EXPLICIT AND SPONTANEOUS CP VIOLATION IN LIGHT OF TRIPLET LEPTOGENESIS

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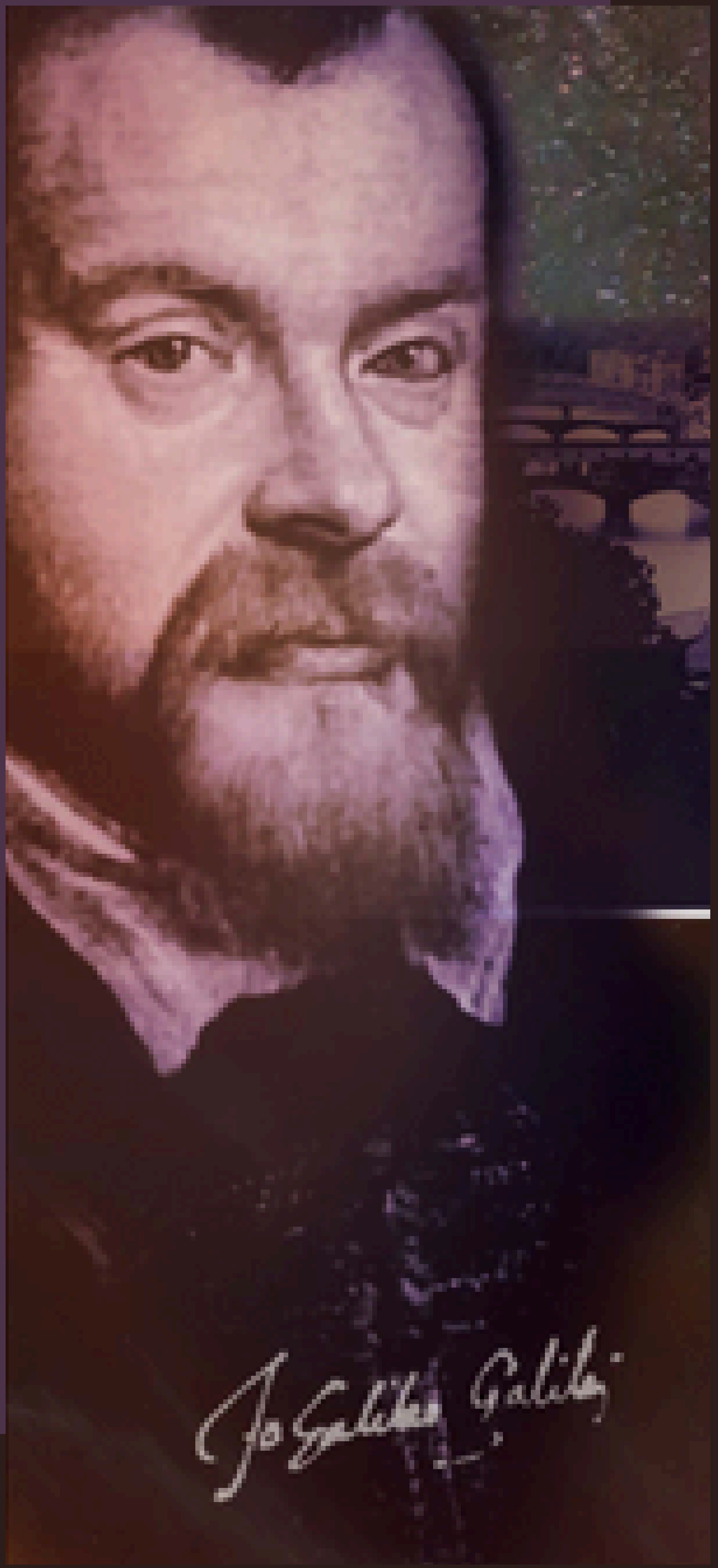
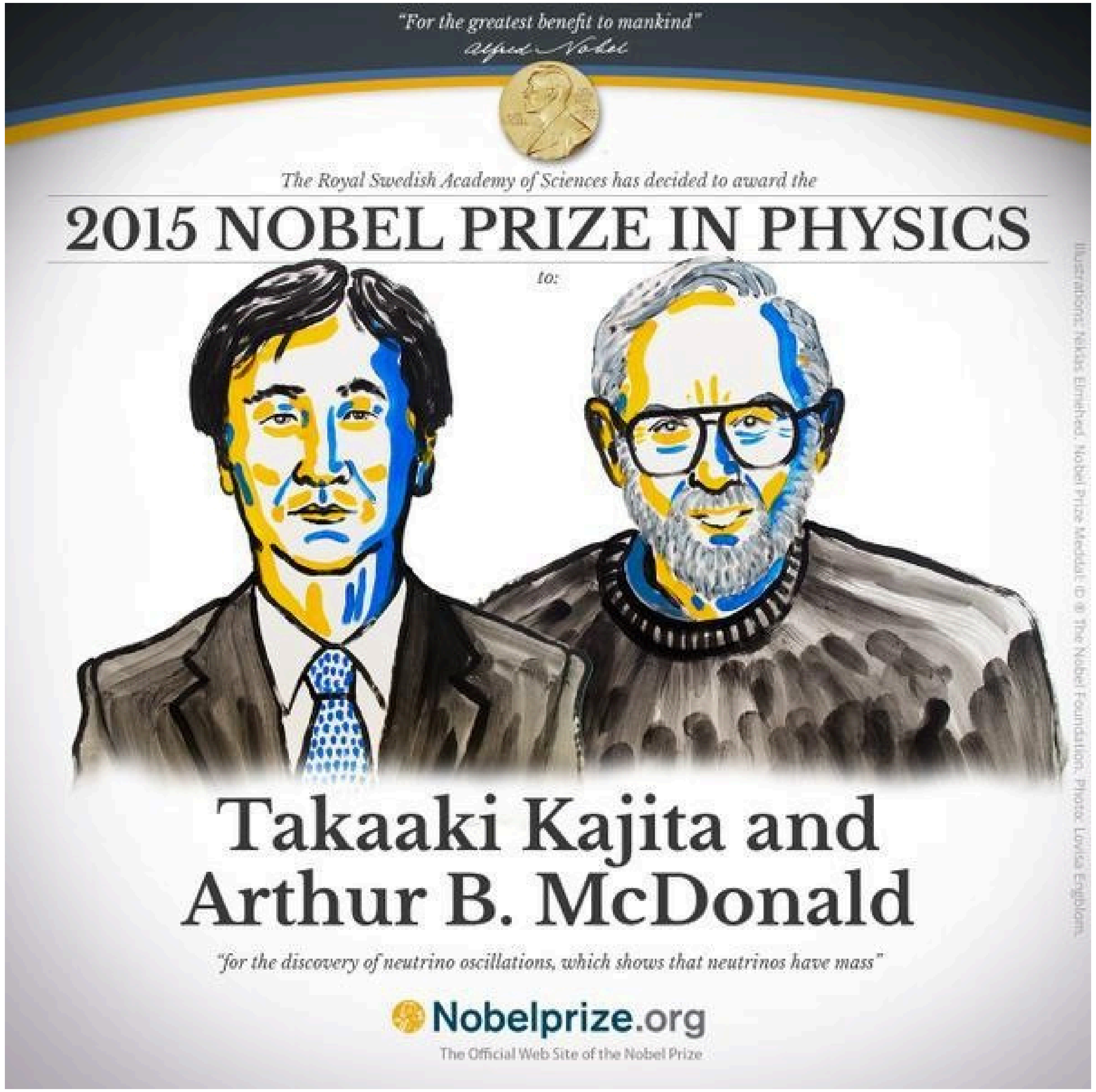


Solar and atmospheric neutrino deficit

Neutrino Flavour Oscillation

Non-zero neutrino mass

(forbidden in SM)



Neutrino Mass generation

+

Missing antimatter

Neutrino Mass generation $+$ **Baryogenesis!!**

$$\eta_B = \frac{n_B - n_{\overline{B}}}{n_\gamma}$$ [Kolb, Turner (1990)]

$$4.7 \times 10^{-10} \leq \eta_B \leq 6.5 \times 10^{-10}$$ [Amsler (2008)]

BBN, CMB

"Baryogenesis through Leptogenesis"

SAKHAROV'S CONDITIONS:

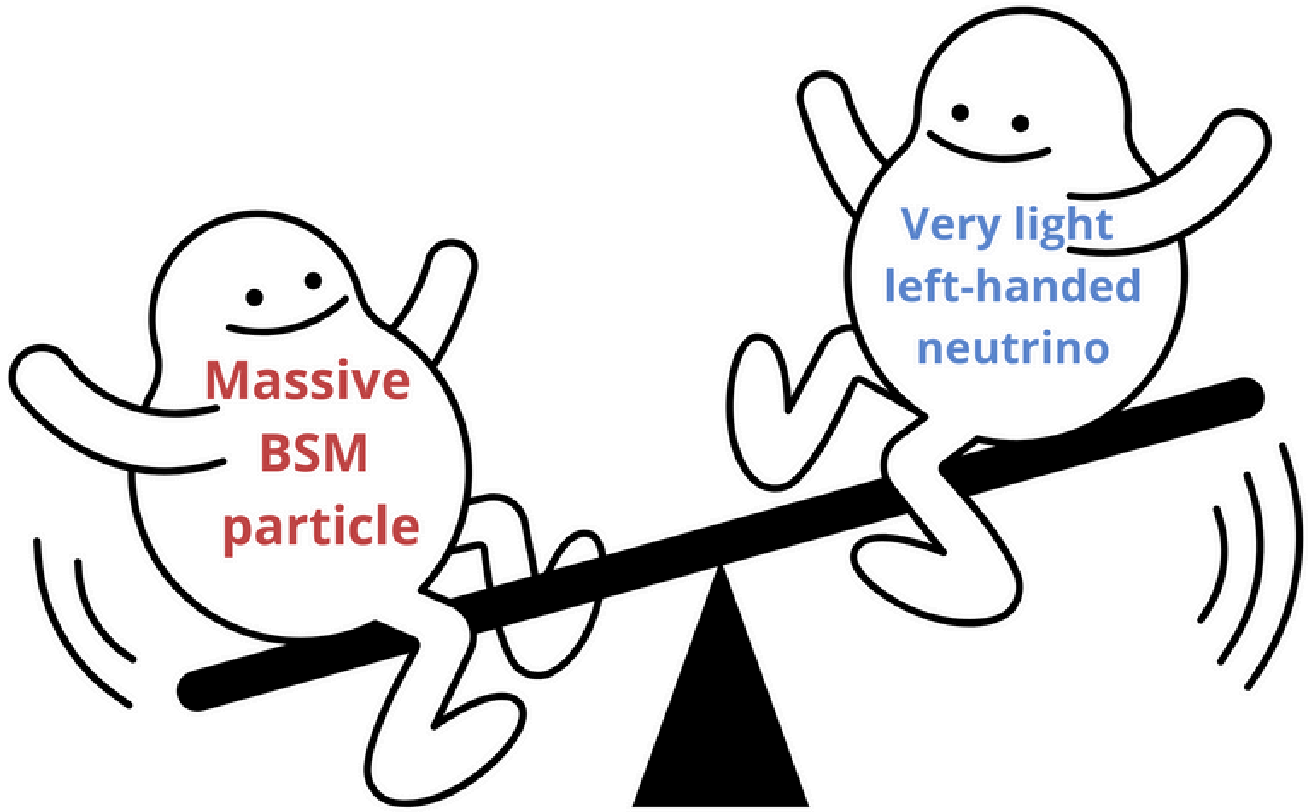
1. Baryon number violation
2. C and CP violation
3. Departure from thermal equilibrium

(We need new physics beyond SM)

Neutrino Mass generation + **Baryogenesis through Leptogenesis**

$$\underbrace{\qquad\qquad\qquad\qquad\qquad\qquad}$$

Seesaw Mechanism



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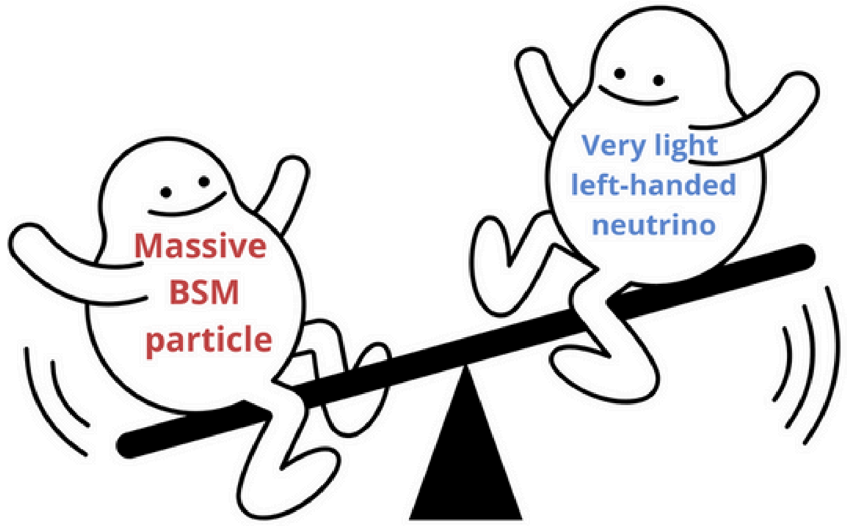
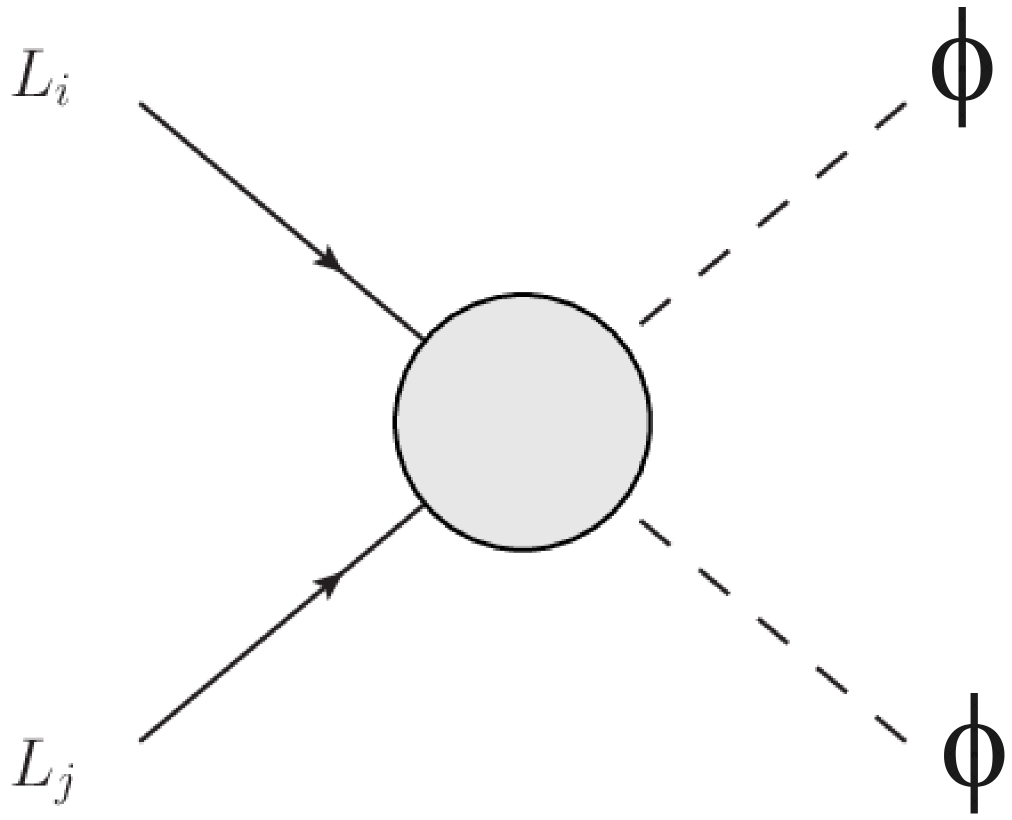


Weinberg dimension-5 operator



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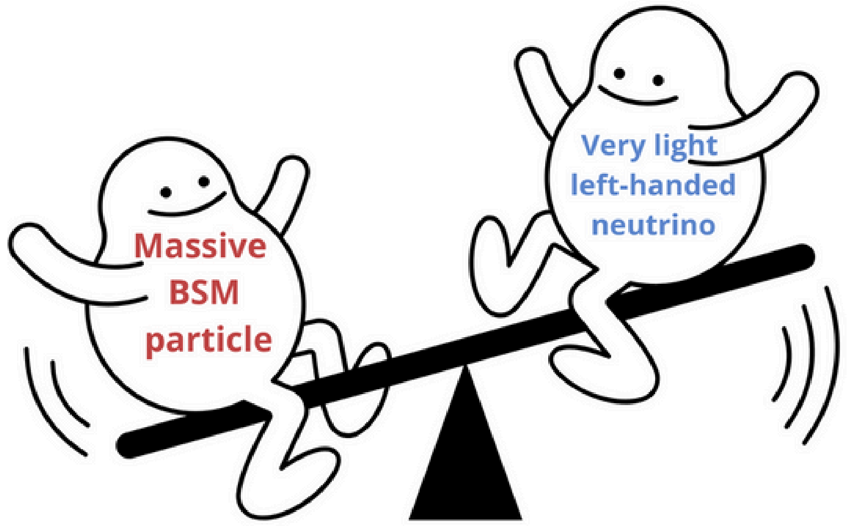
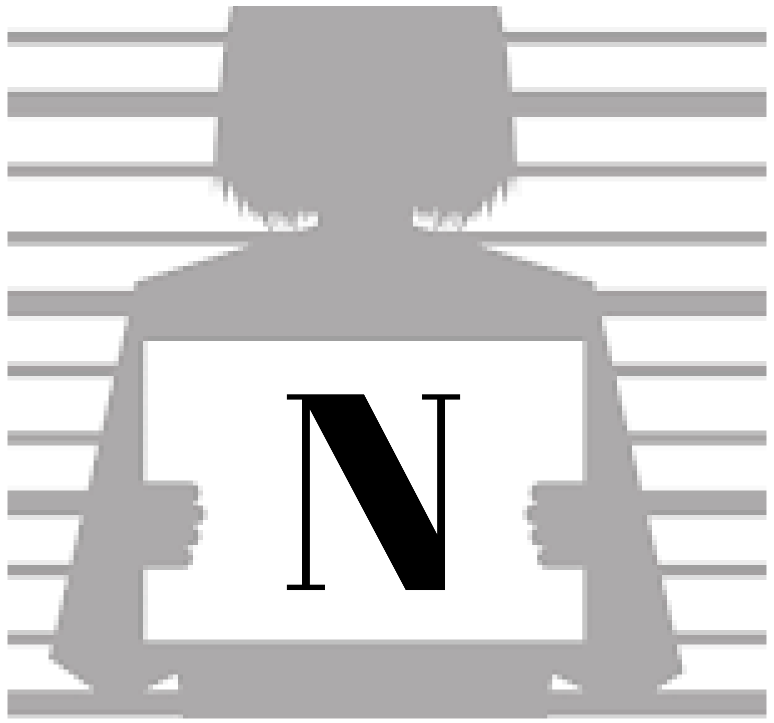
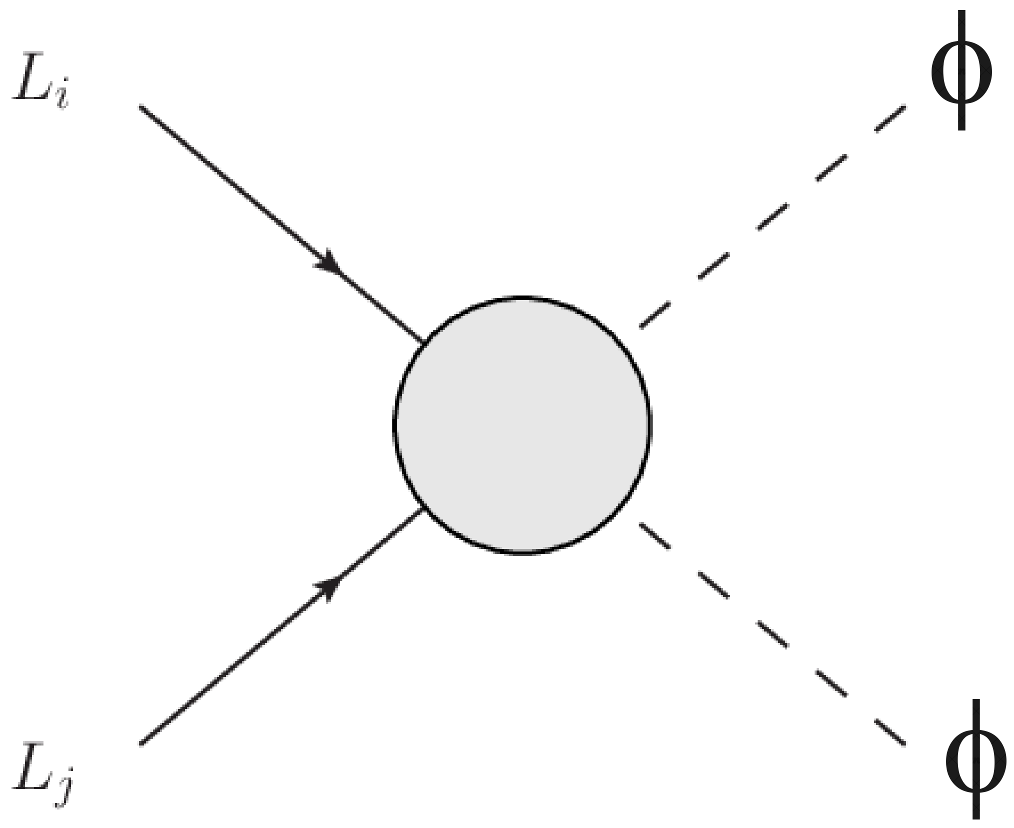


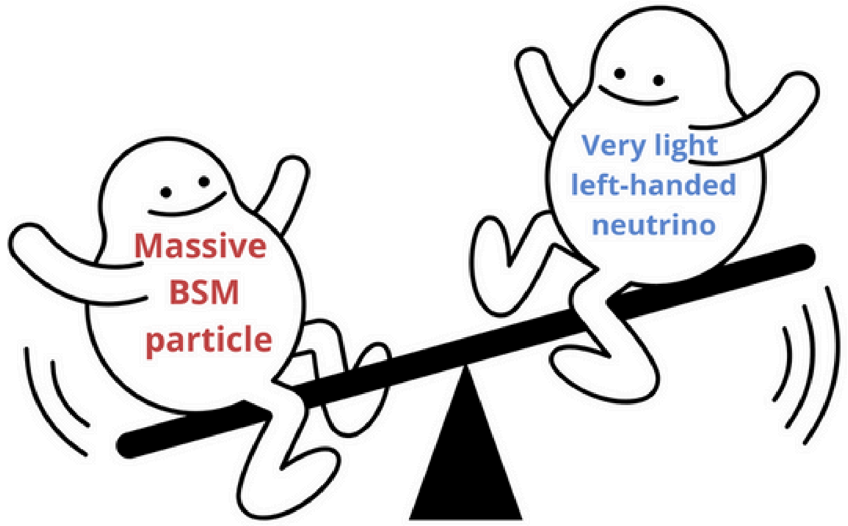


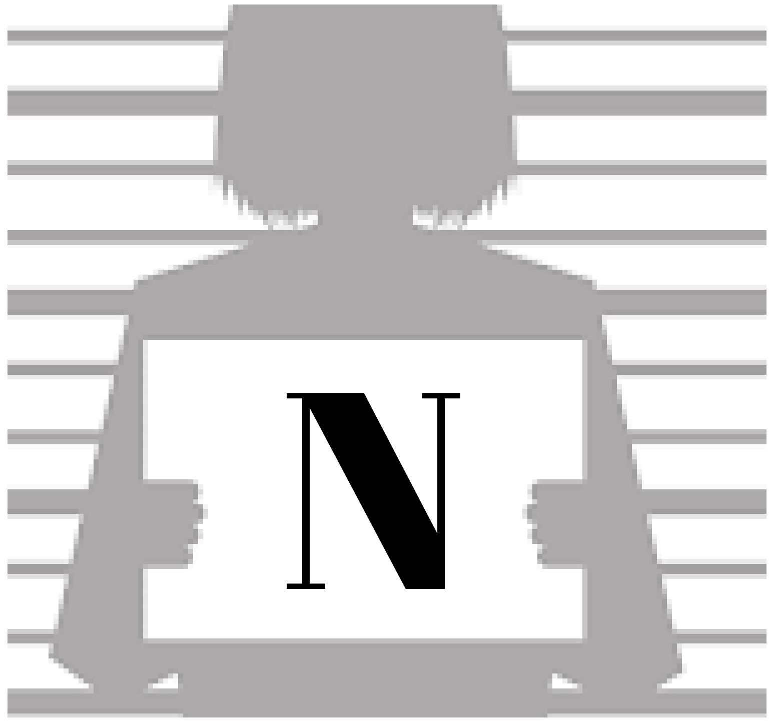
Right-handed neutrino

Weinberg dimension-5 operator



Seesaw Mechanism





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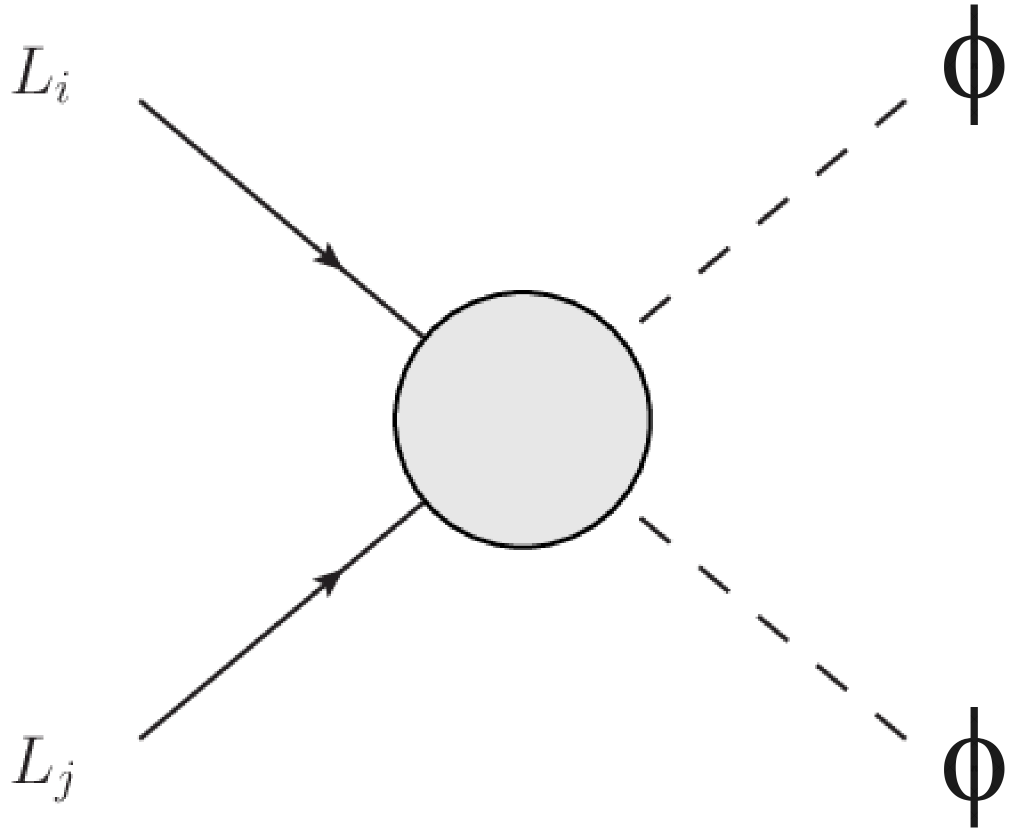
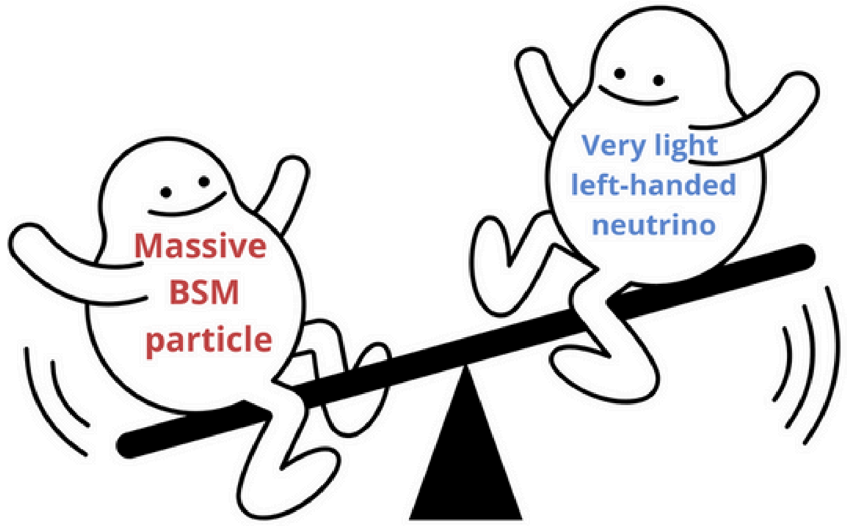
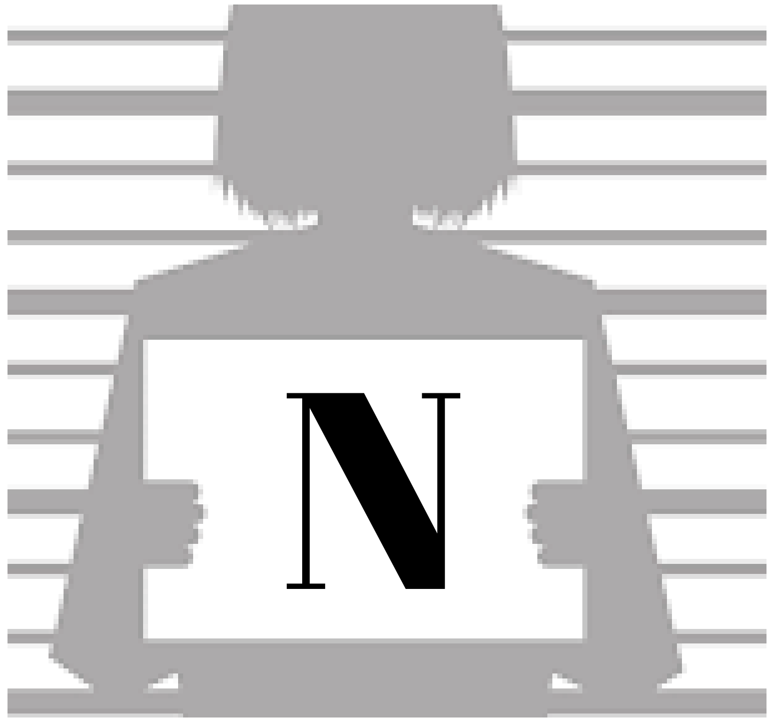


Triplet Higgs Scalar

Seesaw Mechanism





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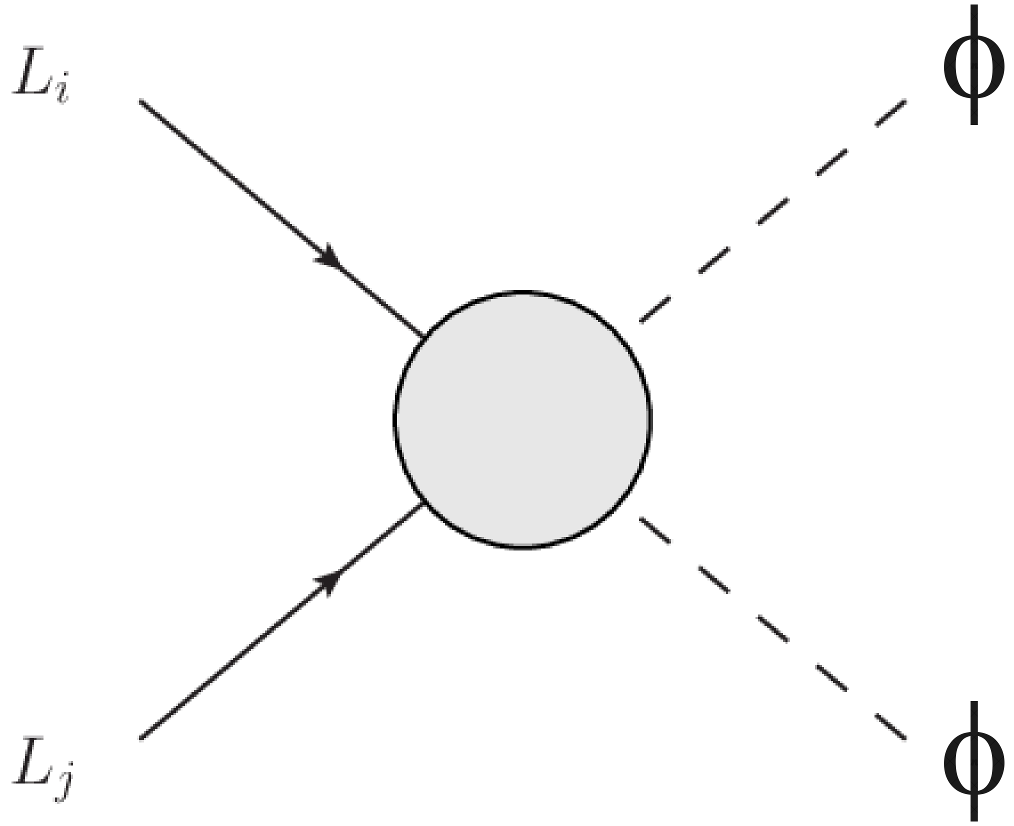
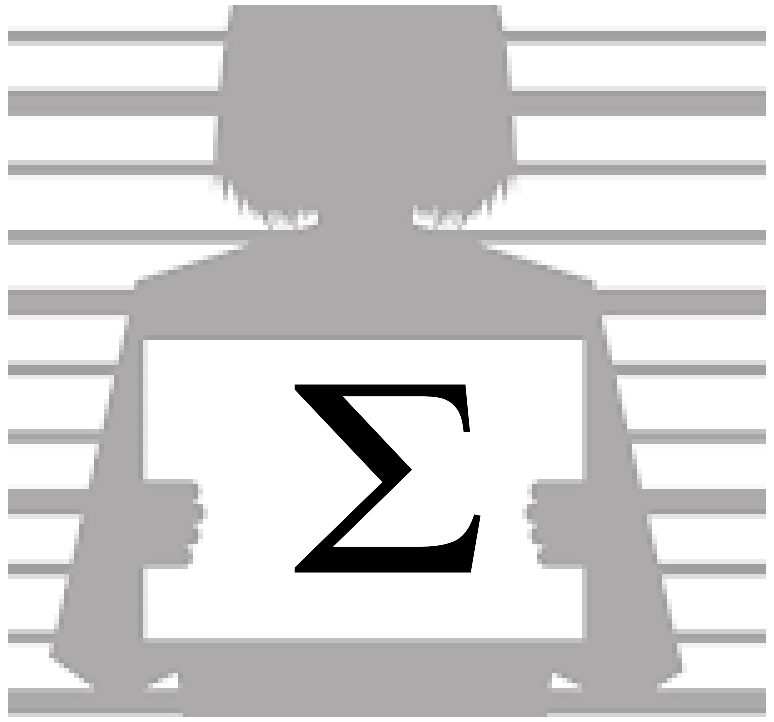
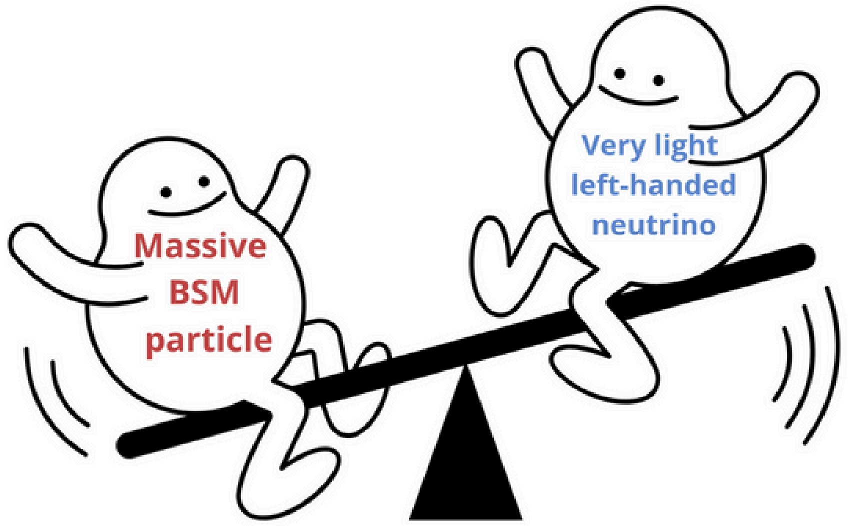
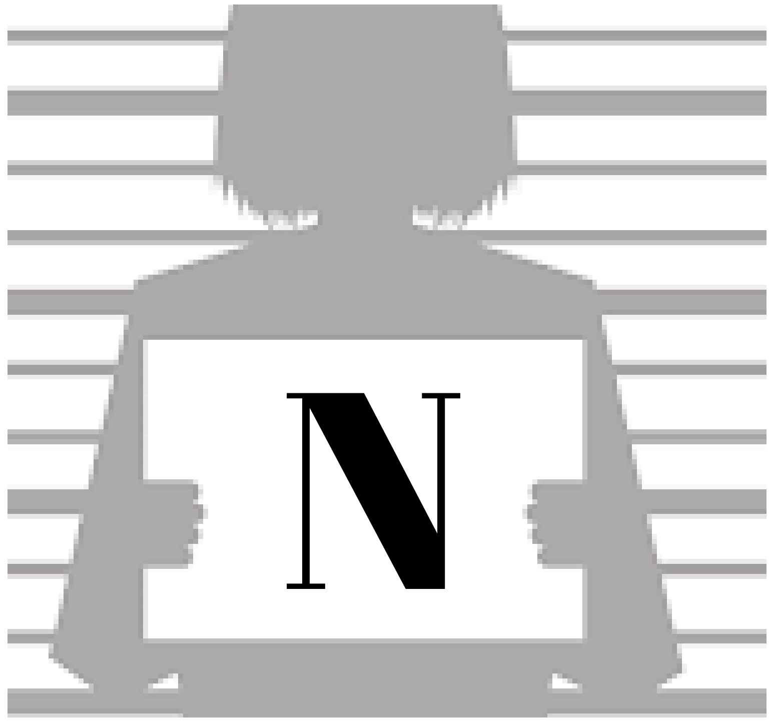




Fermion Triplet

Seesaw Mechanism

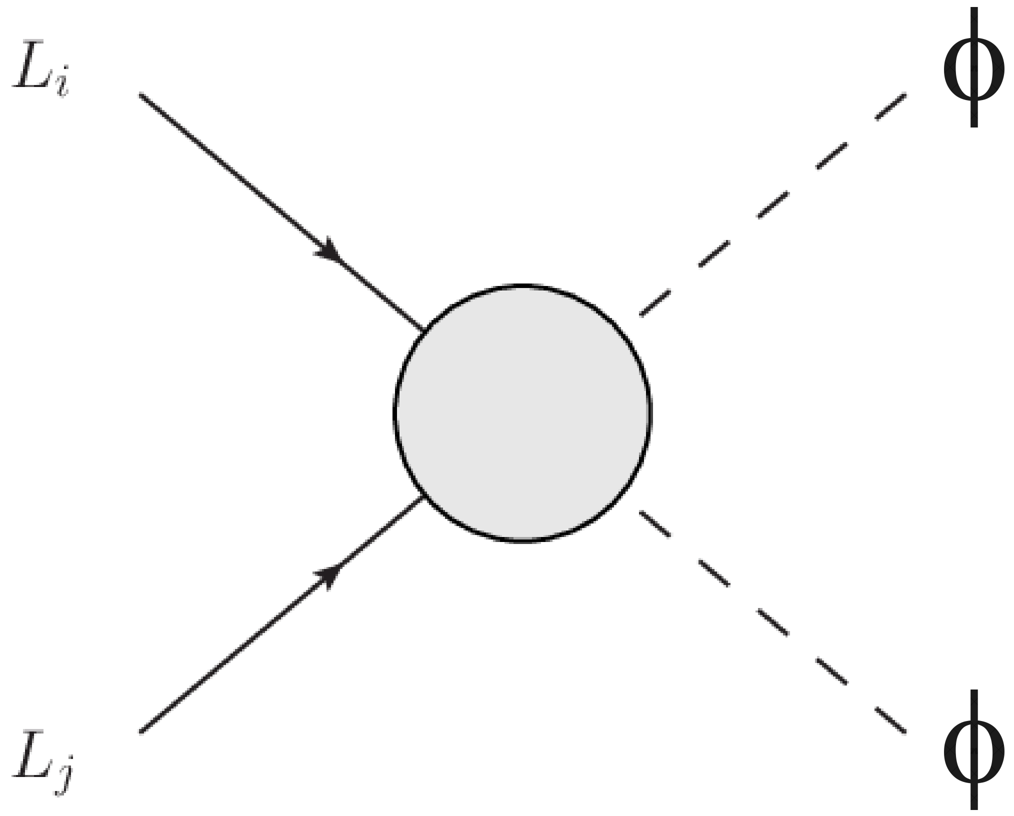




Type-I seesaw mechanism

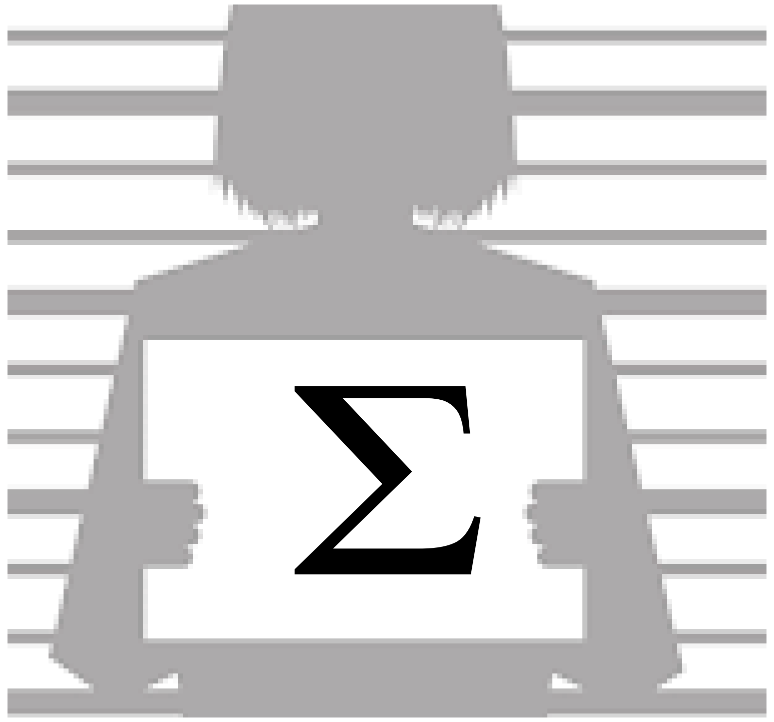
[Mahapatra, Senjanovic (1980)]

Weinberg dimension-5 operator



Type-II seesaw mechanism

[Mahapatra, Senjanovic (1981)]



Type-III seesaw mechanism

[Ma (1998)]

Δ

Neutrino mass generation through type-II seesaw mechanism

[Mahapatra, Senjanovic (1981)]

The additional terms in the total Lagrangian, apart from the SM lagrangian terms are given by

$$\mathcal{L}_{ssII} = \mathcal{L}_{kinetic} + \mathcal{L}_{Yuk} - V(\phi, \Delta)$$

$$\mathcal{L}_{ssII} = Tr[(D_\mu \Delta)^\dagger (D^\mu \Delta)] - \frac{(Y_\Delta)_{ij} L_i^T C i \sigma_2 \Delta L_j}{\sqrt{2}} + h.c. - V(\phi, \Delta)$$

Δ

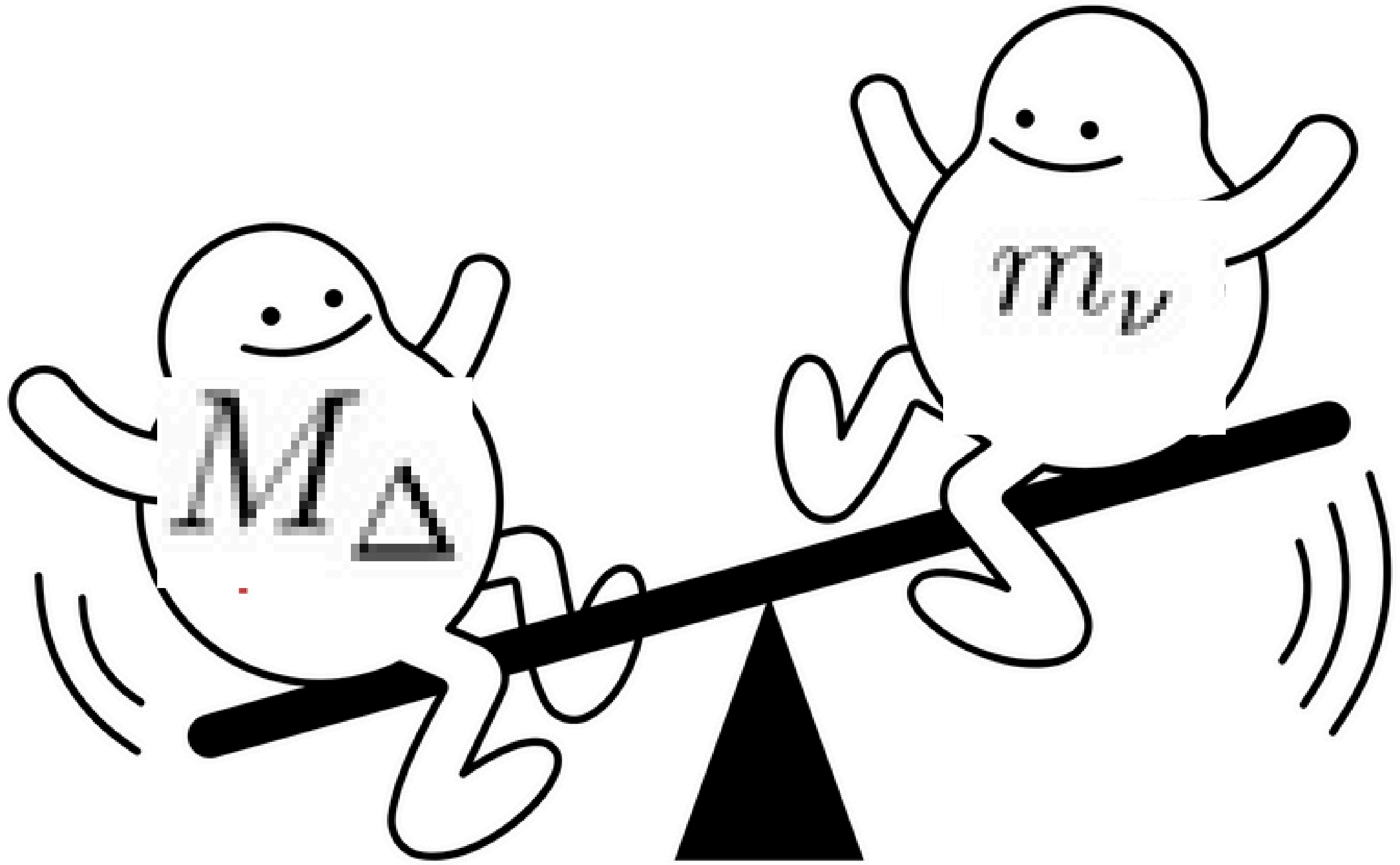
$$\Delta = (\delta^{++}, \delta^{+}, \delta^{0})$$

$$\langle \delta^0 \rangle = \omega_\Delta$$

$$(m_\nu)_{ij} = \omega_\Delta (Y_\Delta)_{ij}$$

type-II seesaw generated neutrino mass

Neutrino mass generation through type-II seesaw mechanism [Mahapatra, Senjanovic (1981)]



$$\omega_\Delta = \frac{\mu v^2}{2M_\Delta^2}$$

the neutrino mass is given by

$$(m_\nu)_{ij} = \omega_\Delta (Y_\Delta)_{ij}$$

$$m_\nu \propto M_\Delta^{-1}$$

Neutrino mass generation through type-II seesaw mechanism

[Mahapatra, Senjanovic (1981)]

$$V(\phi,\Delta) = -m_\phi^2(\phi^\dagger\phi) + \frac{\lambda}{2}(\phi^\dagger\phi)^2 + M_\Delta^2 Tr(\Delta^\dagger\Delta) + \frac{(\lambda_1+\lambda_2)}{2}[Tr(\Delta^\dagger\Delta)]^2$$
$$-\frac{\lambda_2}{2}[Tr(\Delta^\dagger\Delta)^2] + \lambda_4(\phi^\dagger\phi)Tr(\Delta^\dagger\Delta) + \lambda_5\phi^\dagger[\Delta,\Delta^\dagger]\phi$$
$$+(\mu\phi^T i\sigma_2\Delta^\dagger\phi + h.c.),$$

The trilinear term in the scalar potential breaks the lepton number by two units

Baryogenesis via triplet leptogenesis

> The trilinear term in the scalar potential breaks the lepton number by two units

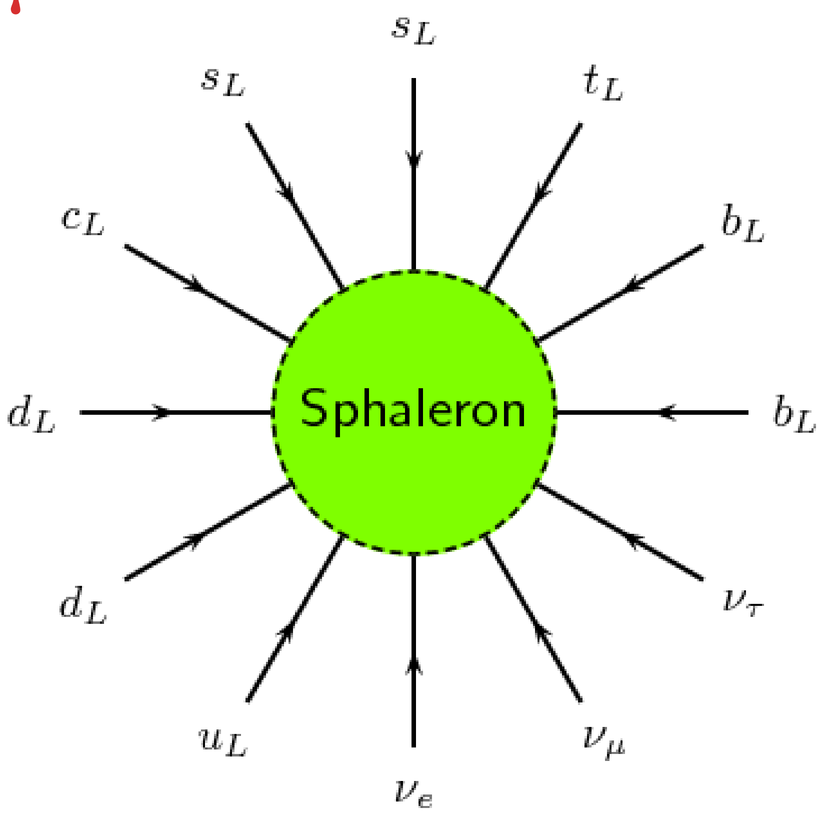
Lepton asymmetry

- Lepton number violation
- C and CP violation
- Out-of-thermal equilibrium decay

Baryogenesis via triplet leptogenesis

- Lepton number violation
- C and CP violation
- Out-of-thermal equilibrium decay

Lepton asymmetry

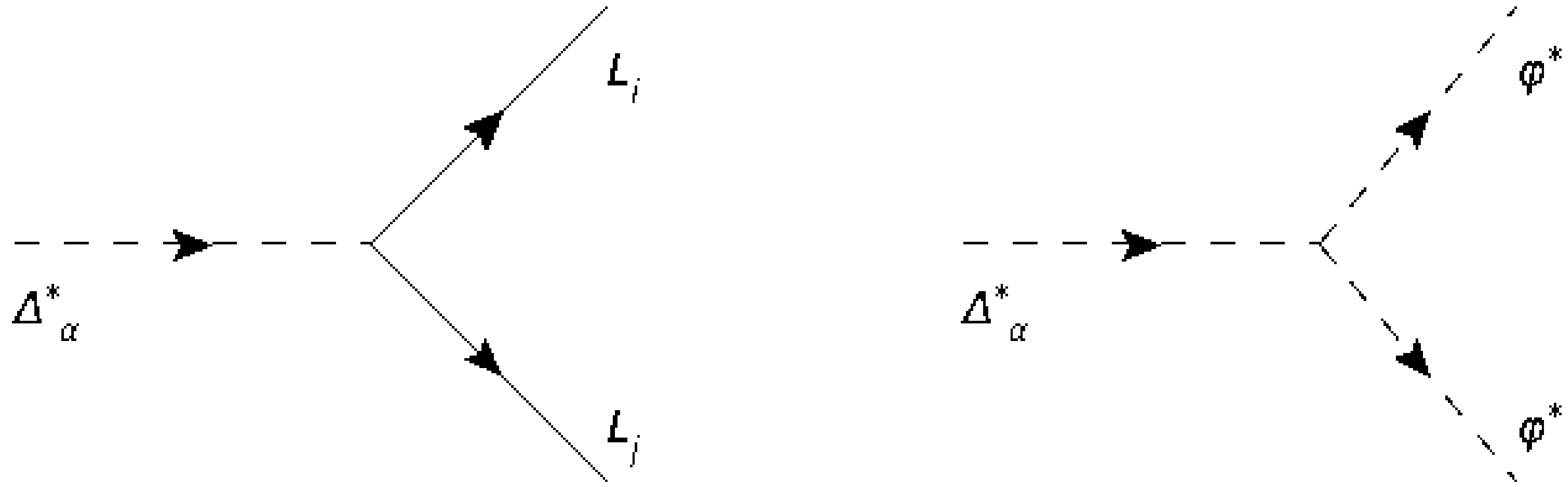


Baryon asymmetry

Purely Triplet Leptogenesis

CP Violation
in
type-II seesaw mechanism

[Branco, Felipe, Joaquim (2012)]



[Tree-level decays]

Δ

Purely Triplet Leptogenesis

CP Violation
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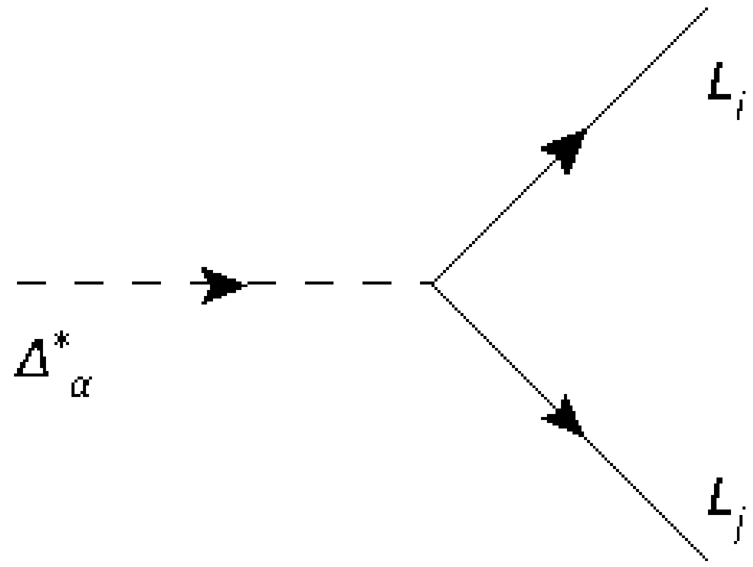
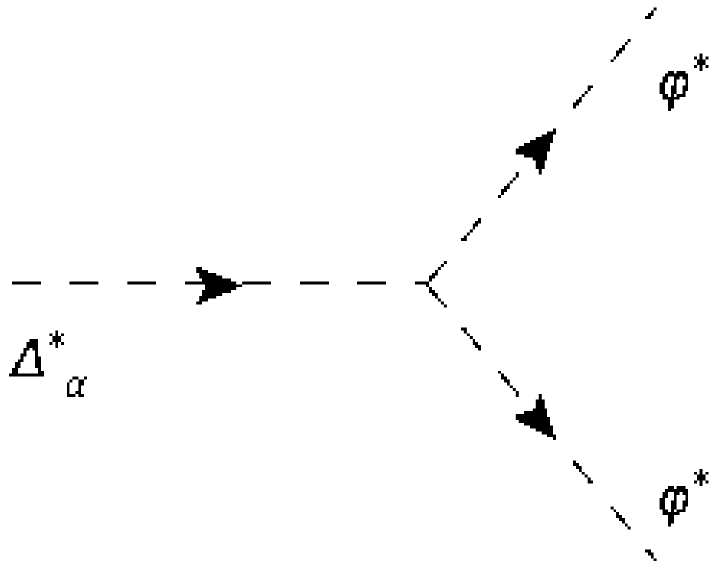
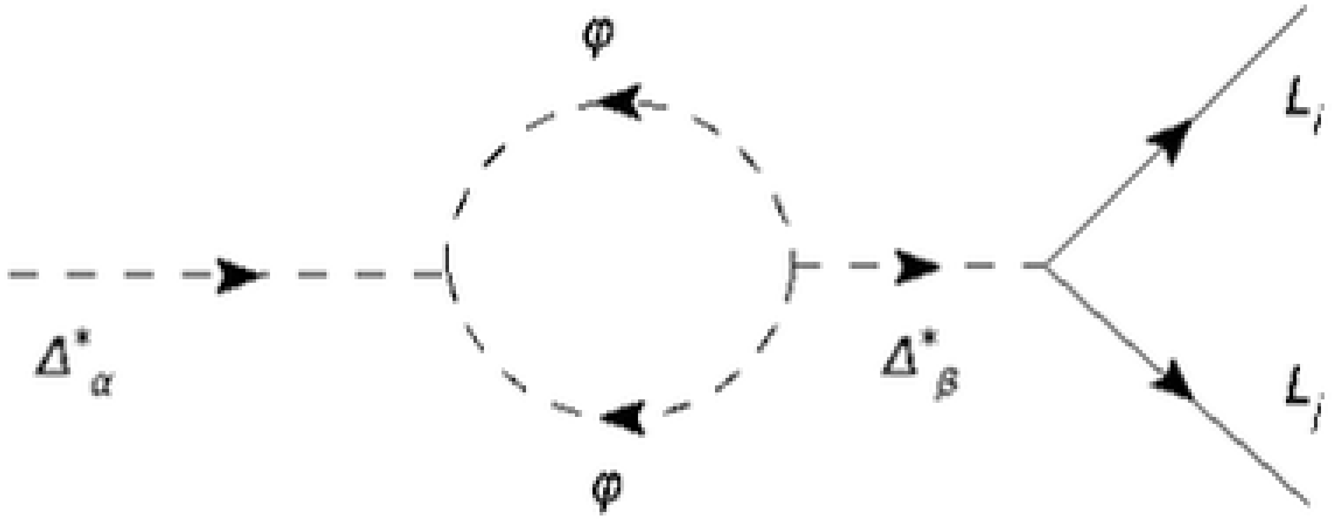
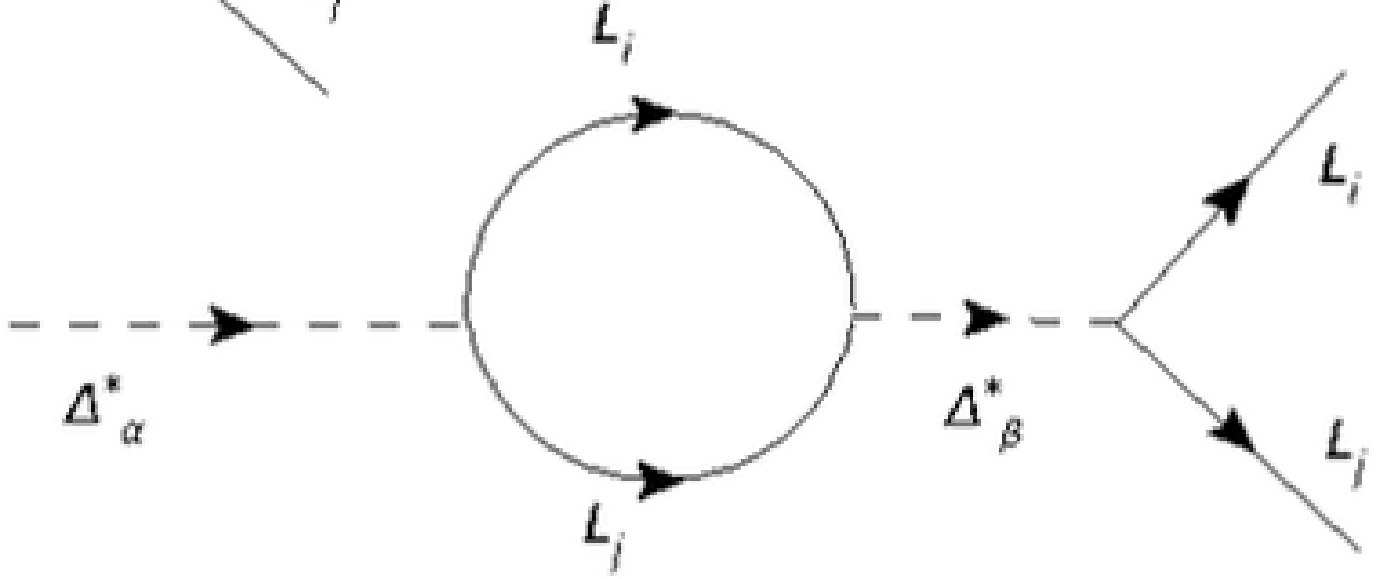
[Branco, Felipe, Joaquim (2012)]





[Tree-level decays]



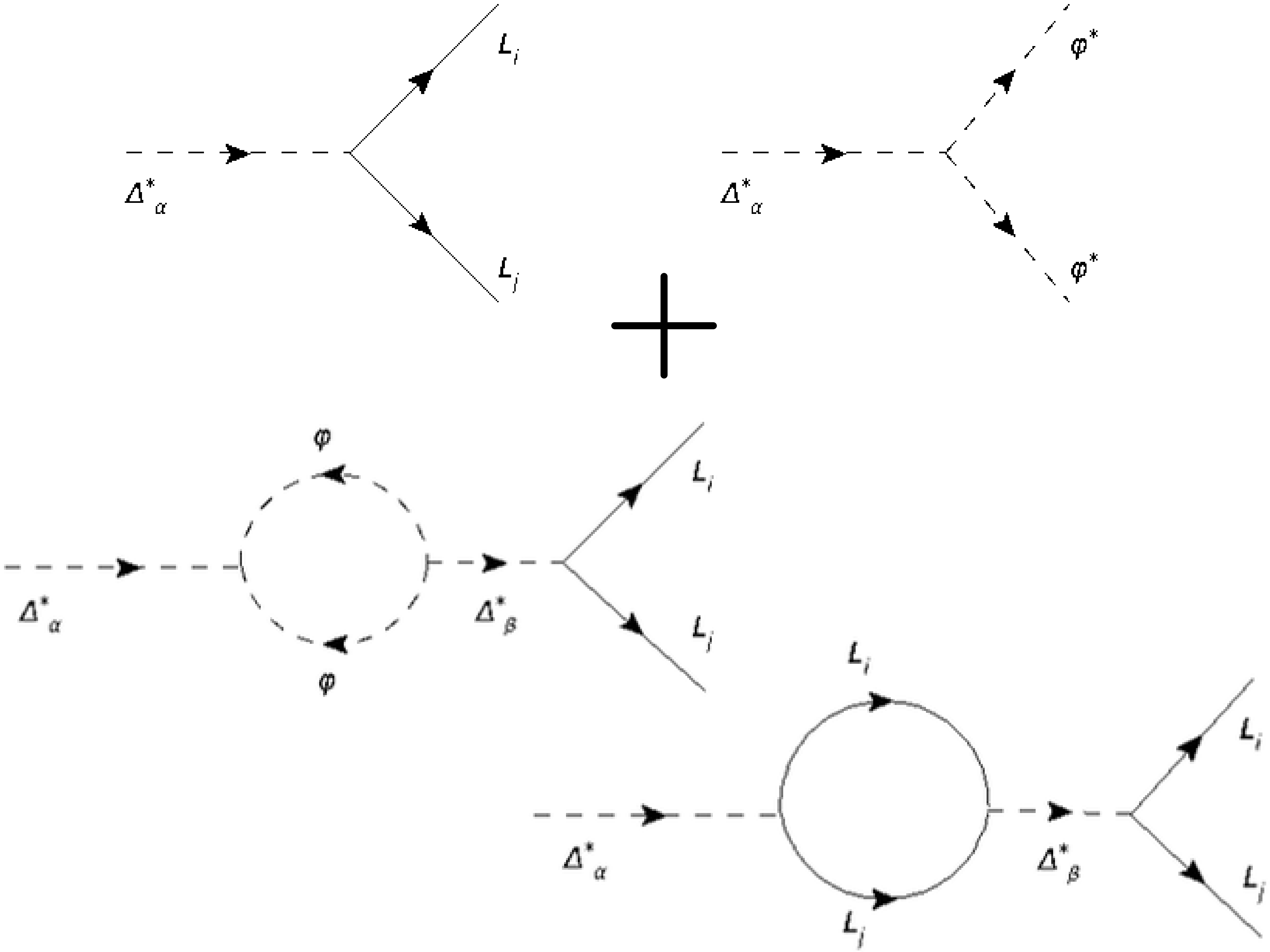


[One-loop decays]

Δ

Purely Triplet Leptogenesis

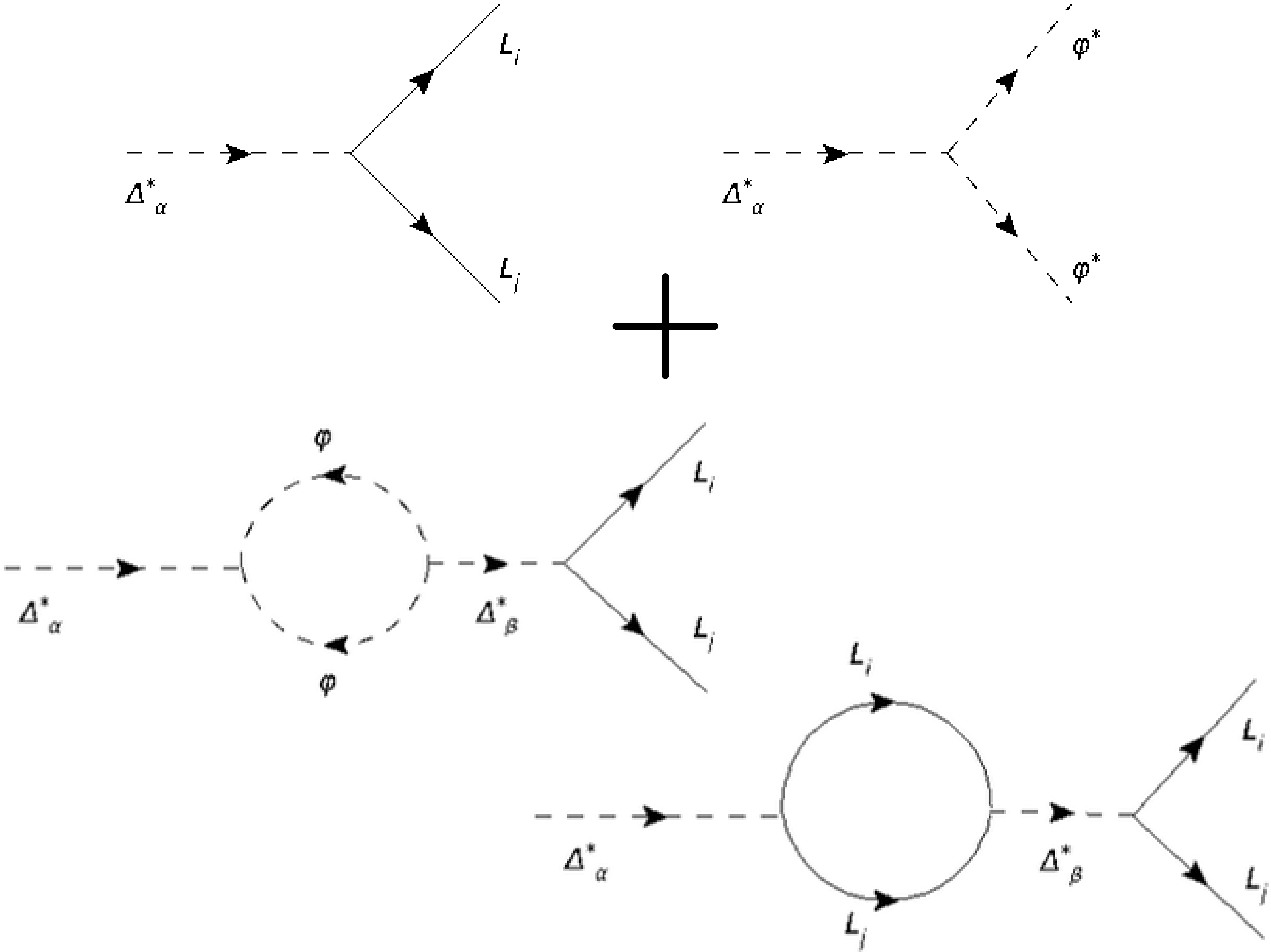
Only one triplet is
not enough



Purely Triplet Leptogenesis

Another heavier particle is needed

$\Delta_2 << \Delta_1$



Purely Triplet Leptogenesis

How did the CP symmetry get broken?!

Possibilities:

1. Explicit CP Violation [Branco, Lavoura, Silva (1999)]
2. Spontaneous CP Violation [Lee (1973)]

Purely Triplet Leptogenesis with Explicit CP Violation

$\Delta_2 \ll \Delta_1$

"CP symmetry gets violated at the Lagrangian level"

Purely Triplet Leptogenesis with Spontaneous CP Violation

$\Delta_2 \ll \Delta_1$

"CP symmetry is conserved in Lagrangian level!!"

Purely Triplet Leptogenesis with Spontaneous CP Violation

Model requires...

$\Delta_2 \ll \Delta_1$

Purely Triplet Leptogenesis with Spontaneous CP Violation

Model requires...

$\Delta_2 \ll \Delta_1$

Flavons

Purely Triplet Leptogenesis with Spontaneous CP Violation

Model requires...

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Φ Ψ

Flavons

Purely Triplet Leptogenesis with Spontaneous CP Violation

Model requires...

$\Delta_2 \ll \Delta_1$

Φ Ψ

Flavons

Scalar singlet

Purely Triplet Leptogenesis with Spontaneous CP Violation

[Branco, Felipe, Joaquim, Serodio (2012)]

Complex vev of the scalar singlet breaks the CP symmetry "spontaneously"

$$\langle S \rangle = v_S e^{i\alpha}$$

$\Delta_2 \ll \Delta_1$

Φ Ψ

Flavons

S

Scalar singlet

Flavoured Leptogenesis

[Sierra, Dhen, Hambye (2014)]

- $|l> = \Sigma_\alpha c_{1\alpha}|l_\alpha>$

  $\alpha = e, \mu, \tau$

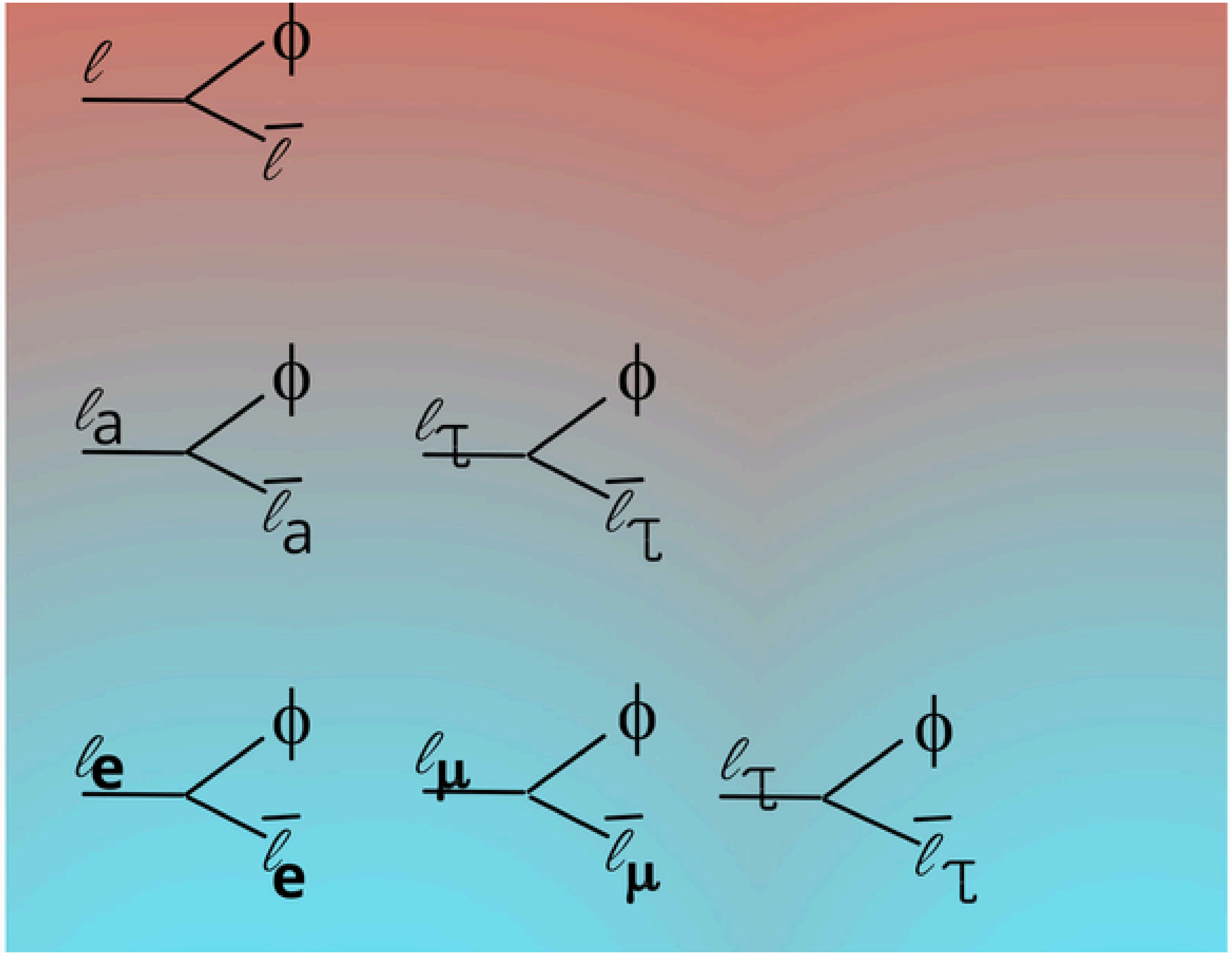
- $\Gamma_\tau \propto Y_\tau^2 T > H(T)$

- $\Gamma_\mu \propto Y_\mu^2 T > H(T)$

T >10^{13}GeV
(Unflavoured)

T ~10^{11}GeV
(2-flavoured)

T ~10^{9}GeV
(fully-flavoured)



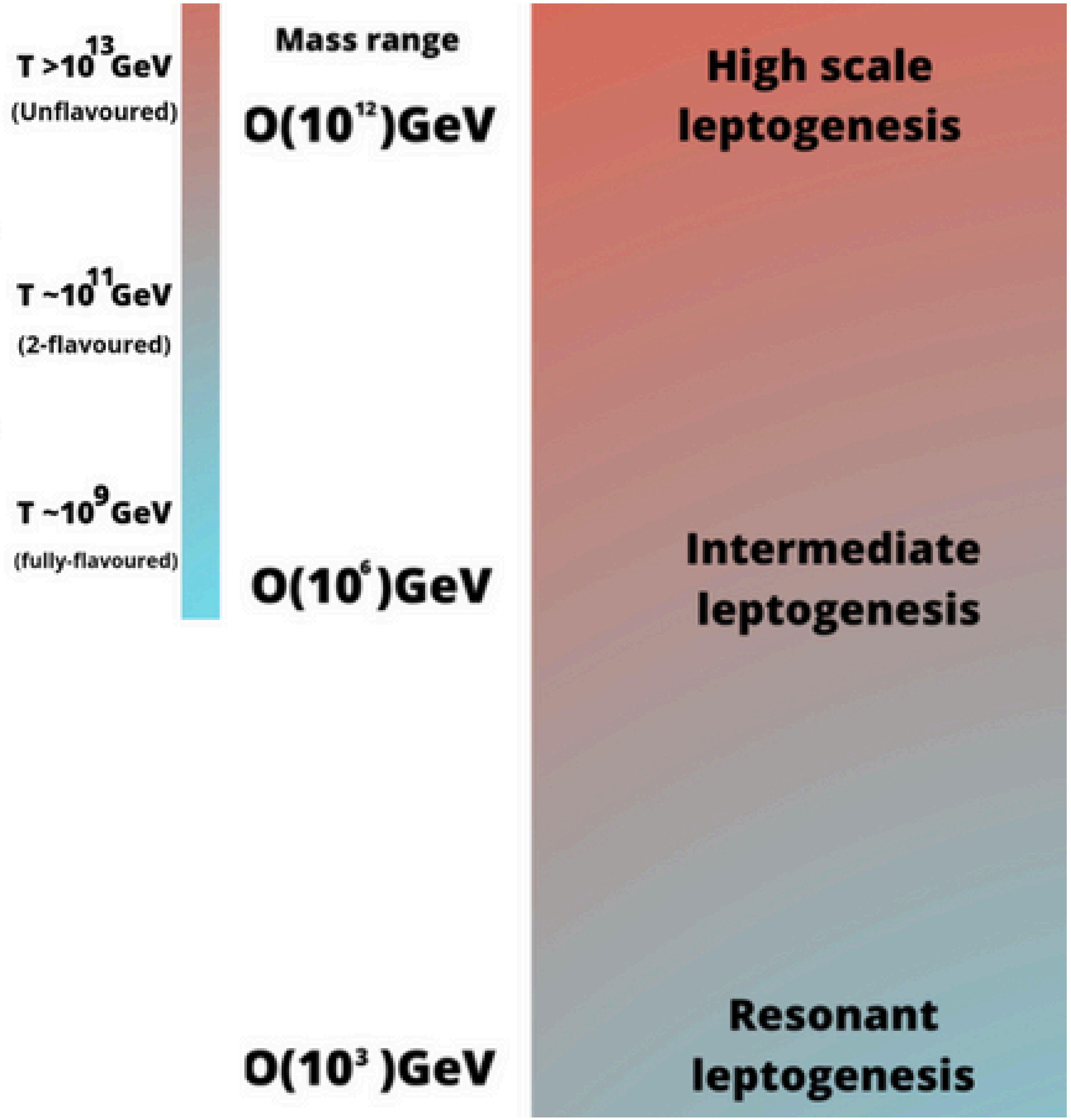
Flavoured Leptogenesis mediated by heavy triplet scalar

[Lavignac, Schmauch (2015)]

Δ_2

$$M_\Delta \sim 10^{10}\ \text{GeV}$$

[2-flavoured leptogenesis]



Tracking footprints: Neutrino mass generation to Baryogenesis

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1. *Constructing neutrino mass matrix from the model*

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3. *Computing flavoured CP asymmetries from model using neutrino mass matrix elements*

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4. *Inspecting the evolutions of the flavoured lepton asymmetries using the CP asymmetries in a suitable set of flavoured Boltmann equations*

Tracking footprints: Neutrino mass generation to Baryogenesis

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4. *Inspecting the evolutions of the flavoured lepton asymmetries using the CP asymmetries in a suitable set of flavoured Boltmann equations*
5. *Estimation of final Baryon asymmetry via sphaleron conversion of the flavoured lepton asymmetries*

Explicit CPV Model: Neutrino mass generation

[Chongdar, Mishra (2023)]

Generated neutrino mass matrix: $m_\nu = m_\nu^{(1)} + m_\nu^{(2)} = Y_\Delta^{(1)} |\omega_1| e^{i\alpha} + Y_\Delta^{(2)} \omega_2$

Parameter space study is done using neutrino oscillation data: $\longrightarrow$ NuFIT 5.0 (2020) [Esteban et al. (2020)]

"The model disfavours Inverse Hierarchy of neutrino mass"

Two-flavoured CP asymmetries: ϵ_a & ϵ_τ

Explicit CPV Model: Baryon asymmetry result and plot

[Chongdar, Mishra (2023)]

Baryon asymmetry calculated from flavoured lepton asymmetries :

$$\eta_B = 7.04 \times 3 \times \frac{12}{37} \sum_i \Delta_{B/3-L_i}$$

Parameters taken:

$$M_{\Delta_2} \sim 1 \times 10^{10} \text{ GeV}$$

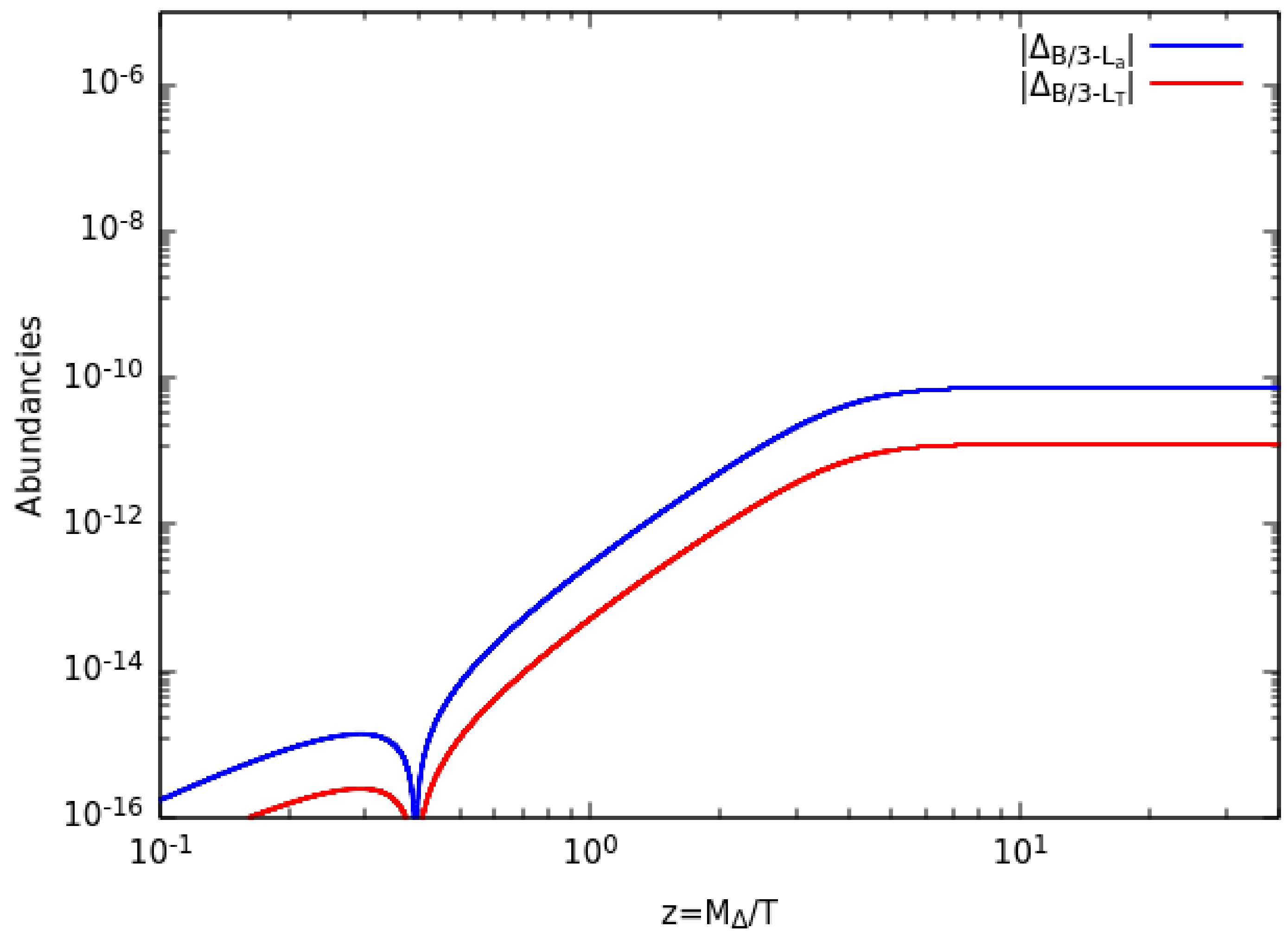
$$\epsilon_a \sim -1.83{\times}10^{-8}, \quad \epsilon_\tau \sim -3.29{\times}10^{-9}$$

Final Baryon asymmetry:

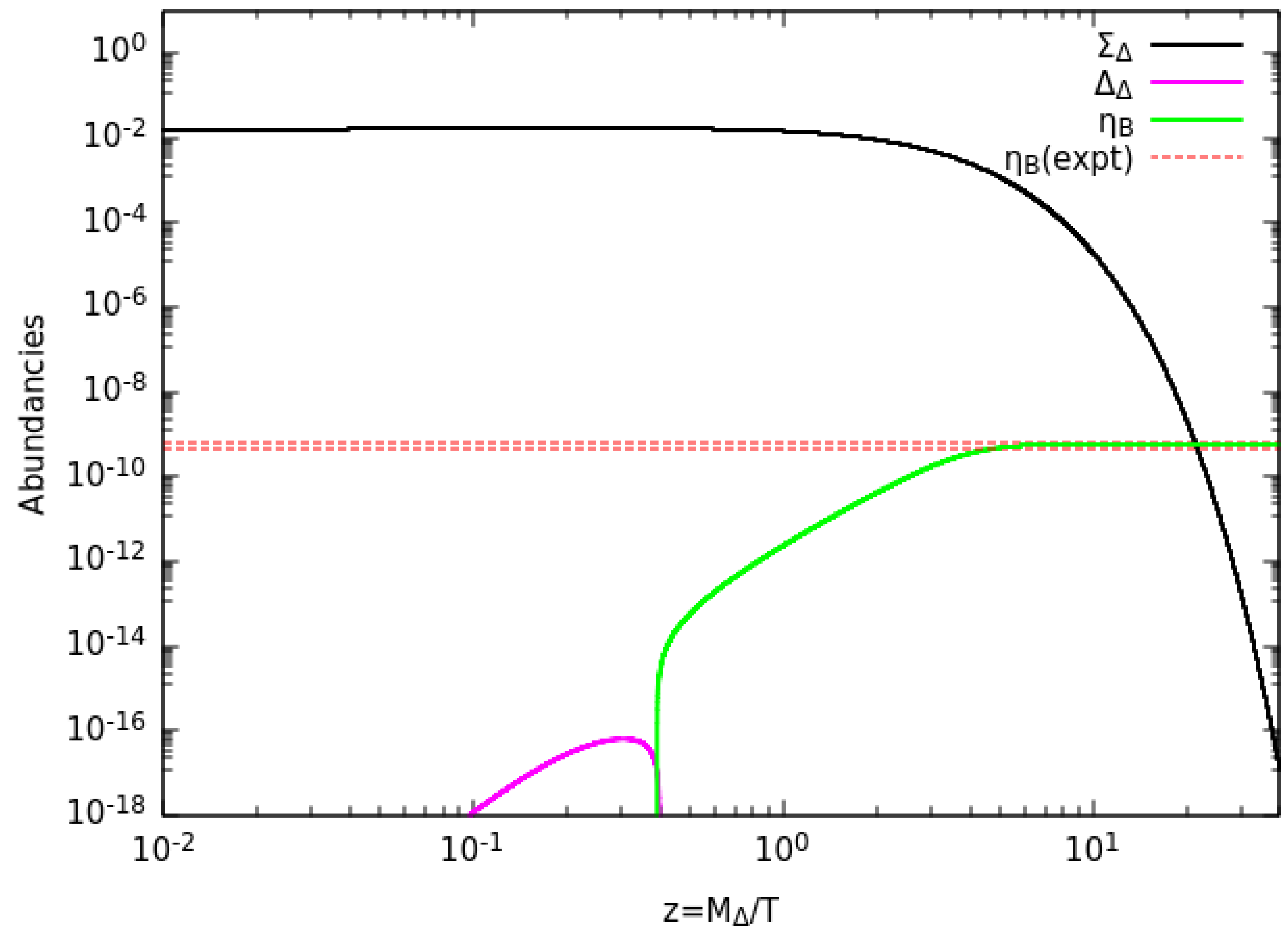
$$\boxed{\eta_B \sim 5.93 \times 10^{-10}}$$

After numerically solving a set of two-flavoured Boltzmann equations

Plot of flavoured lepton asymmetries vs z



Plot of final baryon asymmetry vs z



*z (dimensionless parameter)=Triplet mass/ Temperature of the Universe

Spontaneous CPV Model: Neutrino mass generation

[Branco, Felipe, Joaquim, Serodio (2012)]

[Chongdar, Mishra (2024)]

$A_4 \times Z_4$ symmetry

Generated neutrino mass matrix: $$m_\nu = m_\nu^{(1)} + m_\nu^{(2)} \propto Y_\Delta^{(1)}\omega_1 + Y_\Delta^{(2)}\omega_2$$

$\mu - \tau$ symmetry

magic symmetry

*indicating **Tribimaximal** mixing matrix*
which is in conflict with non-zero reactor mixing angle

TBM scenario is modified taking *perturbative corrections* in the flavon VEV

$$\langle \Phi \rangle = (r, 0, 0) \longrightarrow r(1, \varepsilon_1, \varepsilon_2)$$

$|\varepsilon_{1,2}| \ll 1$ (small perturbations)

Spontaneous CPV Model: Neutrino mass generation

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Flavour covariant CP asymmetries in two-flavoured regime: $$\epsilon_a \sim \begin{pmatrix} \epsilon_{ee} & \epsilon_{e\mu} \\ \epsilon_{\mu e} & \epsilon_{\mu\mu} \end{pmatrix} \quad \& \quad \epsilon_{\tau\tau}$$

[Lavignac, Schmauch (2015)]

Spontaneous CPV Model: Baryon asymmetry result and plot

[Chongdar, Mishra (2024)]

Baryon asymmetry calculated from flavoured lepton asymmetries :

$$\eta_B = 7.04 \times \frac{12}{37} \times \sum_i \Delta_{B/3-L_i}$$

Parameters taken:

$$M_{\Delta_2} \sim 1.4 \times 10^{10}\ \mathrm{GeV}$$

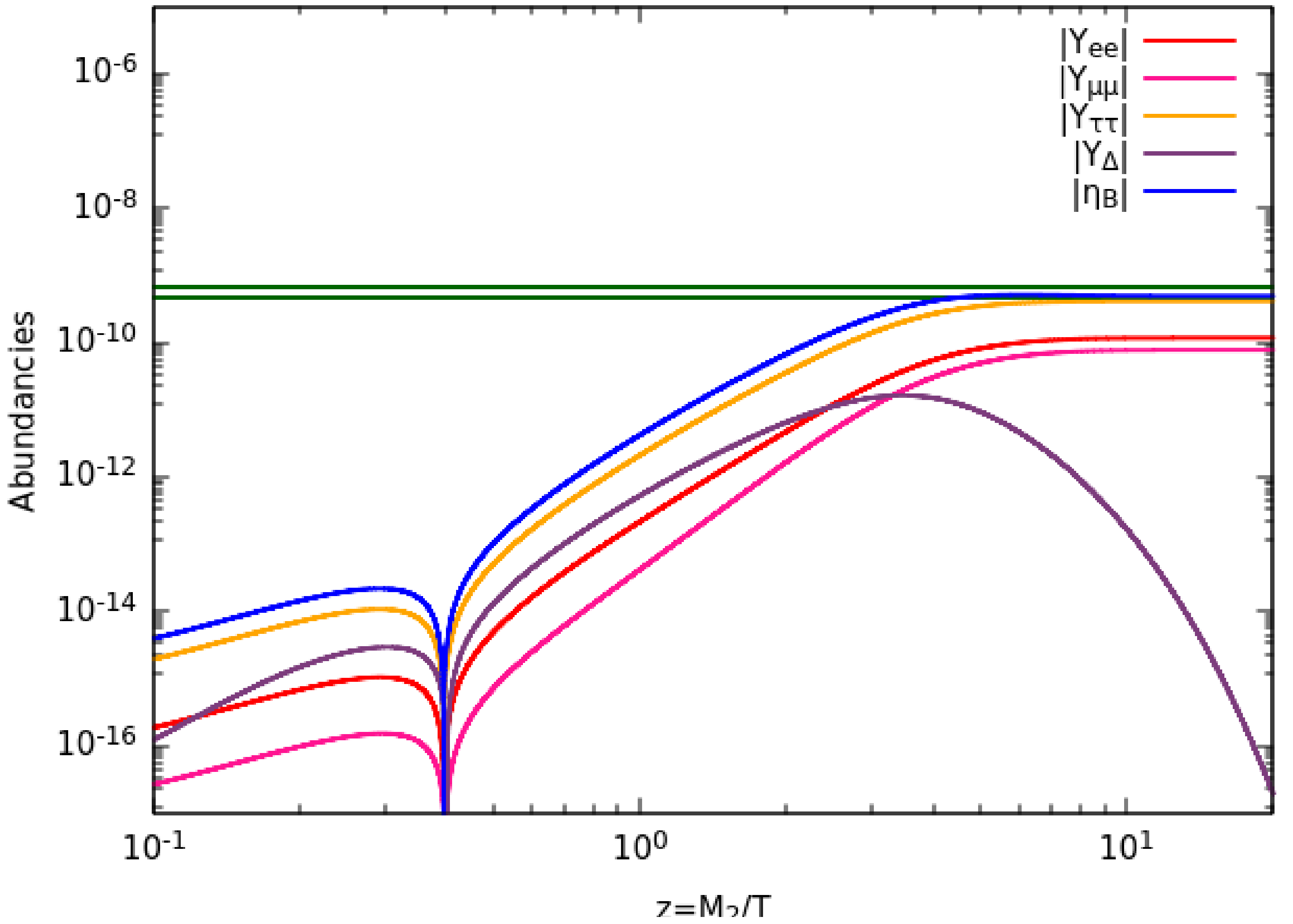
$$\epsilon_{ee} \sim -1.00\times10^{-8}, \quad \epsilon_{e\mu} \sim -1.20\times10^{-9}$$
$$\epsilon_{\mu\mu} \sim -1.44\times10^{-9}, \quad \epsilon_{\tau\tau} \sim 1.04\times10^{-7}$$

Final Baryon asymmetry:

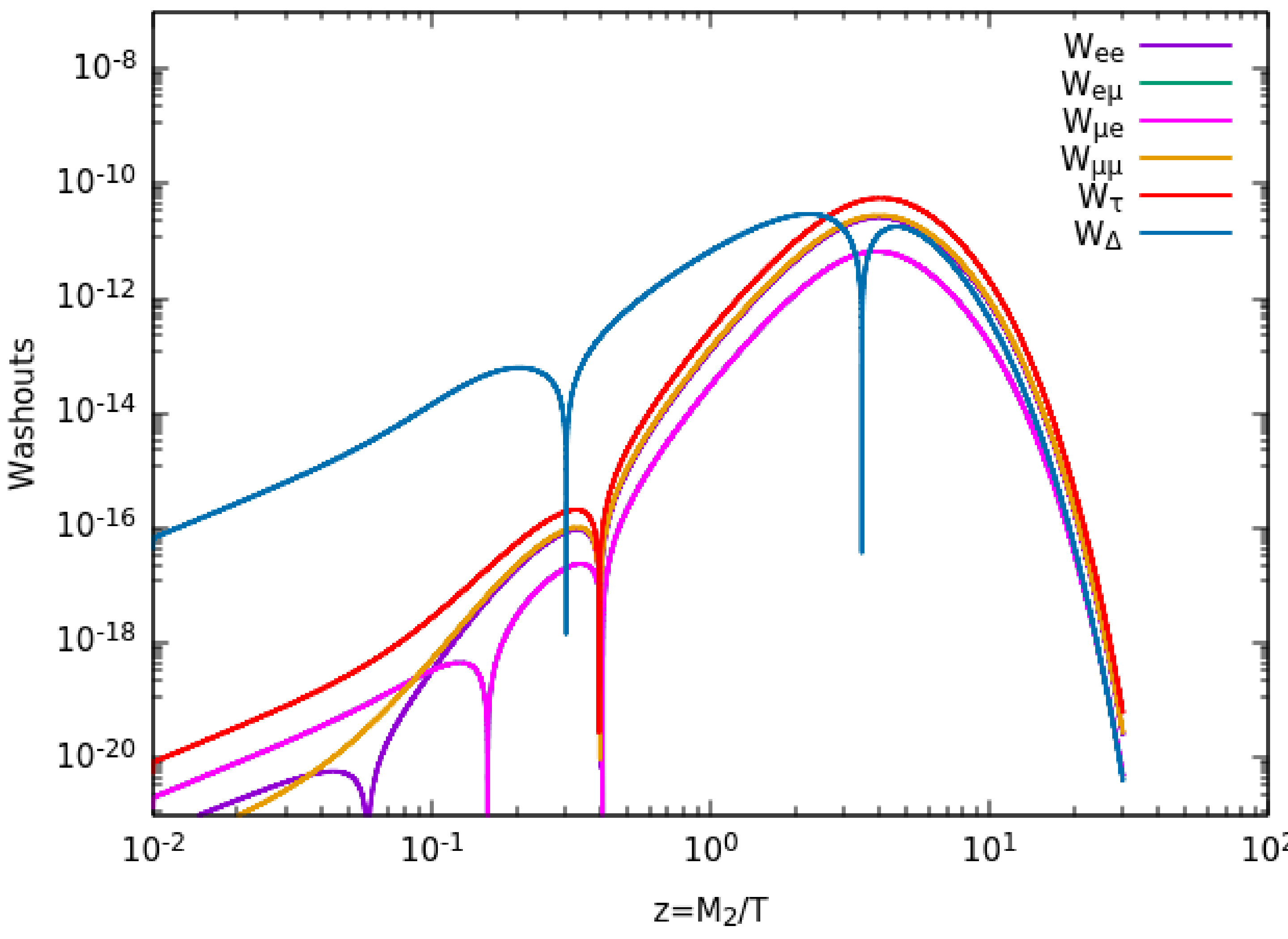
$$\boxed{\eta_B \sim 4.92 \times 10^{-10}}$$

After numerically solving a set of two-flavoured Boltzmann equations in Density Matrix Formalism

Plot of flavoured lepton asymmetries and final baryon asymmetry vs z



Plot of flavoured washouts vs z



*z (dimensionless parameter)=Triplet mass/ Temperature of the Universe

Summary: Purely Triplet Leptogenesis

- Tiny neutrino mass generation
- NH of neutrino mass is favoured
- Baryogenesis through Flavoured leptogenesis
- Branching ratio hierarchy enhances efficiency of leptogenesis

Explicit CP violation model

- Efficiency of leptogenesis is enhanced in flavoured regime in comparison to unflavoured regime
- CP violating phase in complex vev of the heavier triplet scalar enhances baryon asymmetry

Spontaneous CP violation model

- The flavour structure of the model suppresses the unflavoured CP asymmetry,
  hence ~~unflavoured leptogenesis~~
- CP violating phase coming through the complex vev of the singlet scalar enhances baryon asymmetry

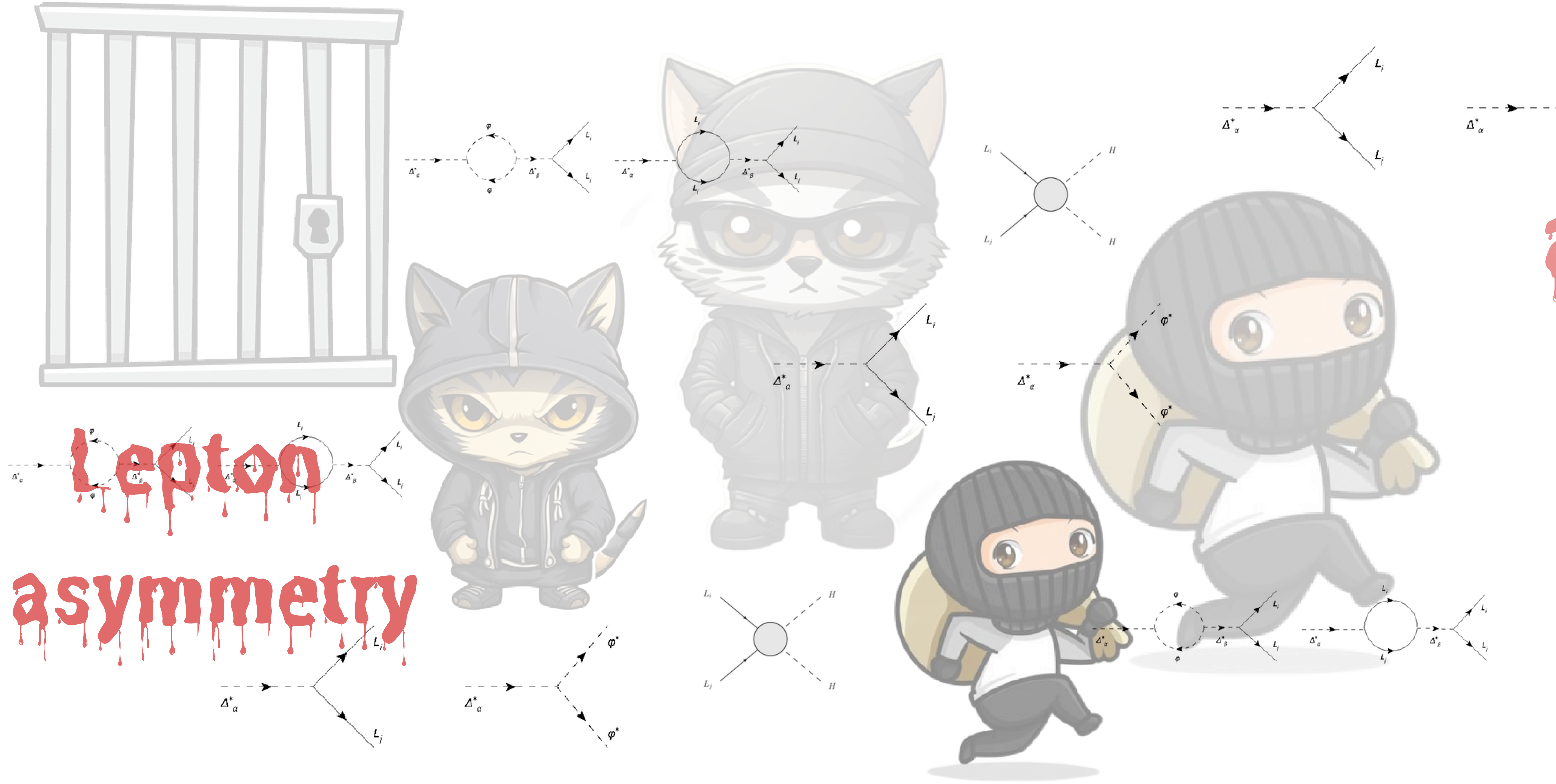
BUT...

High scale leptogenesis
mediated by massive triplet scalar
is not possible
to be probed experimentally
in near future

Δ

Low scale/Resonant
leptoegnesis

to be continued...



Scalar Triplet Leptogenesis with a CP violating phase

https://doi.org/10.1016/j.nuclphysb.2023.116346

Triplet scalar flavored leptogenesis with spontaneous CP violation

https://doi.org/10.1088/1475-7516/2024/04/054