Introduction to Leptogenesis

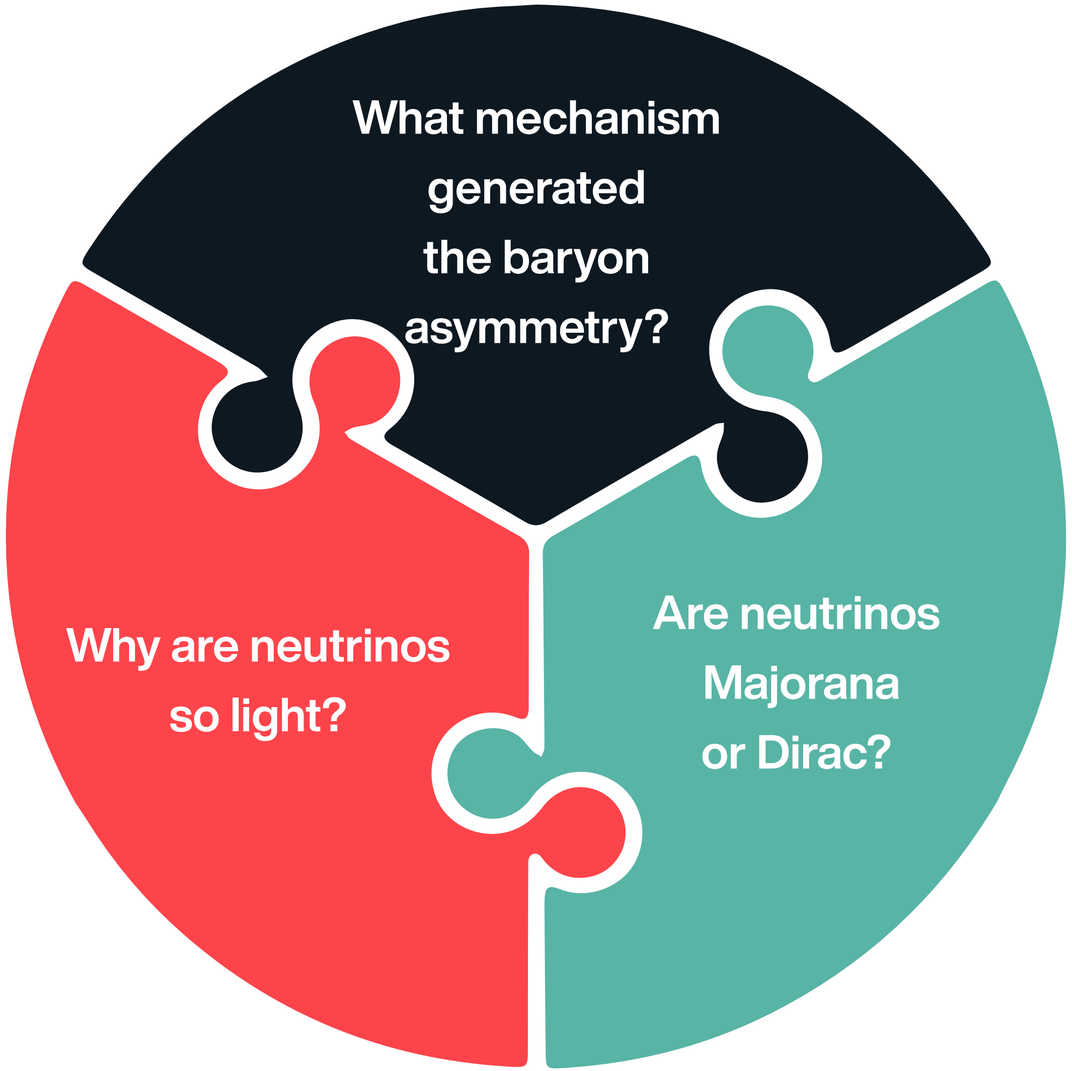
Neutrino University, 12th July 2023

Jessica Turner

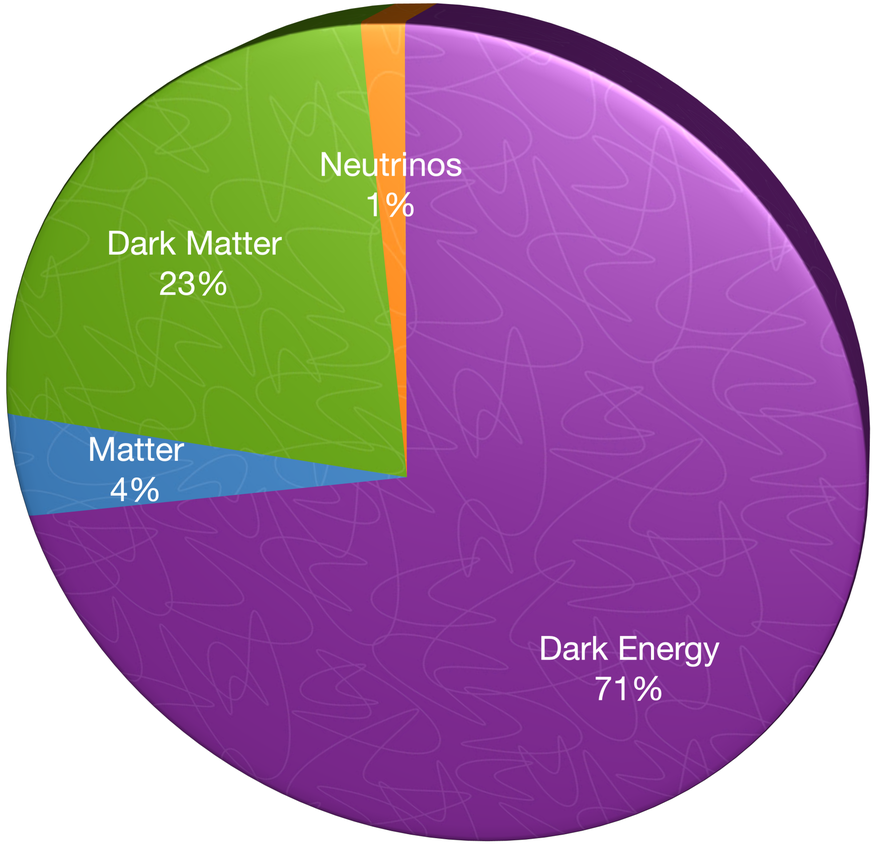
Durham University

Fermilab

Leptogenesis: the motivation



Matter-Antimatter Asymmetry



$$\eta_B = (6.02 - 6.18) \times 10^{-10}$$

Planck 1807.06209

Sakharov's Conditions

- ☑ Baryon number violation — Kuzmin, Rubakov & Shaposhnikov (1985)
- ☒ C & CP-violation — Gavela, Hernandez, Orloff & Pene (1994)
- ☒ Departure from thermal equilibrium — Kajantie, Laine, Rummukainen & Shaposhnikov (1996)

Measuring the Matter Antimatter Asymmetry

free electrons

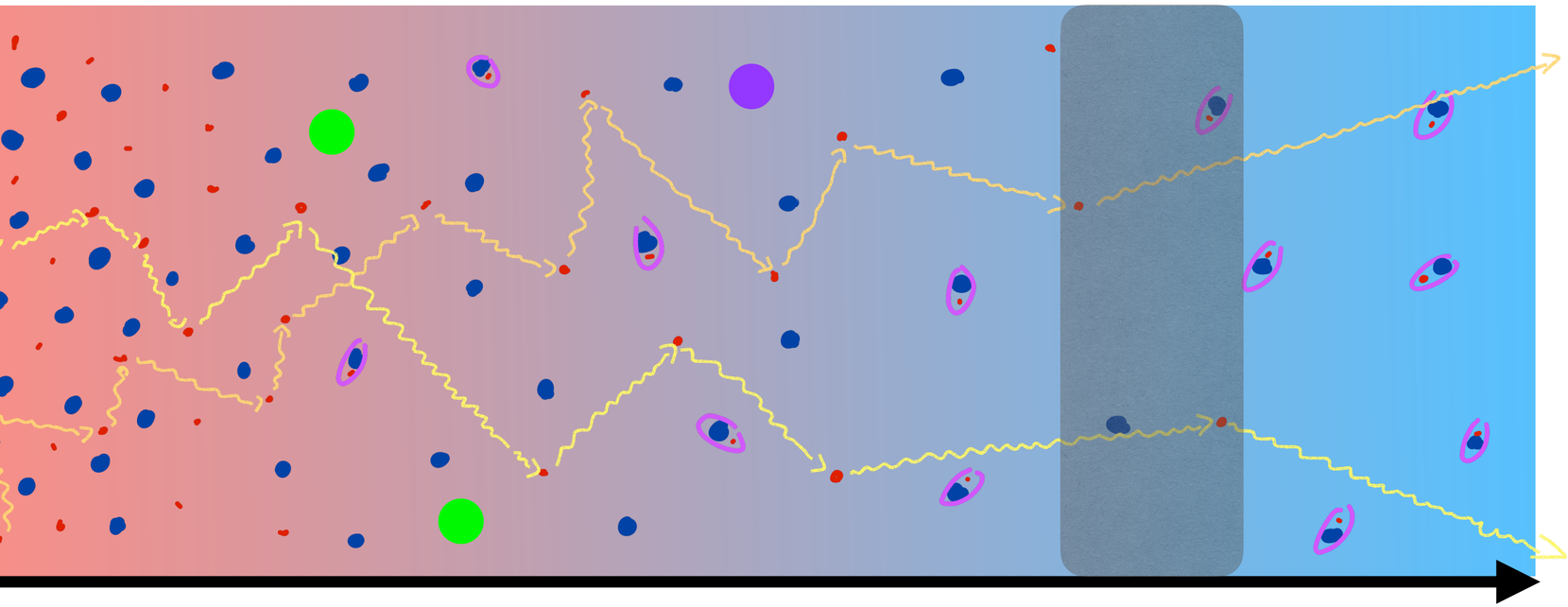
free protons

neutral hydrogen

Helium

Lithium

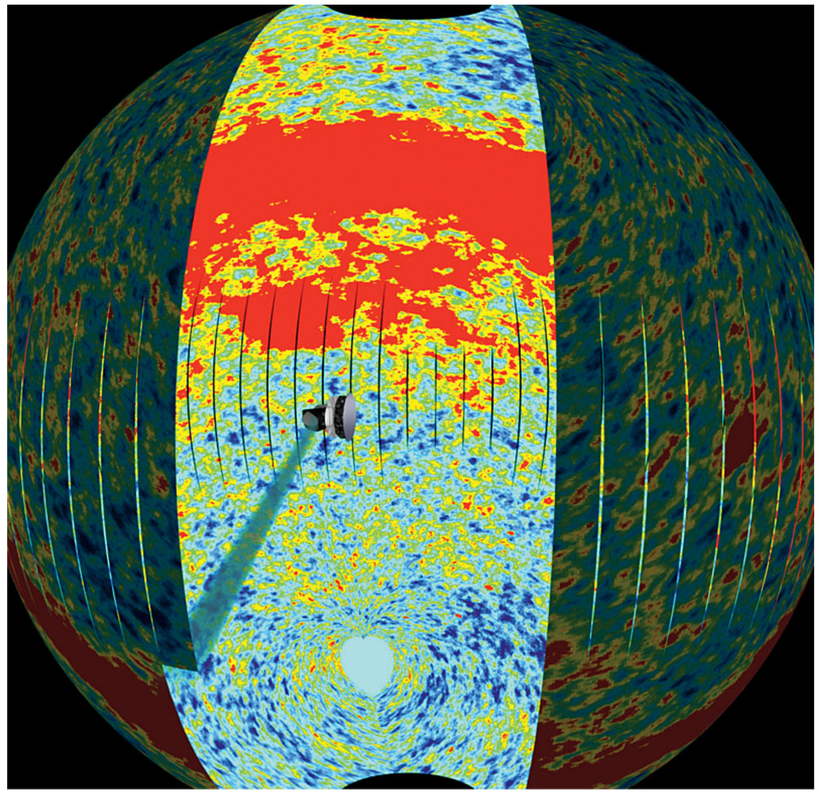
last scattering



Time

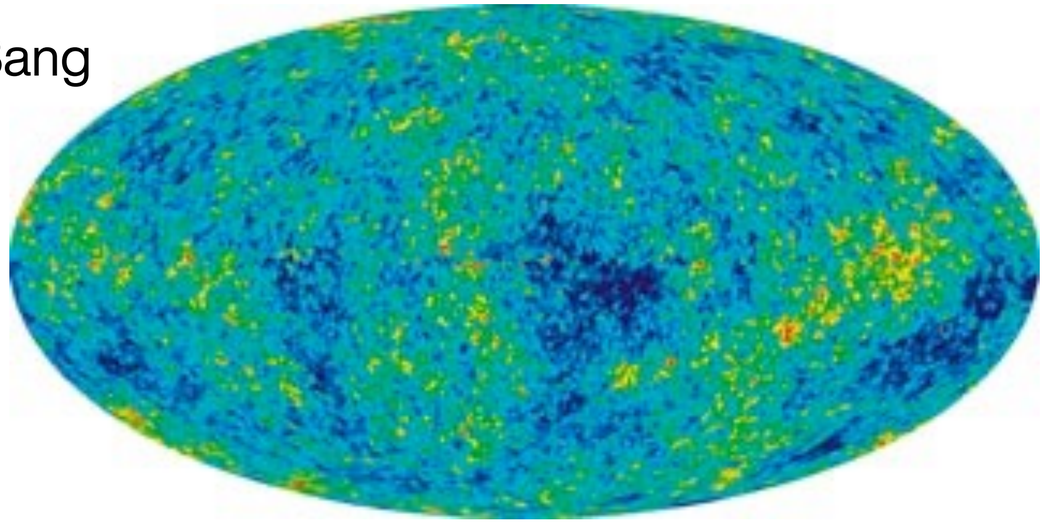
time ~ 380,000 yr

Temperature ~ 3000 K

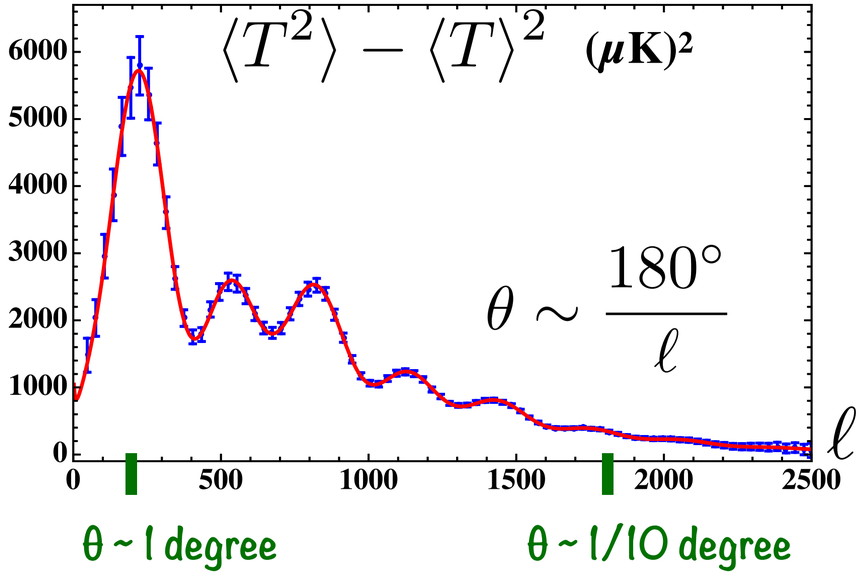


Time: 380,000 years after Big Bang

Temperature: ~ 3000 K



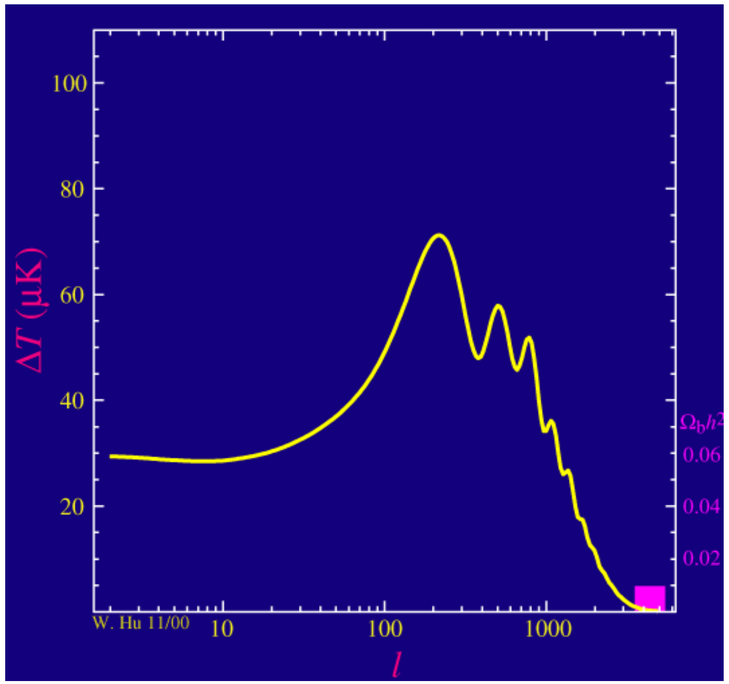
Angular power spectrum = **variance of temperature as a function of angular scale**



Planck 2018 (error bars x 5)

Best-fit model (6 parameters)

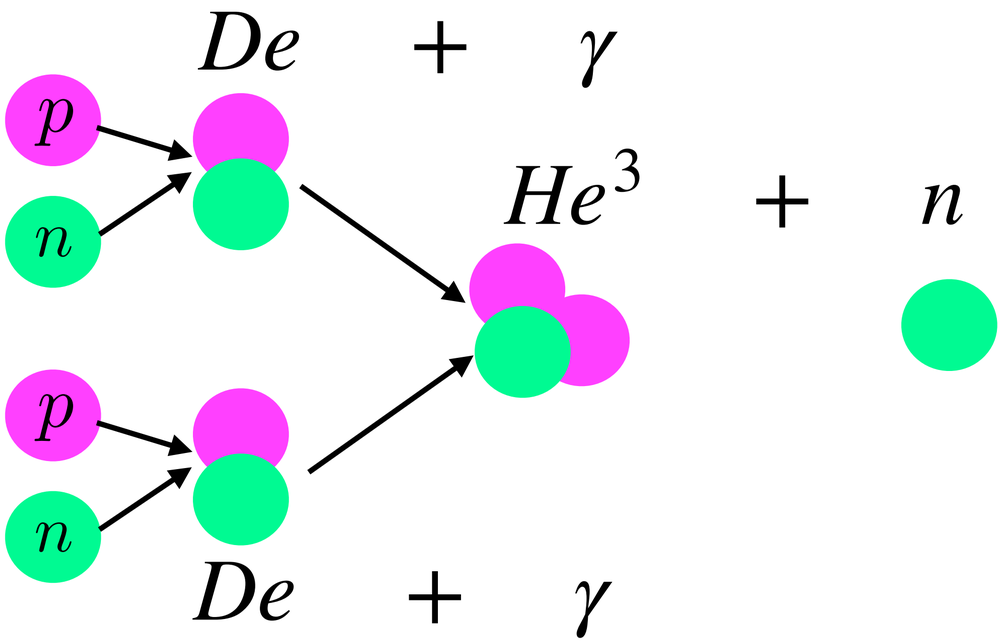
Wayne Hu's Website



$$6.02 \times 10^{-10} \leq \eta_B \leq 6.18 \times 10^{-10}\,(95\%\mathrm{CL})$$

Time: 3 minutes after Big Bang

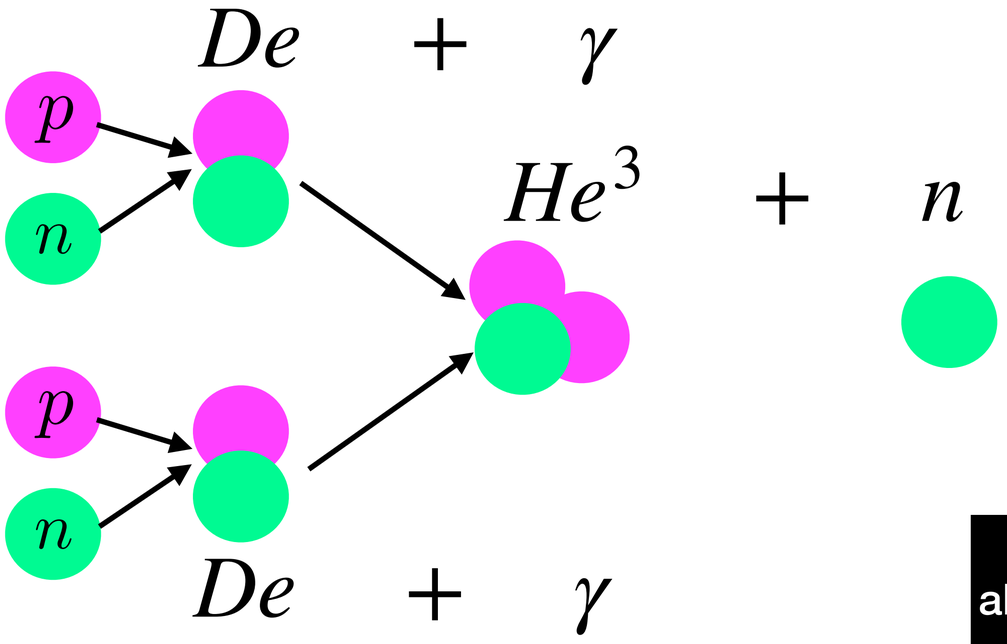
Temperature: ~ 10^9 K



Synthesis of light elements such as Deuterium, Helium and Lithium

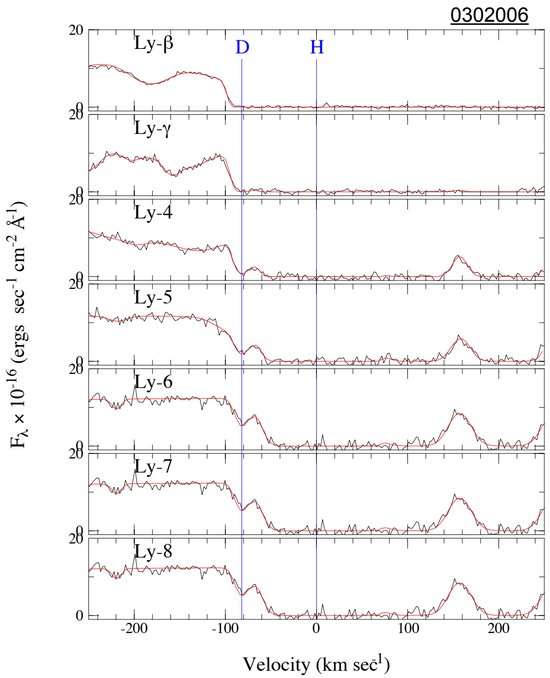
Time: 3 minutes after Big Bang

Temperature: ~ 10^9 K

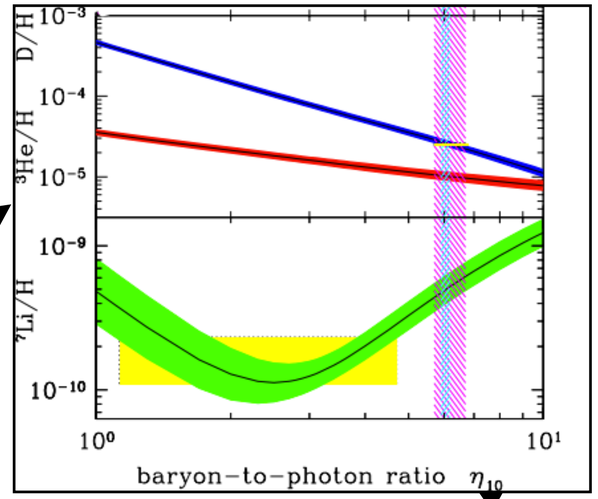


Synthesis of light elements such as Deuterium, Helium and Lithium

Quasars

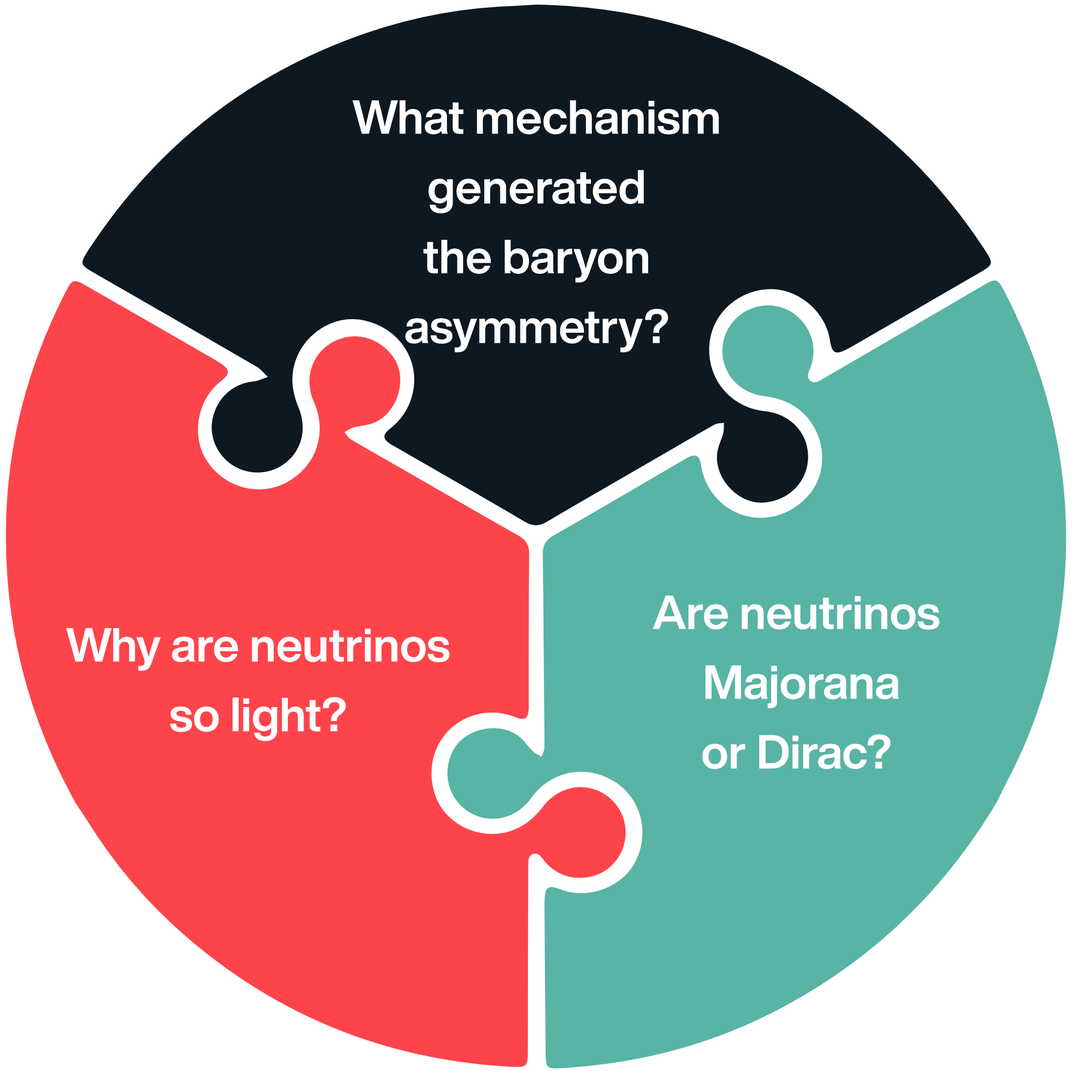


Light element abundance after BBN



How many protons & neutrons at the start

$$5.8 \times 10^{-10} \leq \eta_B \leq 6.5 \times 10^{-10}\ (95\%\mathrm{CL})$$


What mechanism generated the baryon asymmetry?
Why are neutrinos so light?
Are neutrinos Majorana or Dirac?


Are neutrinos
Majorana
or Dirac?

Charged particles can be distinguished from their antiparticles

$$u \qquad\qquad \overline{u}$$

$$Q = +\frac{2}{3} \qquad\qquad Q = -\frac{2}{3}$$

Particles like this are called “Dirac particles”

What about neutrinos which are electrically neutral?
How would we distinguish them from antineutrinos?

$$\nu \qquad\qquad \overline{\nu}$$

$$Q = 0 \qquad\qquad Q = 0$$

$$?$$

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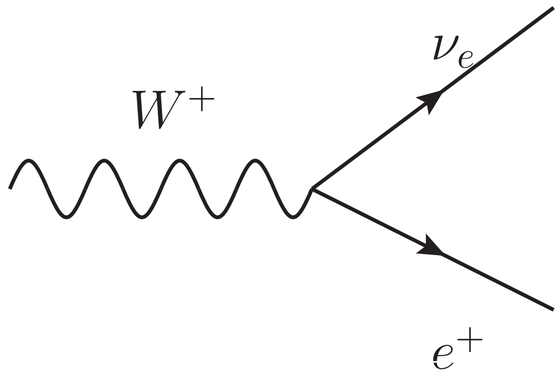
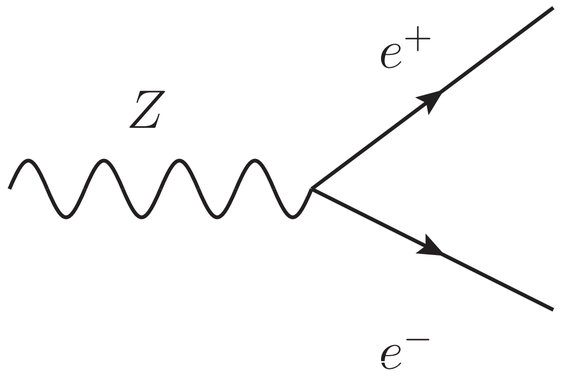
We can introduce **lepton number** to distinguish neutrinos and antineutrinos

We have only ever observed lepton number conserving processes

$$e^-$$
$$\nu$$
$$L = +1$$

$$e^+$$
$$\overline{\nu}$$
$$L = -1$$





We have only ever observed lepton number conserving processes

$$e^-$$
$$\nu$$
$$L = +1$$

$$e^+$$
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$$L = -1$$

If lepton number is conserved in nature then neutrinos can be distinguished from antineutrinos & neutrinos would be classed as Dirac particles

It is possible that lepton number is in fact violated in nature!

If this were the case then neutrinos would be “Majorana particles”
As opposed to Dirac particles and we could identify the neutrino and antineutrino

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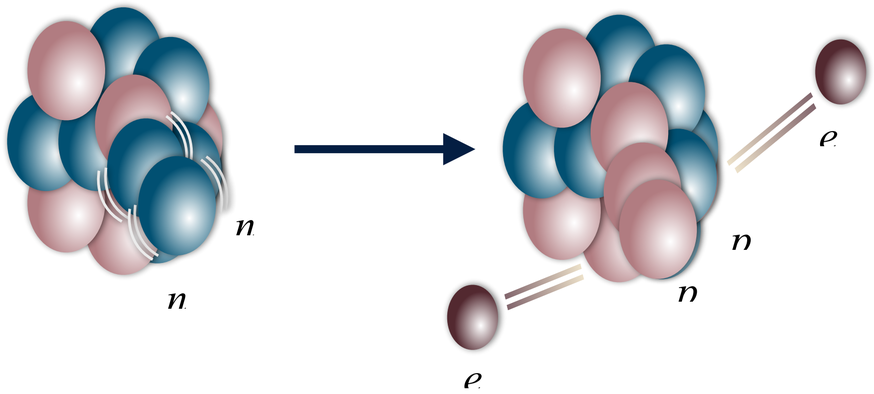
Neutrinoless double beta decay experiments are searching for Lepton number violation



$L = 0$ $L = +2$

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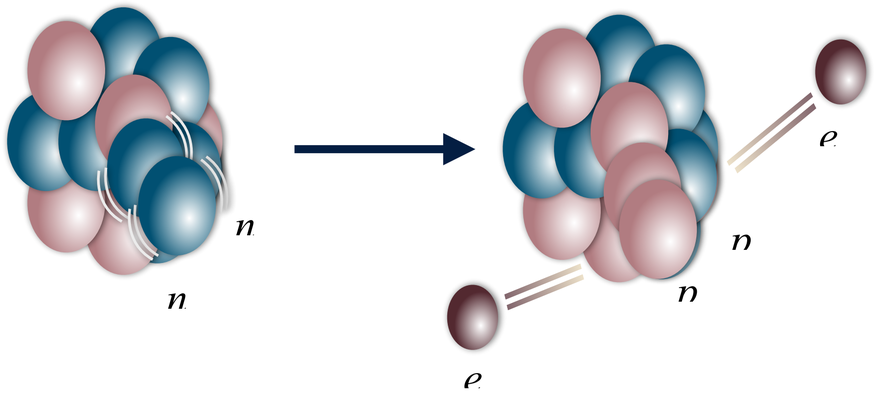

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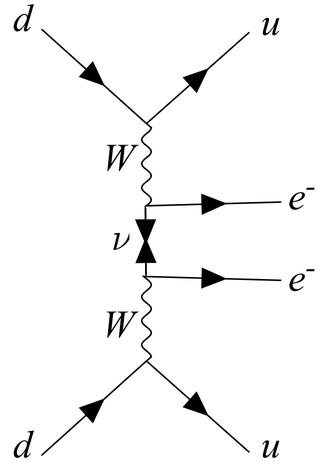


$\Delta L = 2 \implies$
neutrinos Majorana

As neutrinos are electrically neutral so they could be Majorana particles

Majorana Condition: $$\nu = C\bar{\nu}^T$$

Majorana neutrinos $\Longrightarrow$ global $U(1)_L$ symmetry violated $\Longrightarrow$ lepton number violation

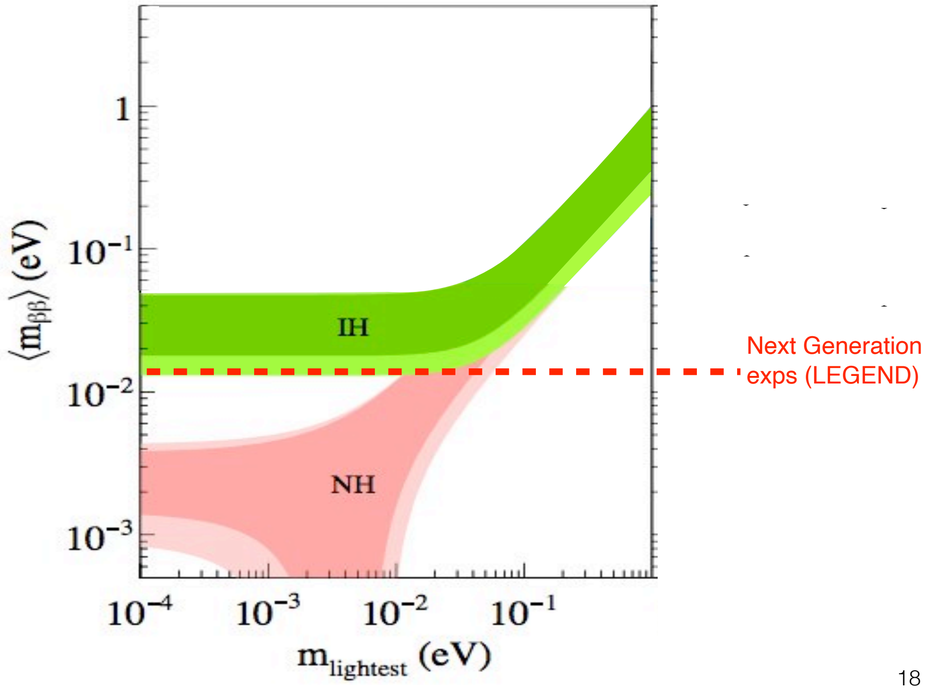
$0\nu\beta\beta$ rate $$\frac{1}{T_{1/2}^{0\nu\beta\beta}} = G_{0\nu}(Q_{\beta\beta}, Z) g_A^4 |M_{0\nu}|^2 \frac{\langle m_{\beta\beta} \rangle^2}{m_e^2}$$

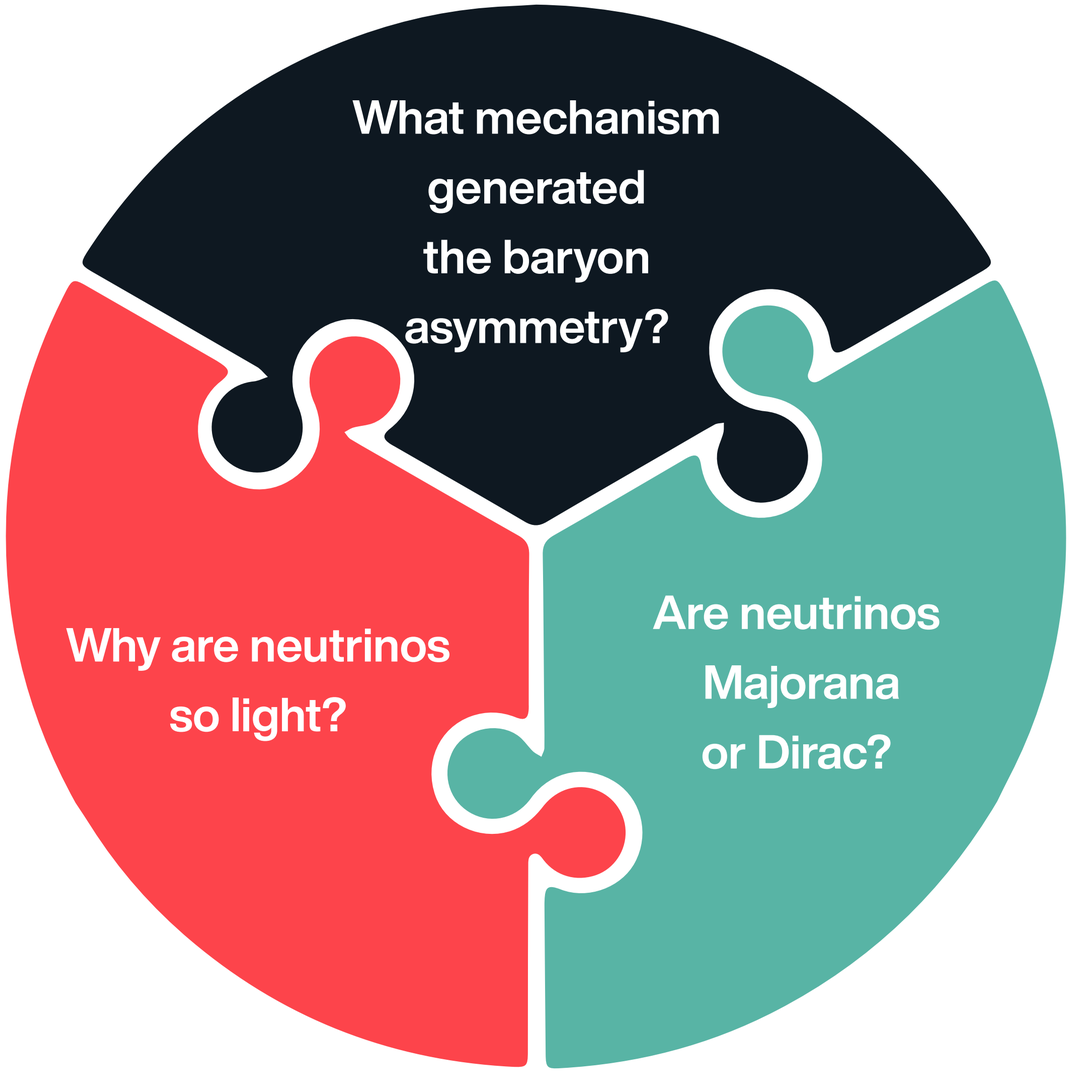
Isotope-dependent

$$m_{\beta\beta} = c_{12}^2 c_{13}^2 m_{\nu_1} + s_{12}^2 c_{13}^2 m_{\nu_2} e^{i\phi_{12}} + s_{13}^2 m_{\nu_3} e^{i\phi_{13}}$$

Individual neutrino masses

CP-violating Majorana phases

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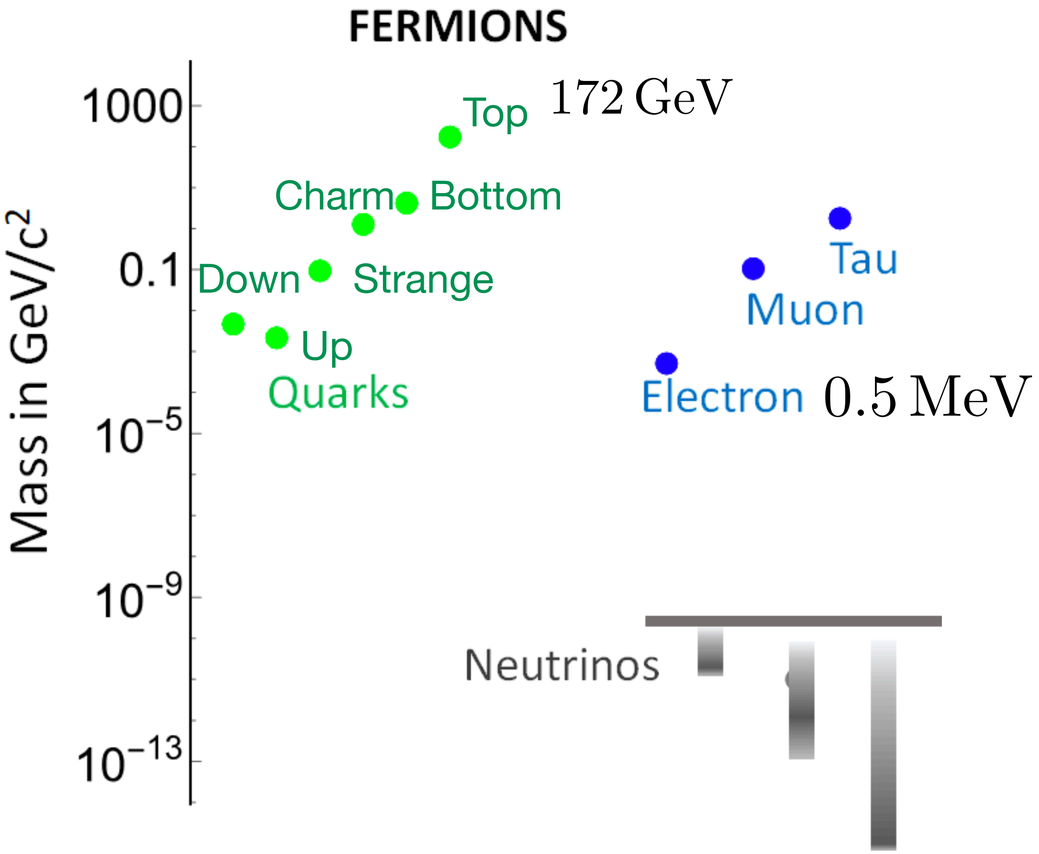
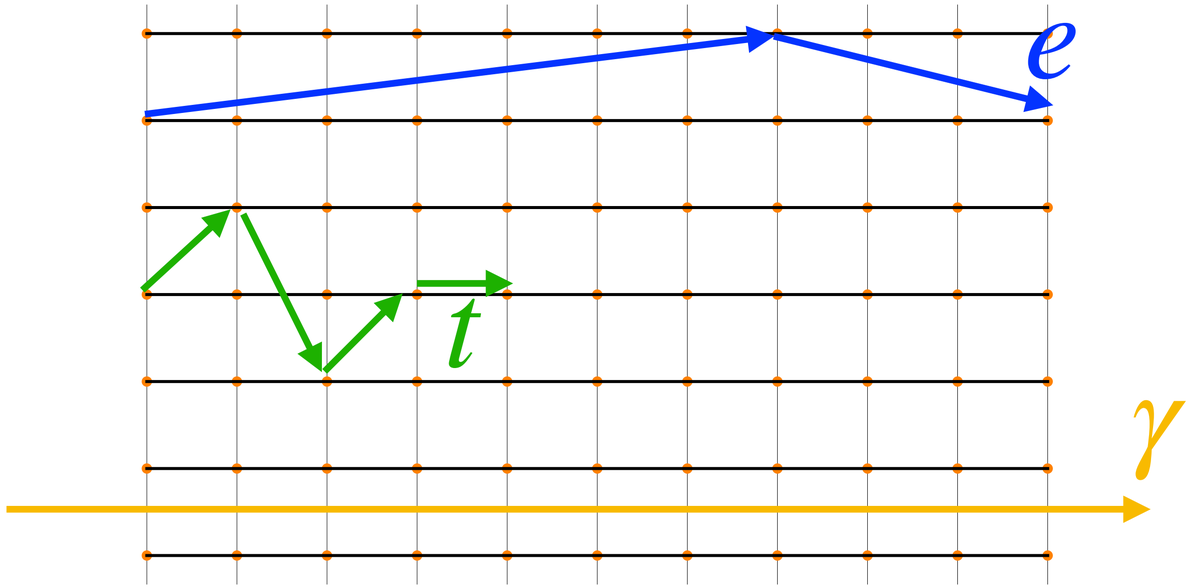
Why are neutrinos
so light?

The observation of Neutrino Oscillations implies **neutrinos have mass**

"Ordinary" particles get their mass from the Higgs Mechanism



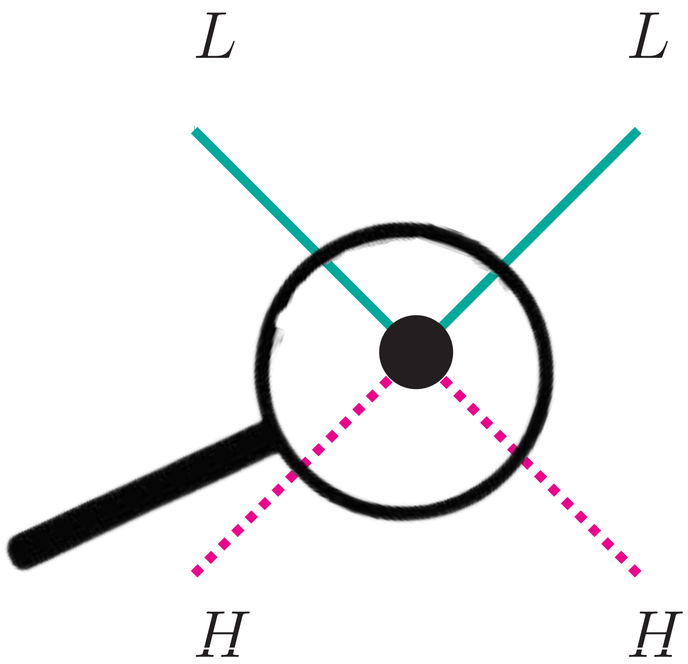


Neutrinos are so much lighter than other fundamental particles they may get their mass in a **different way**

Seesaw Mechanism

The Standard Model is an effective theory which contains non-renormalisable operators

$$\mathcal{L}_5 = \frac{Y_\nu}{2M}\left(\overline{L^c}\tilde{H}^*\right)\left(\tilde{H}^\dagger L\right)$$



Weinberg, 1973

Seesaw Mechanism

3 UV completions at tree-level. Neutrinos acquire mass after EWSB

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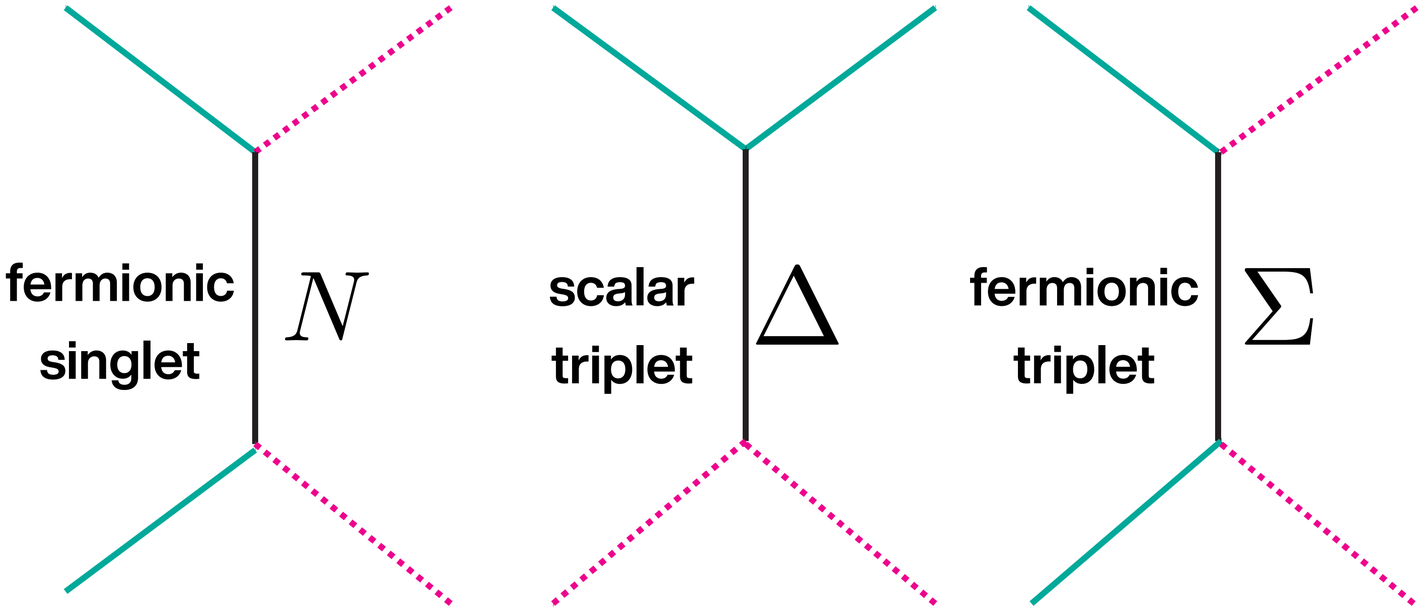

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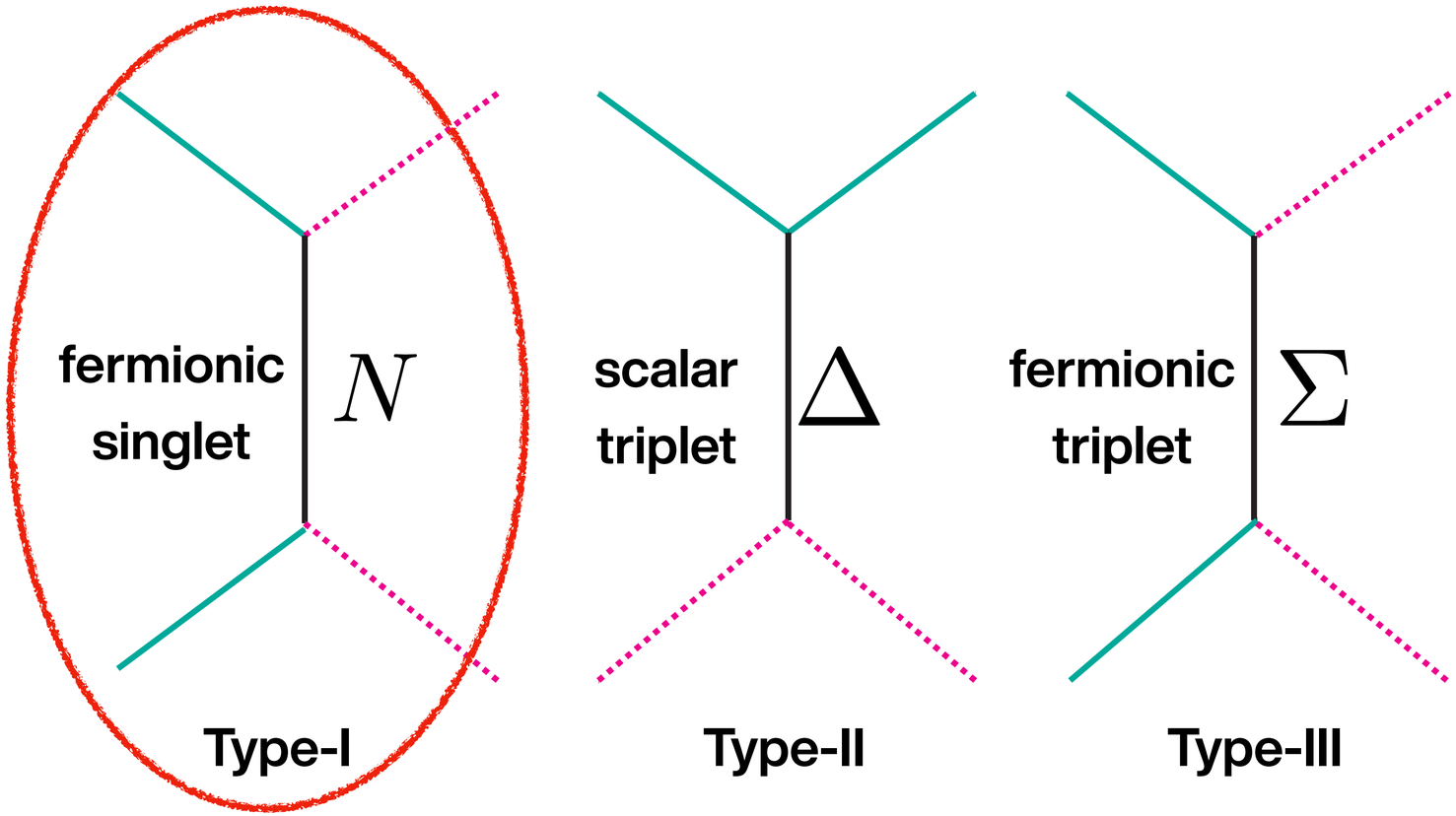

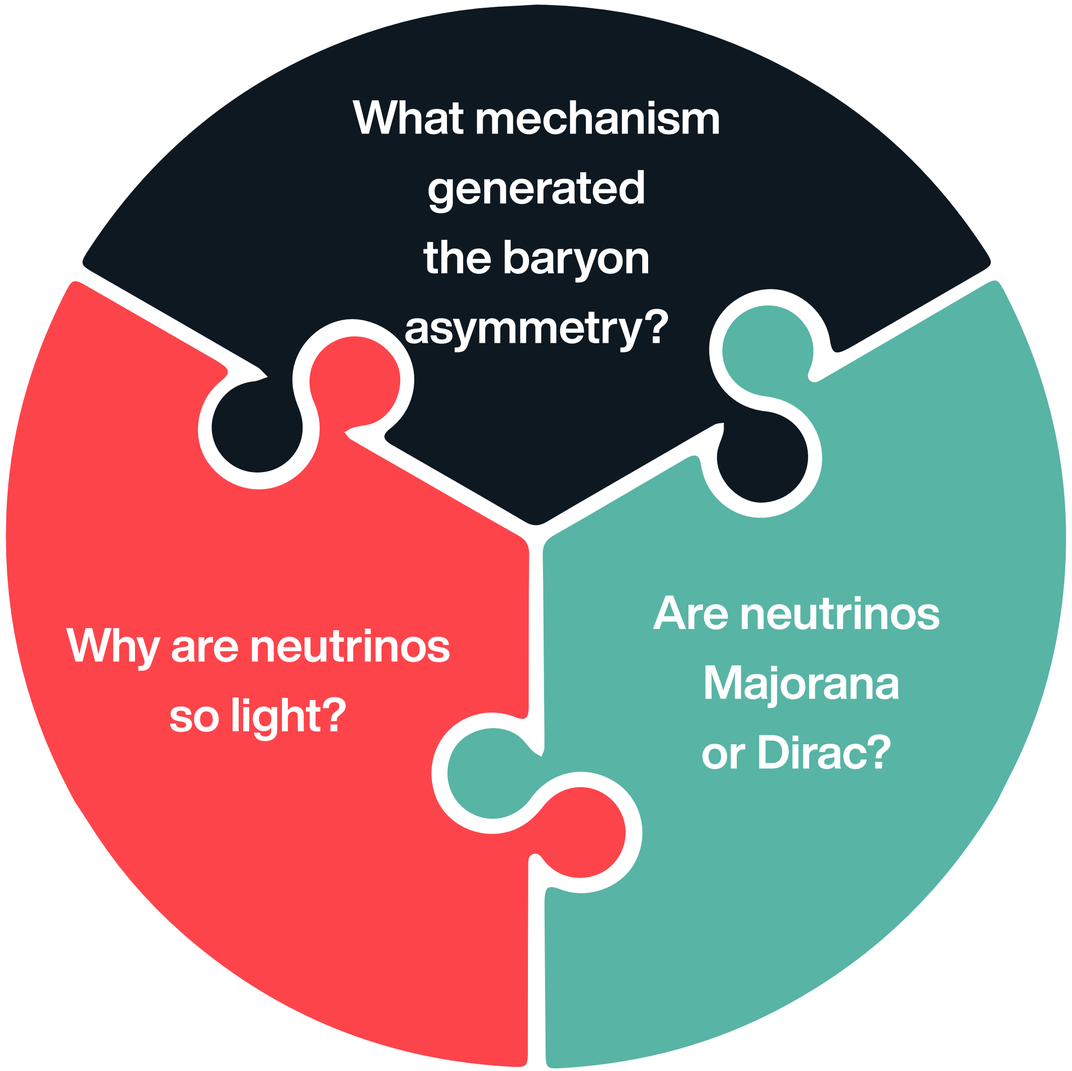
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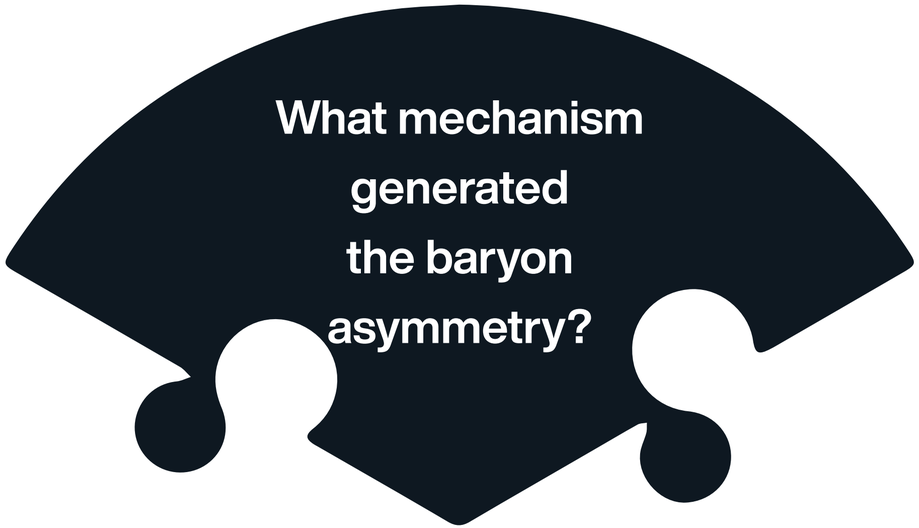
What mechanism
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Seesaw Mechanism

$$\mathcal{L} = Y_\nu \bar{L} \tilde{H} N - \frac{1}{2} M_N \overline{N^c} N$$

$$= -\frac{1}{2} (\bar{\nu}_L, \overline{N^c}) \begin{pmatrix} 0 & m_D \\ m_D & M_N \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N \end{pmatrix}$$

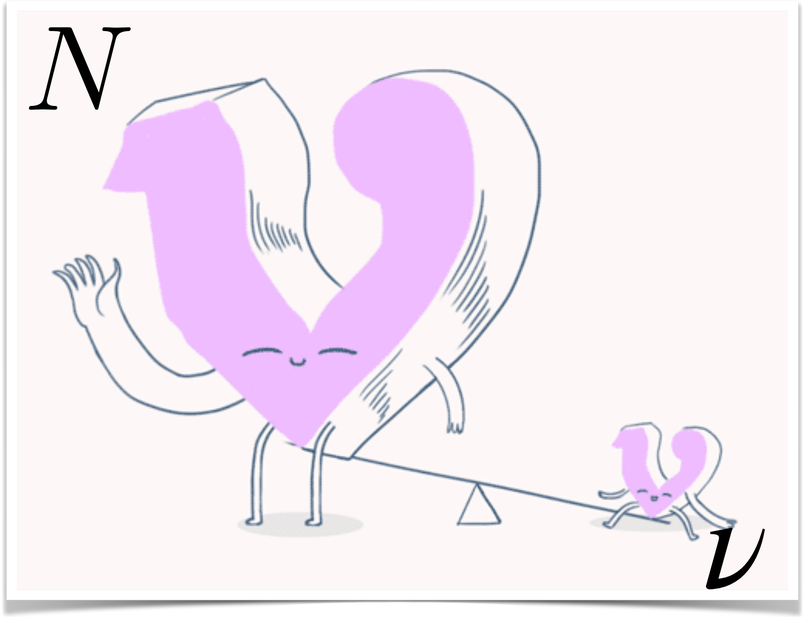


Image courtesy of Symmetry Magazine

$$m_D = \frac{Y_\nu v}{\sqrt{2}}$$

$$m_\nu = \frac{m_D m_D^T}{M_N} = \frac{Y_\nu^2 v^2}{2 M_N} \sim 0.1\text{eV}$$

$$Y_\nu \sim \mathcal{O}(1) \implies M_N \sim 10^{14}\,\text{GeV}$$

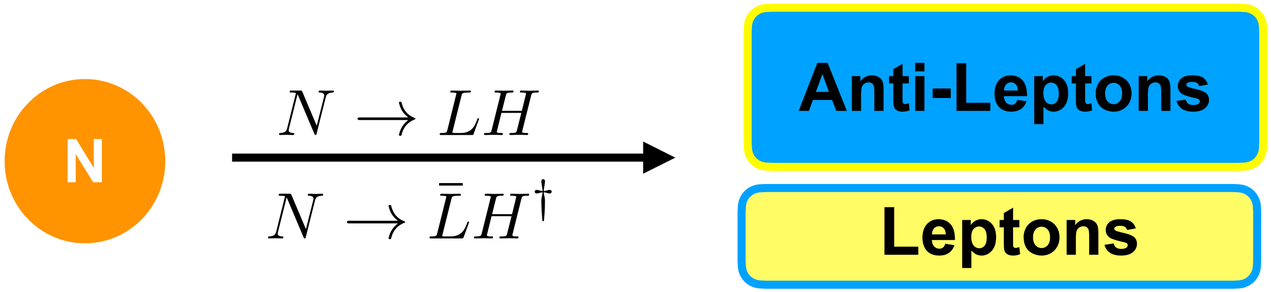
Sakharov's conditions satisfied!

Thermal Leptogenesis

Fukugita & Yanagida (1986)

Thermal Leptogenesis

Fukugita & Yanagida (1986)

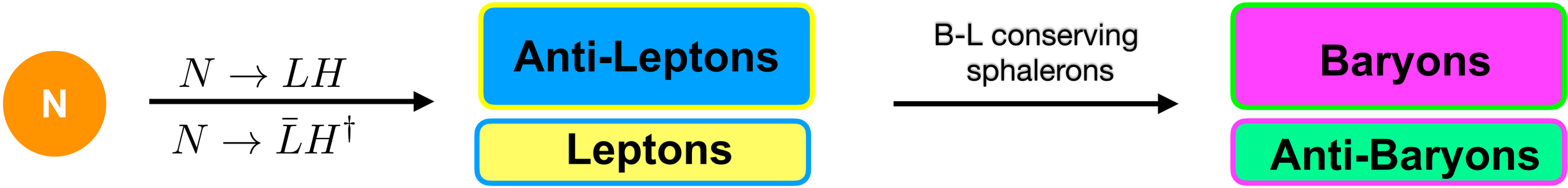


Decays Occurs when $T \sim M_N$

$$\Gamma_N \sim H$$

Thermal Leptogenesis

Fukugita & Yanagida (1986)



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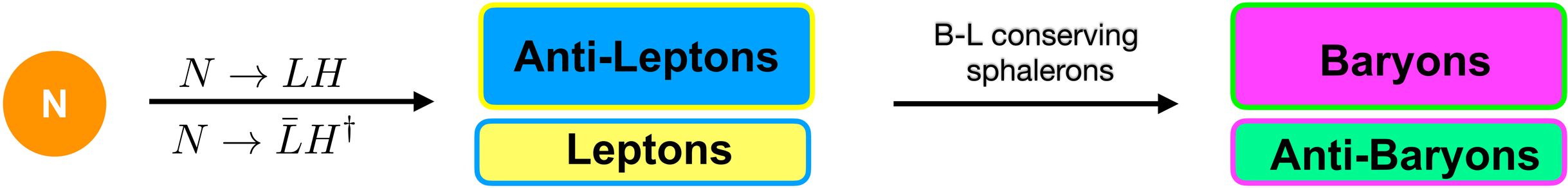

Decays Occurs when $T \sim M_N$

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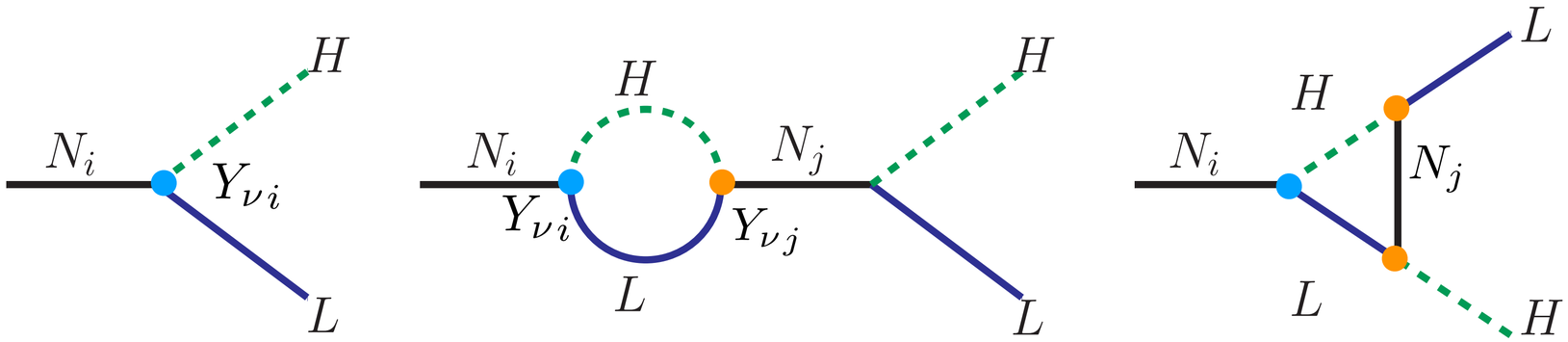
Decay asymmetry from interference between tree and loop level diagrams

Covi, Roulet, Vissani

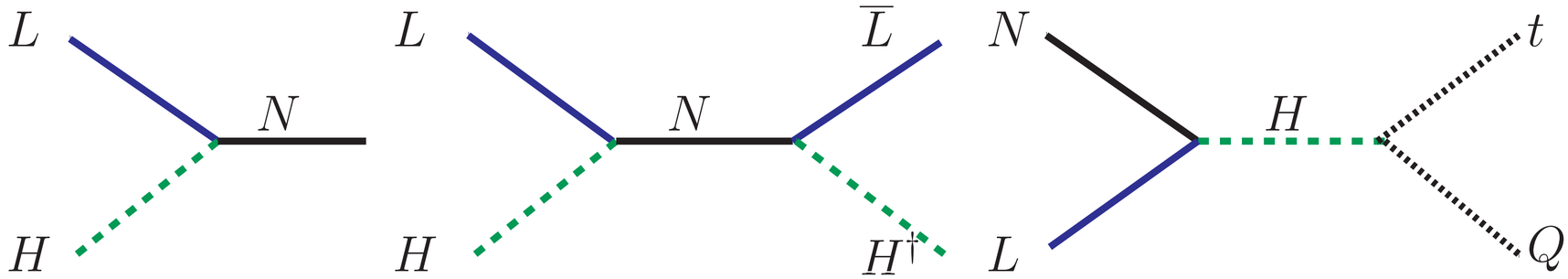


$$\epsilon_i = \frac{\Gamma_i - \overline{\Gamma_i}}{\Gamma_i + \overline{\Gamma_i}}$$

Thermal Leptogenesis

Fukugita & Yanagida (1986)

Washout and Scattering Processes



Inverse Decays $\Delta L = 2$ $\Delta L = 1$

Thermal Leptogenesis

Fukugita & Yanagida (1986)

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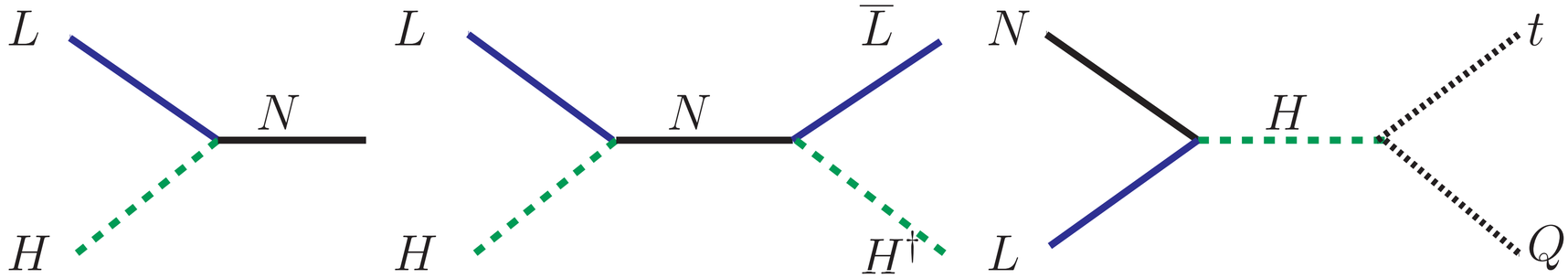

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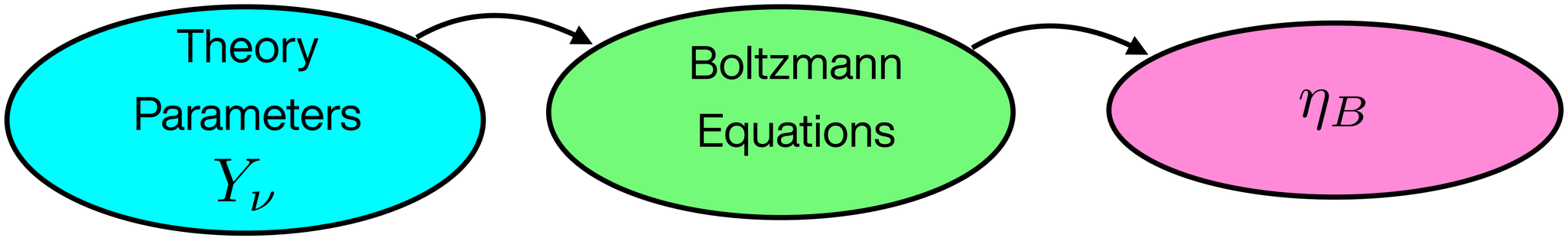
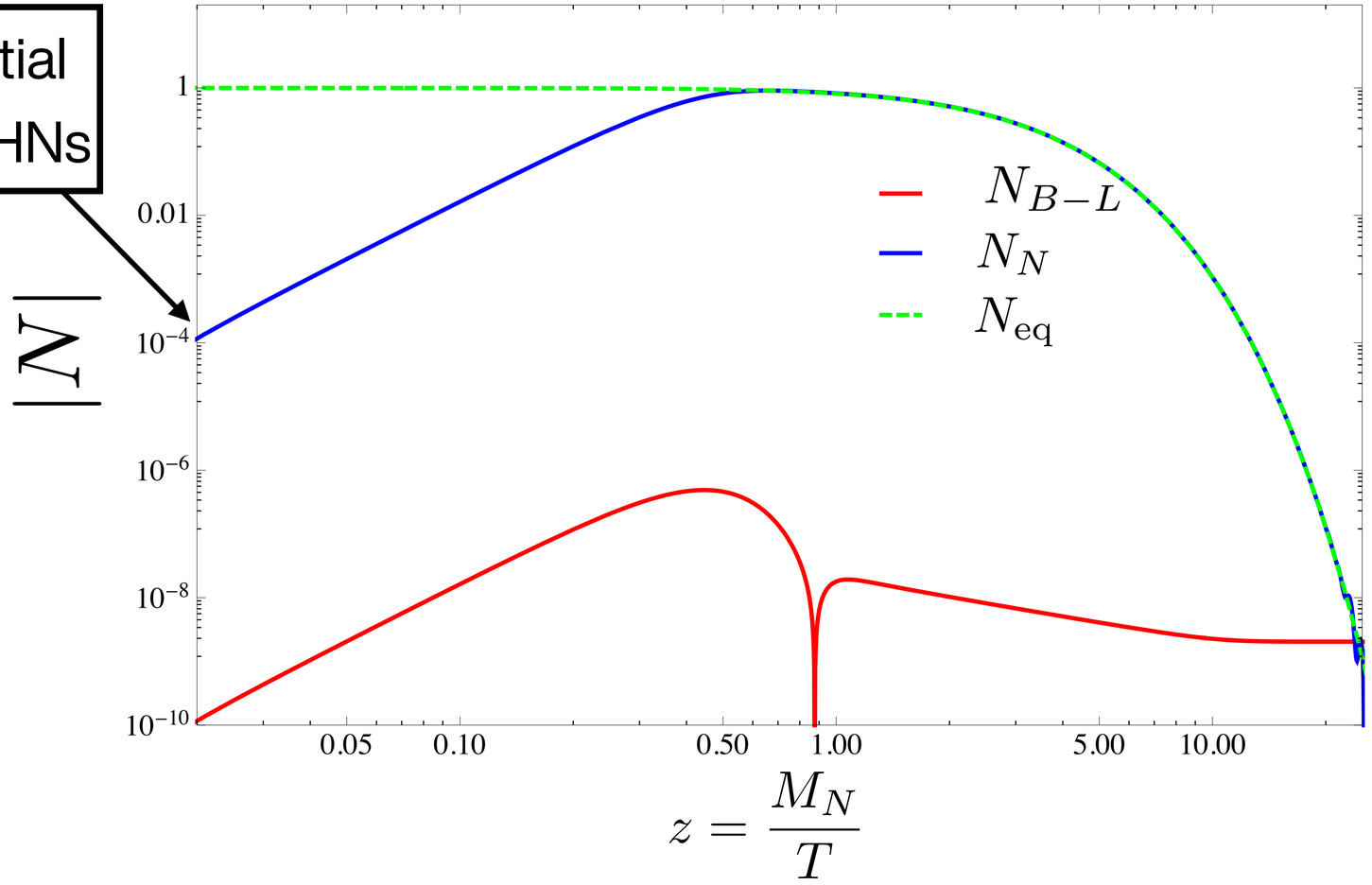
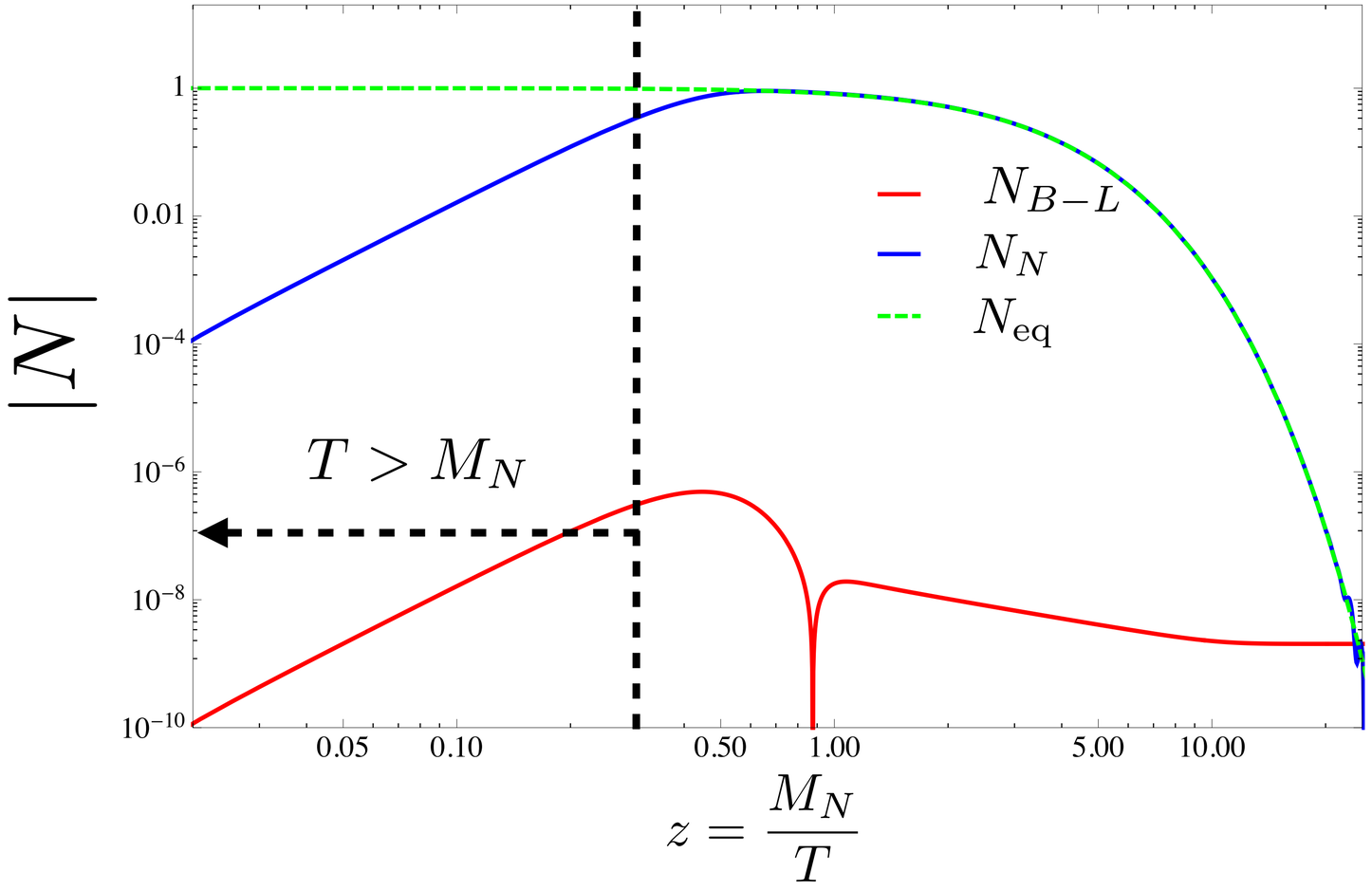


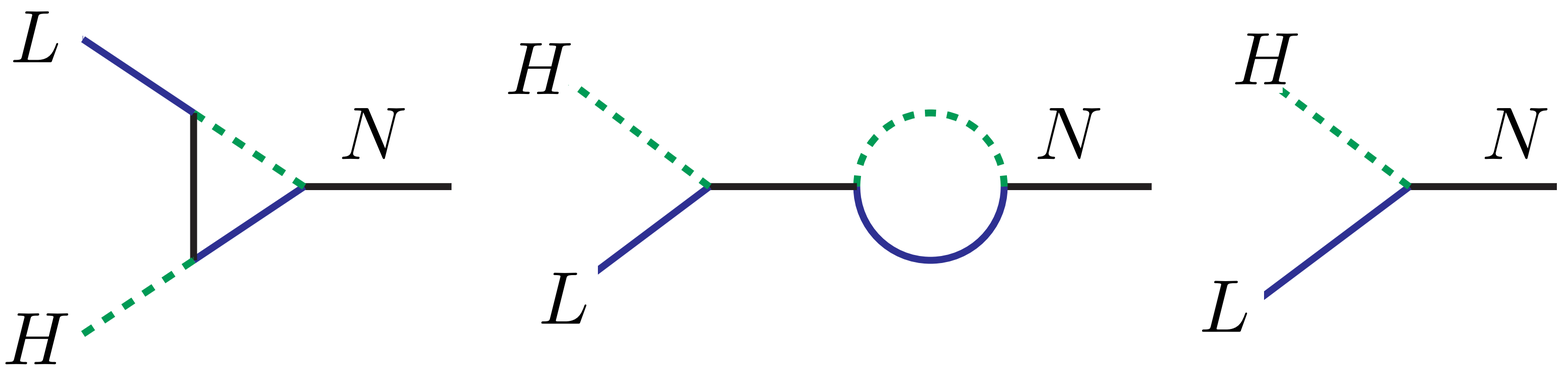
$$\frac{dN_N}{dz} = -D(z)\left(N_N - N_N^{\rm eq}\right)$$

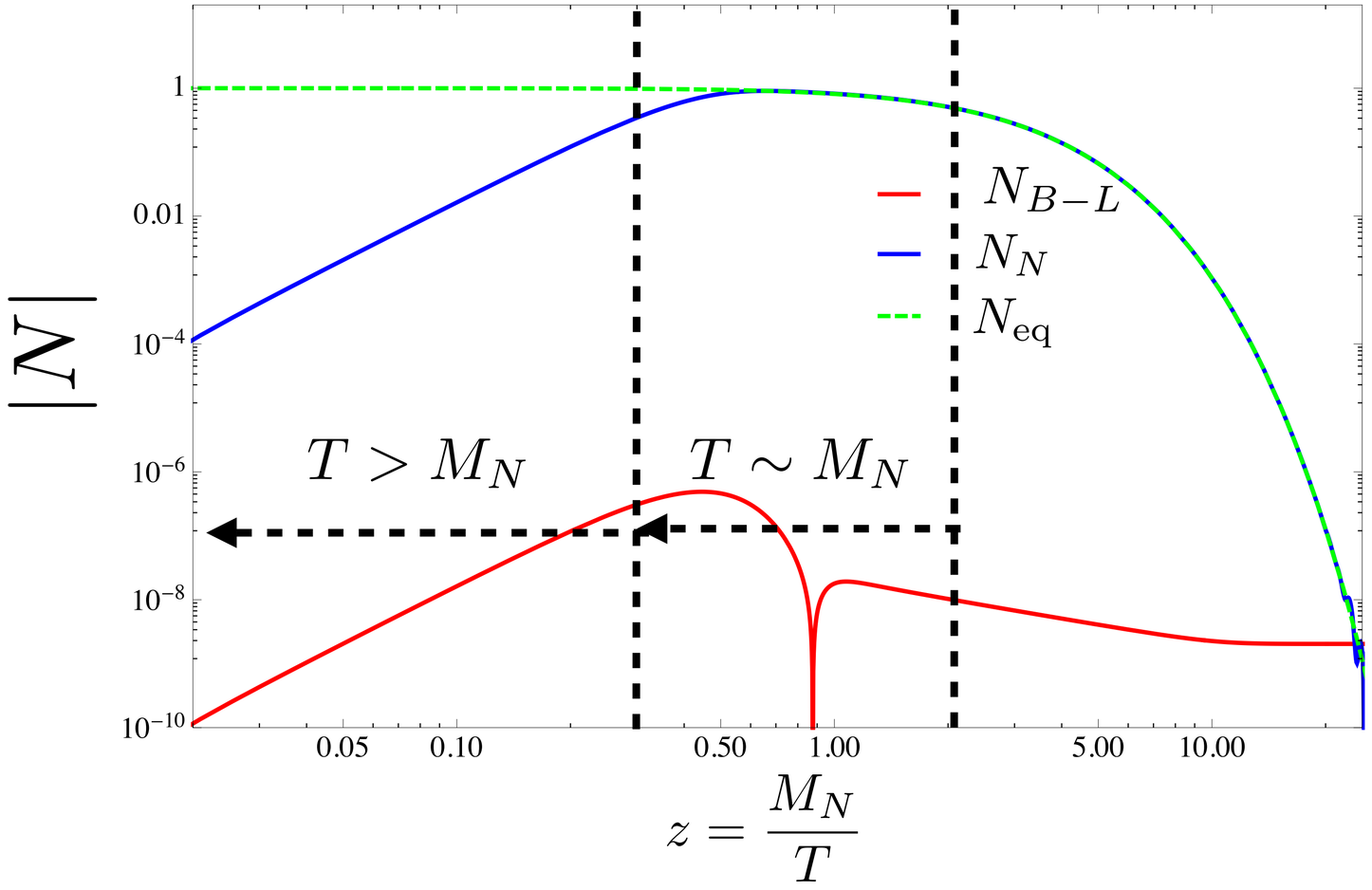
$$\frac{N_{B-L}}{dz} = \epsilon D(z)\left(N_N - N_N^{\rm eq}\right) - W(z)N_{B-L}$$

assume zero initial abundance of RHNs




$|N|$
1
0.01
10^{-4}
10^{-6}
10^{-8}
10^{-10}
0.05
0.10
0.50
1.00
5.00
10.00
N_{B-L}
N_N
$N_{\rm eq}$
$T > M_N$
$z = \frac{M_N}{T}$


L
N
H
H
N
L
H
N
L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1
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N_{B-L}
N_N
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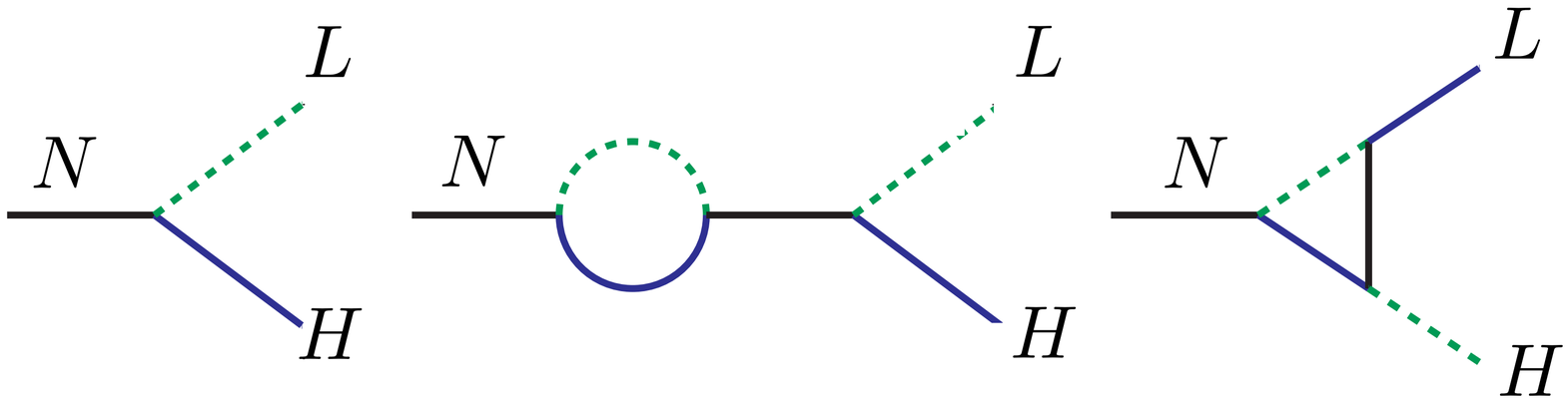
N
L
H
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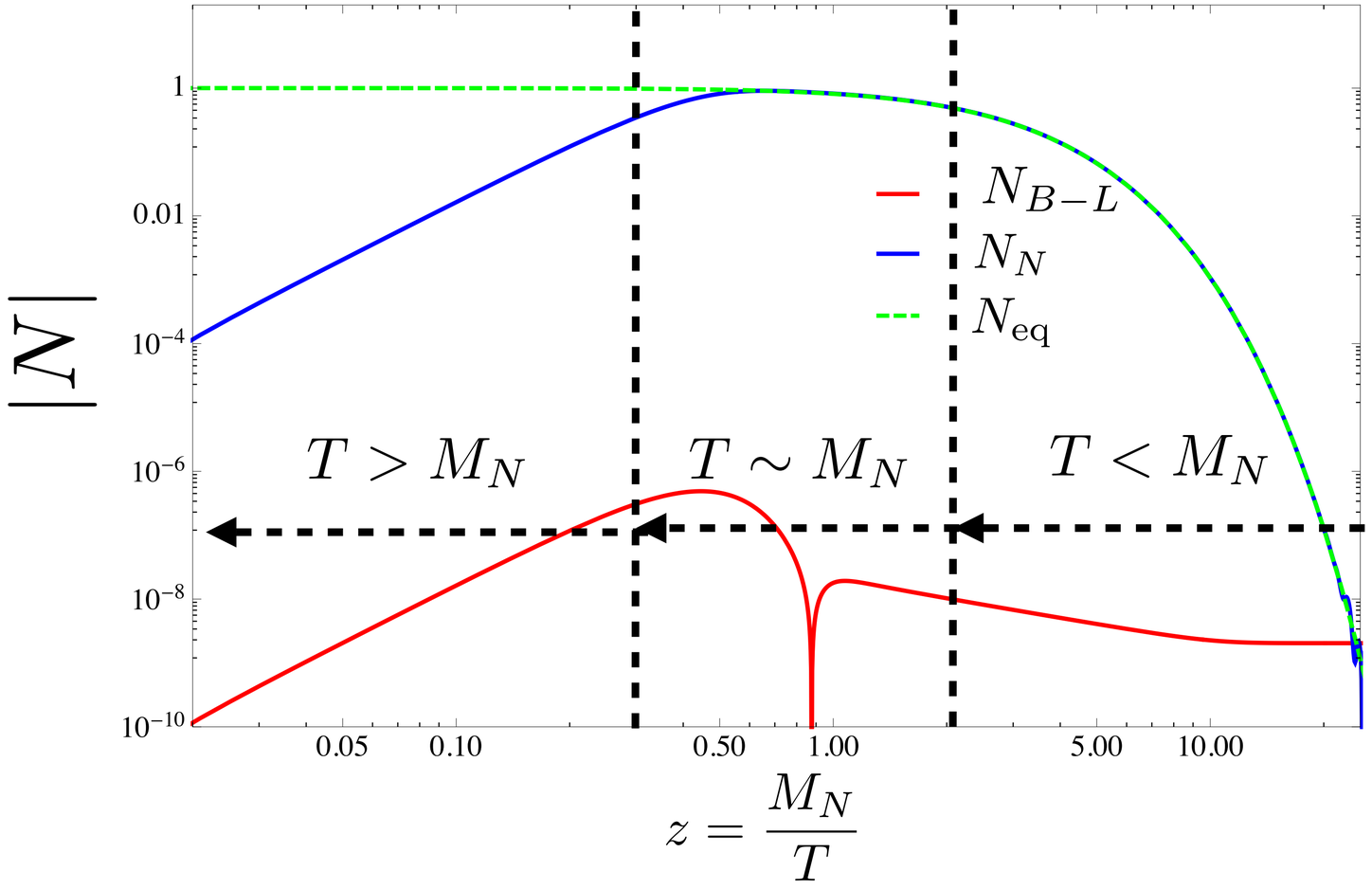
N
L
H



RHN abundance is depleted. Lepton asymmetry freezes out

Parameter Space

Casas, Ibarra (2001)

$$Y_\nu = \frac{1}{v} U_{\mathrm{PMNS}} \sqrt{m} R^T \sqrt{M}$$

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low-energy scale: 3 phases, 3 mixing angles and 3 masses

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high-energy scale: 3 phases, 3 mixing angles and 3 masses

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Casas, Ibarra (2001)

$$Y_\nu = \frac{1}{v} U_{\mathrm{PMNS}} \sqrt{m} R^T \sqrt{M}$$

low-energy scale: 3 phases, 3 mixing angles and 3 masses

high-energy scale: 3 phases, 3 mixing angles and 3 masses

Without any symmetry constraints 18 parameters in total

CI model-independent way $m_\nu \leftrightarrow$ leptogenesis

Mass RHN

$\mathcal{O}(10^{12})\,\mathrm{GeV}$

Fukugida & Yanagida

$\mathcal{O}(10^{6})\,\mathrm{GeV}$

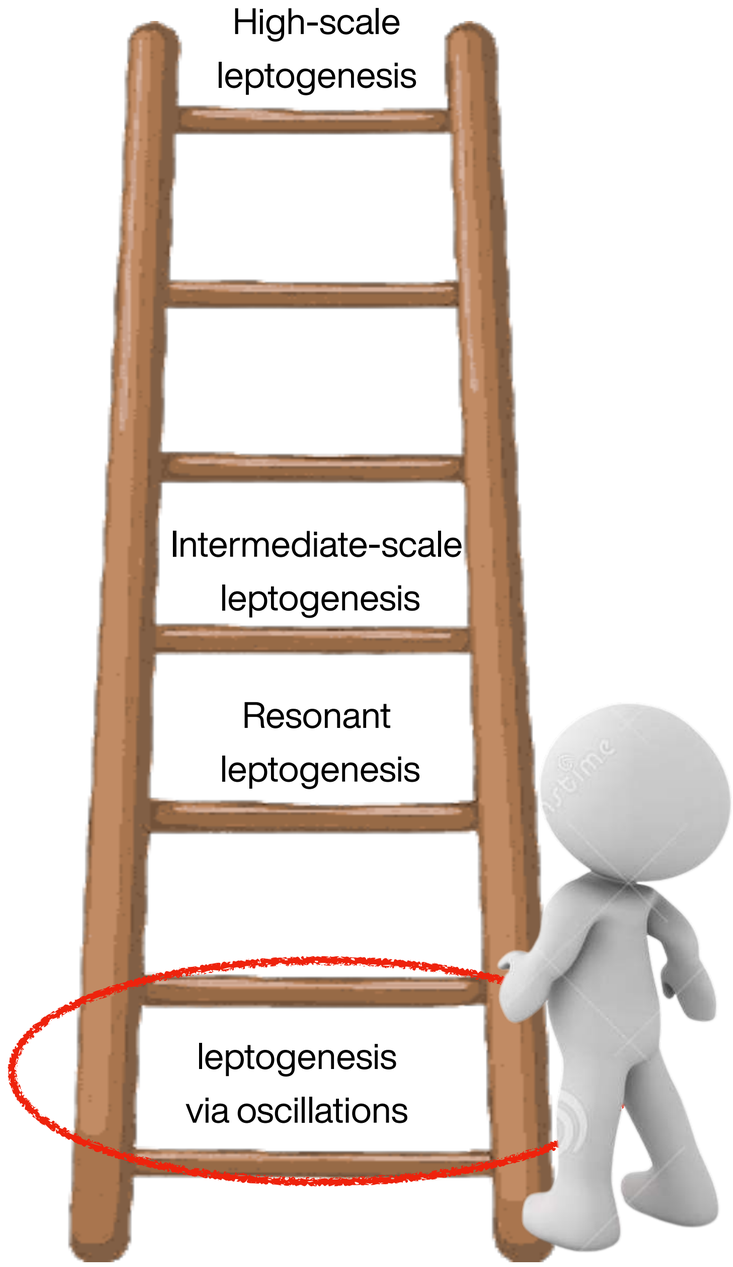
Racker, Rius & Pena

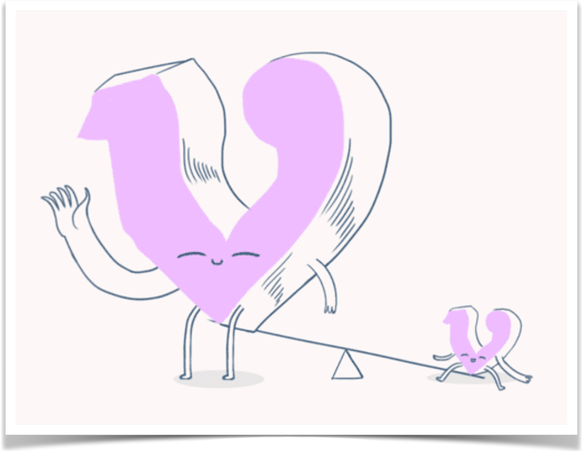
$\mathcal{O}(10^{3})\,\mathrm{GeV}$

Pilaftis & Underwood

$\mathcal{O}(1)\,\mathrm{GeV}$

Akhmedov, Rubakov & Smirnov





RHNs GeV mass

$$\Longrightarrow \; Y_\nu \sim 10^{-8} - 10^{-7}$$

Leptogenesis via Oscillation: Mechanism

Assume initially zero abundance of RHNs , they have highly degenerate masses & produced via scattering at $T > T_{EW.}$

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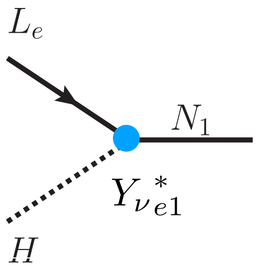

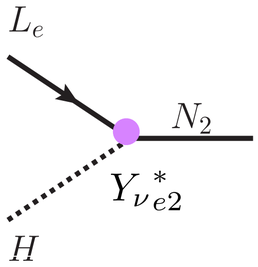

For simplicity, consider two flavour system

(1,2) & (e, μ)

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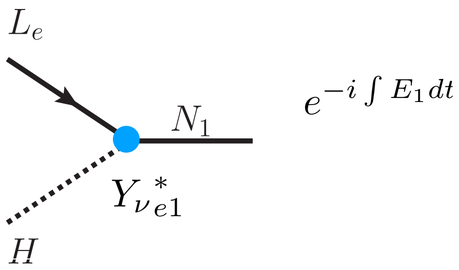
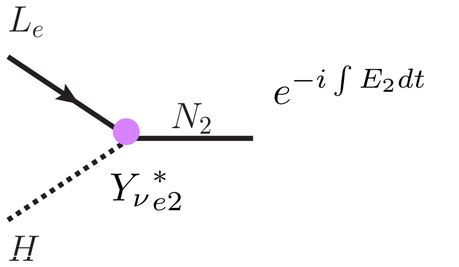


$e^{-i\int E_1 dt}$



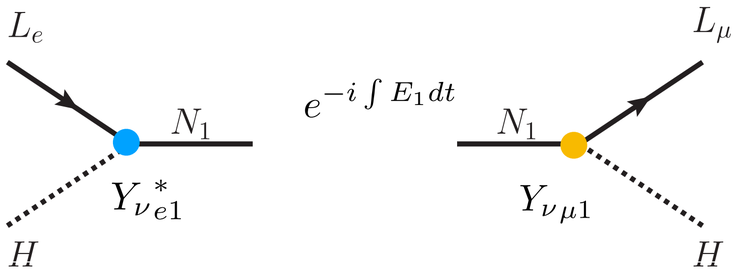
$e^{-i\int E_2 dt}$

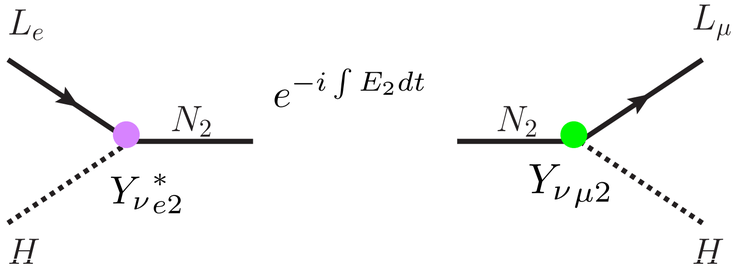
For simplicity, consider two flavour system

(1,2) & (e, μ)

Leptogenesis via Oscillation: Mechanism

Assume initially zero abundance of RHNs , they have highly degenerate masses & produced via scattering at $T > T_{EW}$.





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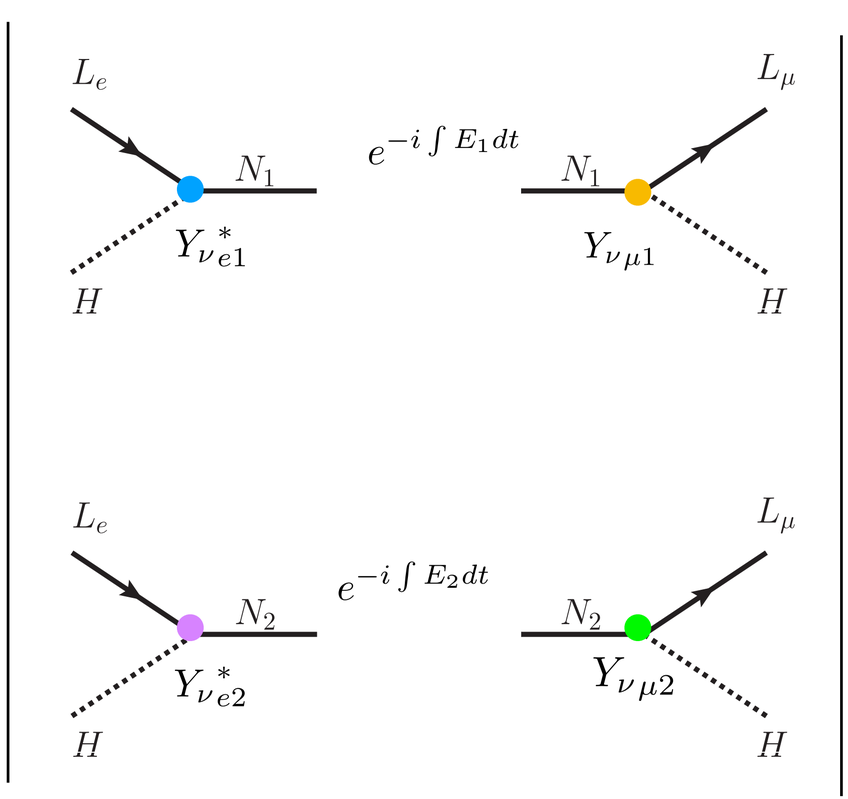
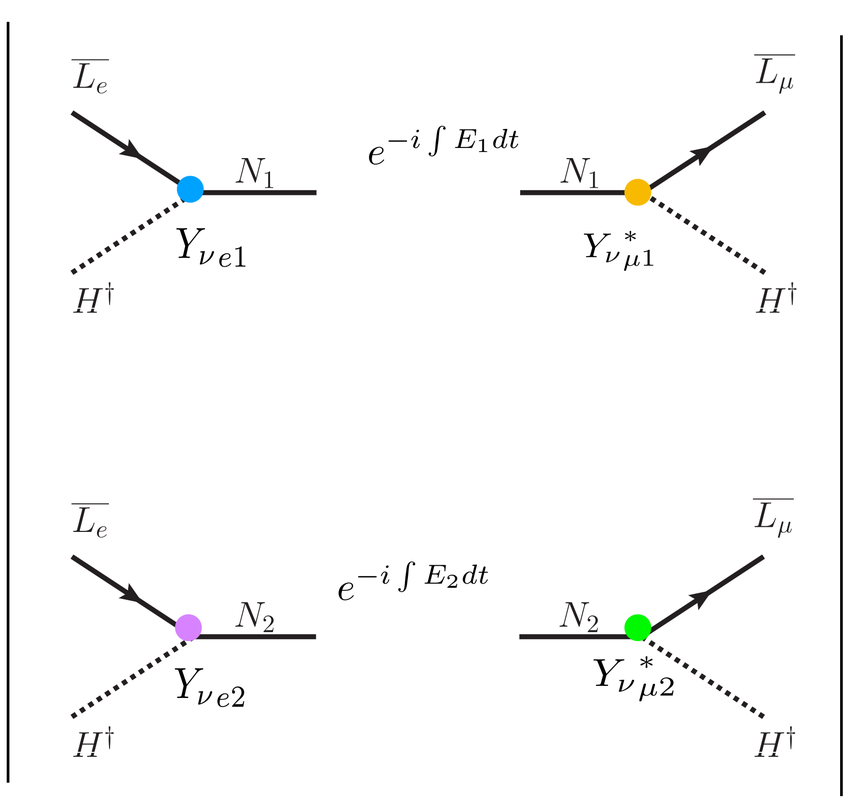
Leptogenesis via Oscillation: Mechanism



^{2}

$$\Gamma(L_e \to L_\mu) \propto e^{-i\int \frac{\Delta m^2_{21}}{2|\vec{p}|}dt} \times \left(Y^*_{\nu e1} Y_{\nu\mu 1} Y^*_{\nu e2} Y_{\nu\mu 2}\right)$$

Leptogenesis via Oscillation: Mechanism



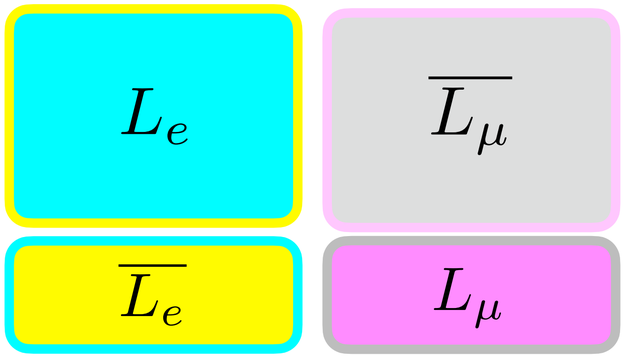
^{2}

CP conjugate process

$$\Gamma(\overline{L_e} \to \overline{L_\mu}) \propto e^{-i\int \frac{\Delta m^2_{21}}{2|\vec{p}|}dt} \times \left(Y_{\nu e1} Y^*_{\nu\mu 1} Y_{\nu e2} Y^*_{\nu\mu 1}\right)$$

Leptogenesis via Oscillation: Mechanism

$$\Gamma\left(L_e \to L_\mu\right) - \Gamma\left(\overline{L_e} \to \overline{L_\mu}\right) \propto \sin\left(\int \frac{\Delta m^2_{21}}{2|\vec{p}|} dt\right) \times \mathrm{Im}\left(Y_{\nu e1} Y^*_{\nu\mu 1} Y_{\nu e2} Y^*_{\nu\mu 1}\right)$$



$$\left.\begin{array}{l} \Delta L_e \neq 0 \\ \Delta L_\mu \neq 0 \\ \Delta L = 0 \end{array}\right\}$$

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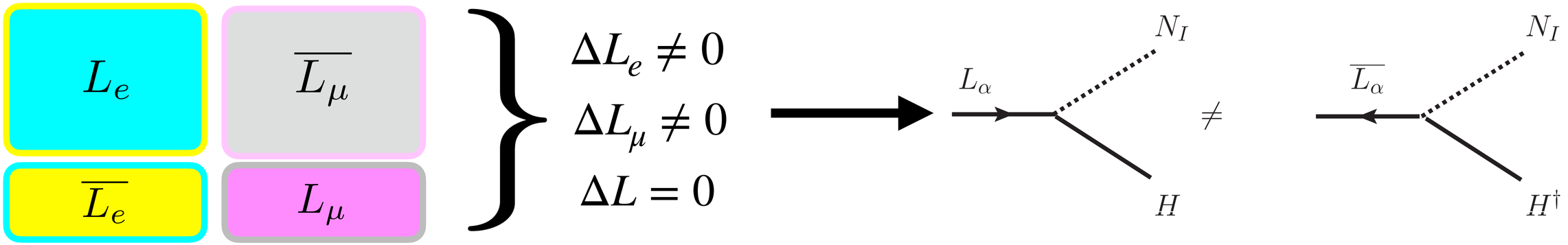

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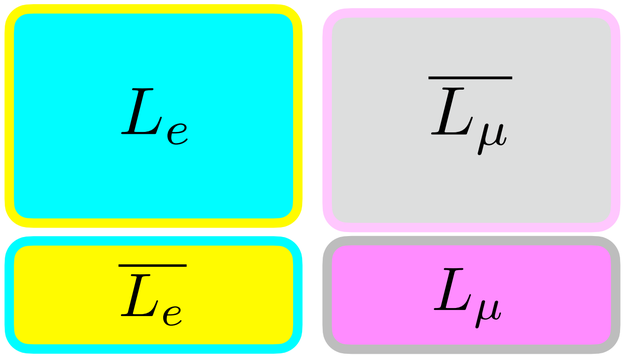

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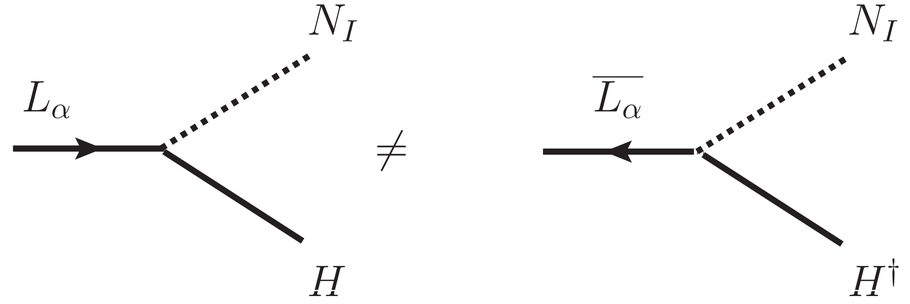

$$\Delta L \neq 0$$

EW sphalerons
convert SM lepton asymmetry
to baryon asymmetry

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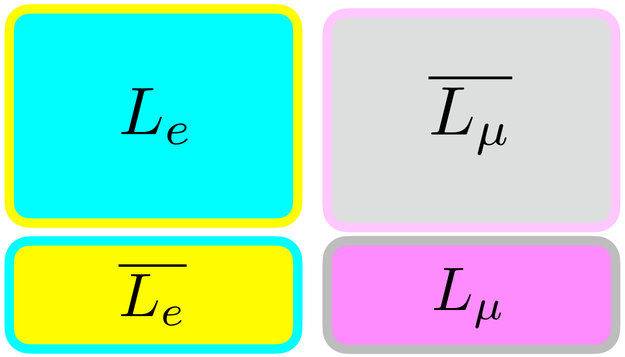

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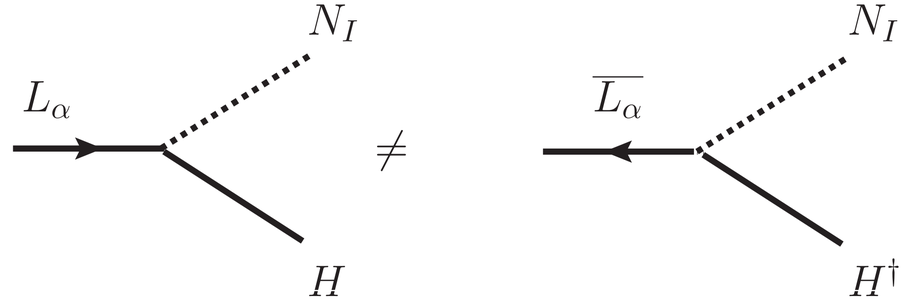

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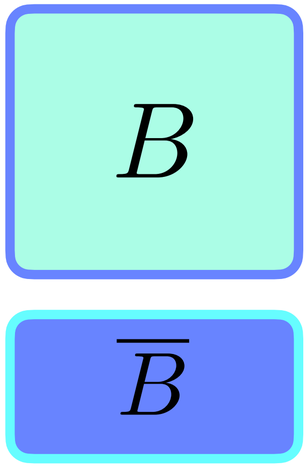


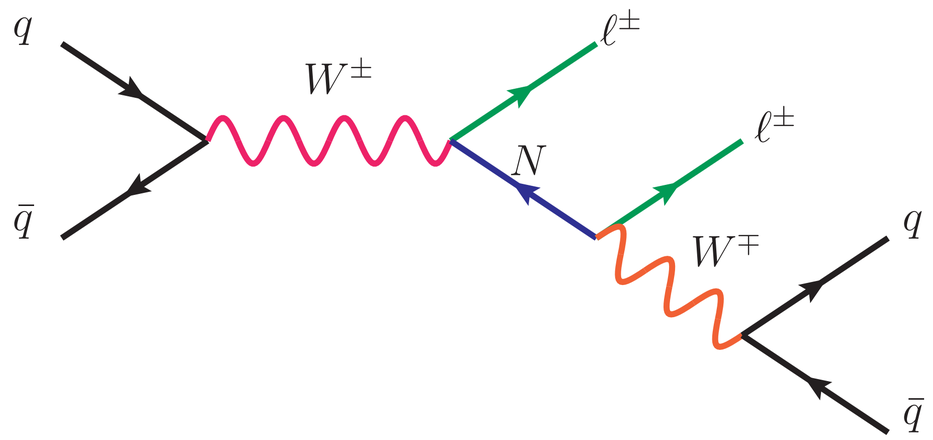
Leptogenesis via Oscillation: Phenomenology

Minimal case

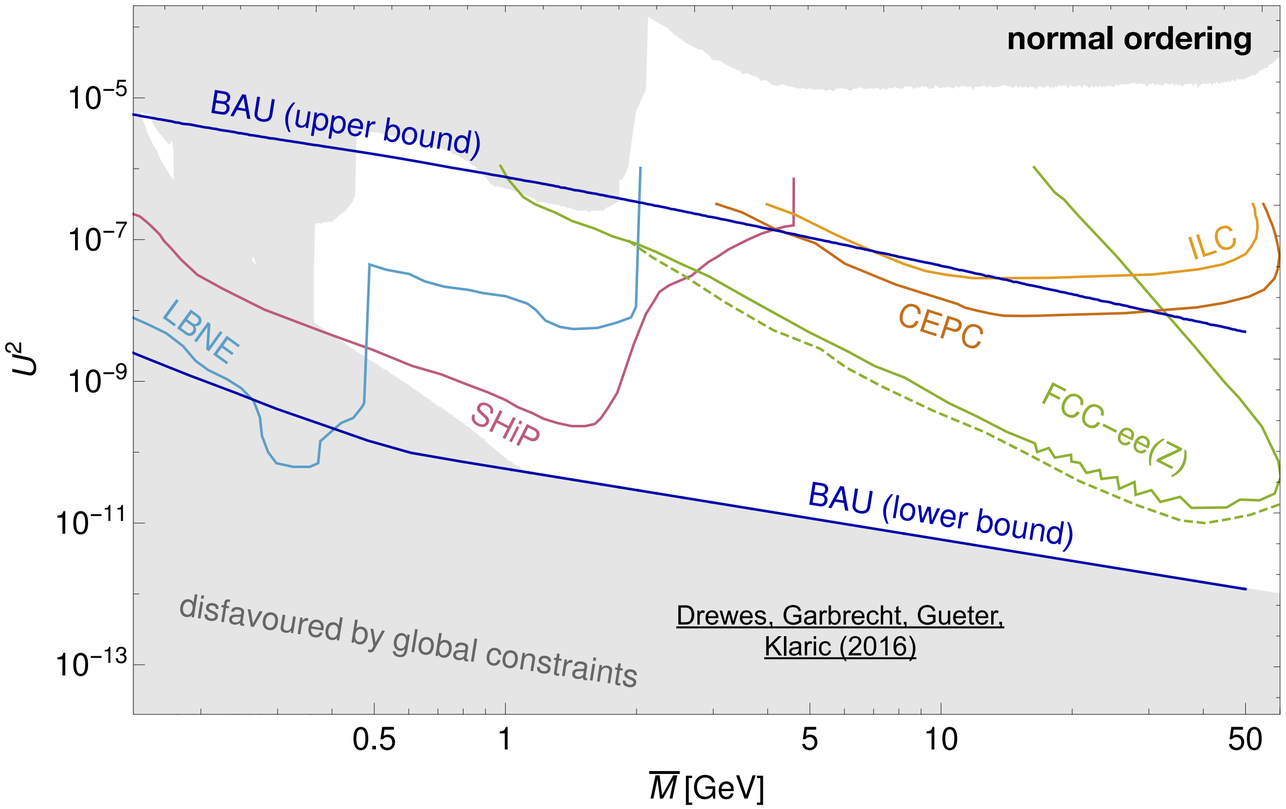
2 RHNs → 4 masses, 4 mixing angles, 3 phases

$$Y = \frac{1}{v} U \sqrt{m} R^T \sqrt{M}$$

$$\nu_\alpha = U_{\alpha i}\nu_i + \Theta_{\alpha I} N_I^c \qquad |U|^2 = \sum_{\alpha I} |\Theta_{\alpha I}|^2 \qquad \overline{M} = \frac{M_1 + M_2}{2}$$



Like-sign lepton + dijet



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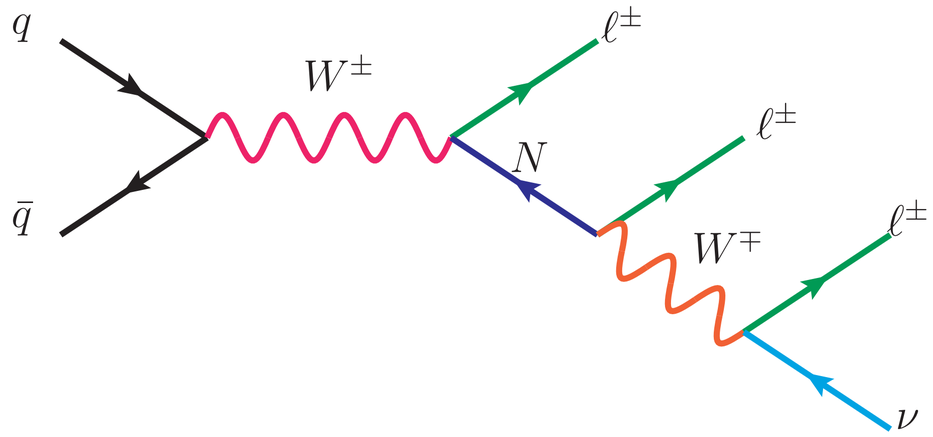
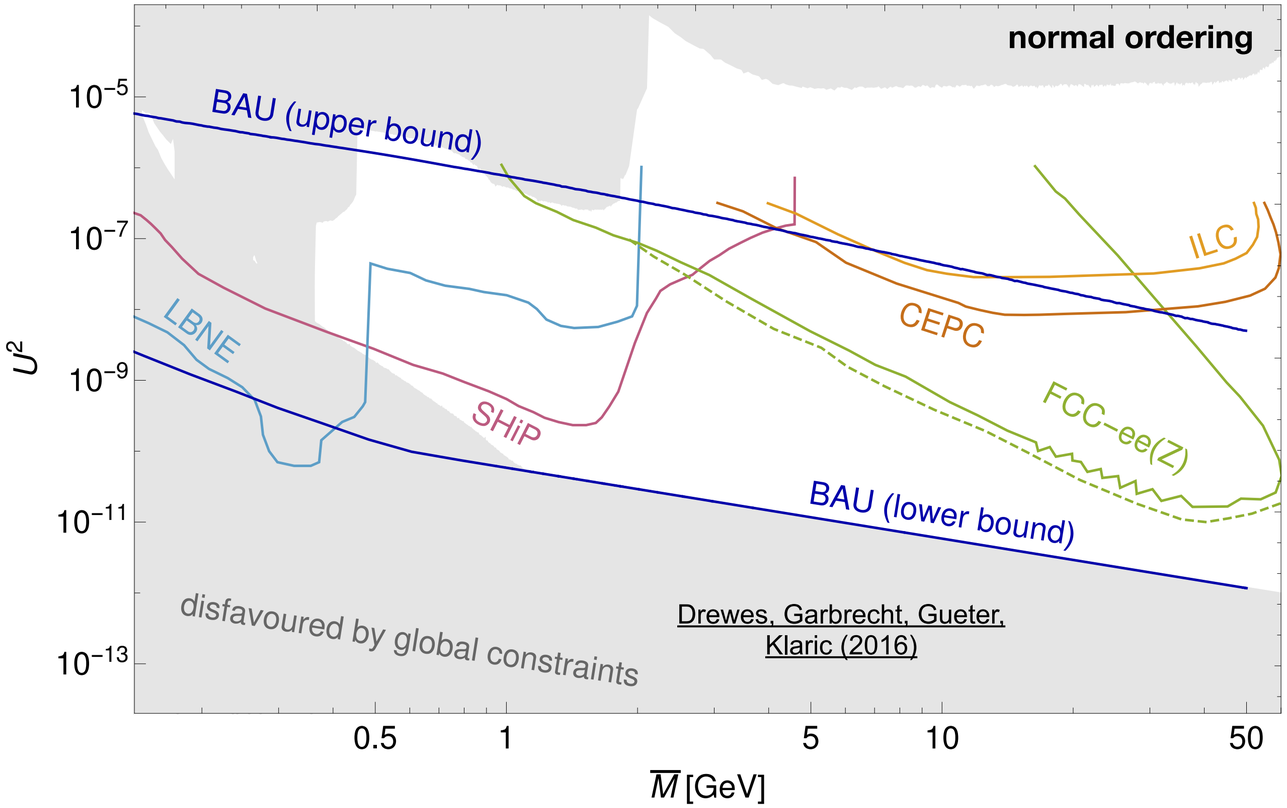


Trilepton



Mass RHN

$\mathcal{O}(10^{12})\,\mathrm{GeV}$

Fukugida & Yanagida

$\mathcal{O}(10^{6})\,\mathrm{GeV}$

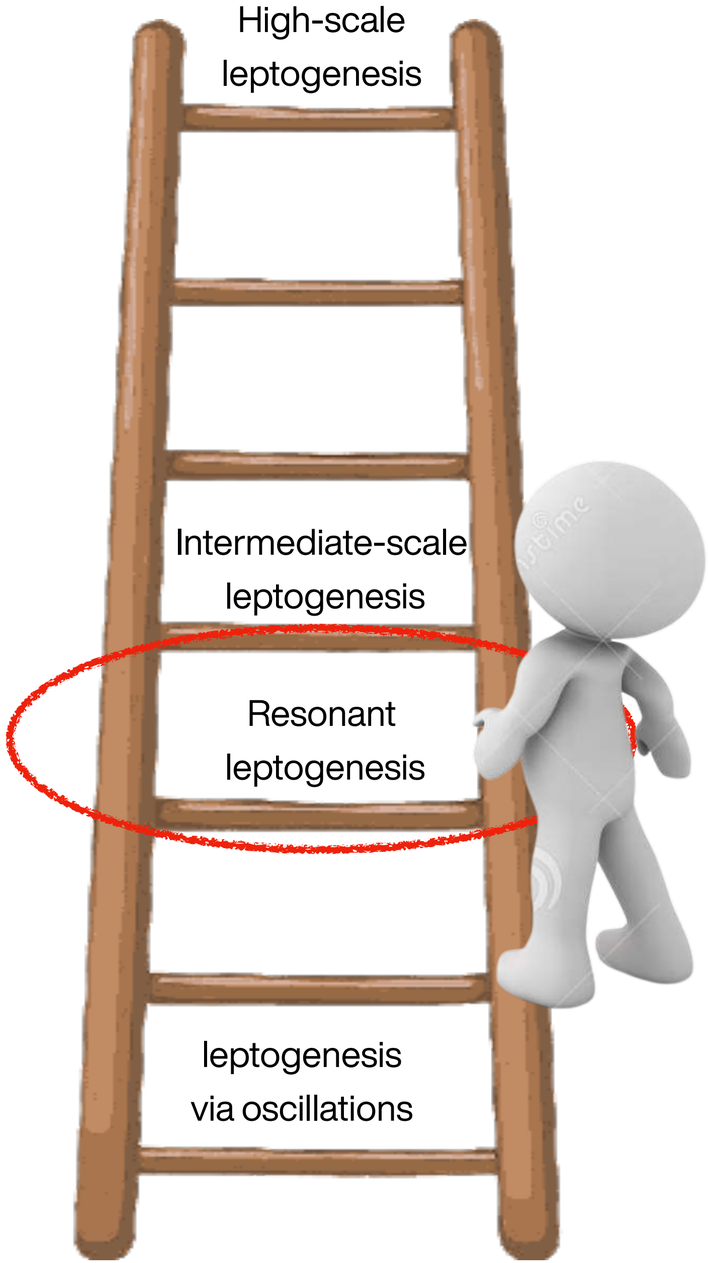
Racker, Rius & Pena

$\mathcal{O}(10^{3})\,\mathrm{GeV}$

Pilaftis & Underwood

$\mathcal{O}(1)\,\mathrm{GeV}$

Akhmedov, Rubakov & Smirnov



RHNs TeV mass

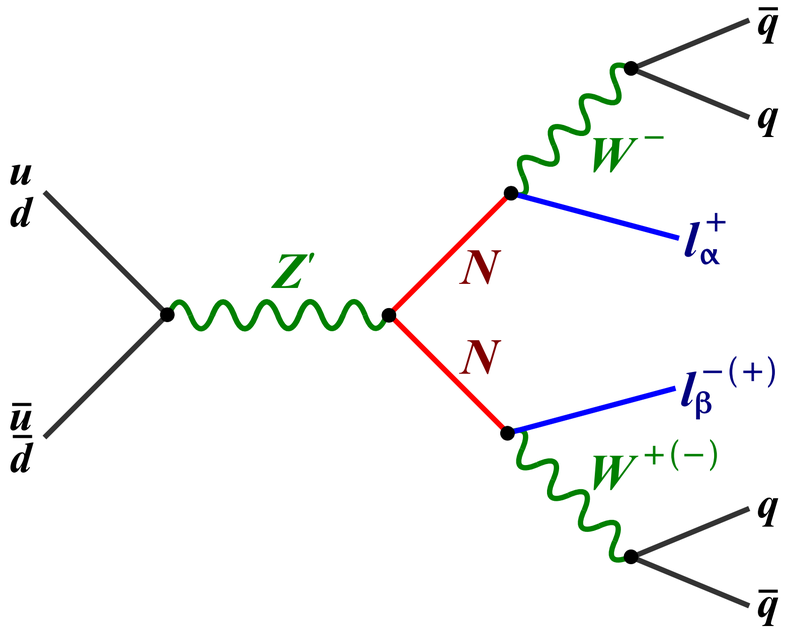
$\Longrightarrow\ Y_\nu \sim 10^{-5} - 10^{-4}$

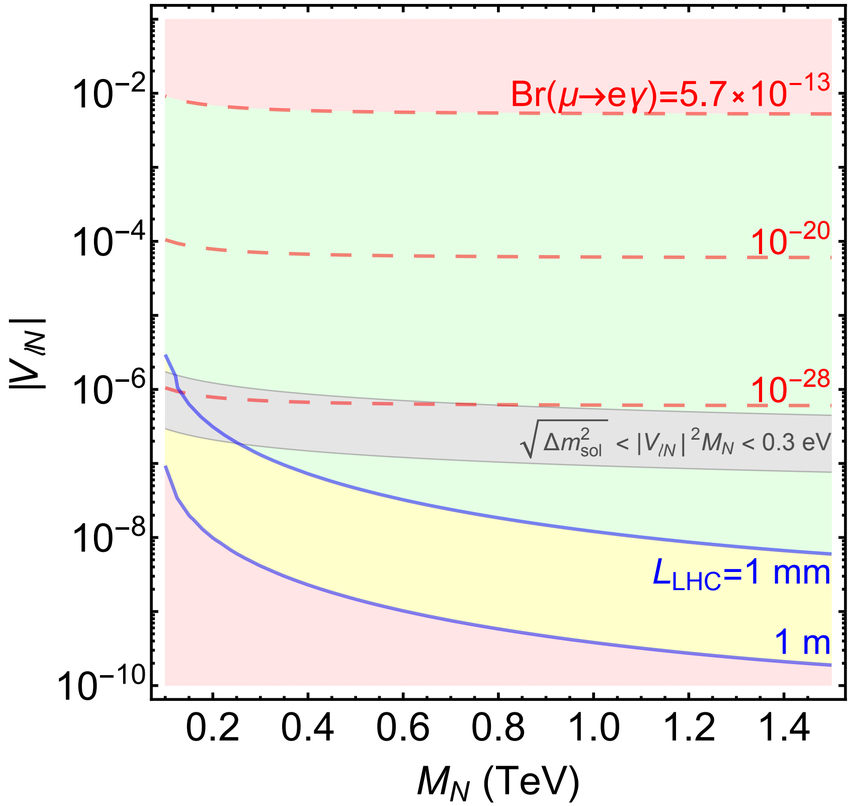
Resonant Leptogenesis

TeV scale RHN $\Longrightarrow Y_\nu \sim 10^{-6} \Longrightarrow D \ll 1$

If $\Delta M_N \ll M_N \Longrightarrow \epsilon \gg 1$

RHN masses can be explained by additional $U(1)_{B-L}$ symmetry → displaced-vertex signature searched for at LHC, MATHUSLA or SHiP





Deppisch, Dev, Pilaftsis (2015)

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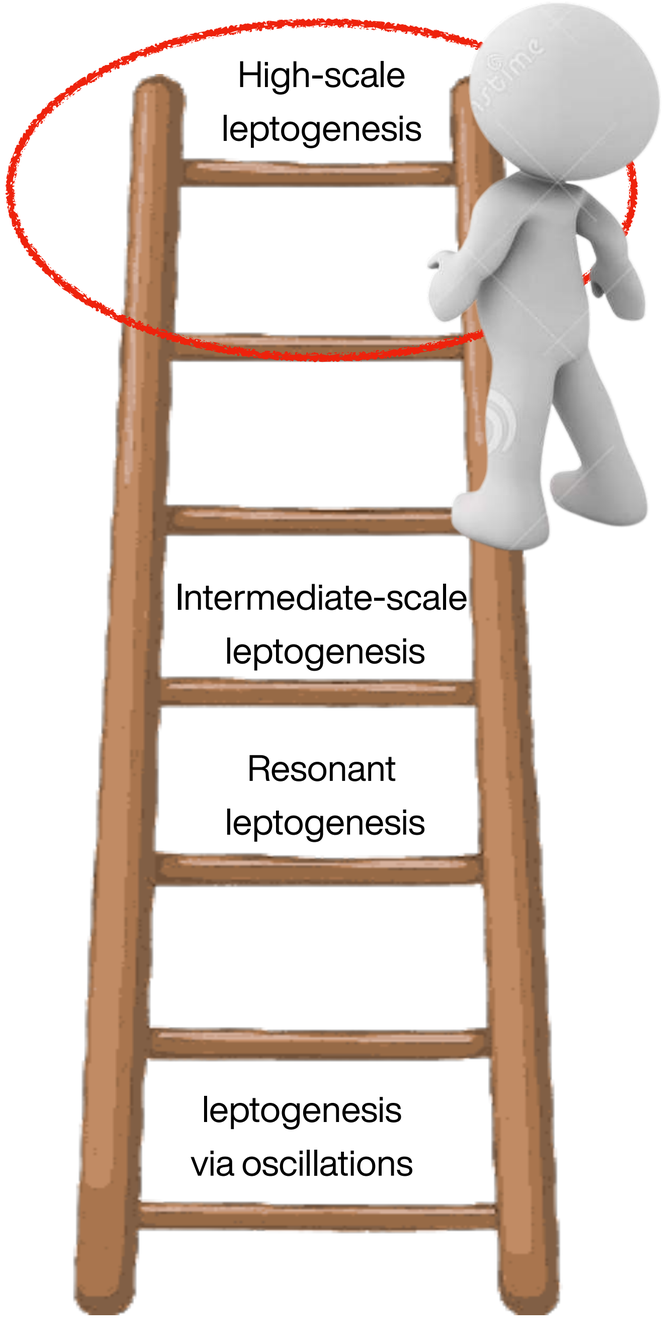
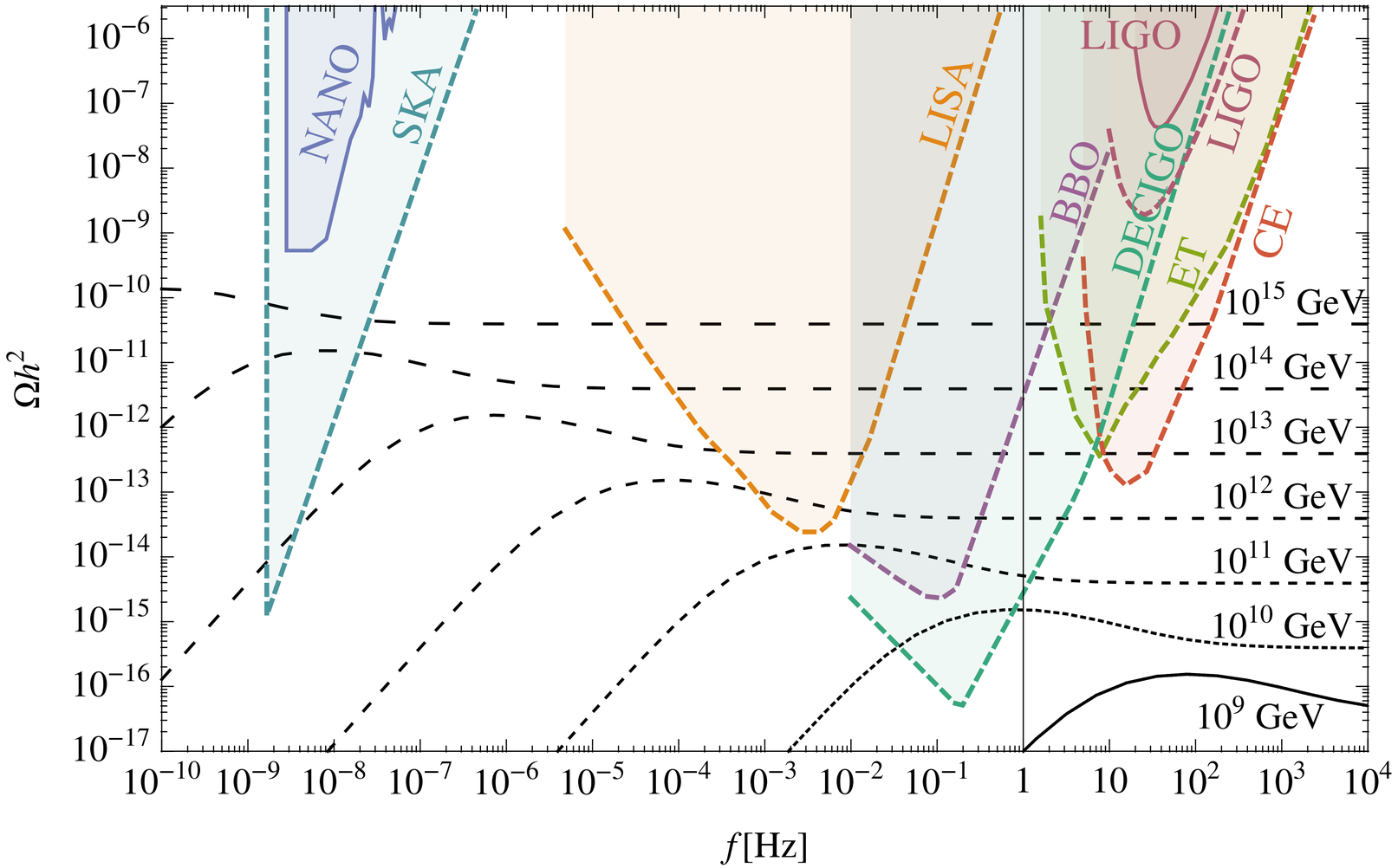


Tough to test
but gravitational waves
offer an additional
probe

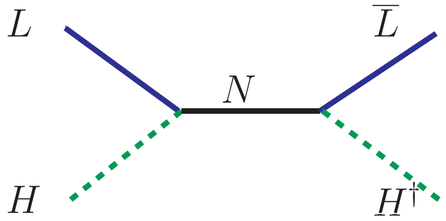
High-Scale Leptogenesis

Highlighted by Dror et al that GWs from cosmic string network generic prediction of seesaw mechanism

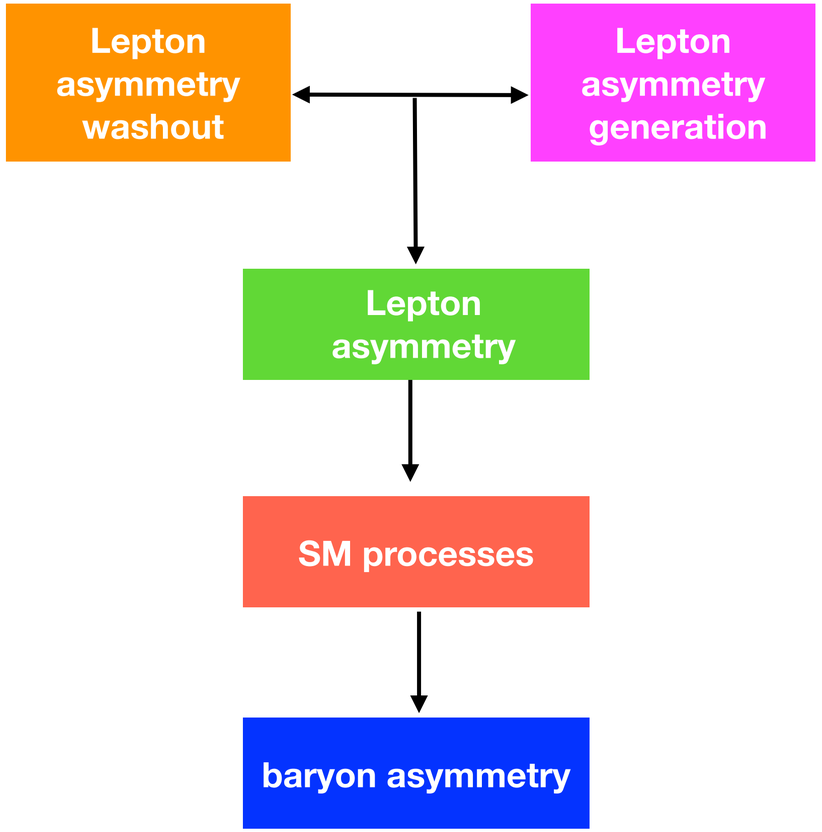


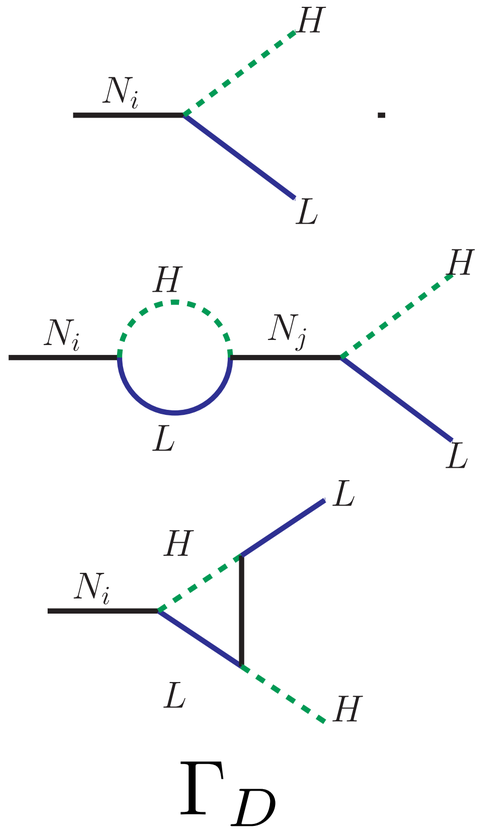
Dror, Hiramatsu, Kohri , Murayama & White (2020)

Falsifying High-Scale Leptogenesis



Γ_W



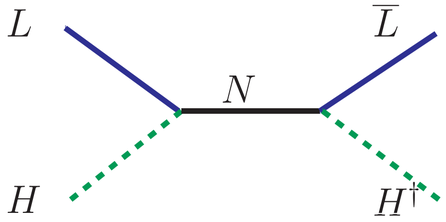


Γ_D

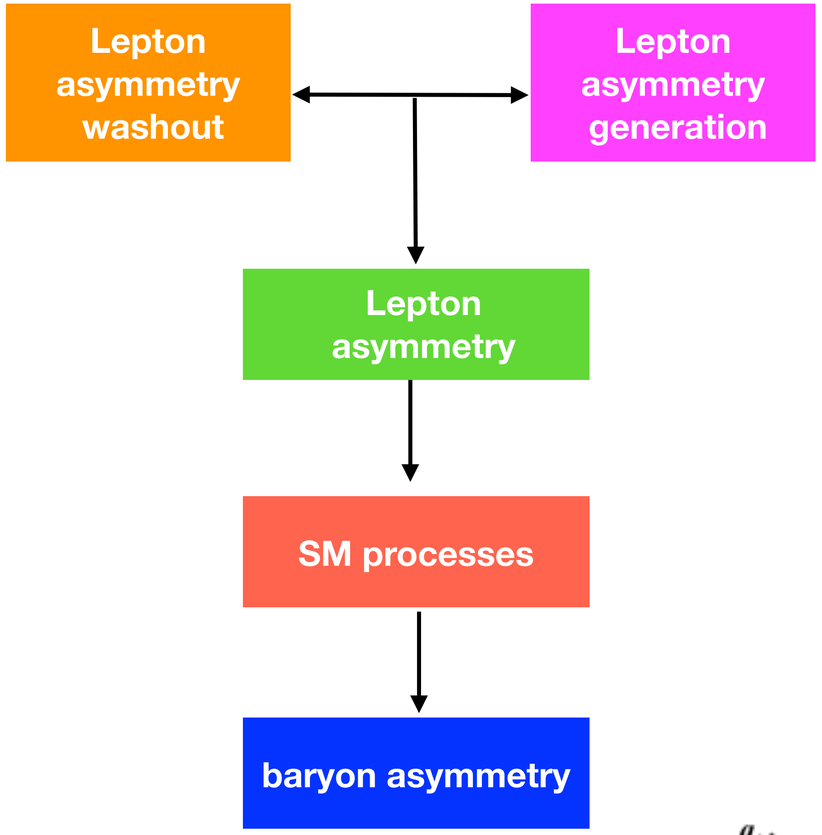
Deppisch & Harz (2014)

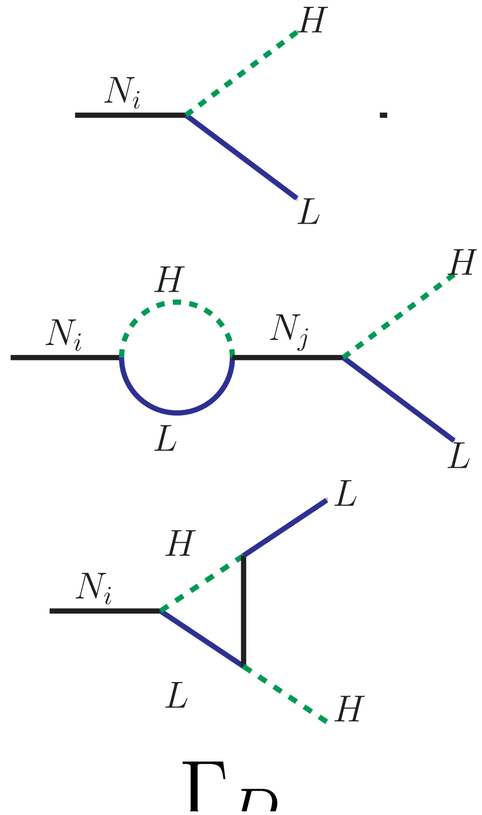
If $\Gamma_D \ll H$ and $\Gamma_W \gg H$ no lepton asymmetry since washout too large

Falsifying High-Scale Leptogenesis



Γ_W





Γ_D

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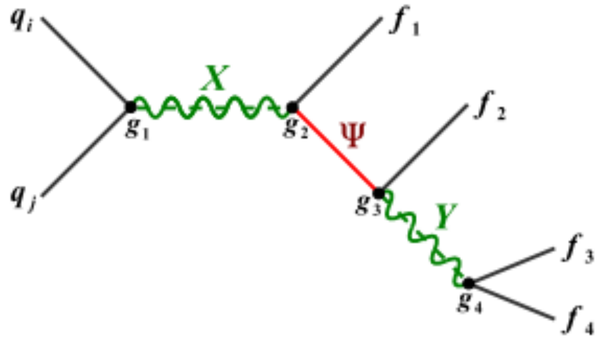
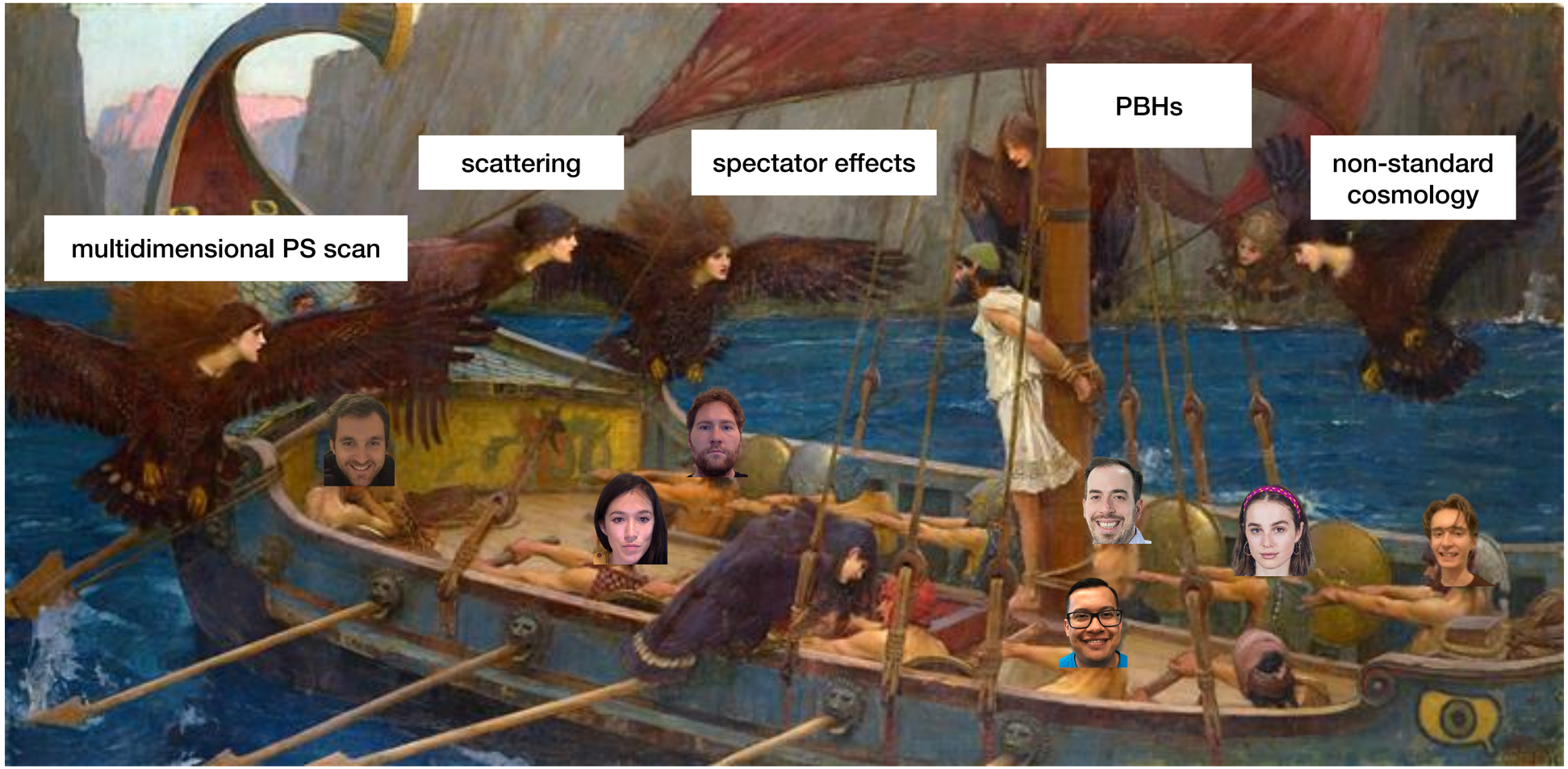


This scenario $\Longrightarrow \Delta L = 2$ LNV at colliders

$pp \rightarrow l^{\pm}l^{\pm} + 2$ jets

ULYSSES: Universal LeptogeneSiS Equation Solver



- Python package for solving BE for **thermal, resonant & leptogenesis via oscillations & non-standard cosmologies such as PBH induced leptogenesis**
- Easy parallelisation, easy to scan parameters
- Modular format, we always looking to expand so if you're interested get in touch!

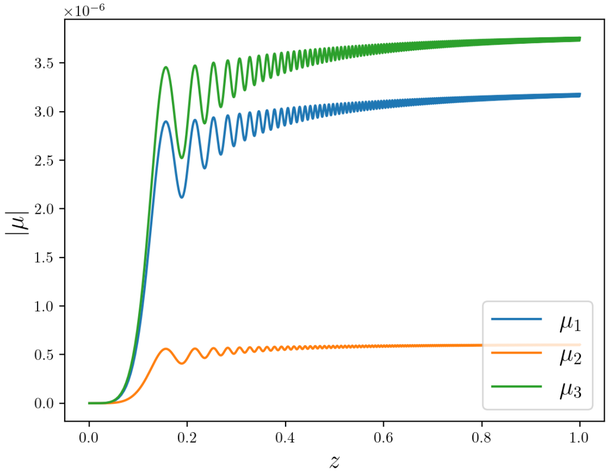
ULYSSES: Universal LeptogeneSiS Equation Solver

1. Installation `pip3 install ulysses --user`

2. Input point (volume) in parameter space

```
delta 31.713030
a21 130.953483
a31 649.655874
x1 -72.335979
y1 170.549206
x2 86.969063
y2 2.223559
x3 -1.862141
y3 178.312158
m -0.942835
t12 33.630000
t23 46.633046
t13 8.520000
M1 6.500000
M2 7.200000
M3 7.900000
```

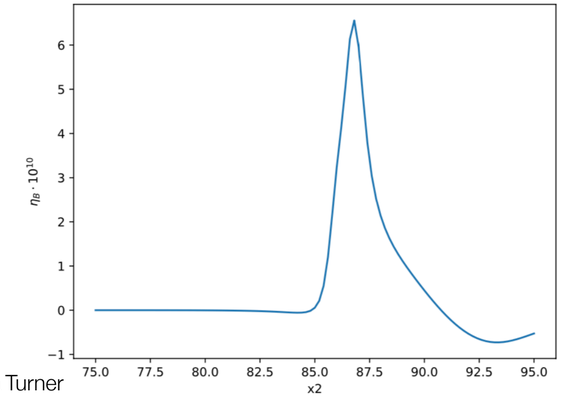
point.txt



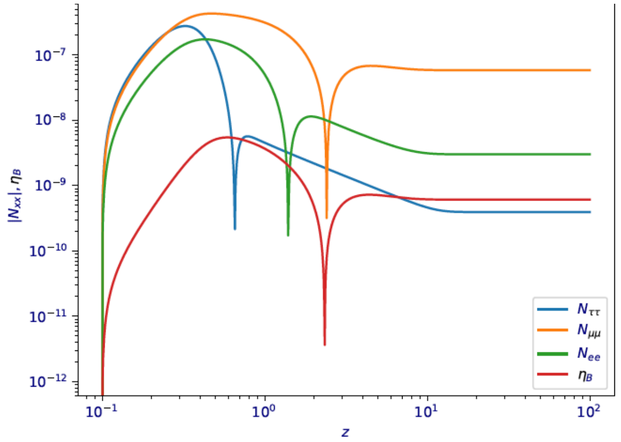
3. Pick a regime to solve `ulc-calc -m 3DME point.txt`

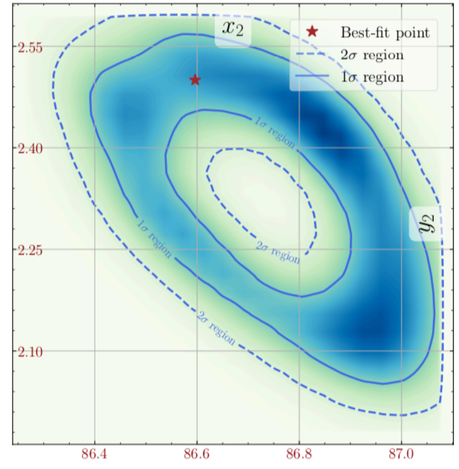
4. Select output including point, scan in 1 or 2D or multidimensional scan

`ulc-scan -m 3DME scan_x2.txt -o scan_x2.pdf -n 40`



`ulc-calc -m 3DME point.txt -o evolution.pdf`





Summary

- Leptogenesis is a plausible explanation for the smallness of neutrino masses and the observed matter anti-matter asymmetry

- In the type-I seesaw framework for leptogenesis, the mass of the RHN can range from $\mathcal{O}(10) - \mathcal{O}(10^{13})$ GeV scale.

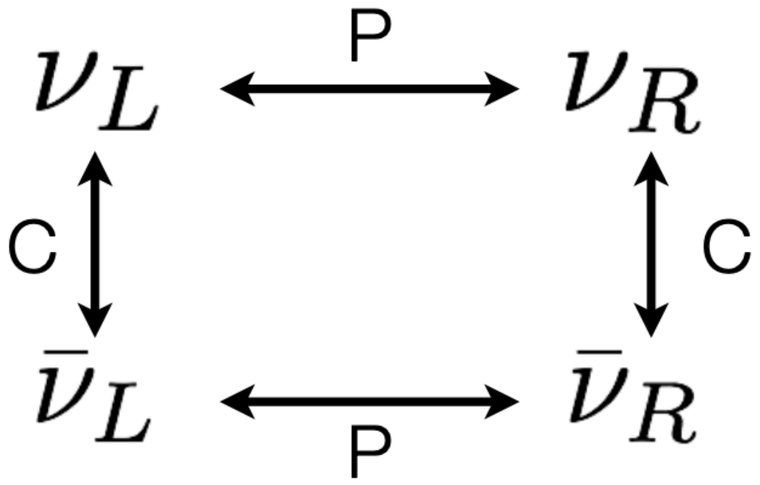
- Low-scale (and some regions of resonant) leptogenesis can be probed by a broad range of present and future experimental facilities.

- Gravitational waves are a complementary probe of intermediate and high-scale leptogenesis


Thank you for listening

Back up Slides

Weak Interactions violate charge conjugation symmetry. Recall that in weak interactions we have **left-handed neutrinos** (ν_L) & **right-handed antineutrinos** ($\overline{\nu}_R$)



If C symmetry is conserved there exists a symmetry between processes and their anti-particle (“conjugate”) counterparts. C does not allow this since left-handed anti-neutrinos don’t exist