Impact of non-standard interactions on low-scale leptogenesis and neutrinoless double beta decay

Sascha Weber

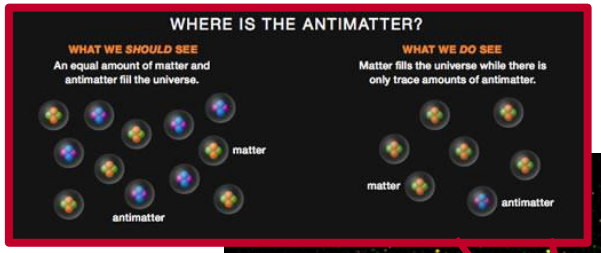
JGU Mainz

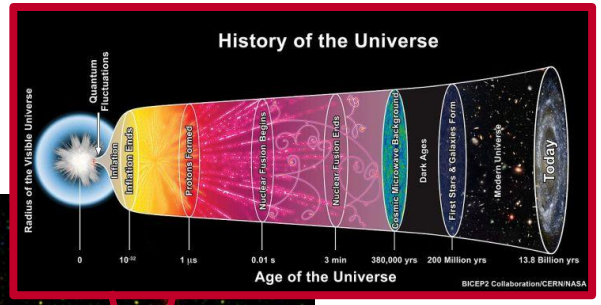
In collaboration with

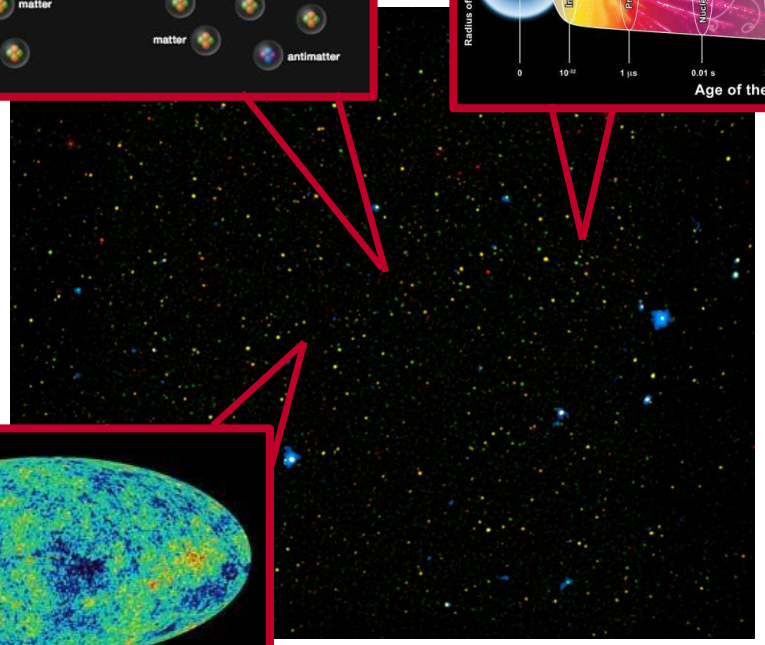
Kaori Fuyuto (LANL) and Julia Harz (JGU)

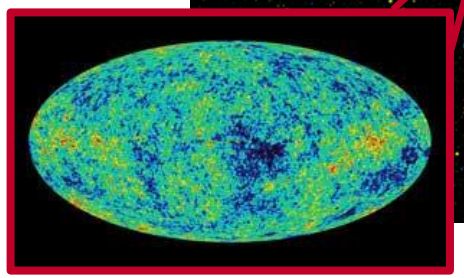
MPA Retreat 2024 – Sep. 30th 2024 – Kloster Höchst, Odenwald

Motivation









[https://www.universetoday.com/tag/223-aas/]
[http://www.spaceandmotion.com/cosmic-microwave-background-radiation.htm]
[https://www.astroblogs.nl/2013/03/23/wordt-het-universum-geregeerd-door-anti-neutrinos/baryon-asymmetry/]
[https://de.m.wikipedia.org/wiki/Datei:The_History_of_the_Universe.jpg]

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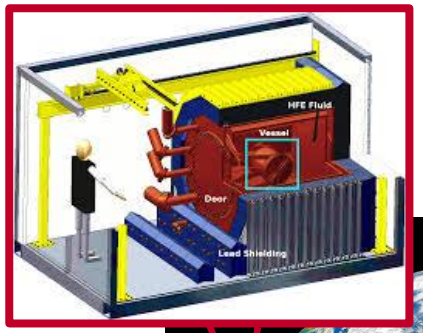
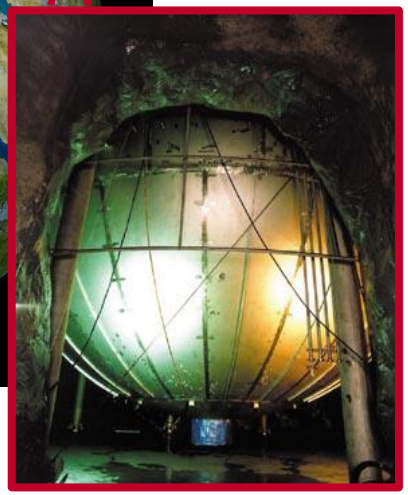


GERDA



KamLAND-Zen

[https://www.pinterest.de/pin/planet-earth-featuring-europe-and-european-union-countries-including-france-ger-sponsored-countries-union-f--850969292074858684/]
[https://www.mpi-hd.mpg.de/gerda/]
[https://www-project.slac.stanford.edu/exo/about.html]
[https://cerncourier.com/a/kamland-experiment-discovers-that-reactor-antineutrinos-disappear/]

Motivation

Baryogenesis via neutrino oscillations

E. Kh. Akhmedov[(a,b)] V. A. Rubakov[(c,a,d)] and A. Yu. Smirnov[(a,c)]

The νMSM, Dark Matter and Baryon Asymmetry of the Universe

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[Dekens et. al. JHEP 2020]

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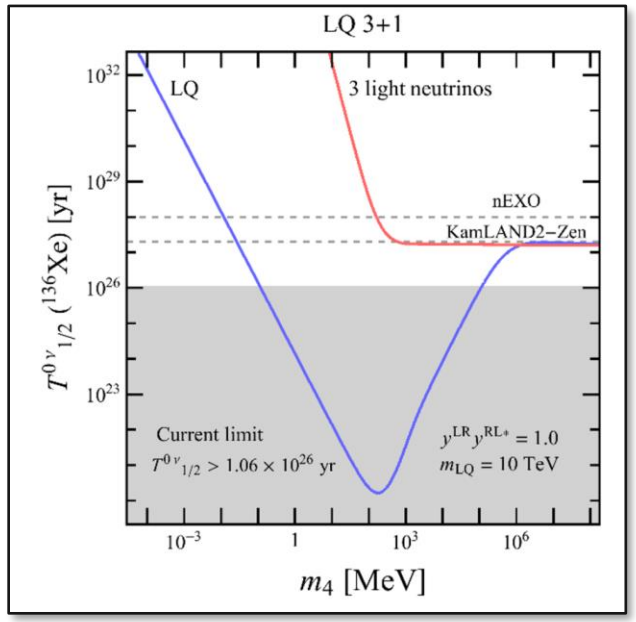
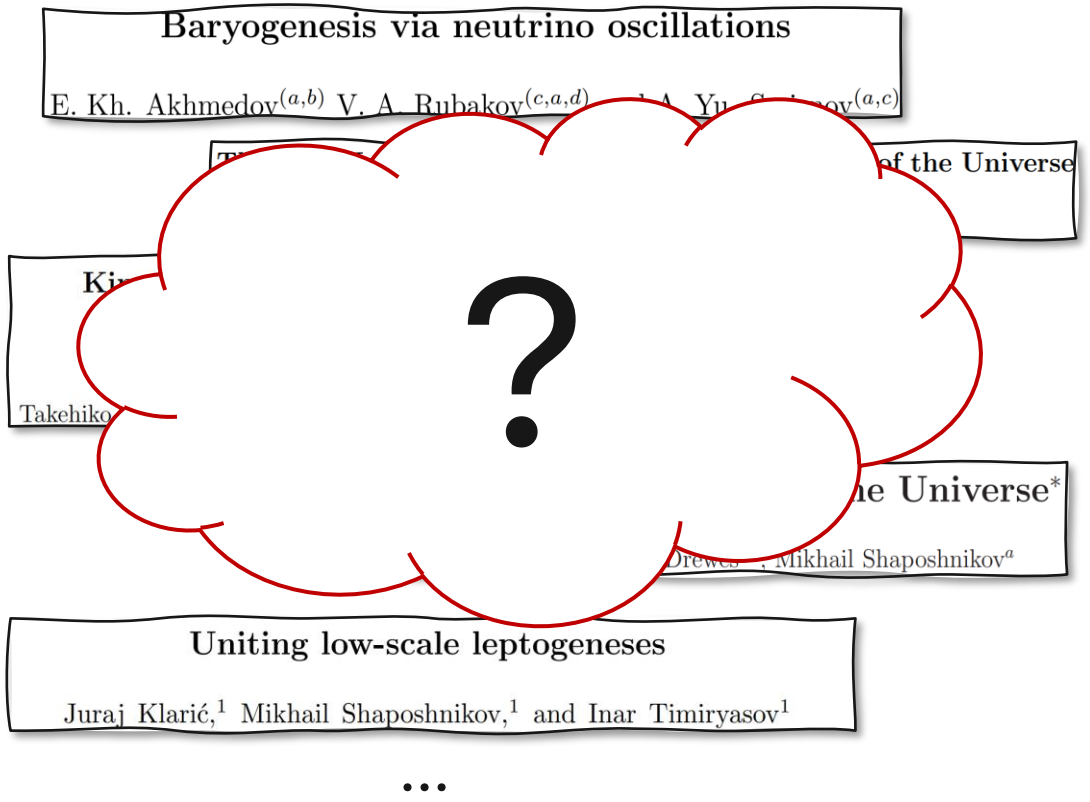
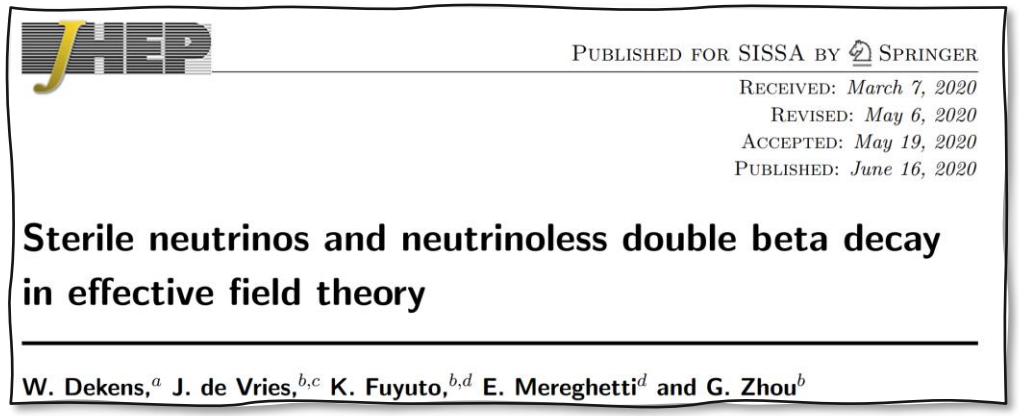


How robust?

Motivation

[Dekens et. al. JHEP 2020]

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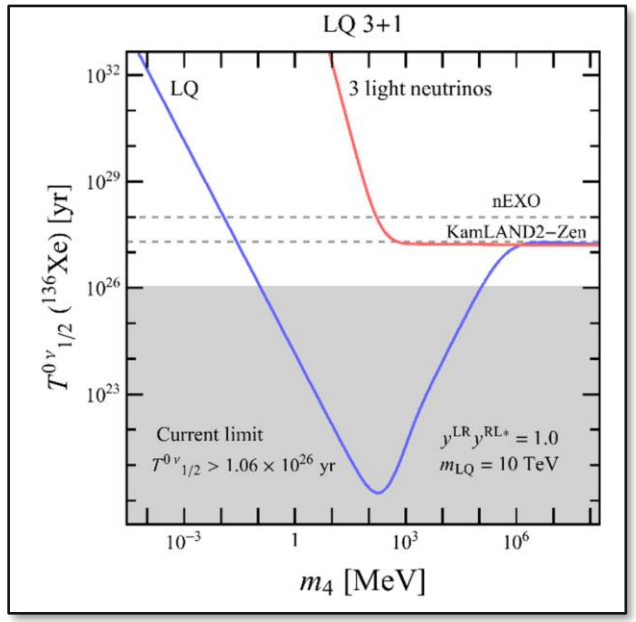


How robust?

Outline

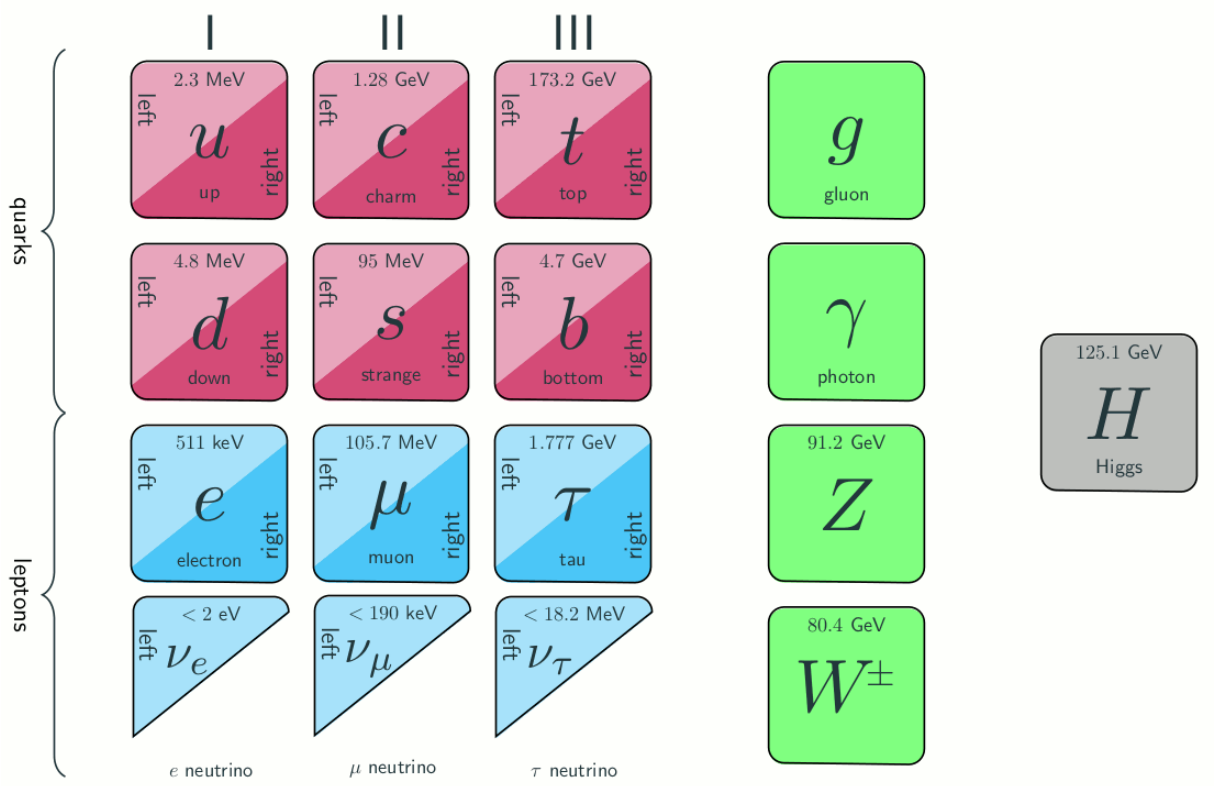
0 Right-handed neutrinos (RHN) and non-standard interactions (NSI)

1 Neutrino masses – Seesaw mechanism

2 Lepton number violation – $0\nu\beta\beta$ decay

3 Baryon Asymmetry of the Universe - Leptogenesis

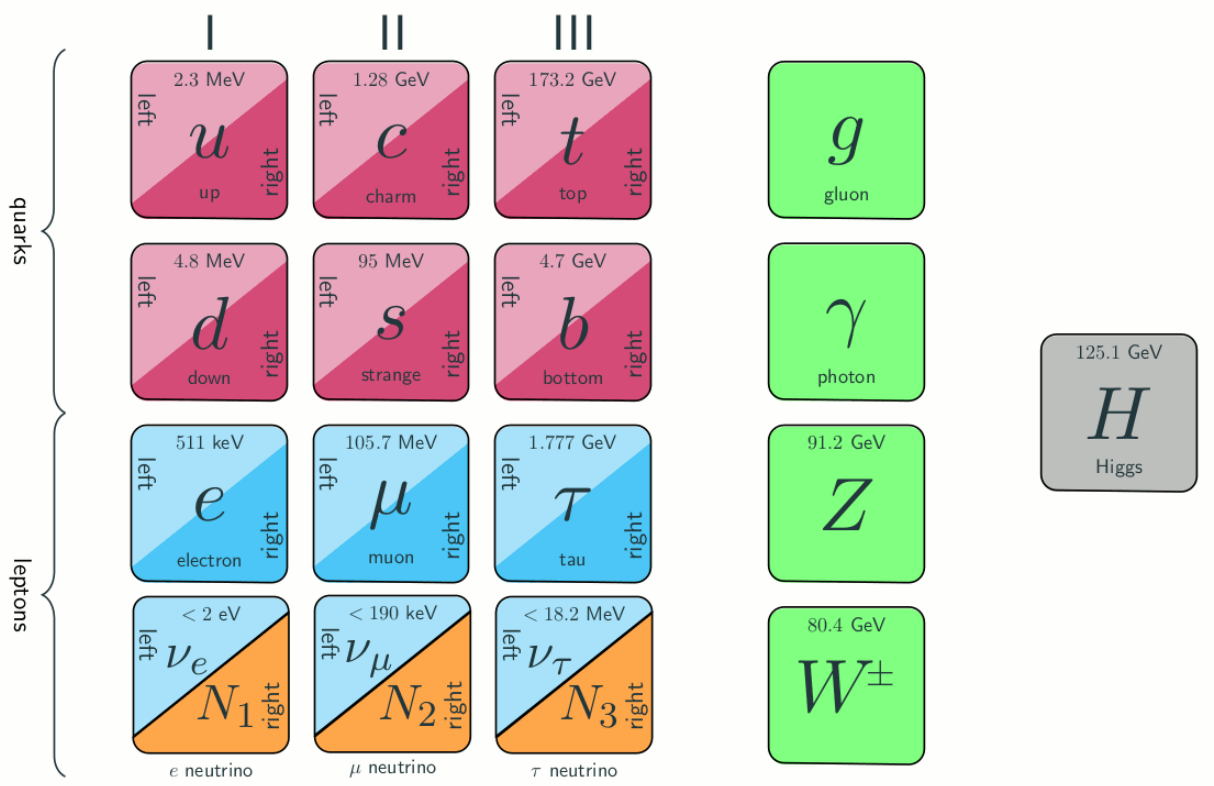
The Standard Case



[https://ep-news.web.cern.ch/uniting-leptogeneses]

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}}$$

The Standard Case



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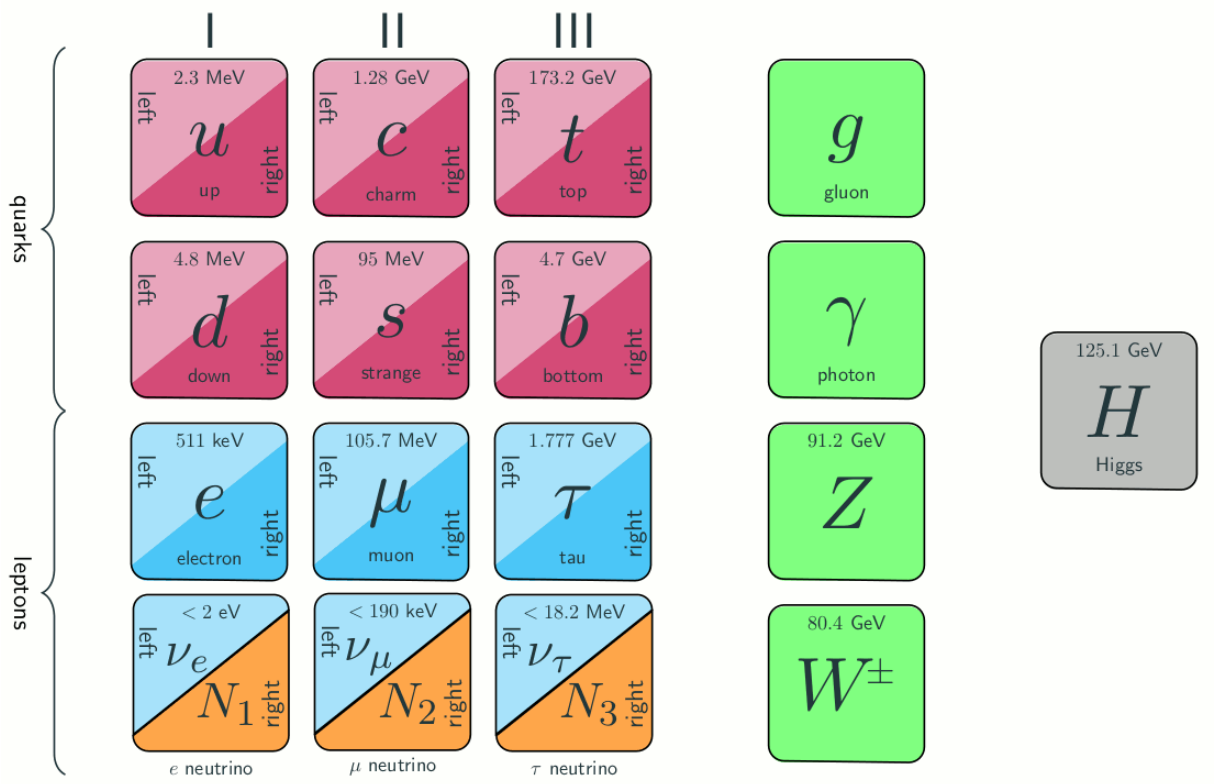
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_N \begin{cases} + \bar{N}(i\partial\!\!\!/)N \\ - Y_{i\alpha}\bar{N}_i H L_\alpha + \text{h.c.} \\ - \bar{N}_i^c M_i N_i + \text{h.c.} \end{cases}$$

Non-Standard Case?



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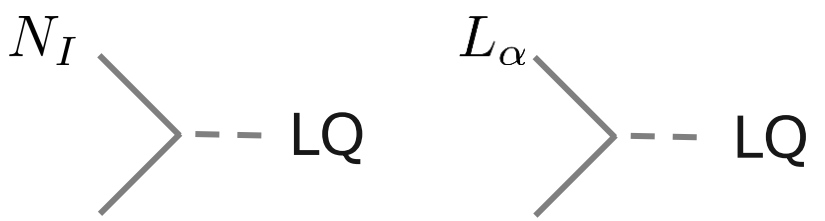
+ more?

Non-Standard Case



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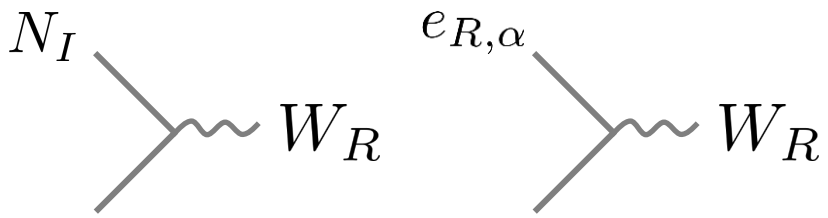
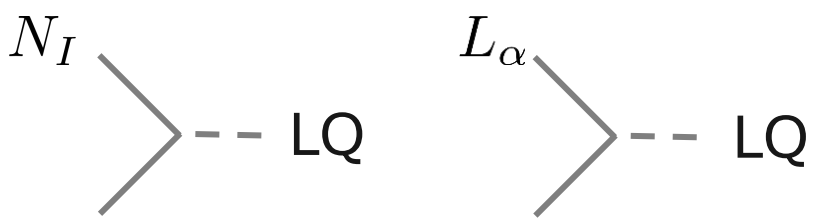


or

Any new particle coupling to RHNs and/or leptons

Non-Standard Case



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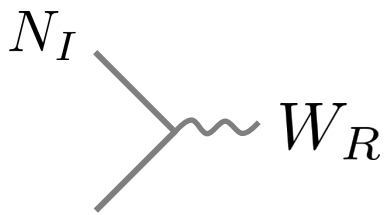

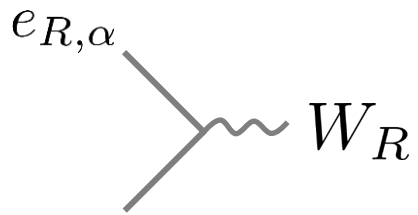

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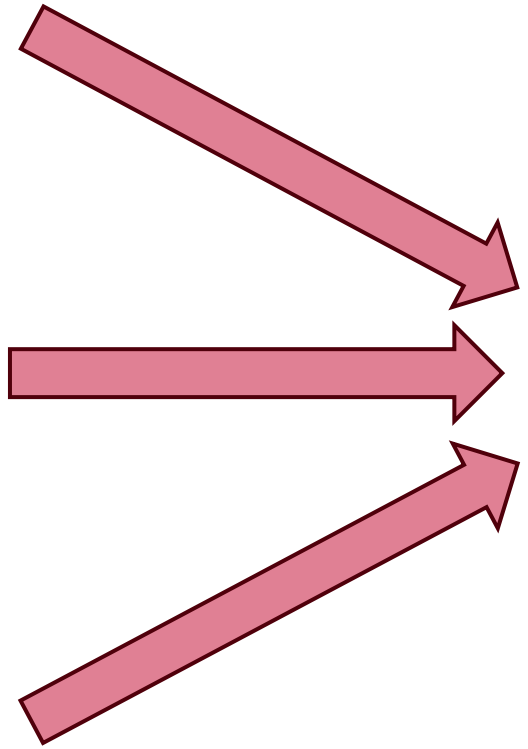
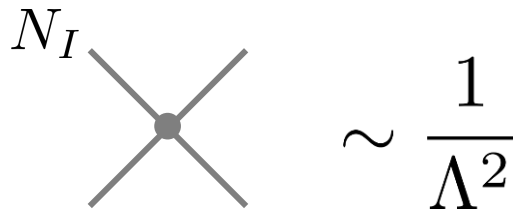
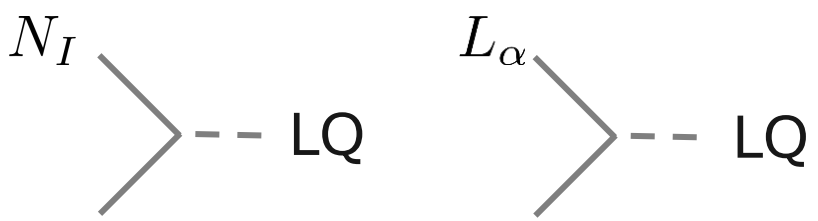




Effective operator description

Non-Standard Case



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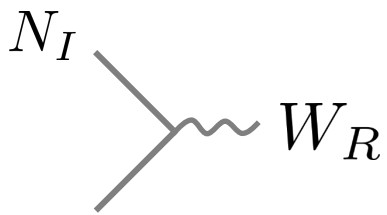

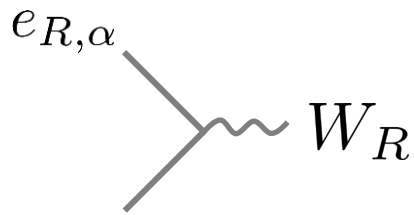

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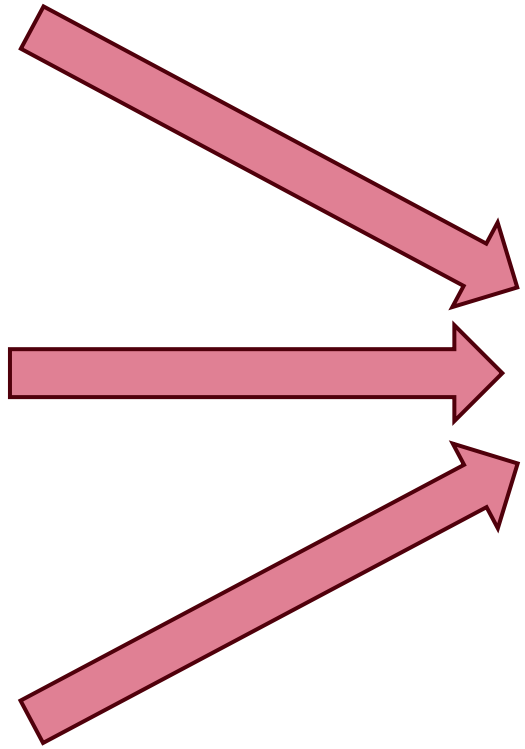
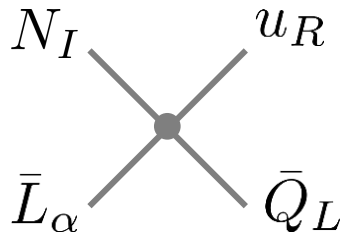
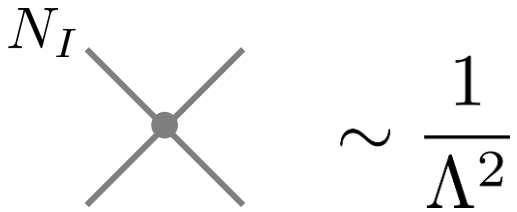


Example operator:





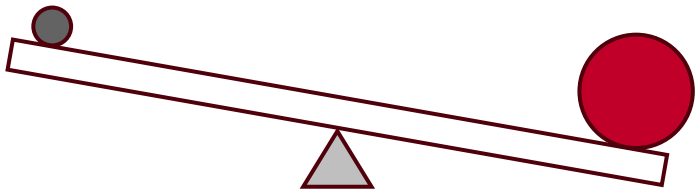
Effective operator description

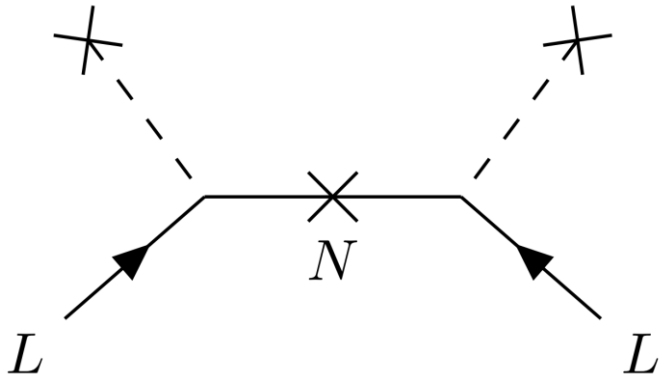
1) Neutrino masses – Standard Case

$$\mathcal{L} \supset -\underbrace{(Y v_{\mathrm{EW}})}_{m_D} \bar{N} \nu_L - M_N \bar{N}^c N$$

Seesaw mechanism: $M_N \gg m_D$

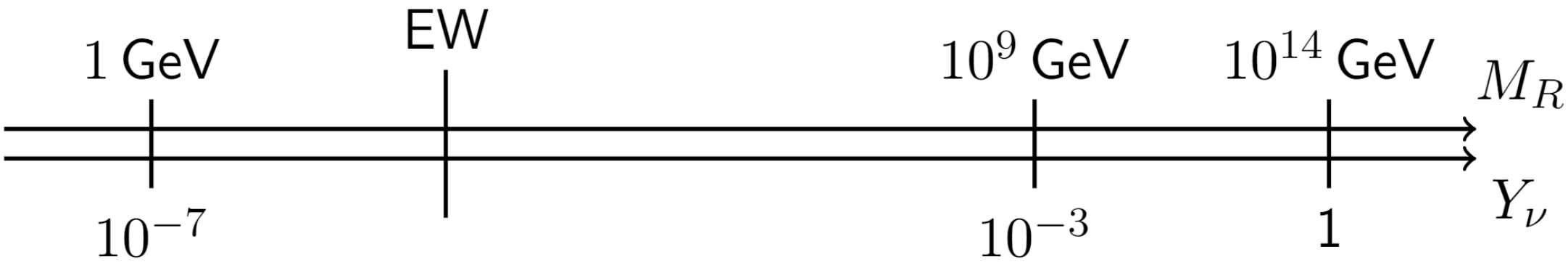
$$\frac{v^2 Y^2}{M_N} \approx m_\nu \qquad m_N \approx M_N$$





[Fridell PhD 2022]

Range of scales



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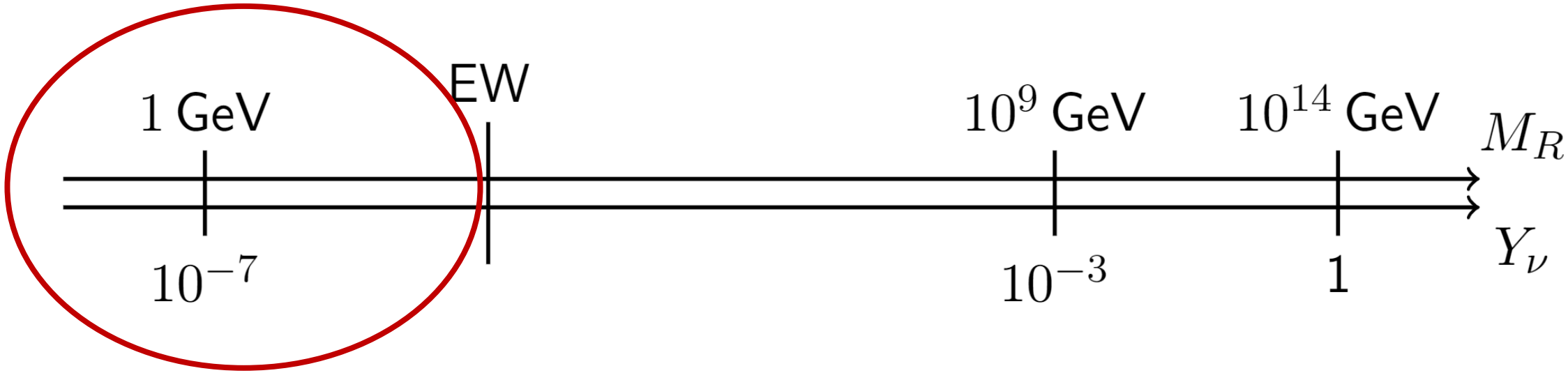
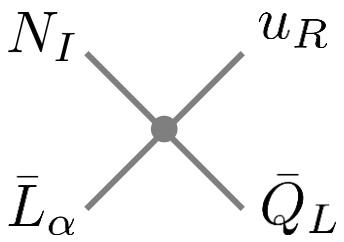


"Low Scale"

Neutrino masses – Non-Standard Case



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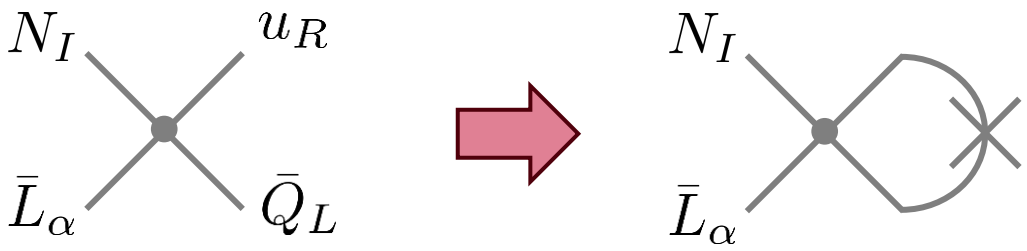

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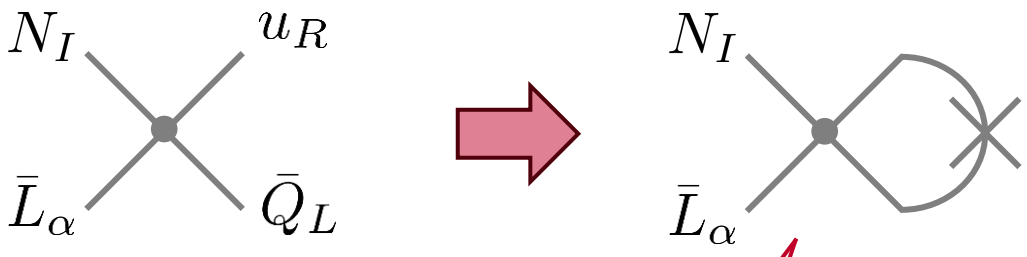
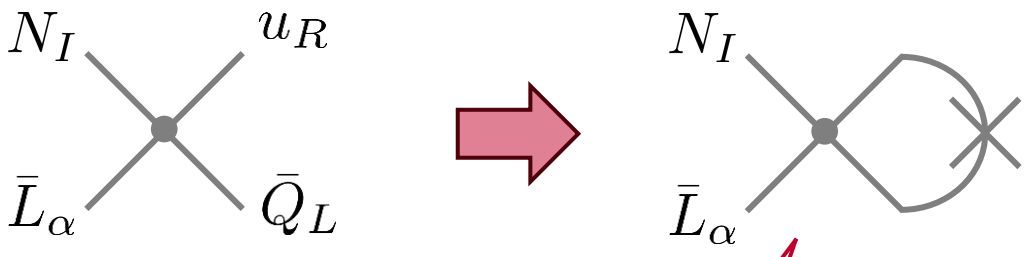


Diagonalize Mass matrix $M = \begin{pmatrix} M_L & M_D^* \\ M_D^\dagger & M_R^\dagger \end{pmatrix}$

Need to satisfy upper bound on m_υ

Neutrino masses – Non-Standard Case



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Need to satisfy upper bound on m_υ

→ Lower bound on Λ

2) Lepton number violation

- Assignment of LN: $\mathcal{L} \supset -Y_{i\alpha}\overline{N_i}HL_\alpha - \overline{N_i^c}M_iN_i + \text{h.c.}$

LNC

LNV

$$L(L_\alpha) = 1$$
$$L(H) = 0$$
$$L(N_i) = 1$$

2) Lepton number violation

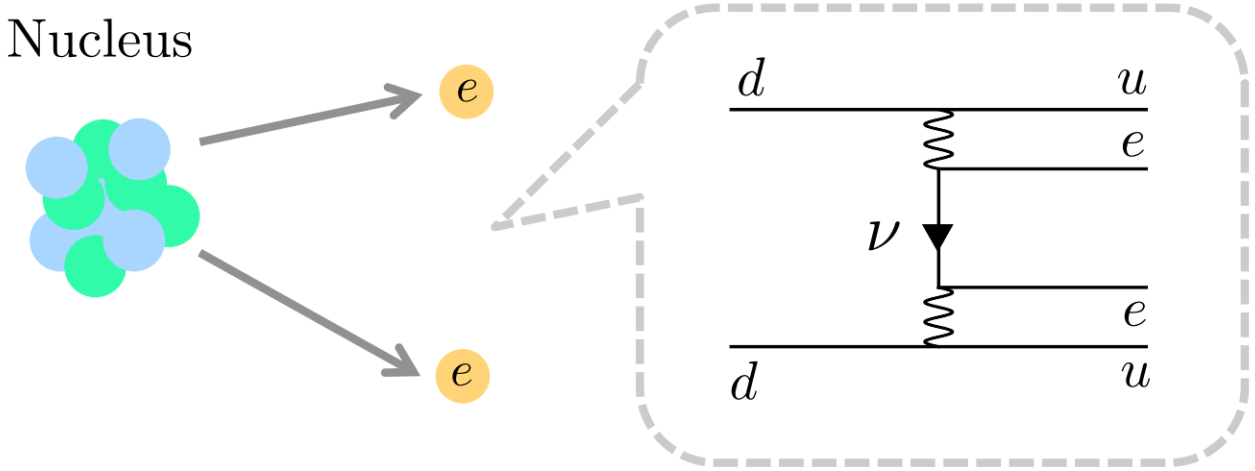
- Assignment of LN: $\mathcal{L} \supset -Y_{i\alpha}\overline{N_i}HL_\alpha - \overline{N_i^c}M_iN_i + \text{h.c.}$

LNC LNV

$$L(L_\alpha) = 1$$
$$L(H) = 0$$
$$L(N_i) = 1$$

- "Most" promising observable: $0\nu\beta\beta$ decay

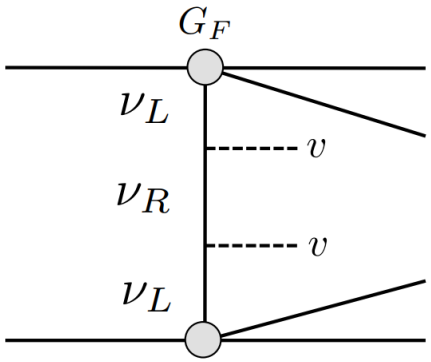
$$\Delta L = 2$$



[by K. Fuyuto]

LNV – Standard Case

- 4-fermion interaction at low scales



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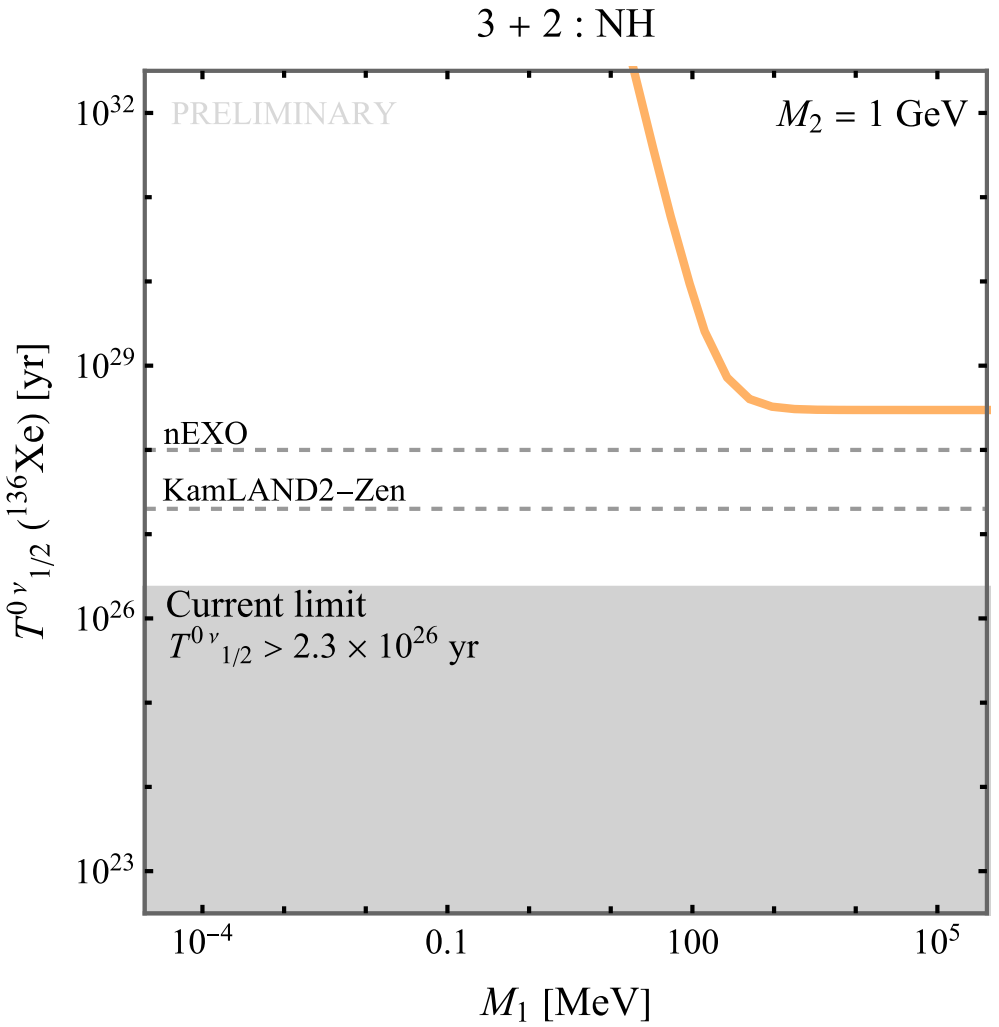
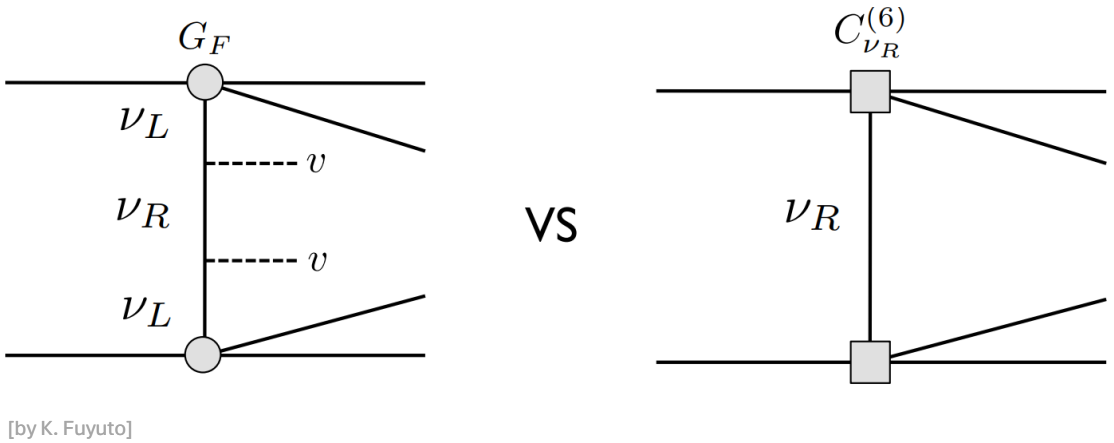


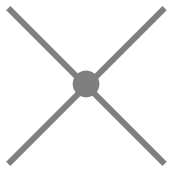
LNV – Non-Standard Case

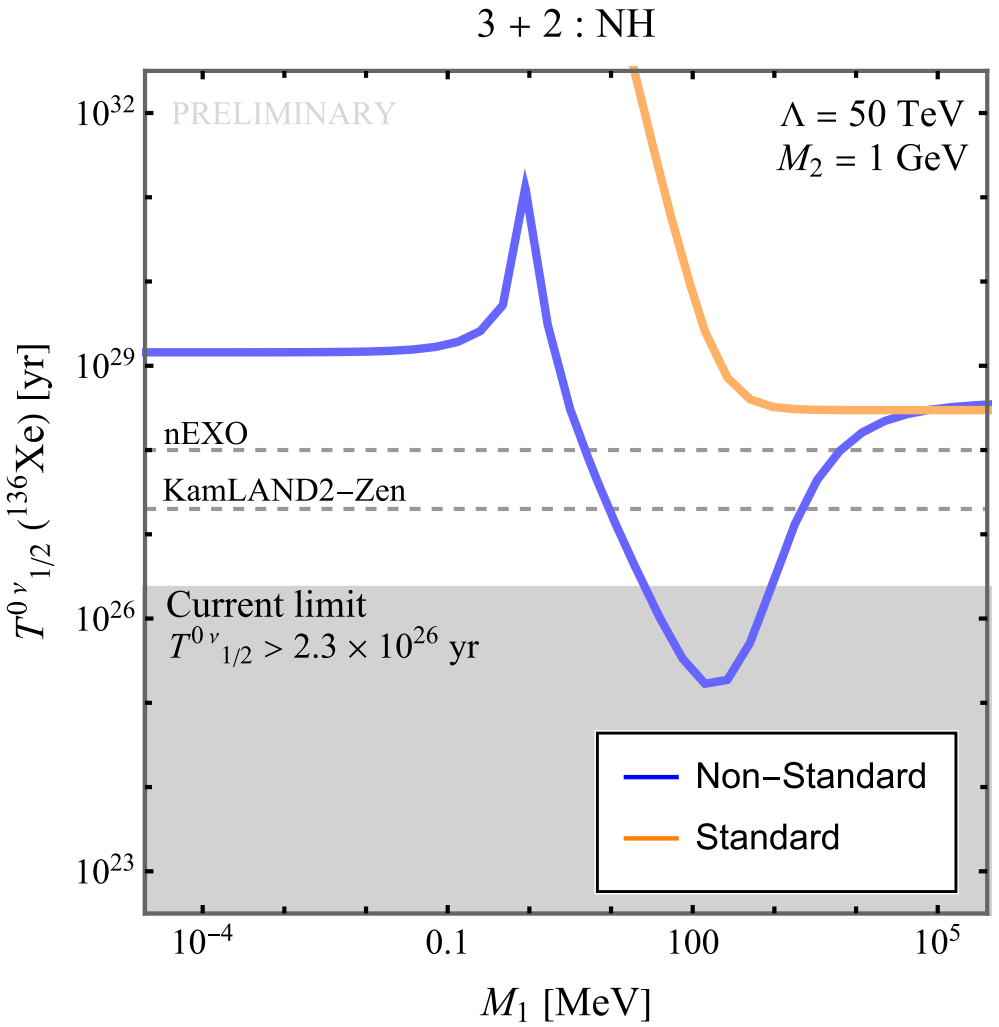
- See also [Dekens et. al. JHEP 2020]



[by K. Fuyuto]

LNC operator:

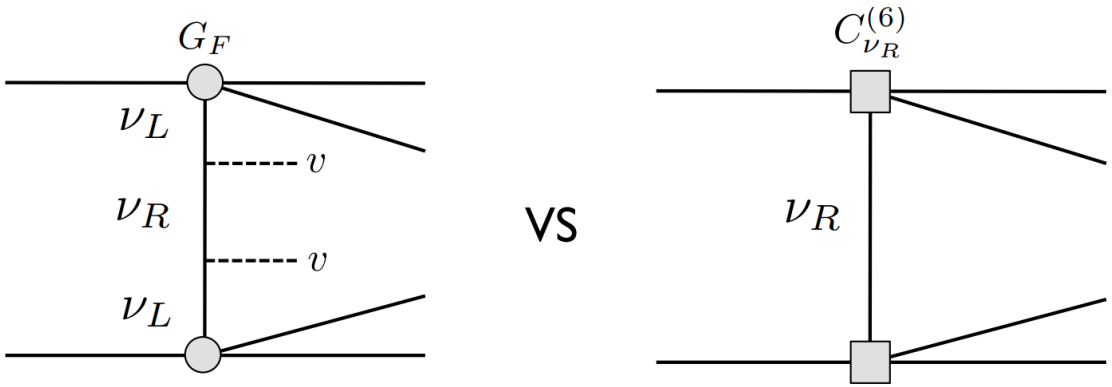




LNV – Non-Standard Case

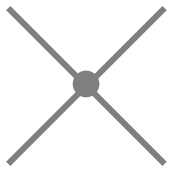
Order of magnitude effect!

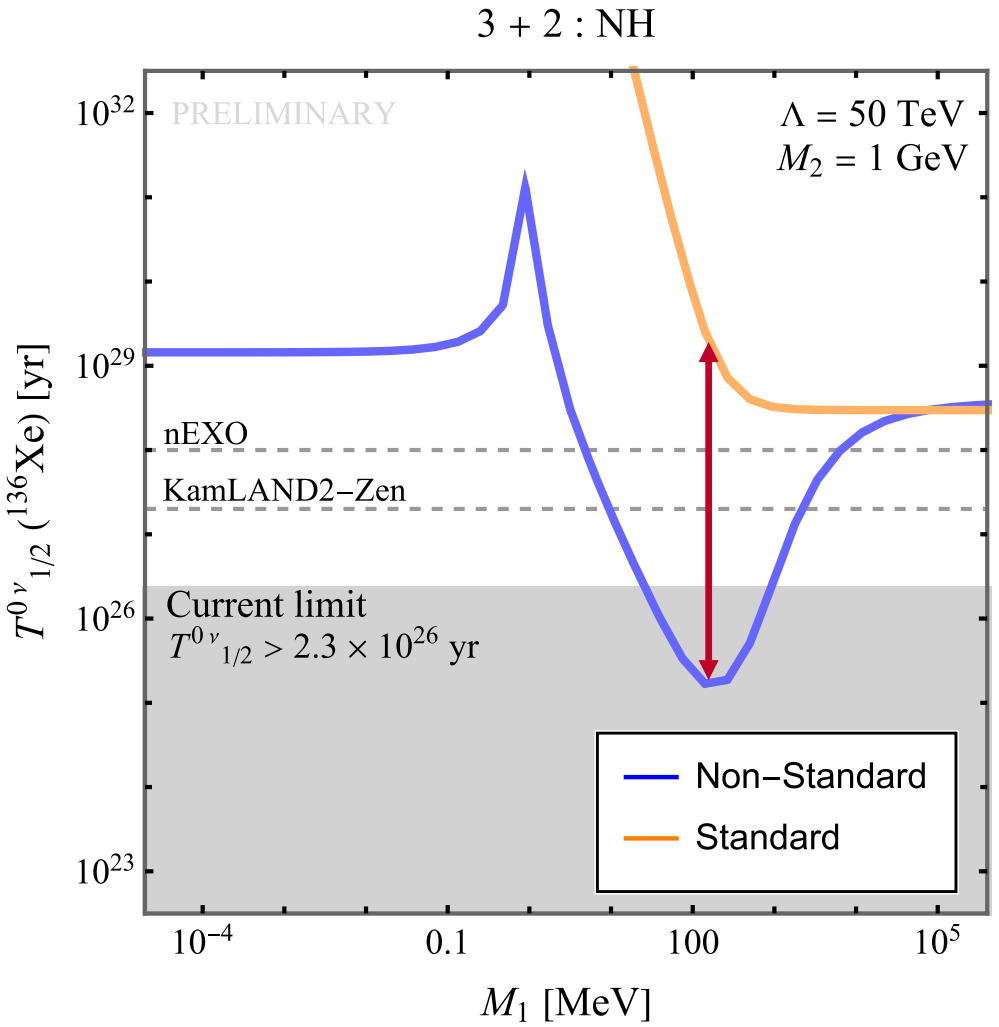
- See also [Dekens et. al. JHEP 2020]



[by K. Fuyuto]

LNC operator:



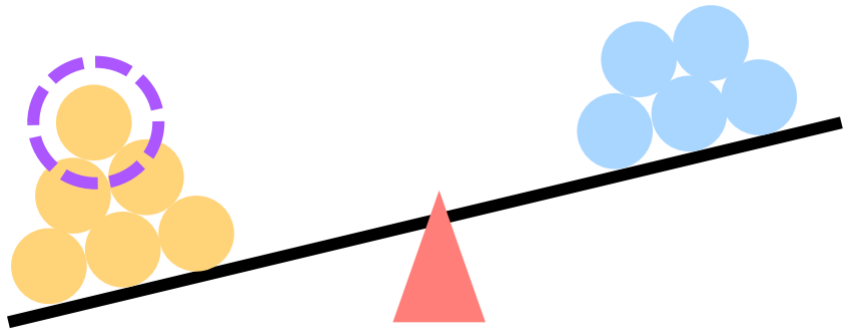


3) Baryon Asymmetry

- Matter-Antimatter asymmetry

$$\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 6 \times 10^{-10}$$

- Sakharov conditions
  1) B violation
  2) C and CP violation
  3) Out-of-equilibrium

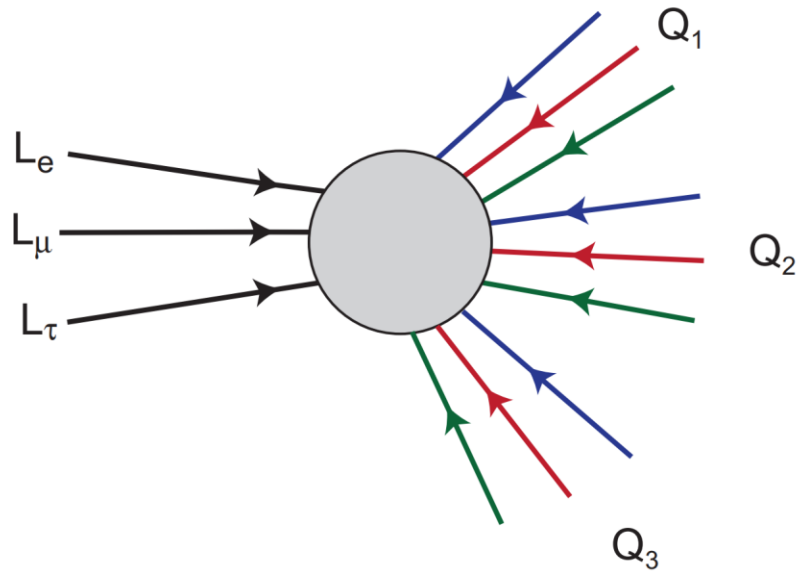


[by K. Fuyuto]

Leptogenesis (LG)

Above EW scale:

- SM sphaleron processes → $B + L$ violation
- Non-perturbative



[Nir 2009]

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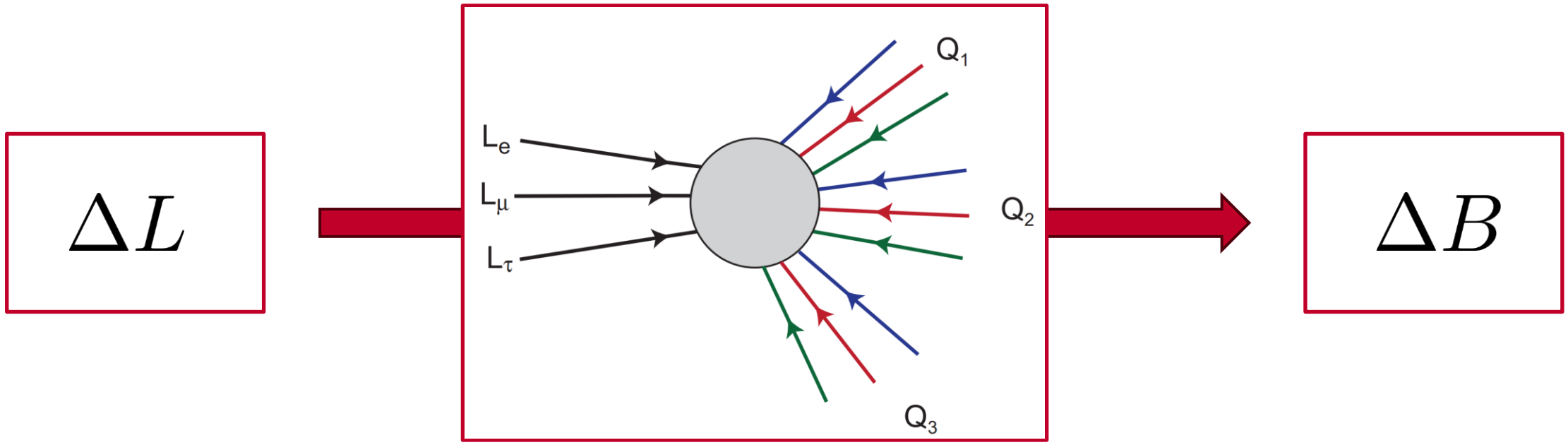
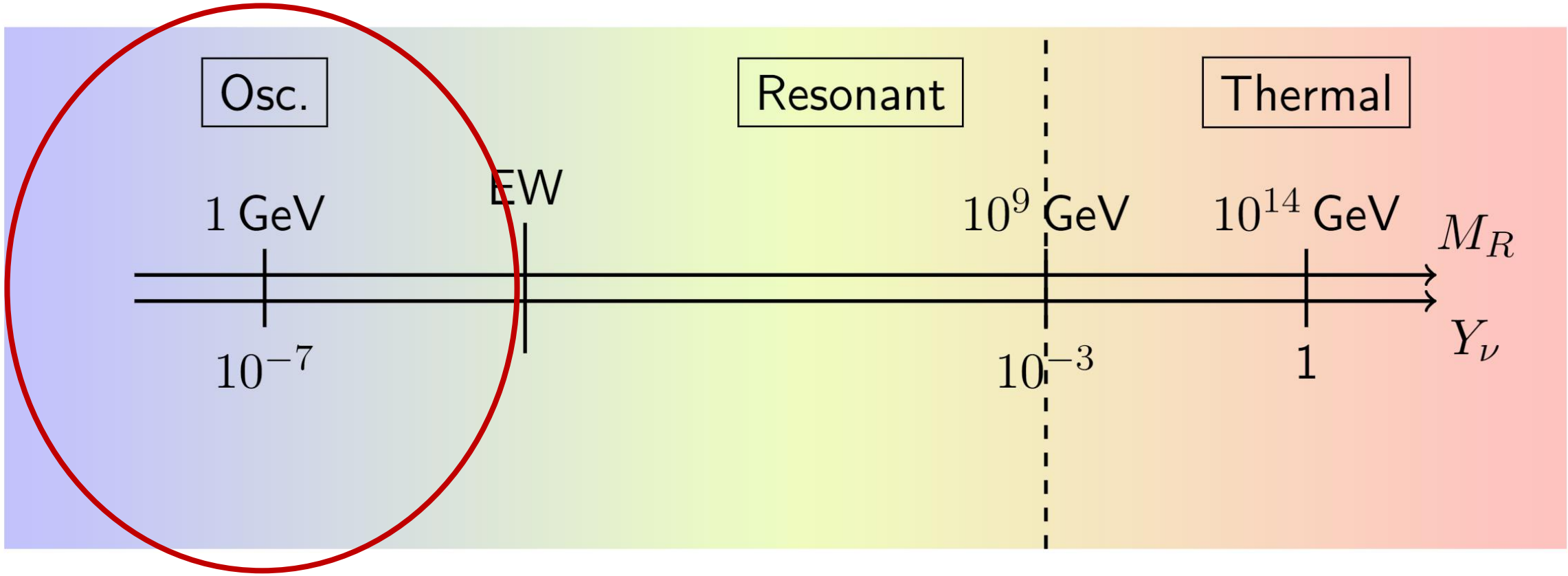
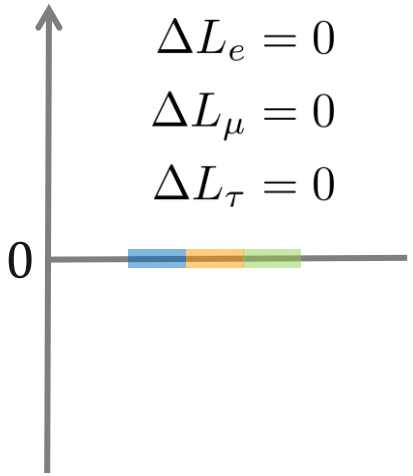


[Nir 2009]

Leptogenesis regimes

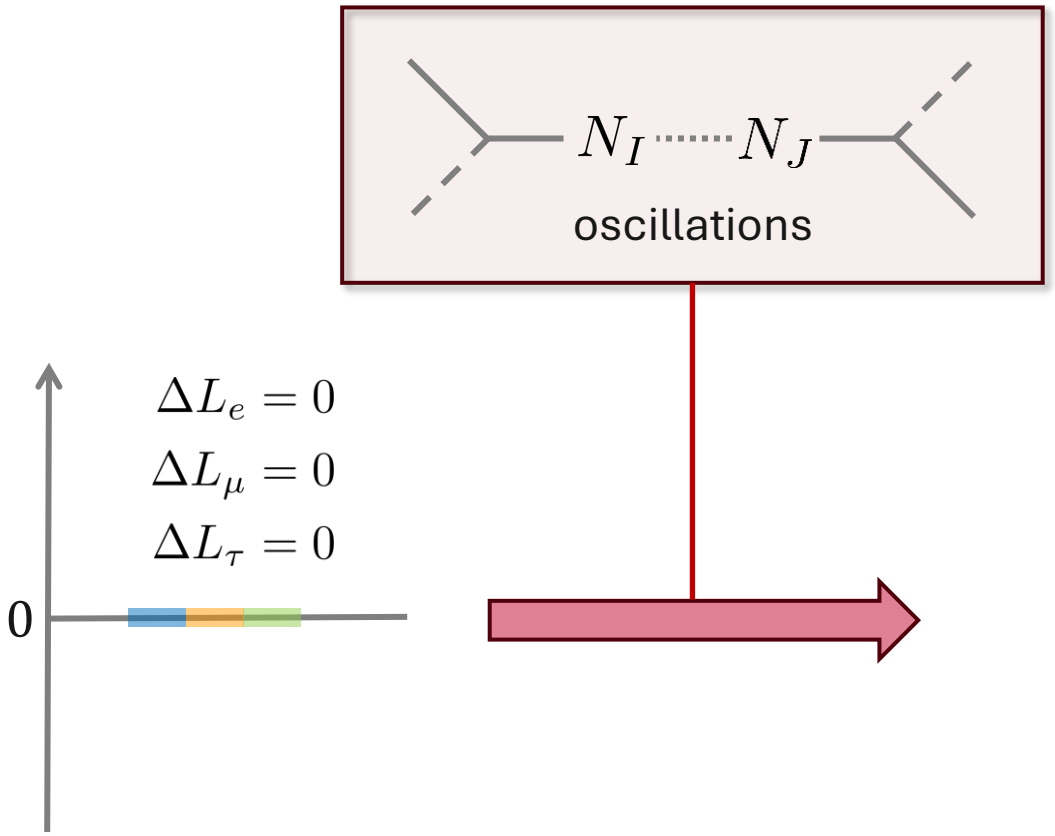


BAU via Neutrino Oscillation – Standard Case



$$\Delta L_{\mathrm{SM}} = 0$$

BAU via Neutrino Oscillation – Standard Case



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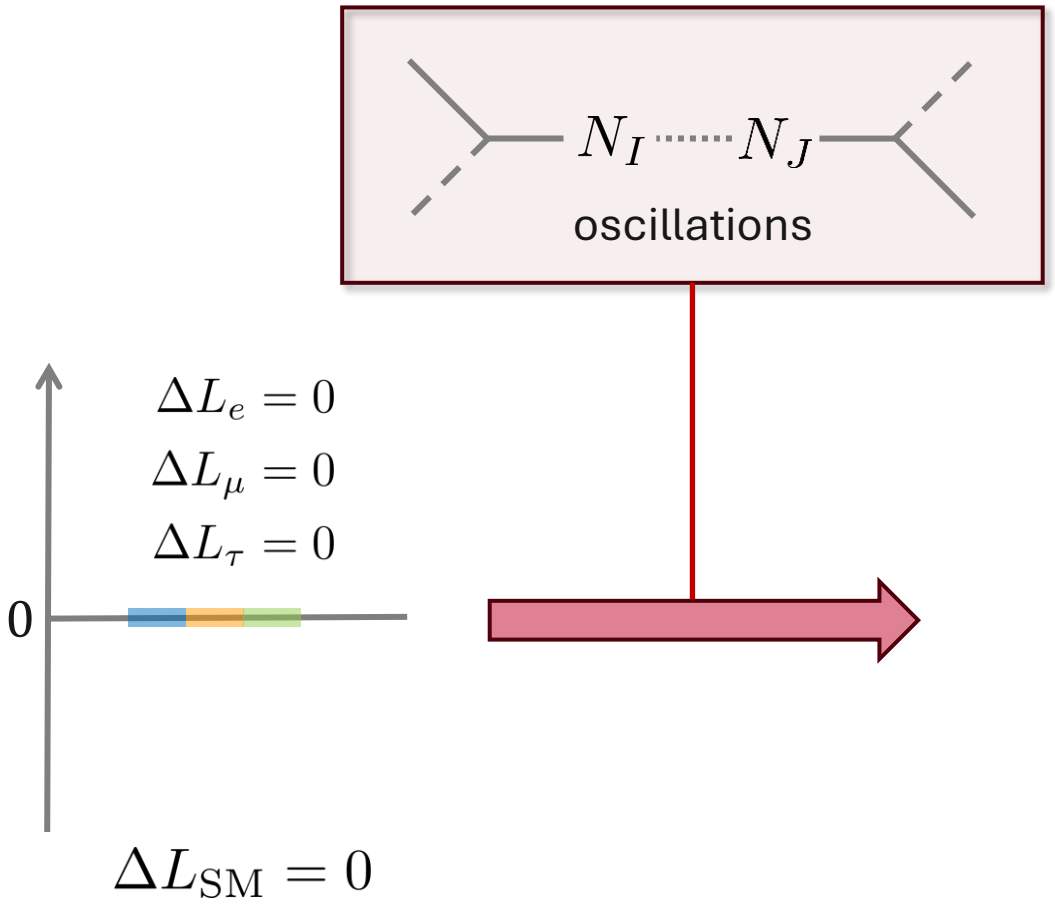
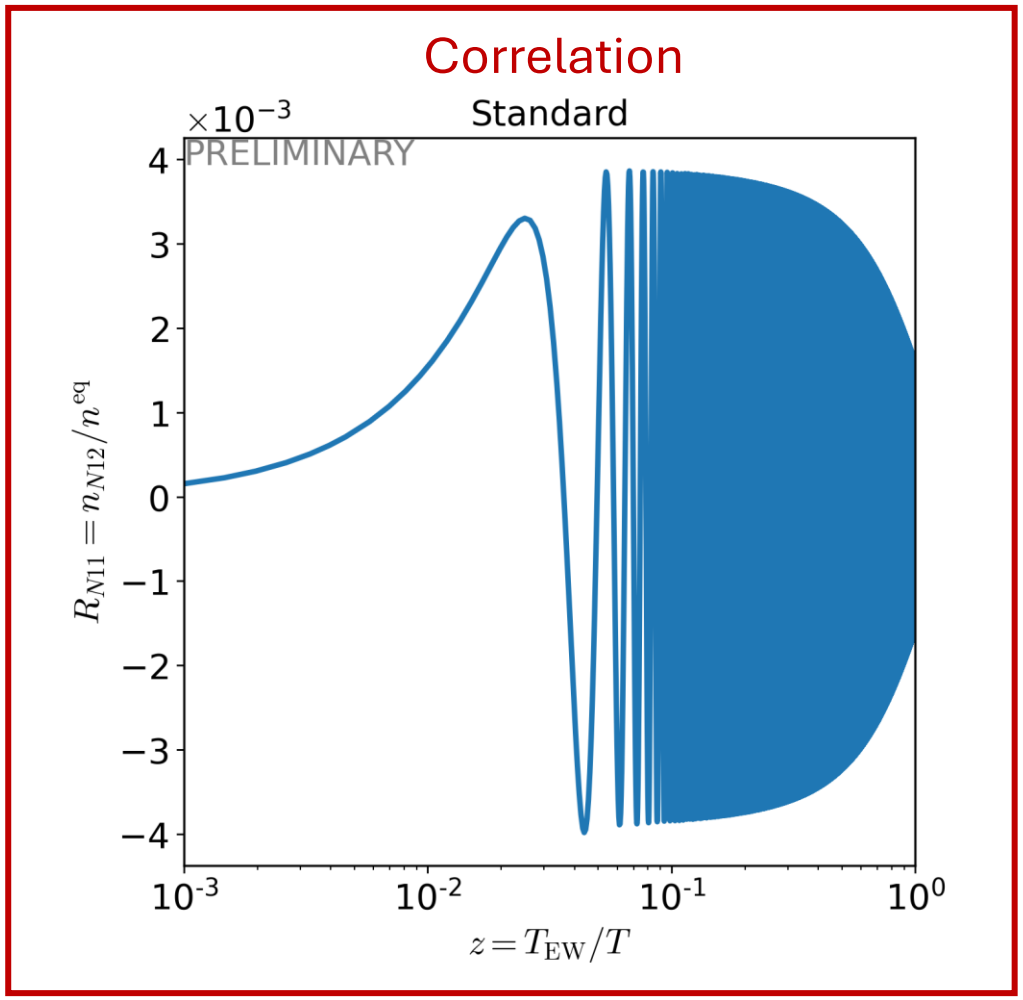
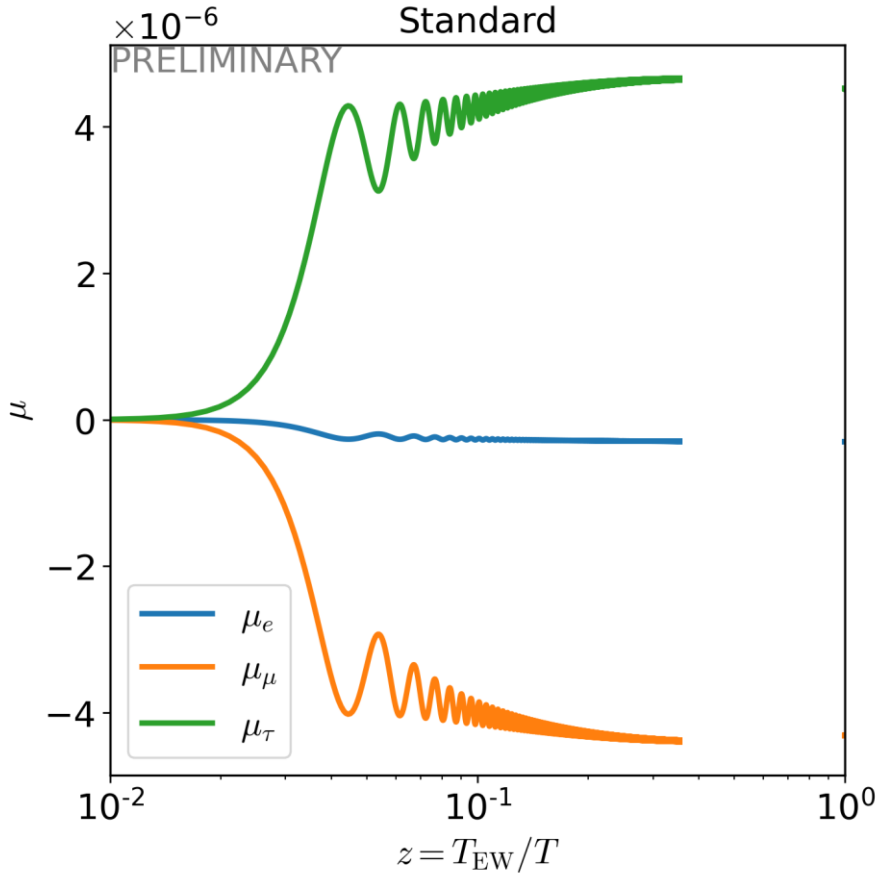


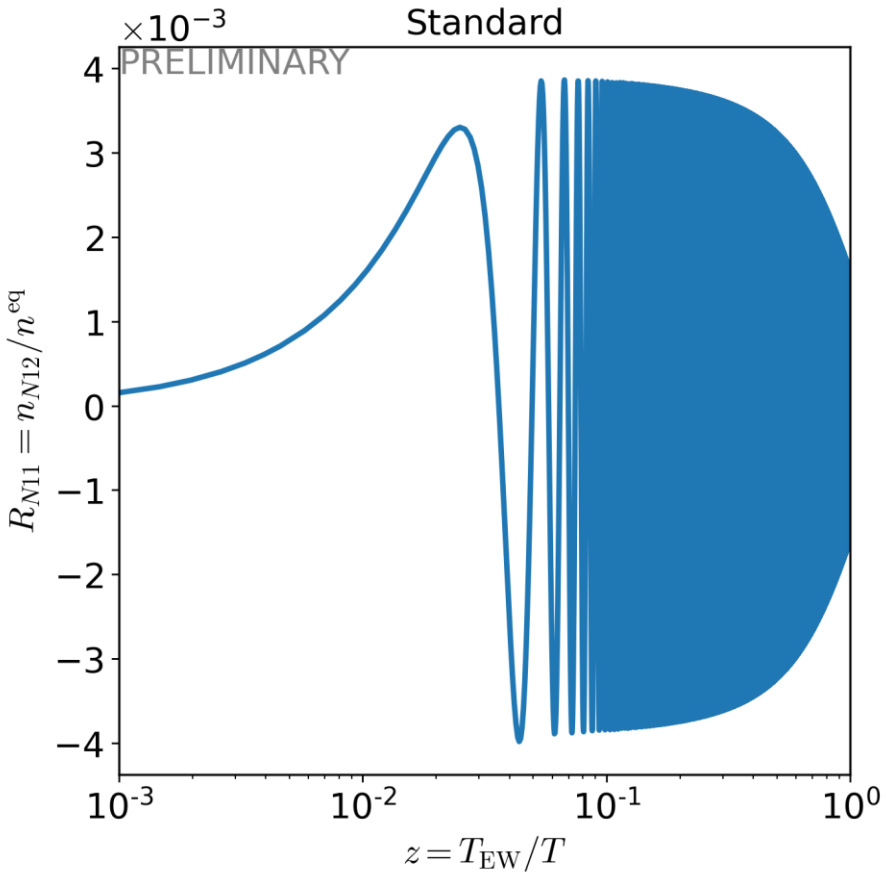


BAU via Neutrino Oscillation – Standard Case

Lepton Flavor Asymmetries

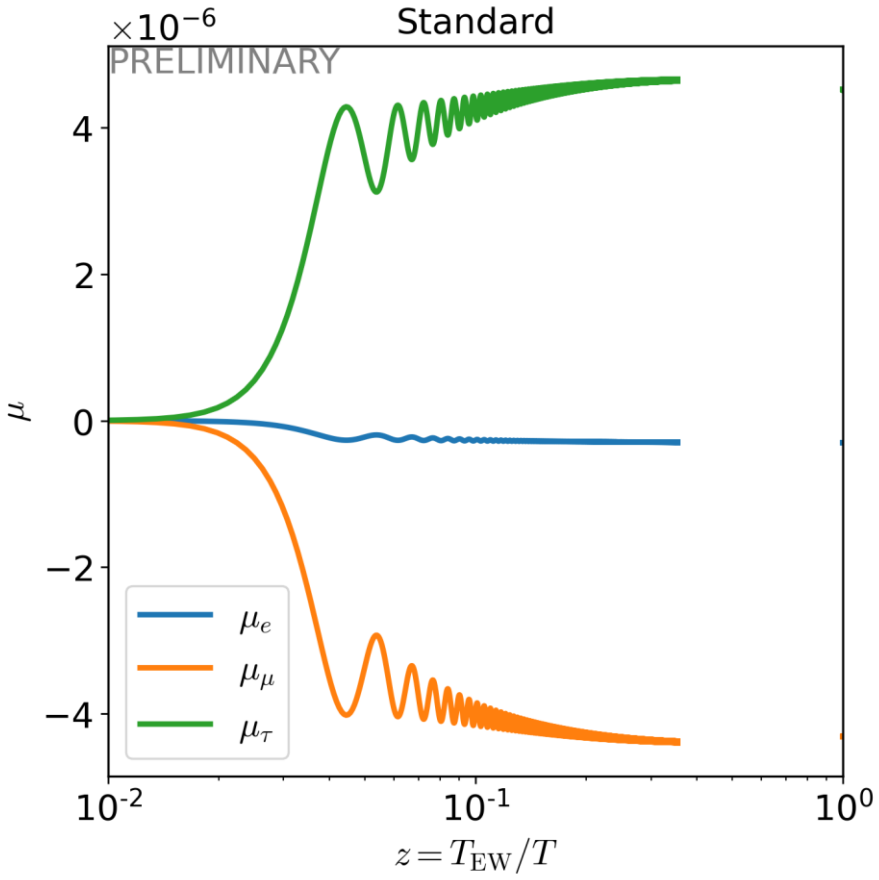


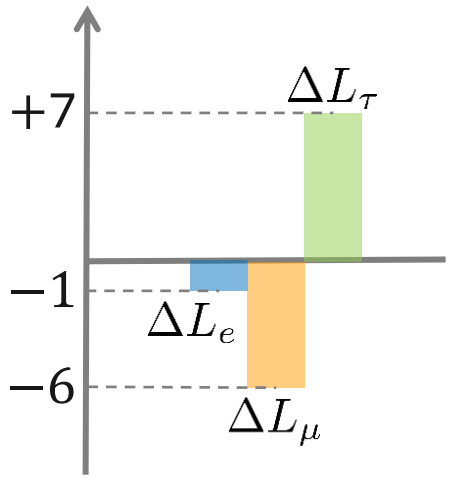
Correlation



BAU via Neutrino Oscillation – Standard Case

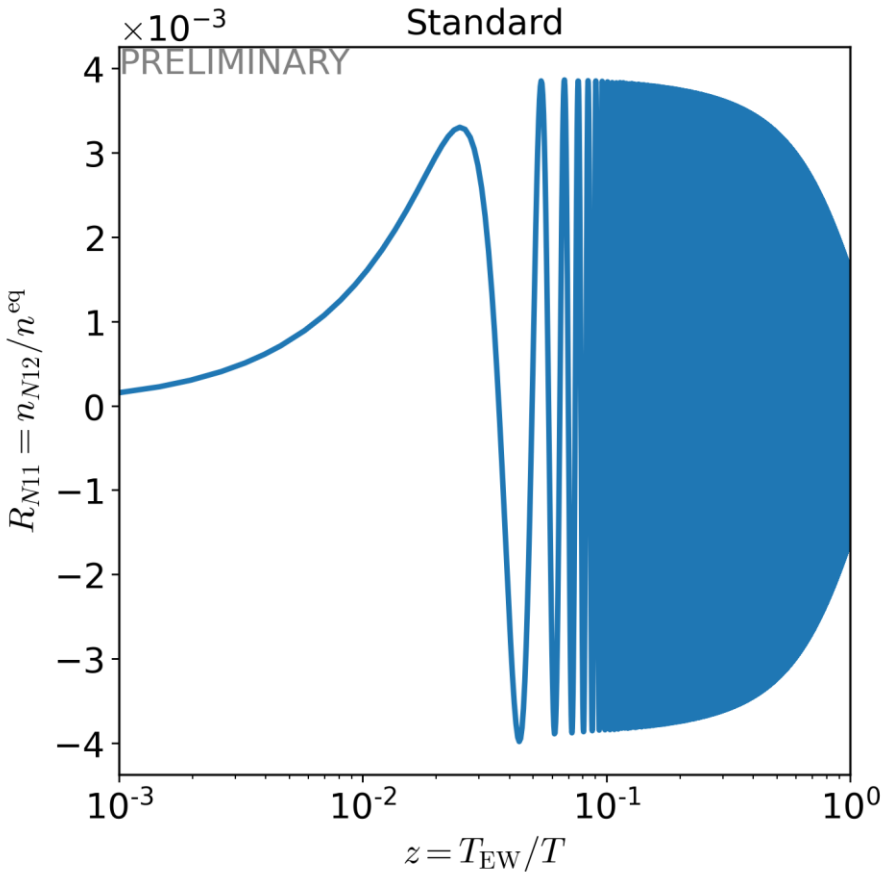
Lepton Flavor Asymmetries





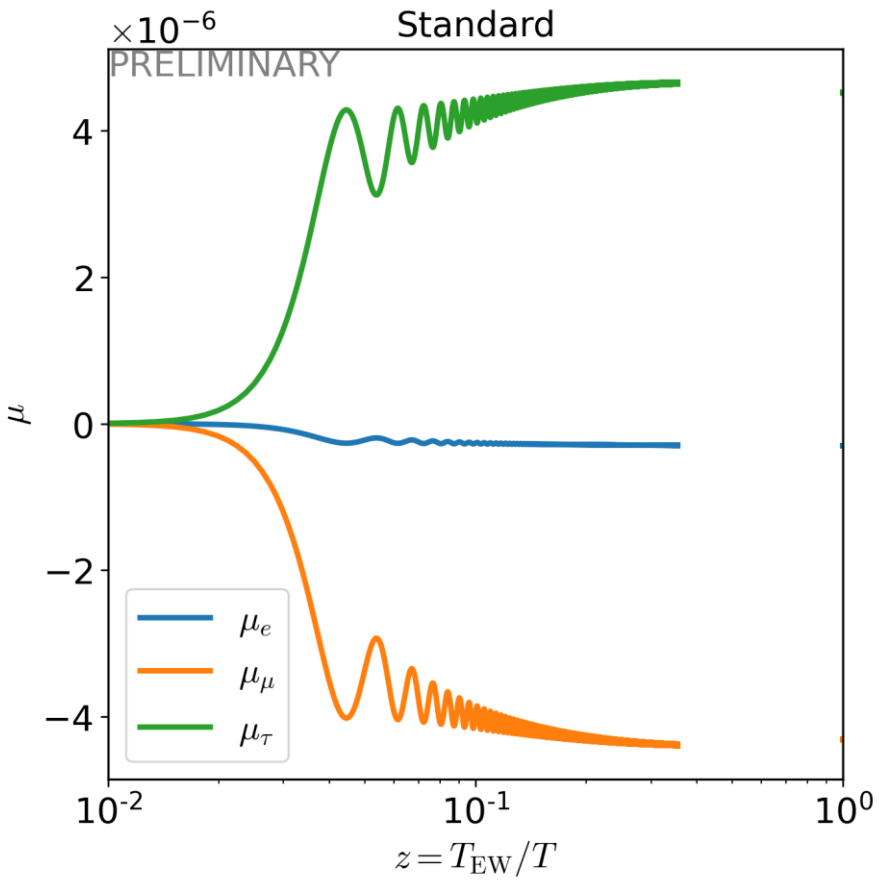
$$\Delta L_{\rm SM} = 0$$

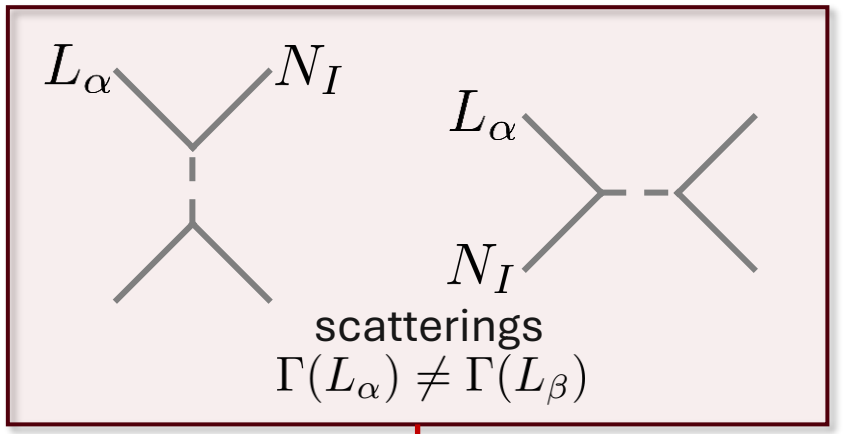
Correlation

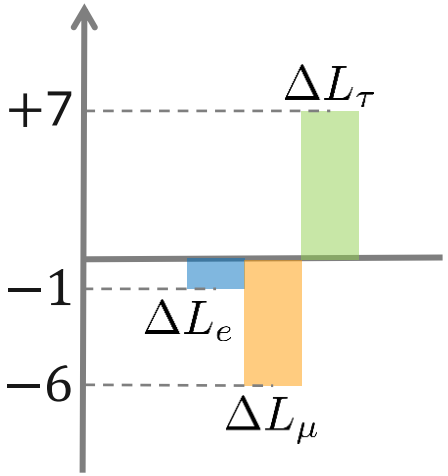


BAU via Neutrino Oscillation – Standard Case

Lepton Flavor Asymmetries



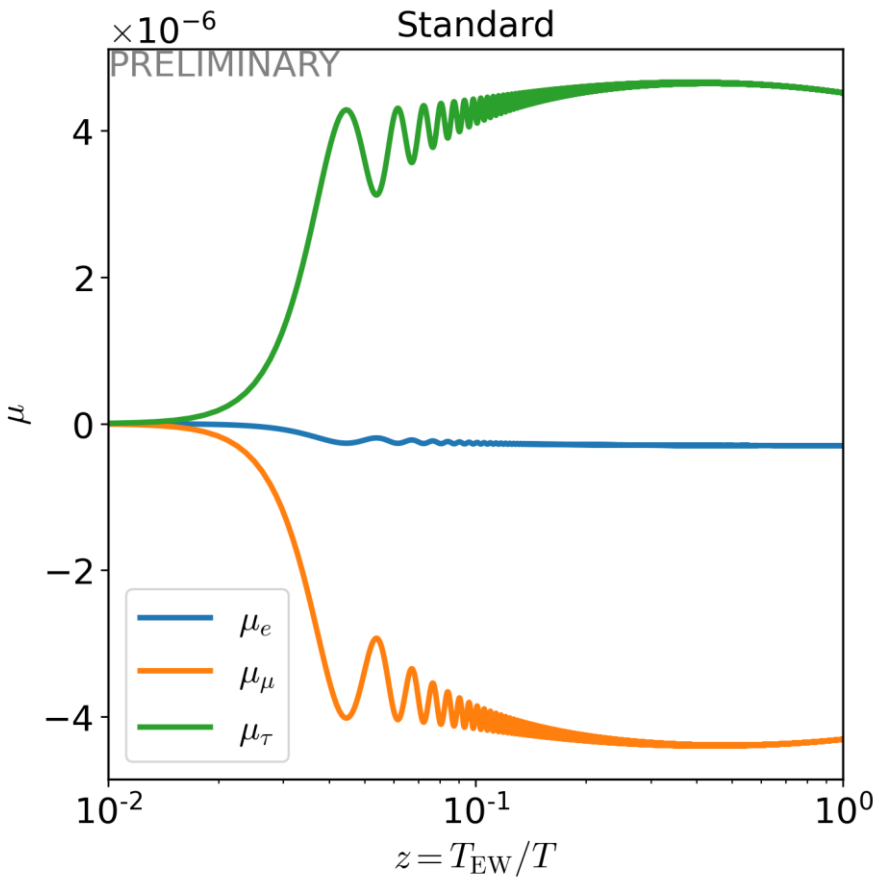


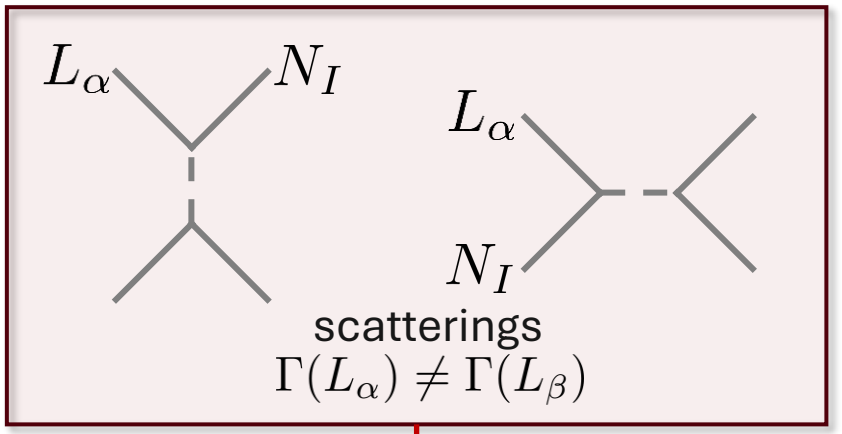


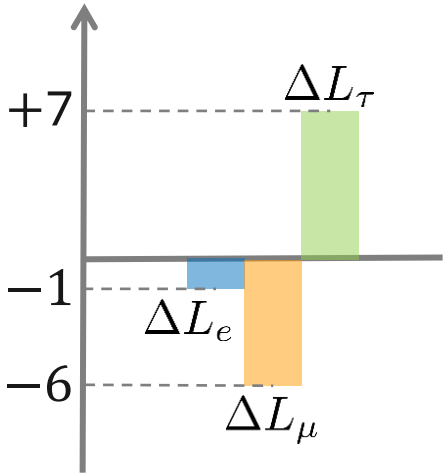
$\Delta L_{\rm SM} = 0$

BAU via Neutrino Oscillation – Standard Case

Lepton Flavor Asymmetries







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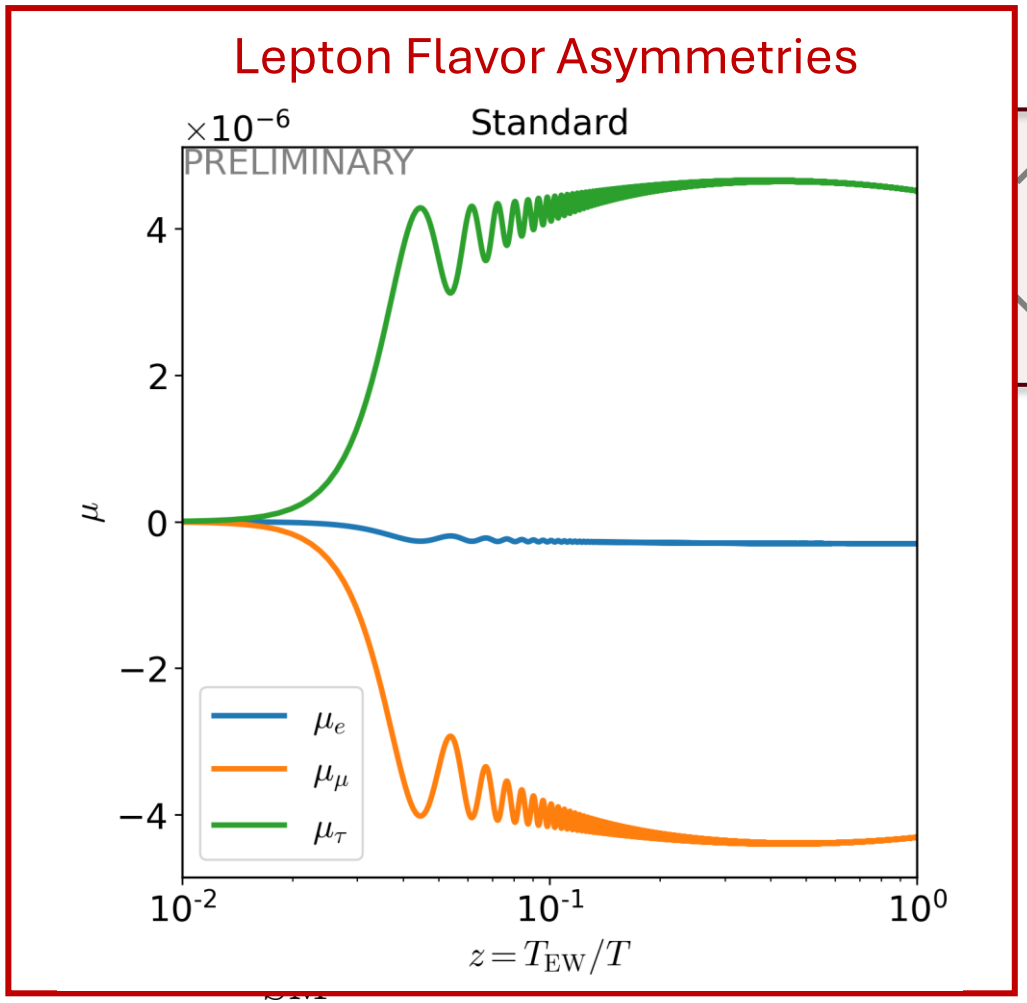
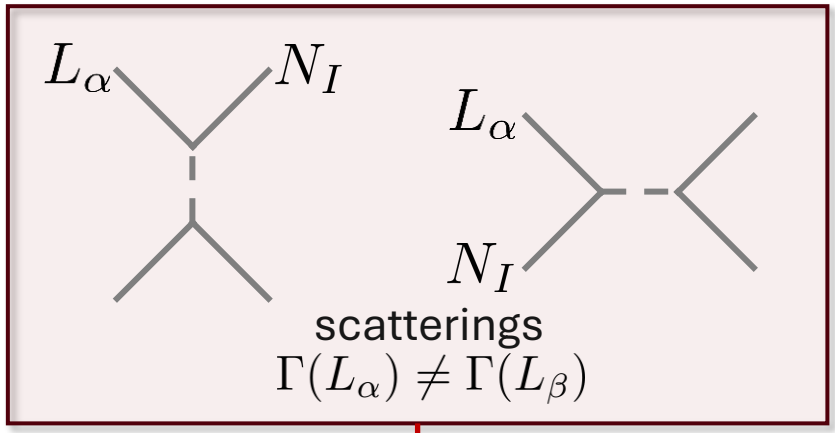
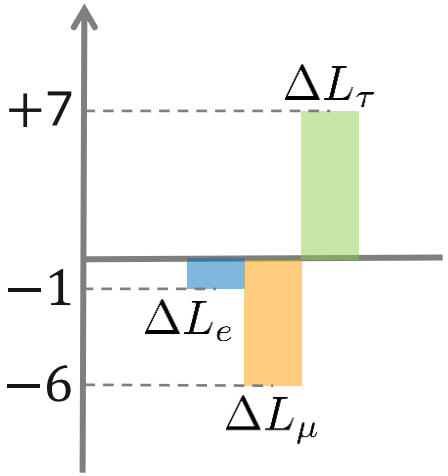
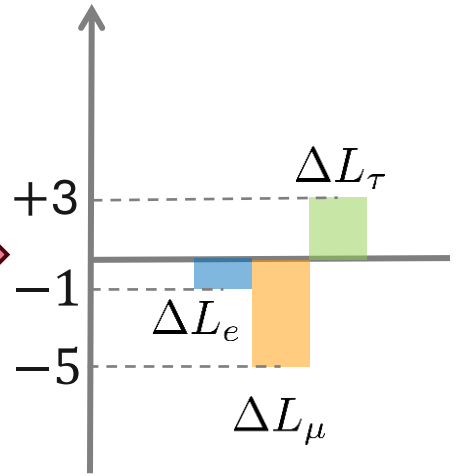
BAU via Neutrino Oscillation – Standard Case

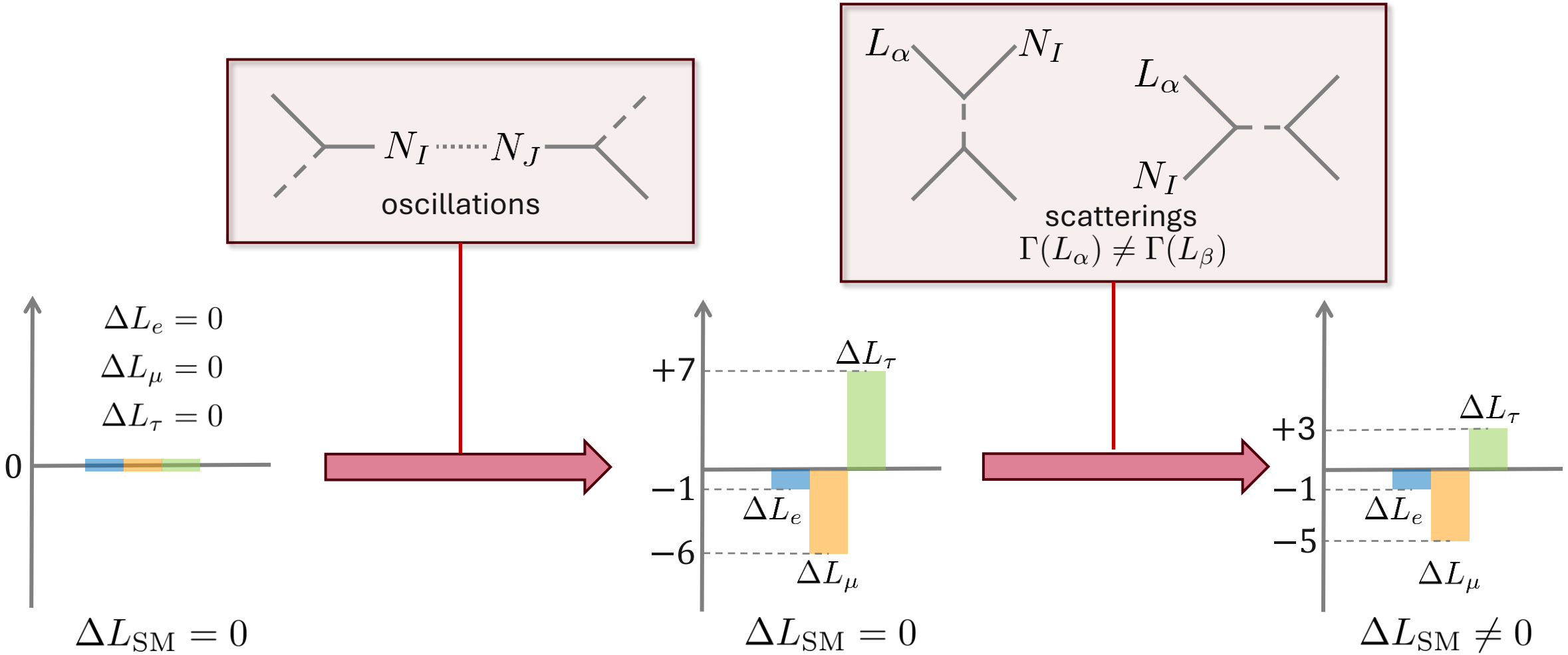




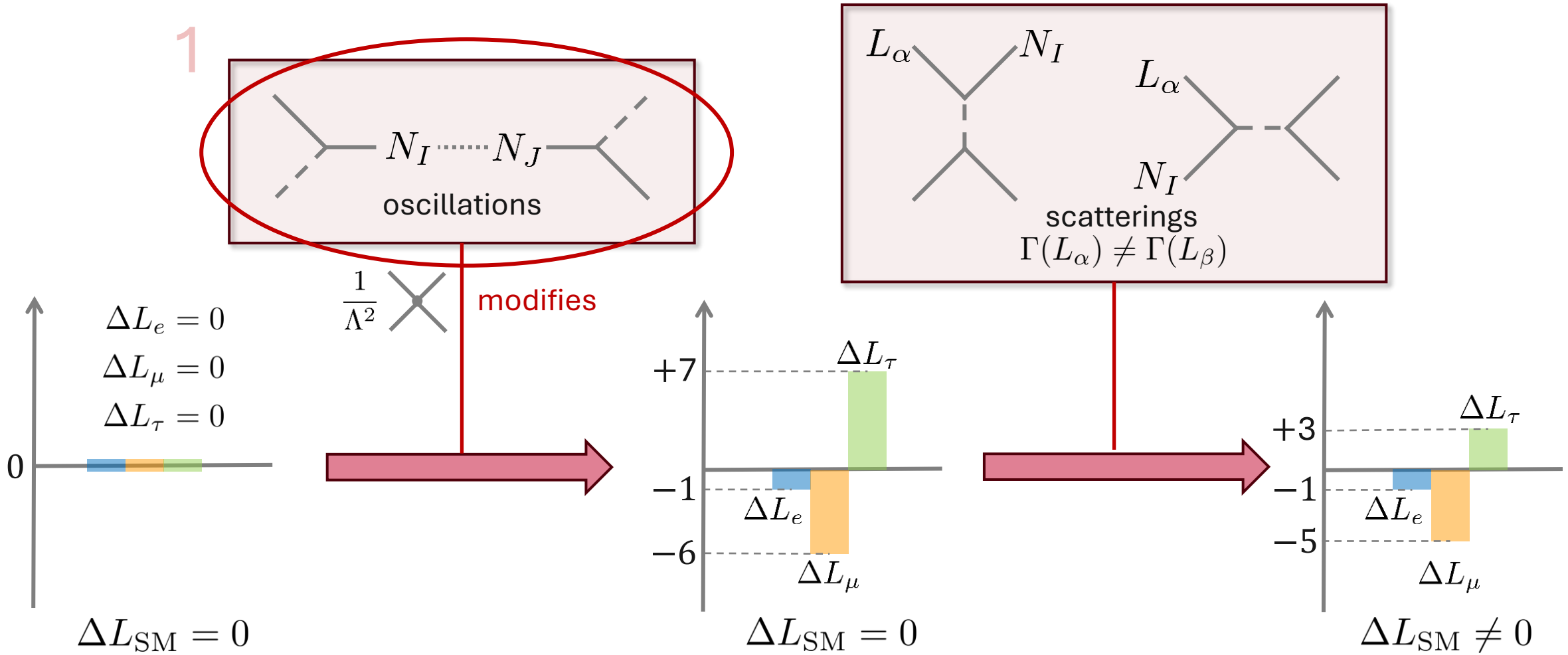




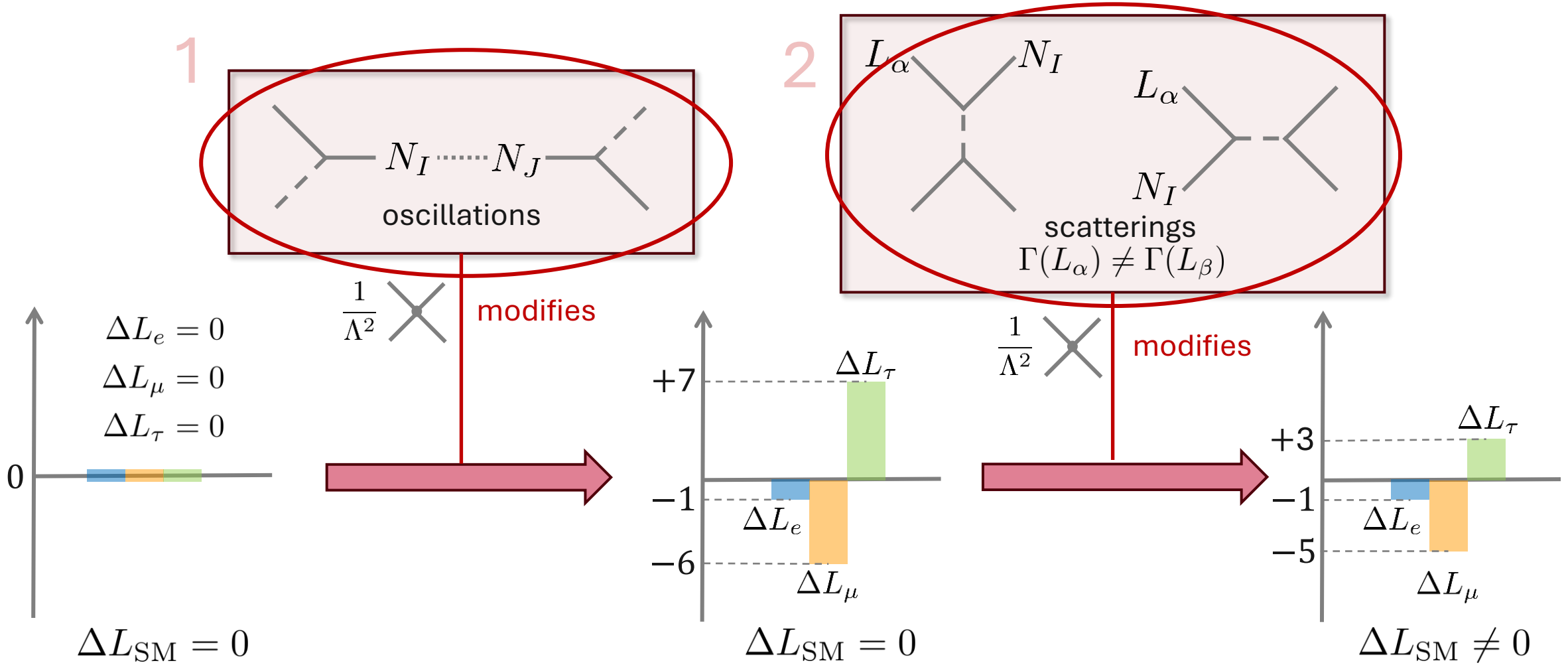
BAU via Neutrino Oscillation – Standard Case



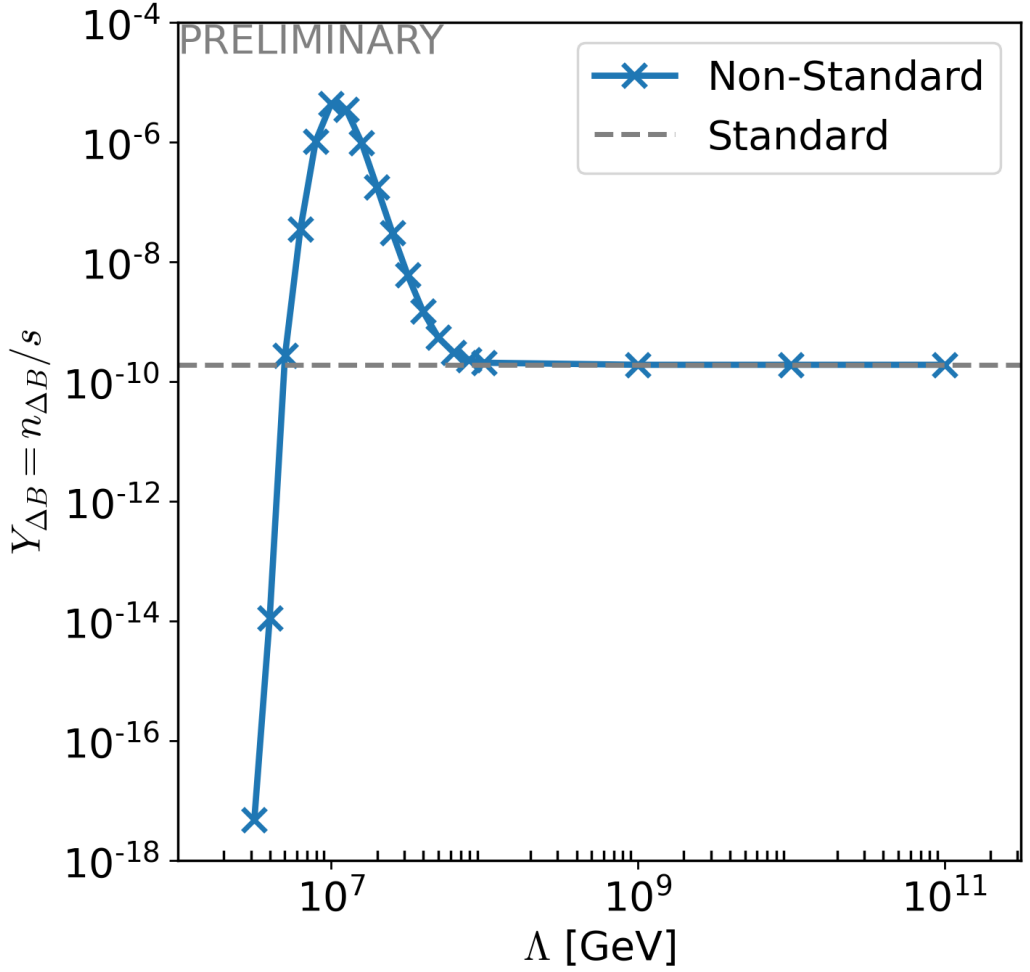
BAU via Neutrino Oscillation – Non-Standard Case



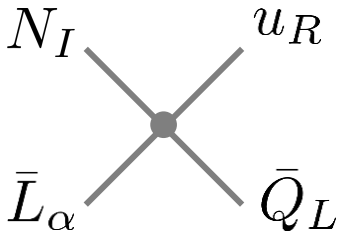
BAU via Neutrino Oscillation – Non-Standard Case



Low scale Leptogenesis – Non-Standard Case



LNC operator:



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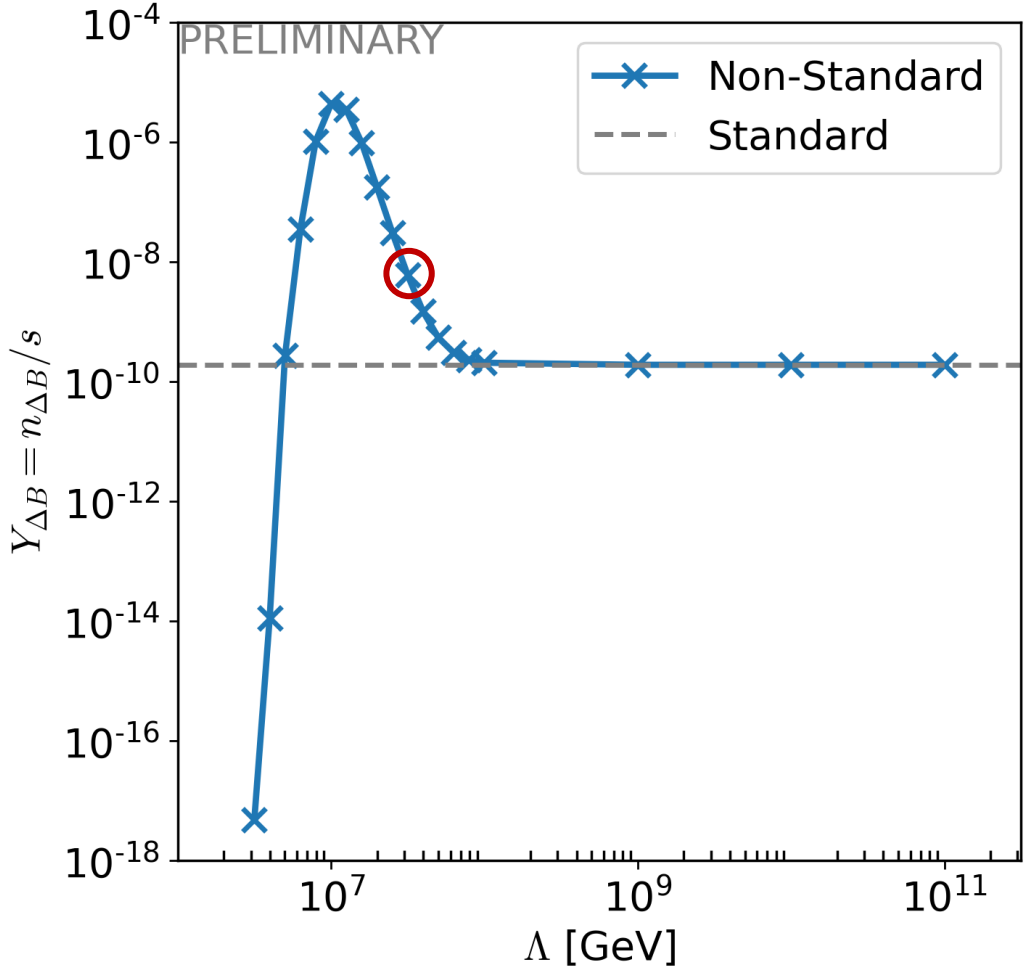
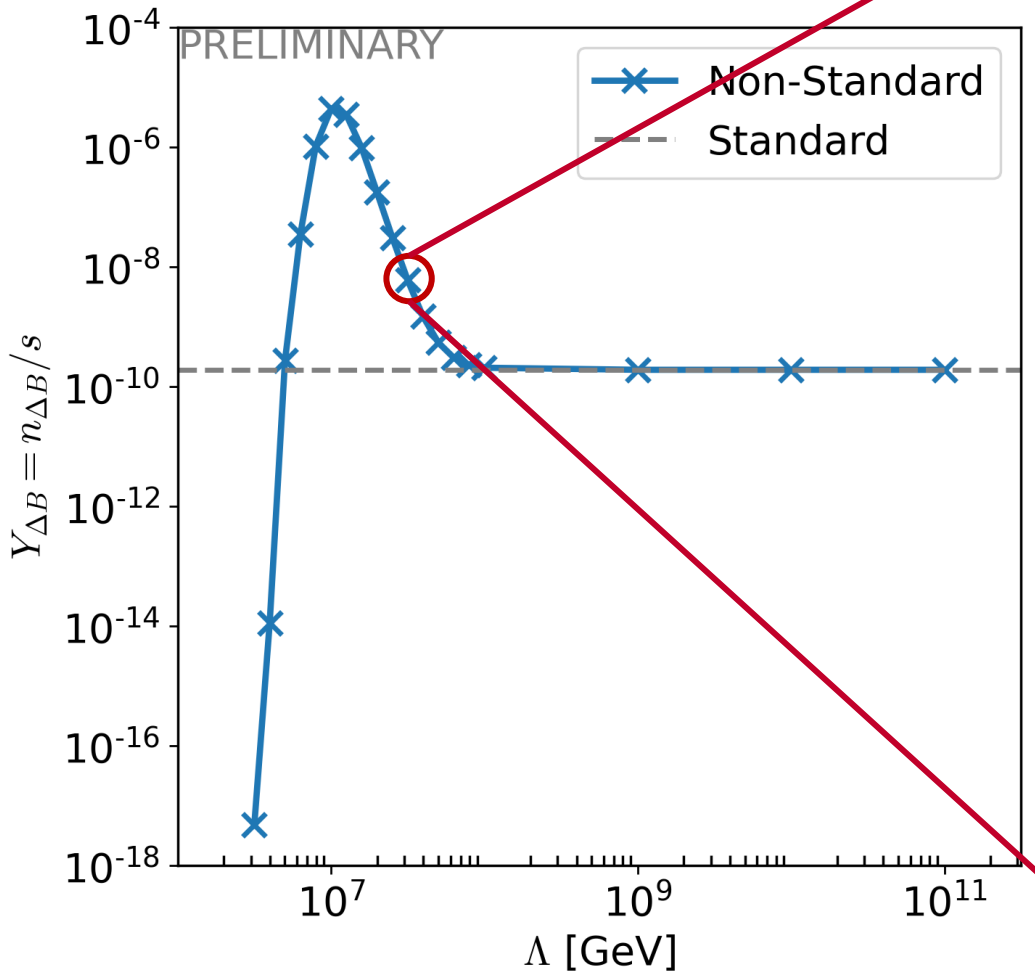
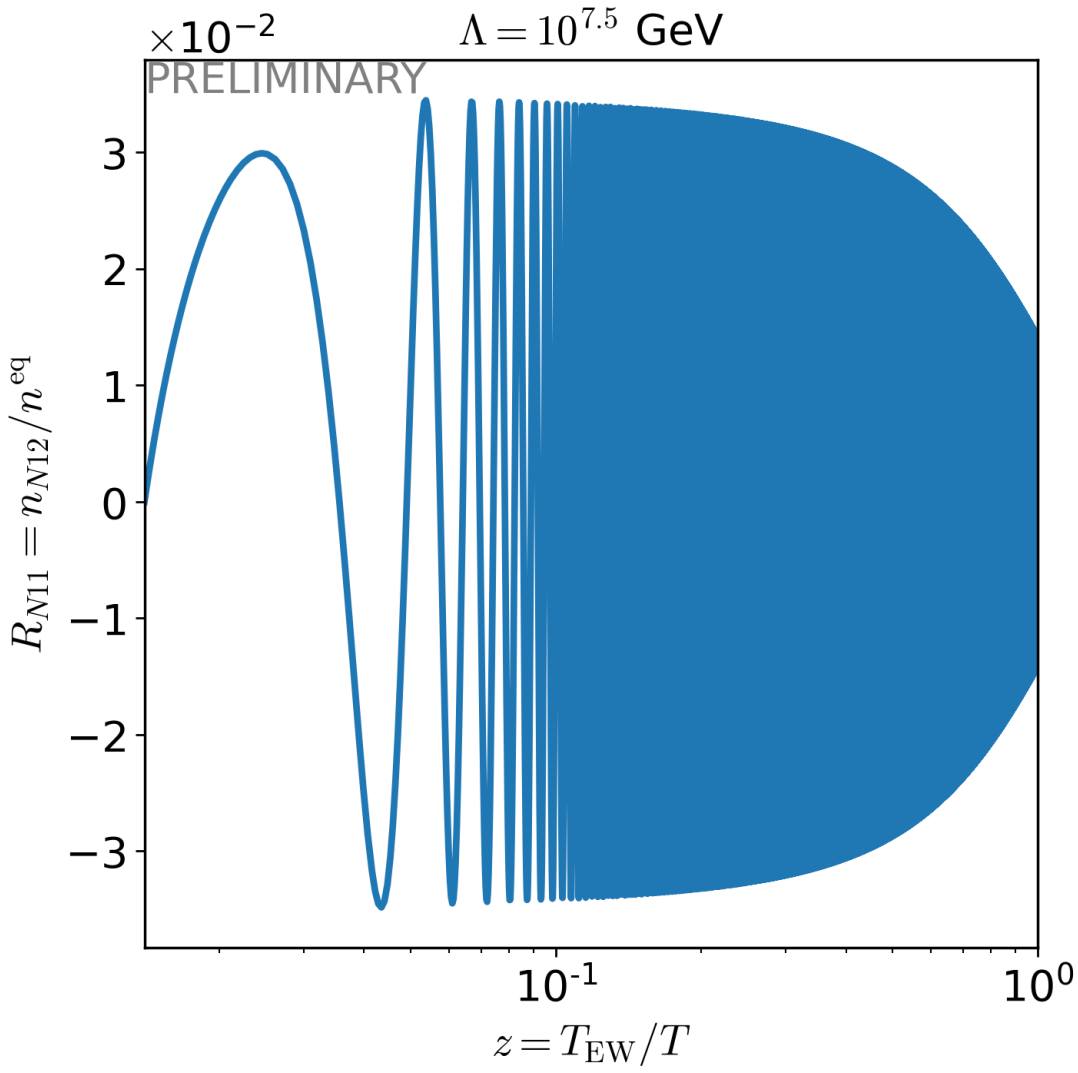


Low scale Leptogenesis





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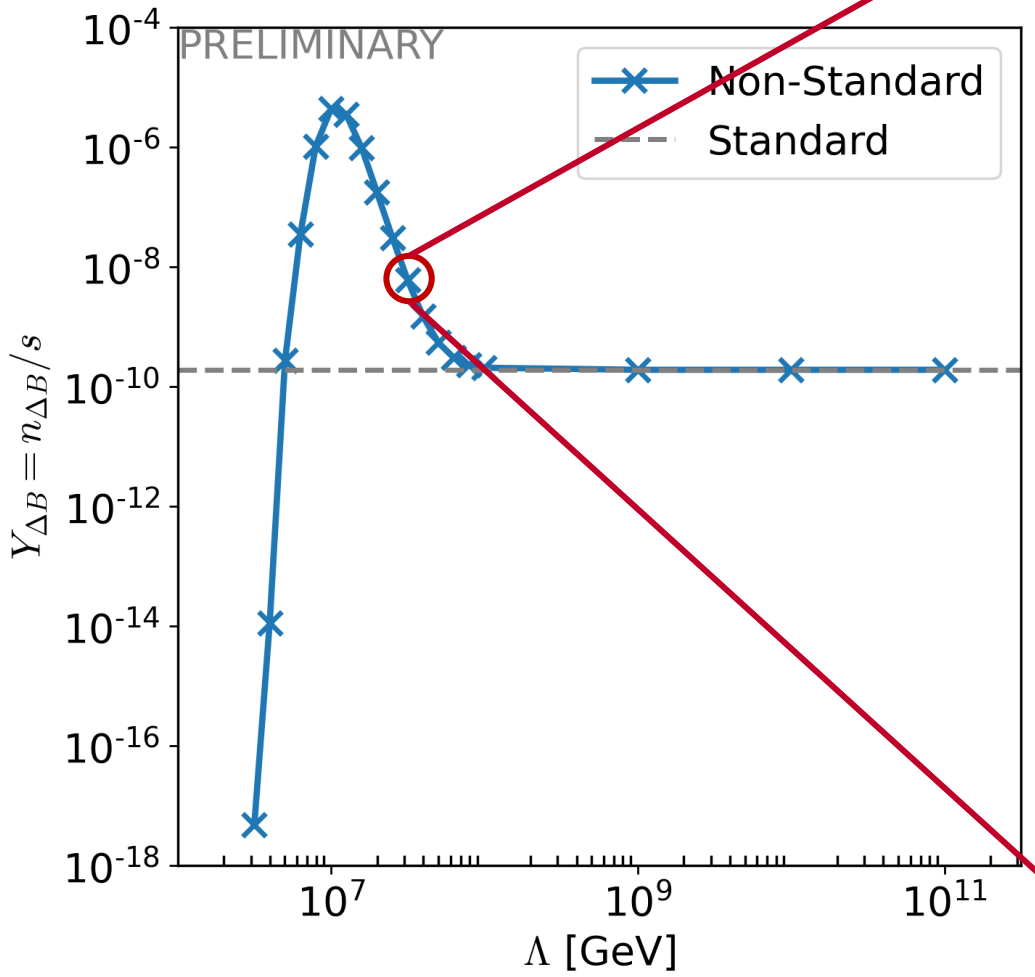
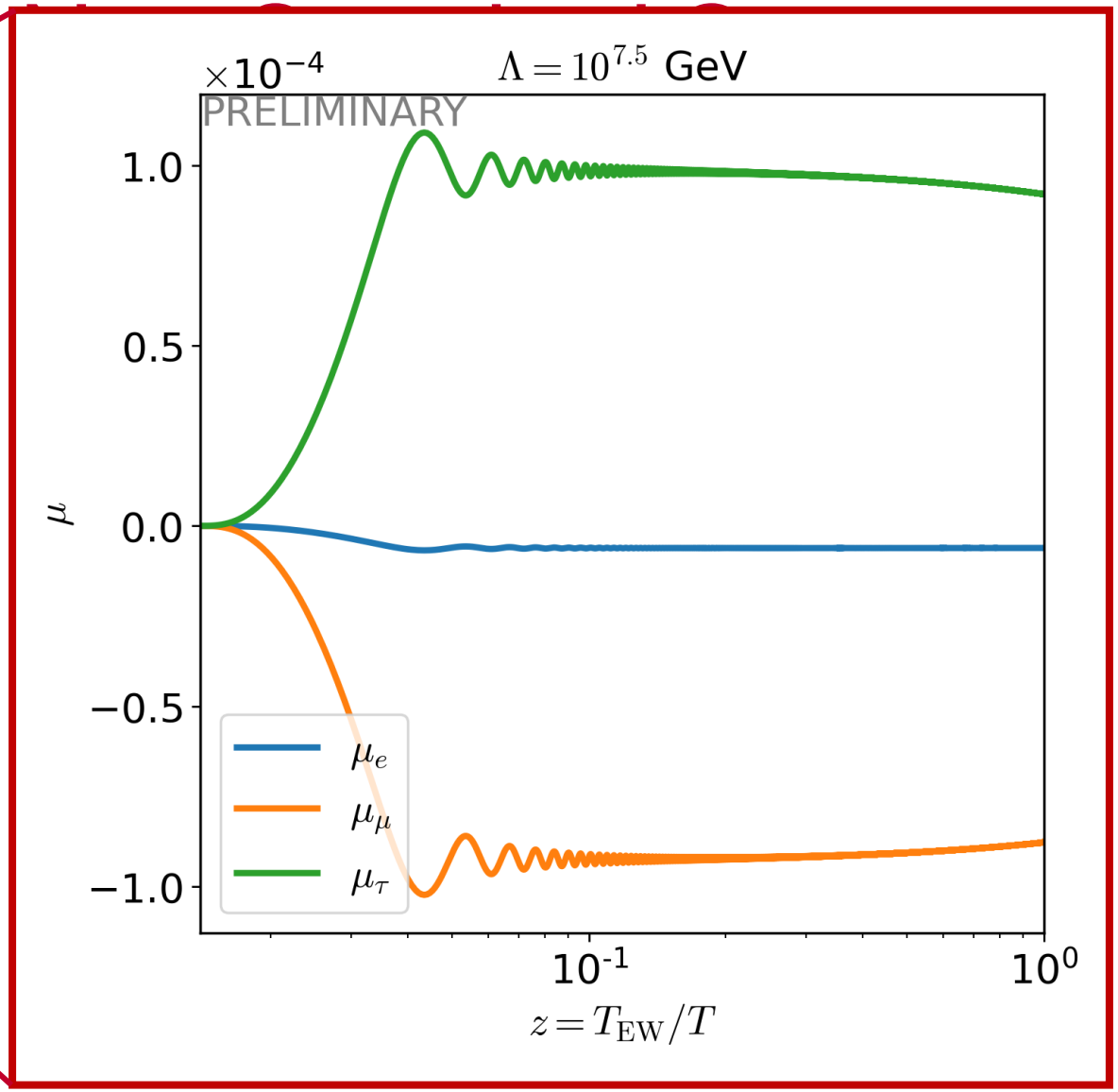
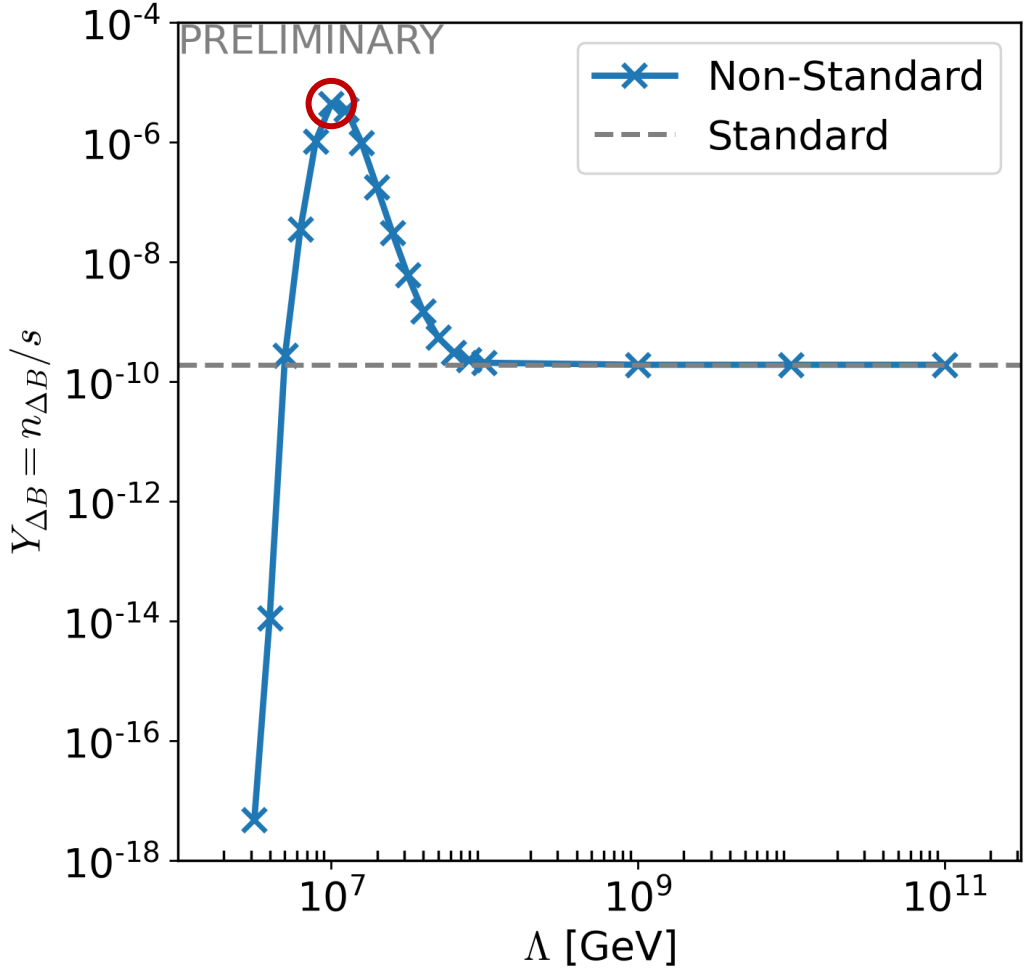
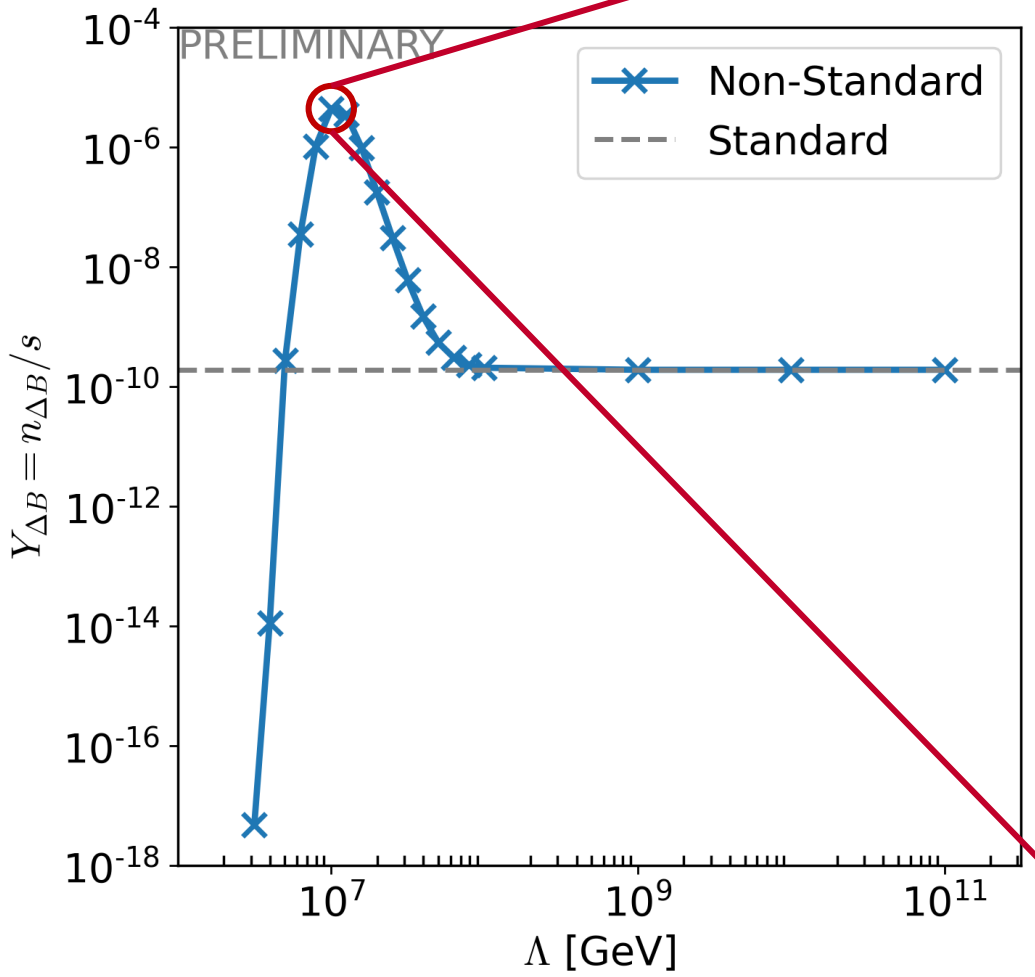


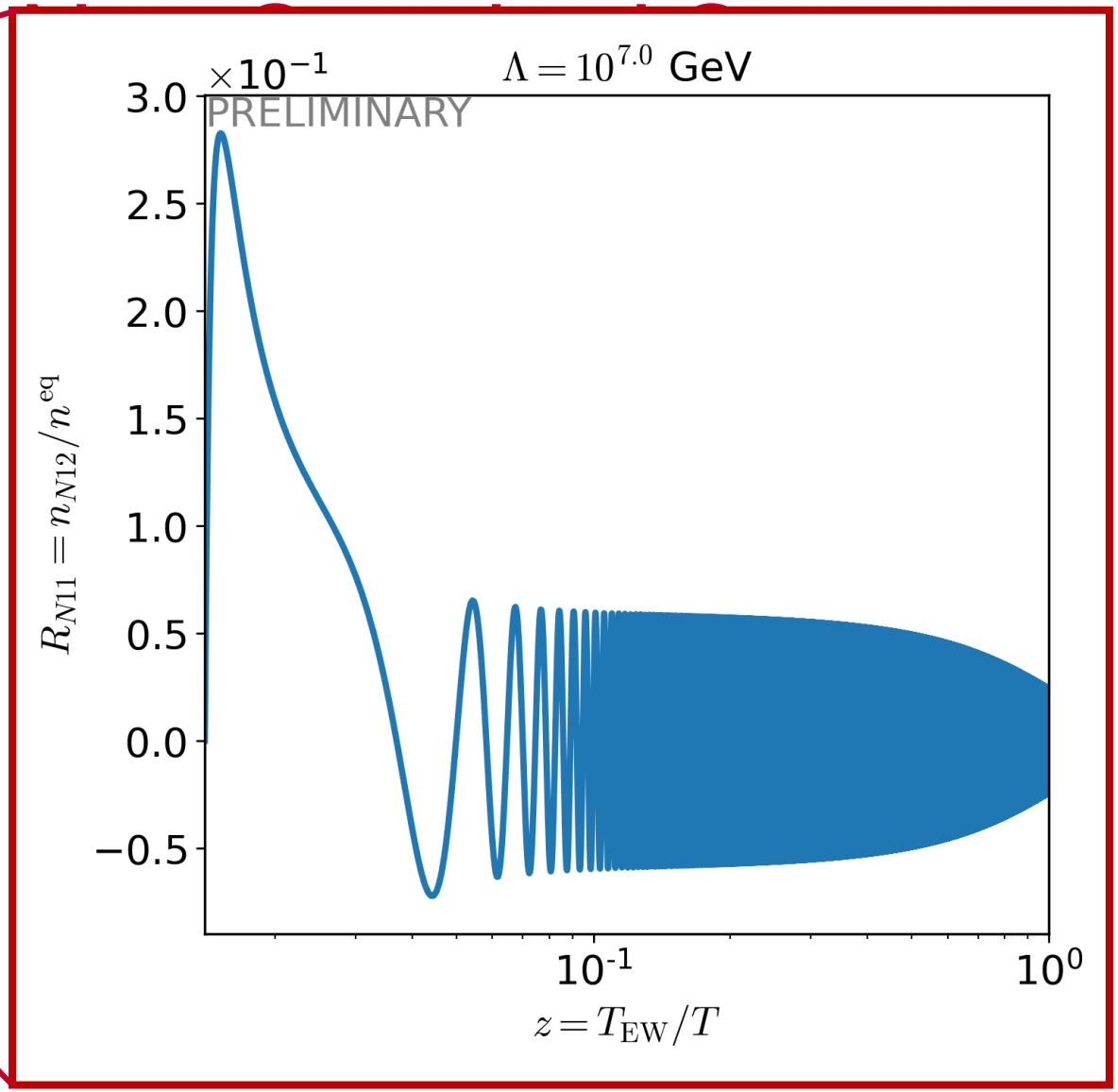


Low scale Leptogenesis – Non-Standard Case



Low scale Leptogenesis –





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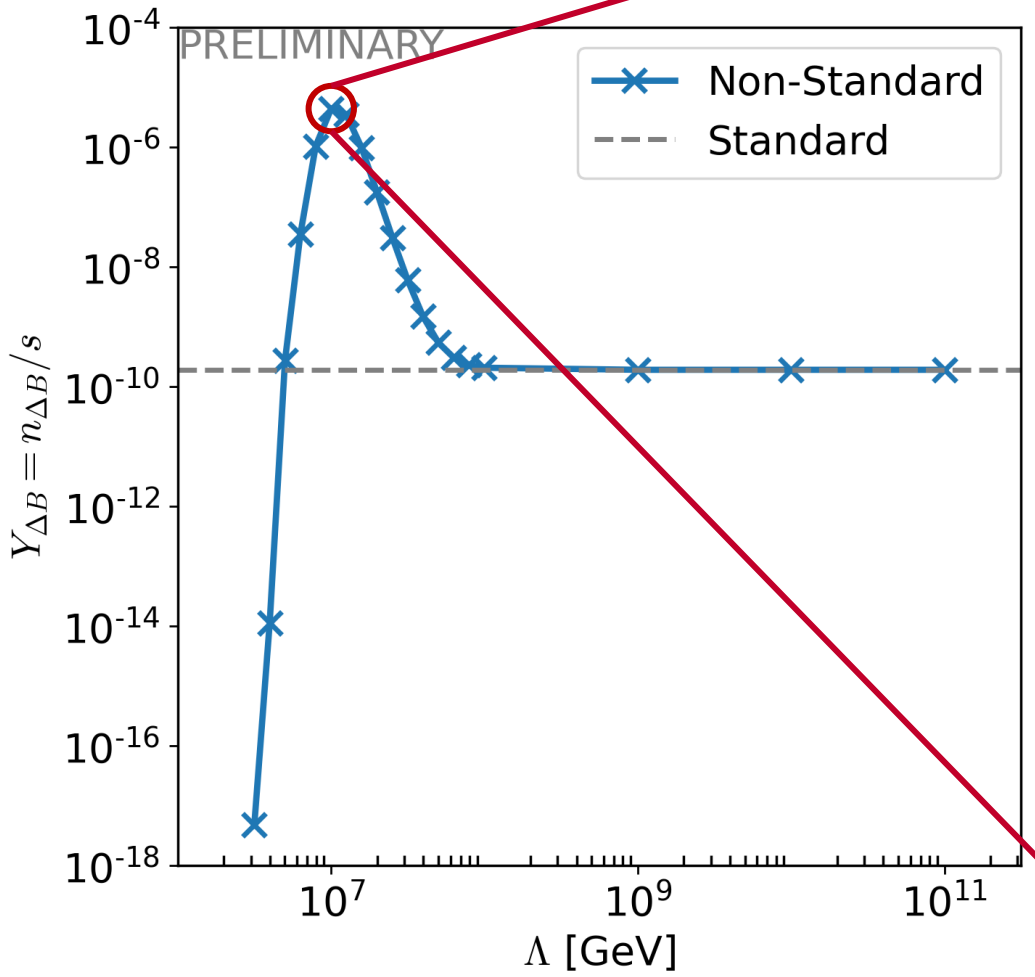
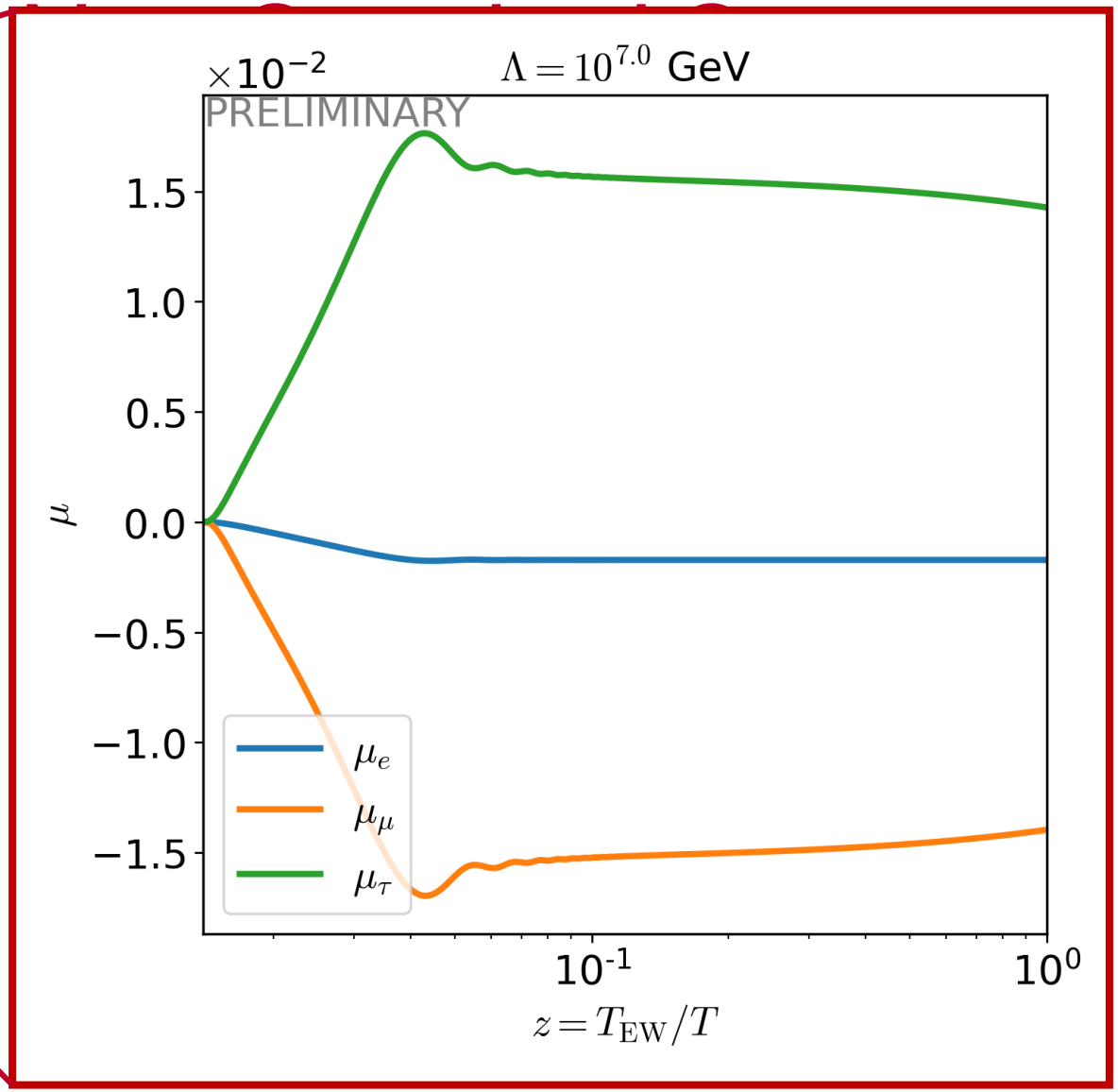
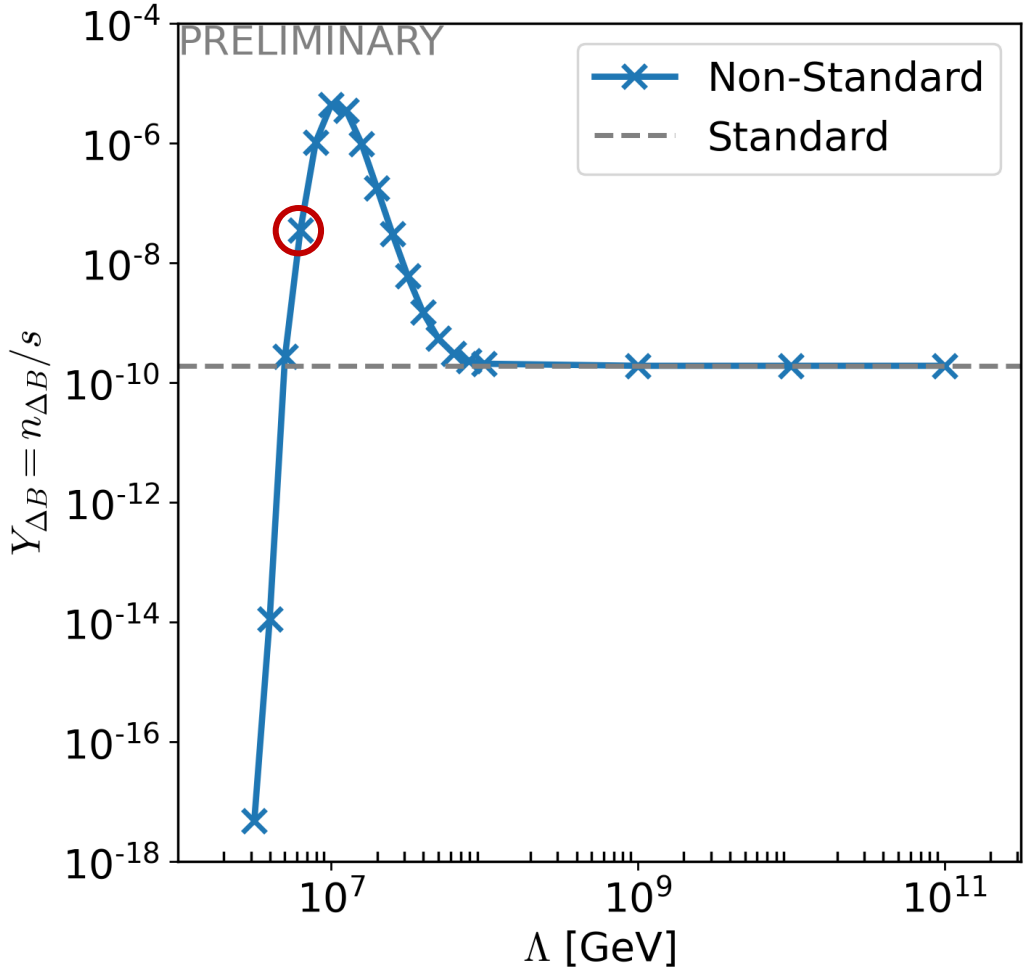
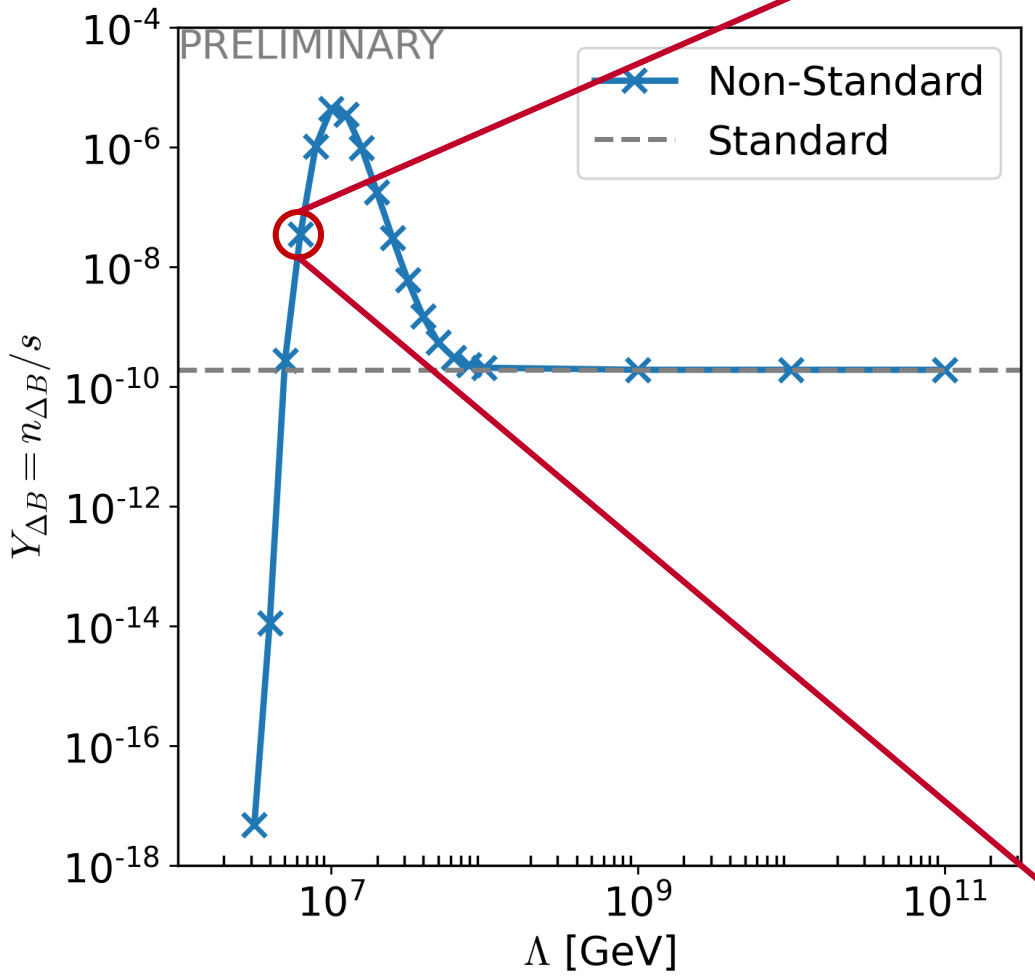


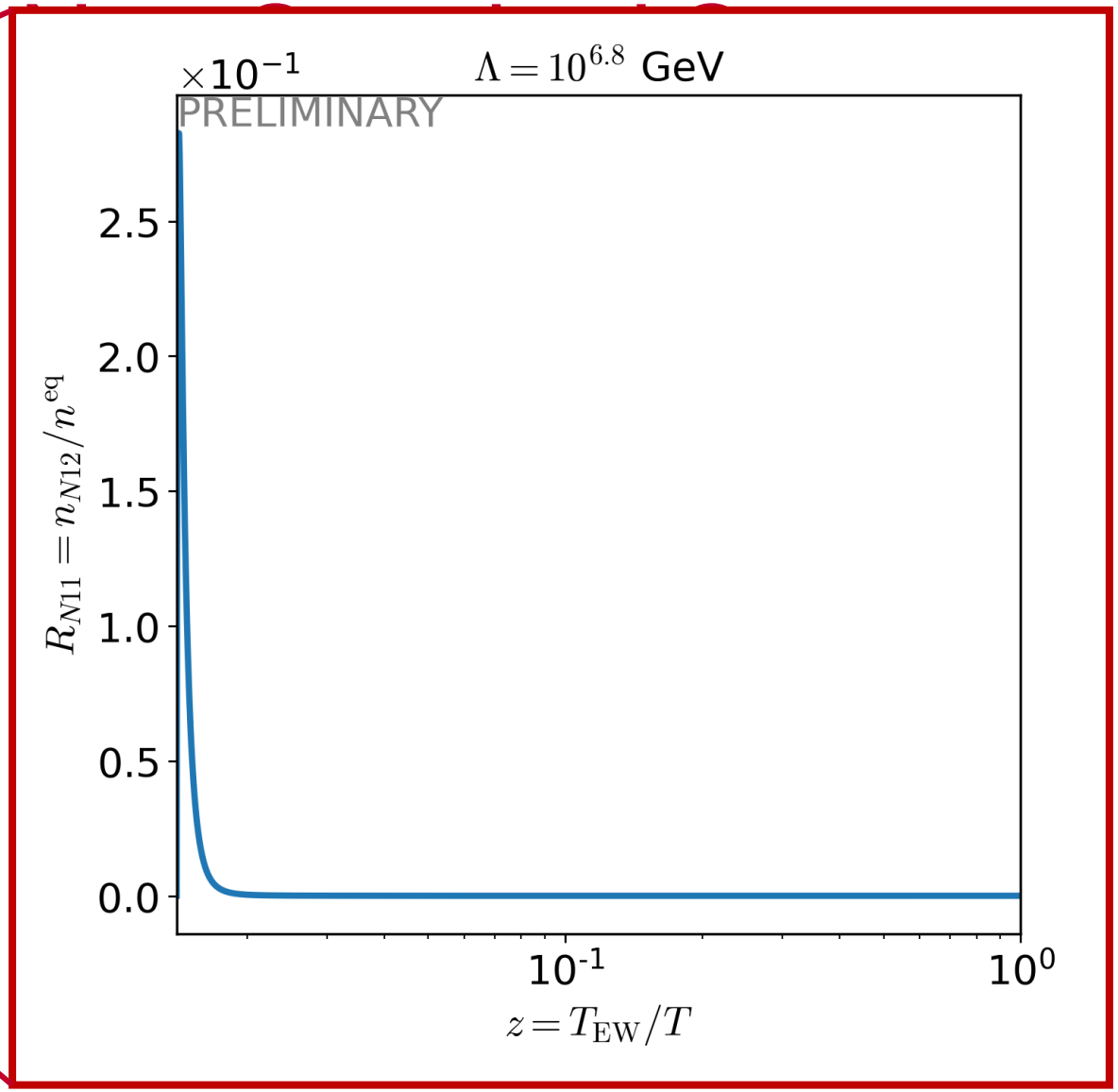


Low scale Leptogenesis – Non-Standard Case

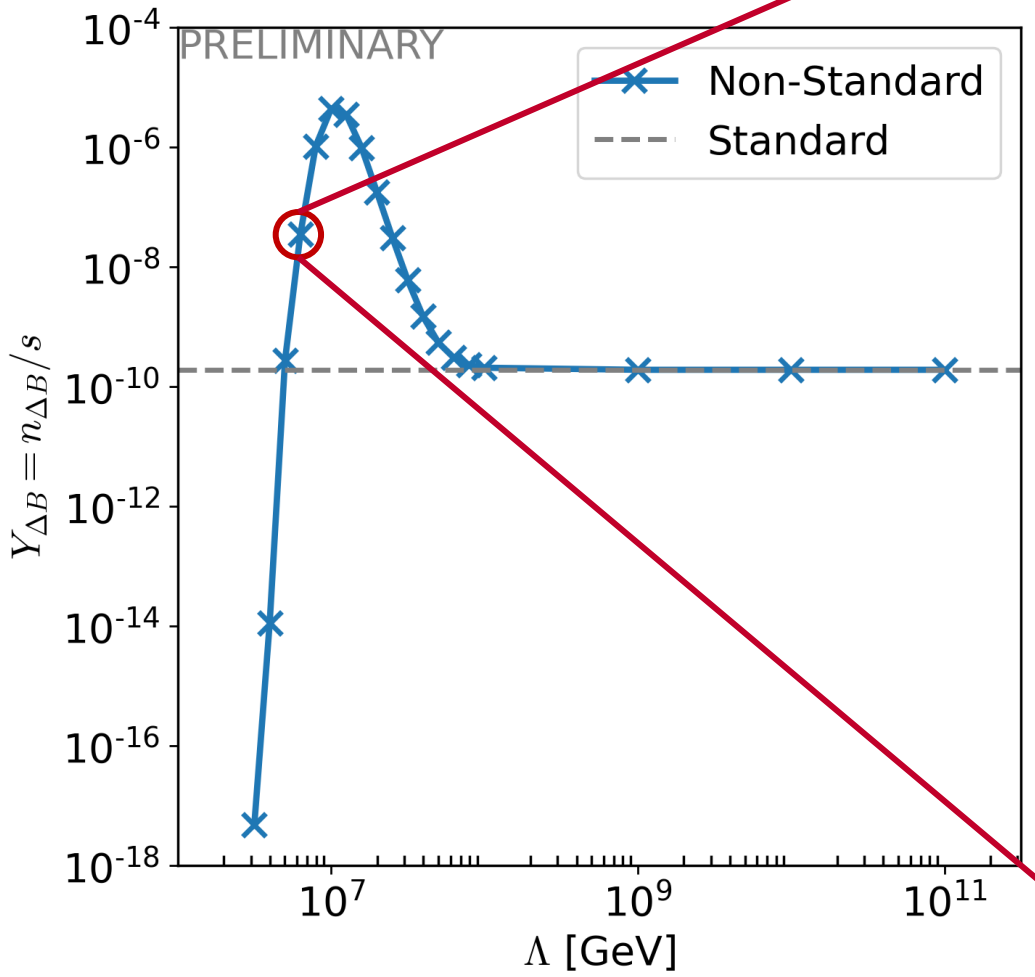


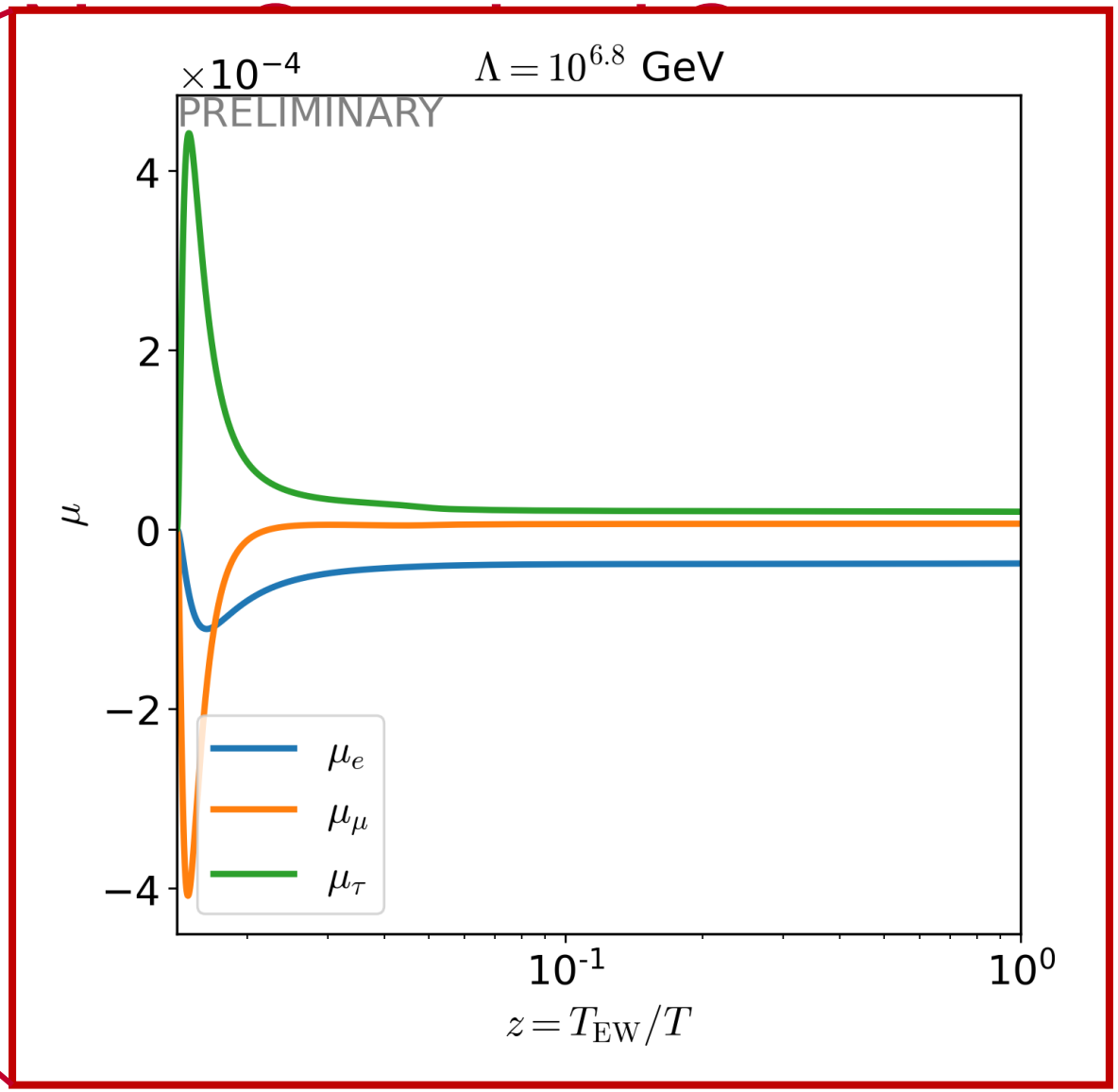
Low scale Leptogenesis –



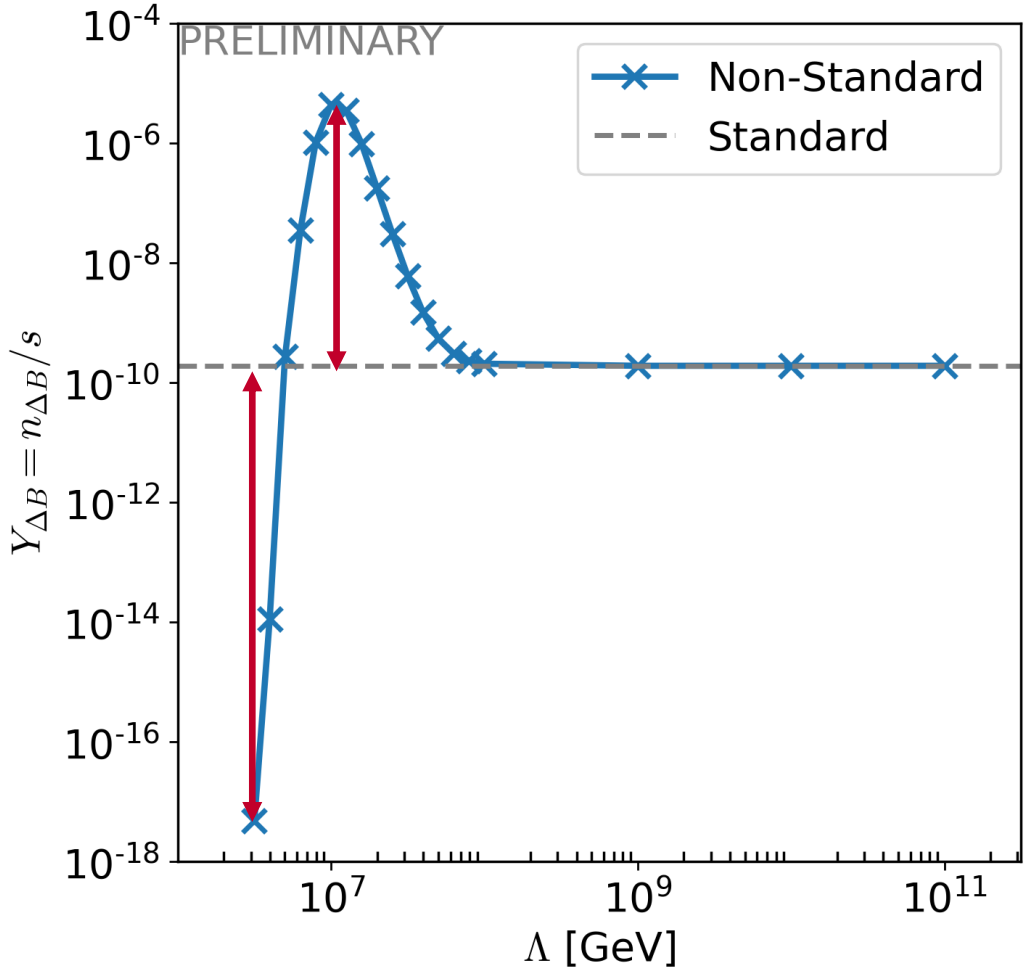


Low scale Leptogenesis –



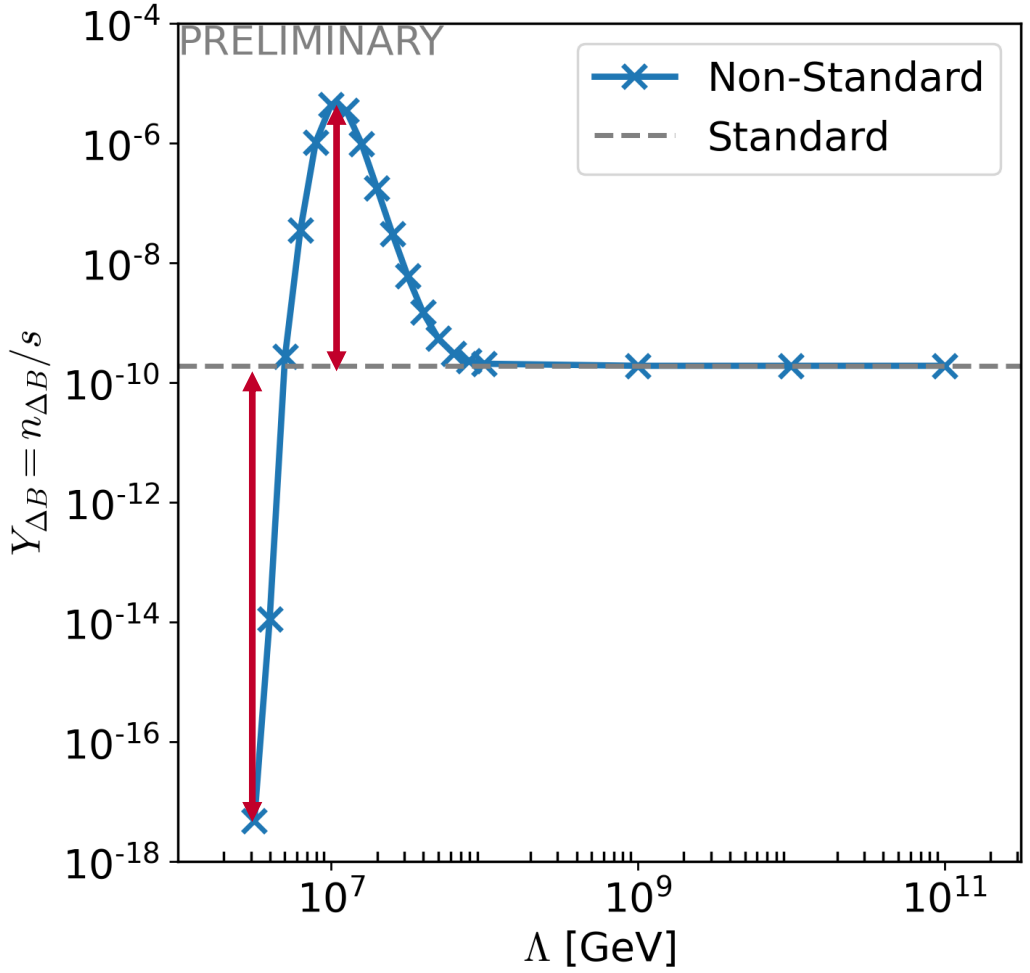


Low scale Leptogenesis – Non-Standard Case



Order of magnitude effect!

Low scale Leptogenesis – Non-Standard Case



Order of magnitude effect!

Work in progress!

Conclusion & Outlook

- Non-standard interactions can change

  → $0\nu\beta\beta$ decay

  → Low-Scale Leptogenesis

  by orders of magnitude

Conclusion & Outlook

- Non-standard interactions can change
  - → $0\nu\beta\beta$ decay
  - → Low-Scale Leptogenesis

  by orders of magnitude

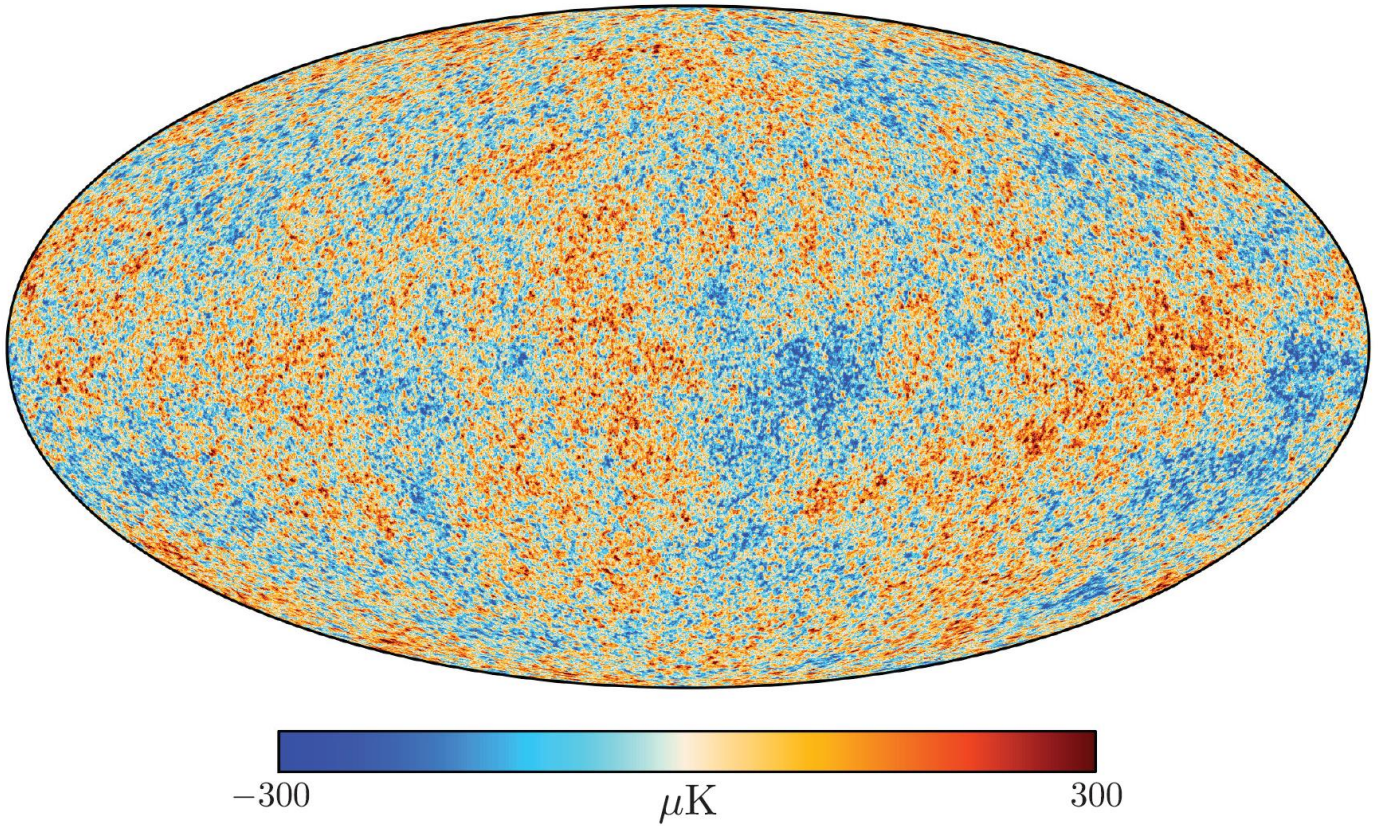
- Conduct full parameter scan
- Go beyond effective operator approach to study the effect of T_{RH}

[https://commons.wikimedia.org/wiki/File:Kloster_H%C3%B6chst_Terrassenhof.JPG#filelinks]

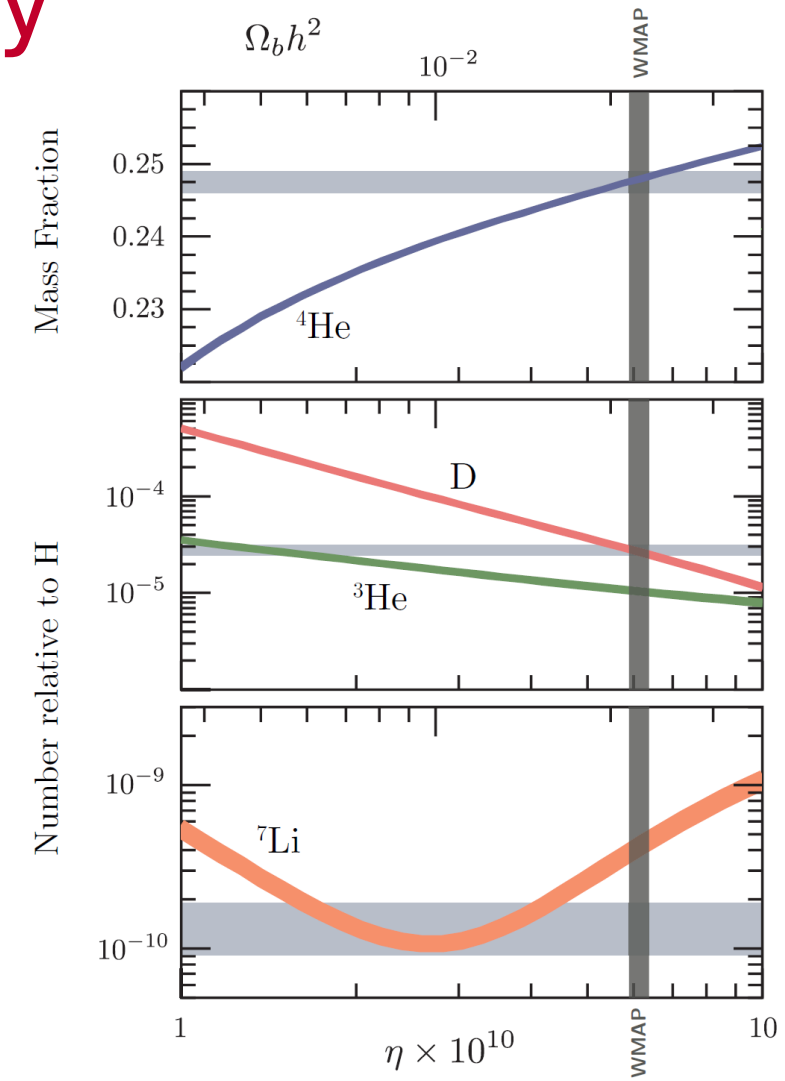
How do we know of the Baryon Asymmetry?

- Earth: no significant proton-antiproton annihilations
- Solar System: satellites, planetary probes
- Galaxy: Cosmic rays (few antiprotons compared to protons, in agreement with secondary production)
- Cluster of galaxies: Absence of Gamma Rays from Annihilation

Measuring the Baryon Asymmetry



Baumann



Sakharov Conditions

- Baryon number violation: Equal baryon and anti-baryon in the universe

- C and CP violation baryons and anti-baryons are CP conjugates

- Out of equlibrium

$$\begin{aligned}\langle B\rangle_T &= \mathrm{Tr}(e^{-\beta H}B)\\ &= \mathrm{Tr}[(CPT)(CPT)^{-1}e^{-\beta H}B)]\\ &= \mathrm{Tr}(e^{-\beta H}(CPT)^{-1}B(CPT)]\\ &= -\mathrm{Tr}(e^{-\beta H}B)\ ,\end{aligned}$$

Derivation Quantum Kinetic Equations (QKEs)

$$\hat{\phi}(x) = \int \frac{\mathrm{d}^3 p}{(2\pi)^3} \left(\hat{a}_p(t) e^{-ipx} + \hat{a}_p^\dagger(t) e^{+ipx} \right)$$

- QM: number operator: $\hat{N} = \hat{a}^\dagger \hat{a}$ $N = \left\langle \hat{N} \right\rangle = \left\langle \hat{a}^\dagger \hat{a} \right\rangle$
- QFT: "number density operator":

$$\frac{d\hat{n}}{\mathrm{d}^3 p} = \hat{a}_p^\dagger \hat{a}_p \qquad \left\langle \hat{a}_p^\dagger \hat{a}_q \right\rangle_T = \underbrace{(2\pi)^3 \delta^{(3)}(p-q)}_{\mathrm{Vol}} f(p) \qquad n = \int \frac{\mathrm{d}^3 p}{(2\pi)^3} f(p)$$

- More generally

$$\left\langle \hat{a}_{p,i}^\dagger(t) \hat{a}_{q,j}(t) \right\rangle_T = (2\pi)^3 \delta^{(3)}(p-q) f_{ij}(p,t)$$

Derivation Quantum Kinetic Equations (QKEs)

$$\frac{d\rho_N(k_N)}{dt} = -i\big[H_N(k_N),\, \rho_N(k_N)\big] - \frac{1}{2}\big\{\Gamma^d_N(k_N),\, \rho_N(k_N)\big\} + \frac{1}{2}\big\{\Gamma^p_N(k_N),\, \mathbf{1} - \rho_N(k_N)\big\}$$

Differential equations

$$
\begin{aligned}
xH_u\frac{\mathrm{d}r_N}{\mathrm{d}x} &= -i[\langle H\rangle, r_N] - \frac{\langle\gamma_N^{(0)}\rangle}{2}\{Y^\dagger Y, r_N - 1\} - x^2\frac{\langle s_N^{(0)}\rangle}{2}\{MY^T Y^* M, r_N - 1\} \\
&+ \langle\gamma_N^{(1)}\rangle Y^\dagger \mu Y - x^2\langle s_N^{(1)}\rangle MY^T\mu Y^* M \\
&- \frac{\langle\gamma_N^{(2)}\rangle}{2}\left\{Y^\dagger\mu Y, r_N\right\} + x^2\frac{\langle s_N^{(2)}\rangle}{2}\{MY^T\mu Y^* M, r_N\}\,, \\
xH_u\frac{\mathrm{d}r_{\bar N}}{\mathrm{d}x} &= -i[\langle H^*\rangle, r_{\bar N}] - \frac{\langle\gamma_N^{(0)}\rangle}{2}\{Y^T Y^*, r_{\bar N} - 1\} - x^2\frac{\langle s_N^{(0)}\rangle}{2}\{MY^\dagger Y M, r_{\bar N} - 1\} \\
&- \langle\gamma_N^{(1)}\rangle Y^T\mu Y^* + x^2\langle s_N^{(1)}\rangle MY^\dagger\mu Y M \\
&+ \frac{\langle\gamma_N^{(2)}\rangle}{2}\left\{Y^T\mu Y^*, r_{\bar N}\right\} - x^2\frac{\langle s_N^{(2)}\rangle}{2}\{MY^\dagger\mu Y M, r_{\bar N}\}\,, \\
xH_u\frac{\mathrm{d}\mu_{B/3-L_\alpha}}{\mathrm{d}x} &= \frac{\int_k \rho_F}{\int_k \rho_F'}\left[\frac{\langle\gamma_N^{(0)}\rangle}{2}(Yr_N Y^\dagger - Y^* r_{\bar N} Y^T) - x^2\frac{\langle s_N^{(0)}\rangle}{2}(Y^* M r_N M Y^T - Y M r_{\bar N} M Y^\dagger)\right. \\
&- \mu_\alpha\left(\langle\gamma_N^{(1)}\rangle YY^\dagger + x^2\langle s_N^{(1)}\rangle YM^2Y^\dagger\right) + \frac{\langle\gamma_N^{(2)}\rangle}{2}\mu_\alpha(Yr_N Y^\dagger + Y^* r_{\bar N} Y^T) \\
&+ \left. x^2\frac{\langle s_N^{(2)}\rangle}{2}\mu_\alpha\left(YMr_{\bar N}MY^\dagger + Y^*Mr_N MY^T\right)\right]_{\alpha\alpha}\,,
\end{aligned}
\tag{4.2}
$$

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Neutrinoless double beta decay and the baryon asymmetry of the Universe

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Non-standard cases

e.g. in connection to Unification