

# 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)*

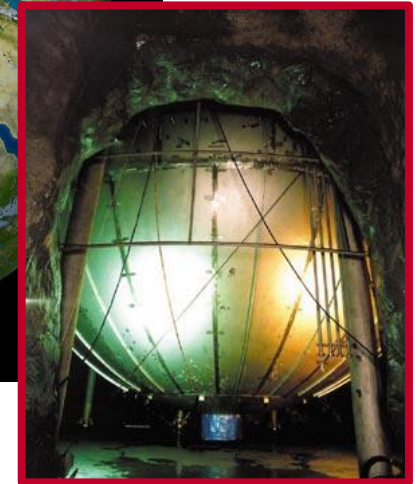
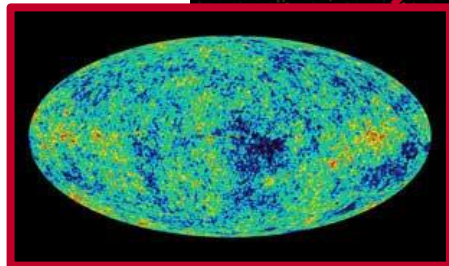
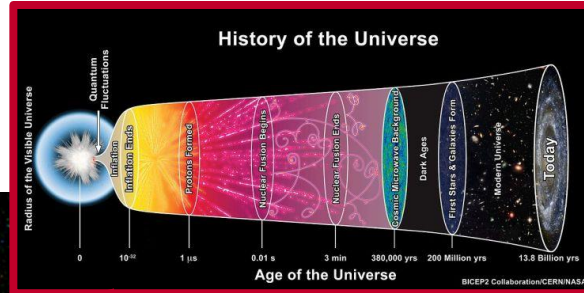
# Motivation

[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/]

**WHERE IS THE ANTIMATTER?**

**WHAT WE SHOULD SEE**  
 An equal amount of matter and antimatter fill the universe.

**WHAT WE DO SEE**  
 Matter fills the universe while there is only trace amounts of antimatter.



**KamLAND-Zen**

[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]

# Motivation

## Baryogenesis via neutrino oscillations

E. Kh. Akhmedov<sup>(a,b)</sup>, V. A. Rubakov<sup>(c,a,d)</sup> and A. Yu. Smirnov<sup>(a,c)</sup>

## The $\nu$ MSM, Dark Matter and Baryon Asymmetry of the Universe

Takehiko Asaka\* and Mikhail Shaposhnikov†

## Kinetic Equations for Baryogenesis via Sterile Neutrino Oscillation

Takehiko Asaka<sup>1,2</sup>, Shintaro Eijima<sup>2,3</sup> and Hirovuki Ishida<sup>2,3</sup>

## Matter and Antimatter in the Universe\*

Laurent Canetti<sup>a</sup>, Marco Drewes<sup>b,c</sup>, Mikhail Shaposhnikov<sup>a</sup>

## Uniting low-scale leptogenesis

Juraj Klarić<sup>1</sup>, Mikhail Shaposhnikov<sup>1</sup> and Inar Timiryasov<sup>1</sup>

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## Testable Baryogenesis in Seesaw Models

P. Hernández<sup>a</sup>, M. Kekic<sup>a</sup>, J. López-Pavón<sup>b</sup>, J. Racker<sup>a</sup>, I. Salvado<sup>a</sup>

## Bounds on right-handed neutrino parameters from observable leptogenesis

P. Hernández, J. López-Pavón, N. Rius, and S. Sandner

## Low-scale leptogenesis with three heavy neutrinos

Asmaa Abada<sup>a</sup>, Giorgio Arcadi<sup>b</sup>, Valerie Domcke<sup>c</sup>, Marco Drewes<sup>d</sup>, Juraj Klarić<sup>e,f</sup> and Michele Lucente<sup>d</sup>

## A Frequentist Analysis of Three Right-Handed Neutrinos with GAMBIT

Marcin Chrzaszcz<sup>1,2</sup>, Marco Drewes<sup>3</sup>, Tomás E. Gonzalo<sup>4,b</sup>, Julia Harz<sup>5</sup>, Suraj Krishnamurthy<sup>6,a</sup>, Christoph Weniger<sup>6</sup>

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How robust?

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[Dekens et. al. JHEP 2020]

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How robust?



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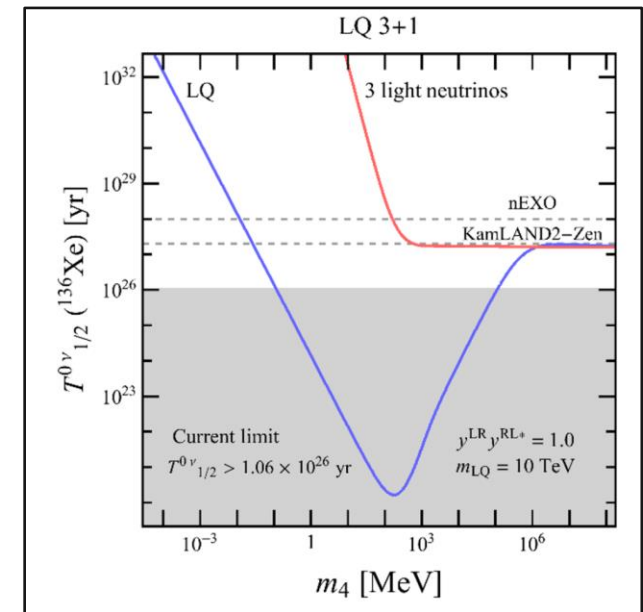
REVISED: May 6, 2020

ACCEPTED: May 19, 2020

PUBLISHED: June 16, 2020

## Sterile neutrinos and neutrinoless double beta decay in effective field theory

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Ki

?

the Universe\*

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JHEP

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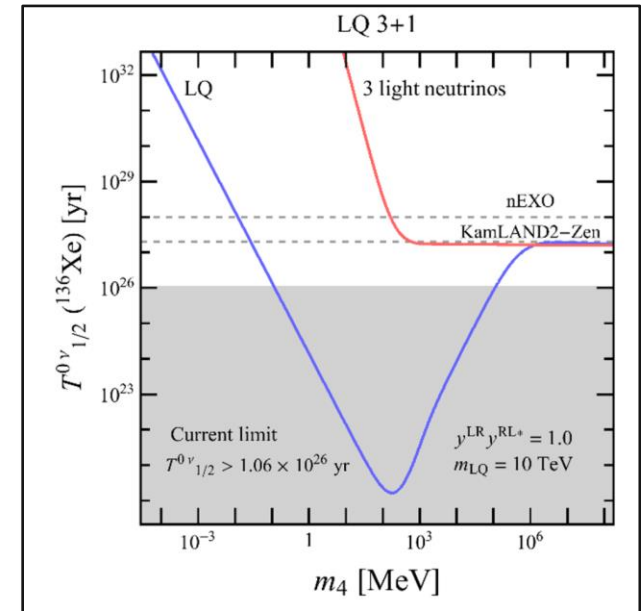
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How robust?

# Outline

0

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

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1

Neutrino masses – Seesaw mechanism

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2

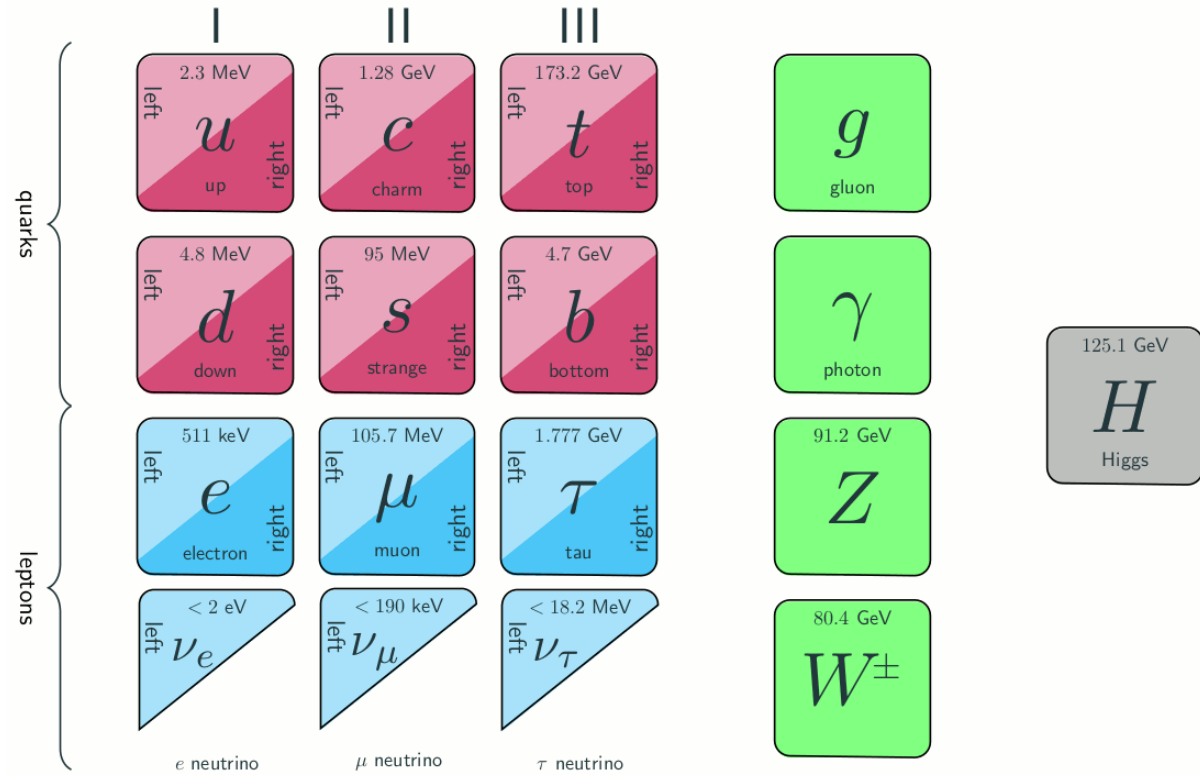
Lepton number violation –  $0\nu\beta\beta$  decay

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3

Baryon Asymmetry of the Universe - Leptogenesis

# The Standard Case

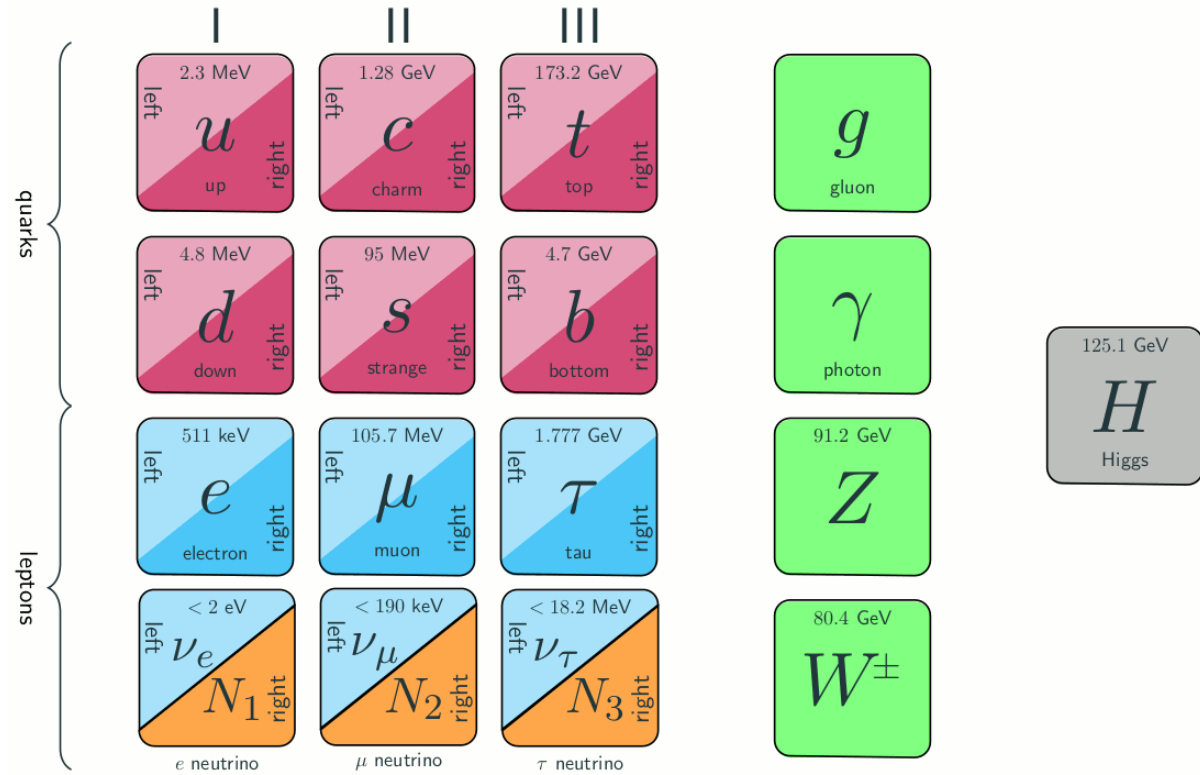


[<https://ep-news.web.cern.ch/uniting-leptogenesis>]

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



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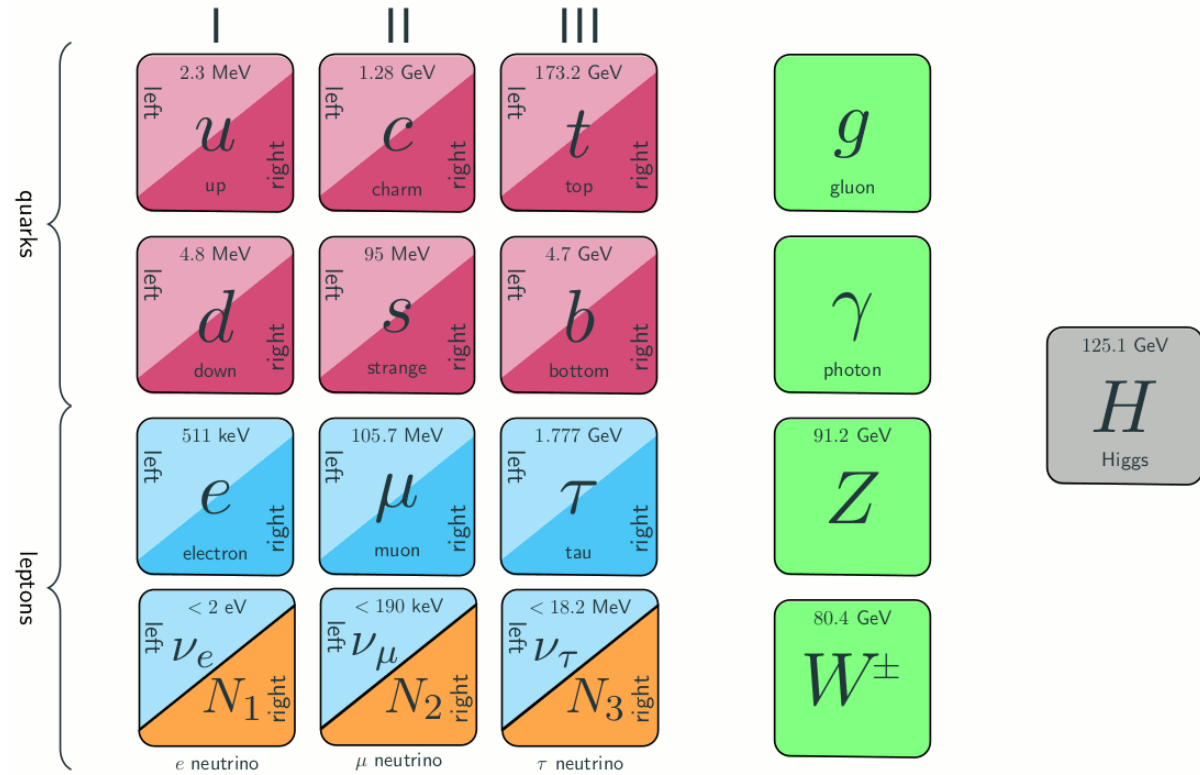


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$$\mathcal{L} = \mathcal{L}_{\text{SM}}$$

$$+ \mathcal{L}_N \left\{ \begin{array}{l} + \bar{N}(i\not{\partial})N \\ - Y_{i\alpha} \bar{N}_i H L_\alpha + \text{h.c.} \\ - \bar{N}_i^c M_i N_i + \text{h.c.} \end{array} \right.$$

# Non-Standard Case?



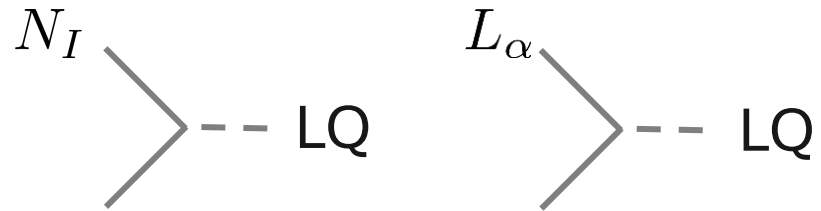
[<https://ep-news.web.cern.ch/uniting-leptogenesis>]

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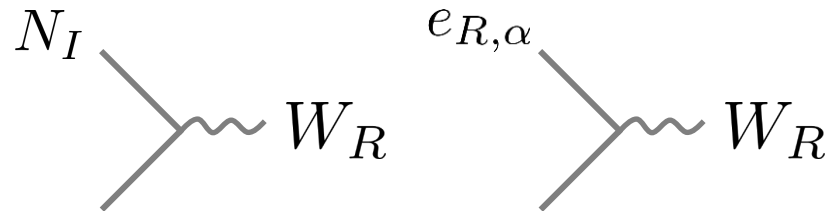
$$+ \mathcal{L}_N \left\{ \begin{array}{l} + \bar{N}(i\not{\partial})N \\ - Y_{i\alpha} \bar{N}_i H L_\alpha + \text{h.c.} \\ - \bar{N}_i^c M_i N_i + \text{h.c.} \end{array} \right.$$

+ more?

# Non-Standard Case



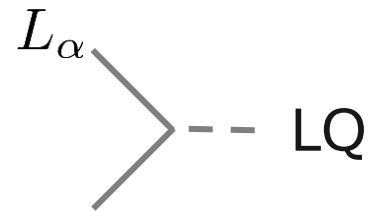
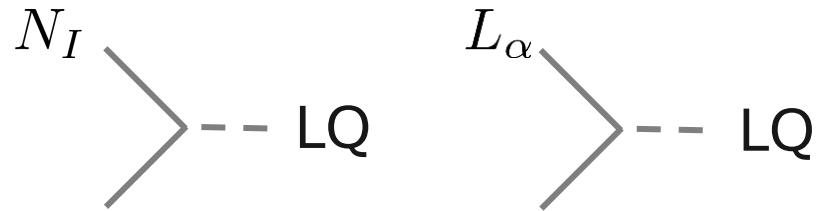
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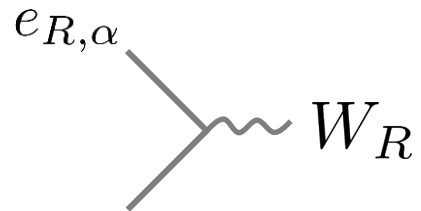
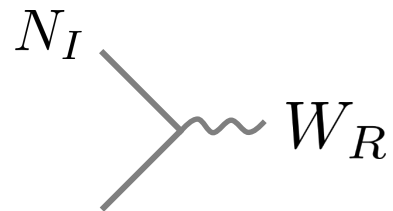
or

Any new particle coupling  
to RHNs and/or leptons

# Non-Standard Case

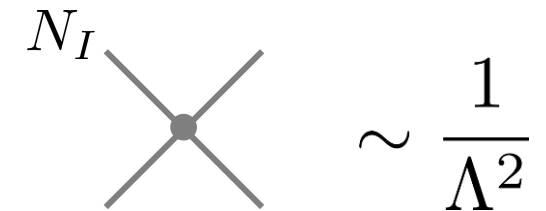
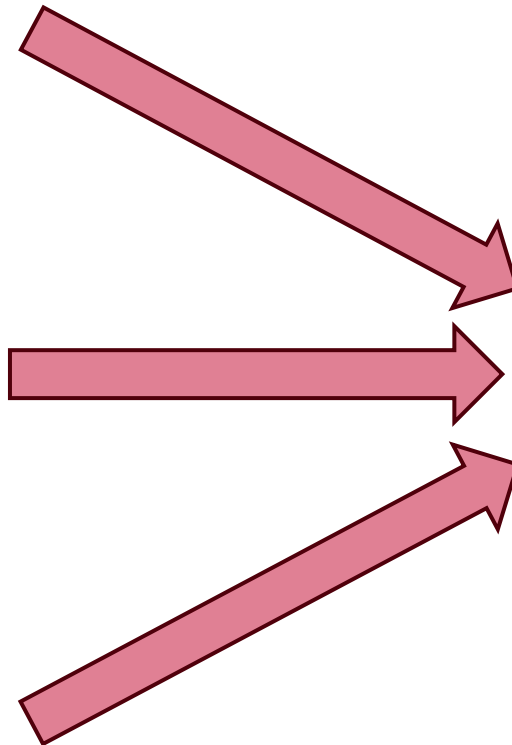


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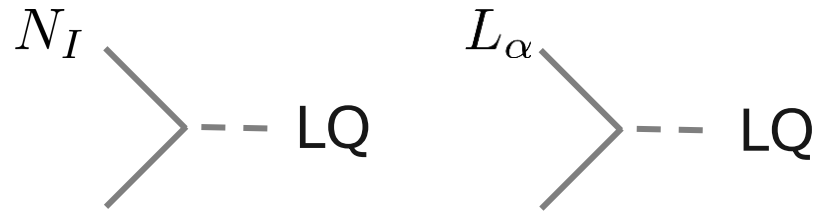
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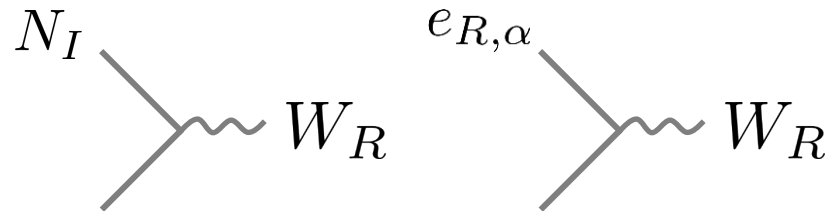


Effective operator  
description  
 $\nu$ SMEFT

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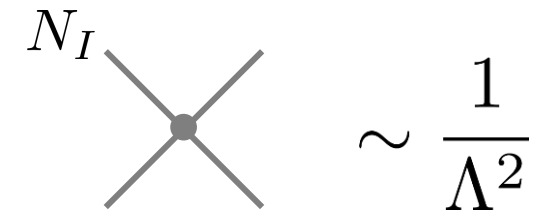
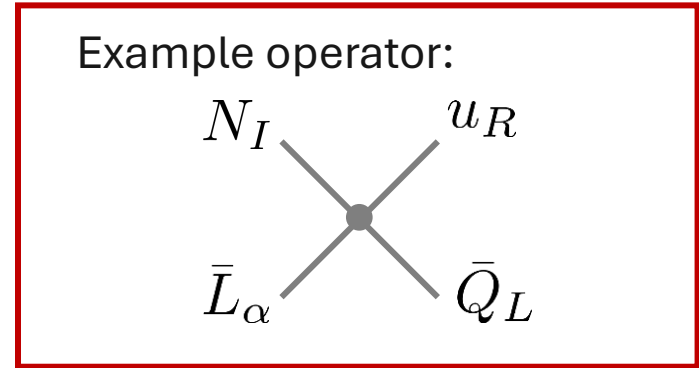
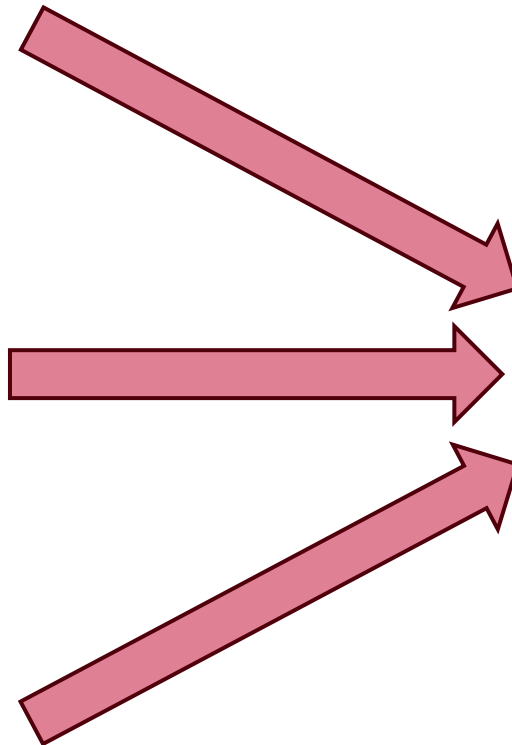


or



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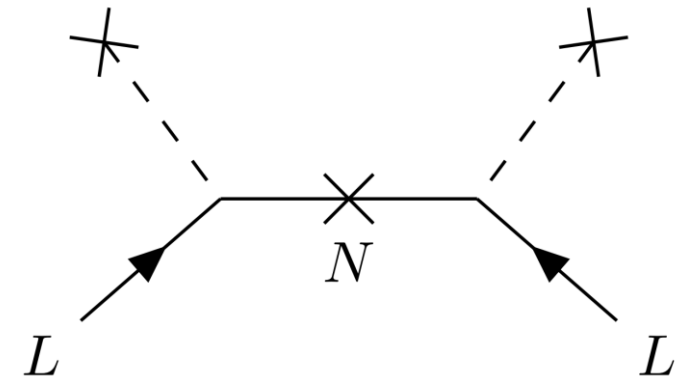
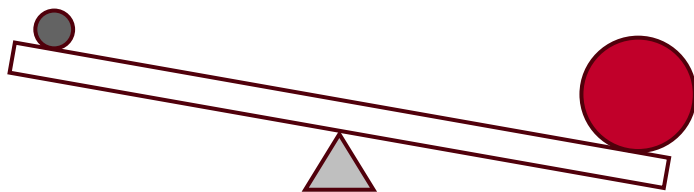
Effective operator description  
 $\nu$ SMEFT

# 1) Neutrino masses – Standard Case

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

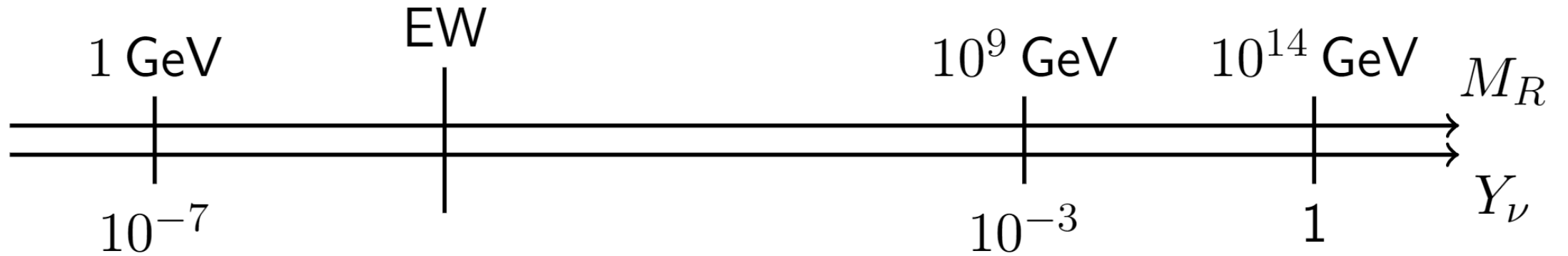
Seesaw mechanism:  $M_N \gg m_D$

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

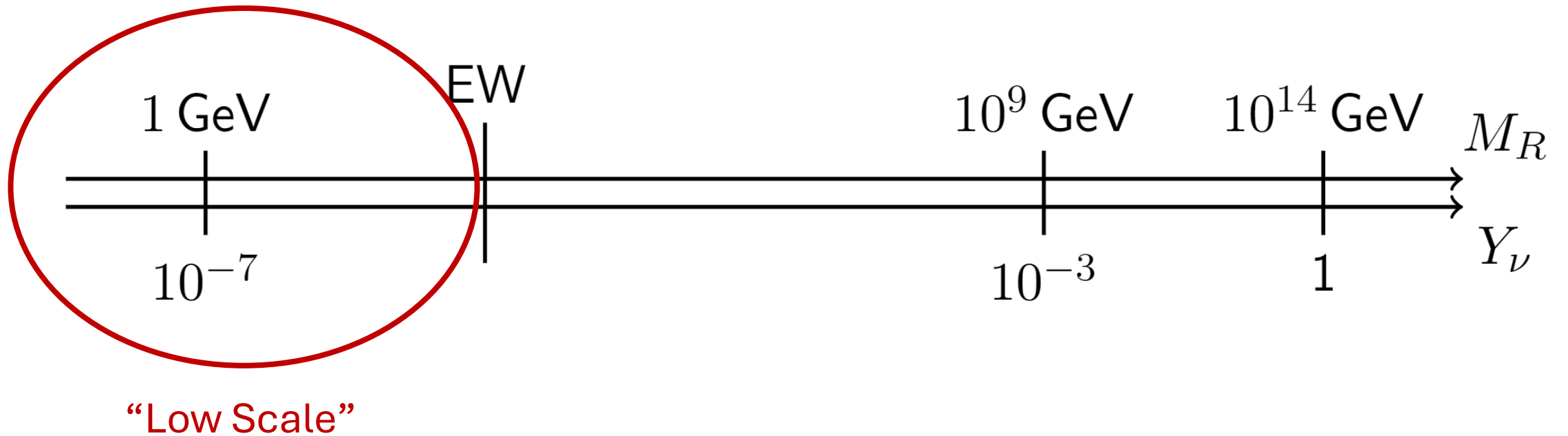


[Fridell PhD 2022]

# Range of scales



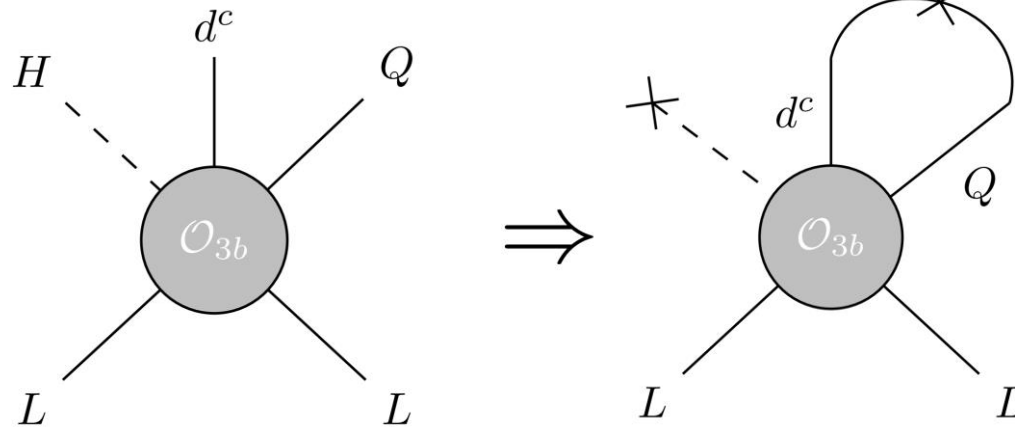
# Range of scales





# Neutrino masses – Non-Standard Case

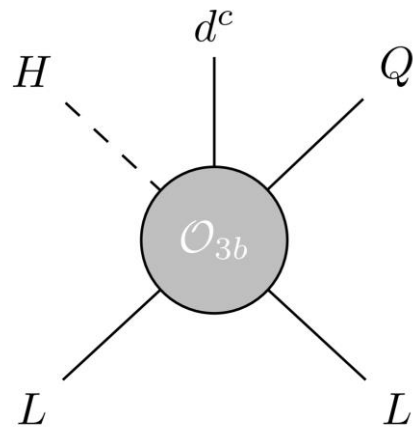
In general:



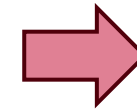
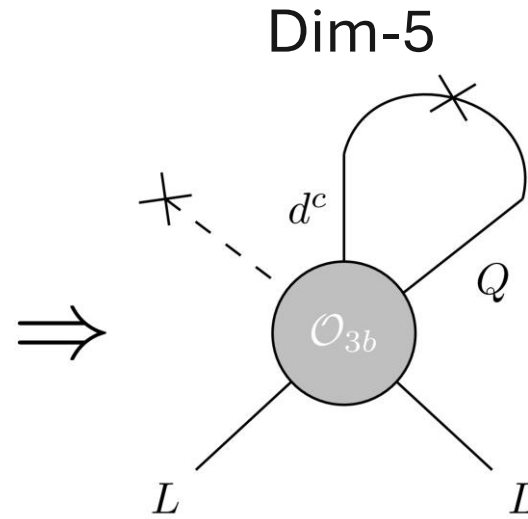
[Fridell PhD 2022]

# Neutrino masses – Non-Standard Case

In general:



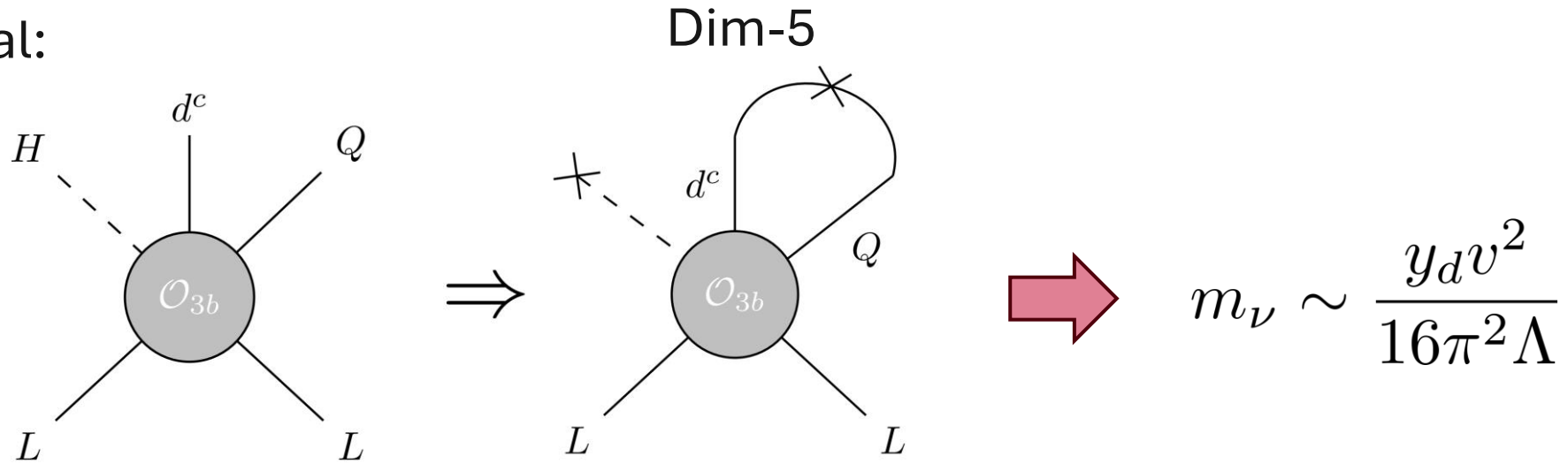
[Fridell PhD 2022]



$$m_\nu \sim \frac{y_d v^2}{16\pi^2 \Lambda}$$

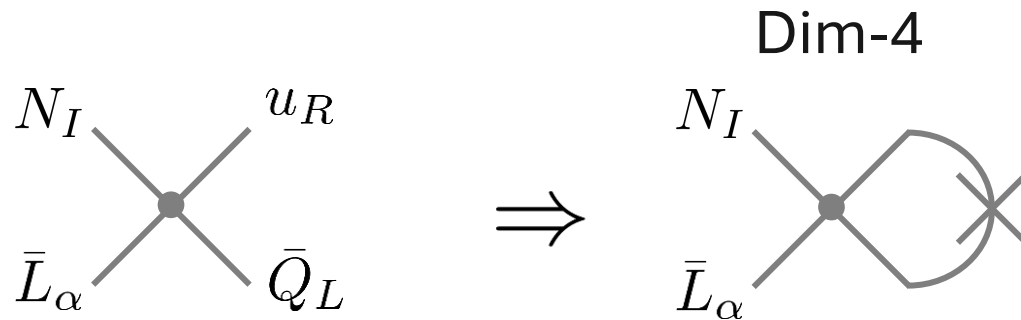
# Neutrino masses – Non-Standard Case

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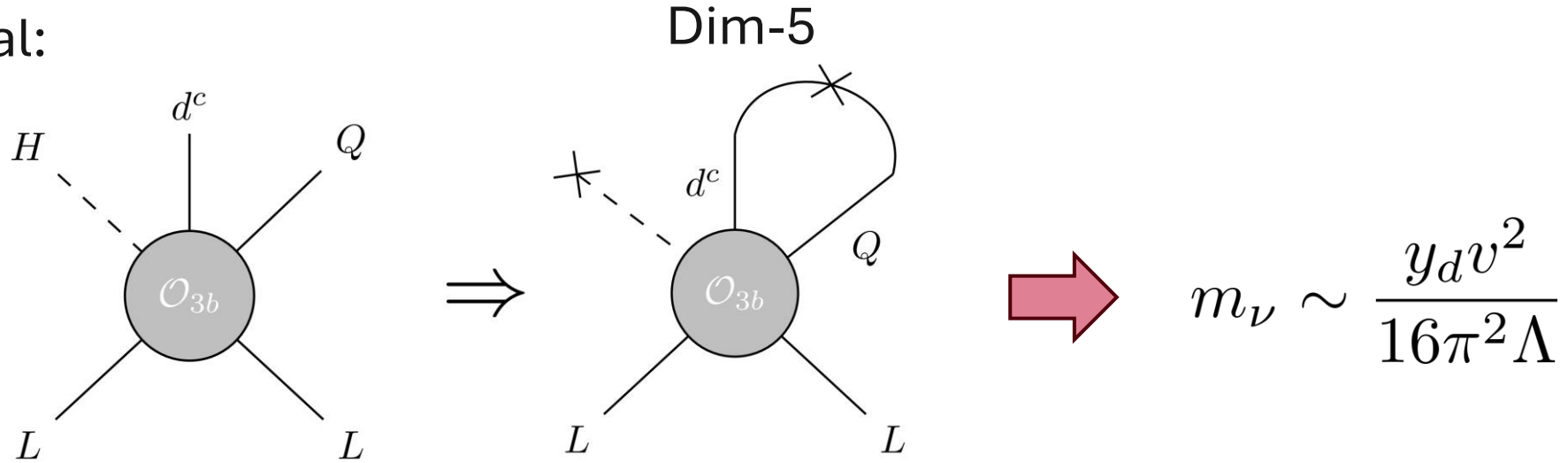
[Fridell PhD 2022]

Here:



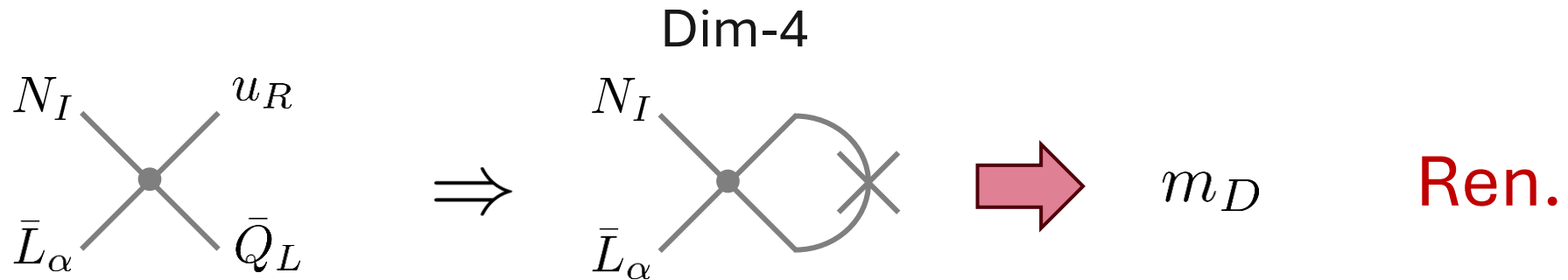
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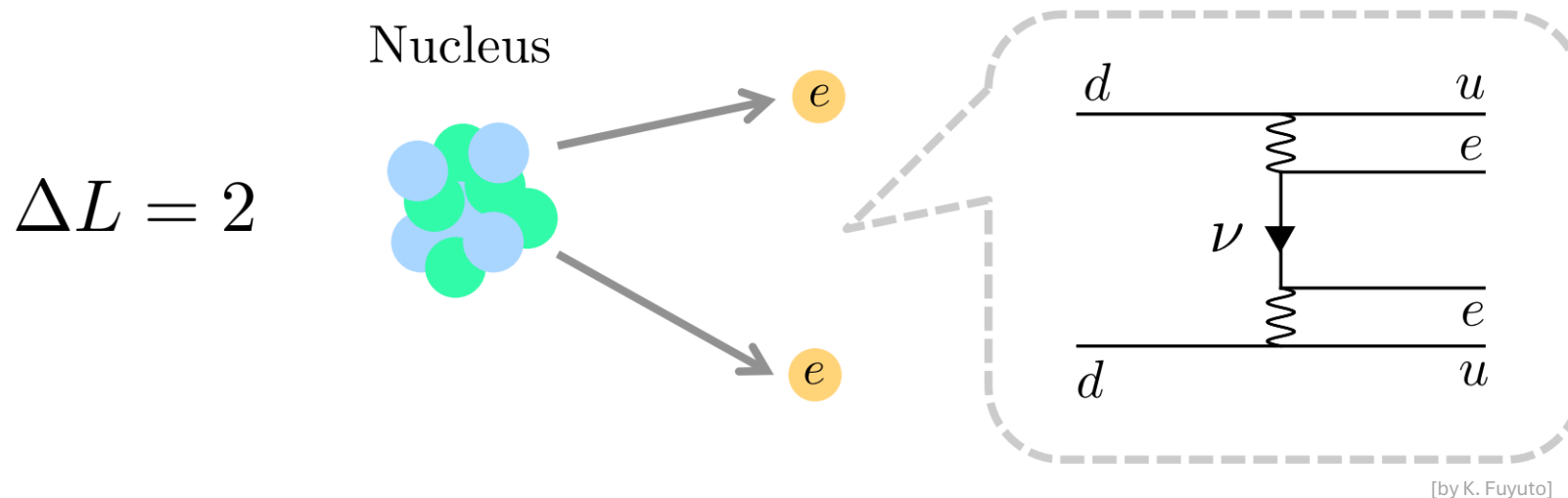
## 2) Lepton number violation

- Assignment of LN:  $\mathcal{L} \supset -Y_{i\alpha} \underbrace{\overline{N}_i H L_\alpha}_{\text{LNC}} - \underbrace{\overline{N}_i^c M_i N_i}_{\text{LNV}} + \text{h.c.}$   
 $L(L_\alpha) = 1$   
 $L(H) = 0$   
 $L(N_i) = 1$

## 2) Lepton number violation

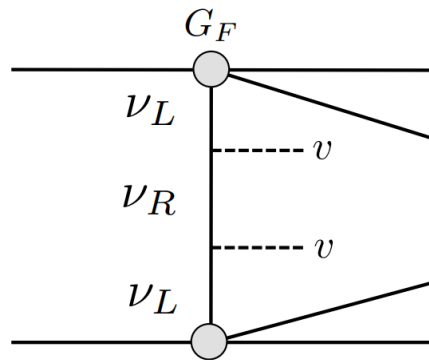
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LNC LNV
- “Most” promising observable:  $0\nu\beta\beta$  decay

$$\begin{aligned} L(L_\alpha) &= 1 \\ L(H) &= 0 \\ L(N_i) &= 1 \end{aligned}$$

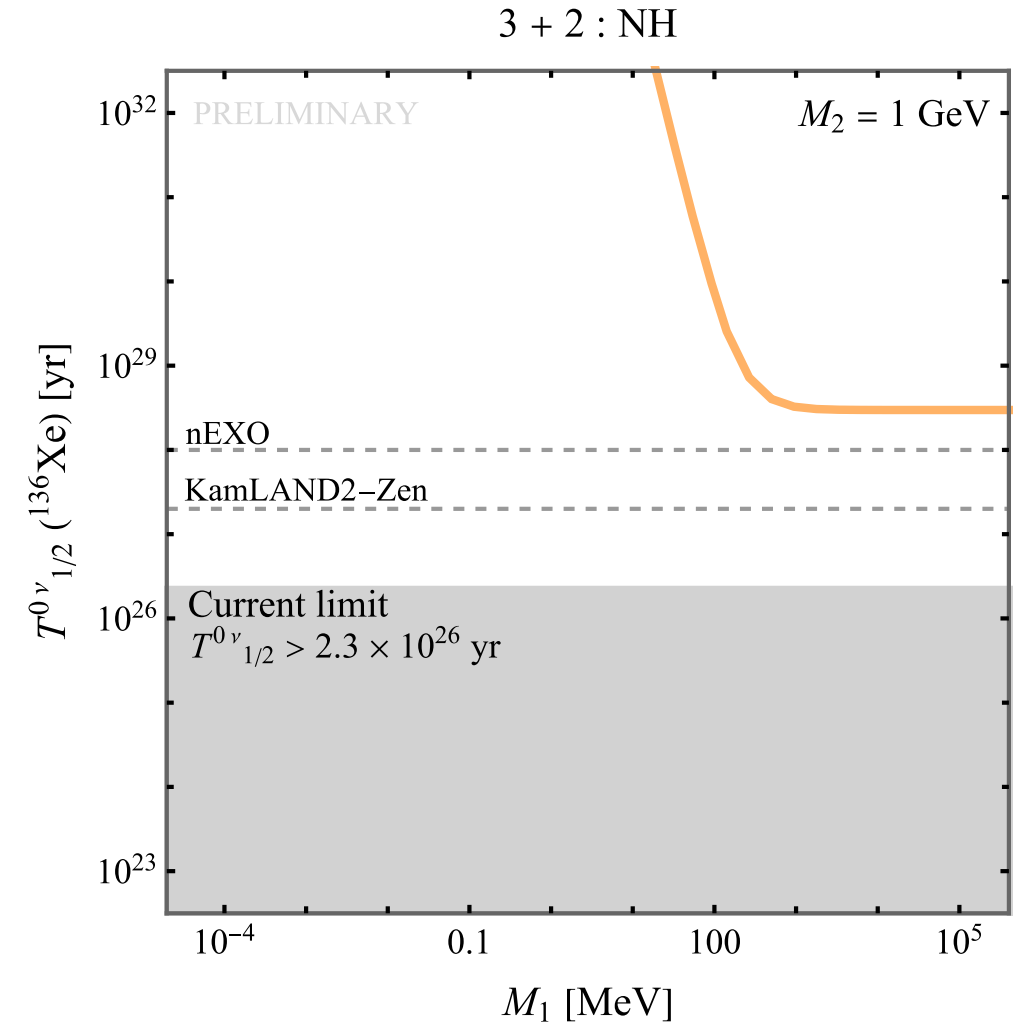


# LNV – Standard Case

- 4-fermion interaction at low scales

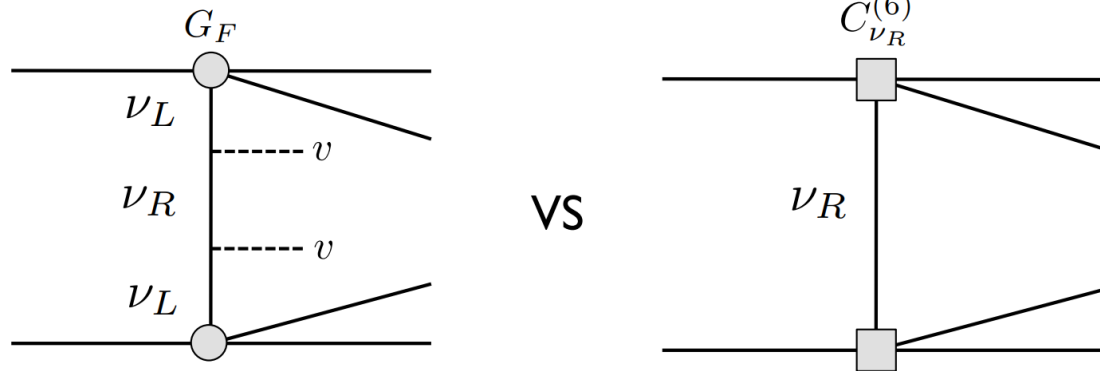


[by K. Fuyuto]



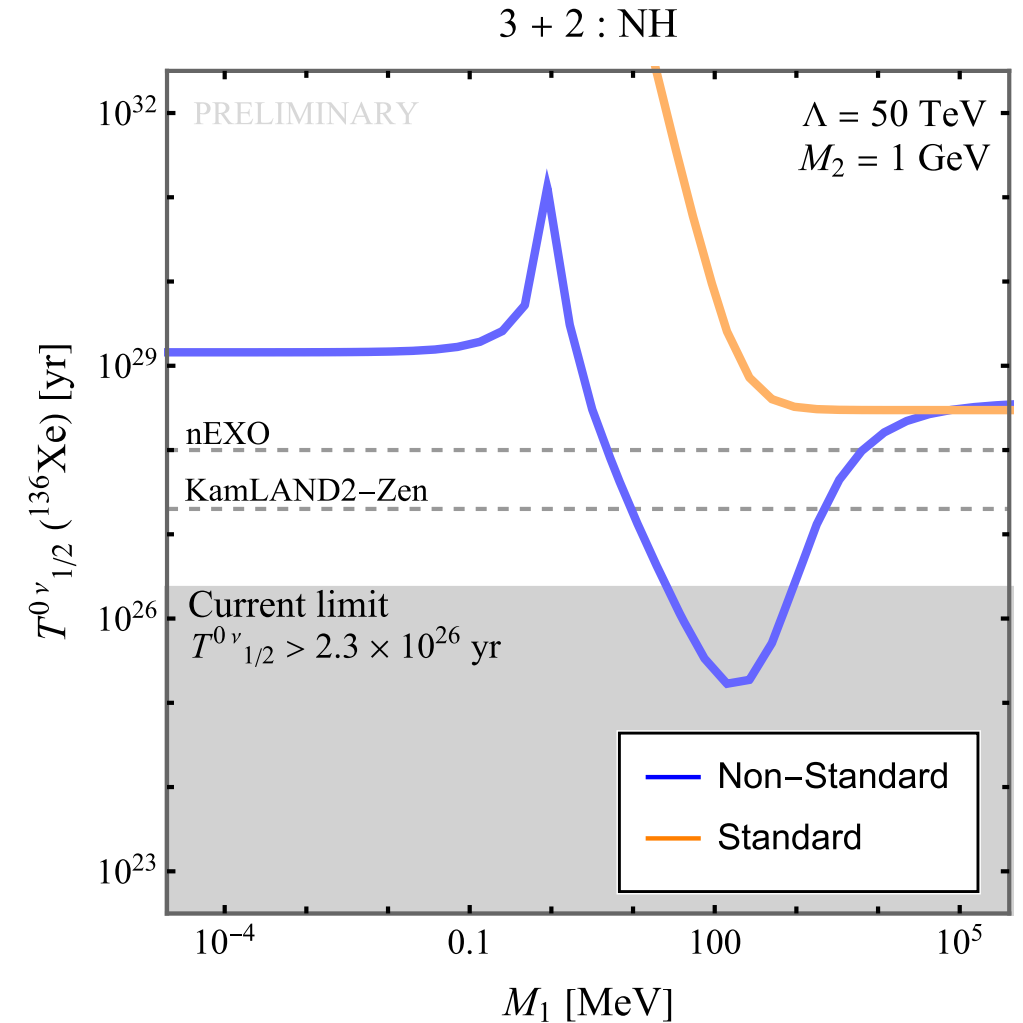
# LNV – Non-Standard Case

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



[by K. Fuyuto]

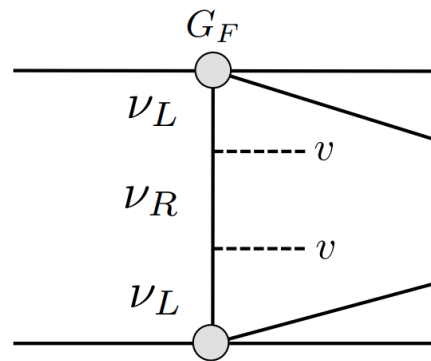
**LNC operator:**





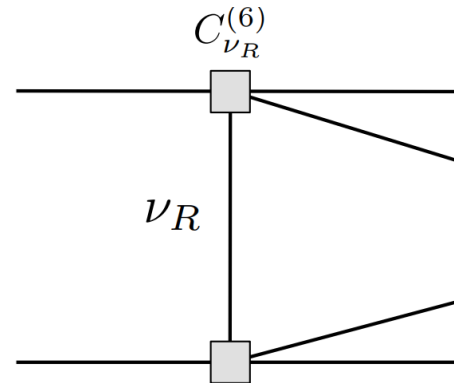
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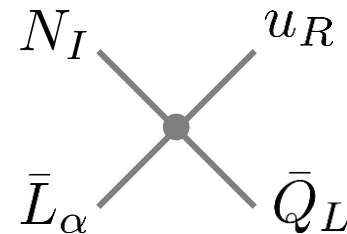


[by K. Fuyuto]

VS

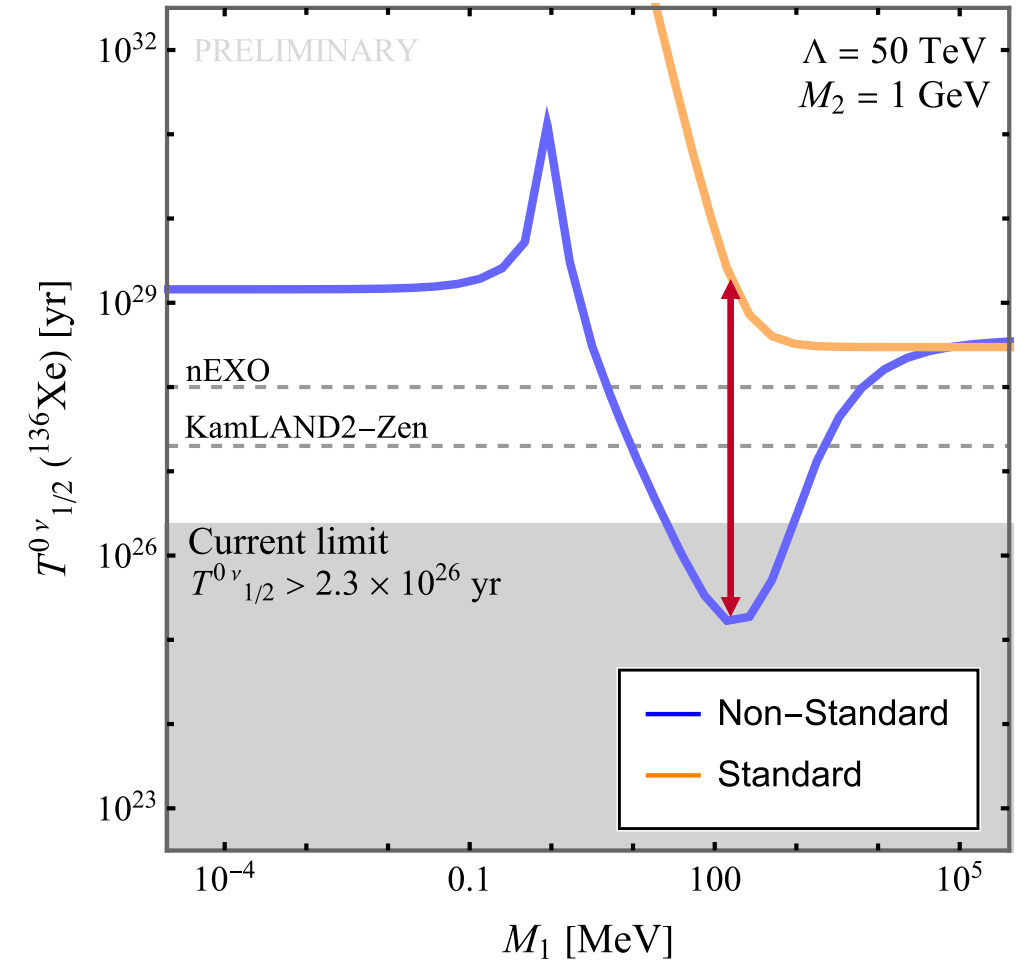


**LNC operator:**



Order of magnitude effect!

3 + 2 : NH

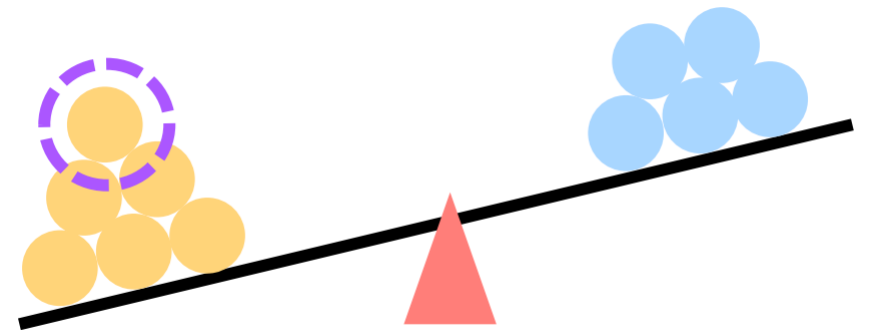


# 3) Baryon Asymmetry

- 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

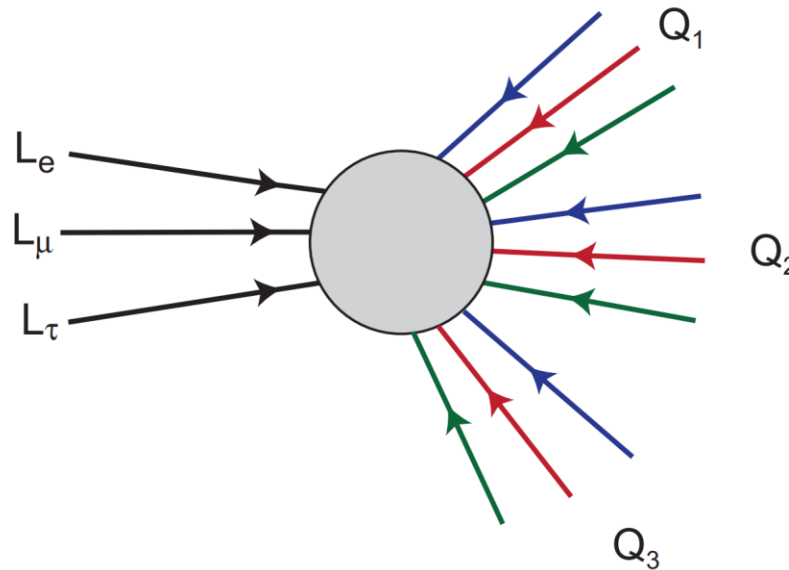


[by K. Fuyuto]

# Leptogenesis (LG)

Above EW scale:

- SM sphaleron processes  $\rightarrow B + L$  violation
- Non-perturbative

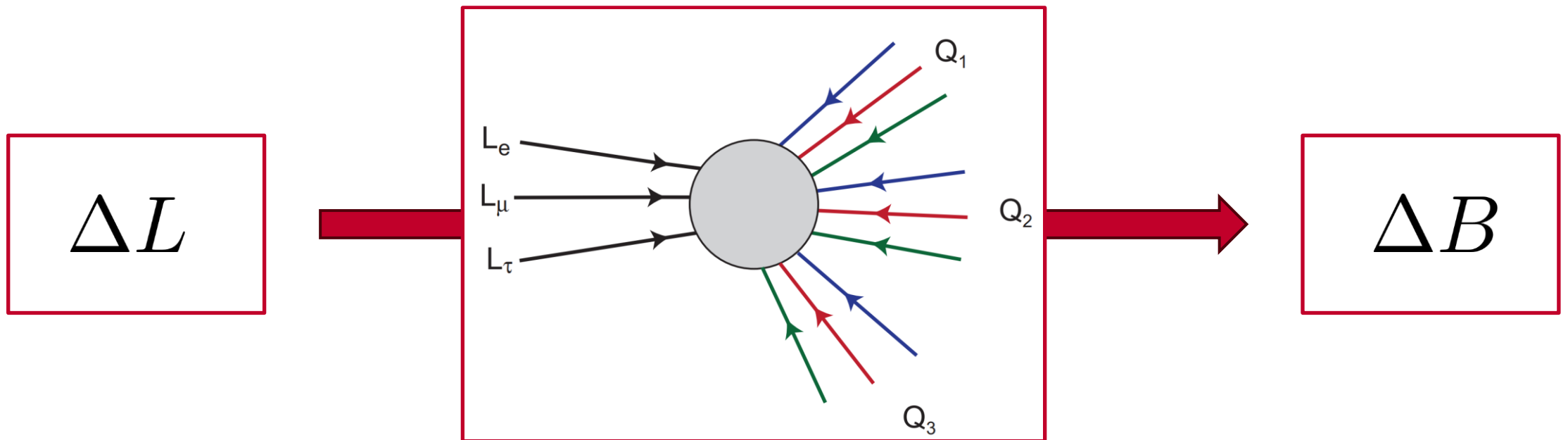


[Nir 2009]

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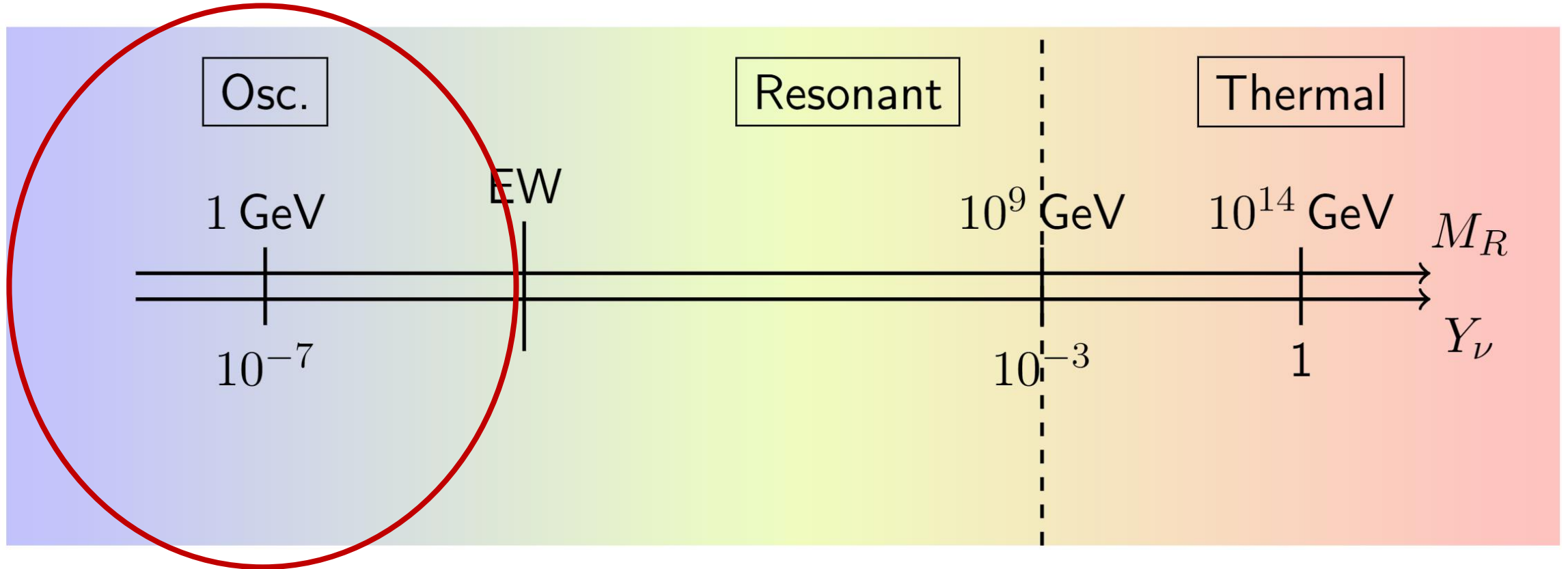
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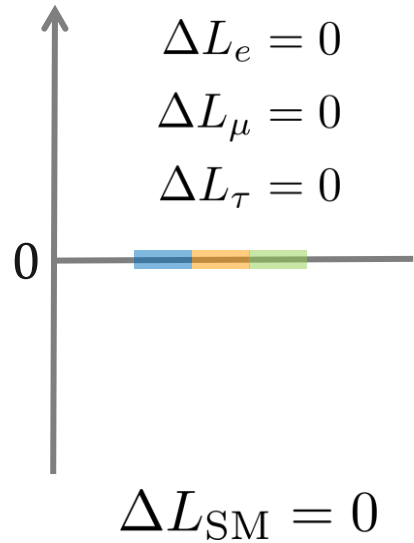


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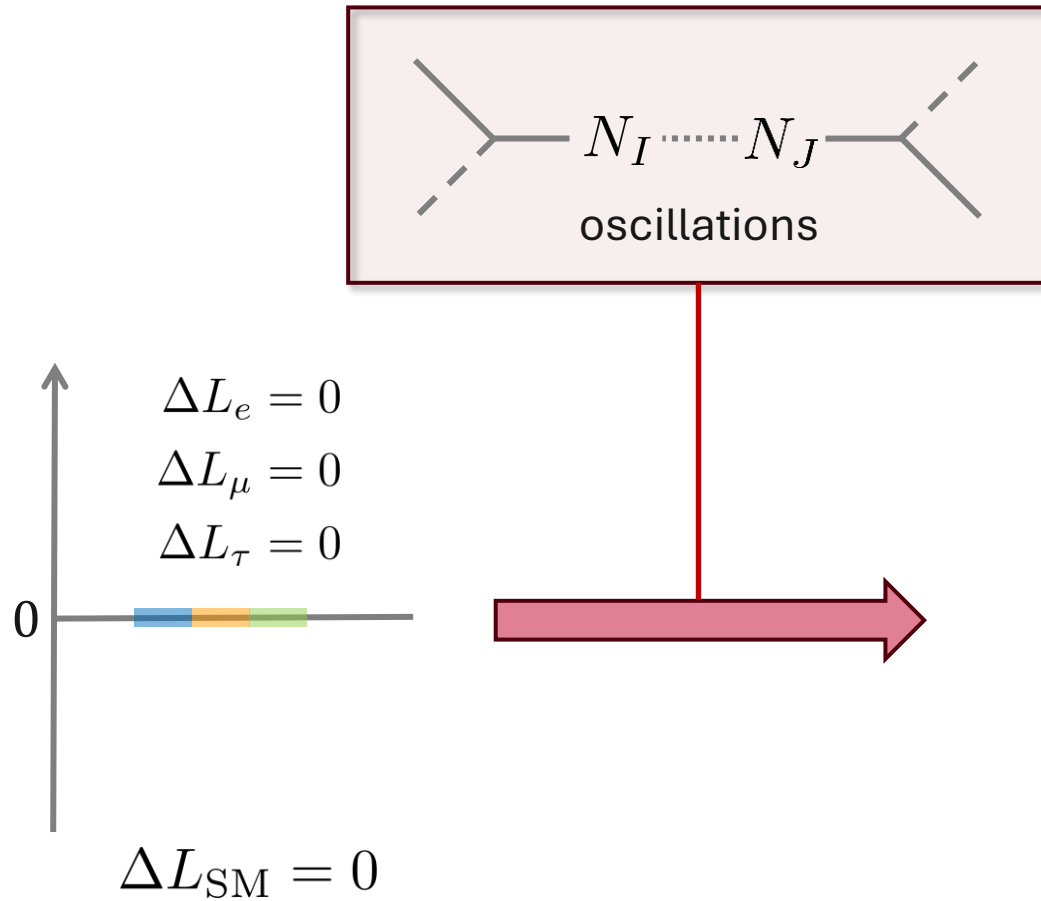
# Leptogenesis regimes



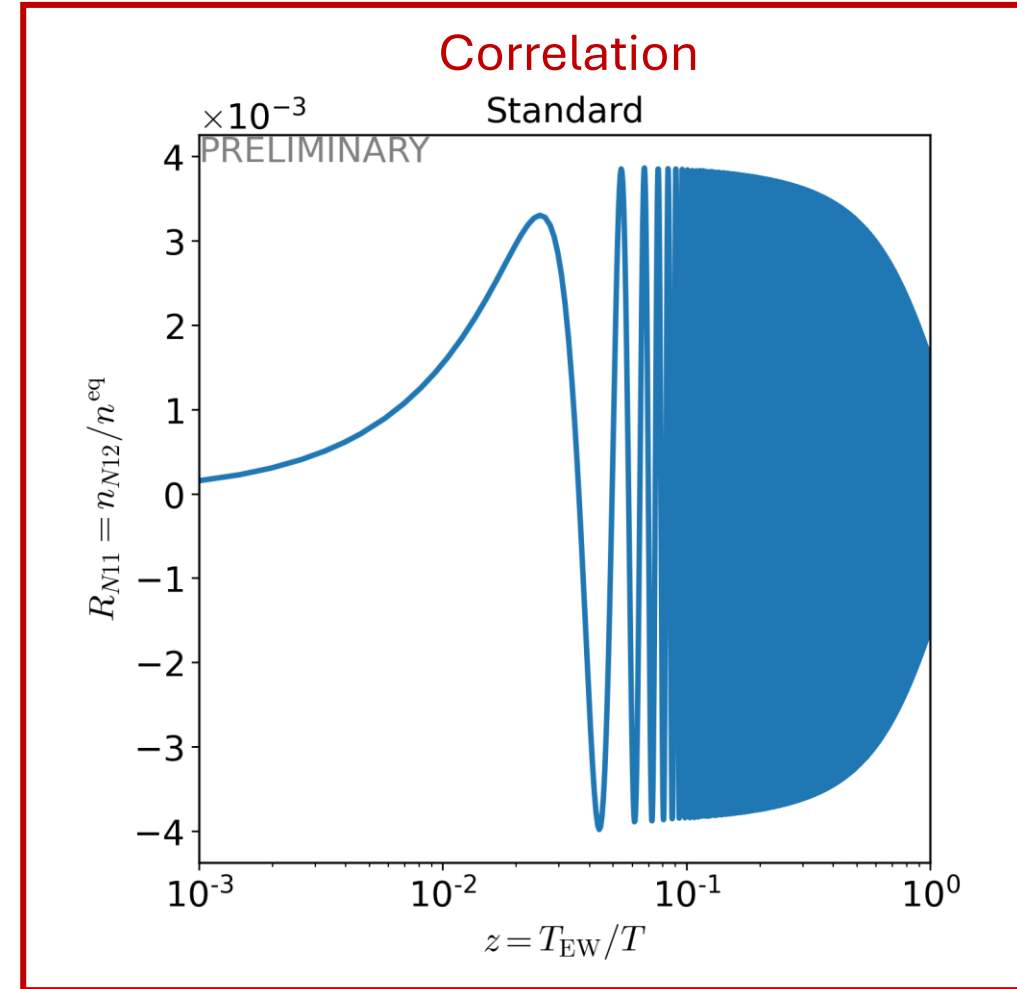
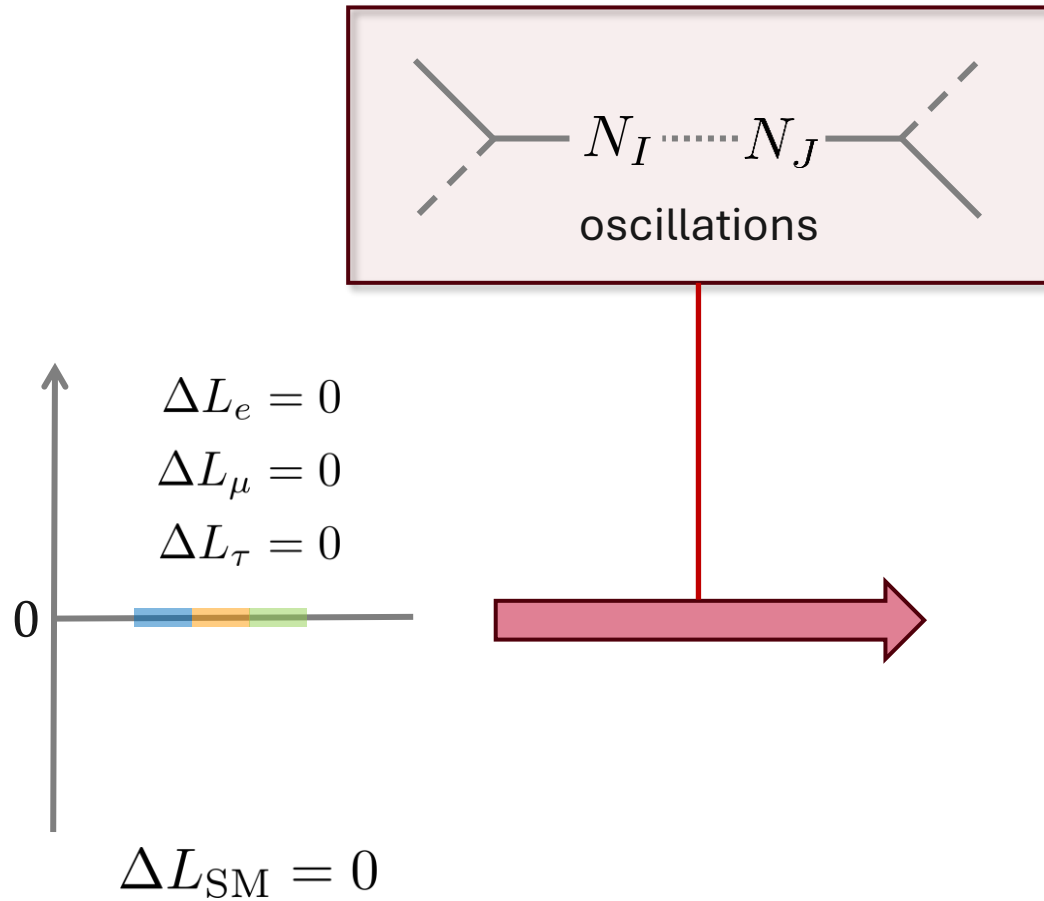
# BAU via Neutrino Oscillation – Standard Case



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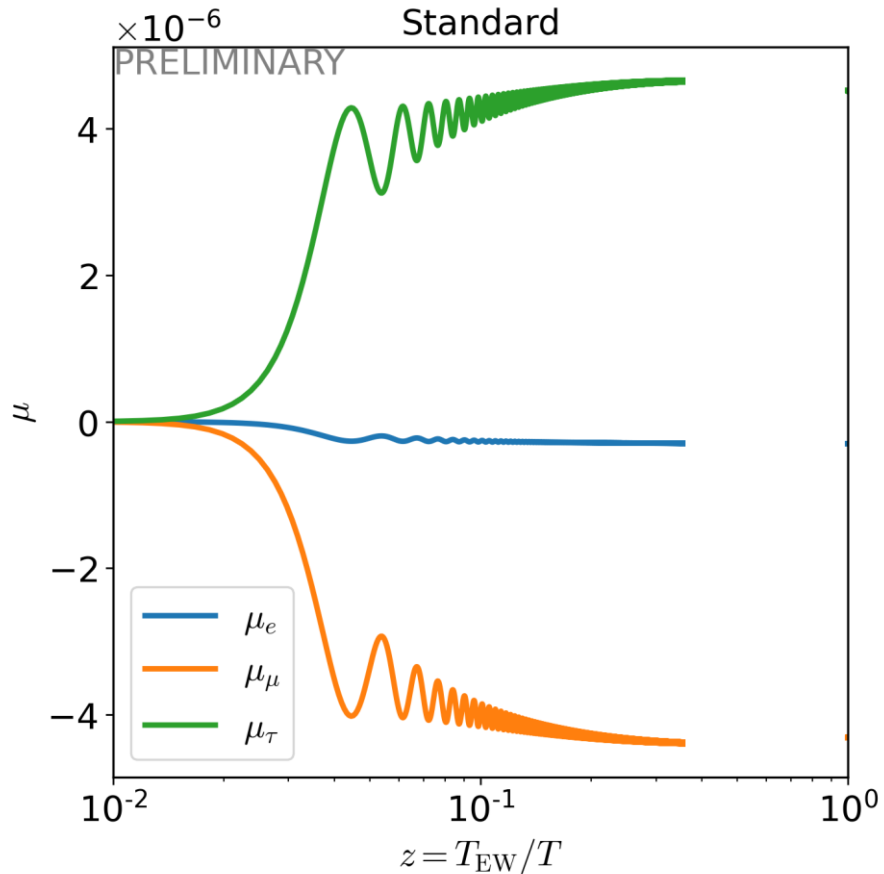
# BAU via Neutrino Oscillation – Standard Case



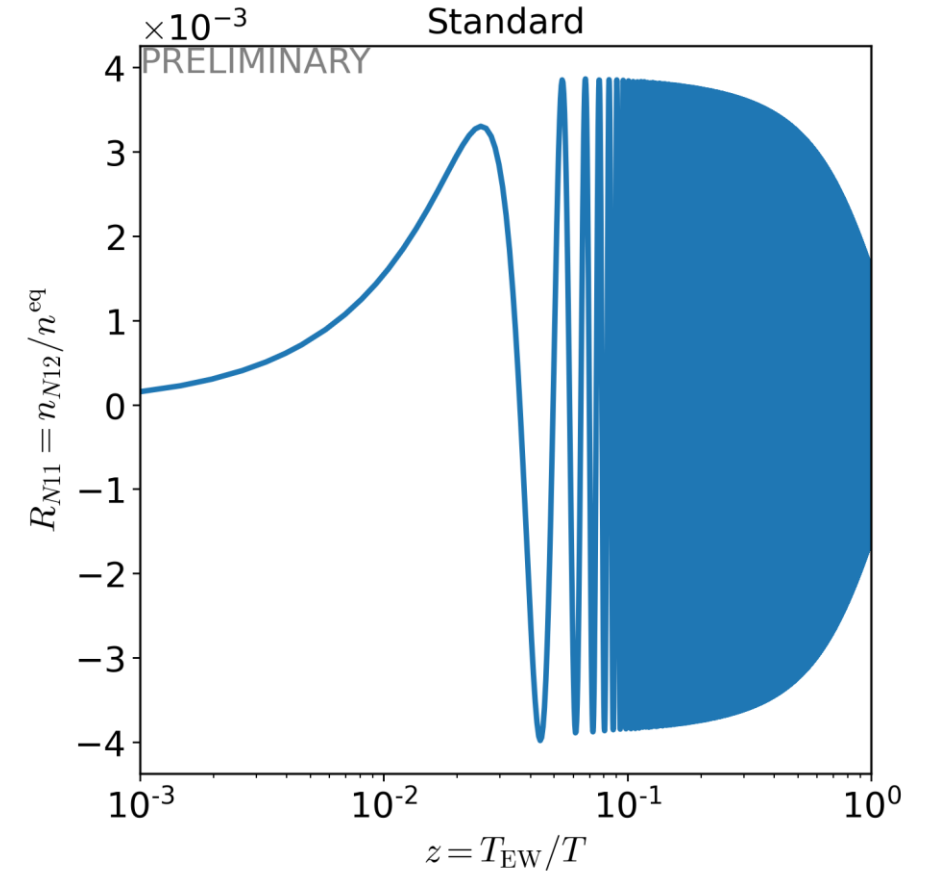


# BAU via Neutrino Oscillation – Standard Case

## Lepton Flavor Asymmetries

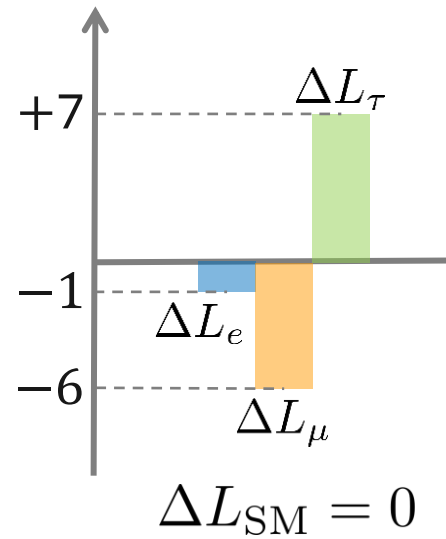
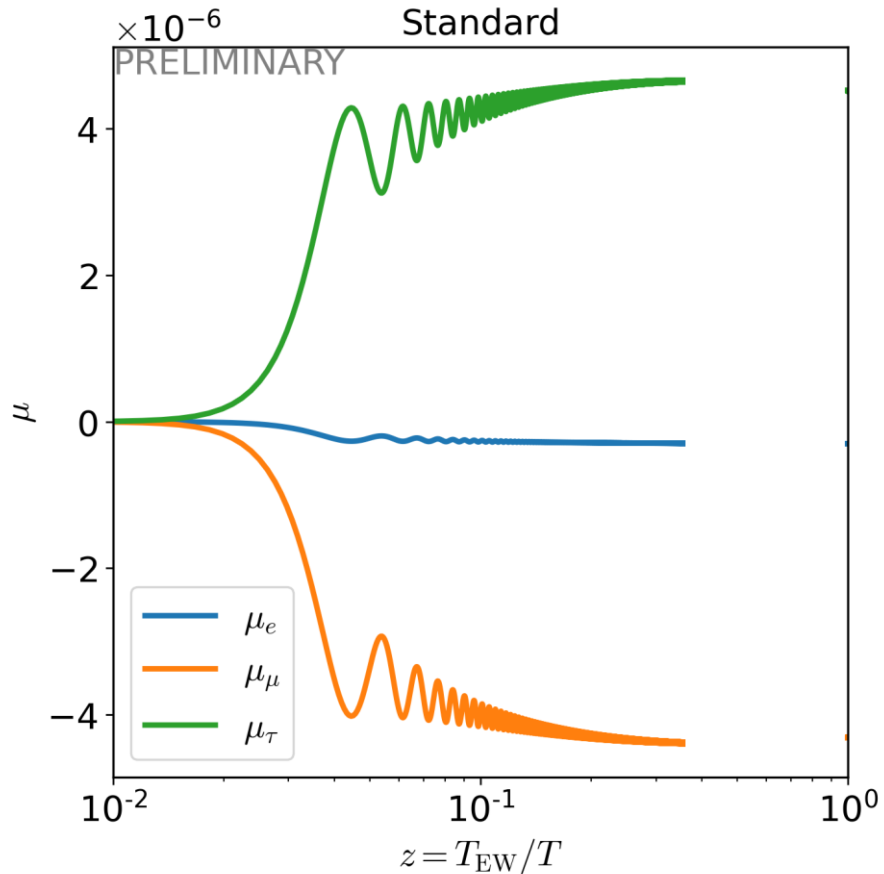


## Correlation

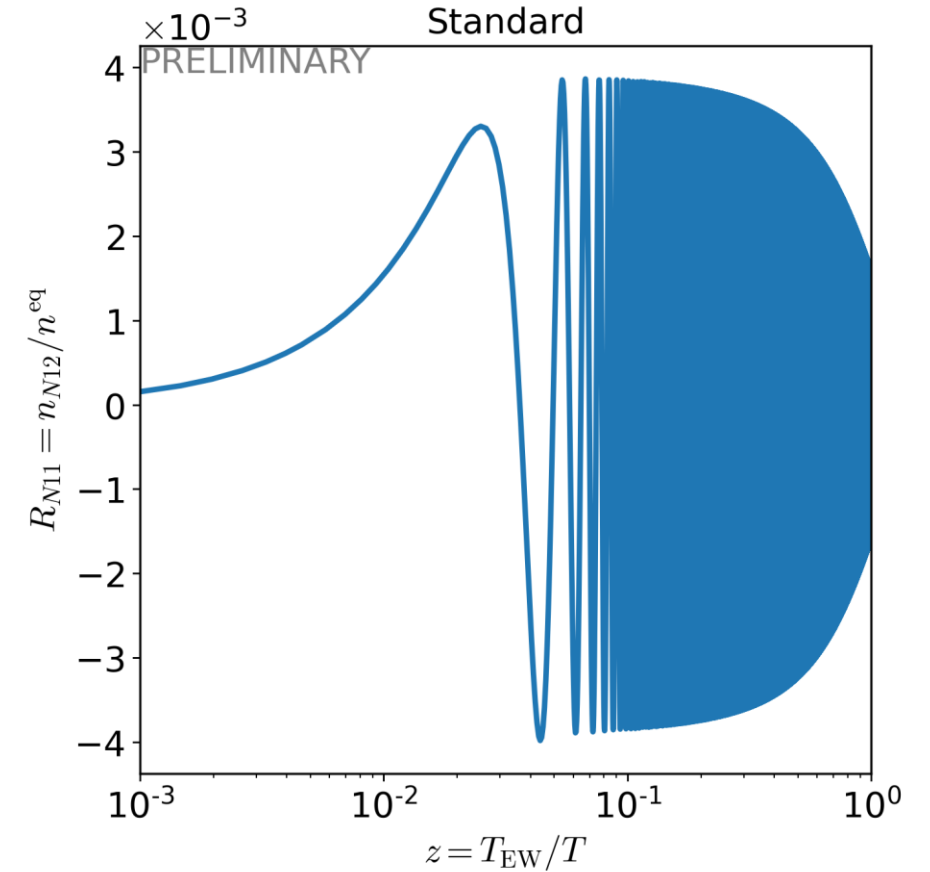


# BAU via Neutrino Oscillation – Standard Case

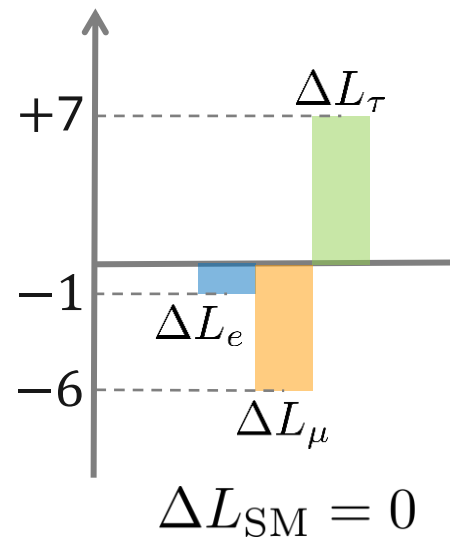
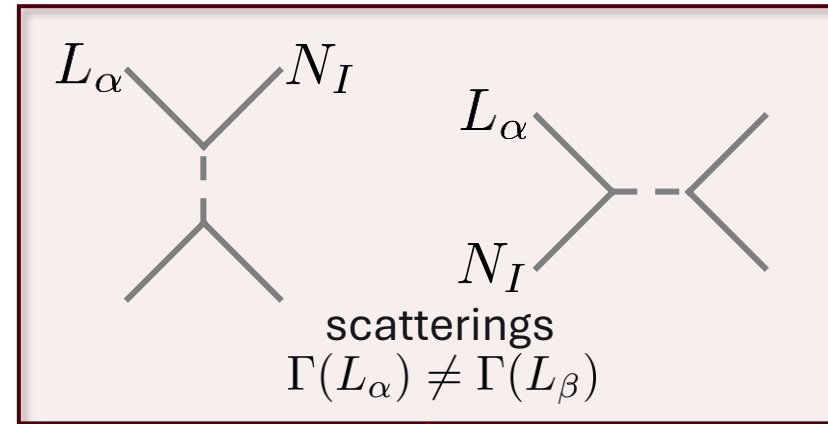
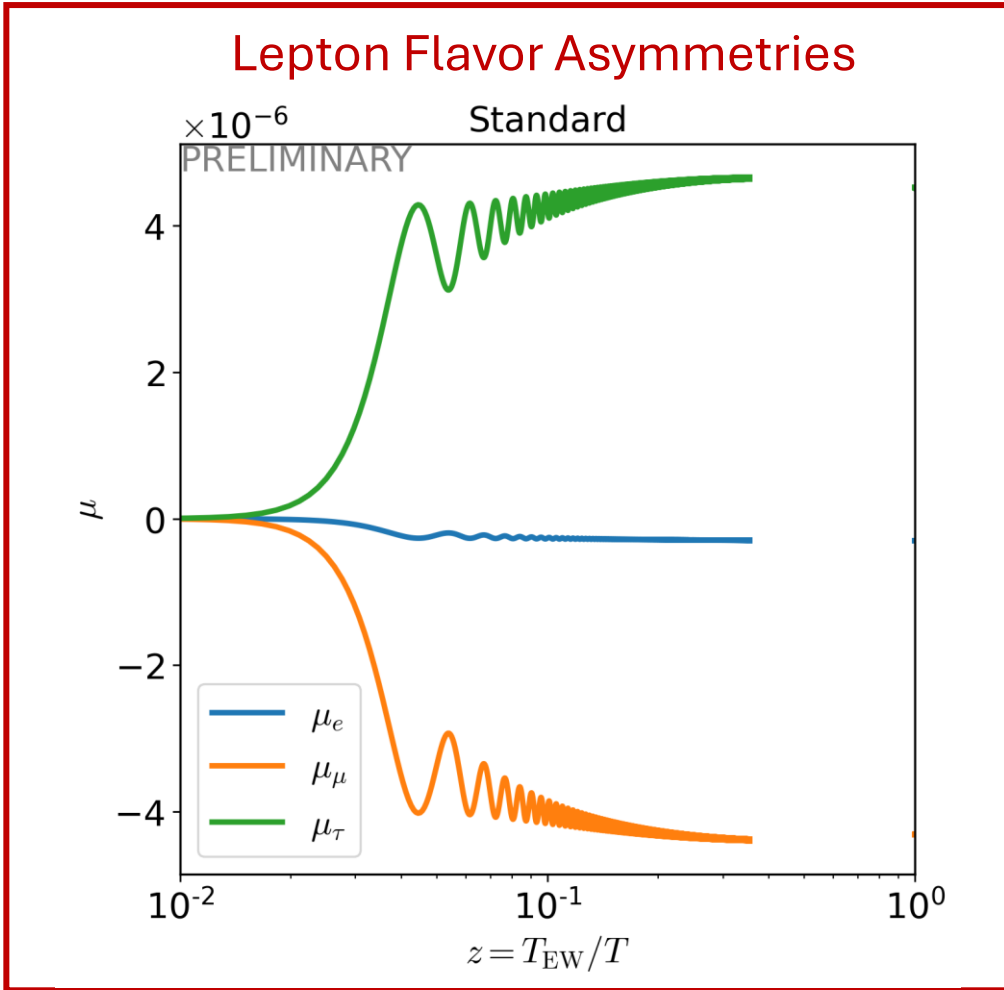
## Lepton Flavor Asymmetries



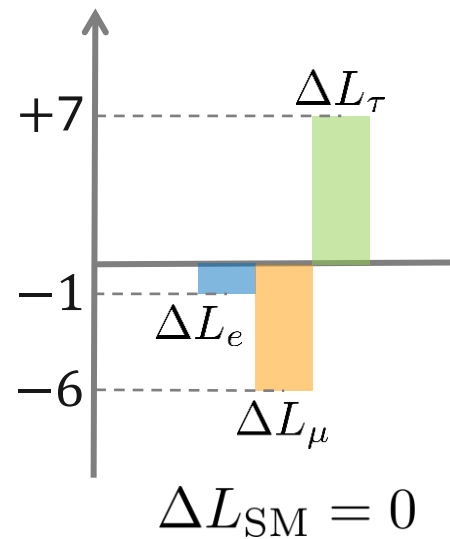
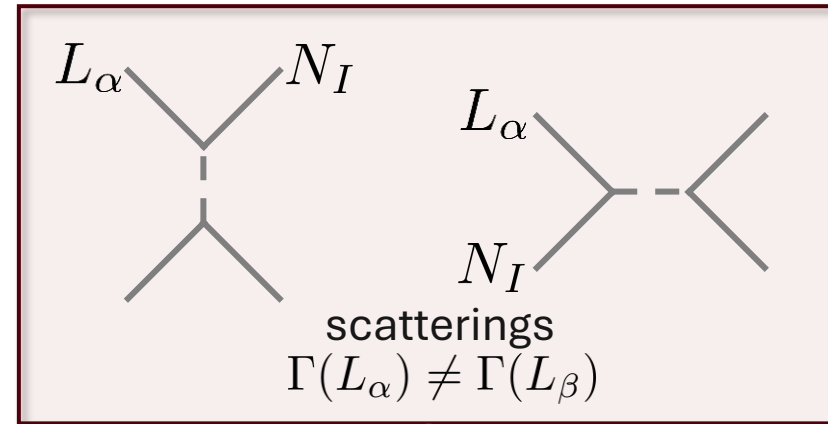
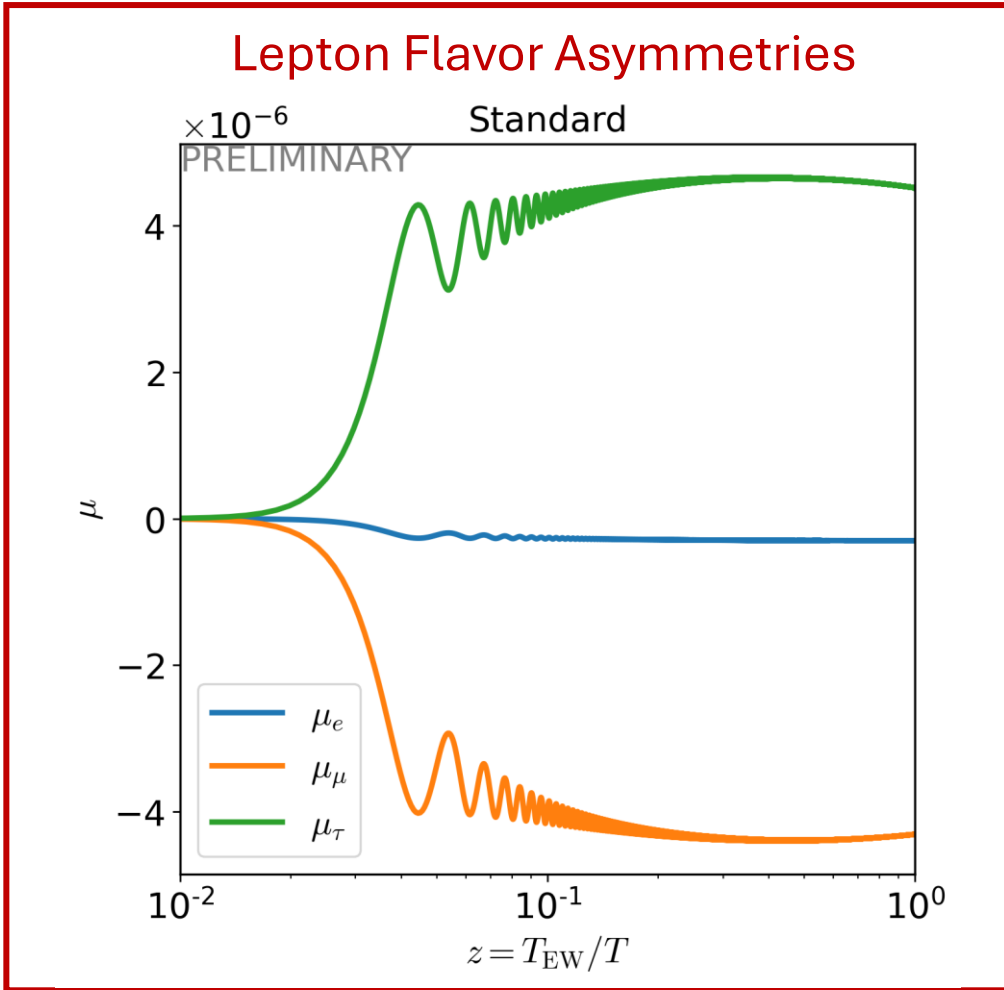
## Correlation



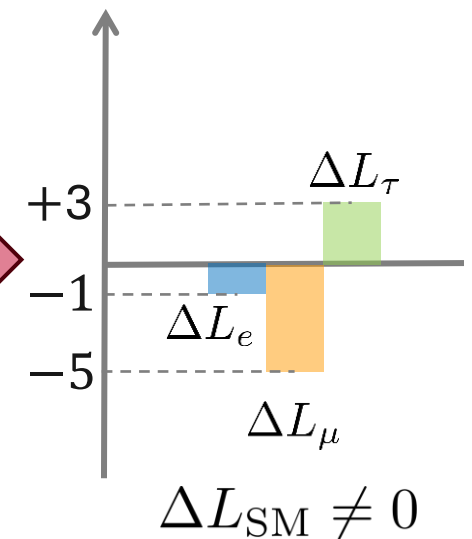
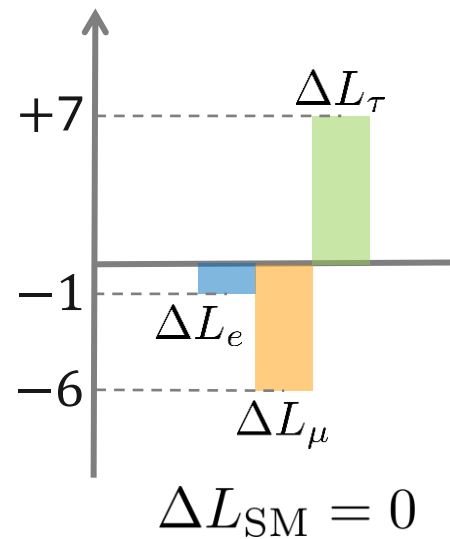
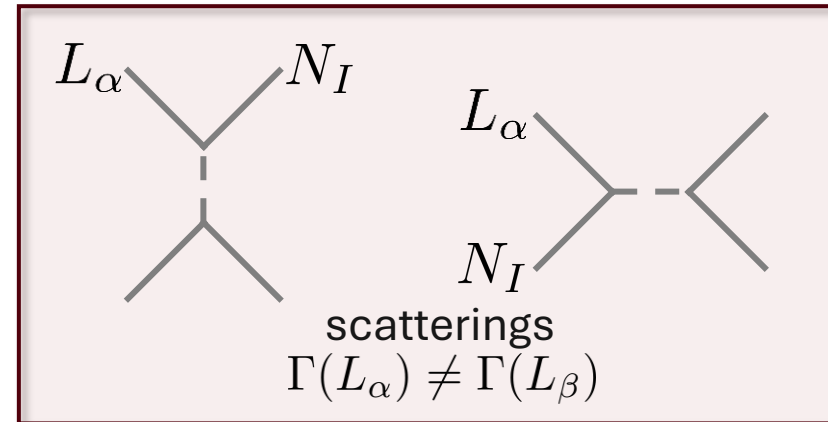
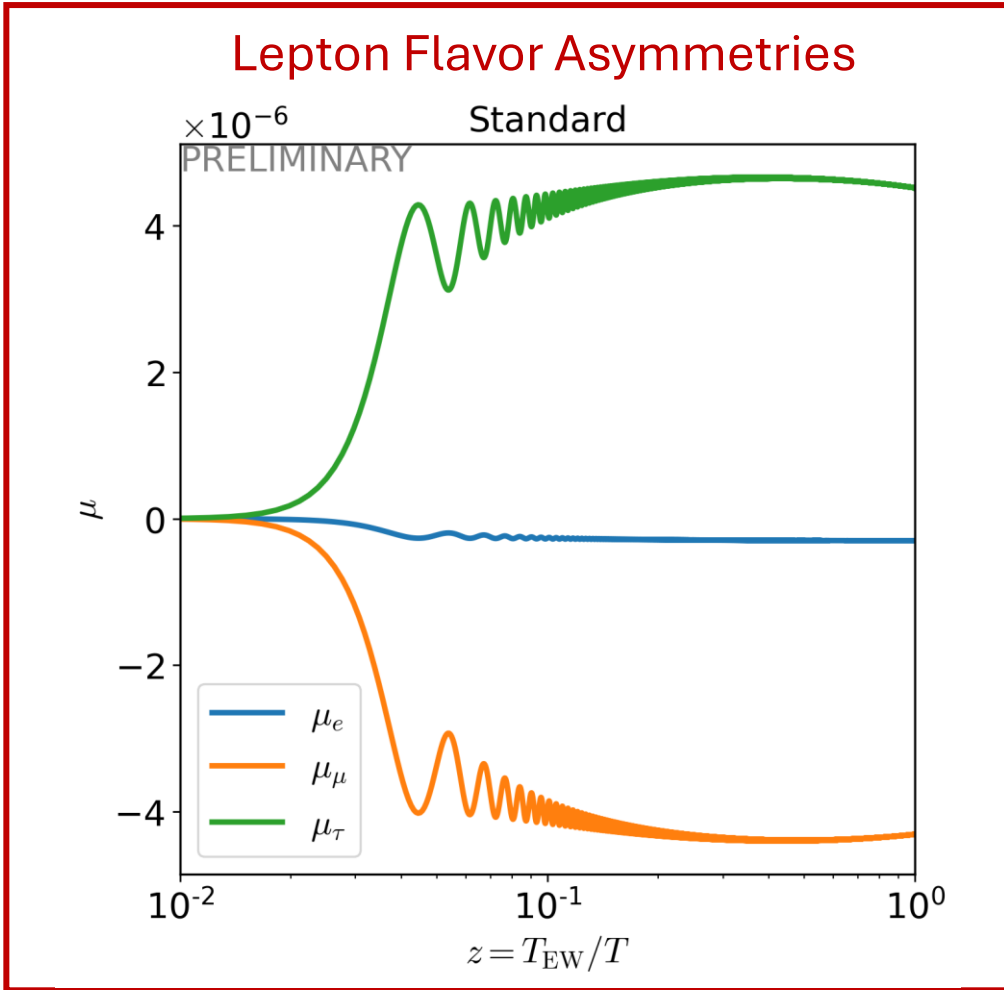
# BAU via Neutrino Oscillation – Standard Case



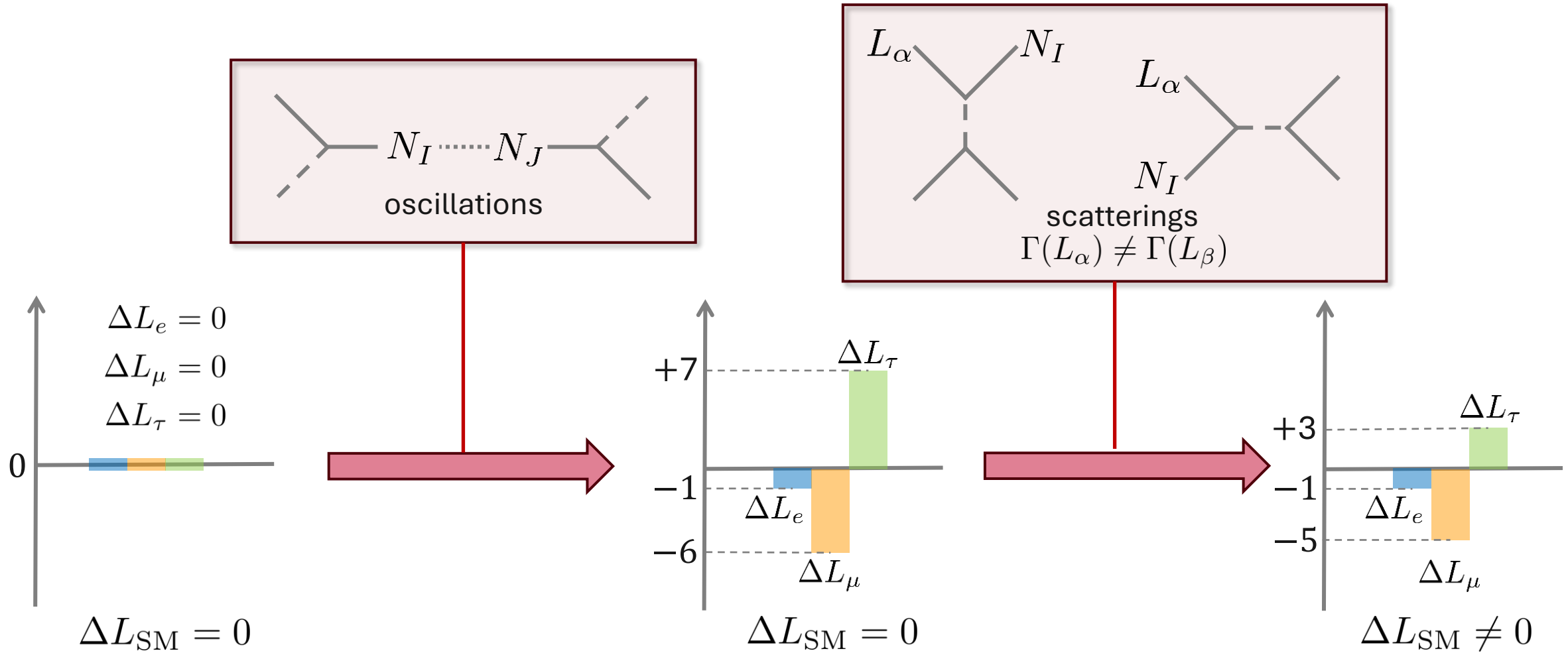
# BAU via Neutrino Oscillation – Standard Case



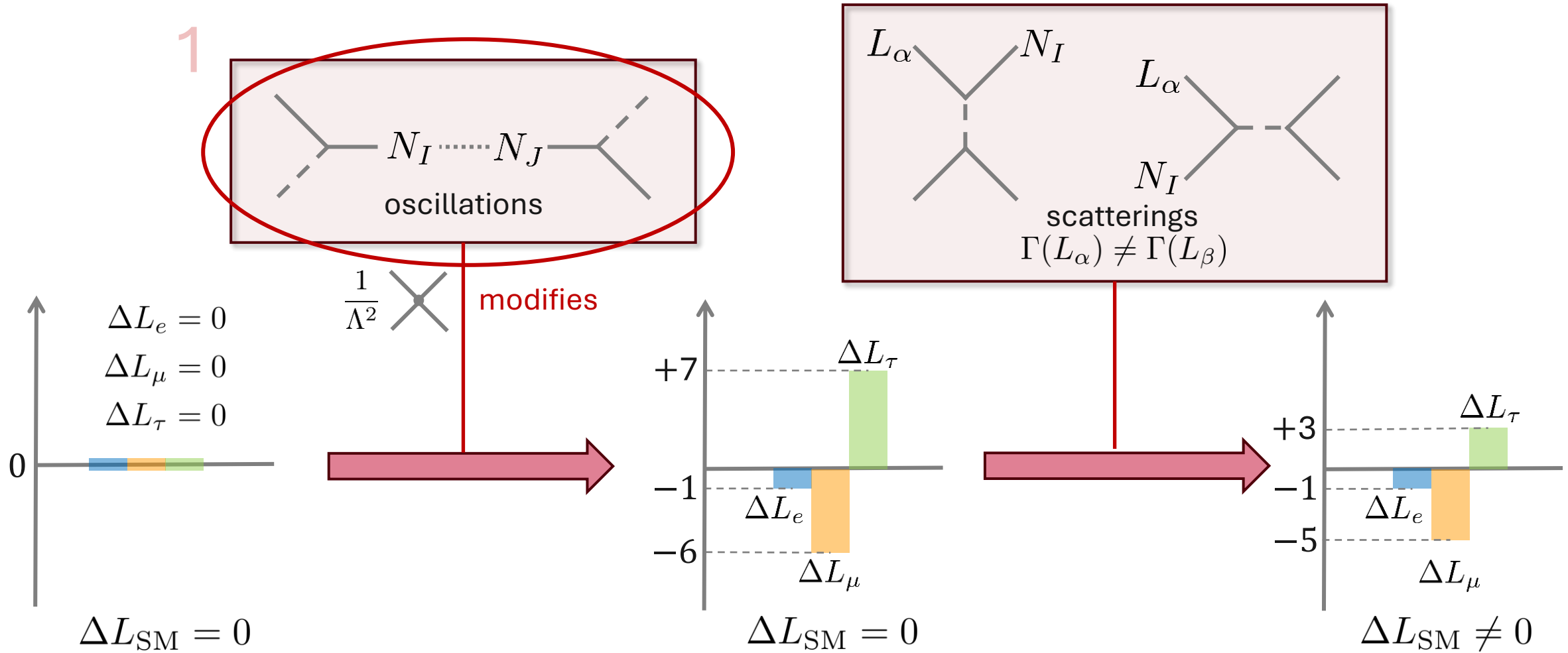
# BAU via Neutrino Oscillation – Standard Case



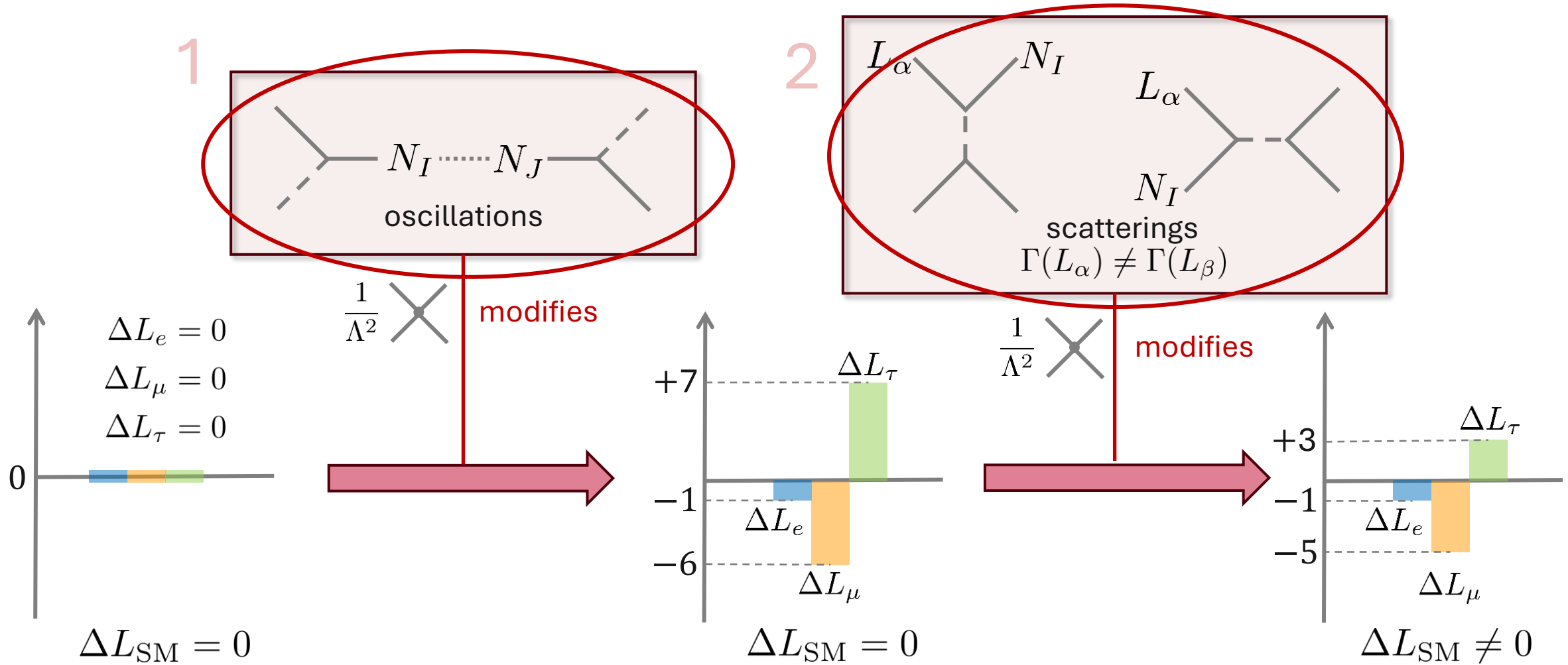
# BAU via Neutrino Oscillation – Standard Case



# BAU via Neutrino Oscillation – Non-Standard Case

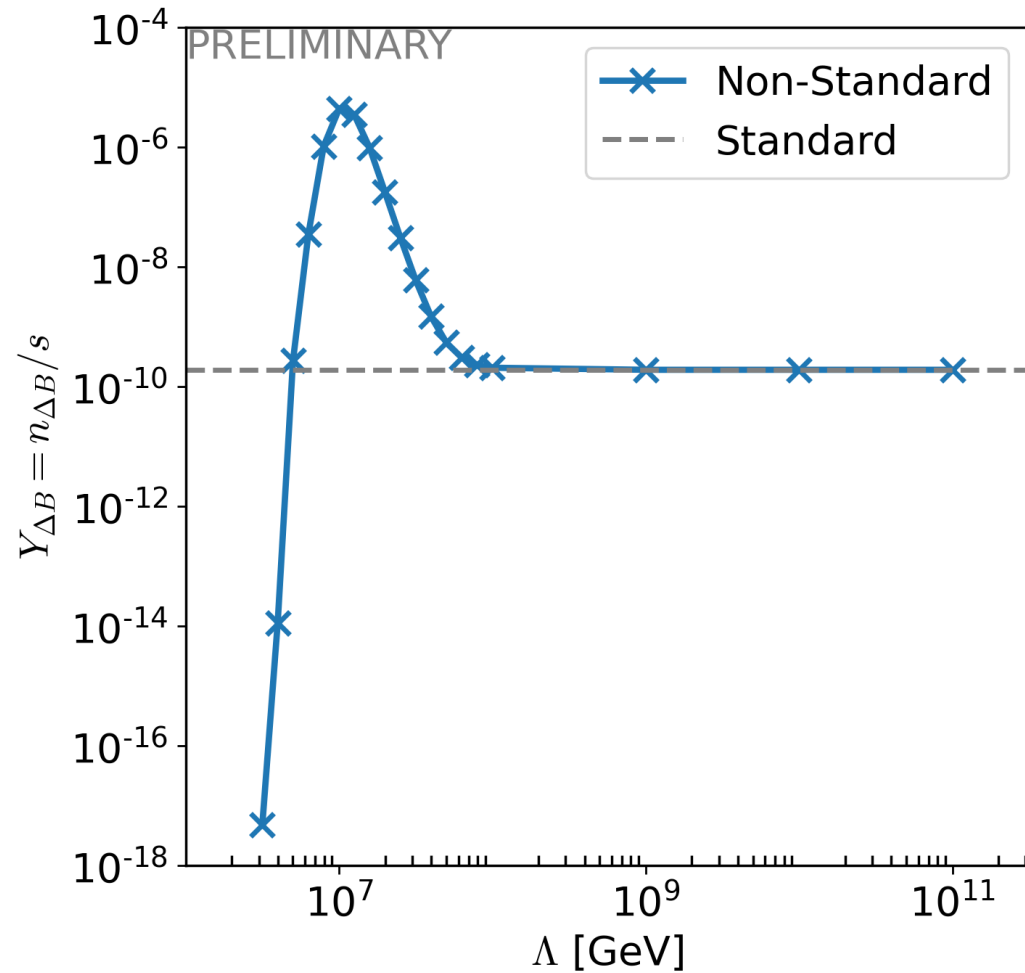


# BAU via Neutrino Oscillation – Non-Standard Case

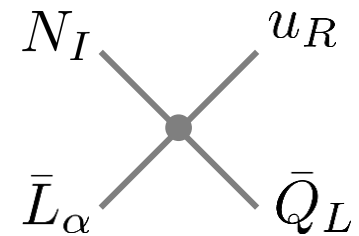




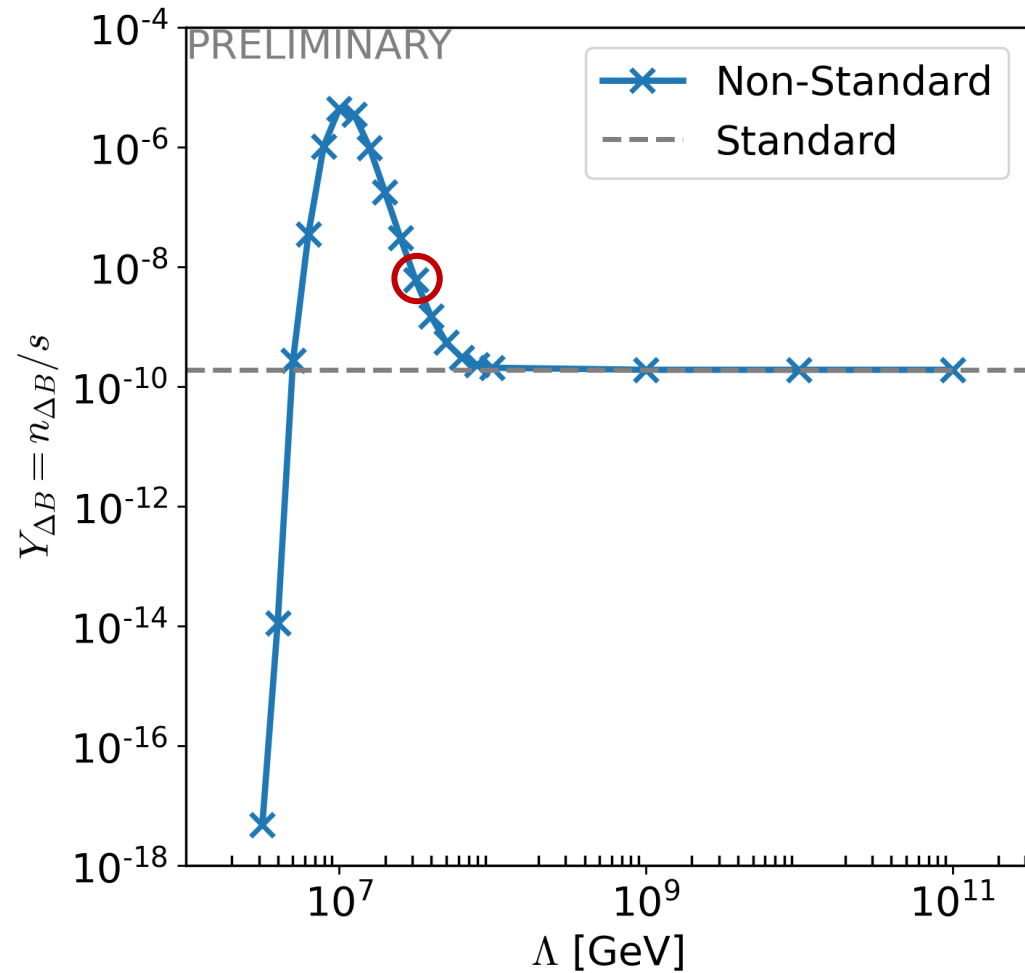
# Low scale Leptogenesis – Non-Standard Case



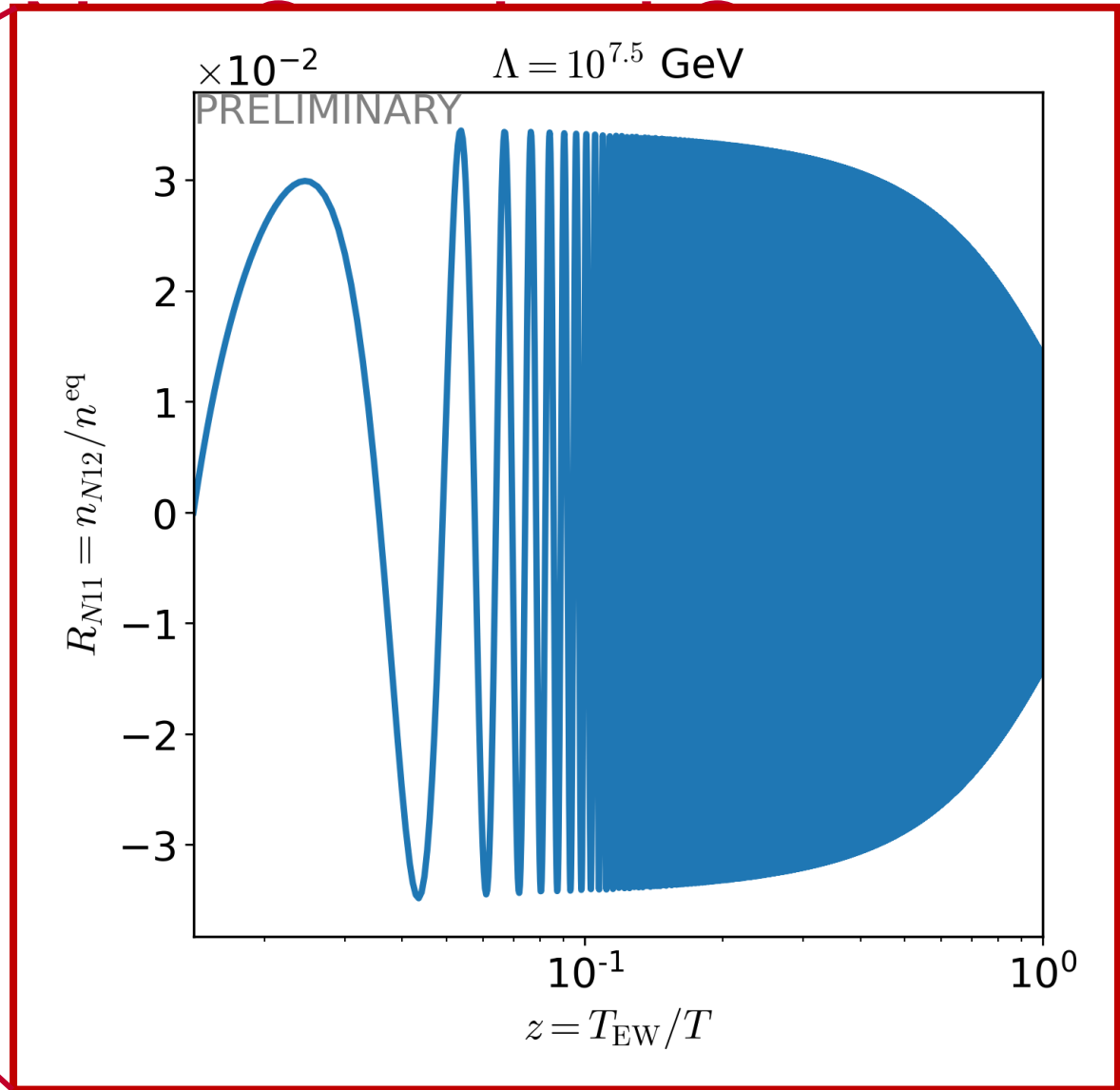
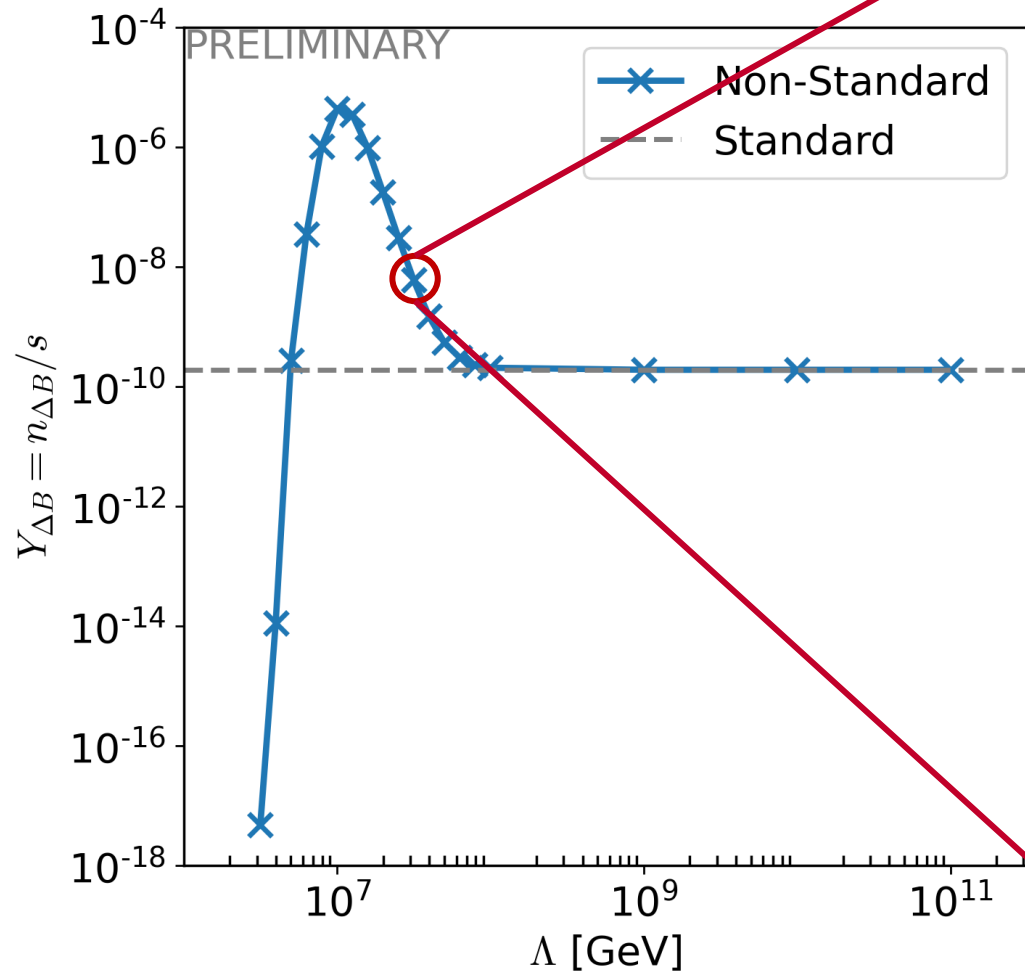
**LNC operator:**



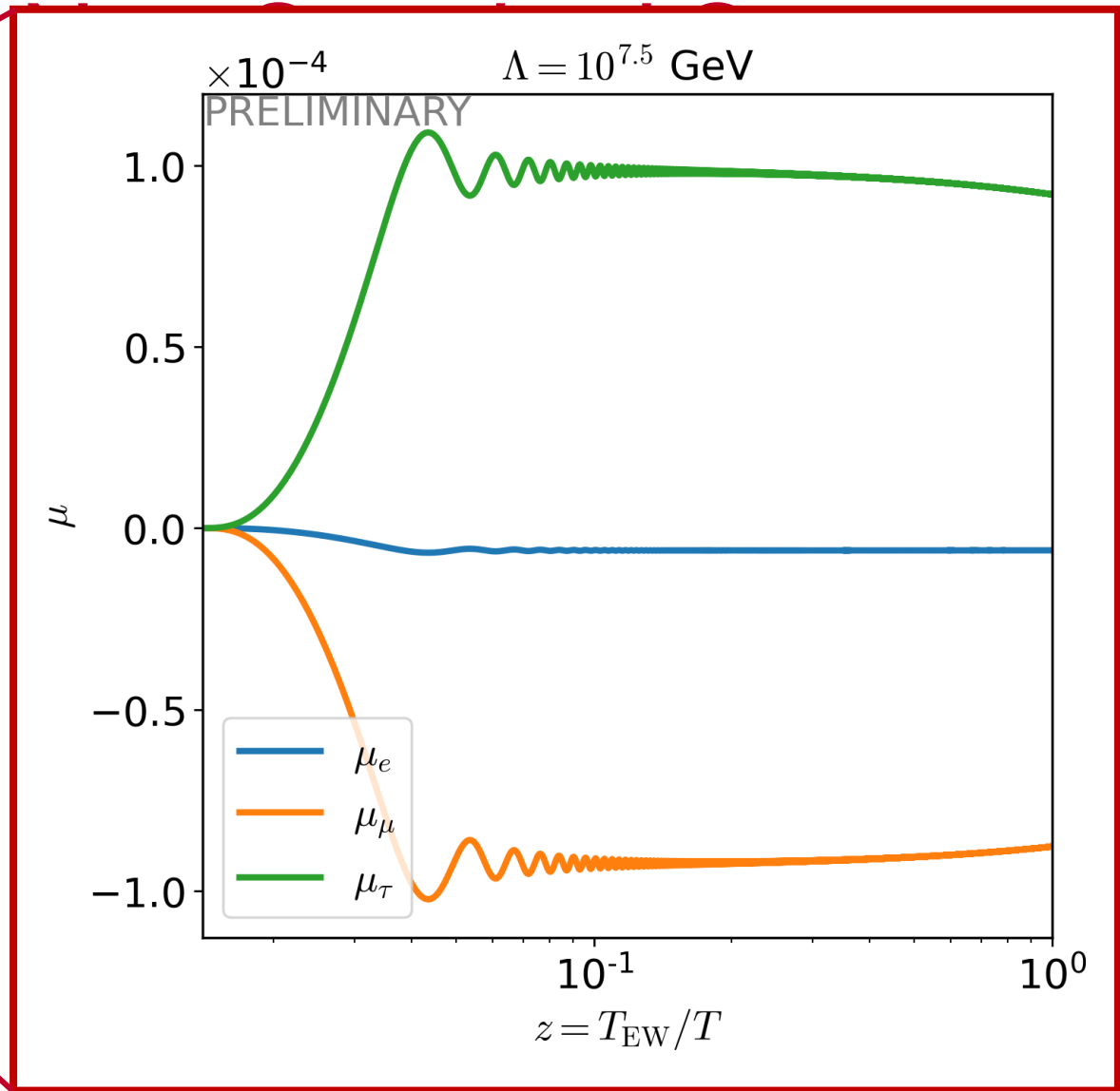
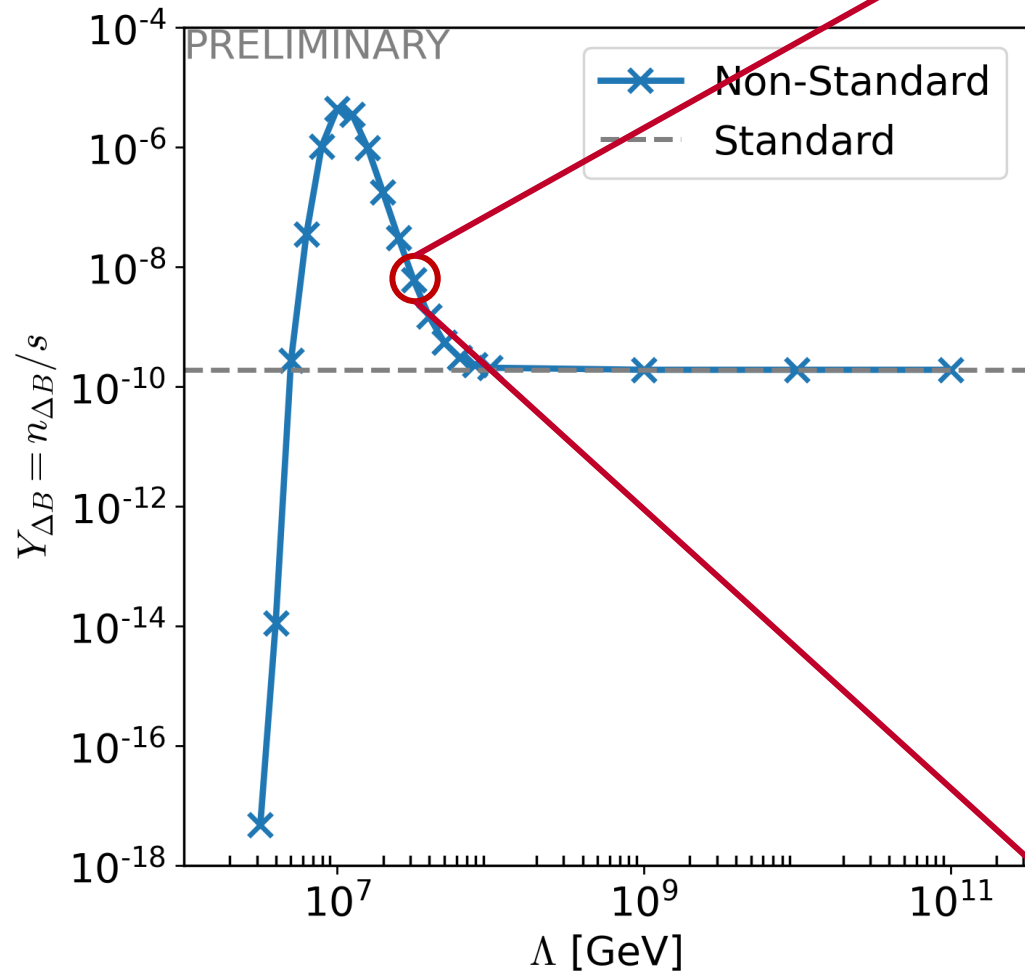
# Low scale Leptogenesis – Non-Standard Case



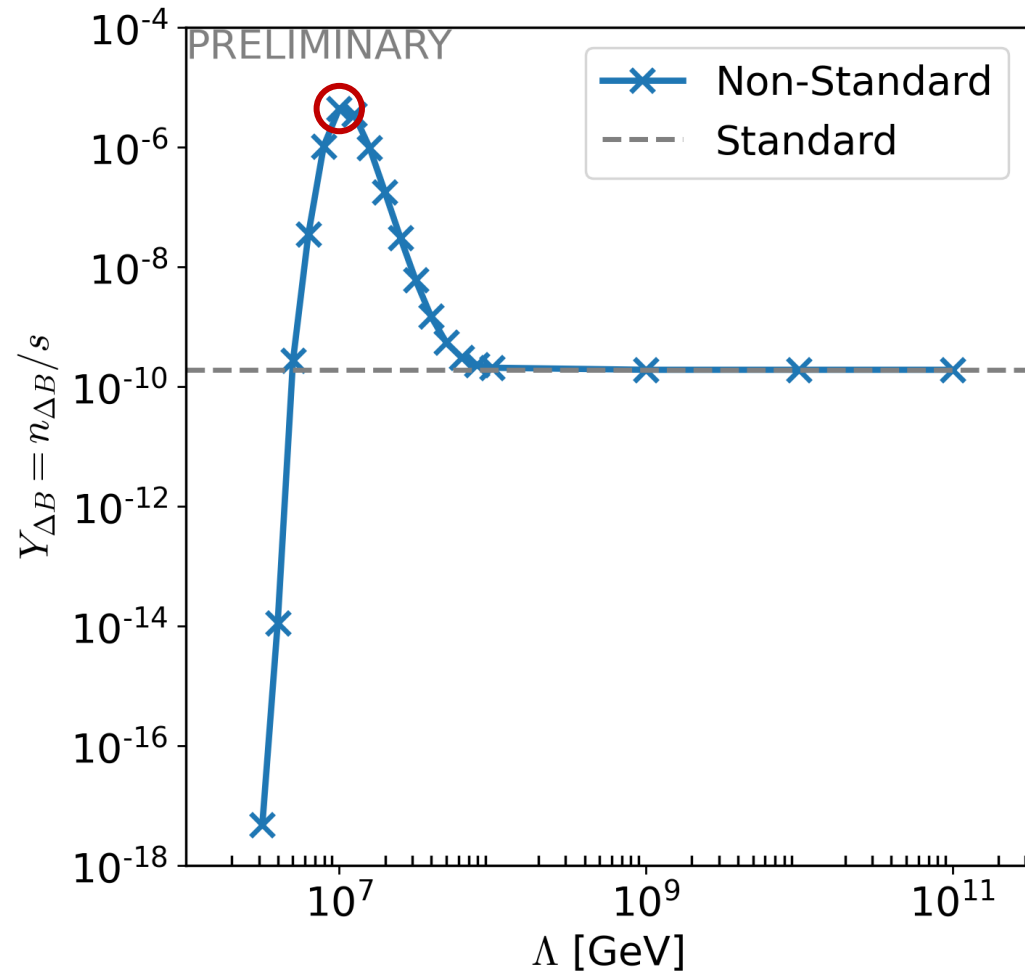
# Low scale Leptogenesis



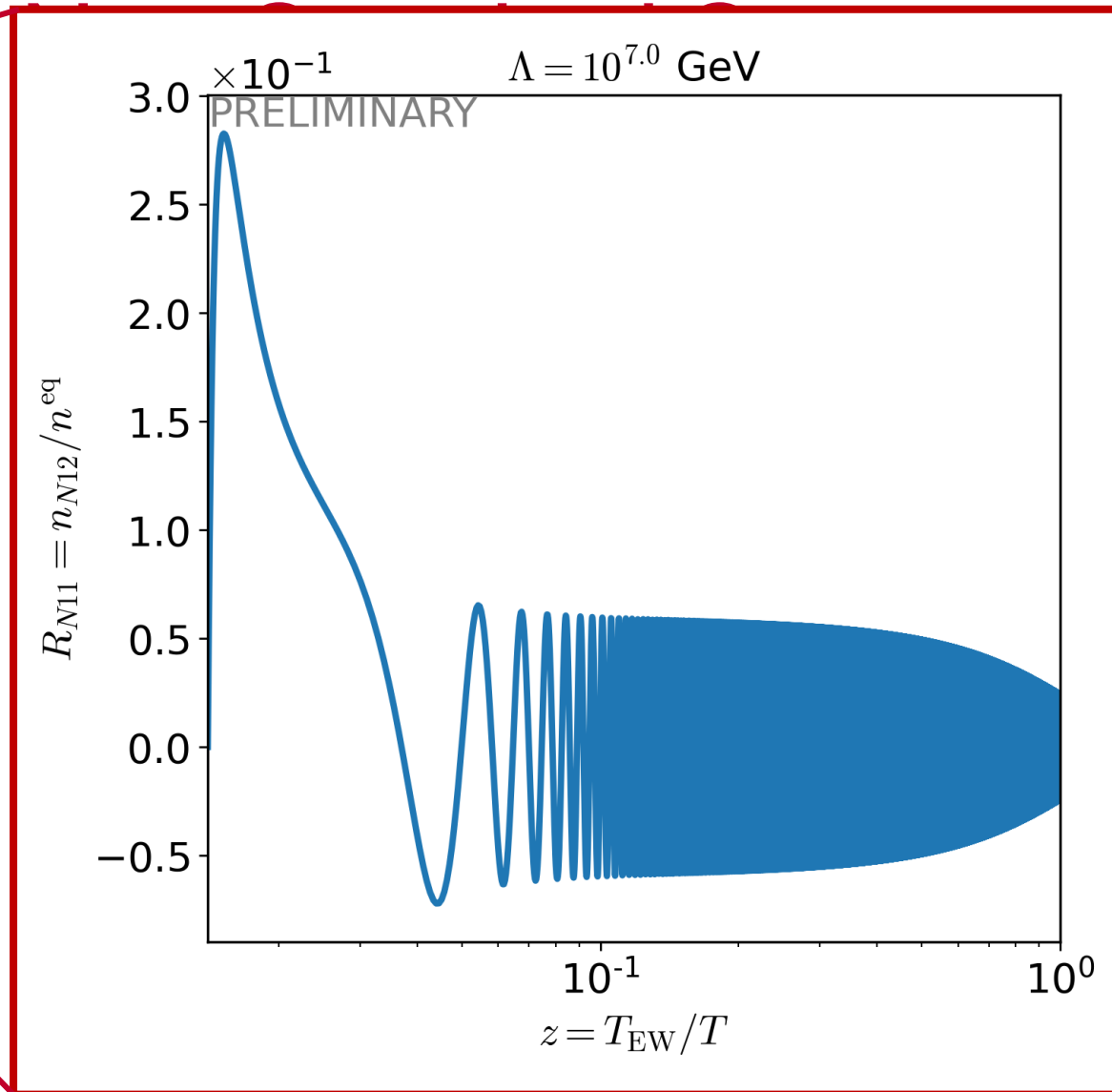
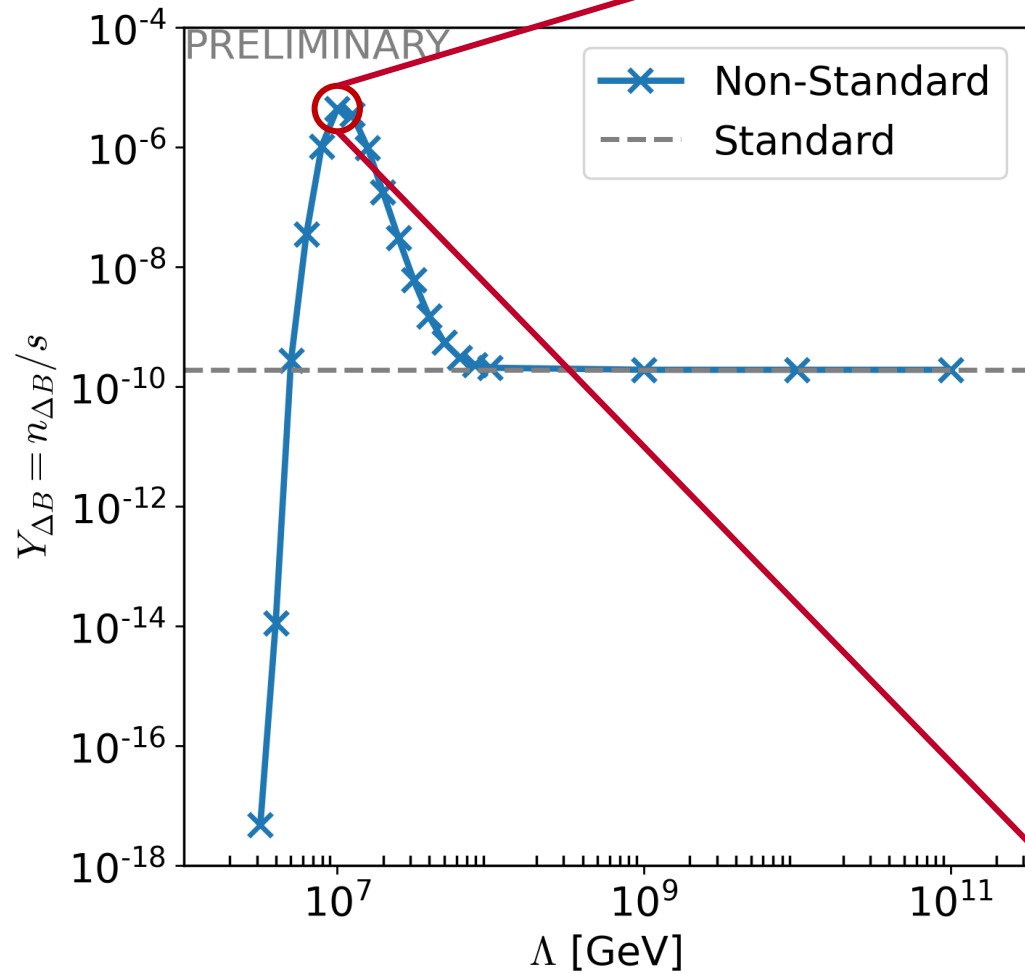
# Low scale Leptogenesis



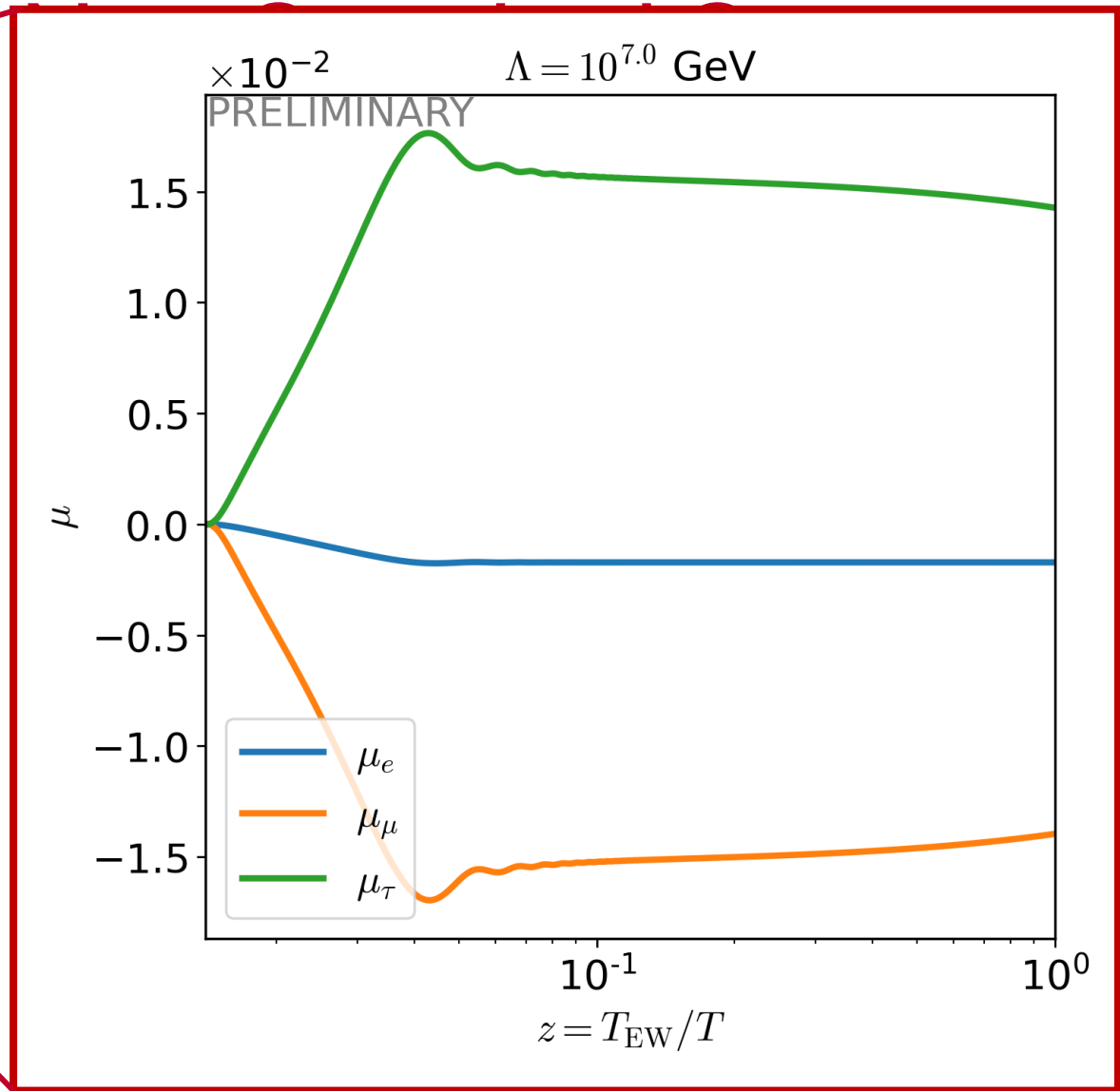
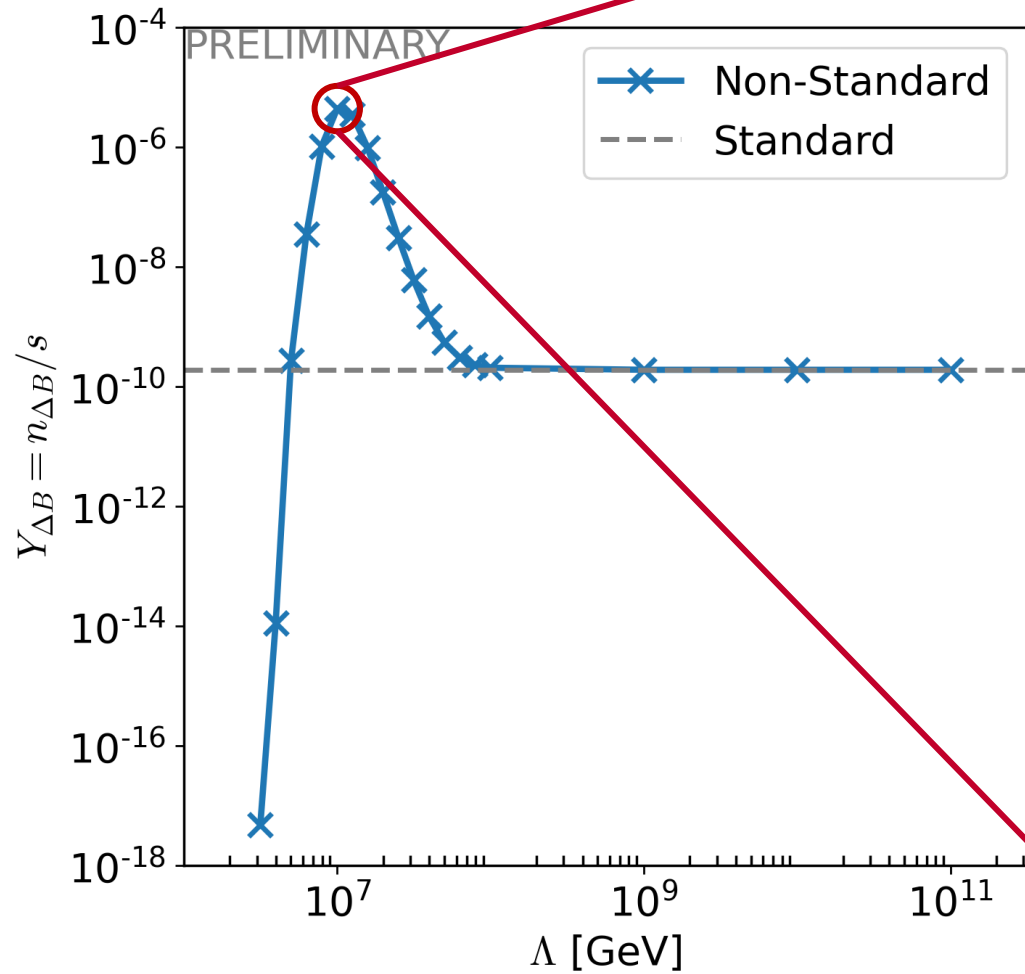
# Low scale Leptogenesis – Non-Standard Case



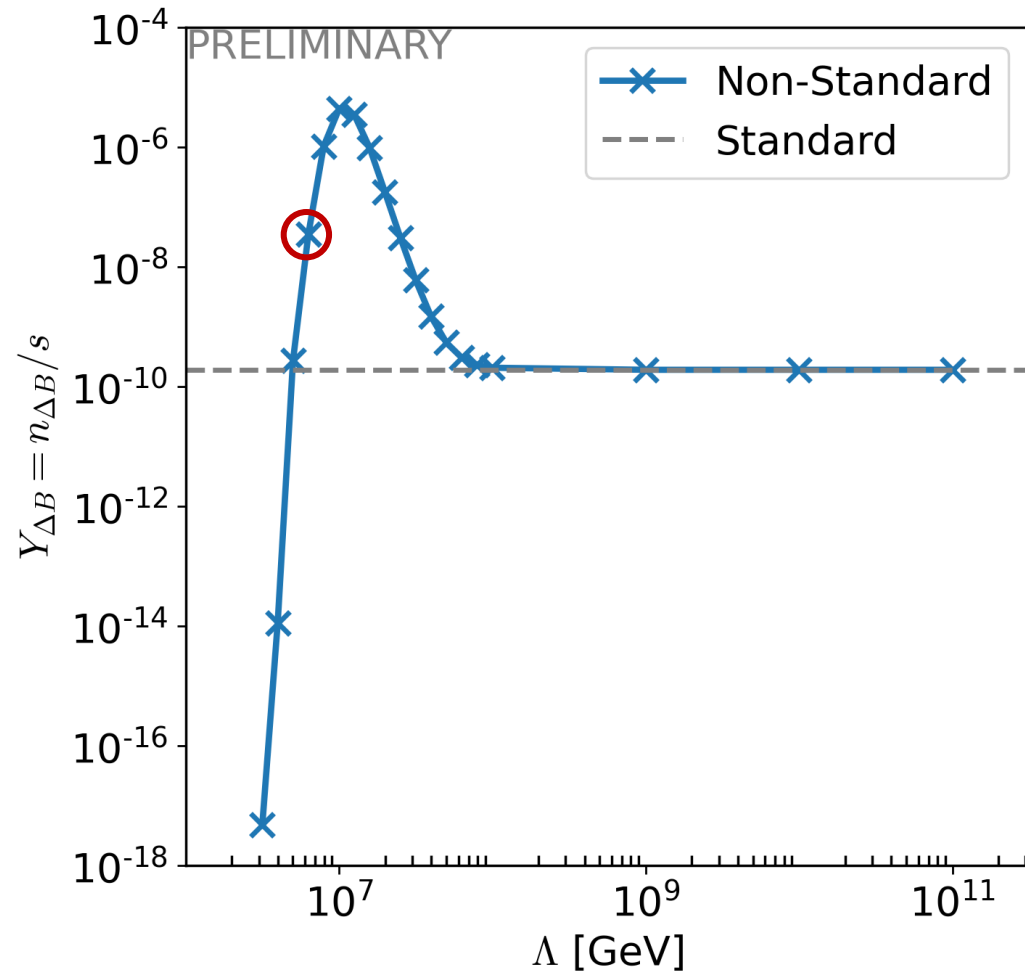
# Low scale Leptogenesis –



# Low scale Leptogenesis –

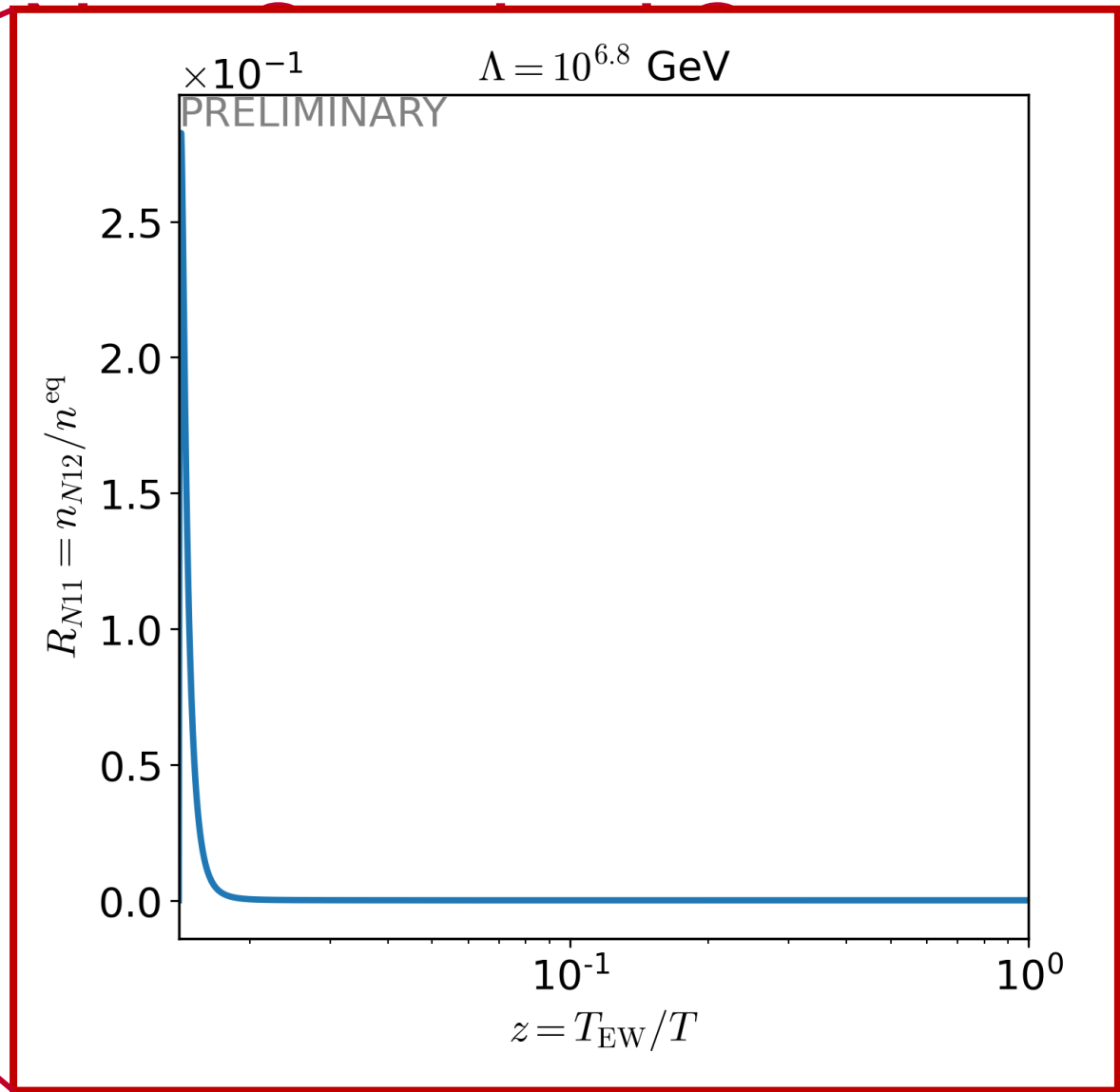
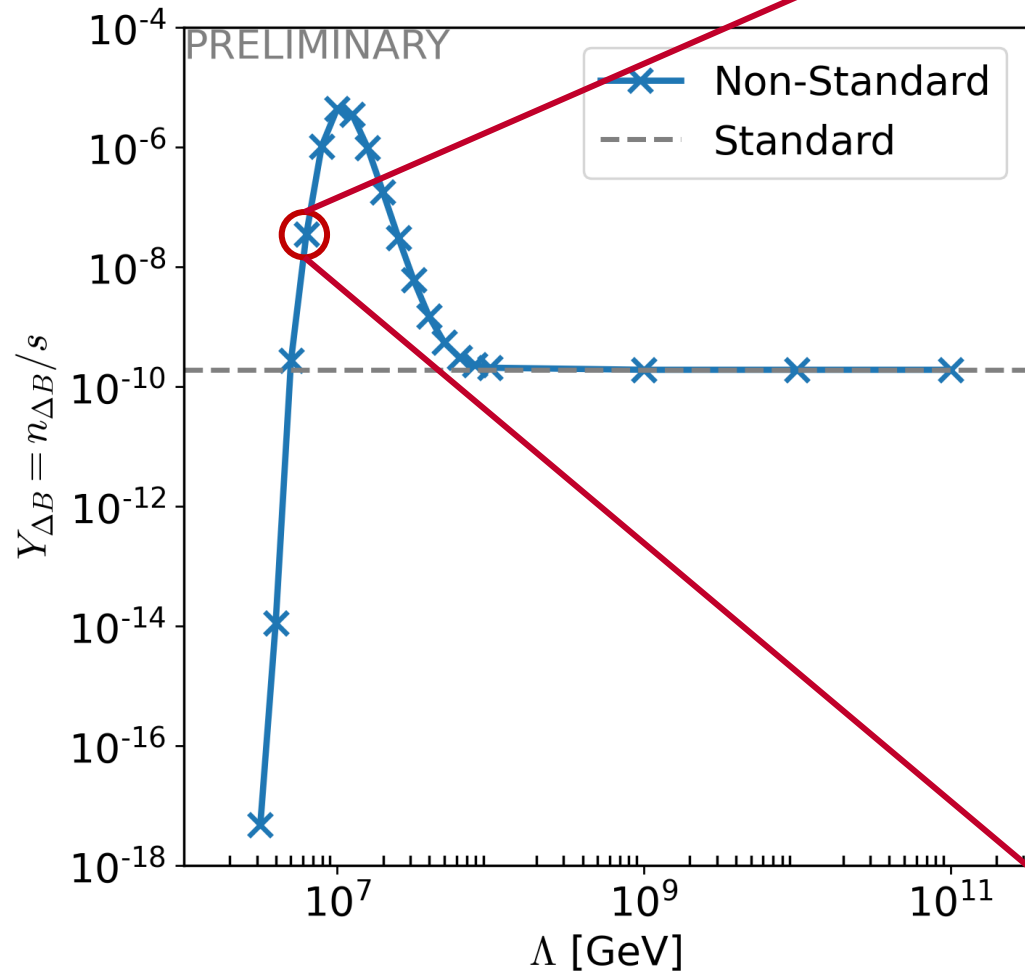


# Low scale Leptogenesis – Non-Standard Case

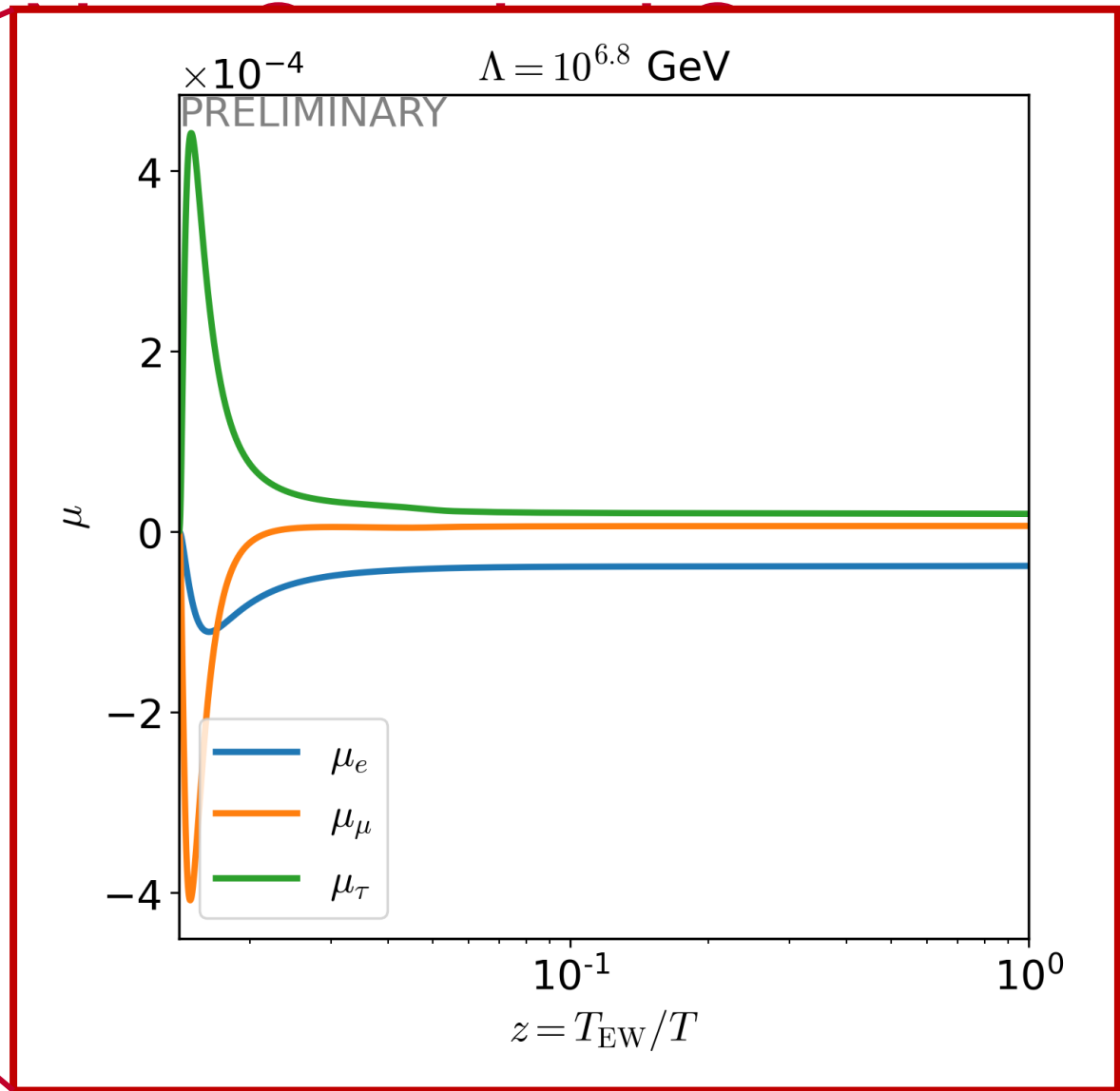
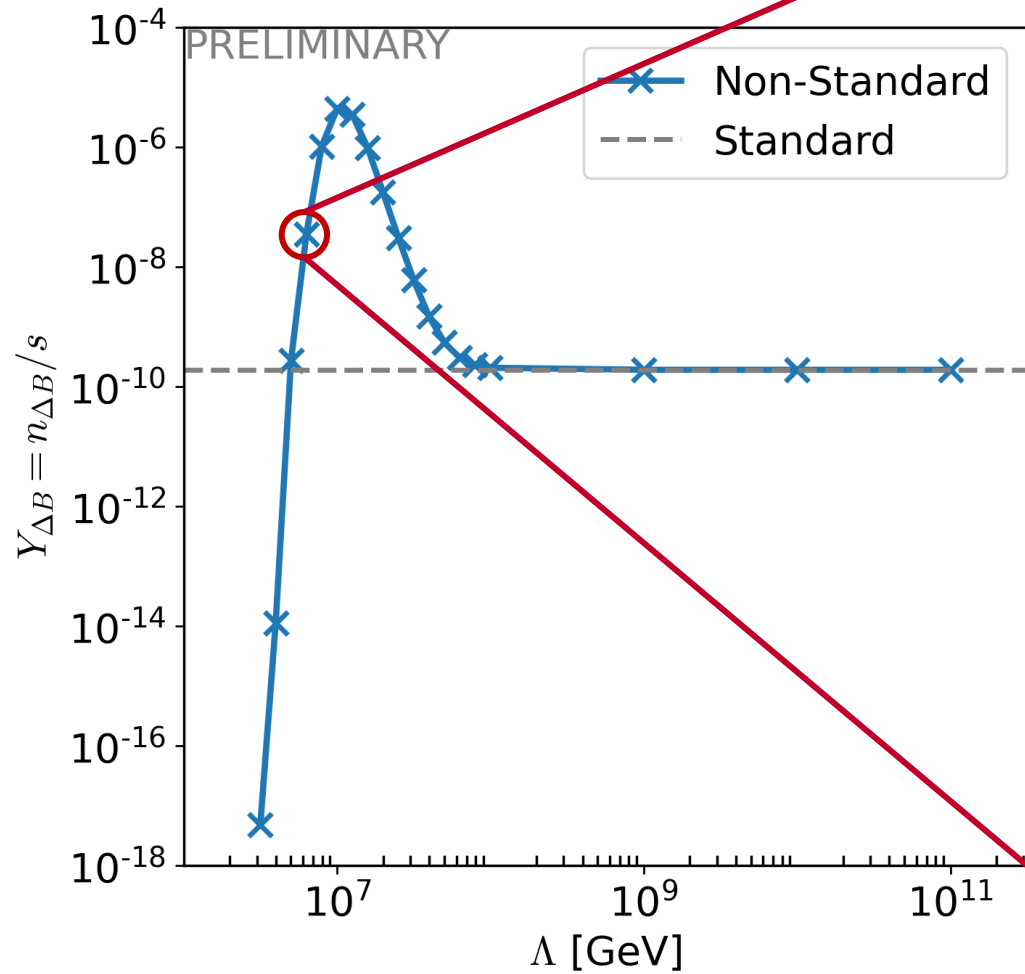




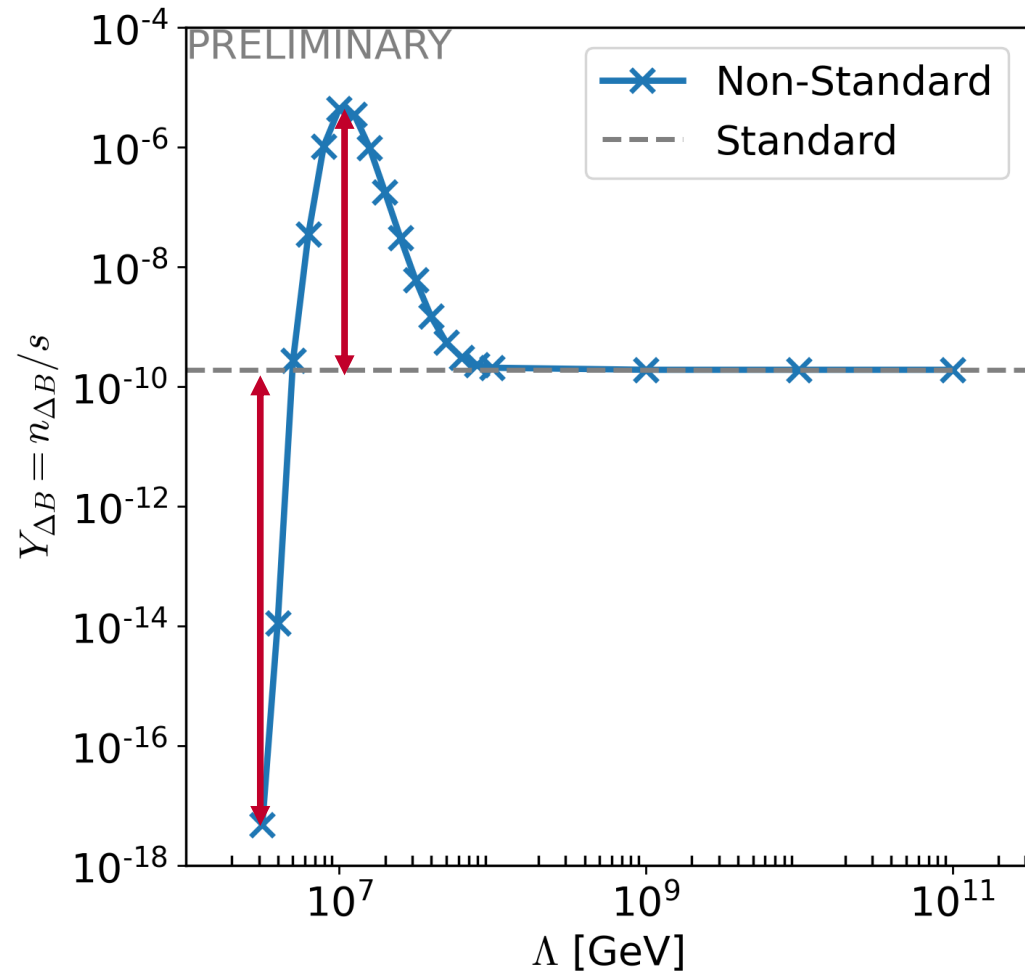
# Low scale Leptogenesis –



# Low scale Leptogenesis –

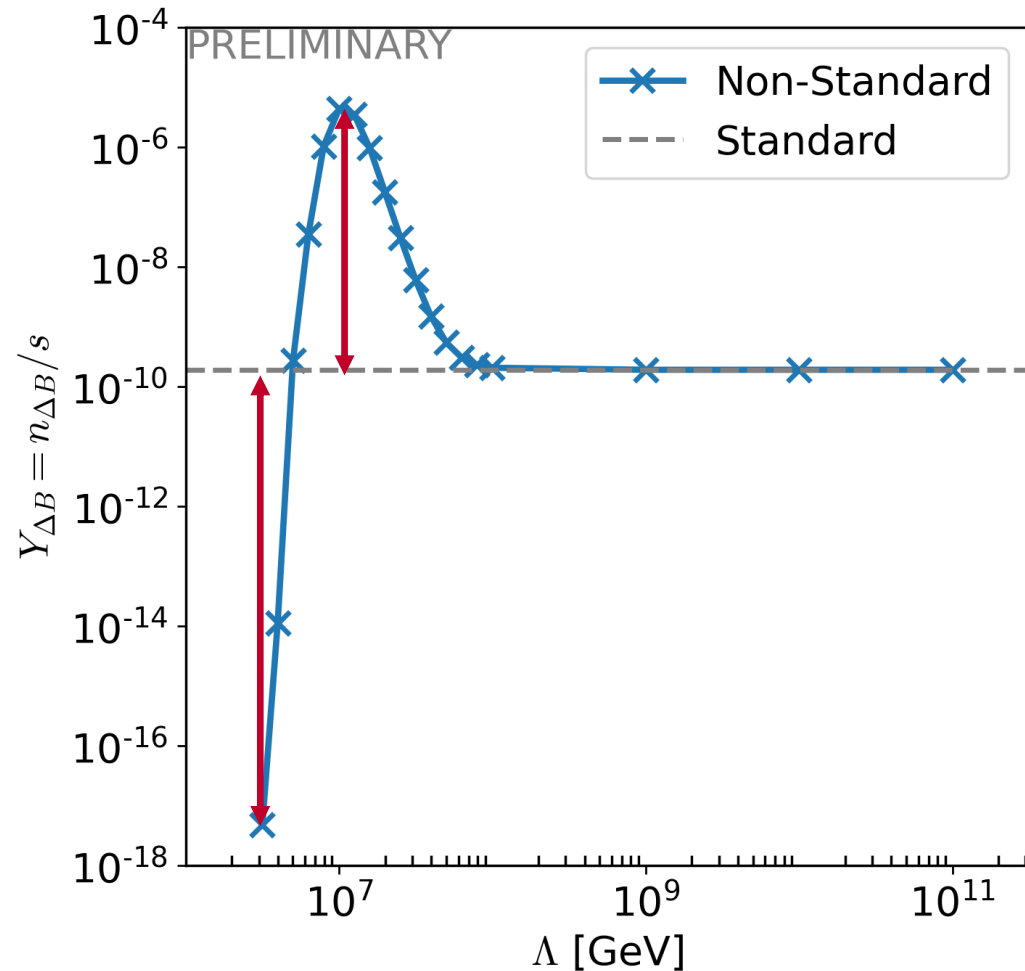


# Low scale Leptogenesis – Non-Standard Case



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 Leptogenesisby orders of magnitude
-

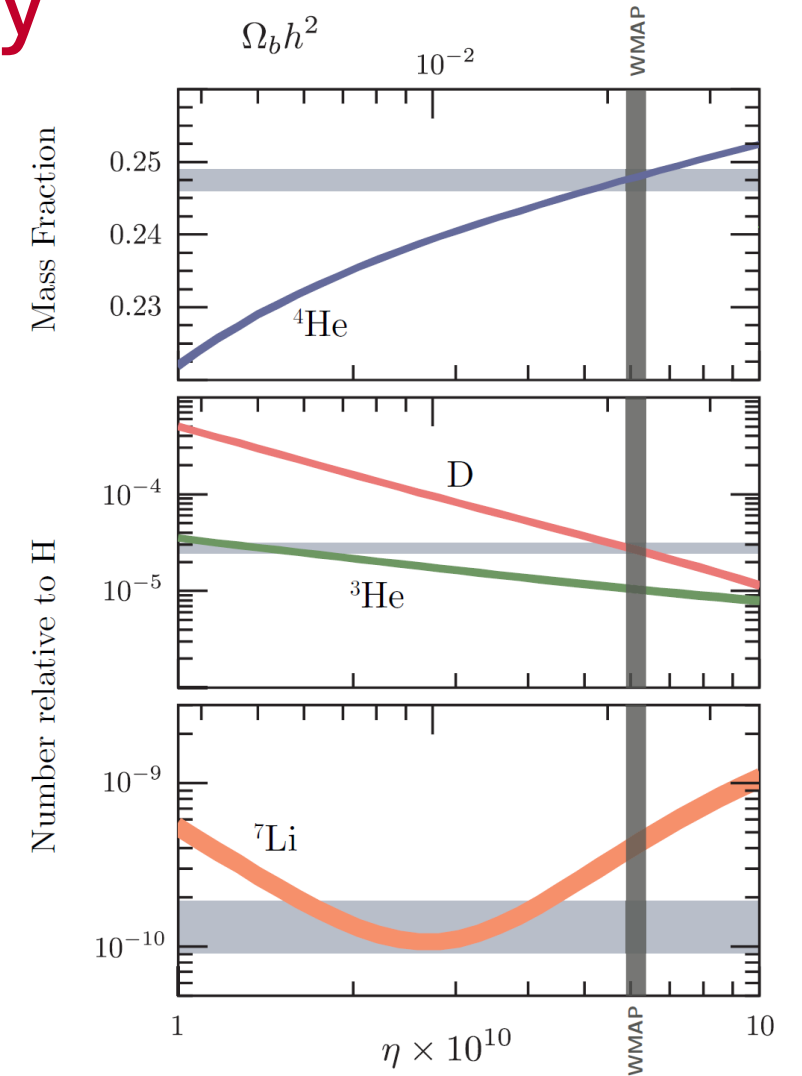
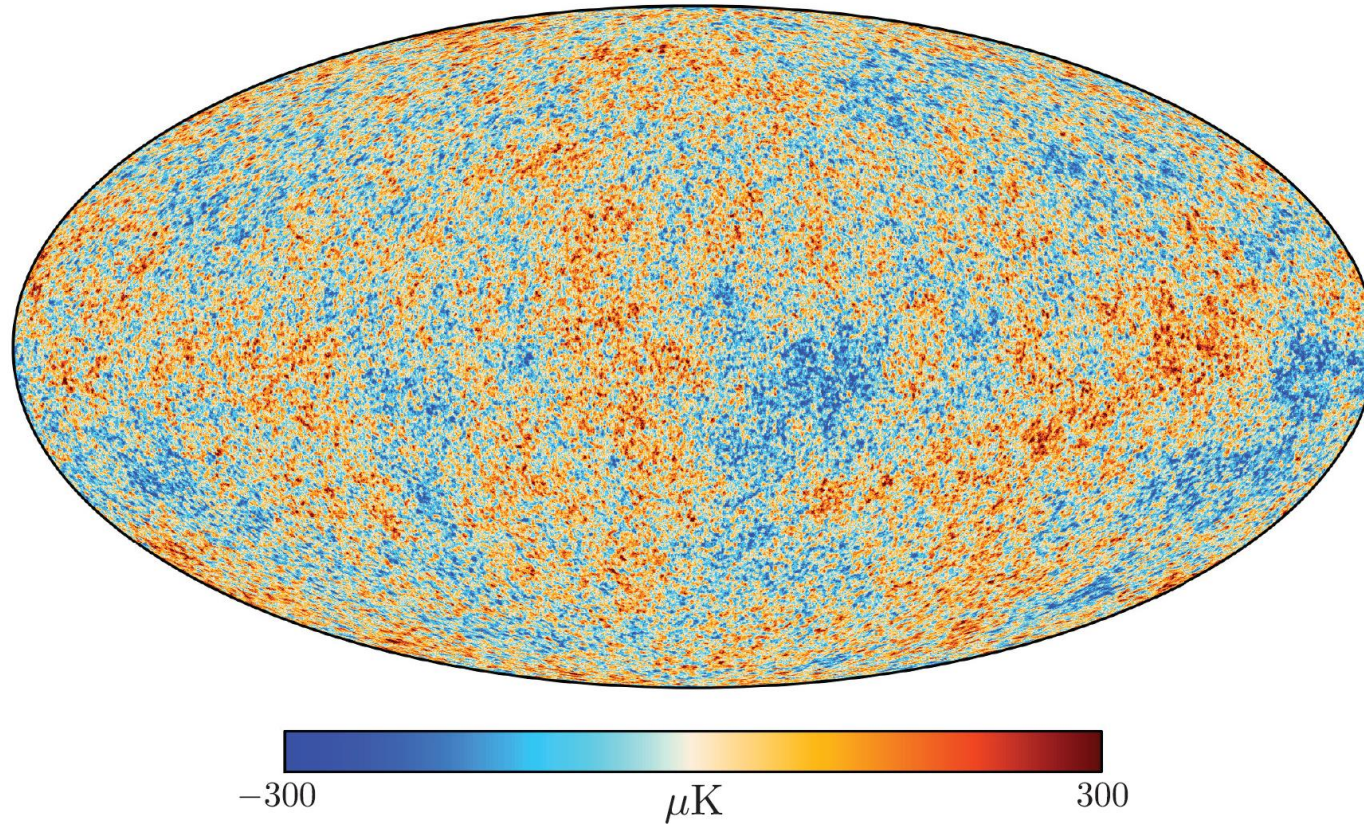
# Conclusion & Outlook

- Non-standard interactions can change
    - $0\nu\beta\beta$  decay
    - Low-Scale Leptogenesisby orders of magnitude
- 
- Conduct full parameter scan
  - Go beyond effective operator approach to study the effect of  $T_{RH}$

An aerial photograph of a university campus, likely the University of Bonn, showing a large central green lawn, several large buildings, and a dense forest of trees. The text "Thank You" is overlaid in the center in a large, red, serif font.

**Thank You**

# Measuring the Baryon Asymmetry



credit: Baumann



# Derivation Quantum Kinetic Equations (QKEs)

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

- QM: number operator:  $\hat{N} = \hat{a}^\dagger \hat{a}$        $N = \langle \hat{N} \rangle = \langle \hat{a}^\dagger \hat{a} \rangle$
- QFT: “number density operator”:

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

- 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)

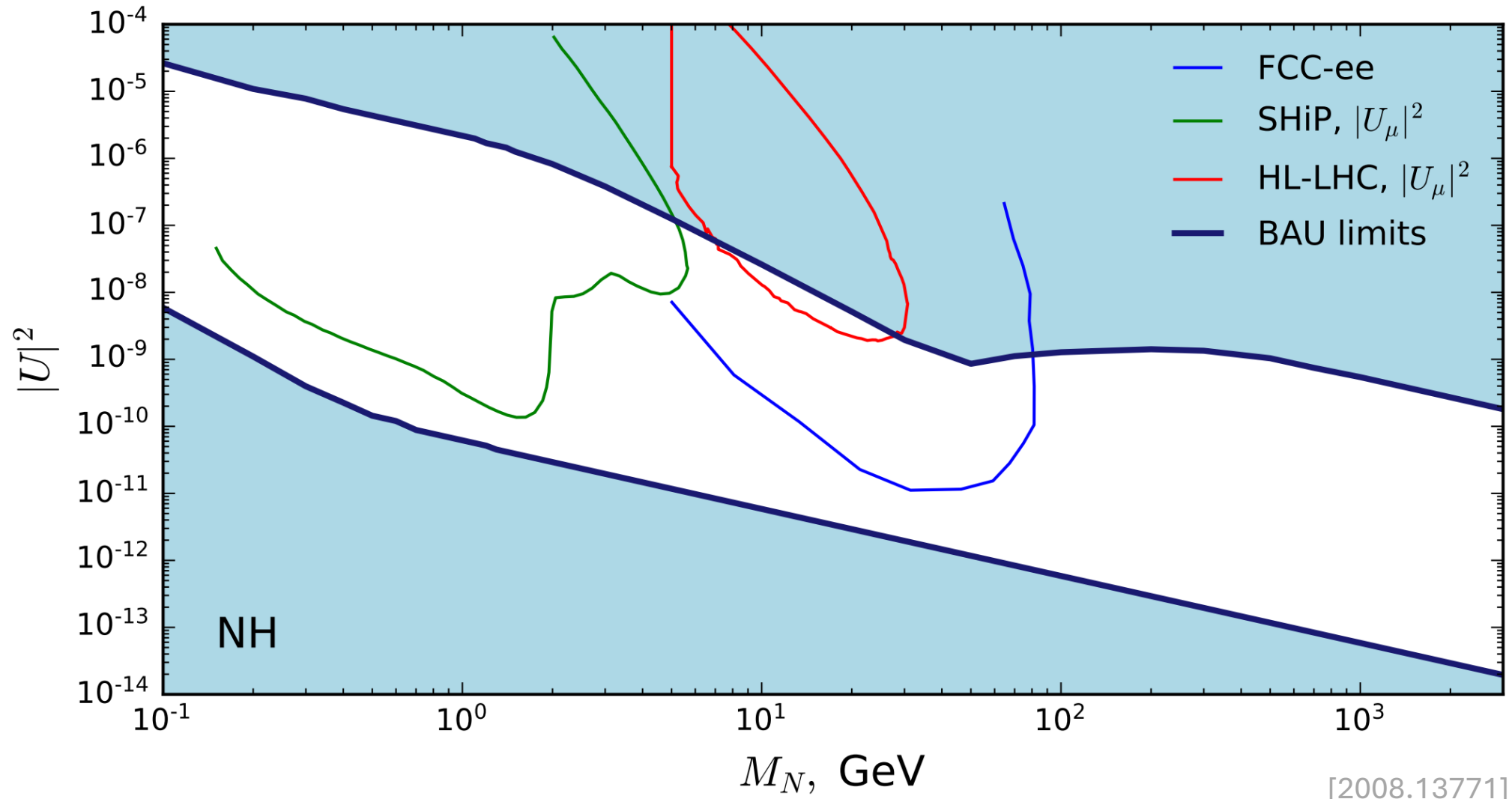
$$\frac{d\rho_N(k_N)}{dt} = -i[H_N(k_N), \rho_N(k_N)] - \frac{1}{2}\{\Gamma_N^d(k_N), \rho_N(k_N)\} + \frac{1}{2}\{\Gamma_N^p(k_N), \mathbf{1} - \rho_N(k_N)\}$$

# Differential equations

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

[2207.01651]

# Parameter Space



[2008.13771]

# Neutrinoless double beta decay and the baryon asymmetry of the Universe

Frank F. Deppisch,<sup>1,\*</sup> Lukas Graf,<sup>1,†</sup> Julia Harz,<sup>2,‡</sup> and Wei-Chih Huang<sup>3,4,§</sup>

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(Received 28 February 2018; published 20 September 2018)

# Non-standard cases

e.g. in connection to Unification

$SU(5)$ ,  $SO(10)$ ,  $G_{PS}, \dots$

