Unifying Neutrino Mass and Cosmology in a Tripte-Doublet Extension

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A two scalar triplets model as common origin for dark matter, neutrino masses, baryon asymmetry and inflation

Sin Kyu Kang, Raymundo Ramos

We propose an extension of the standard model (SM) by two SU(2) triplet scalars and an inert SU(2) doublet. We demonstrate that this setup can simultaneously produce an inflaton and baryon asymmetry in the early universe, provide a dark matter candidate and explain the smallness of neutrino masses. The two triplets are particularly important as they become mediators for the production of dark matter and the generation of lepton asymmetry, as well as contribute an inflaton. The inert doublet results in a dark matter candidate. The required CP-violation for lepton asymmetry is obtained by interference between the triplet mediators that communicate the dark sector to the SM sector. More precisely, the complex Breit-Wigner propagators of the triplets and their mixing, result in an asymmetric production of leptons and antileptons that is boosted before dark matter freeze-out. In this case, simultaneously achieving enough dark matter relic abundance and proper matter-antimatter asymmetry limits the available parameter space of the model. Moreover, the scalar triplets are coupled non-minimally to gravity and give rise to the inflaton. We calculate the inflationary parameters and check that we can obtain predictions consistent with Planck constraints from 2018. We also perform an analysis of the reheating for the inflaton decays/annihilations to relativistic SM particles.

In collaboration with Raymundo Ramos(KIAS), axrXiv: 2510.07107

Outline

- Model setup
- Neutrino Masse Generation
- Cogenesis of Baryon Asymmetry and Dark Matter
- Numerical results
- Inflation and Reheating
- Remarks and Conclusions

Introduction

- The Standard Model successfully describes particle physics, but it leaves several fundamental questions unanswered:
  - ✓ the presence of massive neutrinos
  - ✓ the origin of matter-antimatter asymmetry
  - ✓ the nature of the dark matter (DM)

→ Can we address these three problems in a unified framework BSM ?

- DM is roughly 5 times more abundant than ordinary baryonic matter, $\Omega_{\mathrm{DM}} \approx 5\Omega_B$.

→ Is this coincidence or do they share a common origin?

Introduction

- The key idea of this work is that the same extended scalar sector can simultaneously explain neutrino masses, dark matter, and baryogenesis.

- To realize this, we introduce two SU(2) triplet scalars, which generate neutrino masses, and an inert doublet, which provides a DM candidate.
  → The interplay between two sectors also generates the baryon asymmetry.

- We also explore whether this framework can be extended to describe inflation in the early Universe.

Model Setup

Two scalar triplets and an inert doublet + SM ($SU(2)_L \times U(1)_Y \times Z_2$)

$$\Phi_1 = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(h_1 + v) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \Phi_2^+ \\ \frac{1}{\sqrt{2}}(H^0 + iA^0) \end{pmatrix}, \quad \Delta_n = \begin{pmatrix} \delta_n^+/\sqrt{2} & \delta_n^{++} \\ \delta_n^0 + u_n/\sqrt{2} & -\delta_n^+/\sqrt{2} \end{pmatrix}$$

- Leptonic couplings to the scalar triplets

$$-\mathcal{L}_{\mathrm{Yuk}} = \sum_{n=1}^{2} \sum_{j,k} Y_{jk}^{\Delta_n} L_j^T C^\dagger i\tau_2 \Delta_n L_k + \mathrm{H.c.},$$

To avoid FCNC, we impose Yukawa alignment

$Y^{\Delta_2} = \xi Y^{\Delta_1} \rightarrow Y^{\Delta} = Y^{\Delta_1} = Y^{\Delta_2}\xi^{-1}$

$$-\mathcal{L}_{\mathrm{Yuk}} = \sum_{j,k} Y_{jk}^{\Delta} L_j^T C^\dagger i\tau_2 \left(\Delta_1 + \xi\Delta_2\right) L_k + \mathrm{H.c.}$$

- Scalar potential

$$V = V_{\rm IDM} + V_\Delta + V_{H\Delta} + V_{\rm SB}$$

3 highlighted terms play a key role in neutrino mass generation and leptogenesis

$$V_{\rm IDM} = -m_{\Phi 1}^2 \Phi_1^\dagger \Phi_1 + m_{\Phi 2}^2 \Phi_2^\dagger \Phi_2 + \lambda_{\Phi 1} (\Phi_1^\dagger \Phi_1)^2 + \lambda_{\Phi 2} (\Phi_2^\dagger \Phi_2)^2 + \lambda_{\Phi 12} \Phi_1^\dagger \Phi_1 \Phi_2^\dagger \Phi_2 + \lambda'_{\Phi 12} \Phi_1^\dagger \Phi_2 \Phi_2^\dagger \Phi_1 + \lambda_5 {\rm Re}\left[(\Phi_1^\dagger \Phi_2)^2 \right]$$

$$V_\Delta = \sum_{n=1}^{2} \left\{ M_n^2\, {\rm Tr}\left(\Delta_n^\dagger \Delta_n\right) + \lambda_{\Delta n}\, {\rm Tr}\left[\left(\Delta_n^\dagger \Delta_n\right)^2\right] + \lambda'_{\Delta n} \left[{\rm Tr}\left(\Delta_n^\dagger \Delta_n\right)\right]^2 \right\} + \lambda_{\Delta 12}\, {\rm Tr}(\Delta_1^\dagger \Delta_1 \Delta_2^\dagger \Delta_2) + \lambda'_{\Delta 12}\, {\rm Tr}(\Delta_1^\dagger \Delta_1)\, {\rm Tr}(\Delta_2^\dagger \Delta_2) + \lambda_{\Delta 21}\, {\rm Tr}(\Delta_2^\dagger \Delta_1 \Delta_1^\dagger \Delta_2) + \lambda'_{\Delta 21}\, {\rm Tr}(\Delta_2^\dagger \Delta_1)\, {\rm Tr}(\Delta_1^\dagger \Delta_2)$$

$$V_{\Phi\Delta} = \sum_{n=1}^{2} \sum_{k=1}^{2} \left[\lambda_{\Phi k \Delta n} \Phi_k^\dagger \Phi_k\, {\rm Tr}\left(\Delta_n^\dagger \Delta_n\right) + \lambda'_{\Phi k \Delta n} \Phi_k^\dagger \Delta_n \Delta_n^\dagger \Phi_k \right]$$

$$V_{\rm SB} = \sum_{m=1}^{2} \left\{ \sum_{n=1}^{2} \mu_{nm} \Phi_m^T i\sigma^2 \Delta_n^\dagger \Phi_m + \lambda_{\Phi k \Delta 12} \Phi_m^\dagger \Phi_m\, {\rm Tr}\left(\Delta_1^\dagger \Delta_2\right) + \lambda'_{\Phi k \Delta 12} \Phi_m^\dagger \Delta_1 \Delta_2^\dagger \Phi_m \right\} + M_{12}^2\, {\rm Tr}\left(\Delta_1^\dagger \Delta_2\right) + \sum_{ijkl} \left[\lambda_{ijkl}\, {\rm Tr}\left(\Delta_i^\dagger \Delta_j \Delta_k^\dagger \Delta_l\right) + \lambda'_{ijkl}\, {\rm Tr}\left(\Delta_i^\dagger \Delta_j\right) \left(\Delta_k^\dagger \Delta_l\right) \right] + {\rm H.c.}$$

- SSB and minimization of scalar potential

SSB→ neutral components of Φ_1, $\Delta_{1,2}$ get VEVs

$$\langle\Phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v\end{pmatrix}, \quad \langle\Delta_n\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0 & 0\\ u_n & 0\end{pmatrix}$$

$$u_1^2 + u_2^2 = u^2$$

$$\tan\beta = \frac{u_2}{u_1}$$

- The VEVS must satisfy $v^2 + 2u^2 \approx (246\ \mathrm{GeV})^2$
- Constraints on the ρ parameter requires u to be below 8 GeV.
- Scalar potential minimization conditions :

$$0 = \lambda_{\Phi 1} v^2 - m_{\Phi 1}^2 + u^2\left(\lambda^q_{\Phi 1\Delta 1}\cos^2\beta + \lambda^q_{\Phi 1\Delta 2}\sin^2\beta + 2\lambda^q_{\Phi 1\Delta 12}\cos\beta\sin\beta\right) - \sqrt{2}u\left(\mu_{11}\cos\beta + \mu_{21}\sin\beta\right)$$

$$0 = u^3\left[(\lambda^q_{12} + \lambda^q_{1212})\cos\beta\sin^2\beta + \lambda^q_1\cos^3\beta + 3\left(\lambda^q_{2111} + \lambda^{q\prime}_{2111}\right)\cos^2\beta\sin\beta + \left(\lambda^q_{1222} + \lambda^{q\prime}_{1222}\right)\sin^3\beta\right] + u\left[M_1^2\cos\beta + M_{12}^2\sin\beta + \lambda^q_{\Phi 1\Delta 12}v^2\sin\beta + \lambda^q_{\Phi 1\Delta 1}v^2\cos\beta\right] - \frac{\mu_{11}}{\sqrt{2}}v^2$$

$$0 = u^3\left[(\lambda^q_{12} + \lambda^q_{1212})\cos^2\beta\sin\beta + \lambda^q_2\sin^3\beta + 3\left(\lambda^q_{1222} + \lambda^{q\prime}_{1222}\right)\cos\beta\sin^2\beta + \left(\lambda^q_{2111} + \lambda^{q\prime}_{2111}\right)\cos^3\beta\right] + u\left[M_2^2\sin\beta + M_{12}^2\cos\beta + \lambda^q_{\Phi 1\Delta 12}v^2\cos\beta + \lambda^q_{\Phi 1\Delta 2}v^2\sin\beta\right] - \frac{\mu_{21}}{\sqrt{2}}v^2$$

$$\lambda^q_n \equiv \lambda_{\Delta n} + \lambda'_{\Delta n},$$

$$\lambda^q_{\Phi 1\Delta n} \equiv (\lambda_{\Phi 1\Delta n} + \lambda'_{\Phi 1\Delta n})/2,$$

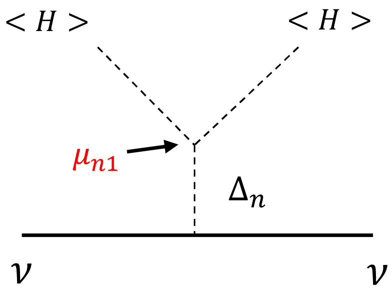
$$\lambda^q_{12} \equiv (\lambda_{\Delta 12} + \lambda_{\Delta 21} + \lambda'_{\Delta 12} + \lambda'_{\Delta 21})/2,$$

$$\lambda^q_{\Phi 1\Delta 12} \equiv (\lambda_{\Phi 1\Delta 12} + \lambda'_{\Phi 1\Delta 12})/2,$$

- SSB and minimization of scalar potential

- Using the minimization conditions, we can rewrite the mass-squared terms

$$
\begin{aligned}
m_{\Phi 1}^2 &= \lambda_{\Phi 1} v^2 + u^2 \left(\lambda^q_{\Phi 1 \Delta 1} \cos^2\beta + \lambda^q_{\Phi 1 \Delta 2} \sin^2\beta + 2\lambda^q_{\Phi 1 \Delta 12} \cos\beta \sin\beta\right) \\
&\quad - \sqrt{2} u \left(\mu_{11} \cos\beta + \mu_{21} \sin\beta\right) \\
M_1^2 &= -u^2 \cos^2\beta \left[\lambda^q_1 + 3\left(\lambda^q_{2111} + \lambda^{q'}_{2111}\right) \tan\beta + \left(\lambda^q_{12} + \lambda^q_{1212}\right) \tan^2\beta + \left(\lambda^q_{1222} + \lambda^{q'}_{1222}\right) \tan^3\beta\right] \\
&\quad - v^2 \left(\lambda^q_{\Phi 1 \Delta 1} + \lambda^q_{\Phi 1 \Delta 12} \tan\beta\right) - M_{12}^2 \tan\beta + \frac{\mu_{11} v^2}{\sqrt{2} u \cos\beta} \\
M_2^2 &= -u^2 \sin^2\beta \left[\lambda^q_2 + 3\left(\lambda^q_{1222} + \lambda^{q'}_{1222}\right) \cot\beta + \left(\lambda^q_{12} + \lambda^q_{1212}\right) \cot^2\beta + \left(\lambda^q_{2111} + \lambda^{q'}_{2111}\right) \cot^3\beta\right] \\
&\quad - v^2 \left(\lambda^q_{\Phi 1 \Delta 2} + \lambda^q_{\Phi 1 \Delta 12} \cot\beta\right) - M_{12}^2 \cot\beta + \frac{\mu_{21} v^2}{\sqrt{2} u \sin\beta}
\end{aligned}
$$



u can be small when M_n^2 is large and/or μ_{n1} is small

→ inverse type-II seesaw

→ smallness of u is responsible for tiny neutrino masses

Generation of neutrino masses

- When $\Delta_{1,2}$ acquire VEVs, Yukawa interactions generate neutrino masses at tree level

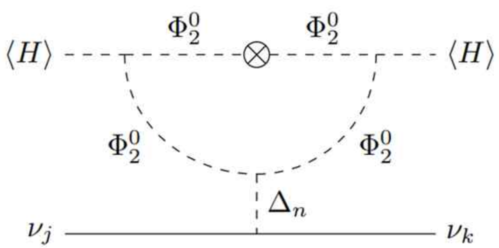
$$-\mathcal{L}_{\rm Yuk} = \sum_{j,k} Y^{\Delta}_{jk} L^T_j \mathcal{C}^\dagger i\tau_2 \left(\Delta_1 + \xi \Delta_2\right) L_k + \text{H.c.}$$

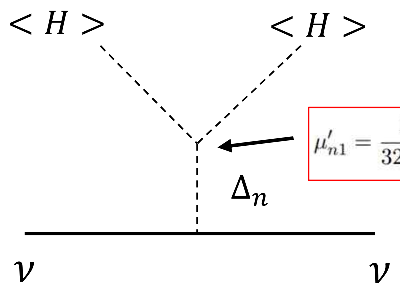
$$\Rightarrow \quad M^\nu_{jk} = \sqrt{2} Y^\Delta_{jk} u \cos\beta \left(1 + \xi \tan\beta\right)$$

$$\sqrt{2} Y^\Delta_{jk} u \cos\beta \left(1 + \xi \tan\beta\right) = \left(U^*_{\rm PMNS} M^\nu_d U^\dagger_{\rm PMNS}\right)_{jk}$$

(we use NuFIT 6)

- 1-loop correction to the masses of the neutrinos can occur due to the λ_5 coupling





$$\mu'_{n1} = \frac{1}{32\pi^2} \mu_{n2} \lambda_A^2 \lambda_5 v^4 f(m^2_{\Phi^0_2})$$

we consider a parameter region where the tree-level contribution dominates.

Cogenesis of Baryon Asymmetry and Dark Matter

Baryon asymmetry → leptogenesis

New mechanism for matter-antimatter asymmetry and connection with dark matter

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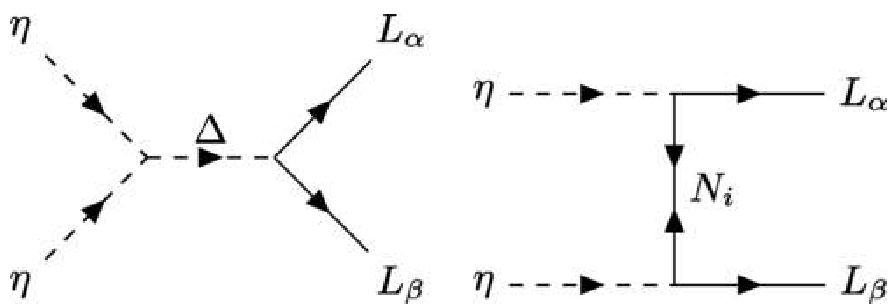
A net lepton or baryon asymmetry can be generated from the interference effect of scattering diagrams with the same initial and final states, as long as the following two conditions are satisfied:

- There is a net nonzero lepton or baryon number between the initial and final states.

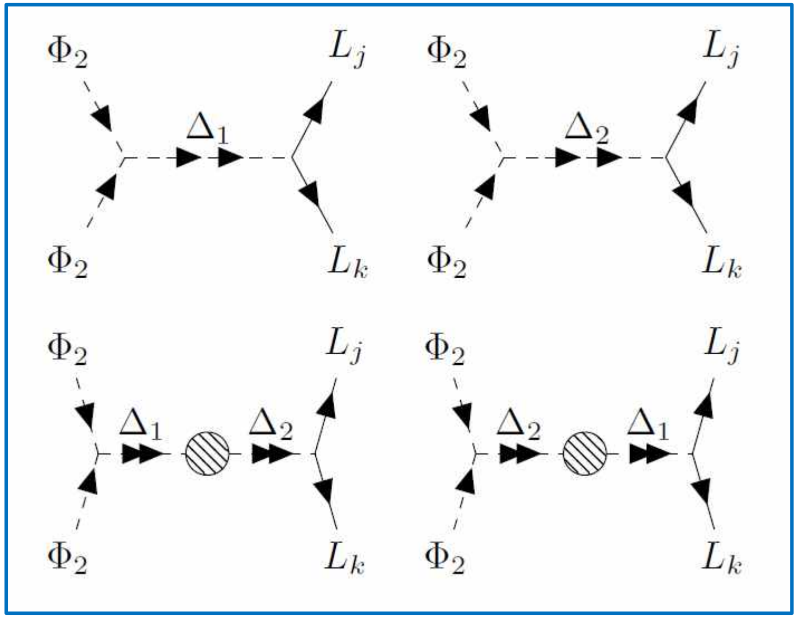
- At least one set of scattering amplitudes is complex such that the squared amplitudes for particles and antiparticles are different, giving rise to a net CP-asymmetry



Cogenesis of Baryon Asymmetry and Dark Matter

In our model

Lepton asymmetry is achieved via interference between scattering mediated by unstable fields



→ Arises from the diagonal and off-diagonal components of the full resummed propagator

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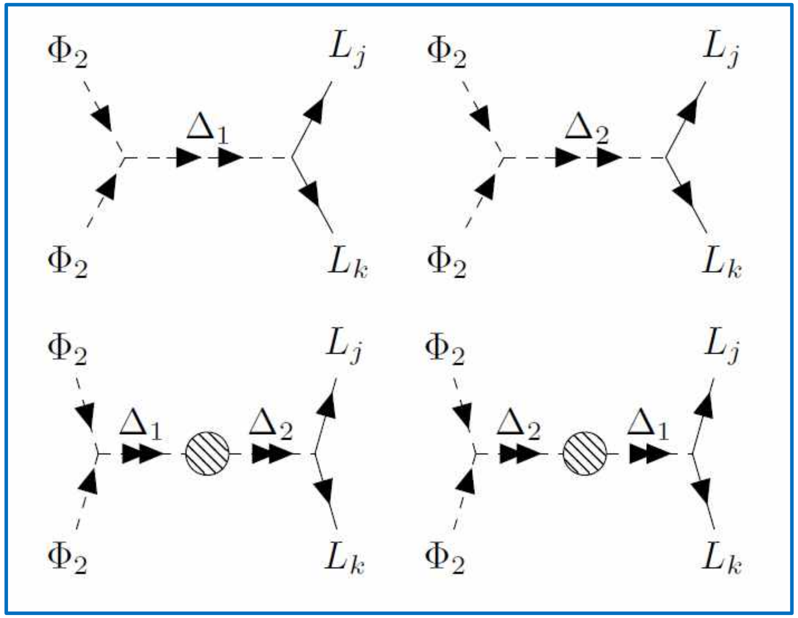


- The off-diagonal mixing can be described as

$$\Delta_a^\dagger \left(M_D^2\right)_{ab} \Delta_b + h.c.$$

$$M_D^2 = \begin{pmatrix} M_{\Delta_1}^2 - iC_{11} & -iC_{12} \\ -iC_{21} & M_{\Delta_2}^2 - iC_{22} \end{pmatrix}$$

$$C_{ab} = \Gamma_{ab} M_{\Delta_b} = \frac{1}{8\pi}\left(\mu_{a2}\mu_{b2}^* + p^2 \sum_{\alpha\beta} Y_{\alpha\beta}^{\Delta_a *} Y_{\alpha\beta}^{\Delta_b}\right)$$

- We proceed to diagonalization of M_D^2

$$M_D^2 = L^\dagger M_{Dd}^2 R$$

- Changing basis : $(\Delta_{R1}, \Delta_{R2})^T = R(\Delta_1, \Delta_2)^T$

$$(\Delta_{L1}^*, \Delta_{L2}^*)^T = L^*(\Delta_1^*, \Delta_2^*)^T.$$

$$\Delta_{Rn} \to \delta_{Rn}^0 \,,\; \delta_{Rn}^+ \,,\; \delta_{Rn}^{++}$$

$$\Delta_{Ln}^* \to \delta_{Ln}^{0*} \,,\; \delta_{Ln}^- \,,\; \delta_{Ln}^{--}$$

$$\Delta_{R1} = \Delta_1 - \frac{iC_{12}\Delta_2}{M_{\Delta_1}^2 - M_{\Delta_2}^2}$$

$$\Delta_{R2} = \frac{iC_{12}^*\Delta_1}{M_{\Delta_1}^2 - M_{\Delta_2}^2} + \Delta_2$$

$$\Delta_{L1}^* = \Delta_1^* - \frac{iC_{12}^*\Delta_2^*}{M_{\Delta_1}^2 - M_{\Delta_2}^2}$$

$$\Delta_{L2}^* = \frac{iC_{12}\Delta_1^*}{M_{\Delta_1}^2 - M_{\Delta_2}^2} + \Delta_2^*$$

This provides a simplified description of the diagonalization of the resummed propagators mediated by Δ_1 & Δ_2

- CP asymmetry

$$\delta \equiv |\mathcal{M}|^2 - |\bar{\mathcal{M}}|^2$$

$$= -4\left[\left|Y_{jk}^{\Delta}\right|^2 \mathrm{Im}\left[\mu_{12}\mu_{22}^*\xi^*\right] \mathrm{Im}\left[\frac{1}{\mathcal{S}_1\mathcal{S}_2^*}\right]\right.$$

$$+ \frac{\left|Y_{jk}^{\Delta}\right|^2}{|\mathcal{S}_1|^2}\left(\left|Y_{lm}^{\Delta}\right|^2 + |\mu_{12}|^2\right) \mathrm{Im}\left[\mu_{12}\mu_{22}^*\xi^*\right] \mathrm{Im}\left[\frac{C_{12}^*}{\mathcal{S}_2^*}\right]$$

$$\left.+ \frac{\left|Y_{jk}^{\Delta}\right|^2}{|\mathcal{S}_2|^2}\left(\left|\xi Y_{lm}^{\Delta}\right|^2 + |\mu_{22}|^2\right) \mathrm{Im}\left[\mu_{12}^*\mu_{22}\xi\right] \mathrm{Im}\left[\frac{C_{21}^*}{\mathcal{S}_1^*}\right]\right] |\mathcal{W}|^2$$

$$\mathcal{S}_i^{-1} = s - M_{\Delta_i}^2 - iM_{\Delta_i}\Gamma_{\Delta_i}$$

→ Wave function of incoming and outgoing particles

- Interference between diagonal propagators

$$\mathrm{Im}\left[\frac{1}{\mathcal{S}_1\mathcal{S}_2^*}\right] = \frac{\left(s - M_{\Delta_1}^2\right) M_{\Delta_2}\Gamma_{\Delta_2} - \left(s - M_{\Delta_2}^2\right) M_{\Delta_1}\Gamma_{\Delta_1}}{\left[\left(s - M_{\Delta_1}^2\right)^2 + M_{\Delta_1}^2\Gamma_{\Delta_1}^2\right]\left[\left(s - M_{\Delta_2}^2\right)^2 + M_{\Delta_2}^2\Gamma_{\Delta_2}^2\right]}$$

- Processes contributing to the lepton asymmetry :

$$\Phi_2^0 + \Phi_2^0 \to \delta_{Rn}^0 \to \bar{\nu}_j + \bar{\nu}_k\,, \quad \Phi_2^{0*} + \Phi_2^{0*} \to \delta_{Ln}^{0*} \to \nu_j + \nu_k\,,$$

$$\Phi_2^+ + \Phi_2^0 \to \delta_{Rn}^+ \to \ell_j^+ + \bar{\nu}_k\,, \quad \Phi_2^- + \Phi_2^{0*} \to \delta_{Ln}^- \to \ell_j^- + \nu_k\,,$$

$$\Phi_2^+ + \Phi_2^+ \to \delta_{Rn}^{++} \to \ell_j^+ + \ell_k^+\,, \quad \Phi_2^- + \Phi_2^- \to \delta_{Ln}^{--} \to \ell_j^- + \ell_k^-\,.$$

  - Those processes can also contribute to the evolution of DM, but are small

- **Φ_2 is DM candidate** and its (co-)annihilation is responsible for relic density
  - For Φ_2 with mass of order TeV, the dominant contributions to the relic density are annihilation into $W^{\pm}$ pair.
  - Annihilations into SM fermions and coannihilations into W & Z are subleading

- **Boltzmann eqs. describing evolution of DM & lepton asymmetry**

$$\frac{dY_{\Phi_2}}{dx} = \frac{-s}{H(x)x}\left(Y_{\Phi_2}^2 - Y_{\mathrm{eq},\Phi_2}^2\right)\langle\sigma v\rangle\,(\Phi_2\Phi_2 \to \mathrm{SM\,SM})\ ,$$

➡ Evolution of DM

$$\frac{dY_{\Delta L}}{dx} = \frac{s}{H(x)x}\Big[\left(Y_{\Phi_2}^2 - Y_{\mathrm{eq},\Phi_2}^2\right)\langle\sigma v\rangle_\delta\,(\Phi_2\Phi_2 \to LL)$$
$$- 2Y_{\Delta L}Y_{\mathrm{eq},\Phi_2}^2 Y_{\mathrm{eq},\ell}^{-1}\langle\sigma v\rangle_{\mathrm{tot}}\,(\Phi_2\Phi_2 \to LL)$$
$$- 2Y_{\Delta L}Y_{\mathrm{eq},\Phi_2}\langle\sigma v\rangle_{\mathrm{tot}}\left(\Phi_2\bar{L} \to \Phi_2^* L\right)\Big]$$

➡ Evolution of Lepton Asy.

$$x = \frac{m_{\Phi_2}}{T} \qquad Y_{(\mathrm{eq})k} = \frac{n_{(\mathrm{eq})k}}{s}$$

$$H(x) = \sqrt{\frac{8\pi^3 g_*(T)}{90}}\,\frac{m_{\mathrm{L}\Phi_2}^2}{x^2 M_{\mathrm{Pl}}}$$

$$\langle \sigma v \rangle_\delta (\Phi_2 \Phi_2 \to LL) \equiv \langle \sigma v \rangle (\Phi_2 \Phi_2 \to LL) - \langle \sigma v \rangle \left(\Phi_2^* \Phi_2^* \to \bar{L}\bar{L}\right) ,$$

$$\langle \sigma v \rangle_{\rm tot} (\Phi_2 \Phi_2 \to LL) \equiv \langle \sigma v \rangle (\Phi_2 \Phi_2 \to LL) + \langle \sigma v \rangle \left(\Phi_2^* \Phi_2^* \to \bar{L}\bar{L}\right) .$$

$$Y_{\Delta B} = -(28/51) Y_{\Delta L}$$

Lepton asym. converted to Baryon asym.

at the sphaleron temperature $T_{\rm sph} = 131.7 \pm 2.3$ GeV

- To make washout processes become inefficient before DM freeze-out, the mass scale for neutral comp. Φ_2 is required to be above O(0.1)TeV, where the main annihilation channel is into $W^{\pm}$ boson pairs.
- This places the DM mass in a regime where coannihilations among nearly degenerate states are required to achieve the correct relic density.

Numerical Results

Table 1:

Parameter	BP1	BP2
u [10^{-10} GeV]	1.502	1.065
$\tan\beta$	4.768	4.765
μ_{11} [10^{-8} GeV]	3.0	4.780
μ_{21} [10^{-8} GeV]	6.911	5.059
μ_{12} [10^{-1} GeV]	1.488	1.653
μ_{22} [10^{-6} GeV]	3.091	5.424
$\|\xi\|$ [10^{-2}]	1.140	1.154
ang(ξ) [rad]	-0.9538	-0.9549
ϕ_1 [rad]	-2.386	-2.728
ϕ_2 [rad]	-0.1452	0.2269
m_{H^0} [TeV]	2.0	
m_{A^0} [TeV]	2.001	
$M_{\Phi_2^\pm}$ [TeV]	2.008	
λ_A	10^{-3}	
m_{ν_1} [eV]	10^{-5}	
M_{12}^2 [GeV^2]	$(10^{-6})^2$	

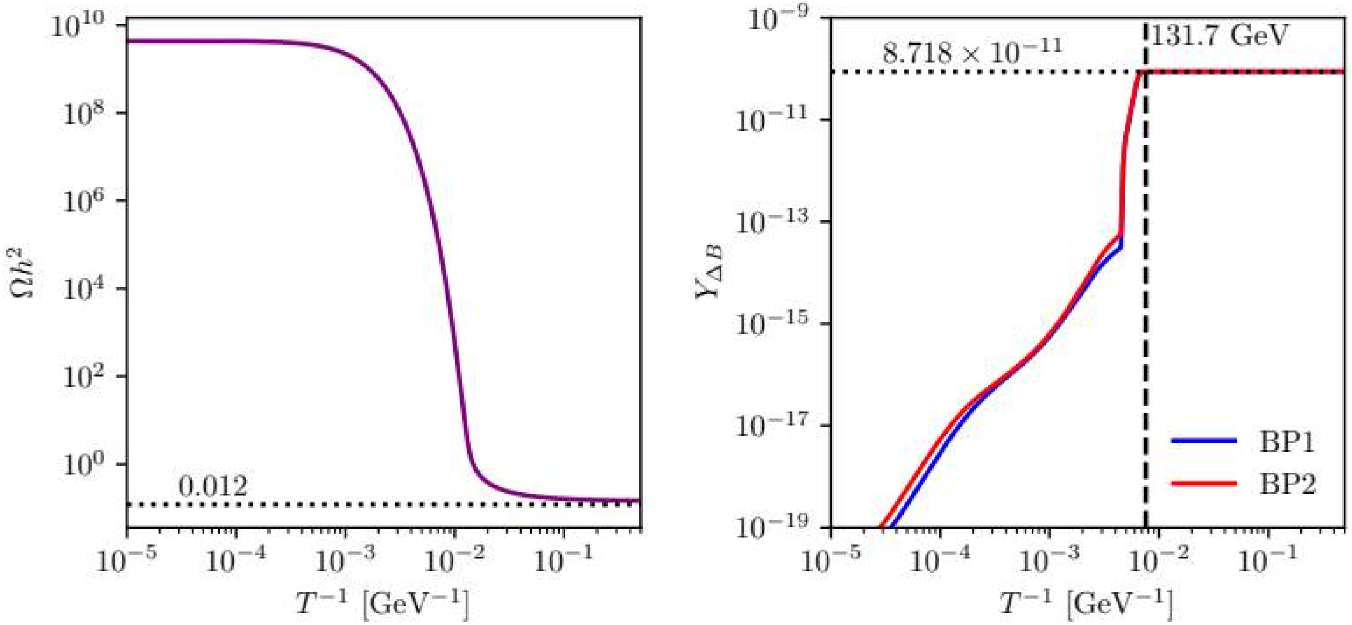
	BP1	BP2
$Y^{\Delta}_{(1,1)}$	$-0.00491 + i0.04129$	$-0.02237 + i0.02083$
$Y^{\Delta}_{(1,2)}$	$-0.1792 + i0.0243$	$-0.2644 + i0.0720$
$Y^{\Delta}_{(1,3)}$	$-0.05340 - i0.05526$	$-0.05757 + i0.00488$
$Y^{\Delta}_{(2,2)}$	$0.5565 + i0.1693$	$0.7666 - i0.1177$
$Y^{\Delta}_{(2,3)}$	$0.5903 + i0.0634$	$0.8478 - i0.1703$
$Y^{\Delta}_{(3,3)}$	$0.4360 + i0.1376$	$0.5987 - i0.0871$
M_{Δ_1} [GeV]	6457	9679
M_{Δ_2} [GeV]	4488	4562
$\sigma_{\rm SI}$ [cm^2]	8.911×10^{-51}	
$\langle \sigma v(W^+W^-)\rangle$ [cm^3 s^{-1}]	3.67×10^{-26}	

TABLE II. Numerical results corresponding to the inputs of Table I.

- 2 BPs used to solve BZ eqs.

$\Omega h^2 = 0.120 \pm 0.001$ $\quad$ $Y_{\Delta B} = (8.718 \pm 0.004) \times 10^{-11}$ ← Observations

Numerical Results

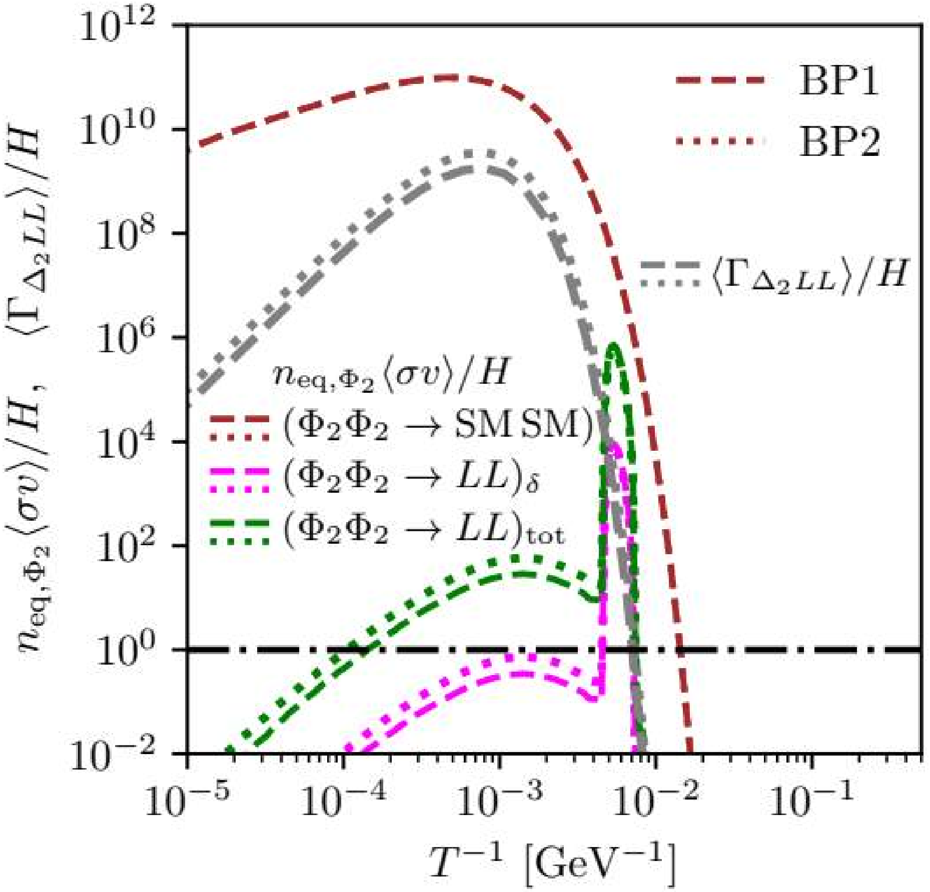


- The onset of freeze-out of DM is at a temperature around
  $T_f^{-1} \sim 10^{-2} [\text{GeV}^{-1}]$
  $(x_f \sim 26)$

- Around this time, L asymmetry is rapidly generated and later converted into B-asymmetry via sphalerons.

Since the DM-relevant parameters are the same, both BPs give identical evolution

Numerical Results



- The dominant process for DM evolution is $\Phi_2\Phi_2 \to \mathrm{SM\,SM}$ which controls the freeze-out of DM
- Leptonic process rates are enhanced near resonance s~$M_{\Delta_2}^2$~$2m_\Phi^2$, but the asymmetry is generated only when DM departs from eq.
- In the NWA, the cross section reduces to

$$\sigma(\Phi_2\Phi_2 \to LL)\big|_{p^2_{\Delta_2}=M^2_{\Delta_2}} \simeq \sigma(\Phi_2\Phi_2 \to \Delta_2) \times \mathrm{Br}(\Delta_2 \to LL)$$

- The asymmetry is not generated by mediator decays, because the triplet remains in thermal equilibrium (gray curves)

Inflation & Reheating

- How can inflation be embedded within this framework addressing other unresolved problems of the SM?

- We examine whether new scalar fields can drive inflation in consistent with both cosmological observations, phenomenological constraints from DM & baryon asym.

- For our purpose, we focus on the neutral components of the scalar fields

$$\Phi_1^0 = \frac{1}{\sqrt{2}} h_1 \,, \quad \Phi_2^0 = \frac{1}{\sqrt{2}} h_2 e^{i\vartheta} \,, \quad \Delta_1^0 = \frac{1}{\sqrt{2}} \delta_1 e^{i\alpha_1} \,, \quad \Delta_2^0 = \frac{1}{\sqrt{2}} \delta_2 e^{i\alpha_2}$$

- In the Jordan framework,

$$\begin{aligned} \frac{\mathcal{L}_{\mathcal{J}}}{\sqrt{-g_J}} = &- \frac{1}{2} M_{\rm Pl}^2 R + \left(\xi_1 h_1^2 + \xi_2 h_2^2 + \xi_{\delta_1} \delta_1^2 + \xi_{\delta_2} \delta_2^2 \right) R \\ &- |D_\mu h_1|^2 - |D_\mu h_2|^2 - |D_\mu \delta_1|^2 - |D_\mu \delta_2|^2 \\ &- V_J \left(\Phi_1^0, \Phi_2^0, \Delta_n^0 \right) \,. \end{aligned}$$

ξ_i : non-minimal coupling (positive and real)

- Making a Weyl transformation $g^J_{\mu\nu} = \frac{g^E_{\mu\nu}}{\Omega^2}$ with $\Omega^2 \equiv 1 + \frac{1}{M_{\rm Pl}^2}\left(\xi_1 h_1^2 + \xi_2 h_2^2 + \xi_{\delta_1}\delta_1^2 + \xi_{\delta_2}\delta_2^2\right)$

- The Lagrangian :

$$\frac{\mathcal{L}_E}{\sqrt{-g_E}} = -\frac{1}{2}M_{\rm Pl}^2 R - \frac{3}{4}\left[M_{\rm Pl}\partial_\mu \log\Omega^2\right]^2 - \frac{(\partial_\mu h_1)^2 + (\partial_\mu h_2)^2 + (\partial_\mu \delta_1)^2 + (\partial_\mu \delta_2)^2}{2\Omega^2}$$
$$- \frac{(h_2\partial_\mu\vartheta)^2 + (\delta_1\partial_\mu\alpha_1)^2 + (\delta_2\partial_\mu\alpha_2)^2}{2\Omega^2} - V_E(\Phi_1^0, \Phi_2^0, \Delta_n^0)\,,$$

- We consider two-triplet inflation : $\phi^I = \{\delta_1, \delta_2\}$

- In the large field limit, $\xi_{\delta_1}\delta_1^2 + \xi_{\delta_2}\delta_2^2 \gg M_{\rm Pl}^2$, only quartic terms in the scalar potential are dominant

$$V_E(\phi^I) = \frac{\lambda_{\Delta_1}\delta_1^4 + \lambda_{\Delta_2}\delta_2^4 + 2\lambda_{\Delta_M}\delta_1^2\delta_2^2}{8\Omega^4}$$

- Redefining $\varphi = \sqrt{\frac{3}{2}} M_{\rm Pl} \log(\Omega^2), \quad s = \frac{\delta_2}{\delta_1}$

$$\frac{\mathcal{L}_E}{\sqrt{-g_E}} \approx -\frac{1}{2} M_{\rm Pl}^2 R - \frac{1}{2}\left(1 + \frac{1}{6}\frac{s^2+1}{\xi_{\delta_2} s^2 + \xi_{\delta_1}}\right)(\partial_\mu \varphi)^2 - \frac{1}{\sqrt{6}}\frac{(\xi_{\delta_1} - \xi_{\delta_2})s}{(\xi_{\delta_2} s^2 + \xi_{\delta_1})^2}(\partial_\mu \varphi)(\partial^\mu \tilde{s}) - \frac{1}{2}\frac{\xi_{\delta_2}^2 s^2 + \xi_{\delta_1}^2}{(\xi_{\delta_2} s^2 + \xi_{\delta_1})^3}(\partial_\mu \tilde{s})^2 - V_E(\varphi, s)\,,$$

$$V_E(\varphi, s) = M_{\rm Pl}^4 \frac{\lambda_{\Delta_1} + \lambda_{\Delta_2} s^4 + 2\lambda_{\Delta_M} s^2}{8\,(\xi_{\delta_2} s^2 + \xi_{\delta_1})^2}\left(1 - e^{-\frac{2\varphi}{\sqrt{6} M_{\rm Pl}}}\right)^2 .$$

Starobinsky potetntial

- By minimizing the scalar potential $V_E(\varphi, s)$ with respect to s, we get a extrema occurred at $s = s_0 = \frac{\lambda_{\Delta_1}\xi_{\delta_2} - \lambda_{\Delta_M}\xi_{\delta_1}}{\lambda_{\Delta_2}\xi_{\delta_1} - \lambda_{\Delta_M}\xi_{\delta_2}}$

$$V_E(\varphi, s)|_{s=s_0} = \frac{\lambda_{\rm eff} M_{\rm Pl}^4}{4\xi_{\rm eff}^2}\left(1 - e^{-2\varphi'/\sqrt{6}}\right)^2 = M_{\rm Pl}^4 \frac{\lambda_{\Delta_1}\lambda_{\Delta_2} - \lambda_{\Delta_M}^2}{8\,(\lambda_{\Delta_1}\xi_{\delta_2}^2 + \lambda_{\Delta_2}\xi_{\delta_1}^2 - 2\lambda_{\Delta_M}\xi_{\delta_1}\xi_{\delta_2})}$$

where $\varphi' = \varphi/M_{\rm Pl}$, $\xi_{\rm eff} = \xi_{\delta_2} s_0^2 + \xi_{\delta_1}$ and $\lambda_{\rm eff} = (\lambda_{\Delta_1} + \lambda_{\Delta_2} s_0^4 + \lambda_{\Delta_M} s_0^2)/2$

- Using the standard slow-roll analysis, we evaluate the observables at $\mathcal{N} = 60$ corresponding to horizon exit

$$r = 16\epsilon \simeq 0.00298,$$

$$n_s = 1 - 6\epsilon + 2\eta \simeq 0.9677,$$

$$n_{rs} = -2\zeta - 24\epsilon^2 + 16\eta\epsilon \simeq -4.86 \times 10^{-5}$$

- Matching the amplitude of the scalar power spectrum with the observational value

(Planck 2018) ⇒ $\xi_{\rm eff} \simeq 5.1 \times 10^4 \sqrt{\lambda_{\rm eff}}$

$$\xi_{\rm eff} = \xi_{\delta_2} s_0^2 + \xi_{\delta_1} \text{ and } \lambda_{\rm eff} = (\lambda_{\Delta_1} + \lambda_{\Delta_2} s_0^4 + \lambda_{\Delta_M} s_0^2)/2$$

Reheating

- After inflation, the energy stored in the inflaton field is transferred to SM particles through reheating, bringing the Universe into a radiation-dominated phase.

- During reheating, the inflaton oscillation produces gauge bosons with field-dependent masses.

$$m_W^2(\varphi) = \frac{g^2}{2\sqrt{6}} \frac{M_{\rm Pl}|\varphi|}{\xi_{\rm eff}} \qquad m_{h_i}^2(\varphi) = \lambda_i \sqrt{\frac{2}{3}} \frac{M_{\rm Pl}|\varphi|}{\xi_{\rm eff}} \qquad m_F(\varphi) = y_F \sqrt{\frac{M_{\rm Pl}|\varphi|}{\sqrt{6}\xi_{\rm eff}}}$$

$$\varphi \simeq \sqrt{\frac{3}{2}} M_{\rm Pl} \frac{\xi_{\rm eff}\delta^2}{M_{\rm Pl}^2}$$

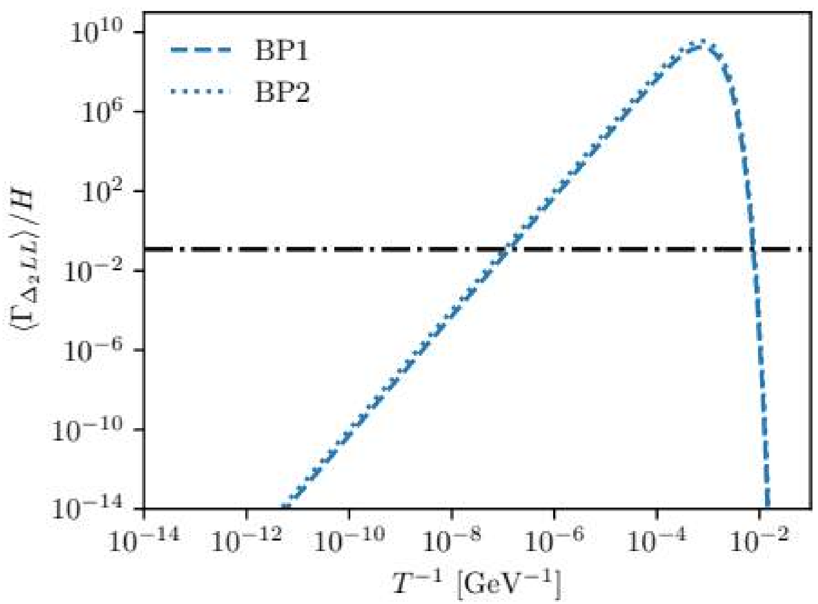
- These particles subsequently decay and scatter, and their interactions, including annihilations, lead to rapid thermalization of the Universe.

- Radiation density is approximately given by $\rho_{\rm rad} = \frac{\pi^2}{30} g_* T_{\rm reh}^4 \approx \frac{1.46\times 10^{57}}{\sqrt{\lambda_{\rm eff}}}$

→ $T_{\rm reh} \sim 10^{14}$ GeV

- Since the reheating process relies on the decay of the inflaton (triplet scalars), a primordial lepton asymmetry can be generated via LNV triplet decay.

- However, the subsequent thermal history of the Universe ensures that this initial asymmetry is efficiently erased in this model.



- For $10^7\,\mathrm{GeV} \geq T \geq T_{sph}$ ($\sim$131.7 GeV), $\frac{\Gamma}{H} \geq 1$

- the triplets enter thermal equilibrium, efficiently washing out any primordial lepton asymmetry generated during the reheating epoch.

- Thus, reheating process does not affect the generation of baryon asymmetry achieved via the LNV scattering.

Remarks

- We use CalcHEP & micrOMEGAs program code to calculate amplitudes, decay width & relic density of DM.
- The parameters $\mu_{m\,n}$ control the triplet masses and the CP-violating mixing responsible for lepton asymmetry.
- The parameters u & β determine the neutrino mass scale and the structure of the triplet VEVs.
- Experimental searches by ATLAS and CMS place lower bounds around the TeV scale on doubly charged scalars, and our triplet masses lie safely above these limits.
- For dark matter direct detection, the predicted spin-independent cross section σ_{SI} is several orders of magnitude below current experimental limits, such as those from XENON1T.

Conclusion

- Three problems in the SM can be explained in the extended SM with new scalar sectors composed of two SU(2) triplets and one inert doublet.
- The two triplet scalars generate light neutrino masses via the type-II seesaw mechanism, and the same interactions induce lepton-number-violating 2-to-2 scatterings.
- The inert doublet is a viable DM candidate and participates in the scattering processes that generate lepton asymmetry, which is later converted into baryon asymmetry via sphaleron processes.
- The triplet scalars can play the role of inflation in consistent with cosmological observation, cogenesis of baryon asymmetry and dark matter.
- *It is tempting to speculate that this model could be embedded in a more fundamental GUT framework.*

Unitarity & CPT invariance

- Amount of CP-violation from 2-to-2 scatterings is constrained by unitarity & CPT
  (Pilaftsis, NPB504(1997), E. Roulet, L. Covi and F. Vissani PLB424(1998))
- For any fixed initial state i, CPT invariance implies $\sum_f, \hat{\sigma}(i \to f) = \sum_f, \hat{\sigma}(\bar{i} \to \bar{f})$
- Defining CP asymmetry of a given channel as $\Delta\hat{\sigma}(i \to f) \equiv \hat{\sigma}(i \to f) - \hat{\sigma}(\bar{i} \to \bar{f})$
  the following sum rule holds : $\sum_f \Delta\hat{\sigma}(i \to f) = 0$
- Separating LNV final states of interest from the LNC channels,

$$\hat{\sigma}(\Phi_2\Phi_2 \to L_l L_m) + \sum_{k \neq L_l L_m} \hat{\sigma}(\Phi_2\Phi_2 \to k) = \hat{\sigma}(\Phi_2\Phi_2 \to \bar{L}_l \bar{L}_m) + \sum_{\bar{k} \neq \bar{L}_l \bar{L}_m} \hat{\sigma}(\Phi_2\Phi_2 \to \bar{k})$$

Unitarity & CPT invariance

- Rearranging the previous expression by using the definition of CP asymmetry,

$$\Delta\hat{\sigma}(\Phi_2\Phi_2 \to L_l L_m) = -\sum_{k \neq L_l L_m} \Delta\hat{\sigma}(\Phi_2\Phi_2 \to k)$$

- This represents L-asymmetry is compensated by LNC asymmetry, but LNC asymmetry does not contribute to the generation of B-asymmetry.

- As a result, a physically relevant asymmetry arises only when the system departs from equilibrium during DM freeze-out.