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CP³ Origins
Cosmology & Particle Physics

Dark Sectors for matter asymmetry and neutrino physics

(Neutrino physics for matter asymmetry and dark matter)

CP^3 Origins, SDU
Wei-Chih Huang
20.10.2021

COST Advanced School on Physics of Dark Matter
and Hidden Sectors: from Theory to Experiment

Outline

- Introduction on neutrino mixing, masses and oscillations
- DM-induced neutrino mass
- Baryon number (*B*) asymmetry generation
- Implications of lepton number (*L*) violation on *B* asymmetry
- Links of *B* and *L* to dark matter (DM) asymmetry
- Conclusions

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CKM (Cabibbo-Kobayashi-Maskawa) matrix

$$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \quad , \quad u_R \quad , \quad d_R$$

$$\mathcal{L} \supset -y^d_{ij} \left(\overline{Q_{L_i}} \cdot H\right) d_{R_j} - y^u_{ij} \left(\overline{Q_{L_i}} \cdot H^\dagger\right) u_{R_j} + h.c.$$

$$u_{L_i} \ (\text{flavor}) = (U_u)_{ij} \ \ u'_{L_j} \ (\text{mass}) \quad , \quad d_{L_i} = (U_d)_{ij} \ \ d'_{L_j}$$

$$u_{R_i} = (V_u)_{ij} \ \ u'_{R_j} \quad , \quad d_{R_i} = (V_d)_{ij} \ \ d'_{R_j}$$

CKM (Cabibbo-Kobayashi-Maskawa) matrix

$$\mathcal{L} \supset -\frac{y_i'^d v}{\sqrt{2}} \, \overline{d'_{L_i}} d'_{R_j} - \frac{y_i'^u v}{\sqrt{2}} \, \overline{u'_{L_i}} u'_{R_j} + h.c.$$

$$\Longrightarrow \; \mathcal{L} \supset \frac{g}{\sqrt{2}} \, \overline{u'_{L_i}} \gamma^\mu \underbrace{\left(U_u^\dagger U_d\right)_{ij}}_{\text{CKM}} d'_{L_j} W_\mu^+$$

$\langle H \rangle = v/\sqrt{2}$ breaks $SU(2)_L$

$\Longrightarrow$ u_L and d_L transform differently between the flavor and mass basis

Neutrino mixing matrix

- In the SM (massless neutrinos), the field redefinition of the neutrinos can rotate away the lepton mixing matrix

$$L = \begin{pmatrix} e_L \\ \nu_L \end{pmatrix} \quad , \quad e_R$$

$$\mathcal{L} \supset -y^e_{ij} \left(\overline{L_i} \cdot H \right) e_{R_j} + h.c.$$

$$e_{L_i} \ (\text{flavor}) = (U_e)_{ij} \ \ e'_{L_j} \ (\text{mass}) \quad , \quad e_{R_i} = (V_e)_{ij} \ \ e'_{R_j}$$

$$\mathcal{L} \supset \frac{g}{\sqrt{2}} \overline{e'_{L_i}} \gamma^\mu \underbrace{\left(U_e^\dagger\right)_{ij}}_{\text{mixing?}} \nu_{L_j} W^-_\mu$$

But one can redefine $\nu \to U_e \ \nu$ to remove unphysical U_e

Neutrino mixing matrix

- The lepton mixing matrix, Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix, in the SM is unphysical if the neutrinos are massless or degenerate in mass

For example, right-handed neutrinos are added:

$$\mathcal{L} \supset -y^{e}_{ij}\left(\overline{L_i}\cdot H\right) e_{R_j} - y^{\nu}_{ij}\left(\overline{L_i}\cdot H^{\dagger}\right)\nu_{R_j} + h.c.$$

$$\mathcal{L} \supset \frac{g}{\sqrt{2}}\overline{e'_{L_i}}\gamma^{\mu}\underbrace{\left(U_e^{\dagger}U_{\nu}\right)_{ij}}_{\text{PMNS}}\nu'_{L_j}W^{-}_{\mu}$$

PMNS matrix

- PMNS has the three rotation angles and one CP phase. There can exist two Majorana phases in the presence of Majorana neutrinos: $m\nu\nu$ (two-component) or $m\,\overline{\nu^c}\nu$ (four-component).
- The Majorana phases might come from high-scale physics that generates the baryon asymmetry via *L*-violation

$$|\nu_\alpha\rangle = (U_{\mathrm{PMNS}})_{\alpha i}\,|\nu_i\rangle$$

$$U_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Neutrino oscillations and masses

$$|\nu_e\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle, \longrightarrow |\nu(t,\vec{x})\rangle = \cos\theta e^{-ip_1x}|\nu_1\rangle + \sin\theta e^{-ip_2x}|\nu_2\rangle$$

$$p_i x = E_i t - \vec{p}_i\vec{x} \simeq (E_i - p_{z,i})L$$

$$E_i - p_{z,i} = (E_i^2 - |\vec{p}|^2)/(E_i + p_{z,i}) \simeq m_i^2/2E_i \simeq m_i^2/2E$$

$$|\nu(L)\rangle = \cos\theta e^{-im_1^2 L/2E}|\nu_1\rangle + \sin\theta e^{-im_2^2 L/2E}|\nu_2\rangle$$

$$\begin{aligned}
P_{ee} &= |\langle\nu_e|\nu(L)\rangle|^2, \\
&= \left|(\cos\theta\langle\nu_1| + \sin\theta\langle\nu_2|)\left(\cos\theta e^{-im_1^2L/2E}|\nu_1\rangle + \sin\theta e^{-im_2^2L/2E}|\nu_2\rangle\right)\right|^2, \\
&= \left|\cos^2\theta e^{-im_1^2L/2E} + \sin^2\theta e^{-im_2^2L/2E}\right|^2, \\
&= \cos^4\theta + \sin^4\theta + 2\sin^2\theta\cos^2\theta\Re\left(e^{-i(m_2^2-m_1^2)L/2E}\right), \\
&= 1 - 4\cos^2\theta\sin^2\theta\left(\frac{1-\cos(\Delta m^2 L/2E)}{2}\right), \\
&= 1 - \sin^2 2\theta\sin^2\left(\frac{\Delta m^2 L}{4E}\right),
\end{aligned} \tag{27}$$

A. de Gouvea, hep-ph/0411274

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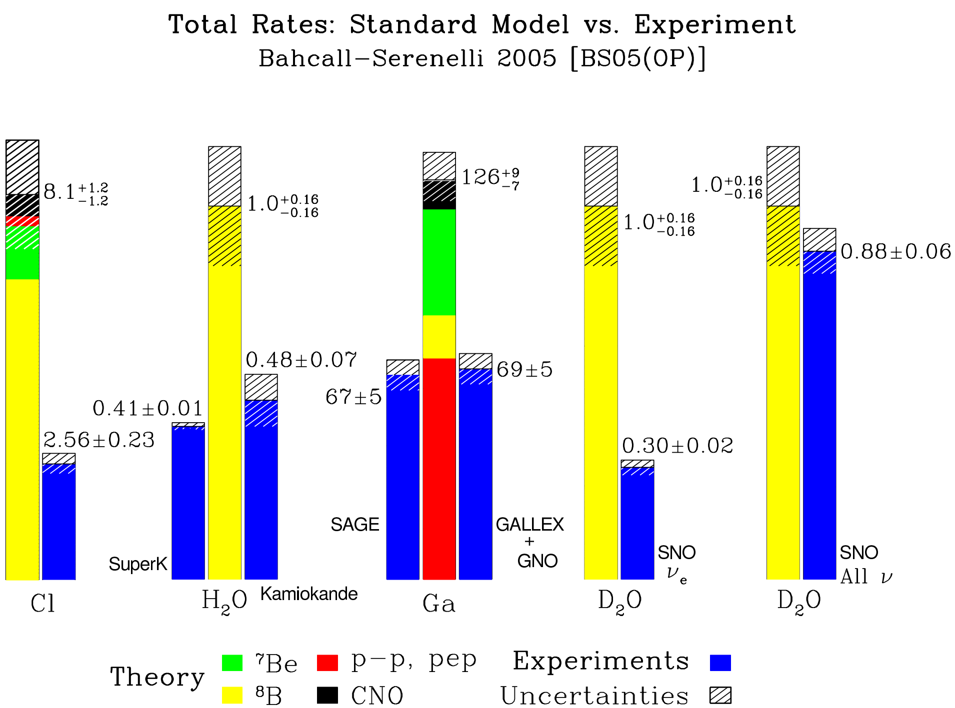
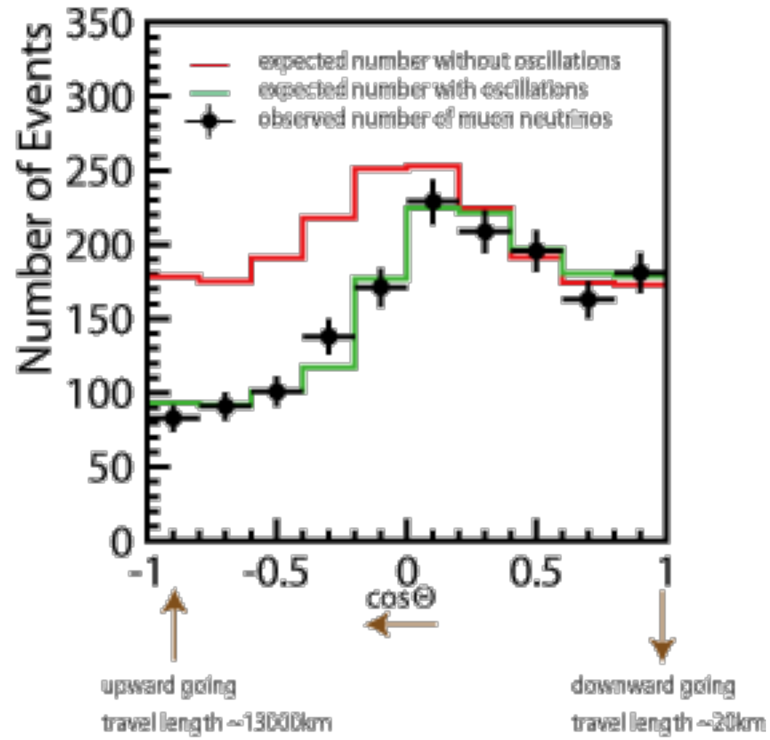
Neutrino oscillations and masses



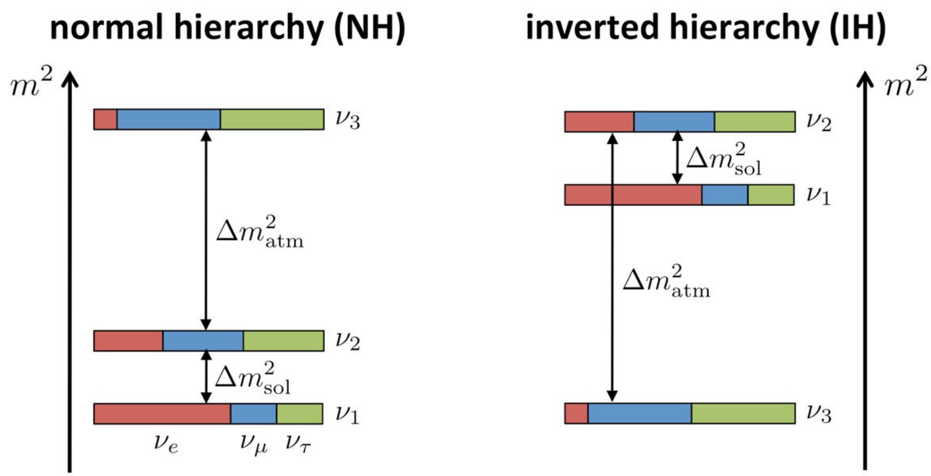
http://www.sns.ias.edu/~jnb/



http://www-sk.icrr.u-tokyo.ac.jp/sk/physics/atmnu-e.html

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2(\mathrm{eV}^2)L(\mathrm{km})}{E_\nu(\mathrm{GeV})}\right)$$

Neutrino oscillations and masses



https://neutrinos.fnal.gov/mysteries/mass-ordering/

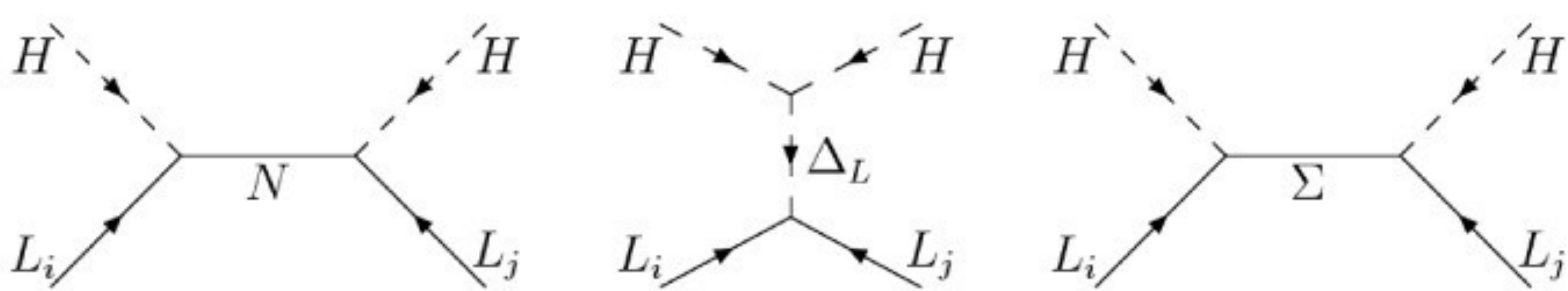
	Ref. [188] w/o SK-ATM	
NO	Best Fit Ordering	
Param	bfp $\pm 1\sigma$	3σ range
$\frac{\sin^2\theta_{12}}{10^{-1}}$	$3.10^{+0.13}_{-0.12}$	$2.75 \to 3.50$
$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$
$\frac{\sin^2\theta_{23}}{10^{-1}}$	$5.58^{+0.20}_{-0.33}$	$4.27 \to 6.09$
$\theta_{23}/^\circ$	$48.3^{+1.2}_{-1.9}$	$40.8 \to 51.3$
$\frac{\sin^2\theta_{13}}{10^{-2}}$	$2.241^{+0.066}_{-0.065}$	$2.046 \to 2.440$
$\theta_{13}/^\circ$	$8.61^{+0.13}_{-0.13}$	$8.22 \to 8.99$
$\delta_{\mathrm{CP}}/^\circ$	222^{+38}_{-28}	$141 \to 370$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
$\frac{\Delta m^2_{32}}{10^{-3}\ \mathrm{eV}^2}$	$2.449^{+0.032}_{-0.030}$	$2.358 \to 2.544$

IO	$\Delta\chi^2 = 6.2$	
$\frac{\sin^2\theta_{12}}{10^{-1}}$	$3.10^{+0.13}_{-0.12}$	$2.75 \to 3.50$
$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$
$\frac{\sin^2\theta_{23}}{10^{-1}}$	$5.63^{+0.19}_{-0.26}$	$4.30 \to 6.12$
$\theta_{23}/^\circ$	$48.6^{+1.1}_{-1.5}$	$41.0 \to 51.5$
$\frac{\sin^2\theta_{13}}{10^{-2}}$	$2.261^{+0.067}_{-0.064}$	$2.066 \to 2.461$
$\theta_{13}/^\circ$	$8.65^{+0.13}_{-0.12}$	$8.26 \to 9.02$
$\delta_{\mathrm{CP}}/^\circ$	285^{+24}_{-26}	$205 \to 354$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
$\frac{\Delta m^2_{32}}{10^{-3}\ \mathrm{eV}^2}$	$-2.509^{+0.032}_{-0.032}$	$-2.603 \to -2.416$

PDG 2018

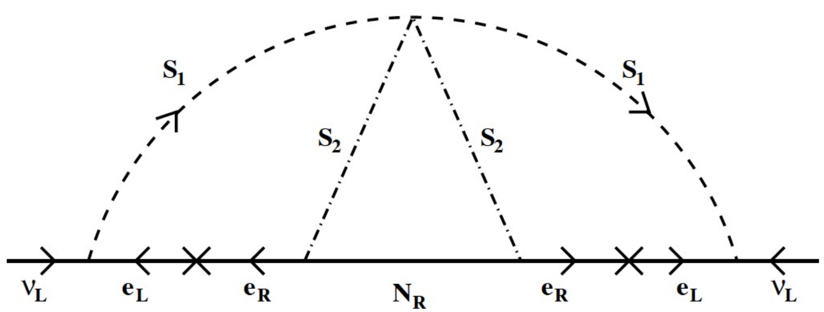
Majorana Neutrino mass

- There are three UV-completions at tree-level for dim-5 ($\Delta L = 2$) Weinberg operator $(LH)(LH)/\Lambda$, dubbed as Type-I, Type-II and Type-III seesaw mechanism:



DM-neutrino interplay: dark neutrino mass

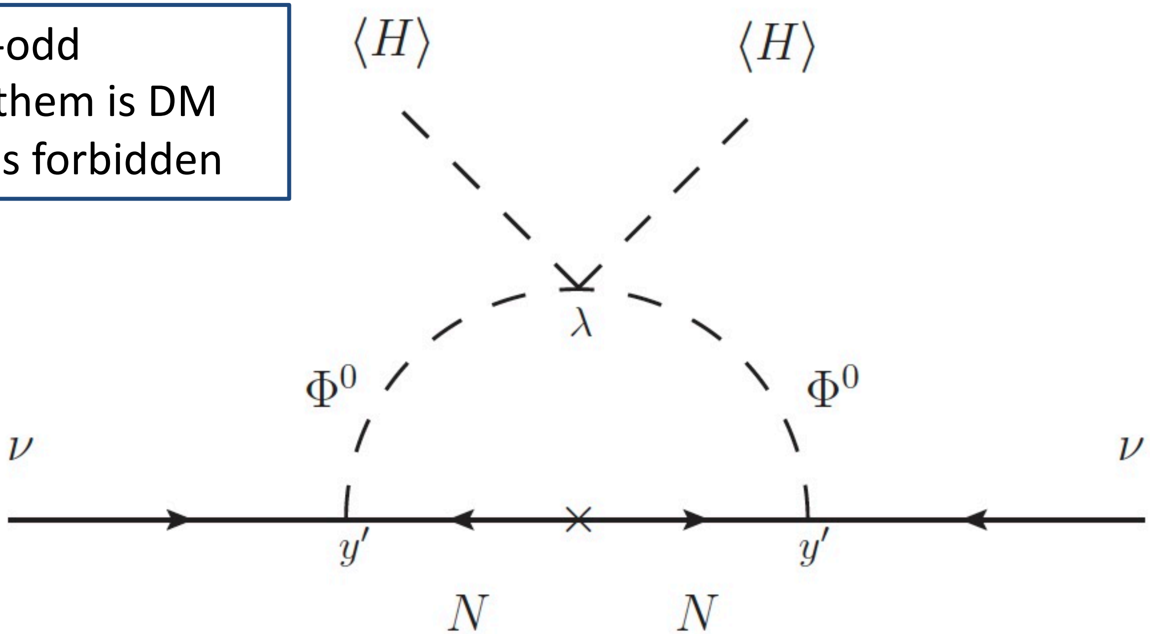
- ➢ The neutrino mass can also be radiatively generated by DM
- ➢ The DM loops, however, contain many parameters, making the DM-neutrino mass correlation obscure



L.M. Krauss et al ’03

Scotogenic model

- Φ and *N* are Z_2-odd
- The lightest of them is DM
- Type-I Yukawa is forbidden



$$\mathcal{L} \supset y'_{ij}\bar{\ell}_i\Phi^* N_j + \frac{M_{N_k}}{2}\overline{N^c_k}N_k + V(\Phi, H),$$

$$\boxed{V(H,\Phi) = \mu_1^2|H|^2 + \mu_2^2|\Phi|^2 + \lambda_1|H|^4 + \lambda_2|\Phi|^4 + \lambda_3|H|^2|\Phi|^2 + \lambda_4|H^*\Phi|^2 + \frac{\lambda_5}{2}\left((H^*\Phi)^2 + \text{h.c.}\right),}$$

Ma, hep-ph/0601225

Scotogenic model

$$(m_\nu)_{ij} = \sum_k \frac{\left(y'_{ik} y'_{jk}\right)^* M_{N_k}}{32\pi^2} \left(\frac{m_R^2}{m_R^2 - M_{N_k}^2} \log \frac{m_R^2}{M_{N_k}^2} - \frac{m_I^2}{m_I^2 - M_{N_k}^2} \log \frac{m_I^2}{M_{N_k}^2} \right)$$

$$m_R^2 = \mu_2^2 + \frac{1}{2}\left(\lambda_3 + \lambda_4 + \lambda_5\right) v^2,$$
$$m_I^2 = \mu_2^2 + \frac{1}{2}\left(\lambda_3 + \lambda_4 - \lambda_5\right) v^2,$$

$M_N \gtrsim 10^{10}$ GeV, $m_R \sim m_I \sim$ TeV and $|m_R - m_I| \ll m_I \sim m_R$

$$\boxed{(m_\nu)_{ij} = \frac{\lambda_5 v^2}{32\pi^2} \sum_k \frac{\left(y'_{ik} y'_{jk}\right)^*}{M_k} \left(\log\left(\frac{M_{N_k}^2}{m_0^2} \right) - 1 \right)}$$

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DM-neutrino interplay: dark neutrino mass

- A very simple idea is proposed to connect the DM and neutrino mass.
- We start with an effective operator (Weyl-spinor notation) connecting the Majorana DM particle (χ) and the standard model (SM) neutrino (ν):

$$\mathcal{L} \supset \frac{\chi\chi\nu\nu}{\Lambda^2} + h.c.,$$

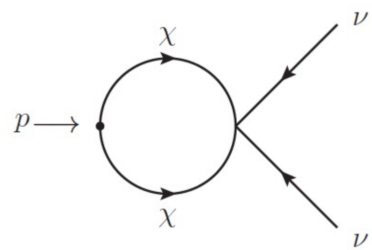
- As shown below, the scale Λ is in fact lower than the electroweak (EW) scale, which justifies explicit $SU(2)_L$ symmetry breaking in the effective operator.

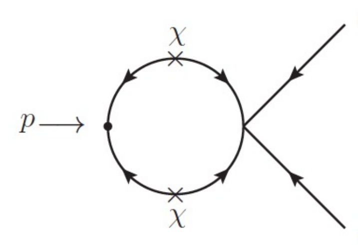
F. Deppisch and WCH, 1412.2027

DM-neutrino interplay: dark neutrino mass

- By contracting two χs, the neutrino receives a radiative mass

$$m_\nu = \frac{m_\chi^3}{2\pi^2\Lambda^2}\left(6\ln\frac{m_\chi}{\mu} - 1\right)$$



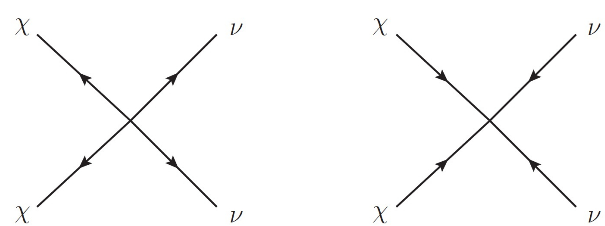


- We use the dimensional regularization scheme with the modified minimum subtraction that can be justified if the underlying UV-complete theory has the same DM-loop diagram.

F. Deppisch and WCH, 1412.2027

DM-neutrino interplay: dark neutrino mass

- The DM-neutrino effective operator also determines the DM annihilation cross section: $$\sigma v_{\rm rel} = \frac{m_\chi^2}{\pi\Lambda^4}\left(1+\frac{1}{2}v_{\rm rel}^2\right)$$
- There are two contributions from opposite chiralities



- The interference between opposite chiralities is nearly zero due to the very small neutrino mass.

F. Deppisch and WCH, 1412.2027

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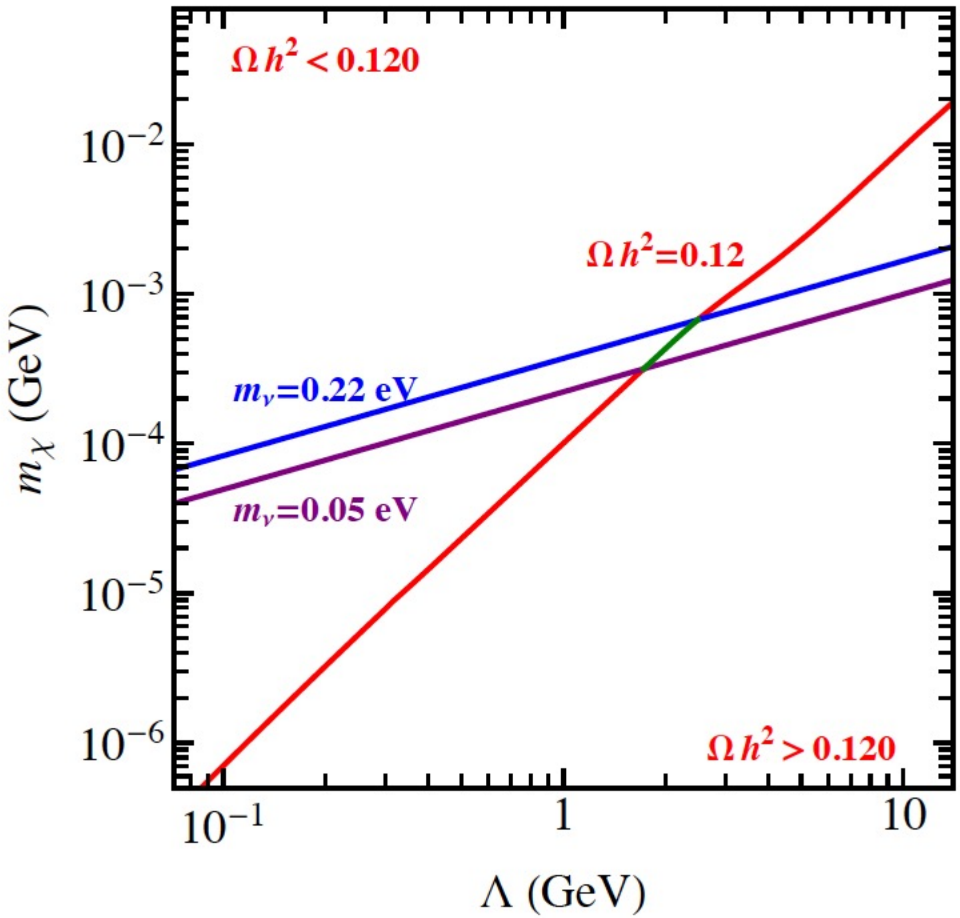
DM-neutrino interplay: dark neutrino mass



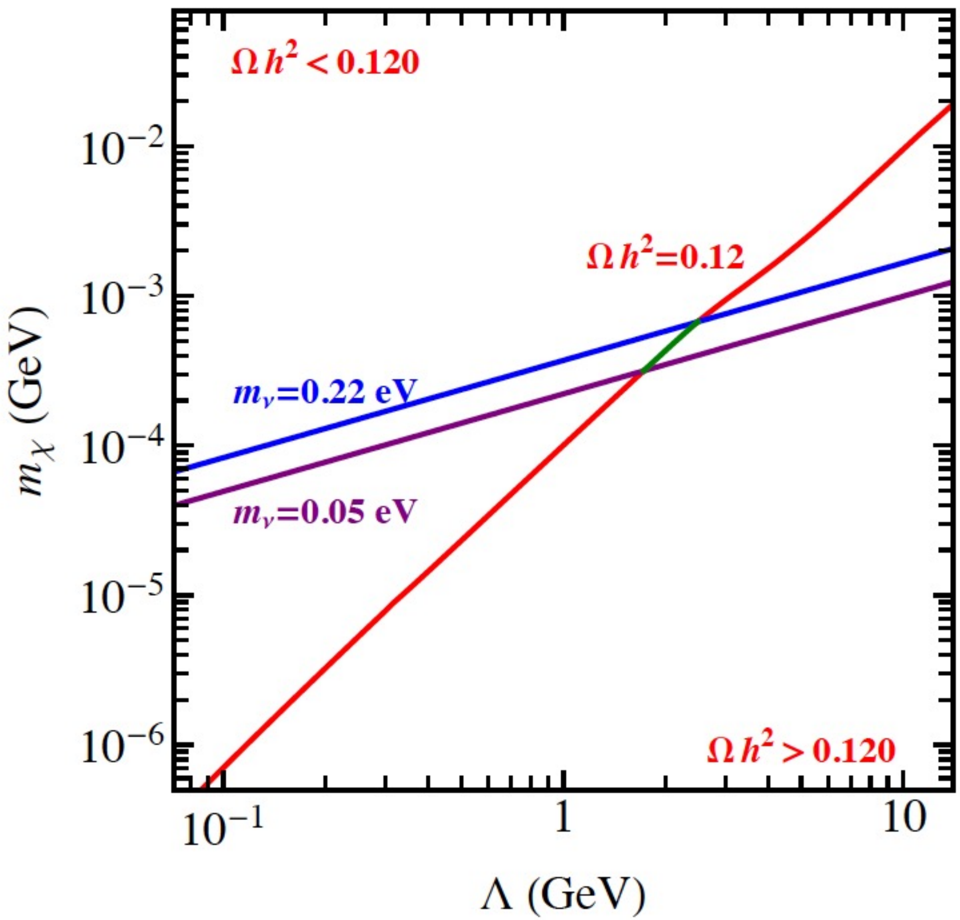
- There are two unknown parameters in the operator, m_χ and Λ.
- They are completely determined, given the DM relic abundance and neutrino mass.
- For demonstration, we only study one neutrino flavor, the heaviest active neutrino, with the mass of 0.05 eV to 0.2 eV (PDG and Planck data).

$$m_\chi \approx 0.4 \text{ MeV} \left(\frac{m_\nu}{0.1 \text{ eV}}\right)^{1/2} \left(\frac{\Omega h^2}{0.12}\right)^{1/4}$$

$$\Lambda \approx 1.5 \text{ GeV} \left(\frac{m_\nu}{0.1 \text{ eV}}\right)^{1/4} \left(\frac{\Omega h^2}{0.12}\right)^{3/8}$$

F. Deppisch and WCH, 1412.2027

DM-neutrino interplay: dark neutrino mass

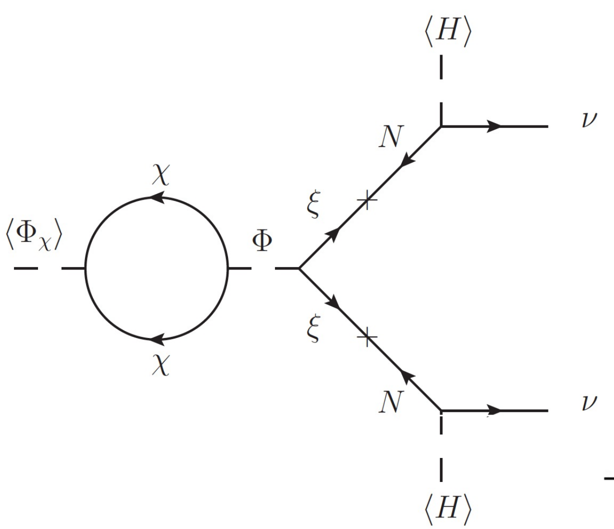


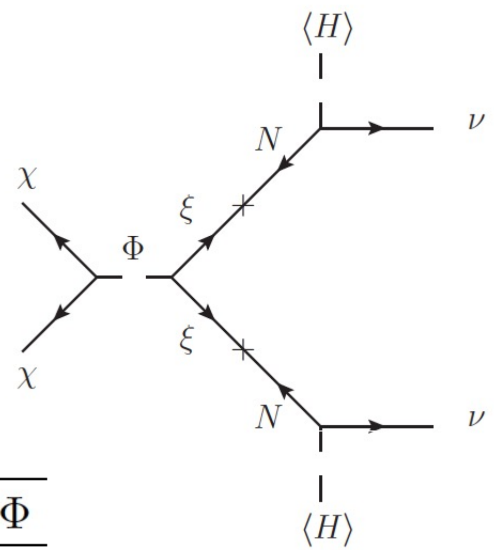
- MeV DM will reheat the neutrino sector when it decouples from the thermal bath, i.e., $N\nu=4.4$ (1207.0497) in conflict with the CMB measurement $N\nu=3.15\pm0.23$ (1502.01589).
- The tension might be alleviated by including three neutrino flavors to increase the DM mass above 8 MeV.

F. Deppisch and WCH, 1412.2027

A UV-complete toy model

$$\mathcal{L} \supset \frac{c_1}{2}\left(\Phi_\chi + \langle\Phi_\chi\rangle\right)\chi\chi + c_2\Phi\chi\chi + c_3\Phi^*\xi\xi$$
$$+\, yLHN - m_{\Phi_\chi}\Phi_\chi\Phi_\chi^* - m_\Phi\Phi\Phi^* - m_N N\xi + h.c.,$$





Field	L	H	N	χ	ξ	Φ_χ	Φ
$[SU(2)_L]_Y$	$2_{-1/2}$	$2_{1/2}$	1_0	1_0	1_0	1_0	1_0
L	1	0	-1	-1	1	2	2
Z_2	$+$	$+$	$+$	$-$	$+$	$+$	$+$

F. Deppisch and WCH, 1412.2027

A UV-complete toy model

- The neutrino mass matrix in the basis of ν, N and ξ reads

$$\begin{pmatrix} 0 & yv & 0 \\ yv & 0 & m_N \\ 0 & m_N & 2\frac{c_2 c_3 \overline{\chi}\chi}{m_\Phi^2} \end{pmatrix}$$

- Comparing the neutrino mass derived from the mass matrix to the one directly from the effective DM-neutrino operator $\chi\chi\nu\nu/\Lambda^2$, the scale Λ can be inferred.
- In fact, it is a realization of the inverse seesaw proposed by Mohapatra and Valle in 1986.

F. Deppisch and WCH, 1412.2027

How to generate *B* asymmetry

- In the following, we describe the criteria of *B* asymmetry generation

- Two representative examples will be discussed

Sakharov Conditions

- *B* violation

$$X \to B$$

$$\overline{X} \to \overline{B}$$

➔ Total baryon number is still conserved if *C* or *CP* is conserved.

Sakharov Conditions

- *C* and *CP* violation:

$$iM_1(X \to B + Y) = A \text{ (tree)}$$

$$iM_2(X \to B + Y) = B \times Ce^{i\theta} \text{ (loop)}$$

$$i\overline{M}_1(\overline{X} \to \overline{B} + \overline{Y}) = A^* \text{ (tree)}$$

$$i\overline{M}_2(\overline{X} \to \overline{B} + \overline{Y}) = B^* \times Ce^{i\theta} \text{ (loop)}$$

$$\Gamma(X \to B + Y) - \Gamma(\overline{X} \to \overline{B} + \overline{Y}) = 4 \int d\Pi_f |AB^*| \sin\phi_{AB} \ \sin\theta$$

$$AB^* = |AB^*| e^{i\phi_{AB}}$$

- Complex couplings
- Particles in loops being on-shell, leading to non-vanishing θ

Sakharov Conditions

- Out of equilibrium dynamics since in thermal equilibrium, we have $\langle B \rangle = 0$

Baryon number B is odd under C, even under P and T
$\Rightarrow B$ is odd under $CPT \equiv \theta$

$$
\begin{aligned}
\langle B \rangle_T &= \mathrm{Tr}\left(\mathrm{e}^{-H/T} B\right) \\
&= \mathrm{Tr}\left(\theta^{-1}\theta\,\mathrm{e}^{-H/T} B\right) \\
&= \mathrm{Tr}\left(\mathrm{e}^{-H/T}\,\theta B \theta^{-1}\right) \\
&= -\langle B \rangle_T
\end{aligned}
$$

M. Plümacher '09

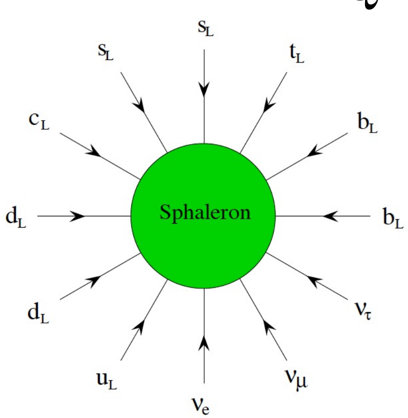
Sphalerons (*B* violation)

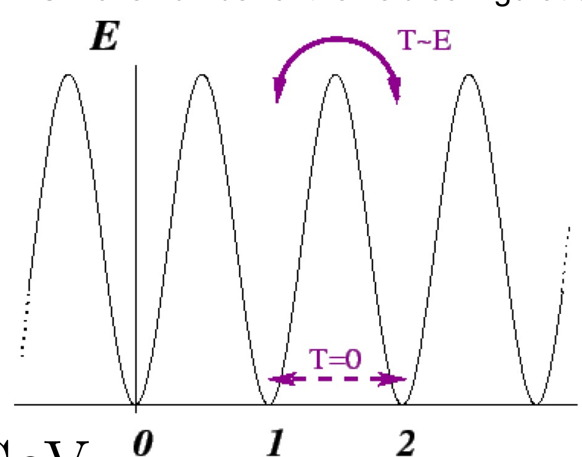
•Sphaleron processes (Klinkhammer & Manton ’84; Kuzmin et al. ’85) convert lepton asymmetry into baryon asymmetry

$$j_5^\mu = \overline{\psi}\gamma_5\gamma^\mu\psi, \qquad \partial_\mu j_5^\mu = \frac{1}{16\pi^2}\widetilde{F}_{\mu\nu}F^{\mu\nu} = \frac{\epsilon_{\rho\sigma\mu\nu}}{16\pi^2}F^{\rho\sigma}F^{\mu\nu} \; .$$

$$\Delta Q^{\ i} = \frac{1}{64\pi^2}\int d^4x F^A_{\mu\nu}\widetilde{F}^{\mu\nu A}$$

Winding or Chern-Simons number of the field configuration





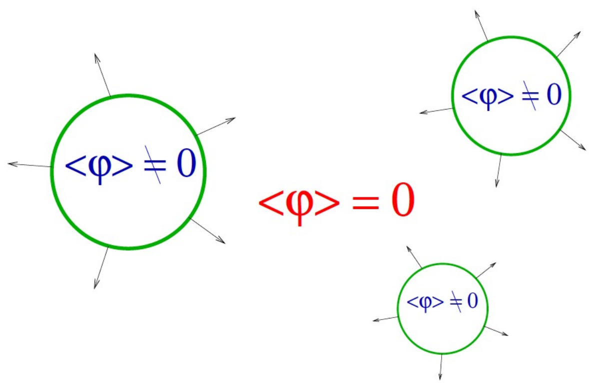
$$\Delta B = \Delta L = 3$$

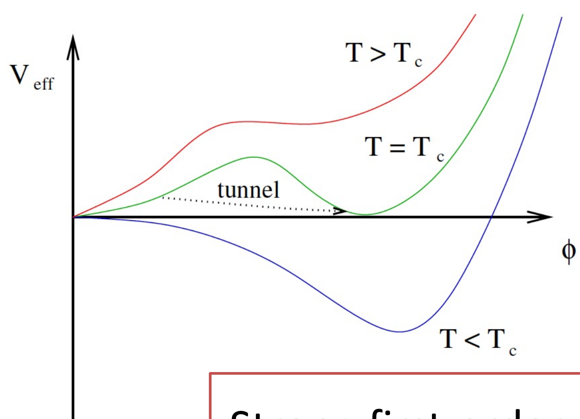
$$\mathcal{O}_{B+L} = \prod_{i=1,2,3}\left(q_{L_i}, q_{L_i}, q_{L_i}\ell_{L_i}\right)$$

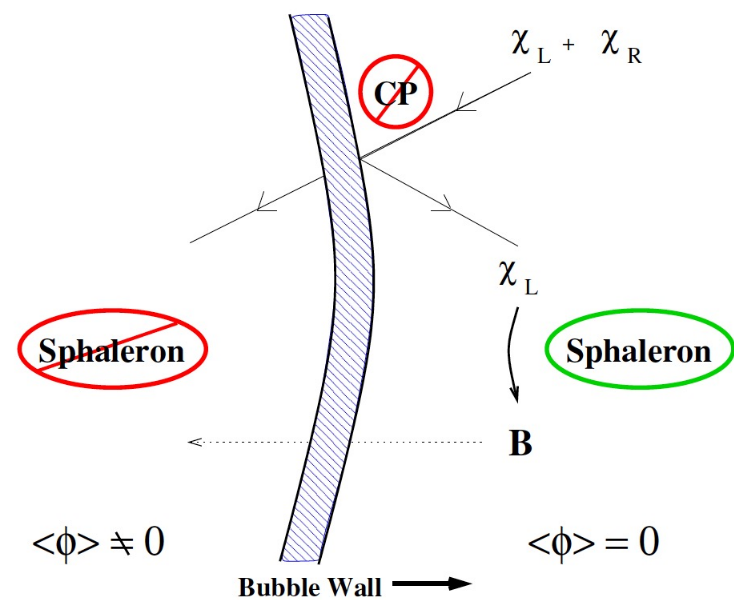
$$\Gamma_{\cancel{B+L}} \simeq 250\,\alpha_W^5\,T \Rightarrow 100 \lesssim T \lesssim 10^{12}\ \text{GeV}$$

Electroweak baryogenesis

- Electroweak baryogenesis occurs at the boundary between different vacuum states (Kuzmin, Rubakov, Shaposhnikov ’85 ’86 ’87)







$$\boxed{\text{Strong first-order phase transition} \Longrightarrow \frac{\phi_c}{T_c} \gtrsim 1}$$

Morrissey et al, 1206.2942

Electroweak baryogenesis

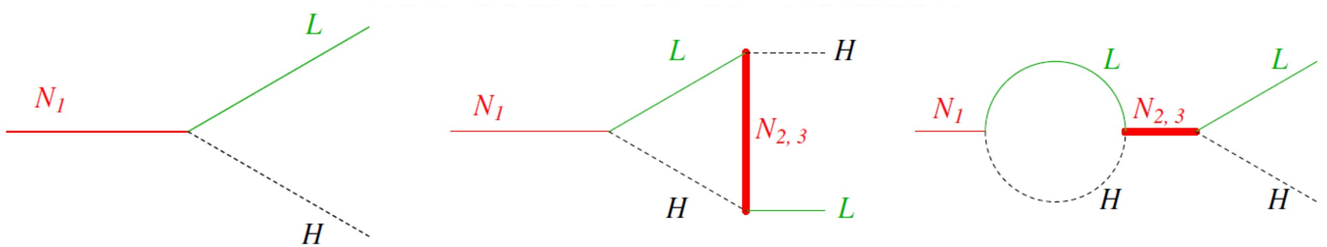
- In the SM, the electroweak phase transition is first-order only if the Higgs boson mass is below 70 GeV (Mod. Phys. Lett. A 2, 417 (1987), hep-lat/9510020).

- In addition, the CP violation induced by the CKM phase is not large enough to create sufficient asymmetries (hep-ph/9312215, hep-ph/9404302, hep-ph/9406289)

Morrissey et al,1206.2942

Leptogenesis

- Heavy neutrinos decay out of equilibrium into leptons and anti-leptons unevenly (Fukugita,Yanagida '86)



A. Strumia, hep-ph/0608347 (2006)

$$\varepsilon_1 \equiv \frac{\Gamma(N_1 \to LH) - \Gamma(N_1 \to \overline{L}\,\overline{H})}{\Gamma(N_1 \to LH) + \Gamma(N_1 \to \overline{L}\,\overline{H})} \approx -\frac{3}{8\pi}\frac{1}{(hh^\dagger)_{11}}\sum_{i=2,3} \mathrm{Im}(hh^\dagger)^2_{li}\frac{M_1}{M_i}$$

$$\boxed{\Delta L \neq 0 \ \rightarrow \ \text{sphalerons} \ \rightarrow \ \Delta B \neq 0}$$

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Implication of *L* violation on *B* asymmetry

Volume 246, number 1, 2 PHYSICS LETTERS B 23 August 1990

Upper bound on baryogenesis scale from neutrino masses

Ann E. Nelson [a,b,1,2] and S.M. Barr [a,c]

[a] *Institute for Theoretical Physics, University of California, Santa Barbara, CA 93106, USA*
[b] *Department of Physics, University of California, San Diego, La Jolla, CA 92093, USA*
[c] *Bartol Research Institute, University of Delaware, Newark, DE 19716, USA*

Received 4 June 1990

We examine the constraints on baryogenesis if anomalous weak baryon violation is in thermal equilibrium at high temperatures. If neutrinos have Majorana masses, there is an upper bound on the scale of baryogenesis: $T_0 \lesssim 10^{12}\,\mathrm{GeV}(1\ \mathrm{eV}/m_\nu)^2$, where m_ν is the mass of the *lightest* neutrino, and no baryon number is generated at temperatures below T_0.

Chemical potential equilibrium

$$-\mu_q + \mu_H + \mu_{d_R} = 0 \ , \quad -\mu_q - \mu_H + \mu_{u_R} = 0 \ , \quad -\mu_\ell + \mu_H + \mu_{e_R} = 0 \ ,$$

$$3\,(3\,\mu_q + \mu_\ell) = 0 \ , \quad \mu_q + 2\mu_{u_R} - \mu_{d_R} - \mu_\ell - \mu_{e_R} + \frac{2}{3}\mu_H = 0 \ ,$$

All chemical potentials vanish after ΔL=2 kicks in !

$$\boxed{\mu_\ell + \mu_H = 0}$$

$$\boxed{\cancel{L} \ , \quad \cancel{B+L} \longrightarrow L = B = 0}$$

Lepton Number Violation (LNV) Operators

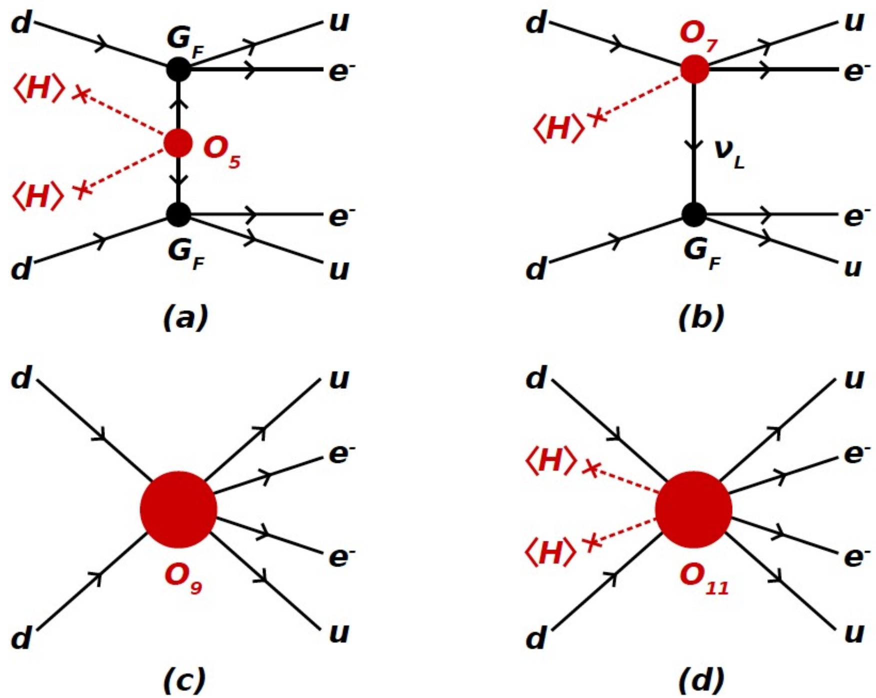


FIG. 1: Contributions to $0\nu\beta\beta$ decay generated by the operators in Eq. (2) in terms of effective vertices, point-like at the nuclear Fermi momentum scale.

- We single out operators which contribute to $0\nu\beta\beta$ decay with short- and long-range interactions.

$$\mathcal{O}_5 = \frac{1}{\Lambda}(L^i L^j) H^k H^l \epsilon_{ik}\epsilon_{jl},$$

$$\mathcal{O}_7 = \frac{1}{\Lambda^3}(L^i d^c)(\bar{e^c}\bar{u^c}) H^j \epsilon_{ij},$$

$$\mathcal{O}_9 = \frac{1}{\Lambda^5}(L^i L^j)(\bar{Q}_i \bar{u^c})(\bar{Q}_j \bar{u^c}),$$

$$\mathcal{O}_{11} = \frac{1}{\Lambda^7}(L^i L^j)(Q_k d^c)(Q_l d^c) H_m \bar{H}_i \epsilon_{jk}\epsilon_{lm},$$

F. Deppisch, J. Harz, WCH, M. Hirsch, H. Päs, arXiv:1503.04825

Lepton Flavor Violation (LFV)

- Since we only study wash-out effects resulting from the $0\nu\beta\beta$ operators, only e-lepton asymmetry is eliminated.
- To washout other flavor asymmetries, one would need LFV operators together with the $0\nu\beta\beta$ operators.
- We study $\ell_i \to \ell_j + \gamma$ and $\ell_i \to \ell_j$ conversion

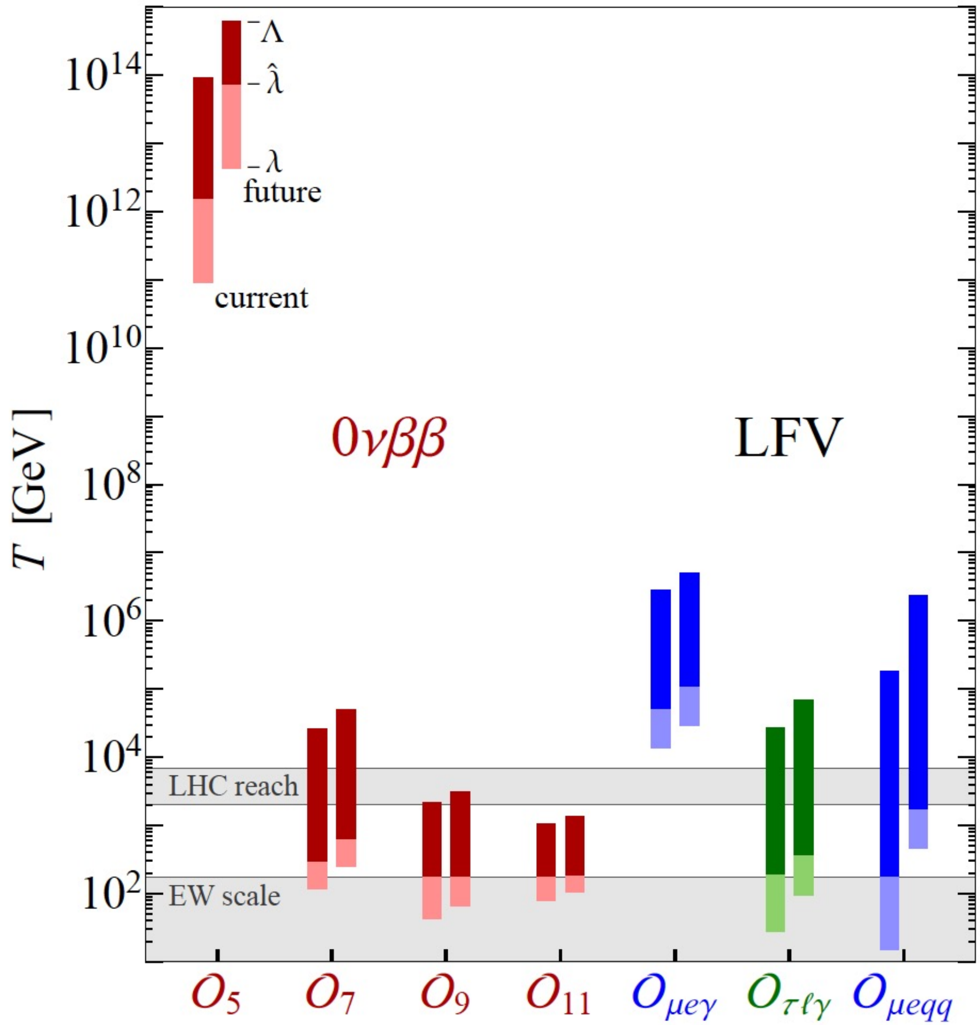
$$\mathcal{O}_{\ell\ell\gamma} = \mathcal{C}_{\ell\ell\gamma} \bar{L}_\ell \sigma^{\mu\nu} \bar{\ell}^c H F_{\mu\nu}$$

$$\mathcal{O}_{\ell\ell qq} = \mathcal{C}_{\ell\ell qq} (\bar{\ell}\, \Pi_1 \ell)(\bar{q}\, \Pi_2 q) \qquad \mathcal{C}_{\ell\ell\gamma} = \frac{eg^3}{16\pi^2 \Lambda^2_{\ell\ell\gamma}}, \quad \mathcal{C}_{\ell\ell qq} = \frac{g^2}{\Lambda^2_{\ell\ell qq}},$$

Π : Lorentz structures

F. Deppisch, J. Harz, WCH, M. Hirsch, H. Päs, arXiv:1503.04825

Numerical results



- From $0\nu\beta\beta$, one can not differentiate O_9 and O_{11} from O_5
- However, O_9 and O_{11} can be probed at the LHC

$$\mathcal{O}_5 = \frac{1}{\Lambda}(L^i L^j) H^k H^l \epsilon_{ik}\epsilon_{jl},$$

$$\mathcal{O}_7 = \frac{1}{\Lambda^3}(L^i d^c)(\bar{e^c}\bar{u^c}) H^j \epsilon_{ij},$$

$$\mathcal{O}_9 = \frac{1}{\Lambda^5}(L^i L^j)(\bar{Q}_i \bar{u^c})(\bar{Q}_j \bar{u^c}),$$

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Caveats

- $0\nu\beta\beta$ decays only probe the electron flavor, so LFV is needed to wash out asymmetries stored in μ and τ flavors

- To carry out the analysis in a model-independent way, we assume no correlation between the generation mechanism and washout

- The existence of a decoupled sector can protect asymmetries from washout in the visible sectors (Phys. Lett. B207, 210 (1988) and 1309.4770)

Links between *B* and (A)DM

- Given the DM relic density and *B* asymmetry are of the same order: $\Omega_{DM} \sim 5.4\ \Omega_B$, it is naturally to conjecture that the DM is also asymmetric — only DM particles or anti-particles exist, aka asymmetric dark matter (ADM) — whose relic density is connected to that of baryon asymmetry.

- Two examples to connect DM and baryon asymmetries are through the neutrino and neutron portal (hep-ph/0510079, 0901.4117, 1009.0270)

$$X_{\rm DM}^2 \left(\ell H\right)^2 \quad , \quad X_{\rm DM} d_R d_R u_R \ (\text{or } X_{\rm DM}^2 d_R d_R u_R)$$

Chemical potential equilibrium

$$-\mu_q+\mu_H+\mu_{d_R}=0\ ,\quad -\mu_q-\mu_H+\mu_{u_R}=0\ ,\quad -\mu_\ell+\mu_H+\mu_{e_R}=0\ ,$$
$$3\,(3\,\mu_q+\mu_\ell)=0\ ,\quad \mu_q+2\mu_{u_R}-\mu_{d_R}-\mu_\ell-\mu_{e_R}+\frac{2}{3}\mu_H=0\ ,$$

All chemical potentials vanish after ΔL=2 kicks in !

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$$\boxed{\cancel{L}\ ,\ \ \cancel{B+L}\longrightarrow L=B=0}$$

PHYSICAL REVIEW D VOLUME 44, NUMBER 10 15 NOVEMBER 1991

Baryogenesis, sphalerons, and the cogeneration of dark matter

S. M. Barr
Bartol Research Institute, University of Delaware, Newark, Delaware 19716
(Received 28 May 1991)

Processes involving the electroweak anomaly can erase completely a primordial baryon and lepton asymmetry if $B-L=0$. This has led to the search for plausible mechanisms for weak-scale baryogenesis, or for the generation of a primordial $B-L$ asymmetry. Here it is emphasized that if another quantum number conserved up to anomalies is present electroweak anomaly processes would not necessarily erase a primordial baryon asymmetry even if $B-L=0$. Moreover, an asymmetry in the new quantum number that is comparable to the baryon asymmetry is generated concomitantly due to the electroweak anomaly. This asymmetry could be the origin of dark matter.

$$\alpha B+\beta L+\gamma X=0 \quad \Longrightarrow \quad B=L=-\left[\frac{\gamma}{\alpha+\beta}\right]X\neq 0$$

Can ADM save the world?

$$-\mu_q + \mu_H + \mu_{d_R} = 0 \;, \quad -\mu_q - \mu_H + \mu_{u_R} = 0 \;, \quad -\mu_\ell + \mu_H + \mu_{e_R} = 0 \;,$$

$$\cancel{3\,(3\,\mu_q + \mu_\ell) = 0}, \quad \mu_q + 2\mu_{u_R} - \mu_{d_R} - \mu_\ell - \mu_{e_R} + \frac{2}{3}\mu_H = 0 \;,$$

$$\mu_\ell + \mu_H = 0 \;,$$

If particles in the dark sector are also charged under *SU(2)$_L$*, then the sphalerons can transfer symmetry between *B*, *L* and *X* (dark charge) $\Longrightarrow$ ADM

$$3\,(3\,\mu_q + \mu_\ell) + n_X \mu_X = 0,$$

M. T. Frandsen, C. Hagedorn, WCH, E. Molinaro, H. Päs, arXiv:1801.09314

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$$-\mu_q+\mu_H+\mu_{d_R}=0\ ,\quad -\mu_q-\mu_H+\mu_{u_R}=0\ ,\quad -\mu_\ell+\mu_H+\mu_{e_R}=0\ ,$$
$$3\,(3\,\mu_q+\mu_\ell)=0\ ,\quad \mu_q+2\mu_{u_R}-\mu_{d_R}-\mu_\ell-\mu_{e_R}+\frac{2}{3}\mu_H=0\ ,$$

$$\mu_\ell+\mu_H=0\,,$$

If models need an extra asymmetry-transfer interaction, then DM asymmetry will also vanish!

$$X_{\rm DM}^2\,(\ell H)^2\quad,\quad X_{\rm DM}d_Rd_Ru_R\ ({\rm or}\ X_{\rm DM}^2d_Rd_Ru_R)$$

M. T. Frandsen, C. Hagedorn, WCH, E. Molinaro, H. Päs, arXiv:1801.09314

Conclusions

- Neutrino masses can be linked to the DM mass.
- Majorana neutrinos could explain observed baryon asymmetry.
- Specific ADM models can prevent baryon asymmetry from washout in case of observations of lepton number violation.
- ADM models that require an extra asymmetry transfer mechanism may be constrained by LNV observations.
- The synergy among DM, baryon asymmetry and neutrino physics is phenomenologically interesting.