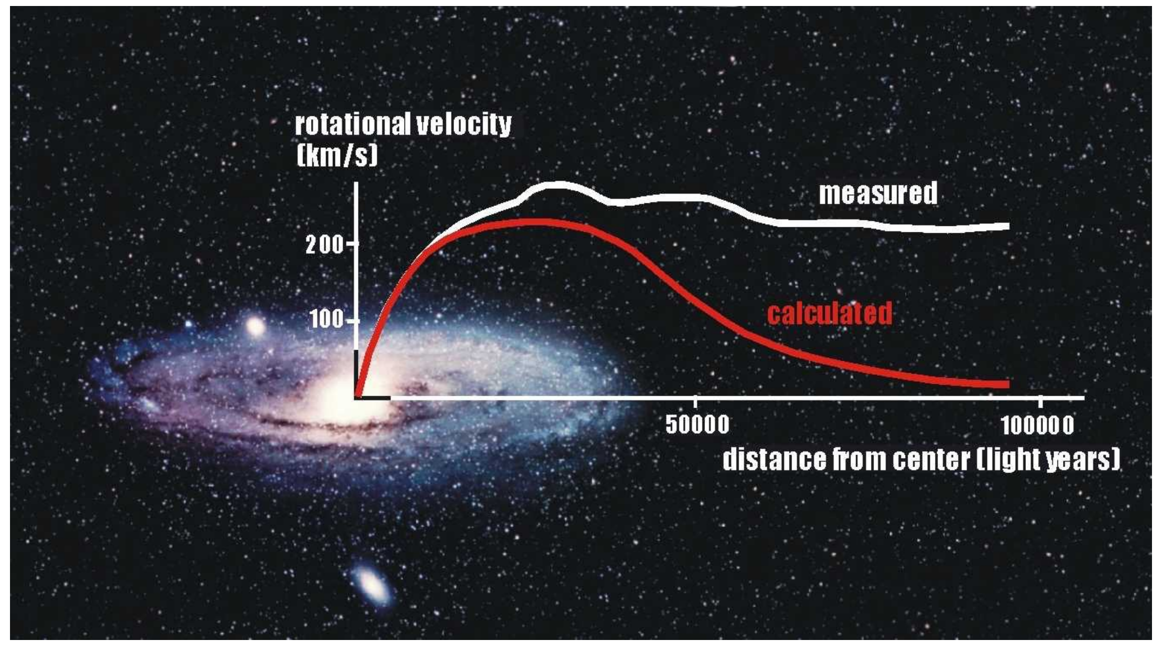
II: The Baryon Asymmetry of the Universe

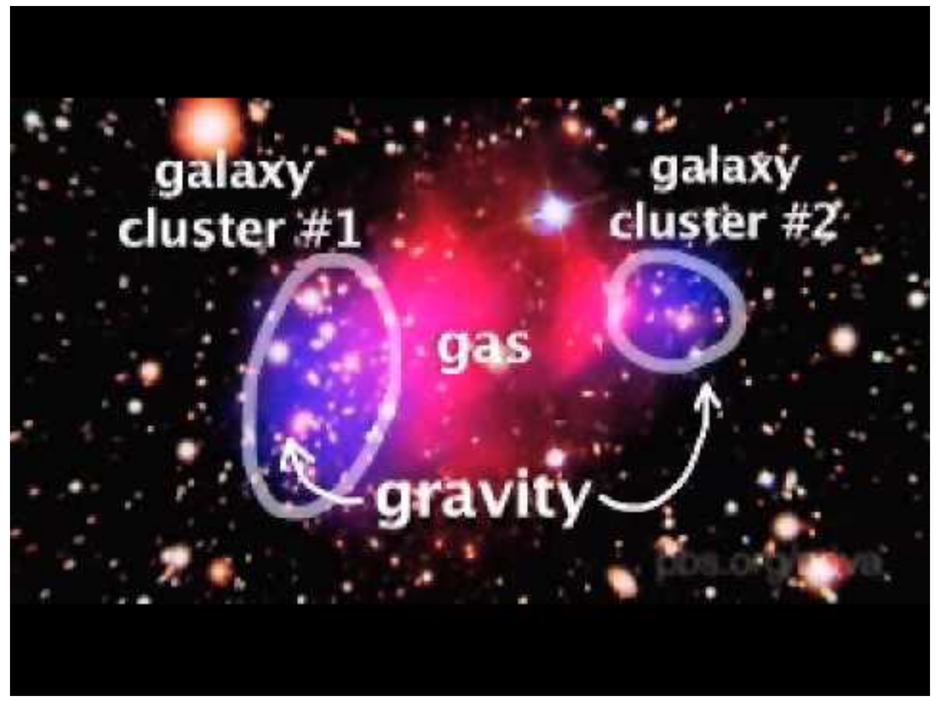


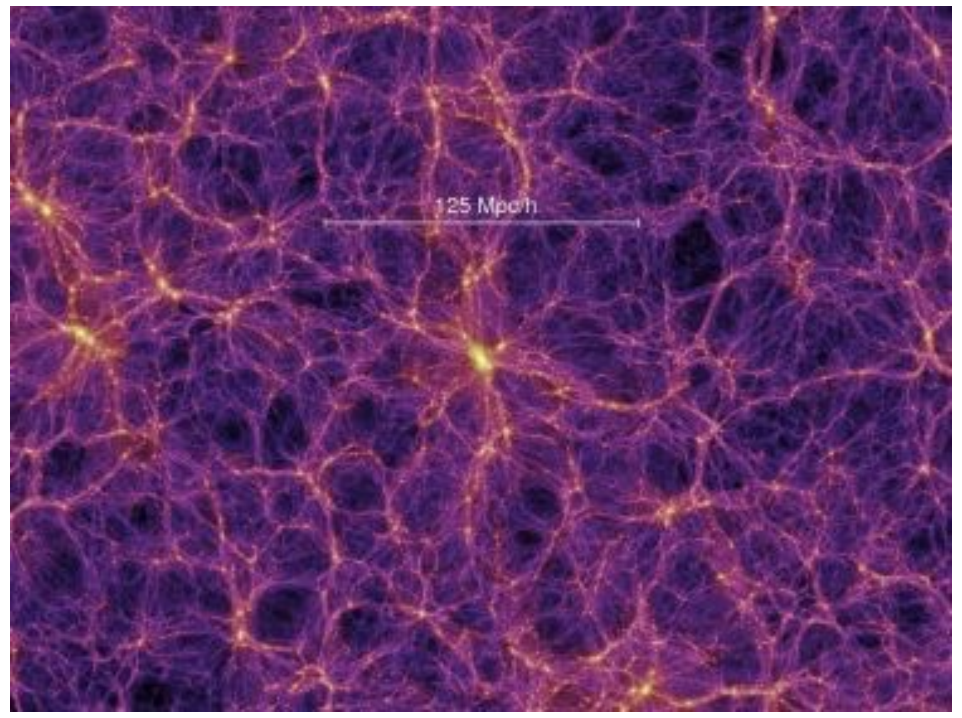
New physics beyond the SM-dark matter

Evidence of dark matter





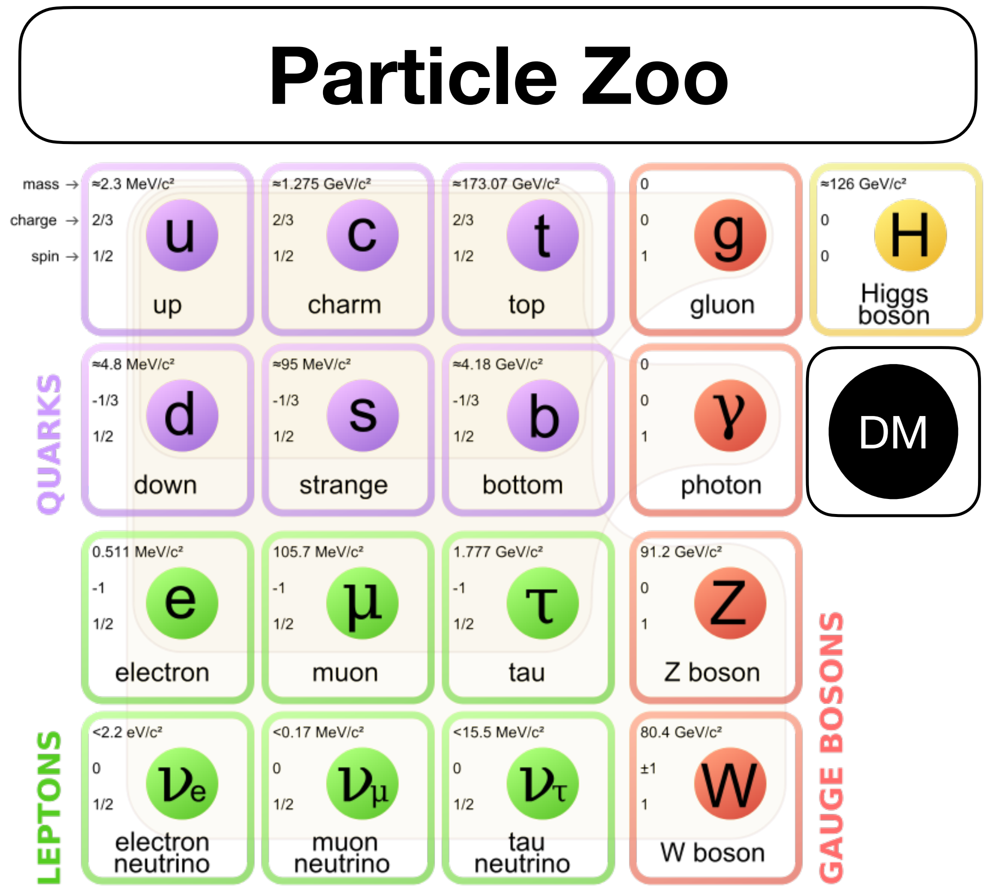


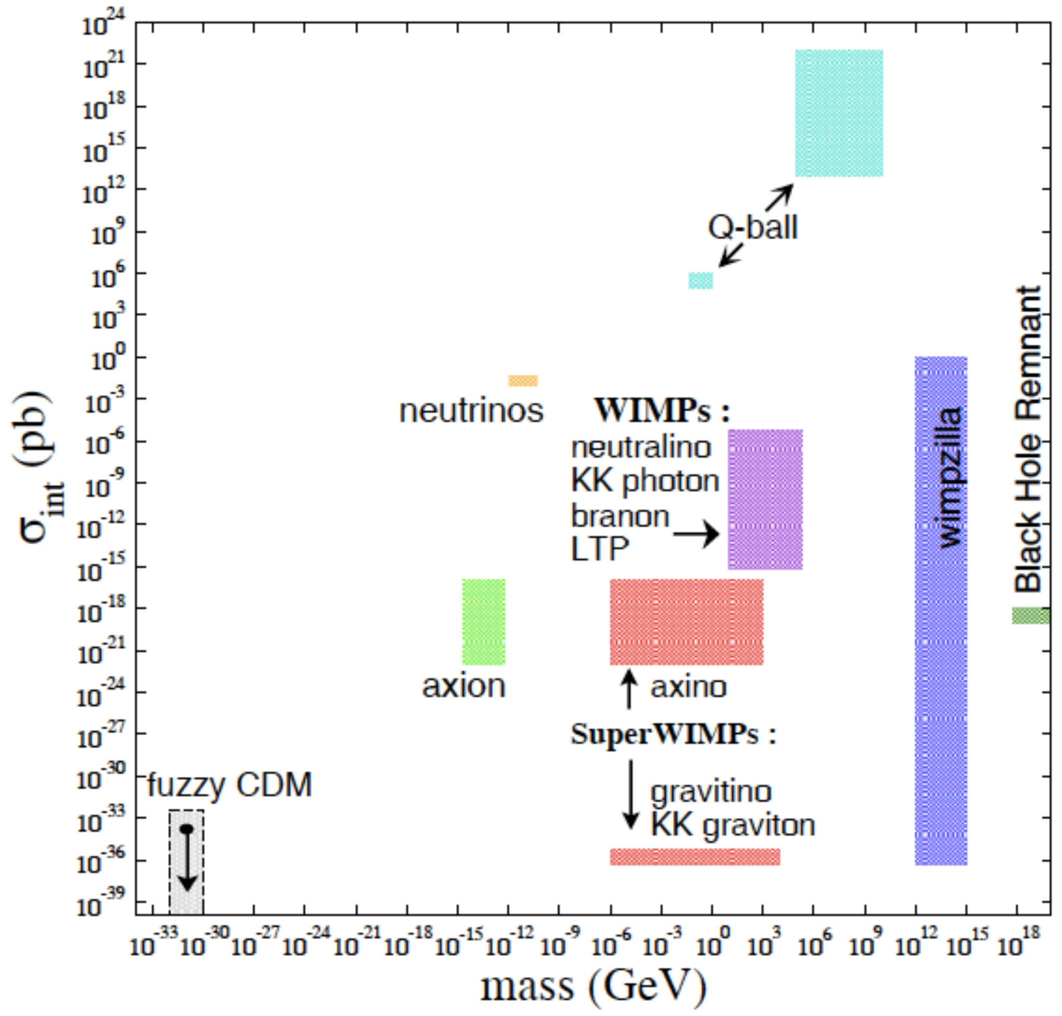


What is dark matter?

Mass ✗ Spin ✗ Interactions ✗

Neutral, non-baryonic, weakly interacting particle!

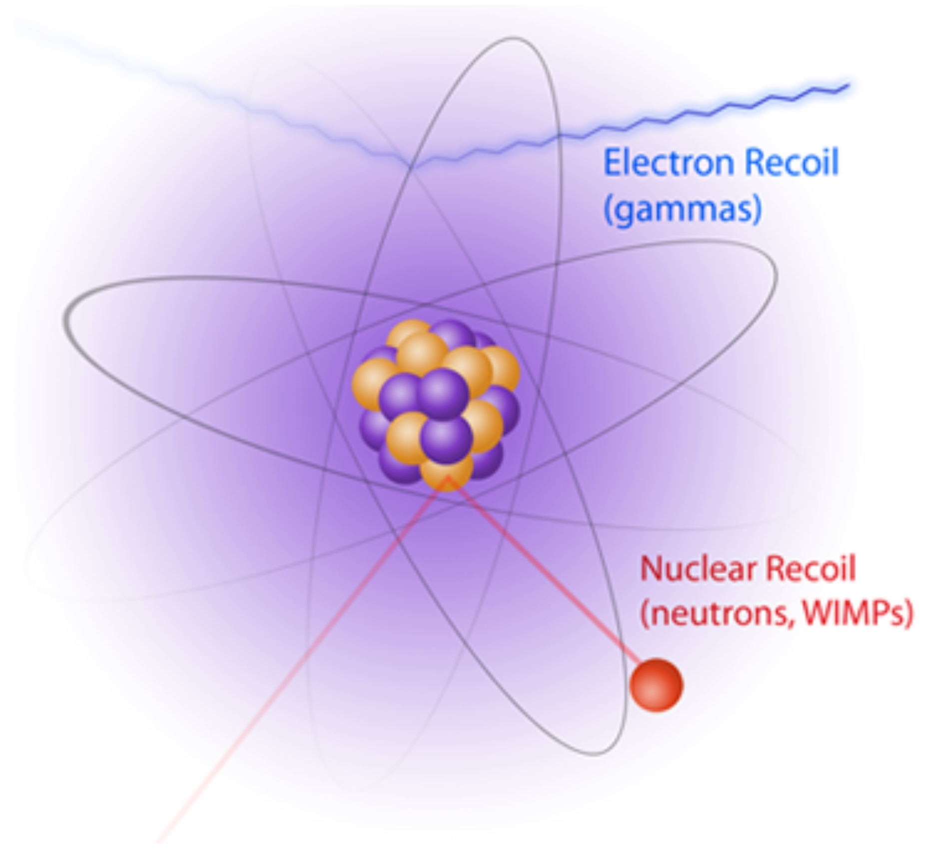


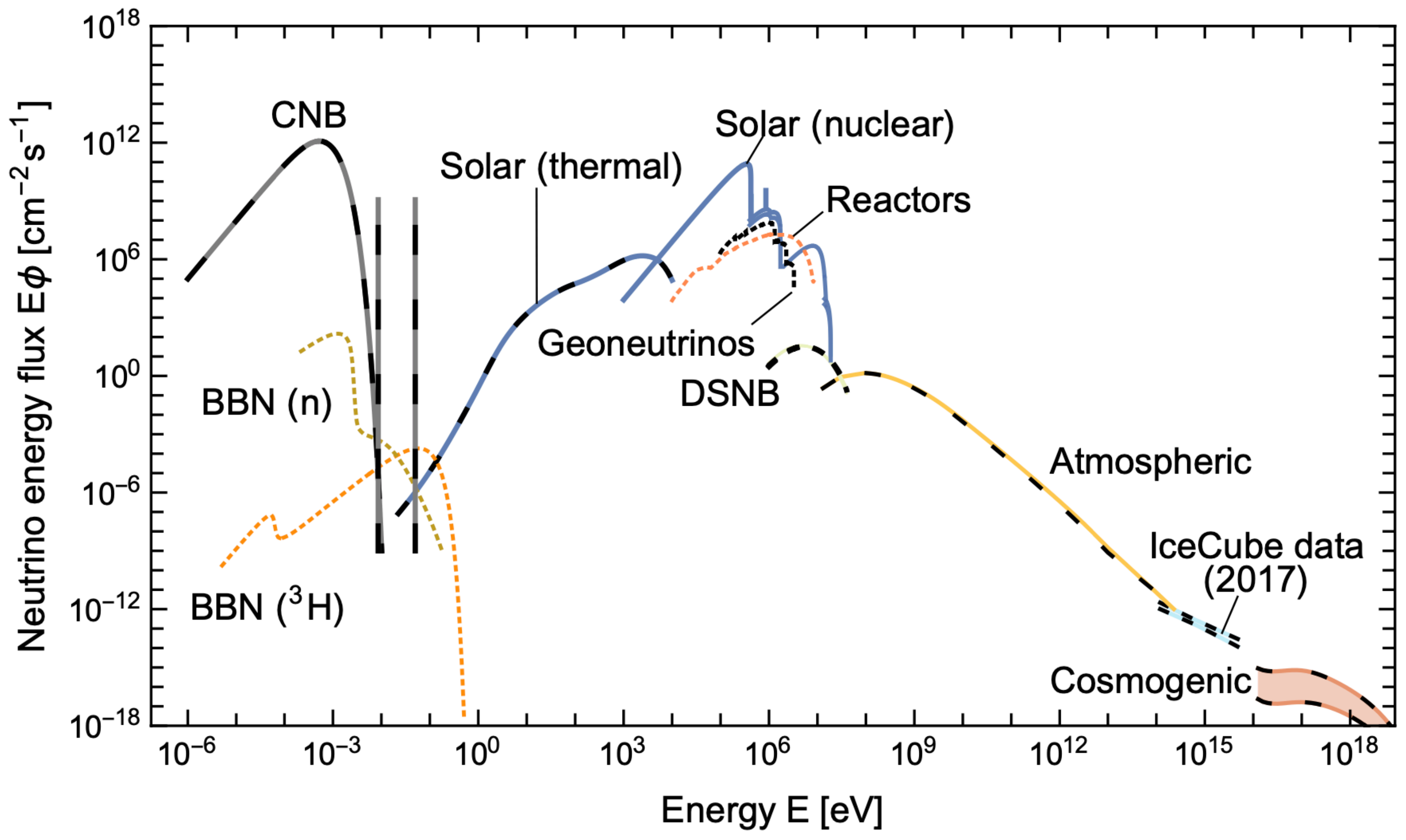


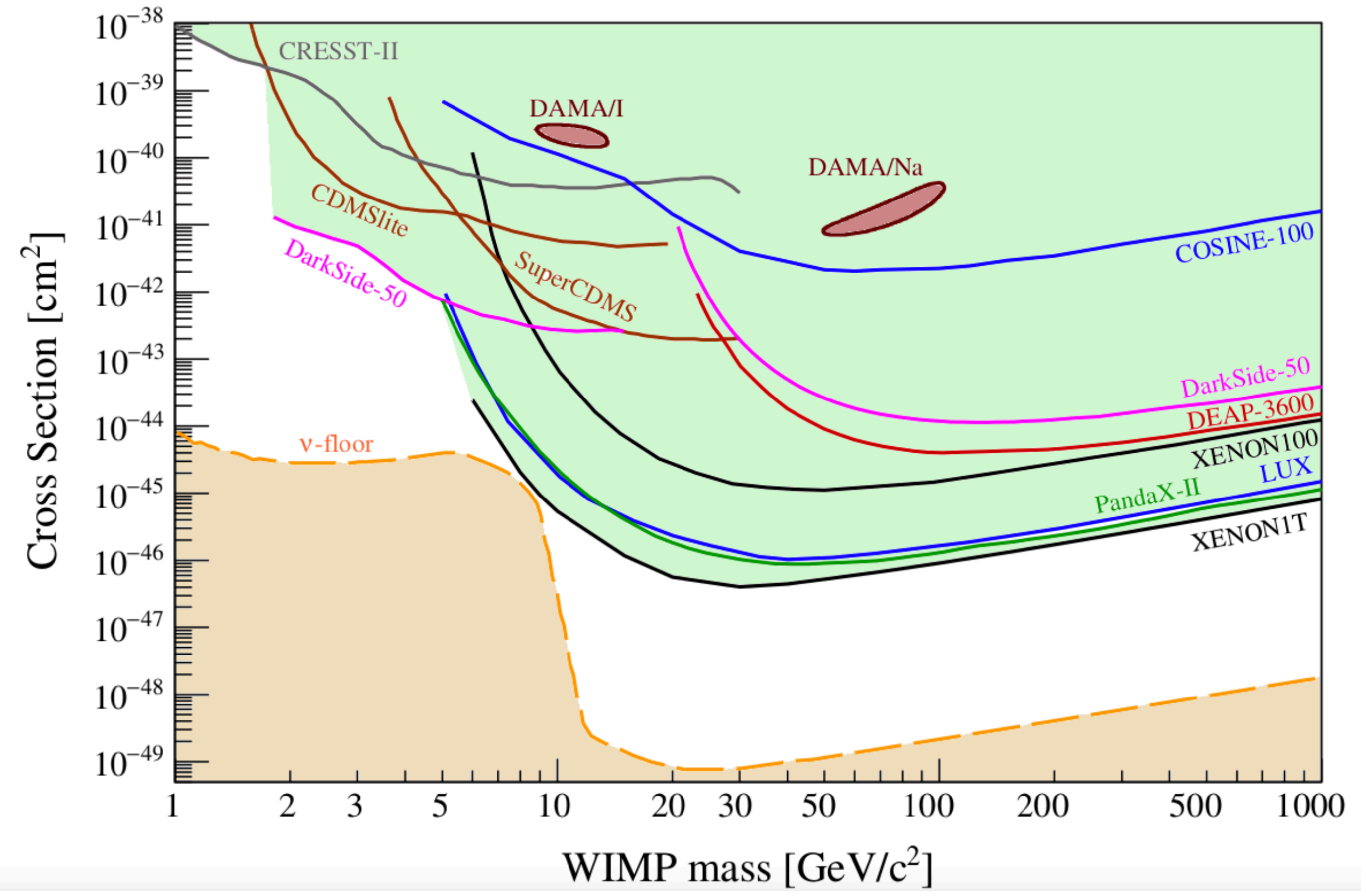
What we convern: construct a DM theory

Where we start from? ν physics

- 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

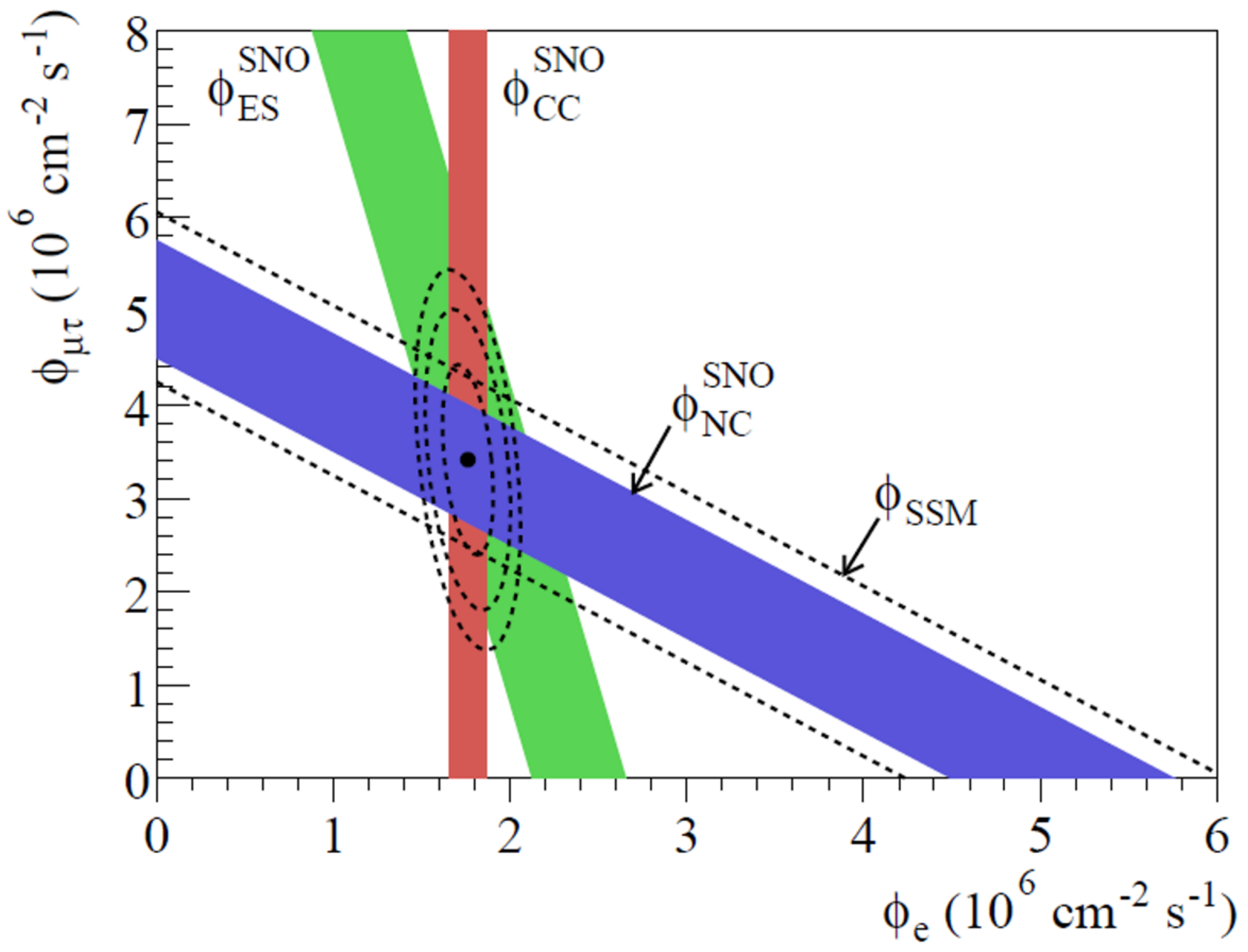






New physics beyond the SM-neutrino physics

Evidence of of neutrino oscillations

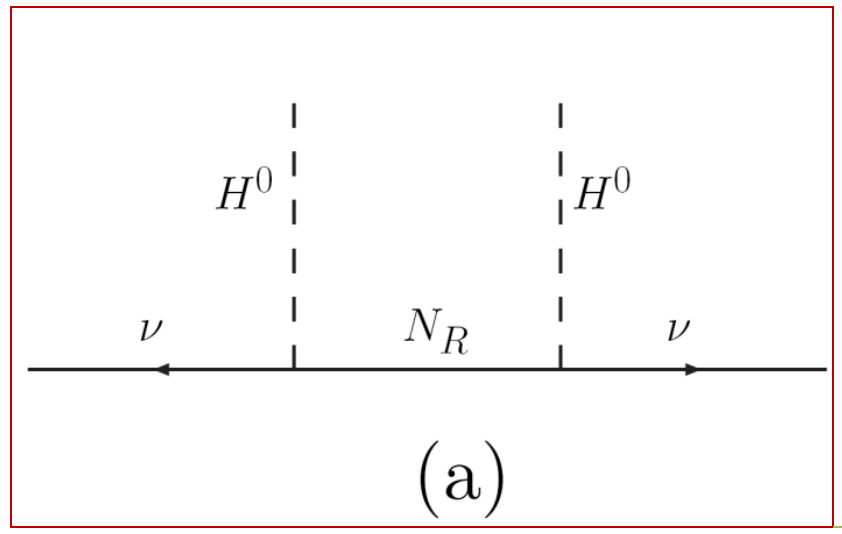


Key issues for neutrino physics

- The origin of tiny but non-zero neutrino masses
- Neutrino mass hierarchy
- CP-violating phase in lepton mixing matrix
- Is neutrino Majorana or Dirac particle?
- ……

Neutrino mass generations

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

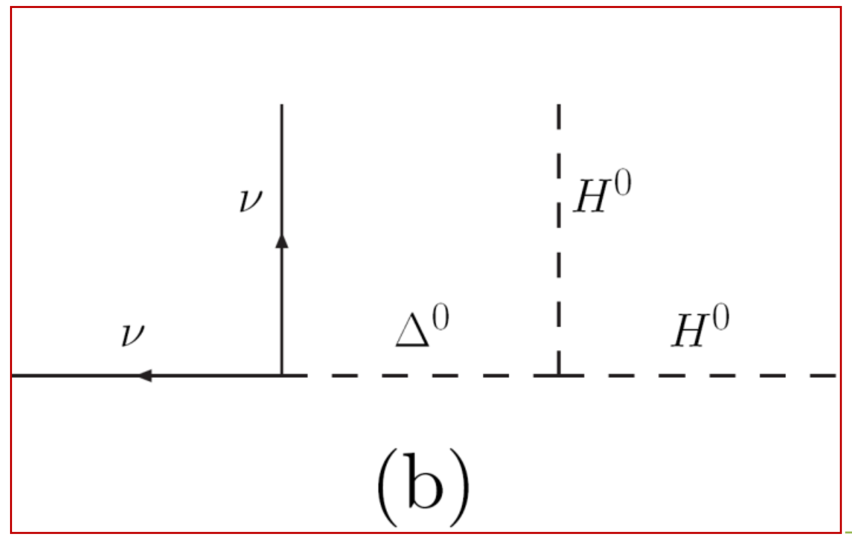


$$-\mathcal{L} = \overline{\ell_L}Y_\nu N_R\tilde{H} + \frac{1}{2}\overline{N_R^C}M_R N_R + \text{h.c.}$$

SU(2)_L fermion singlet

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

Minkowski（77）

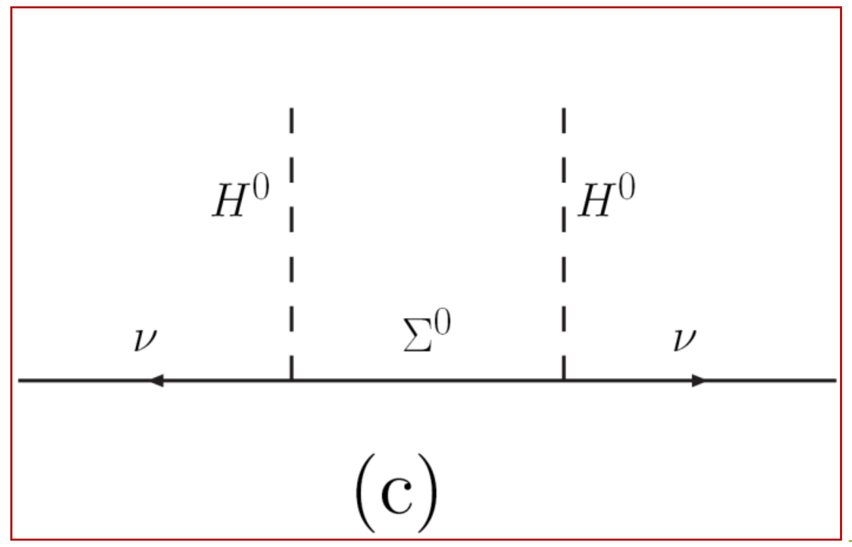


$$-\mathcal{L} = \frac{1}{2}\overline{\ell_L}Y_\Delta\Delta\varepsilon\ell_L^C - \lambda_\Delta M_\Delta H^T\varepsilon\Delta H + \text{h.c.}$$

SU(2)_L scalar triplet

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

Magg, Wetterich（80）

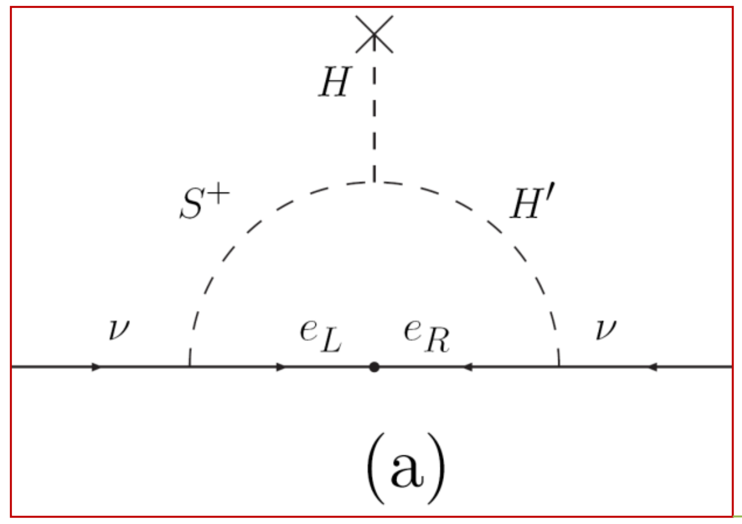


$$-\mathcal{L} = \frac{1}{2}\text{Tr}\left[\Sigma M_\Sigma\Sigma^C\right] + \sqrt{2}\overline{\ell_L}Y_\Sigma\Sigma\tilde{H} + \text{h.c.}$$

SU(2)_L fermion triplet

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

Foot, Lew, He, Joshi（89）

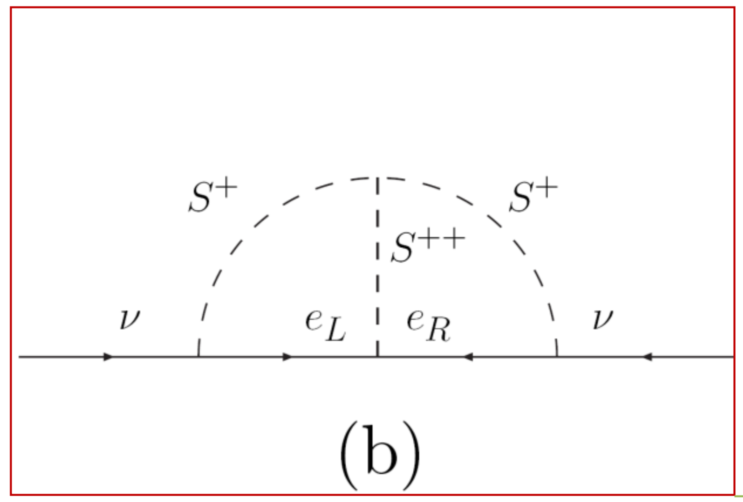


$$-\mathcal{L} = \ell_L^T Y_S\varepsilon\ell_L S^+ - \mu H^T\varepsilon H' S^- + \text{h.c.}$$

Zee（80）

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

Charged scalar singlet+ doublets

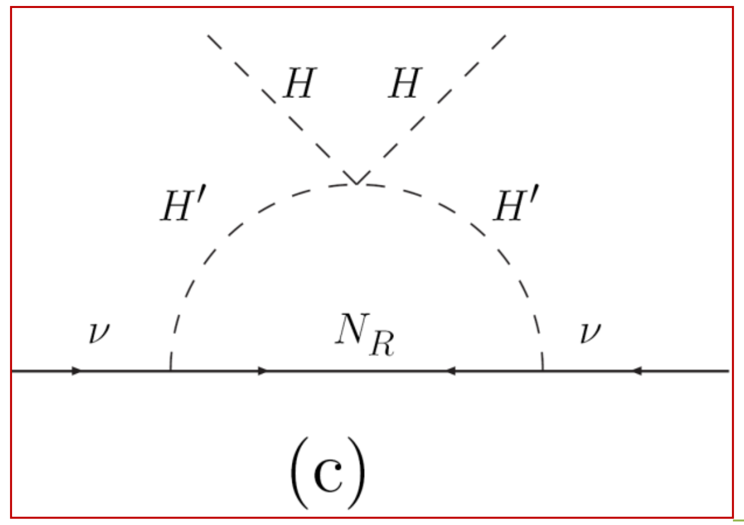


$$-\mathcal{L} = \ell_L^T Y_S\varepsilon\ell_L S^+ + e_R^T F_S e_R S^{++} + \mu S^- S^- S^{++} + \text{h.c.}$$

Babu（88）

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

Two charged scalar singlets



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

Ma（98）

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

Higgs doublets + Majorana neutrino+ Z2 symmetry

● ● ●

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

Neutrino mass generations

Neutrino mass from higher dimensional effective operators

Majorana neutrino mass the tree-level:

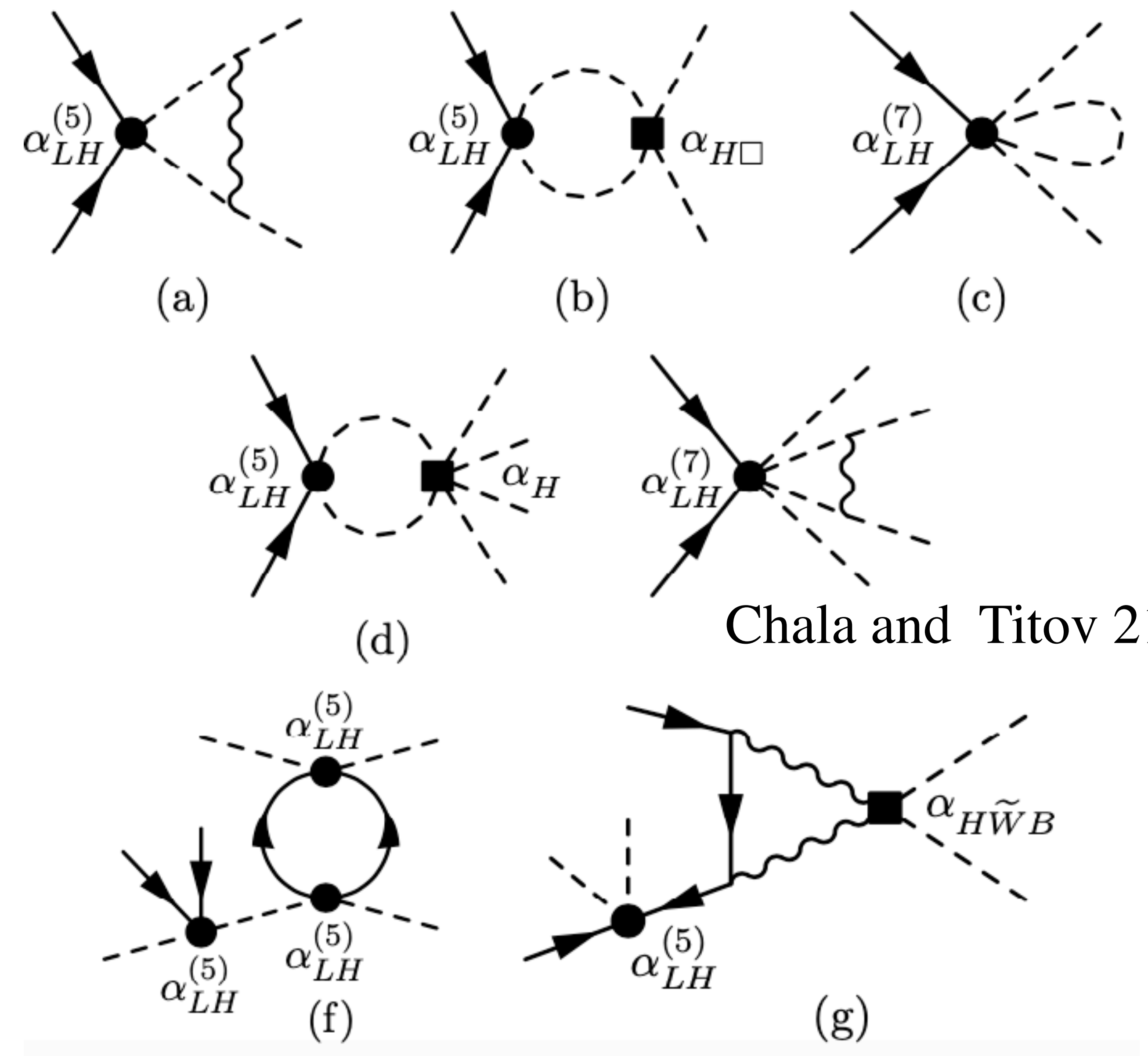
(F. Bonnet et al, 2009; Y. Liao, 2011)

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

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

Connections between ν physics and ALP?

Standard model: Lepton number is accidental global U(1) symmetry

Traditional seesaw mechanisms: $U(1)_L$ is explicitly broken at the tree-level

Is lepton number spontaneously broken, or explicitly broken, or both ?

Connections between neutrino mass and the ALP physics!

Majoron & neutrino mass via type-I seesaw

Type-I seesaw + spontaneous breaking $U(1)_L$ symmetry

$$\mathscr{L}_{\rm BSM} = \left(\partial_\mu \Phi\right)^\dagger (\partial^\mu \Phi) + \mu_\Phi^2 \Phi^\dagger \Phi - \lambda_1 (\Phi^\dagger \Phi)^2 - \lambda_2 (\Phi^\dagger \Phi)(H^\dagger H) - \left[Y_{\rm N} \overline{\ell_L} \tilde{H} N_R + \frac{1}{2} \overline{N_R^C} \left(Y_{\rm M} \Phi + m \right) N_R + {\rm h.c.} \right]$$

LNV term!

$$H = \begin{pmatrix} \phi^+ \\ \dfrac{v_\phi + \phi + i\chi}{\sqrt{2}} \end{pmatrix} \qquad \Phi = \frac{v_s + \tilde{s} + i\tilde{a}}{\sqrt{2}}$$

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

Yukawa Interaction $\quad -Y_{\rm N} \overline{\ell_L} \tilde{H} N_R \to M_D = Y_N v / \sqrt{2}$

Key term: $\quad m \overline{N_R^C} N_R + h.c.$

Quantum Gravity effect!

Majoron interactions and Majoron mass

Field-dependent phase transformation

$$\ell_L \to e^{-\frac{ia}{2f}}\ell_L \qquad S \to e^{+\frac{ia}{f}}S$$

$$E_R \to e^{-\frac{ia}{2f}}E_R \qquad H \to H$$

$$\mathscr{L} \to \mathscr{L} - \frac{a}{2f}\partial_\mu\left(\overline{\ell_L}\gamma^\mu\ell_L + \overline{E_R}\gamma^\mu E_R\right)$$

$$= \mathscr{L} - \frac{a}{2f}\partial_\mu J^L_\mu$$

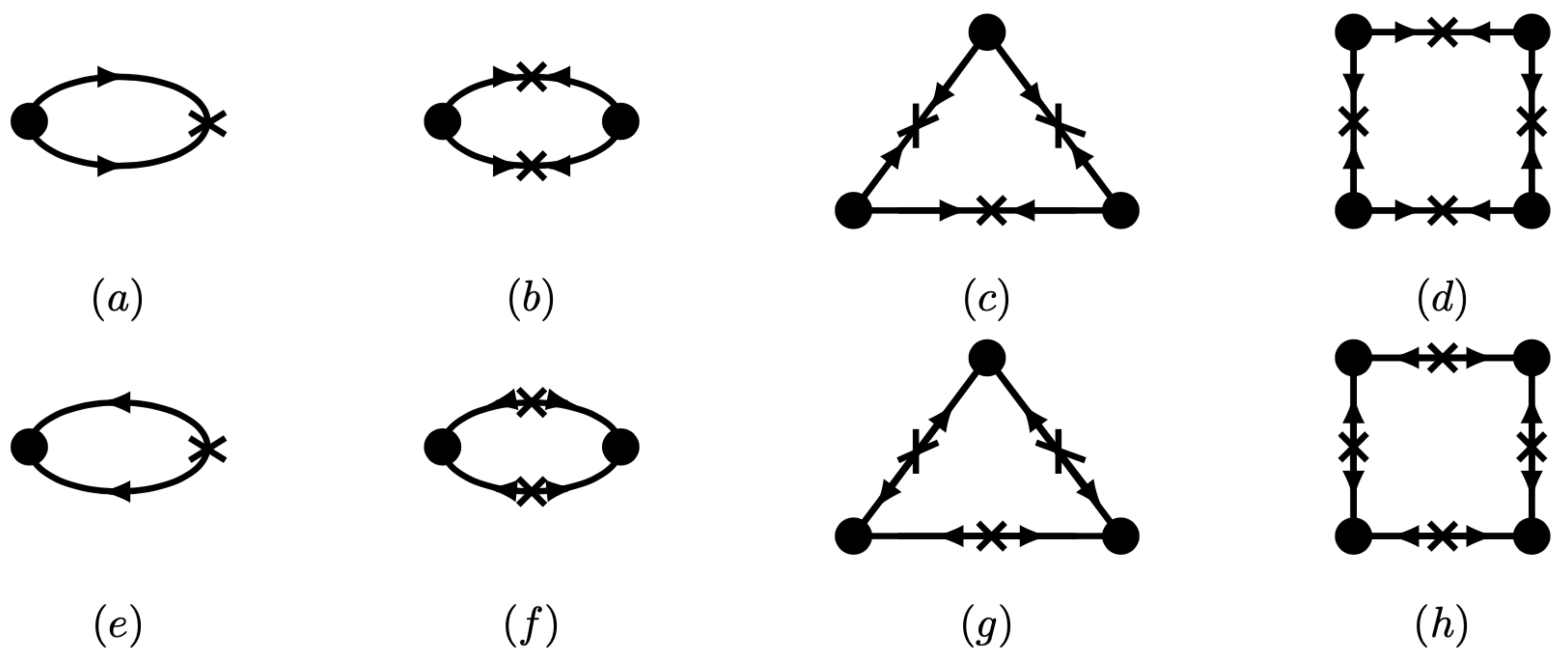
$$= \mathscr{L} + \frac{a}{2f}\frac{N_f}{32\pi^2}\left(g^2 W^a_{\mu\nu}\widetilde{W}^{\mu\nu,a} - g'^2 B_{\mu\nu}\widetilde{B}^{\mu\nu}\right)$$

$$N_R \to e^{-\frac{ia}{2f}}N_R \longrightarrow \frac{1}{2}e^{-i\theta}\overline{N^C_R}mN_R + h.c.$$

Majoron interactions and Majoron mass

$$\frac{1}{2}e^{-i\theta}\overline{N_R^C}mN_R + h.c. \longrightarrow$$

Mass insertion of right-handed neutrino masses:



Before symmetry breaking: $M = m$

After symmetry breaking: $M = f_a Y_M/\sqrt{2} + m$

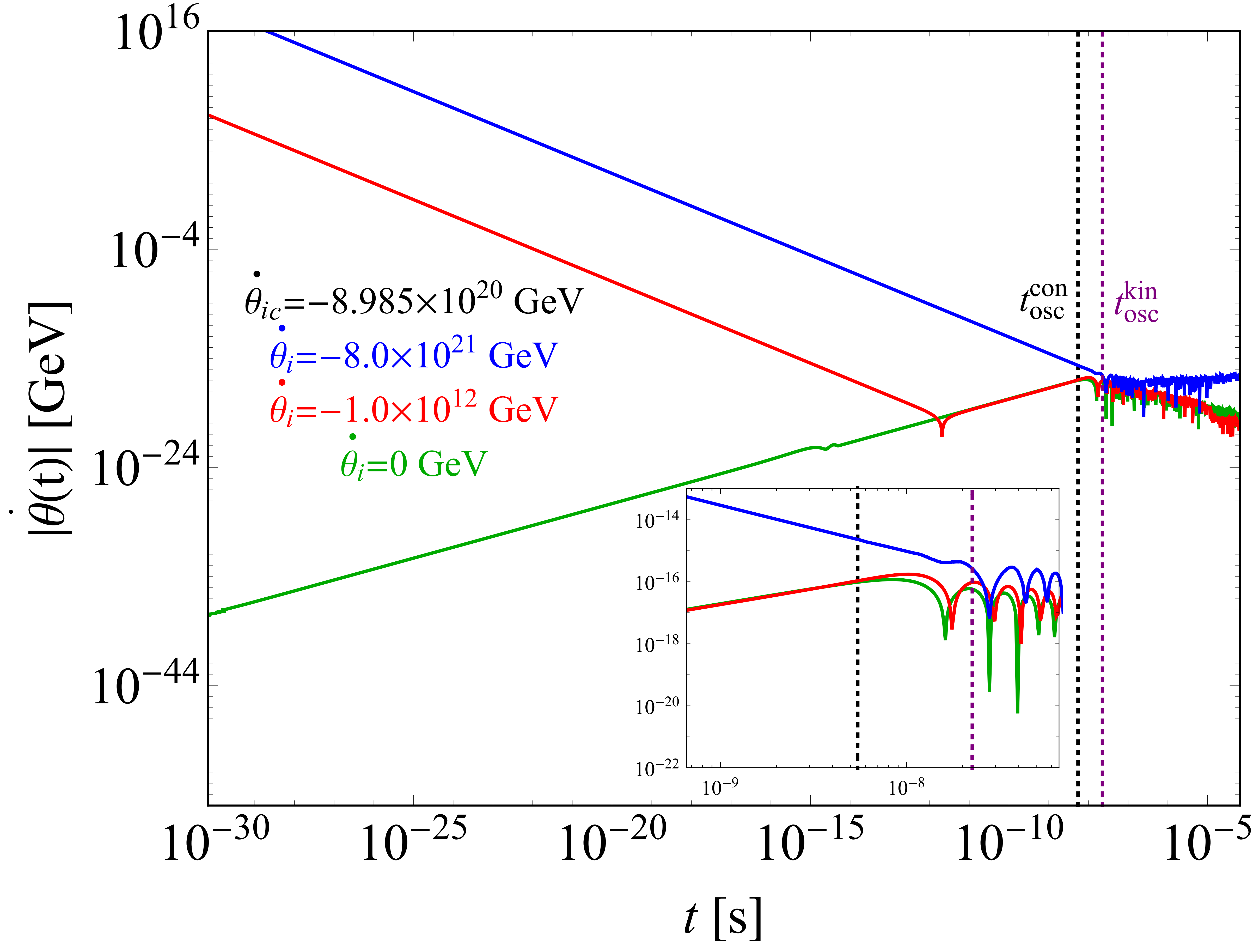
$$V_a \sim -\frac{1}{16\pi^2}\sum_{n=1}^{4} a_n \cos n\theta\,.$$

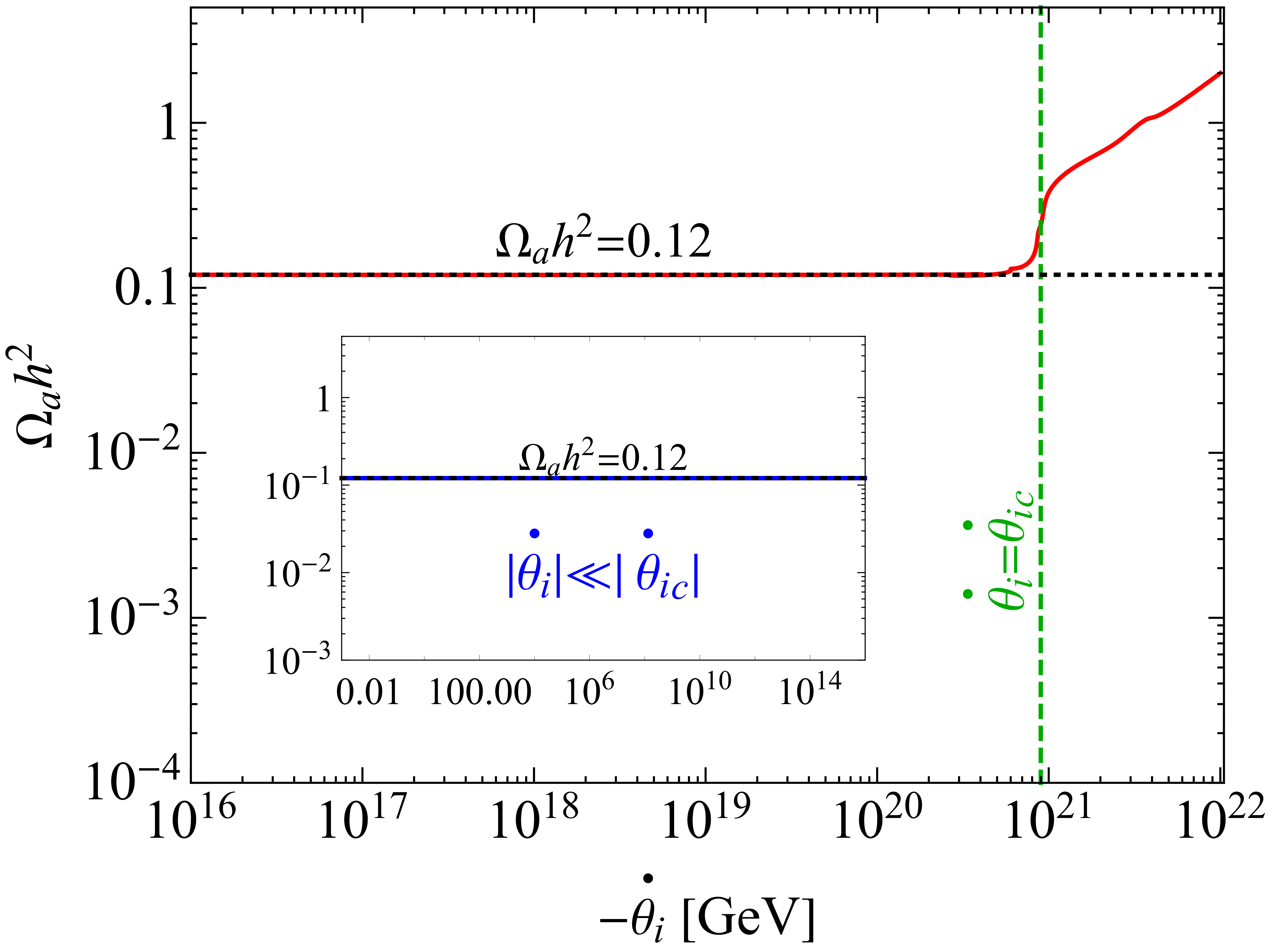
a_1	a_2	a_3	a_4
$mM^3\left(1+\log\frac{M^2}{M_{pl}^2}\right)$	$2m^2M^2\log\frac{M^2}{M_{pl}^2}$	m^3M	m^4

Majoron mass and its relic density

Majoron mass:	$$m_a^2 = \frac{1}{f_a^2}\frac{d^2V}{d\theta^2} = \frac{1}{16\pi^2 f_a^2}\left\vert a_1 + 4a_2 + 9a_3 + 16a_4 \right\vert .$$	
Initial velocity: **(From Noether theorem)**	$$\dot\theta^2 \propto \frac{\mathrm{Tr}[Y_M^4]}{96\pi^2} f_a^2 \cos 4\theta,$$	**In the traditional misalignment mechanism** $\dot\theta_i = 0$
EOM	$$\ddot\theta + 3H\dot\theta + \frac{1}{f_a^2}\frac{dV_a}{d\theta} = 0,$$	**Different oscillation temperature**

Majoron mass and its relic density





Baryon asymmetry of the universe

$m\overline{N_R^C}N_R + h.c.$ → LNV carried by $\dot{\theta}$ → Non-zero B-L

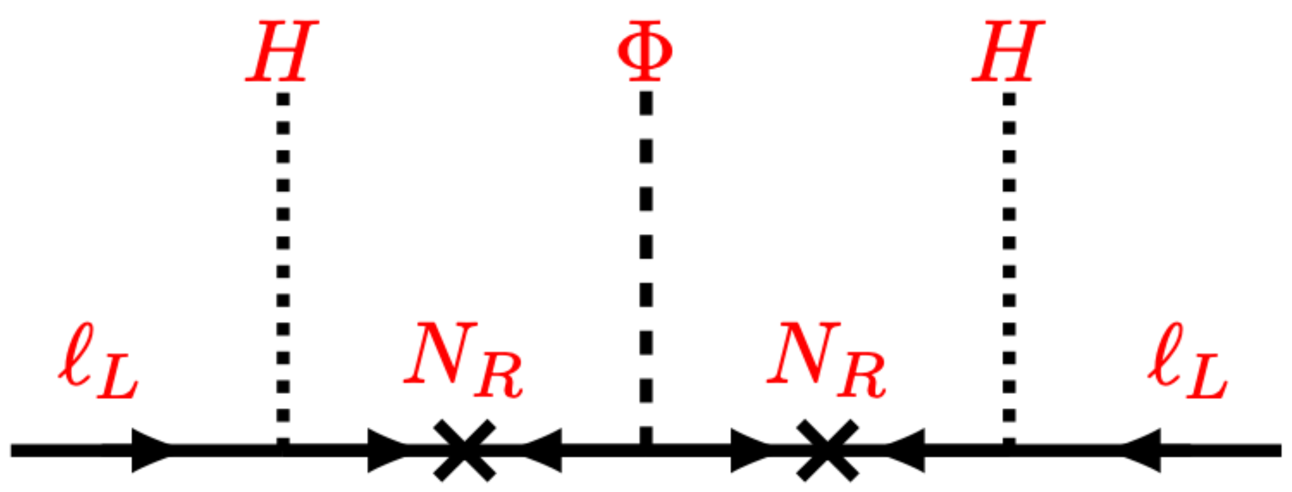
Weinberg operator

Chern-Simons operator

Non-zero B-L → BAU

Sehemas

Key:



$$\mathscr{L}_{\text{int}} \supset \frac{1}{2M}\frac{a}{f_a}\ell\ell HH,$$

$$\mathscr{L}_{\text{int}} \supset \frac{3g^2}{64\pi^2}\frac{a}{f_a}W\widetilde{W}$$

Baryon asymmetry of the universe

Transport equations:

$$-\frac{d}{d\ln T}\left(\frac{\mu_i}{T}\right) = -\frac{1}{g_i}\sum_\alpha n_i^\alpha \frac{\gamma_\alpha}{H}\left[\sum_j n_j^\alpha\left(\frac{\mu_j}{T}\right) - n_S^\alpha \frac{\dot{\theta}(T)}{T}\right],$$

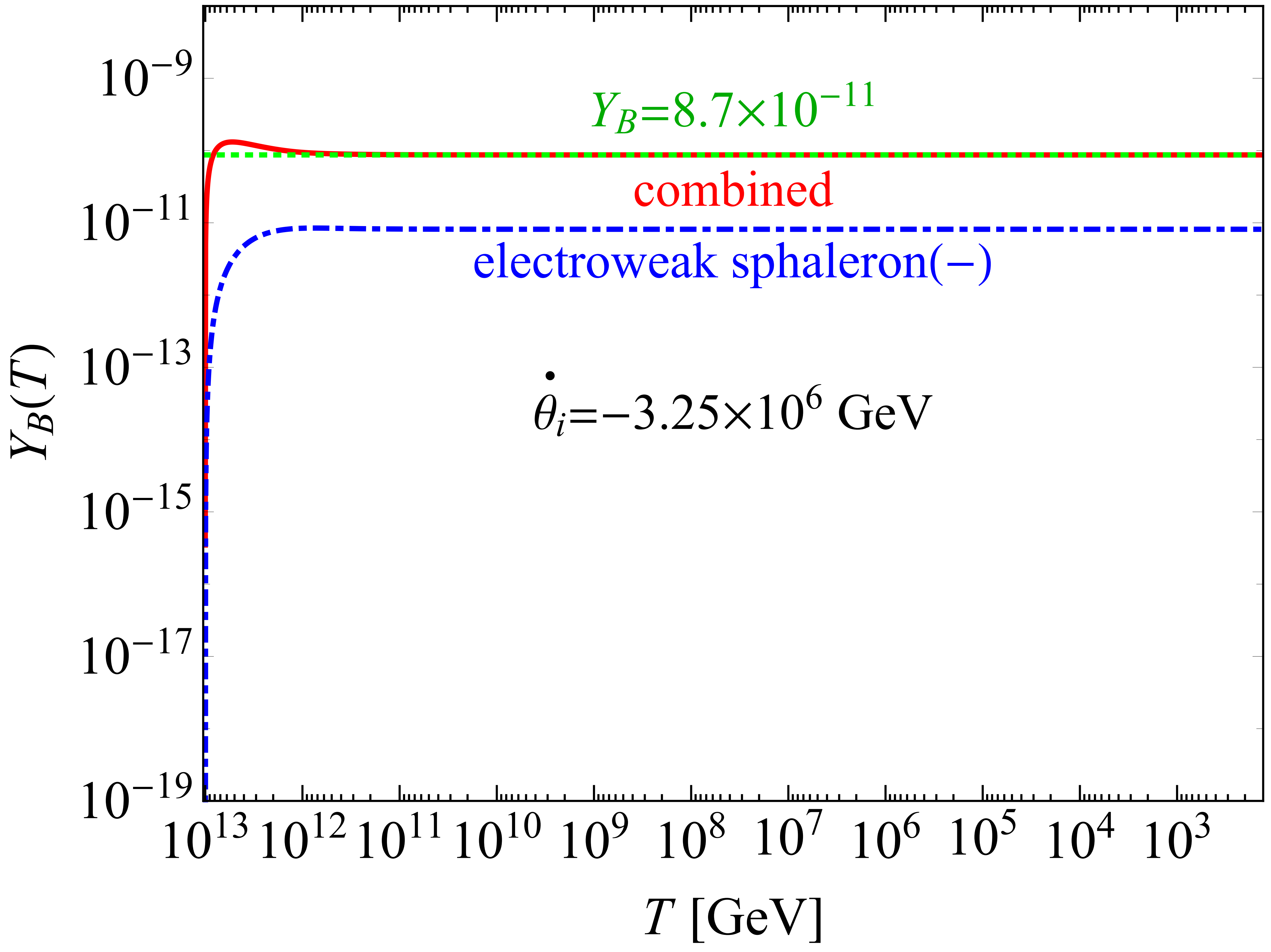
Source term:

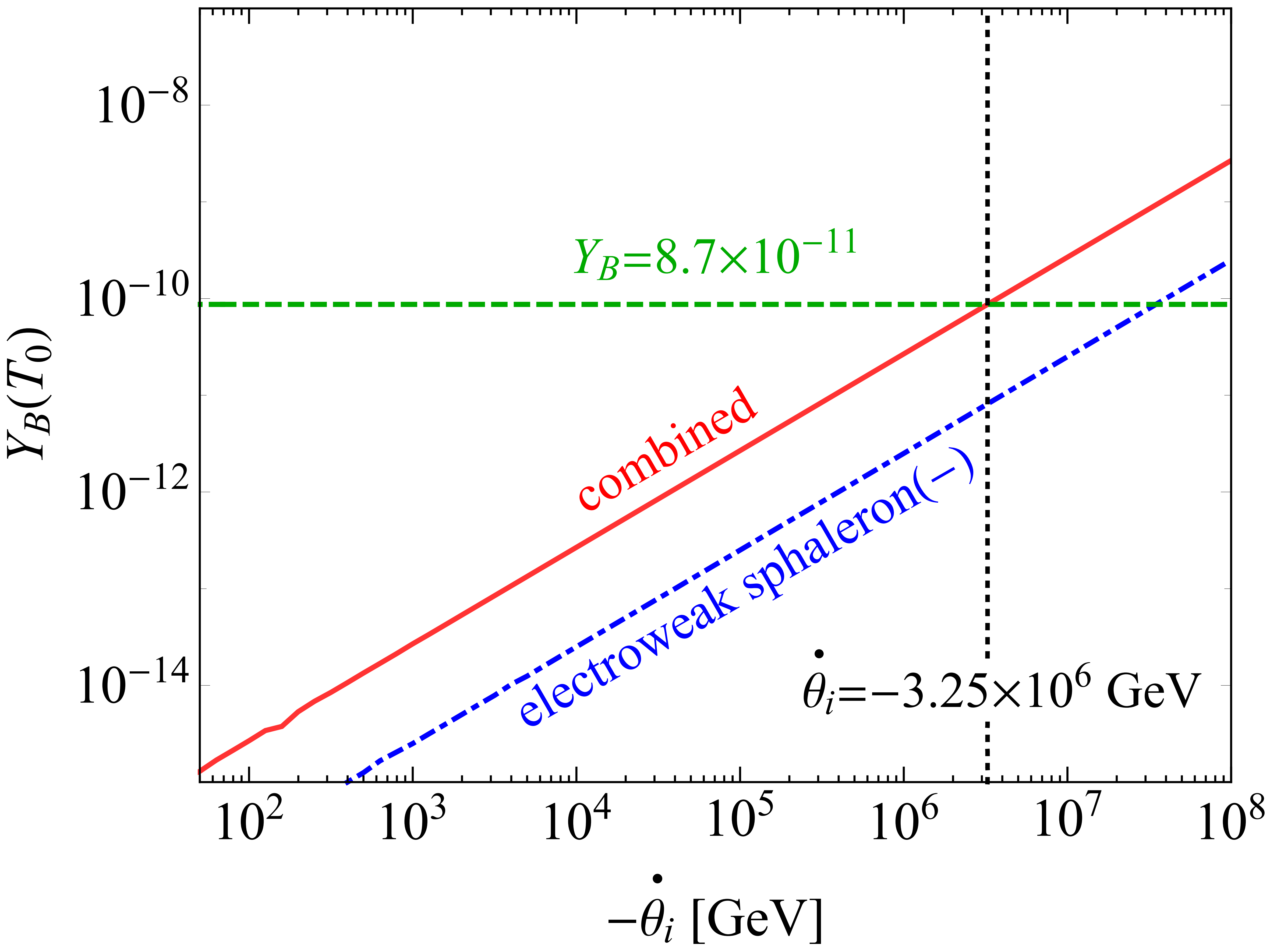
$$\left(n_S^{WS}, n_S^{W_{12}}, n_S^{W_3}, n_S^{SS}, n_S^{Y_\tau}, n_S^{Y_t}, n_S^{Y_b}\right) = \left(\frac{3}{2},1,1,0,0,0,0\right).$$

Weinberg operator decoupling temperature:

$$T_{\rm W} \simeq 6\times 10^{12}\,{\rm GeV}\times\left(\frac{0.05\,{\rm eV}}{m_\nu}\right)^2.$$

Baryon asymmetry of the universe





Summary

Issue-I: We have proposed a novel mass generation mechanism for Axion-like particles: explicit global symmetry breaking →ALP mass

Issue-II We have presented a very simple and natural model that can address the neutrino mass, dark matter and the BAU simultaneously!

Thank you for your attention!