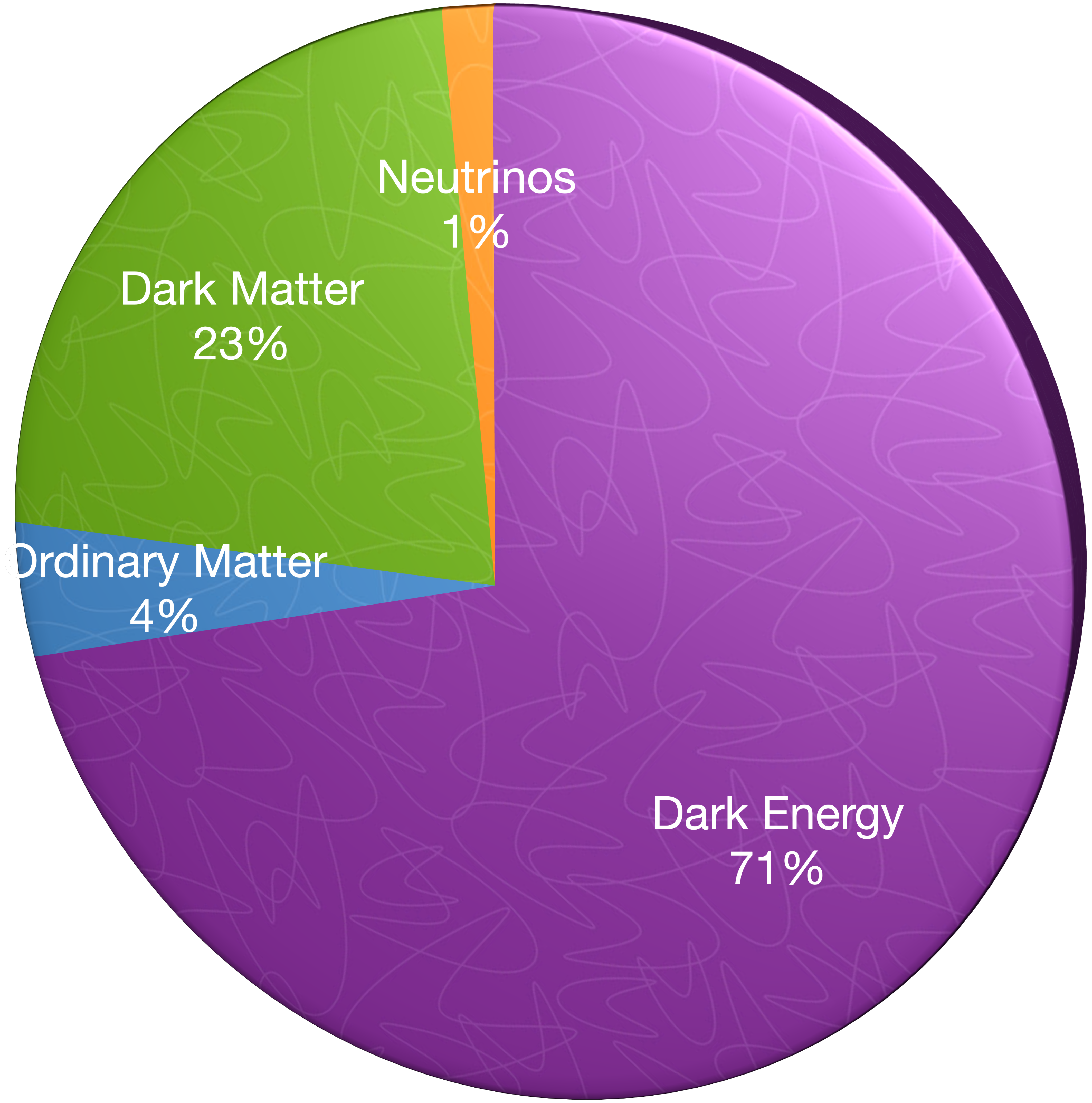
Leptogenesis

YETI 2024 - The 3 Neutrino Problem
Durham, 31st of July 2024

Jessica Turner, Institute for Particle Physics Phenomenology, Durham University

Universe's Energy Budget

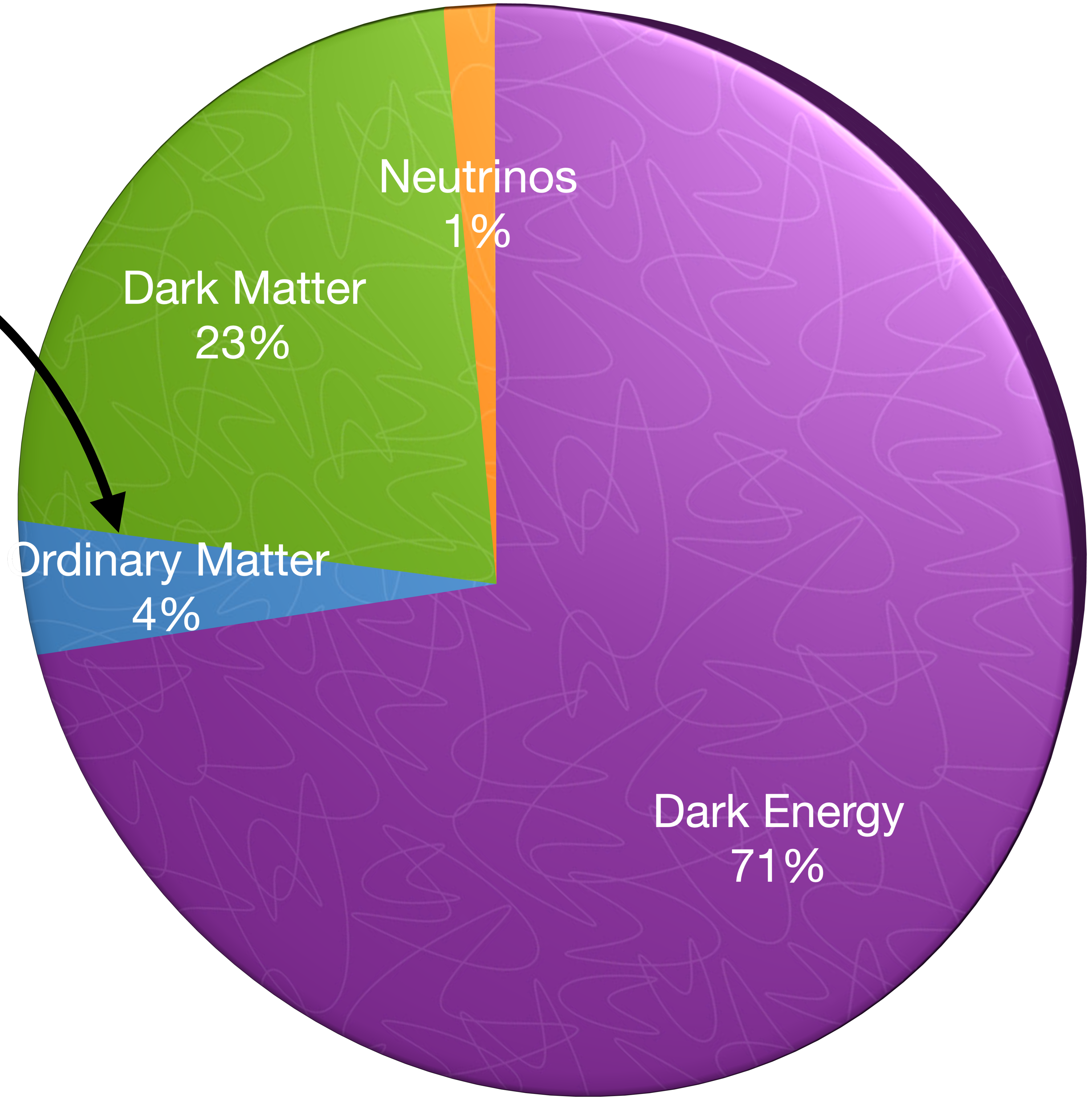


Universe's Energy Budget

Universe contains ordinary matter: p, n, e^-

No appreciable amounts of antimatter: $\overline{p}, \overline{n}, e^+$

$$\eta_B = \frac{n_B - n_{\overline{B}}}{n_\gamma} \sim 6 \cdot 10^{-10}$$



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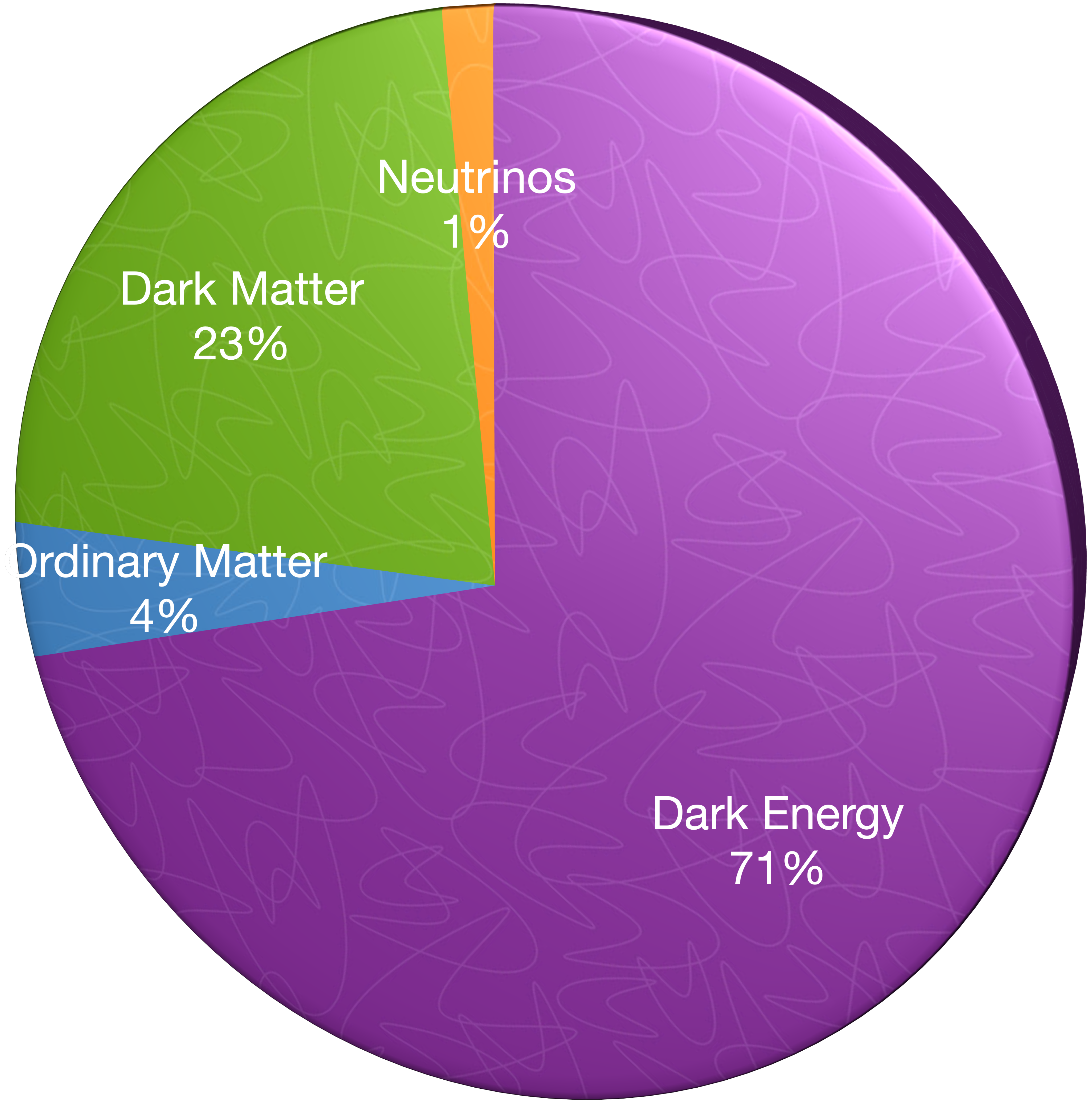
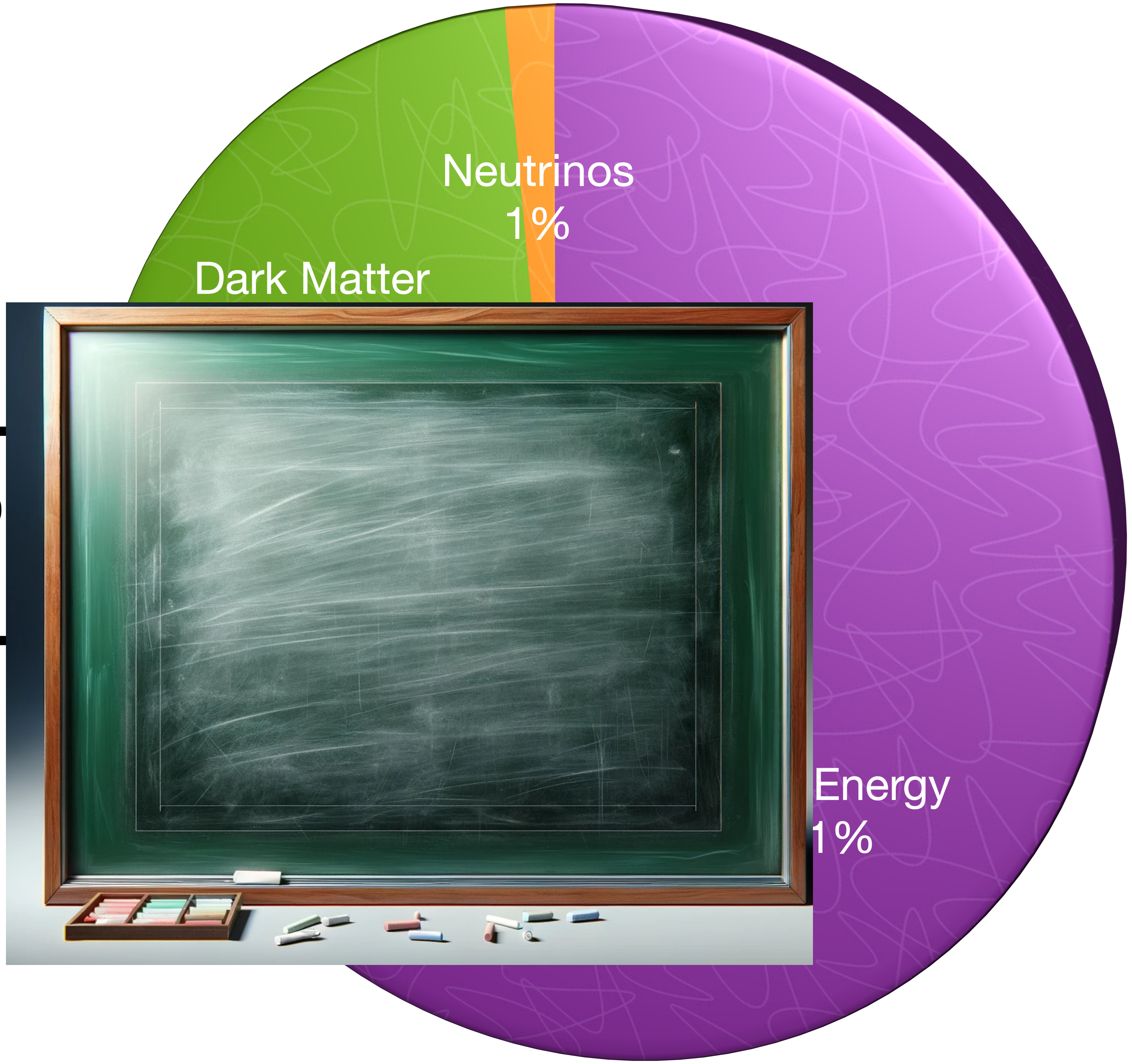


Sakharov's Conditions

- ☐ Baryon number violation
- ☐ C & CP-violation
- ☐ Departure from thermal equilibrium

Universe's Energy Budget



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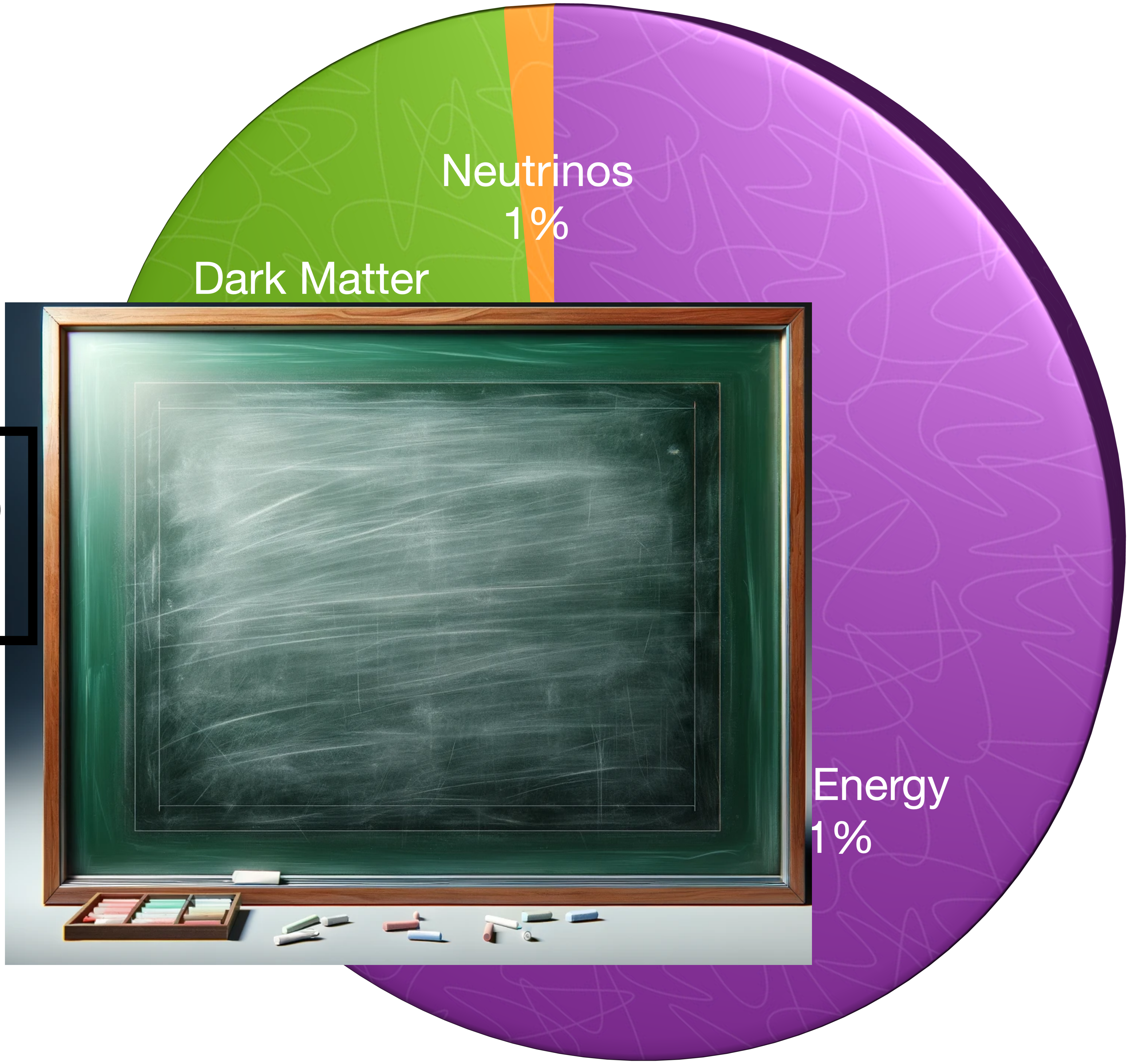

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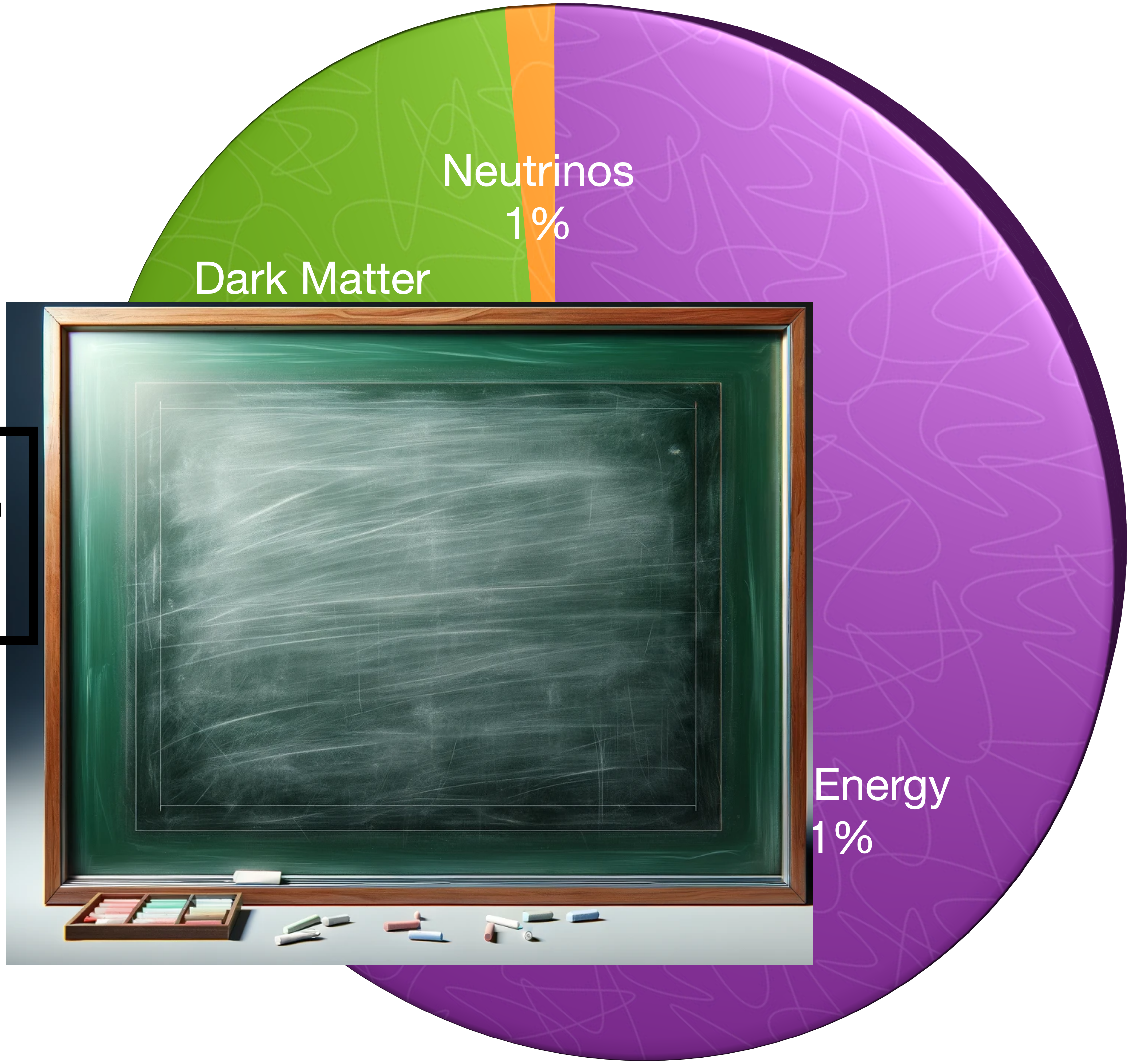

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Measuring the Matter-Antimatter Asymmetry: CMB

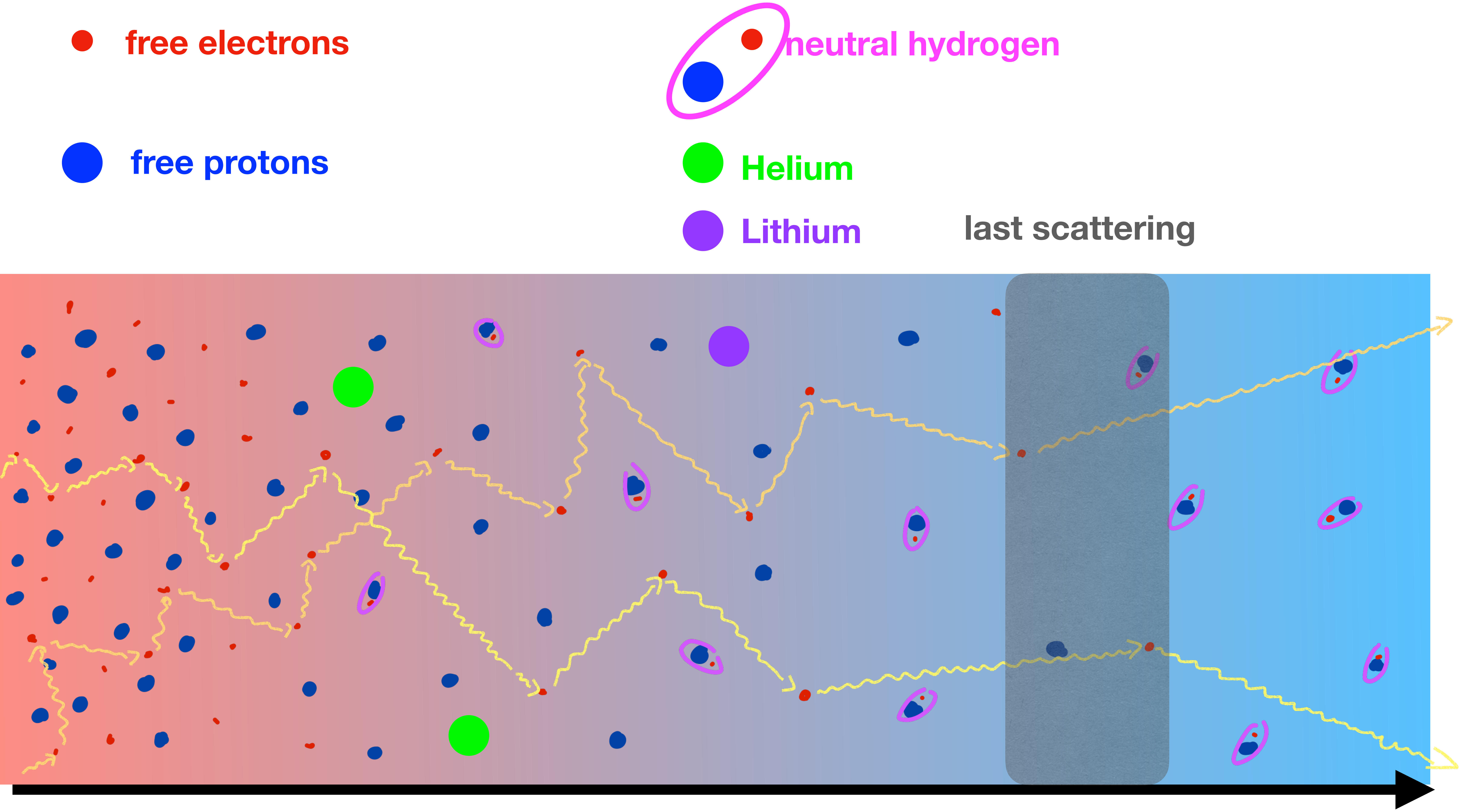
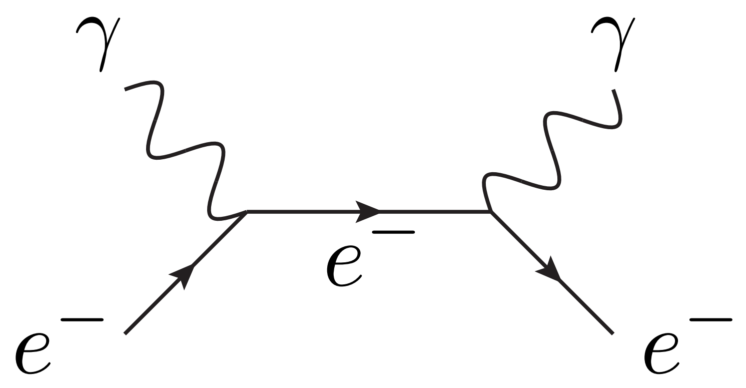
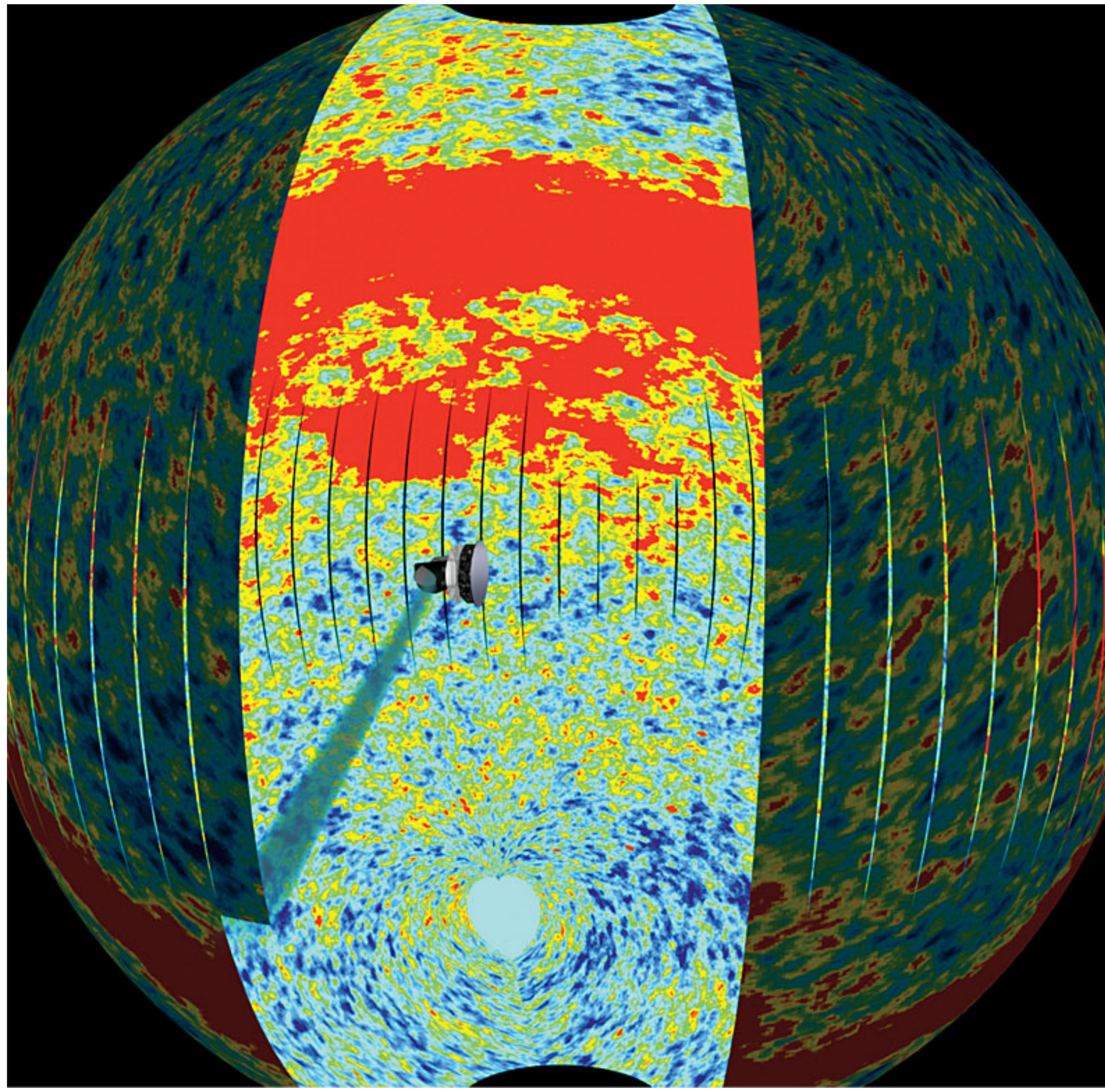


Image credit: Yacine Ali-Haïmoud



time after Big Bang~
380,000 yr
Temperature ~ 3000 K



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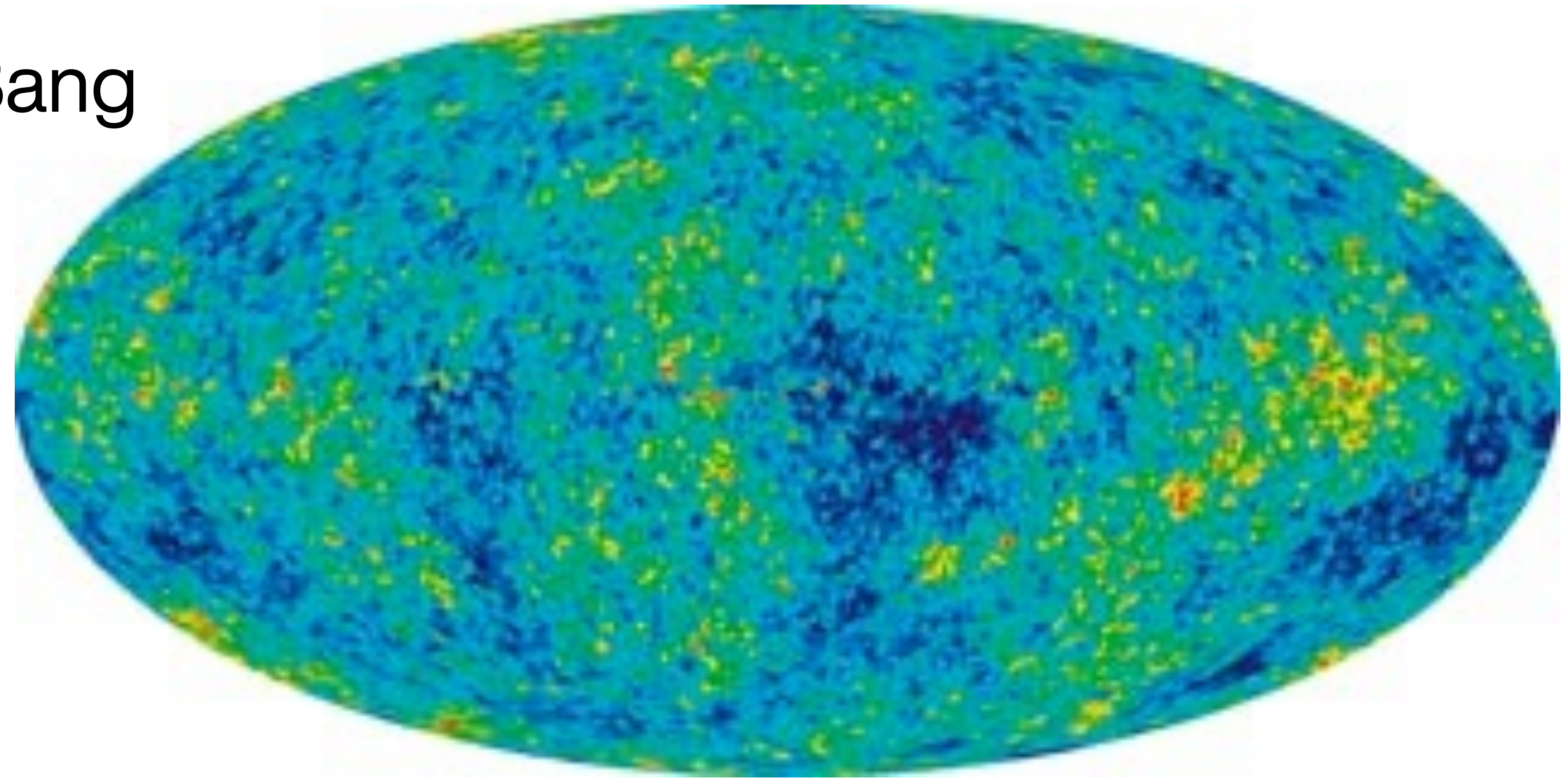
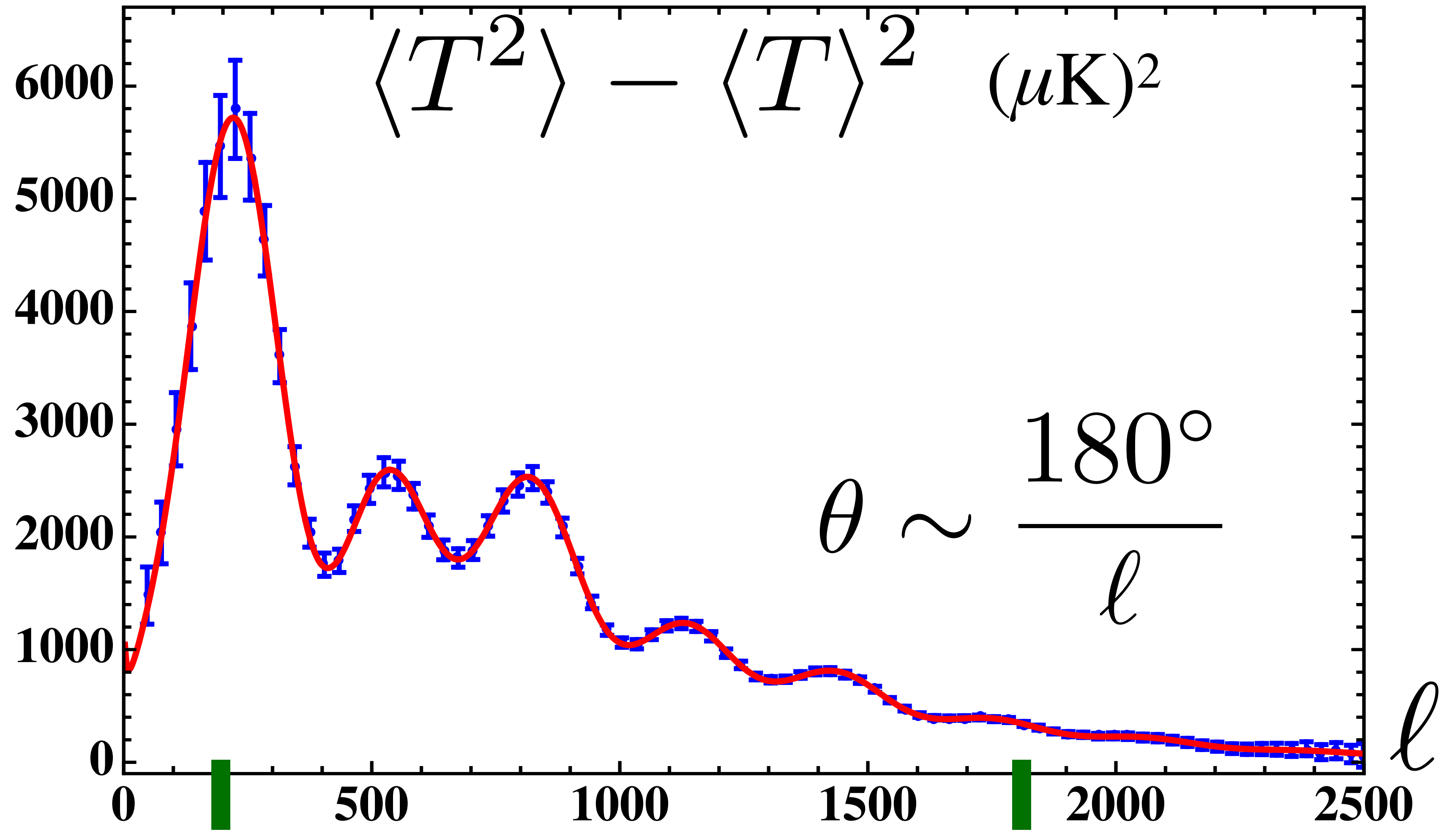


Angular power spectrum = **variance of temperature as a function of angular scale**



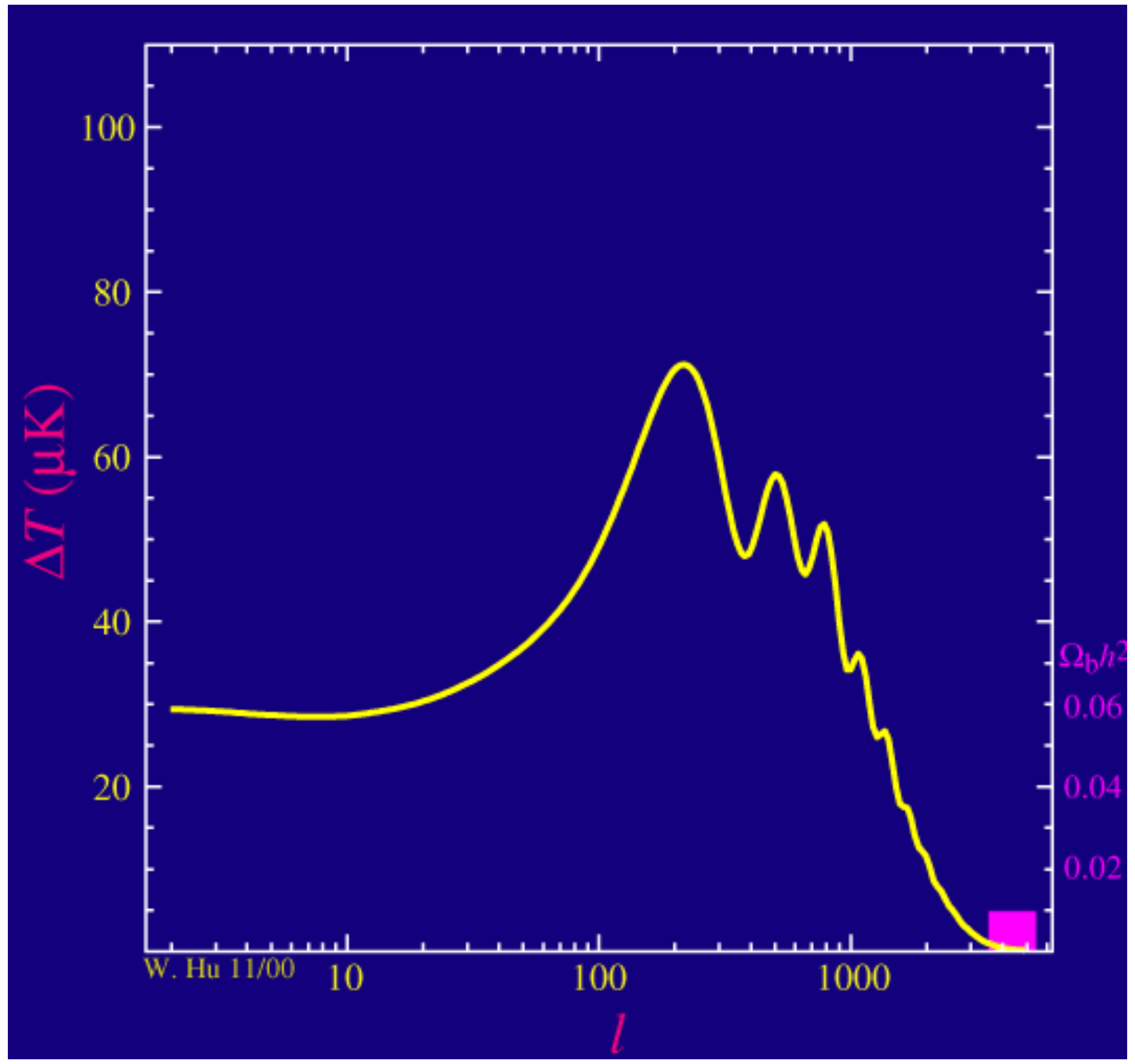
θ ~ 1 degree

θ ~ 1/10 degree

Planck 2018 (error bars x 5)

Best-fit model (6 parameters)

Wayne Hu's Website

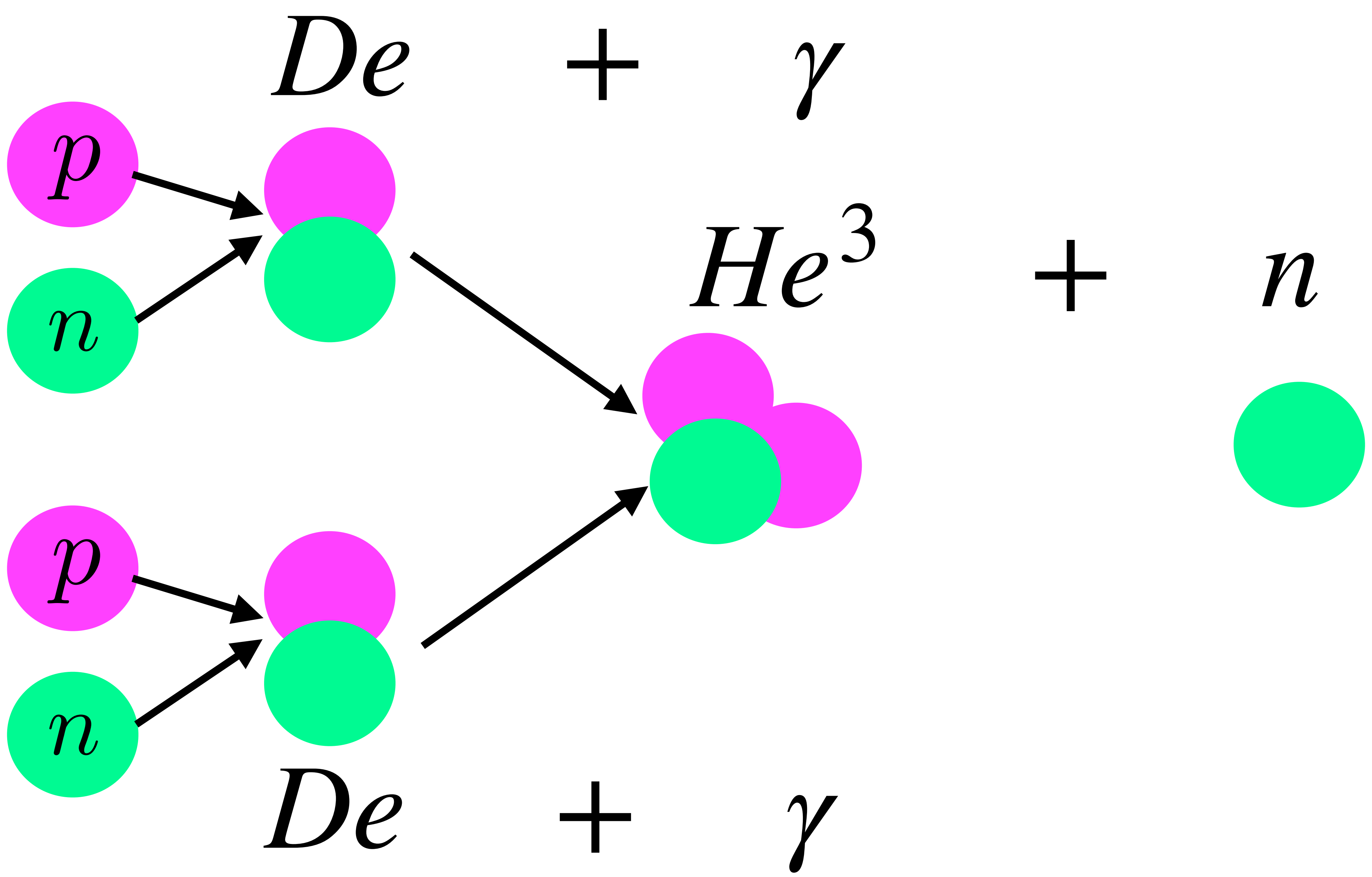


$$6.02 \times 10^{-10} \leq \eta_B \leq 6.18 \times 10^{-10}\,(95\%\mathrm{CL})$$

Measuring the Matter-Antimatter Asymmetry: BBN

Time: 3 minutes after Big Bang

Temperature: ~ 10^{10} K



Synthesis of light elements such as Deuterium, Helium and Lithium

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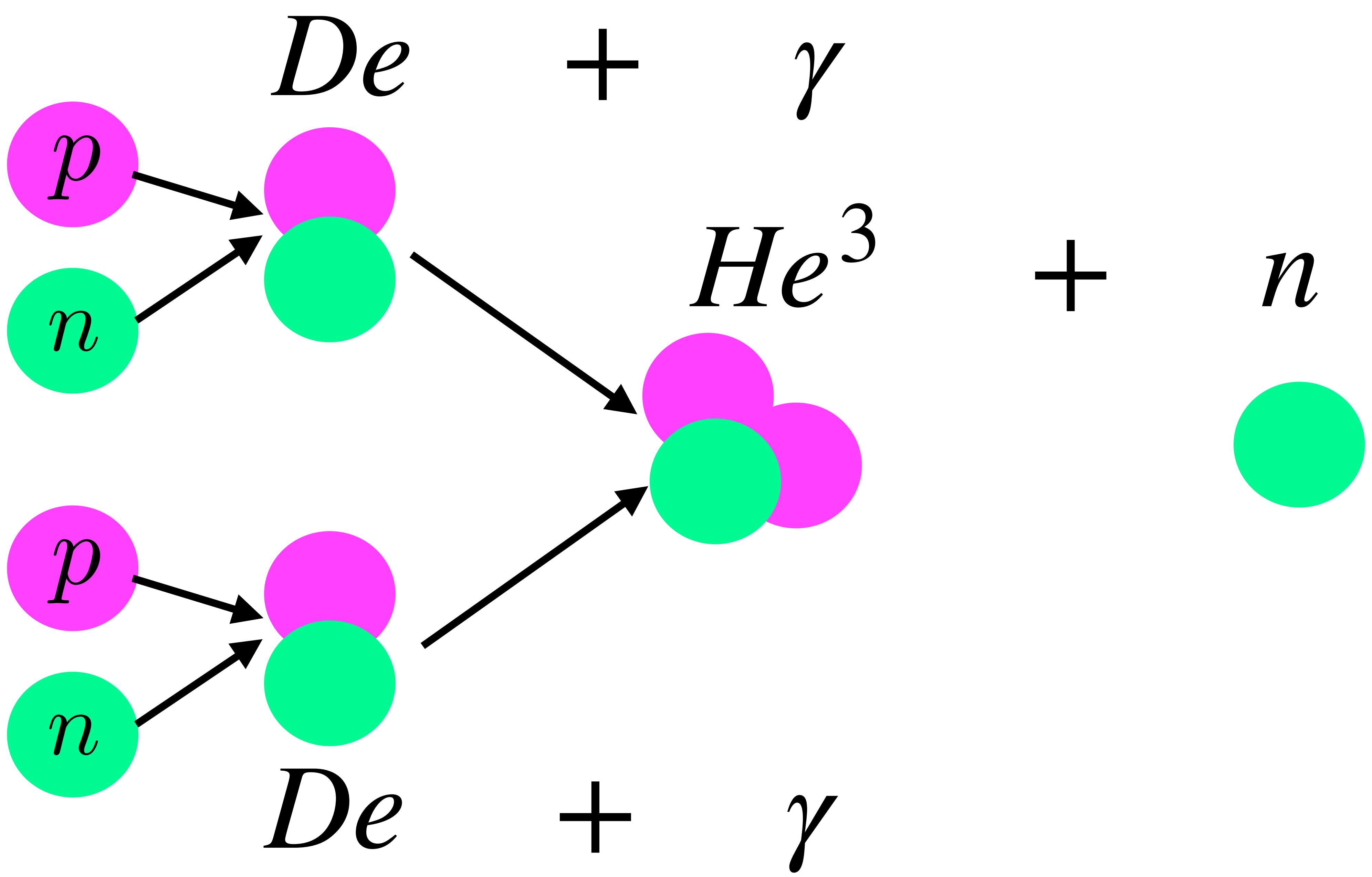
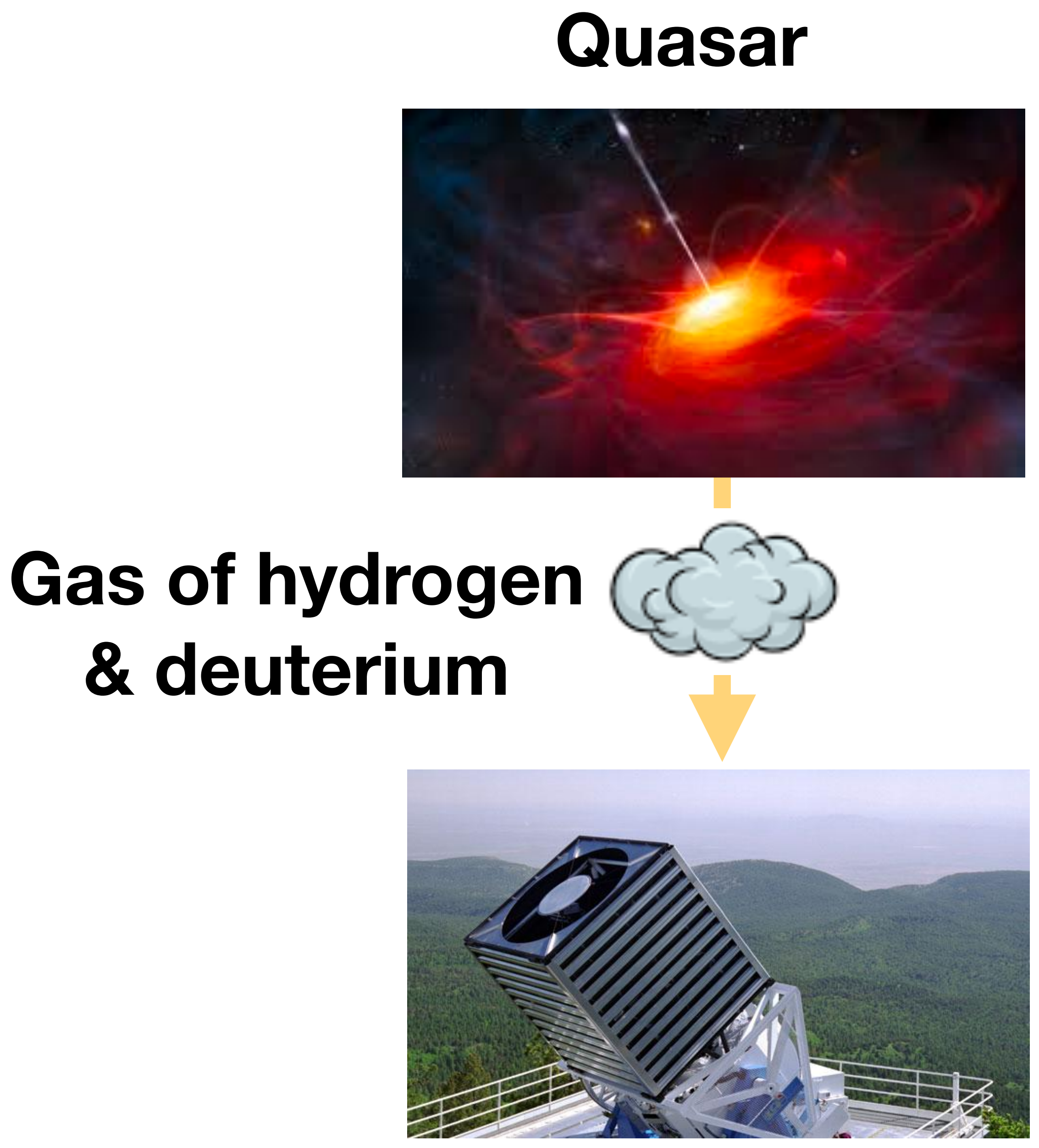
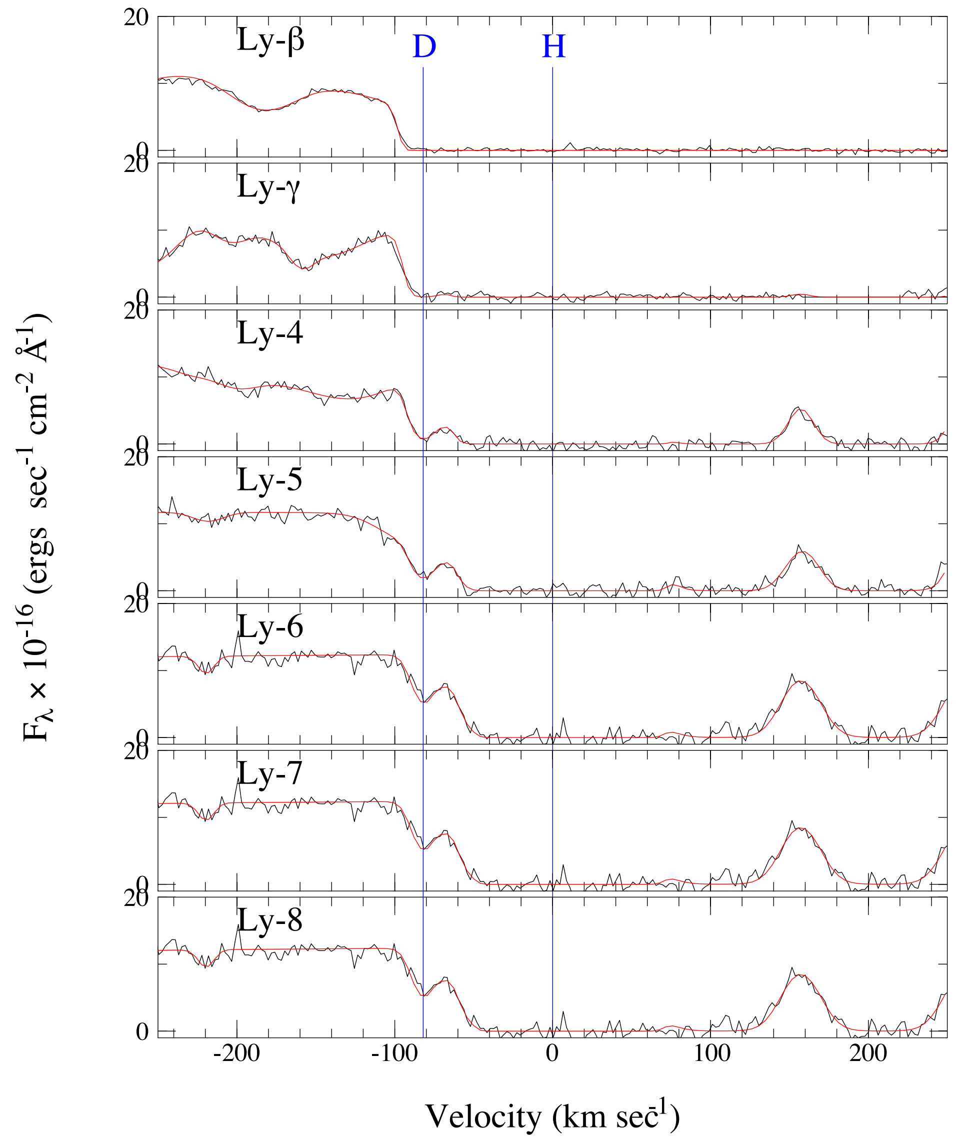
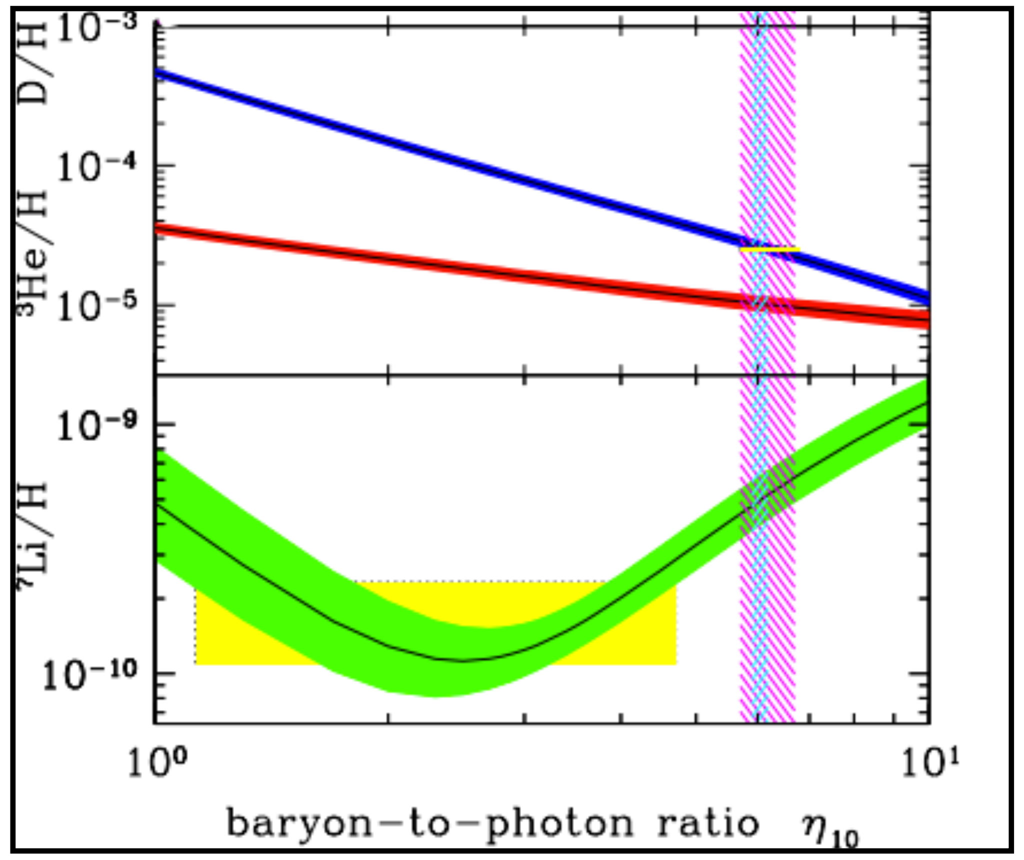








Synthesis of light elements such as Deuterium, Helium and Lithium

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

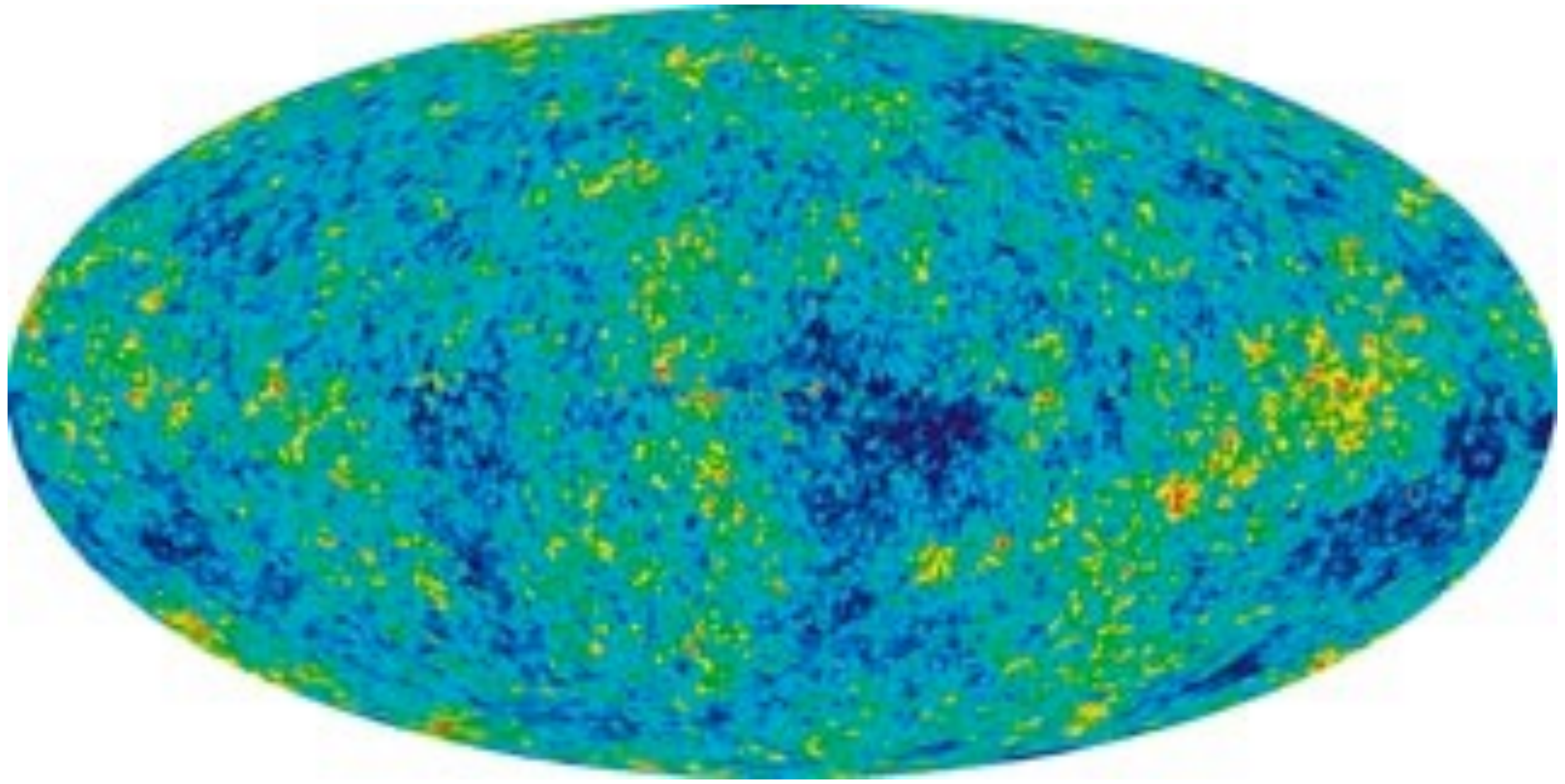
Matter-Antimatter Asymmetry as an initial condition

- Could the Universe have been created more matter than antimatter? Such an **initial condition** is hard to make work with inflation

- Inflation explains how the Universe's temperature is remarkably homogeneous, $T \sim 2.75K$

- Regions of the Universe which are causally disconnected must have been in causal contact at some early time. Inflation can explain this.

$$\overline{T} \sim 2.75\,K$$
$$\Delta T \sim \mu K$$

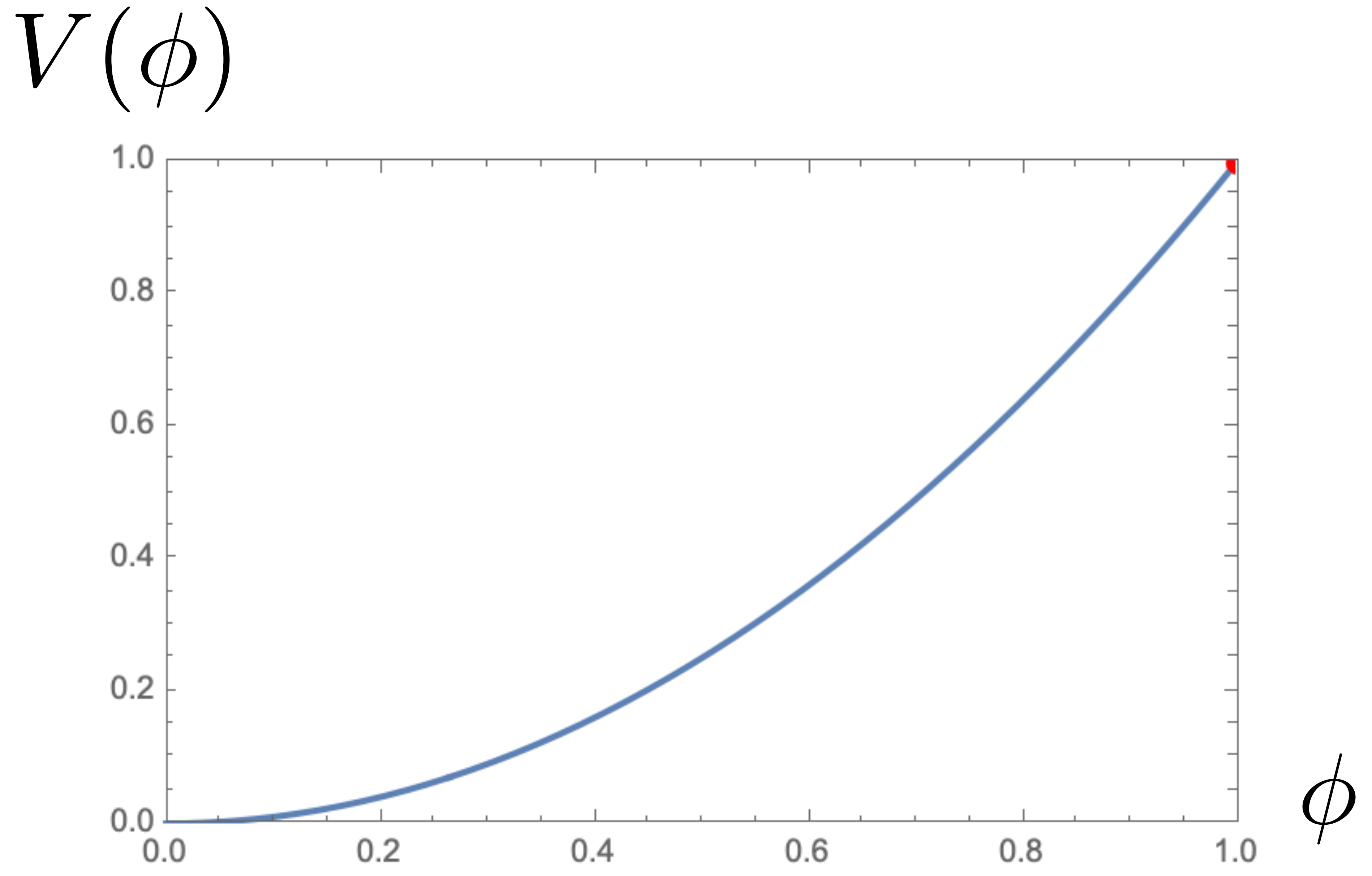


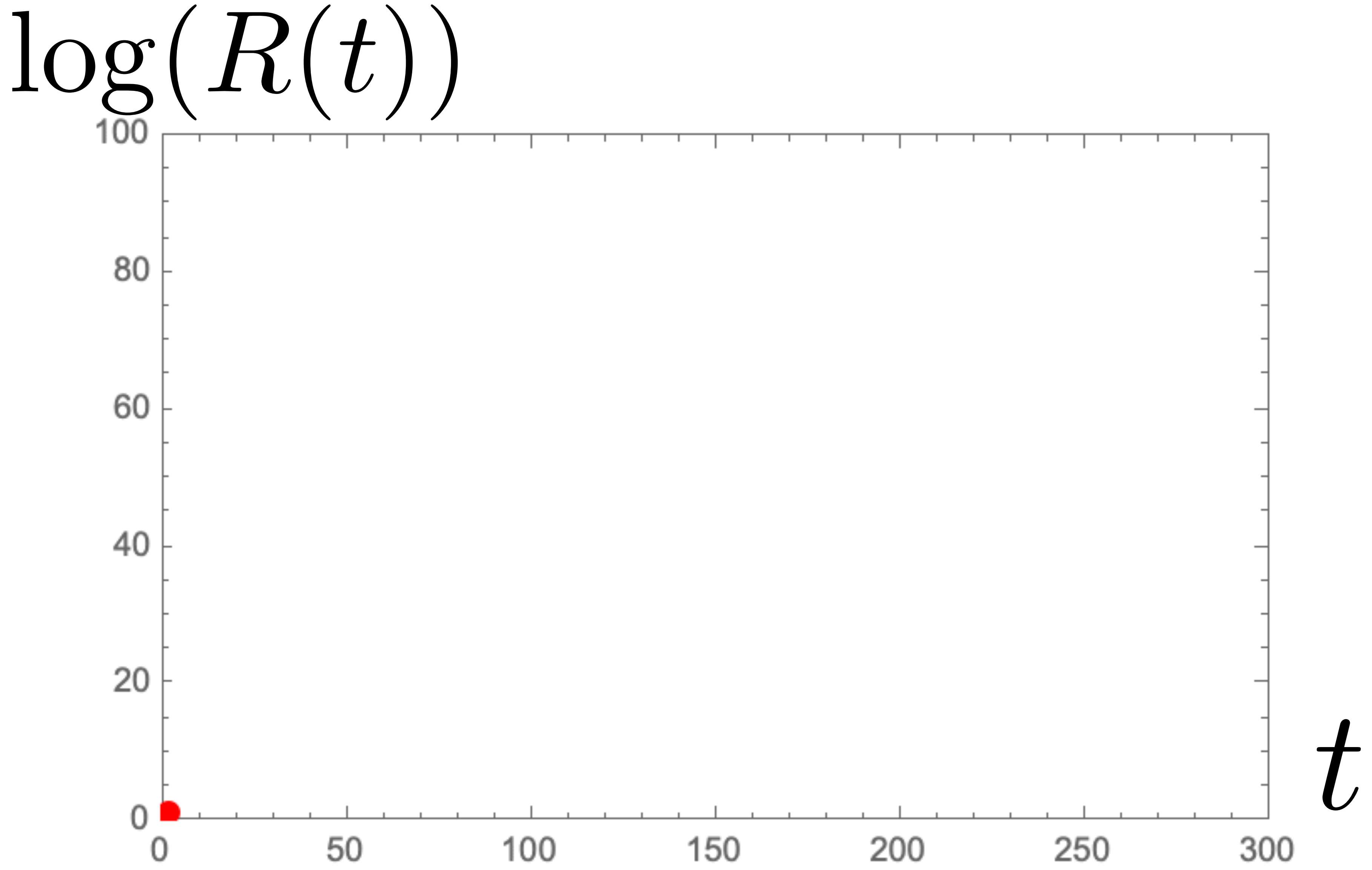
Matter-Antimatter Asymmetry as an initial condition

- New scalar (inflaton) initially displaced from minimum of its potential

- As it rolls down to minimum this causes exponential expansion of the Universe

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3} G_N \rho = \text{ const} \implies a(t) = a(0)e^{Ht}$$





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- Quantum fluctuation of inflaton seed structure formation

- To explain baryon asymmetry today from an initial condition of the Universe we would need to extrapolate back in time: BAU becomes degenerate fermi gas

- This fermi degenerate gas would eventually exceed energy density of inflaton and Universe couldn't have inflated enough i.e. e^N , $N \gtrsim 60$

Matter-Antimatter Asymmetry as an open problem

- There are two independent ways of measuring how much more matter than antimatter there is in the Universe: CMB & BBN data

- Both measurements agree to high statistical significance

- The Standard Model of Particle Physics cannot explain this asymmetry between matter & antimatter so new physics is required

- Theories which dynamically explain this asymmetry are baryogenesis mechanisms

Popular Theories of Baryogenesis

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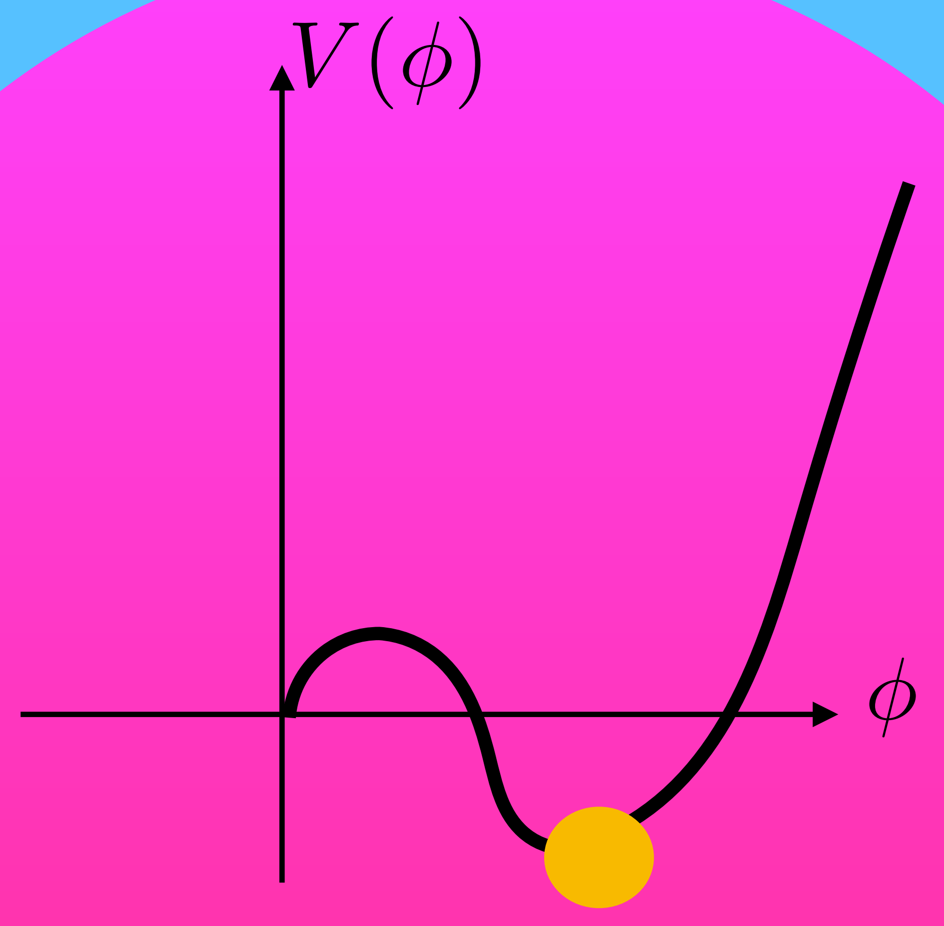
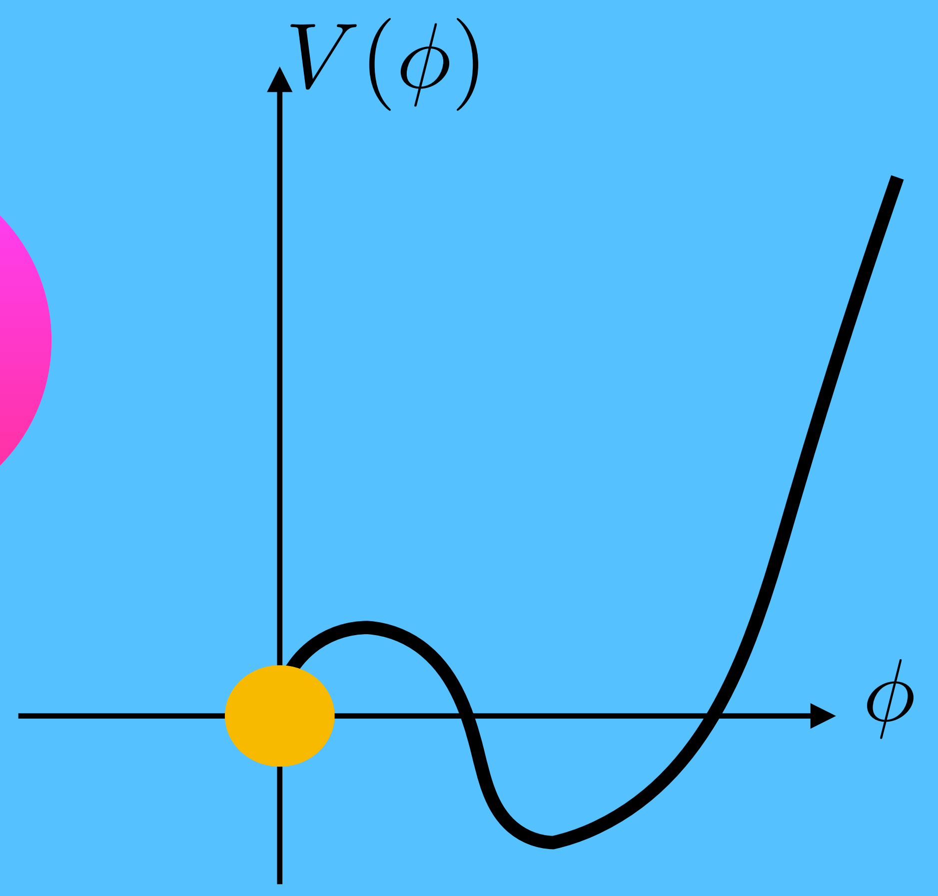
Electroweak Baryogenesis



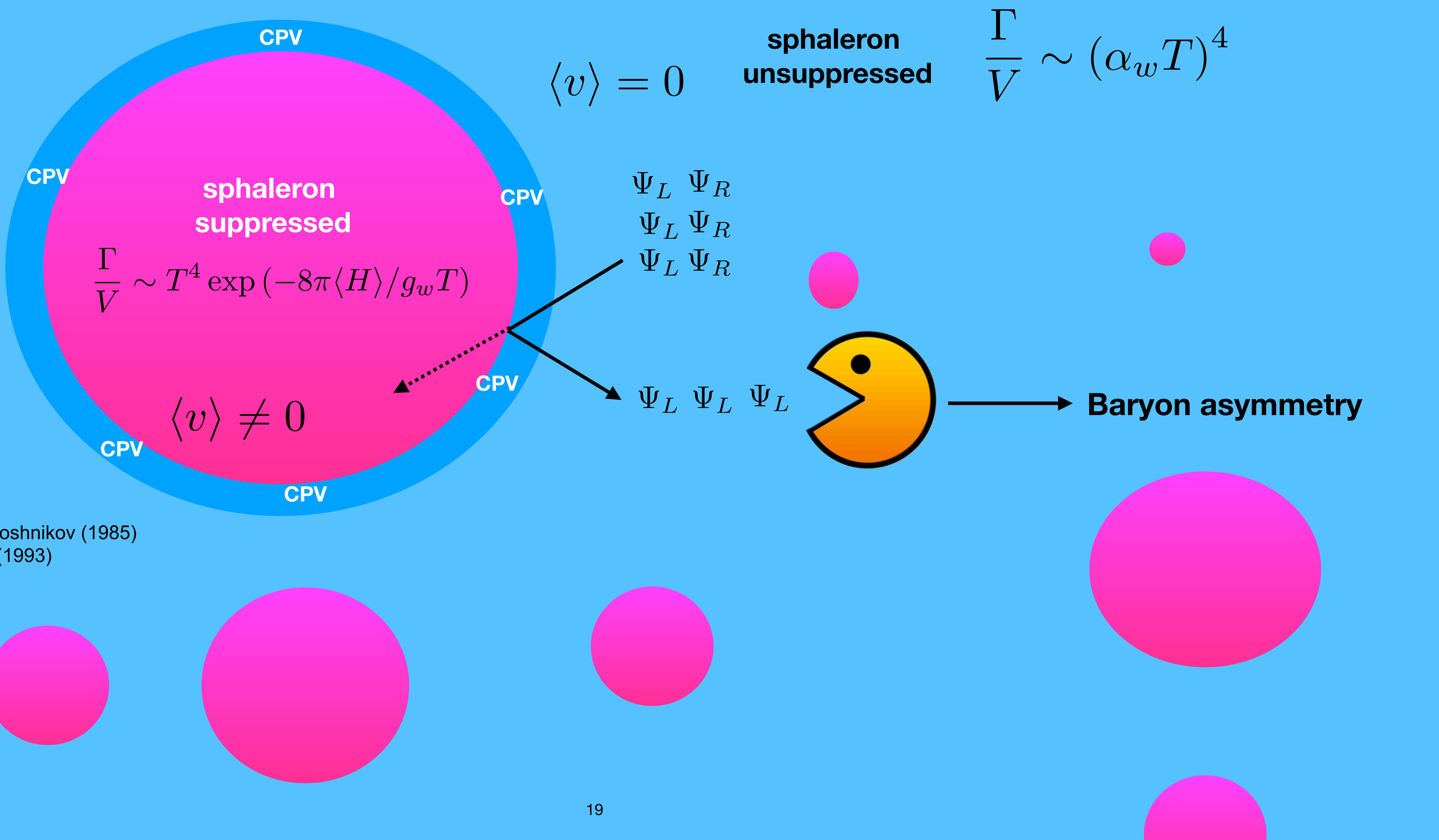
$$\langle v \rangle \neq 0$$

$$\langle v \rangle = 0$$

Kuzmin, Rubakov & Shaposhnikov (1985)
Cohen, Kaplan & Nelson (1993)



Electroweak Baryogenesis

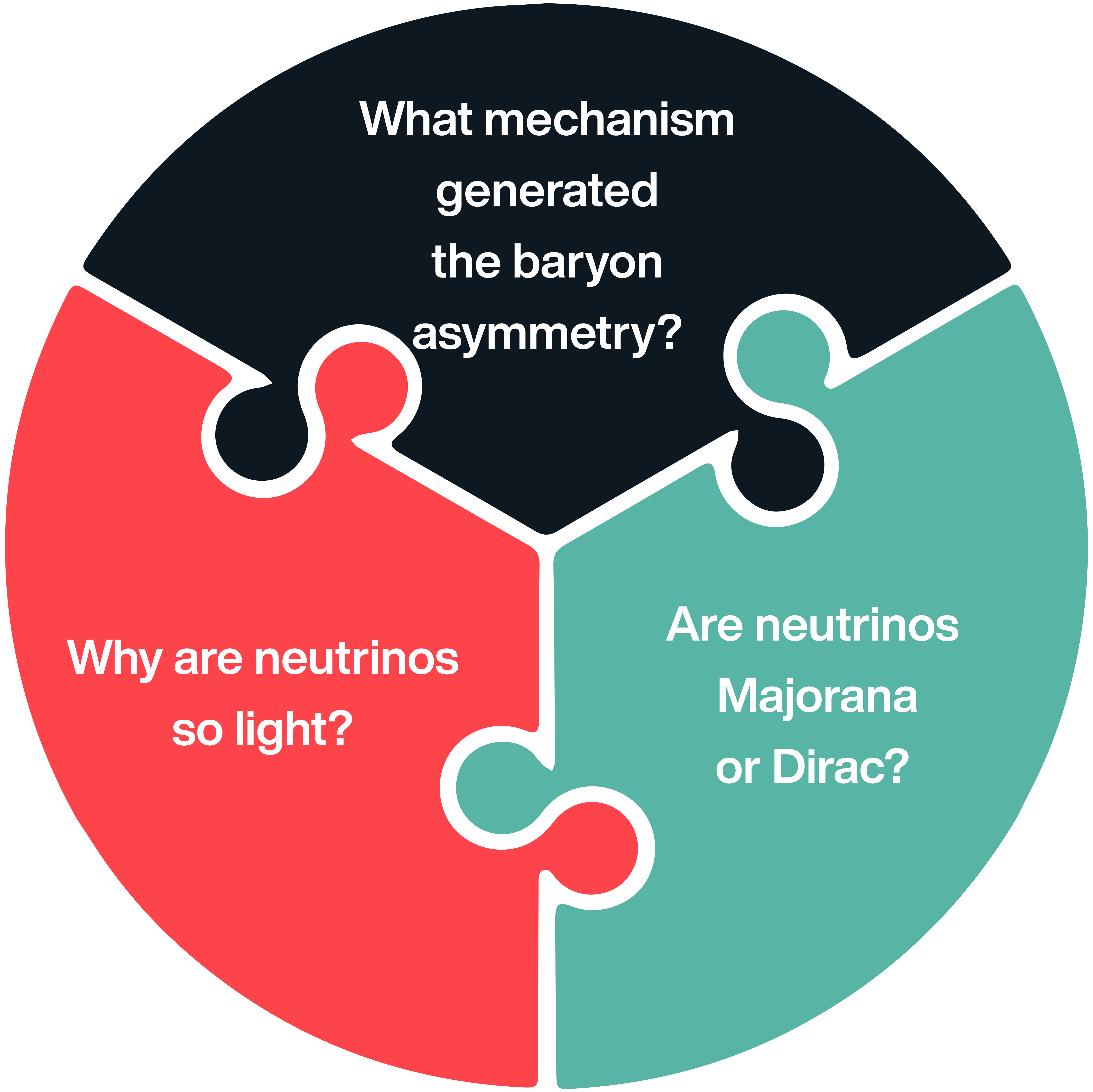


Kuzmin, Rubakov & Shaposhnikov (1985)
Cohen, Kaplan & Nelson (1993)

Electroweak Baryogenesis

- Strong first-order EW phase transition $\Longrightarrow$ modifications in the **Higgs sector**
- Fermion species reflected CP violating at Higgs bubble wall $\Longrightarrow$ **electric dipole moment**
- Constraints rule out many models but few attempts to collider and EDM bounds:
- **Time-varying Yukawa couplings:** CKM varies during EWPT $\Longrightarrow$ Yukawa couplings $\mathcal{O}(1)$ at EW symmetric phase and end with present values in EW broken phase $\Longrightarrow$ CPV not suppressed at PT but evades EDM constraint today. Baldes, Bruggisser, Konstantin, Servant (2016)
- **Composite Higgs:** Higgs arises due to non-zero condensate $\Longrightarrow$ confining PT and EWPT linked. Yukawa couplings depend on mixing between elementary and composite fermion $\Longrightarrow$ vary during confining PT. Bruggisser, von Harling, Matsedonskyi, Servant (2018)

Popular Theories of Baryogenesis


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


Are neutrinos
Majorana
or Dirac?

See tomorrow's talk by Cheryl Patrick
for more details

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

$$e^{-} \qquad\qquad e^{+}$$

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

$$L = +1 \qquad\qquad L = -1$$

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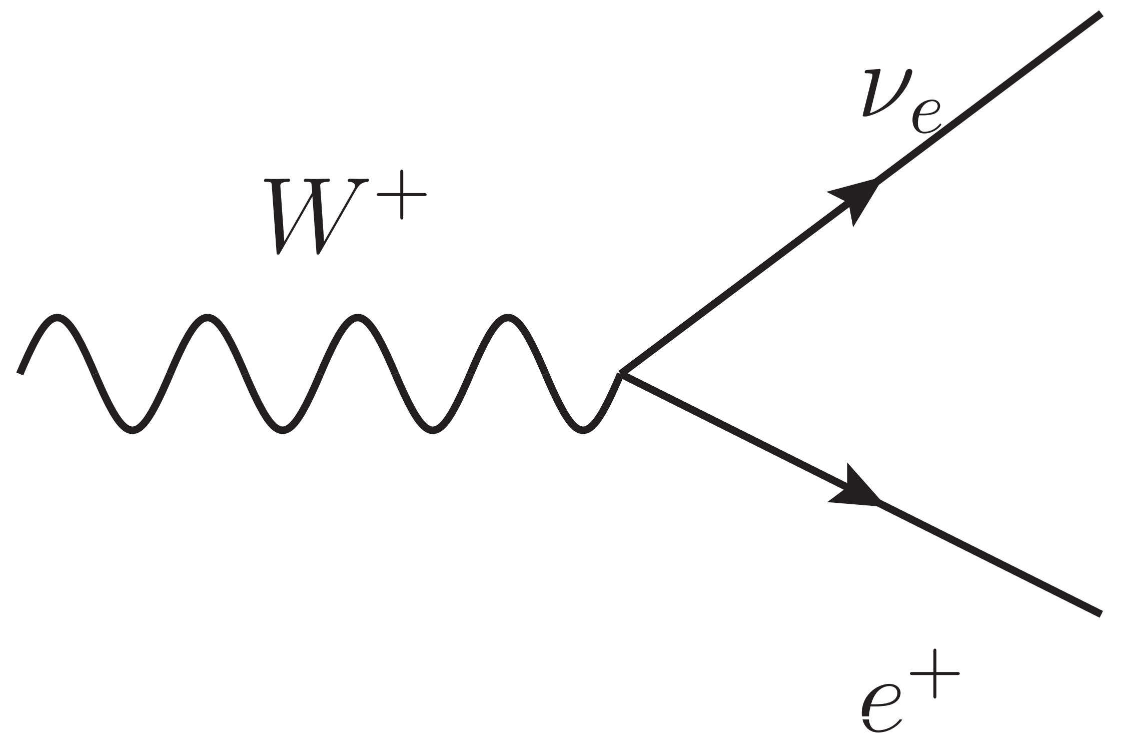

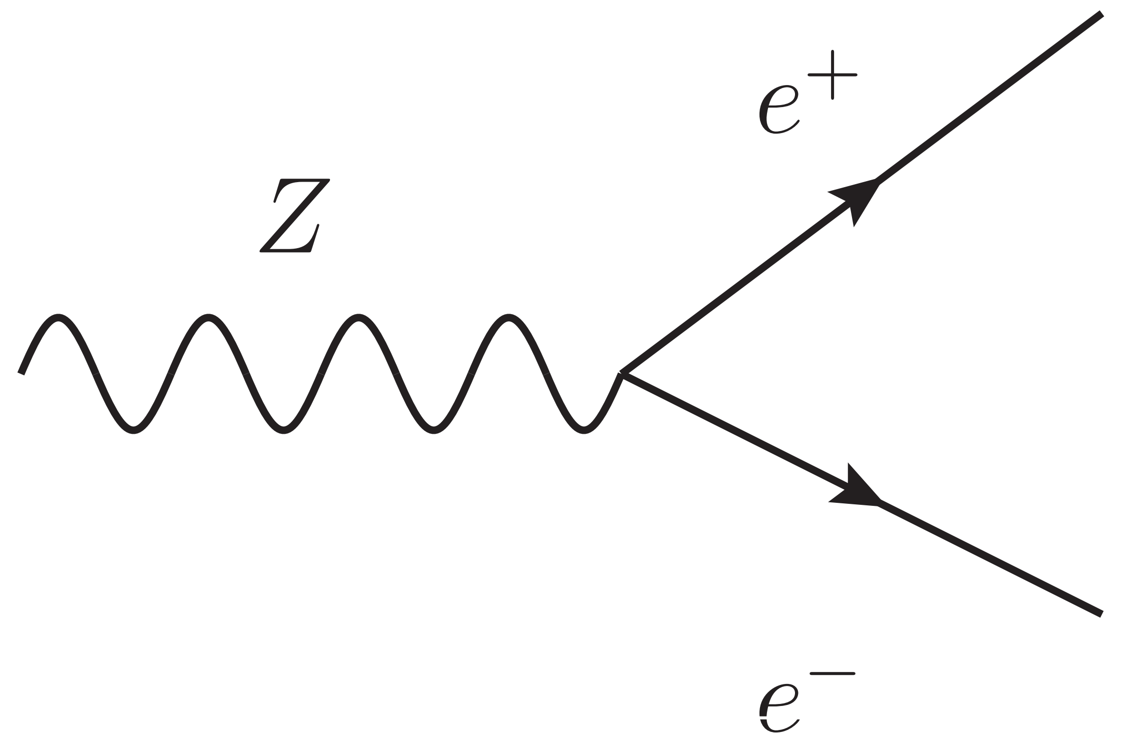

We have only ever observed lepton number conserving processes

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

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

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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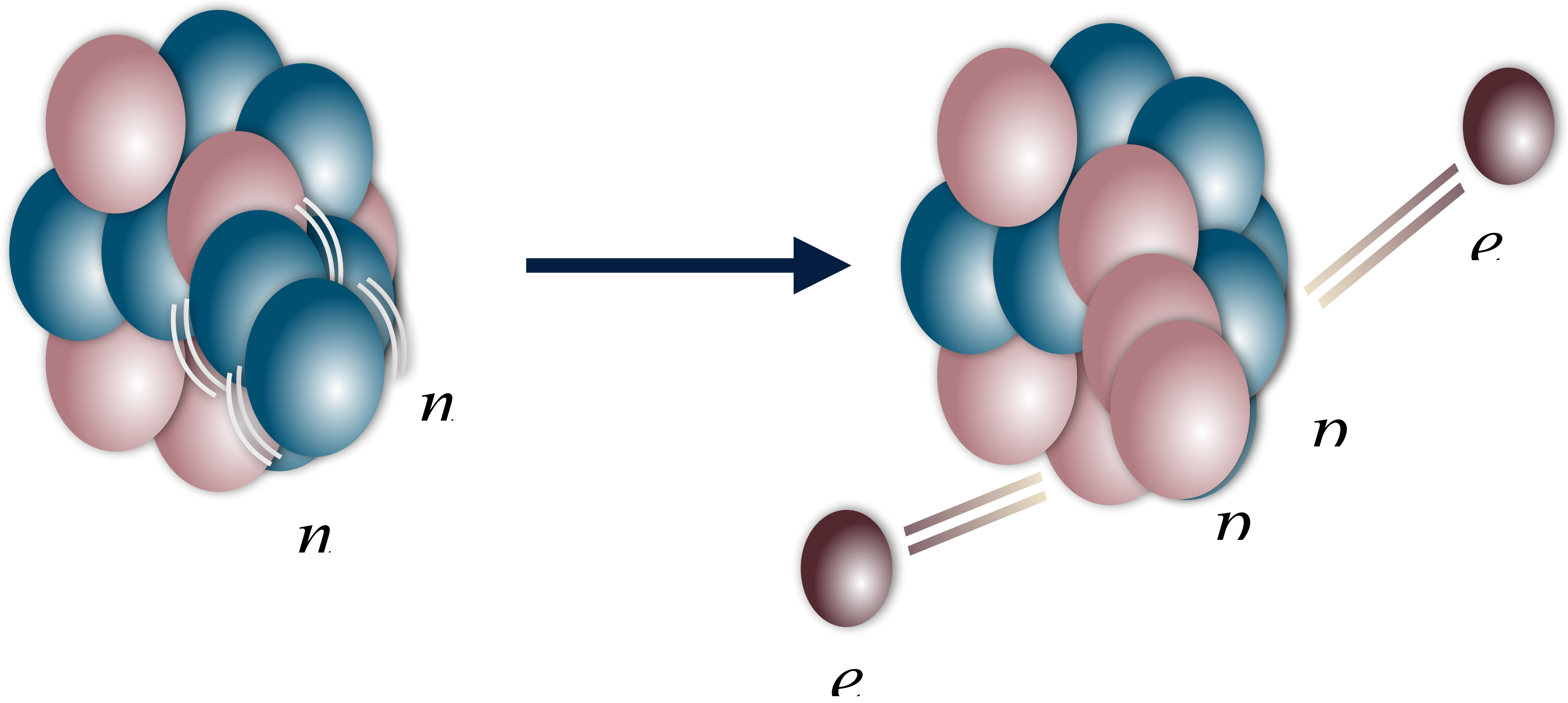
Neutrinoless double beta decay experiments are searching for Lepton number violation



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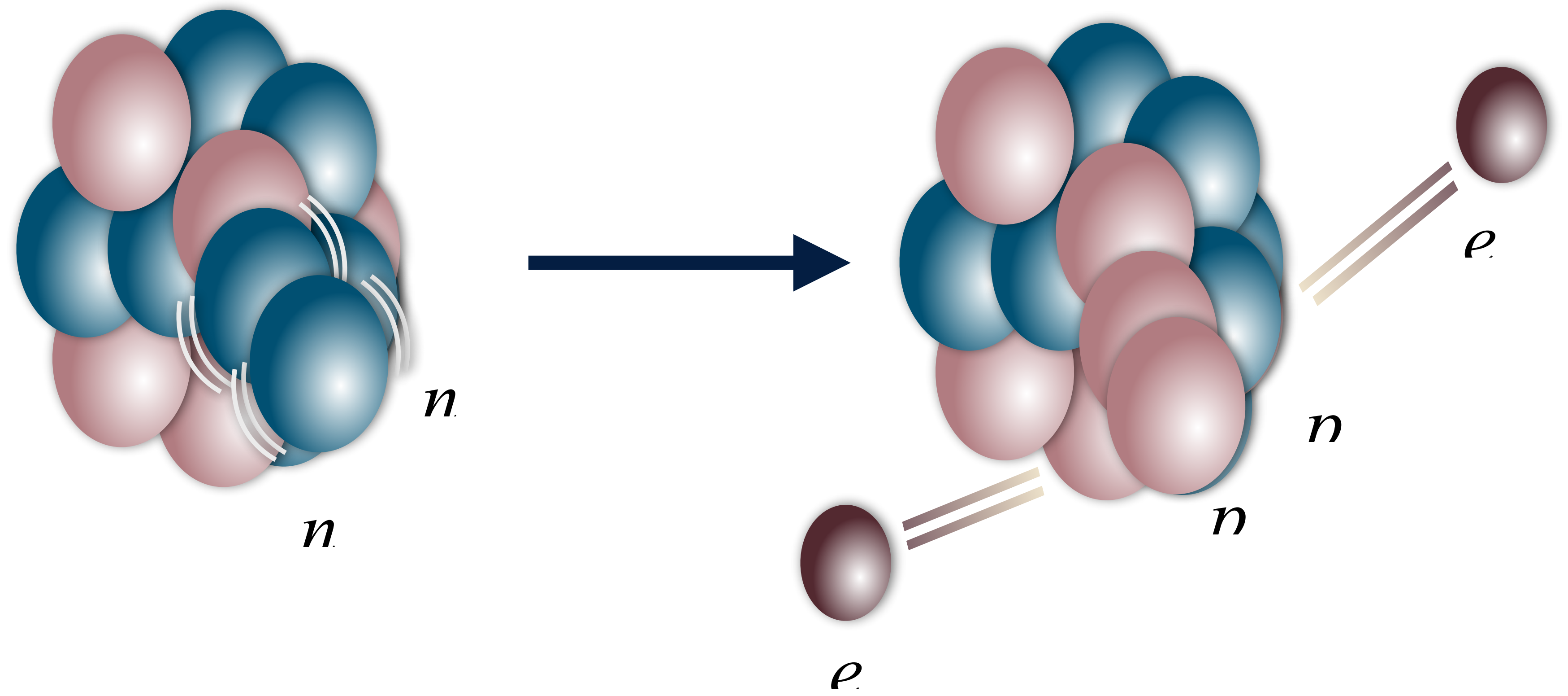

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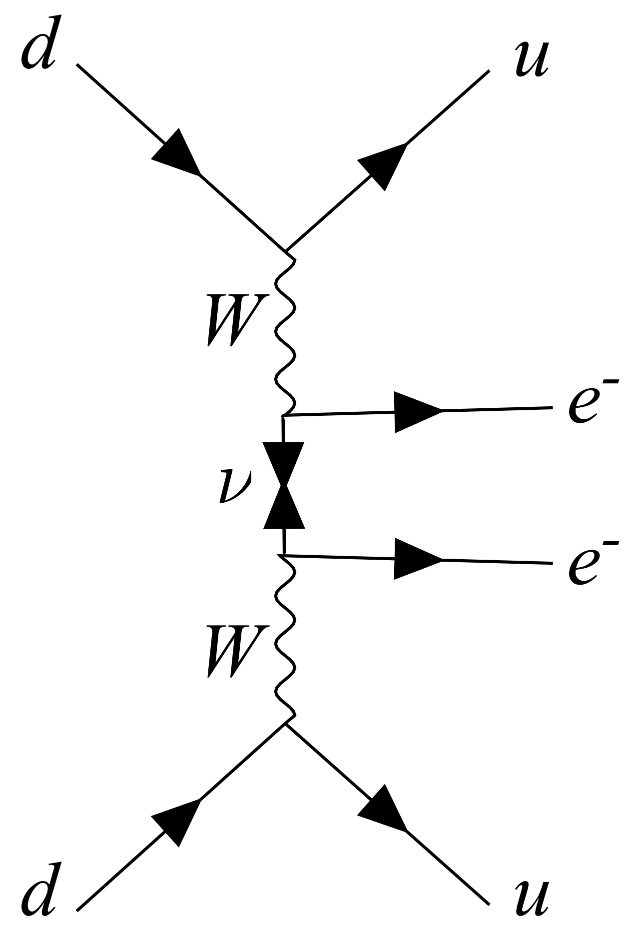

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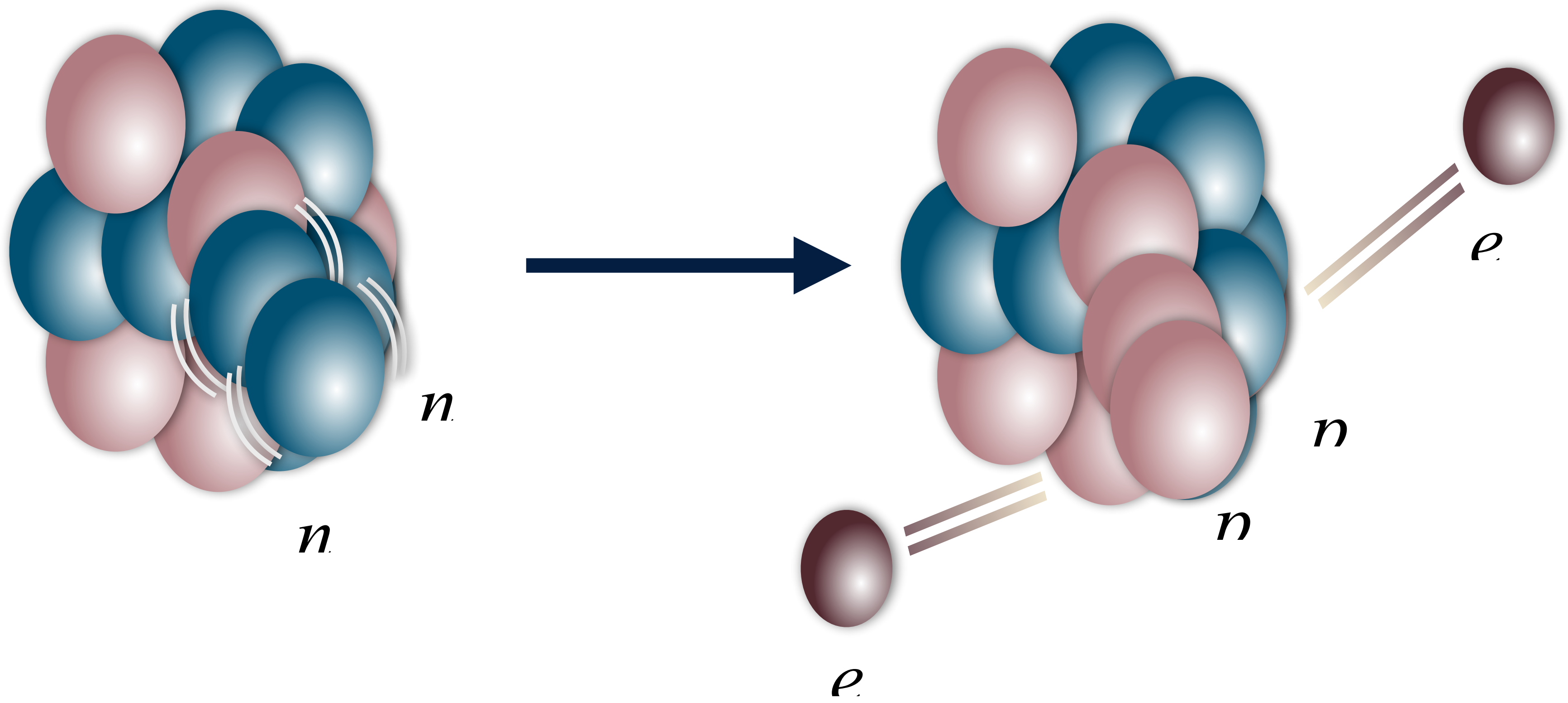

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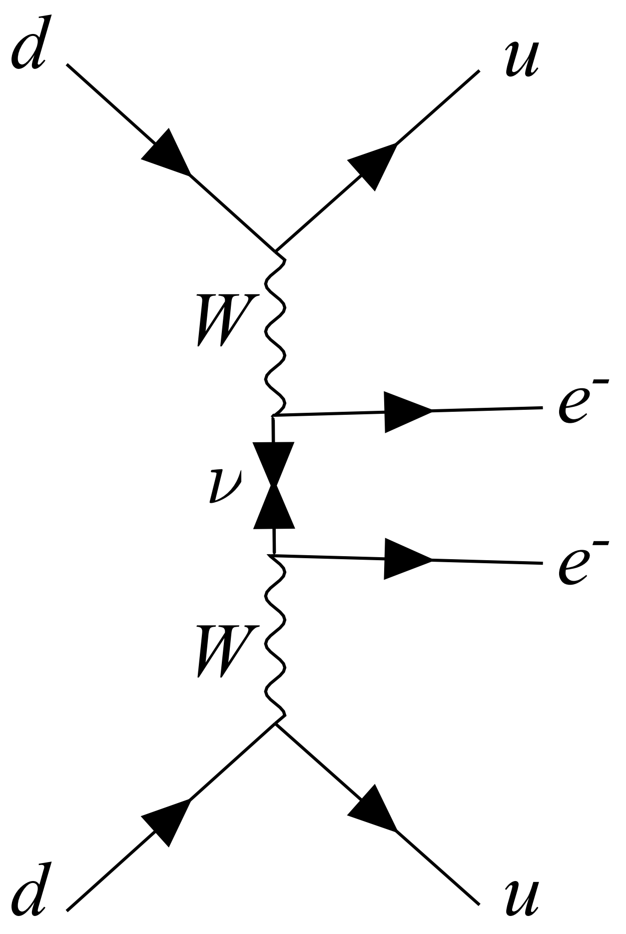
See Concha and Cheryl's talk!



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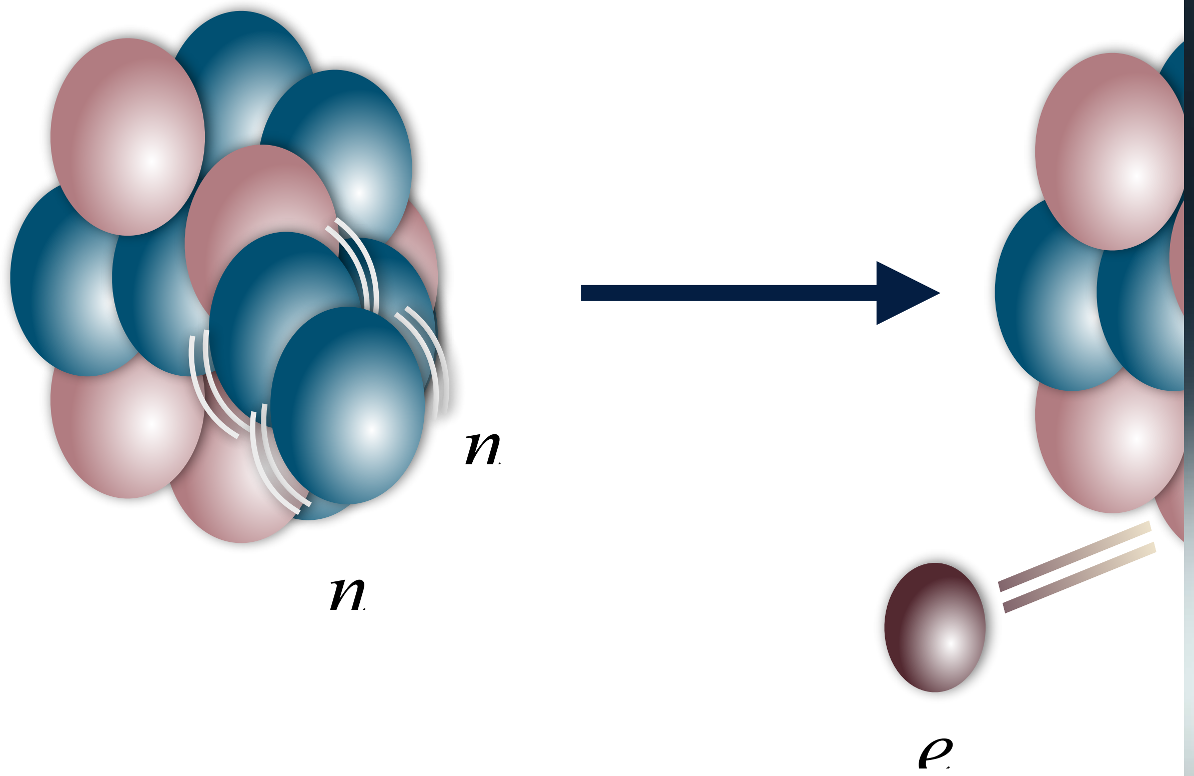

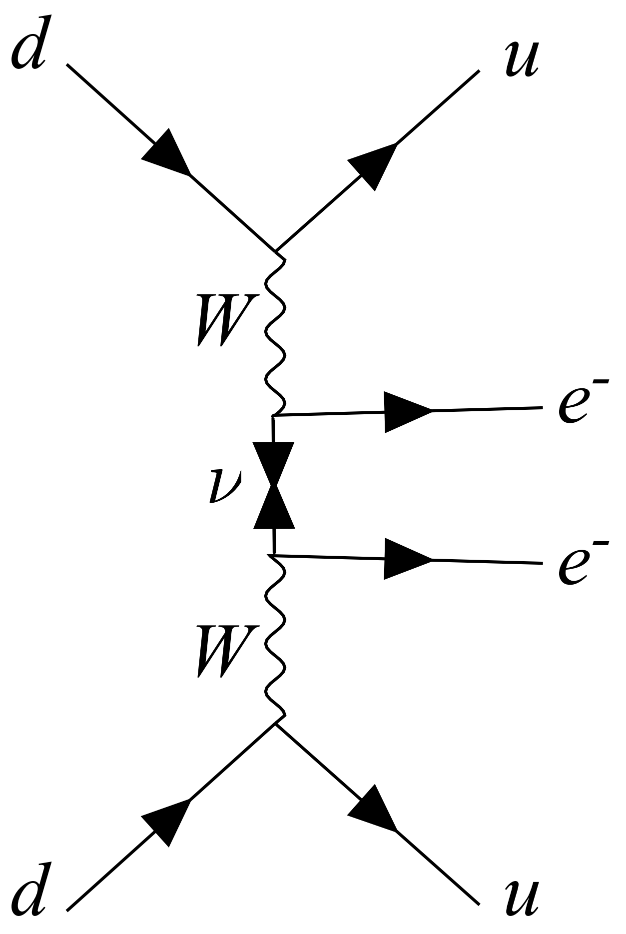

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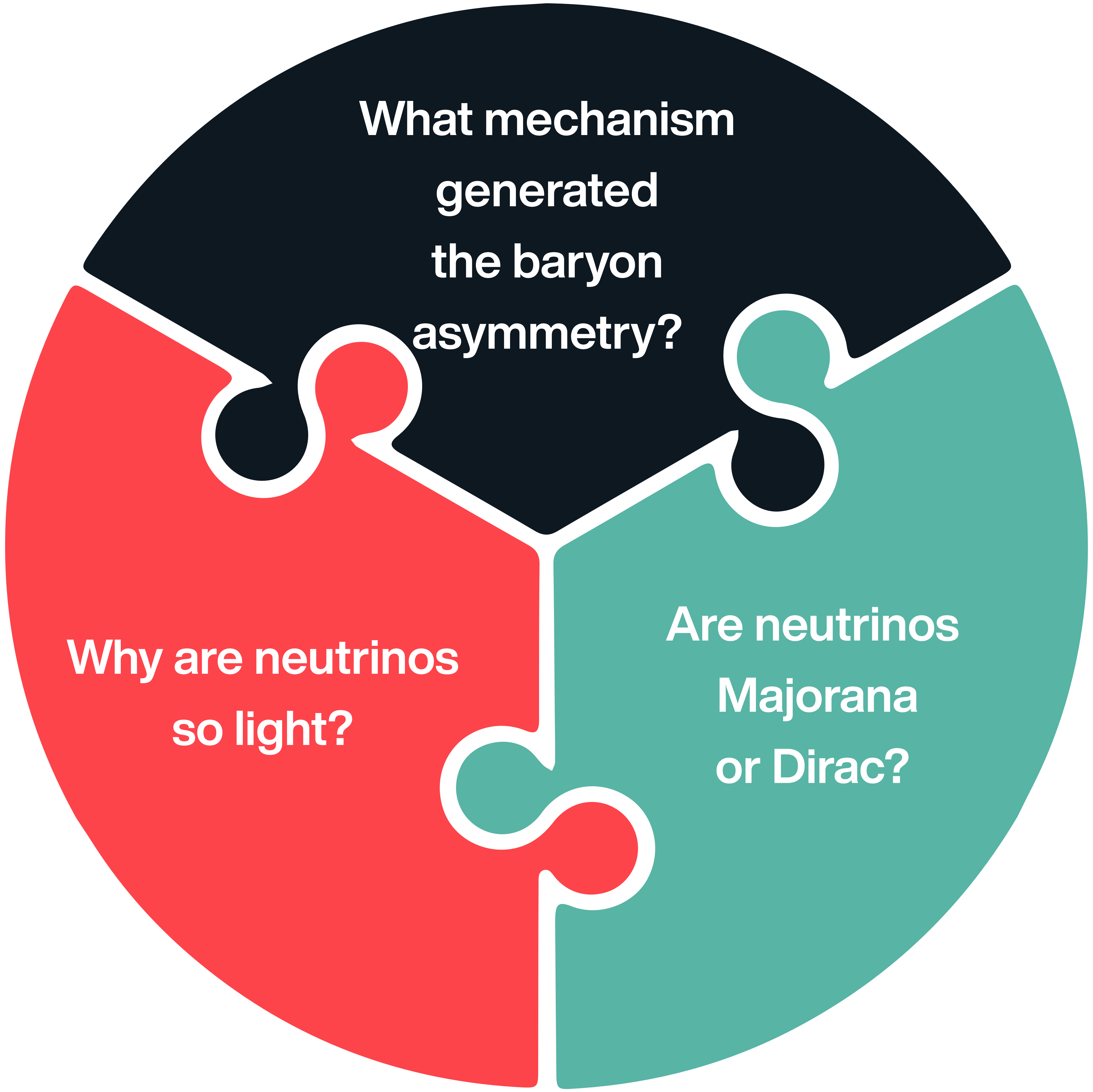
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Why are neutrinos so light?
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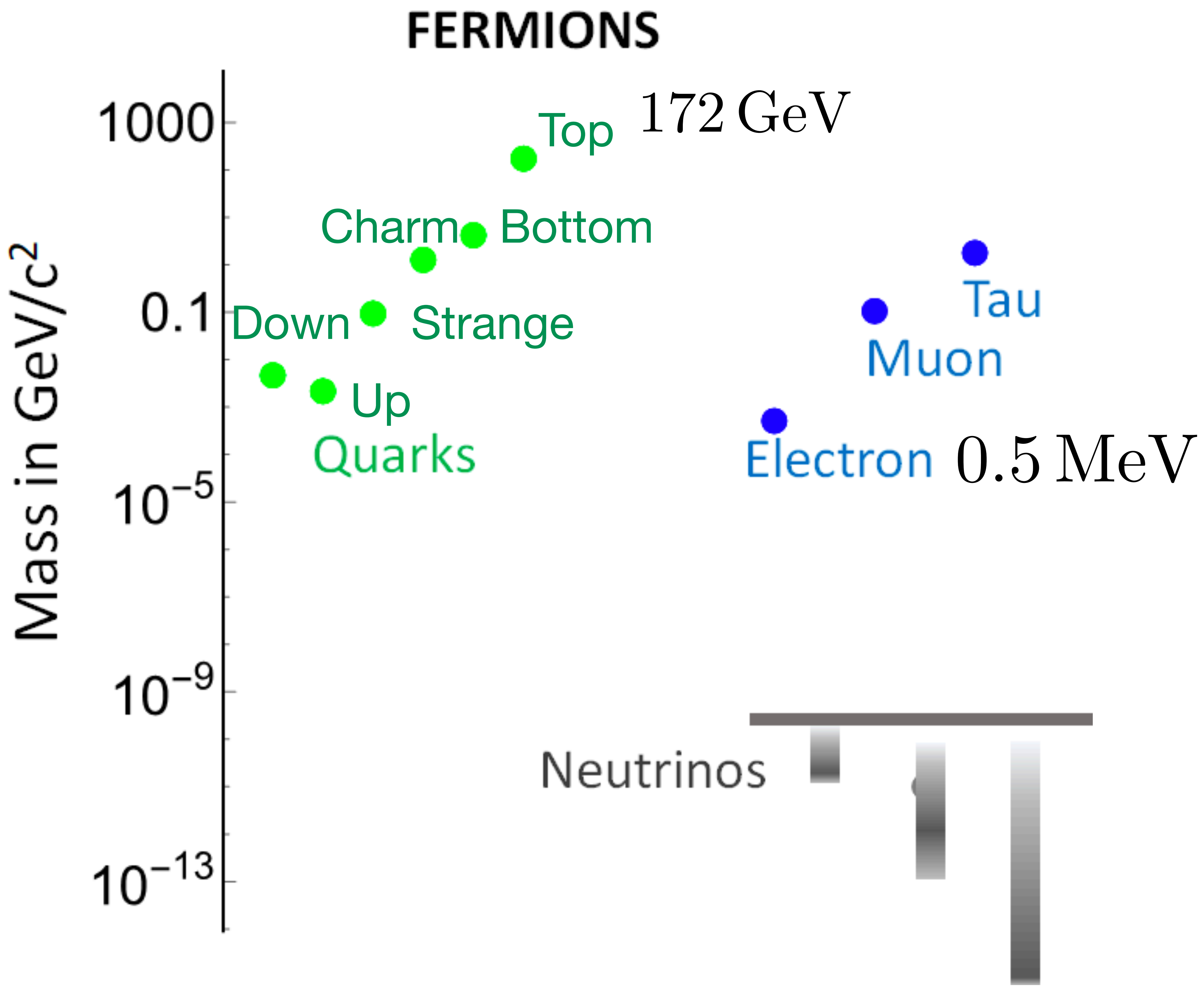
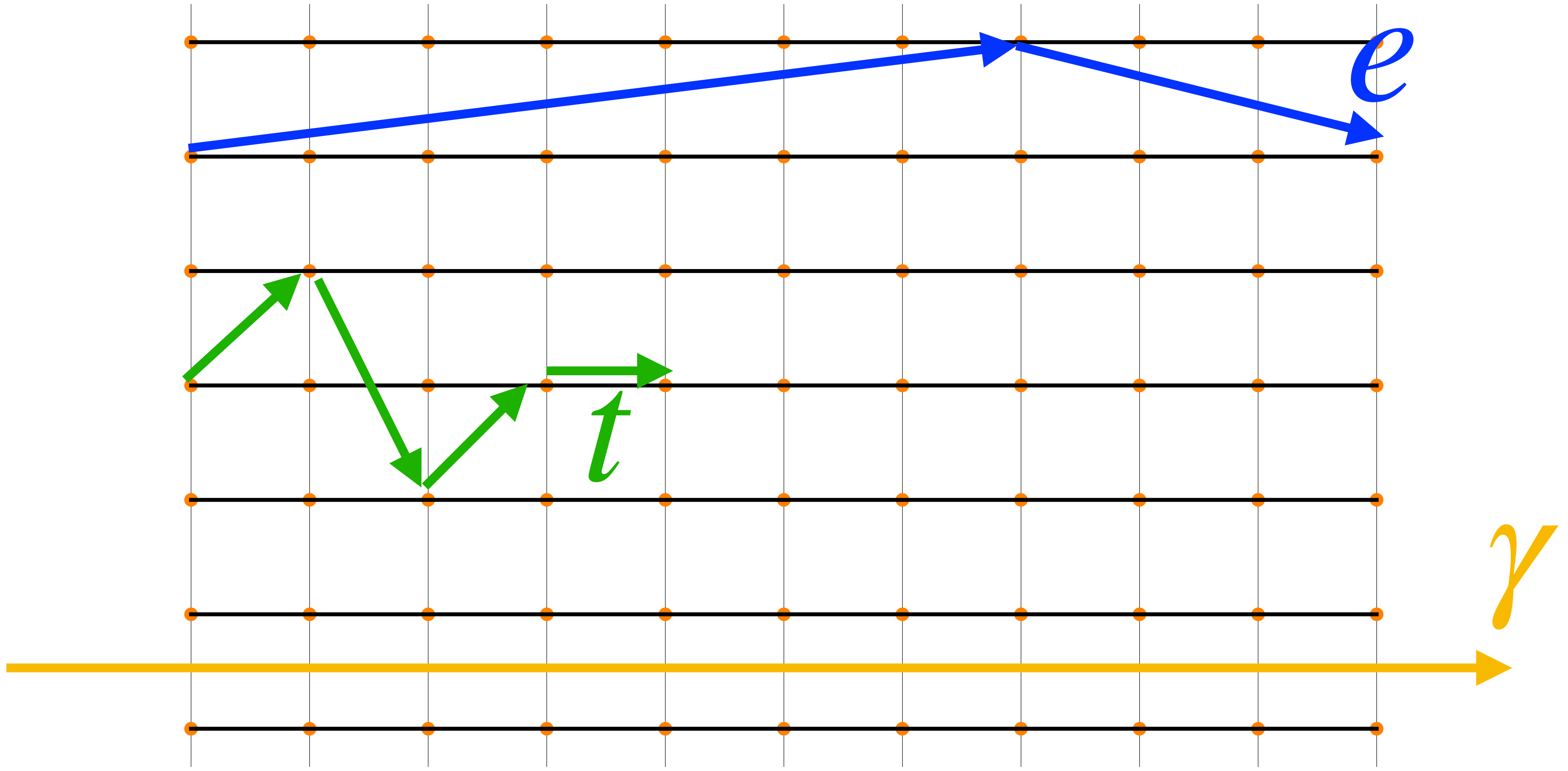
Why are neutrinos so light?

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

"Ordinary" particles get their mass from the Higgs Mechanism



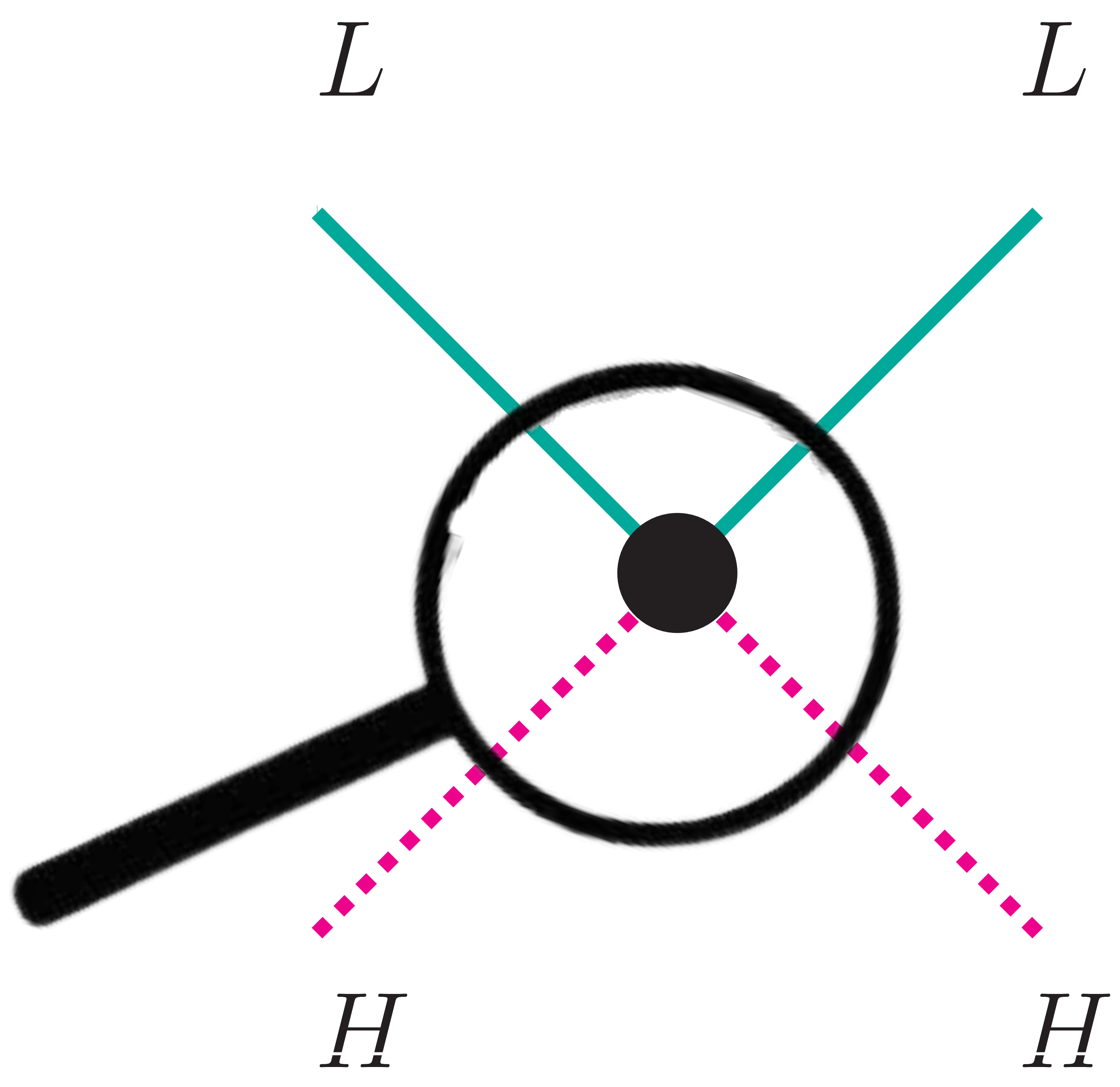


Neutrinos are so much lighter than other fundamental particles they may get their mass in a **different way**

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

$$2 \otimes 2 = 1 \oplus 3$$

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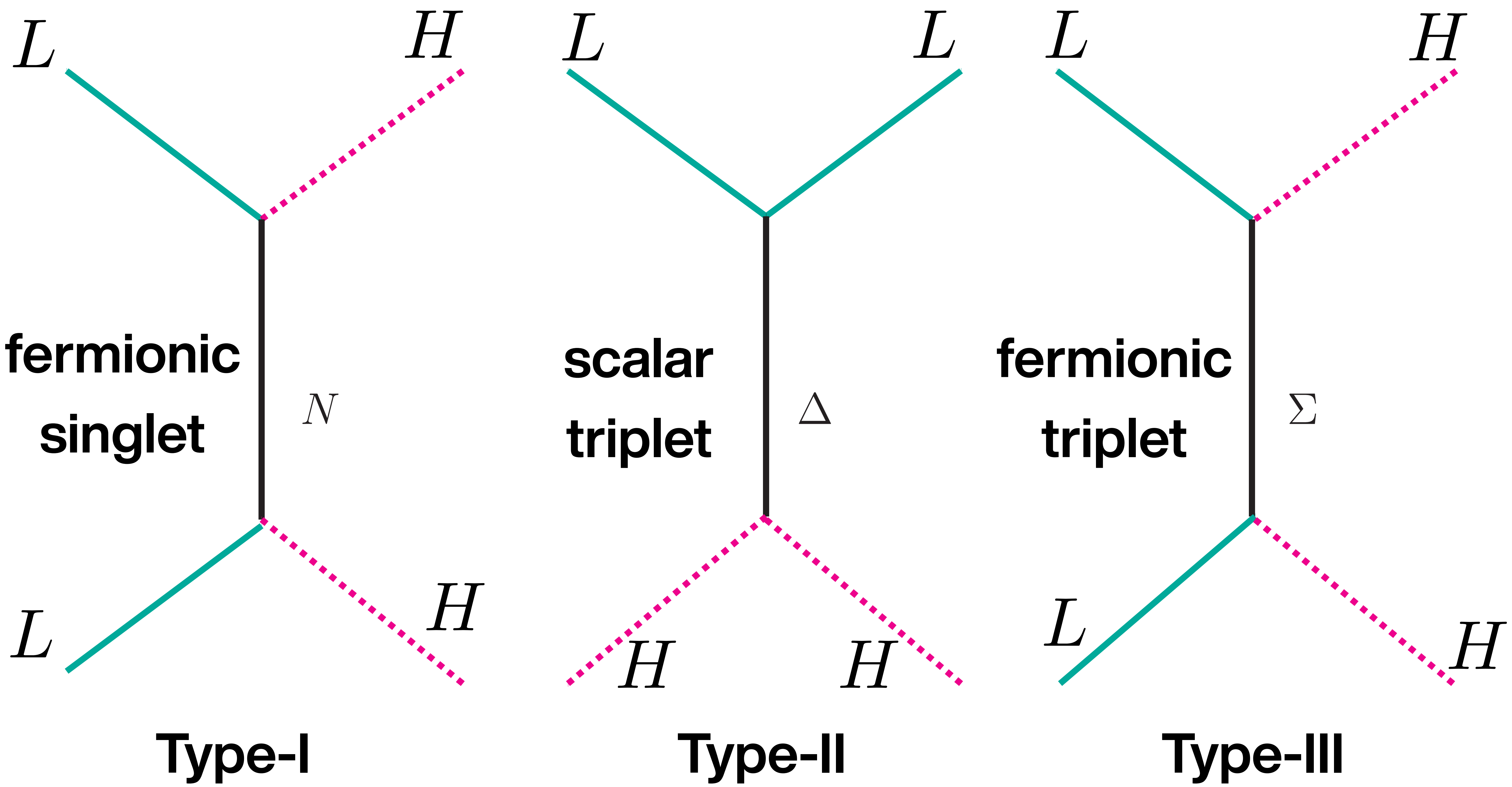

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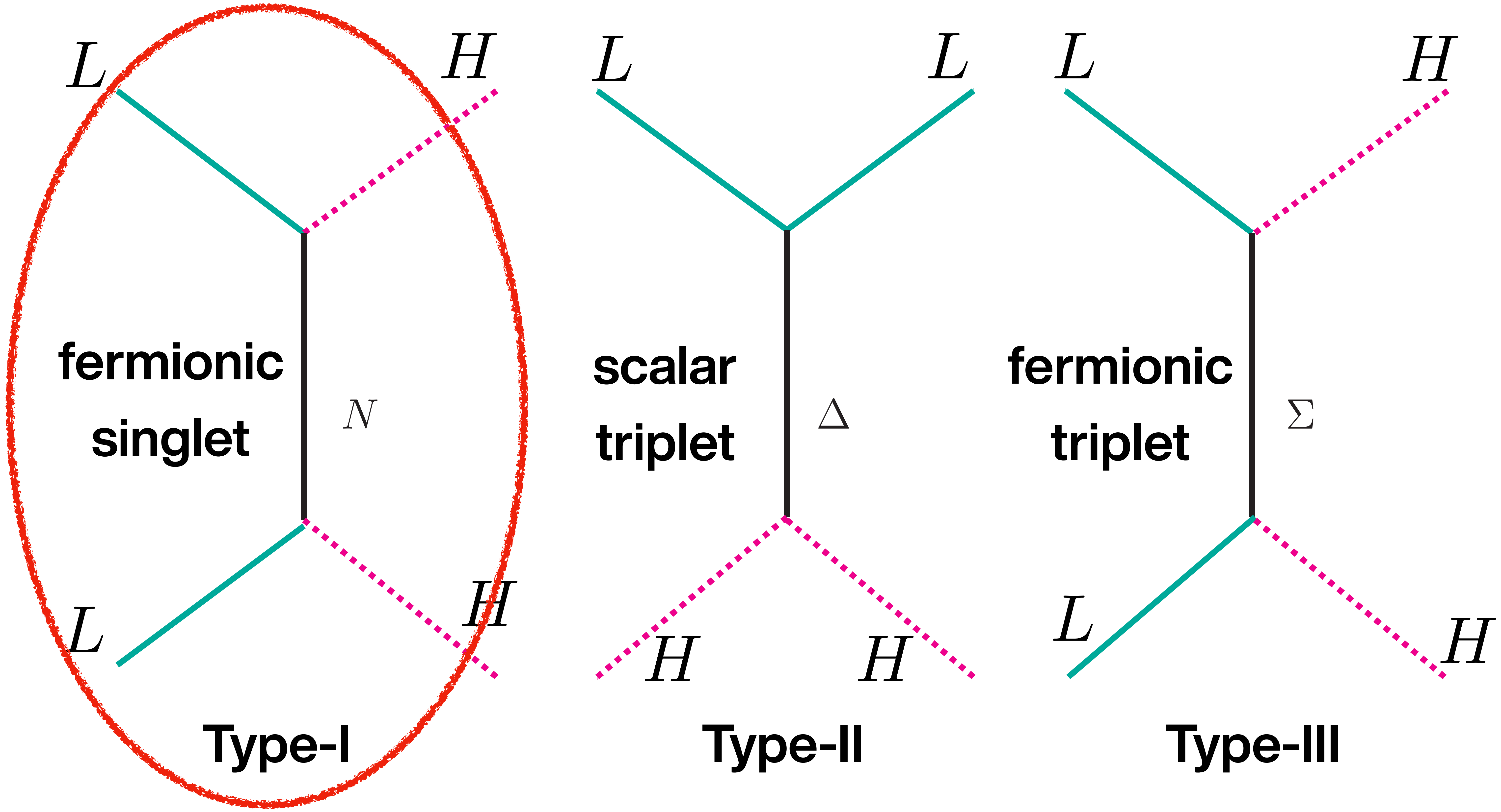

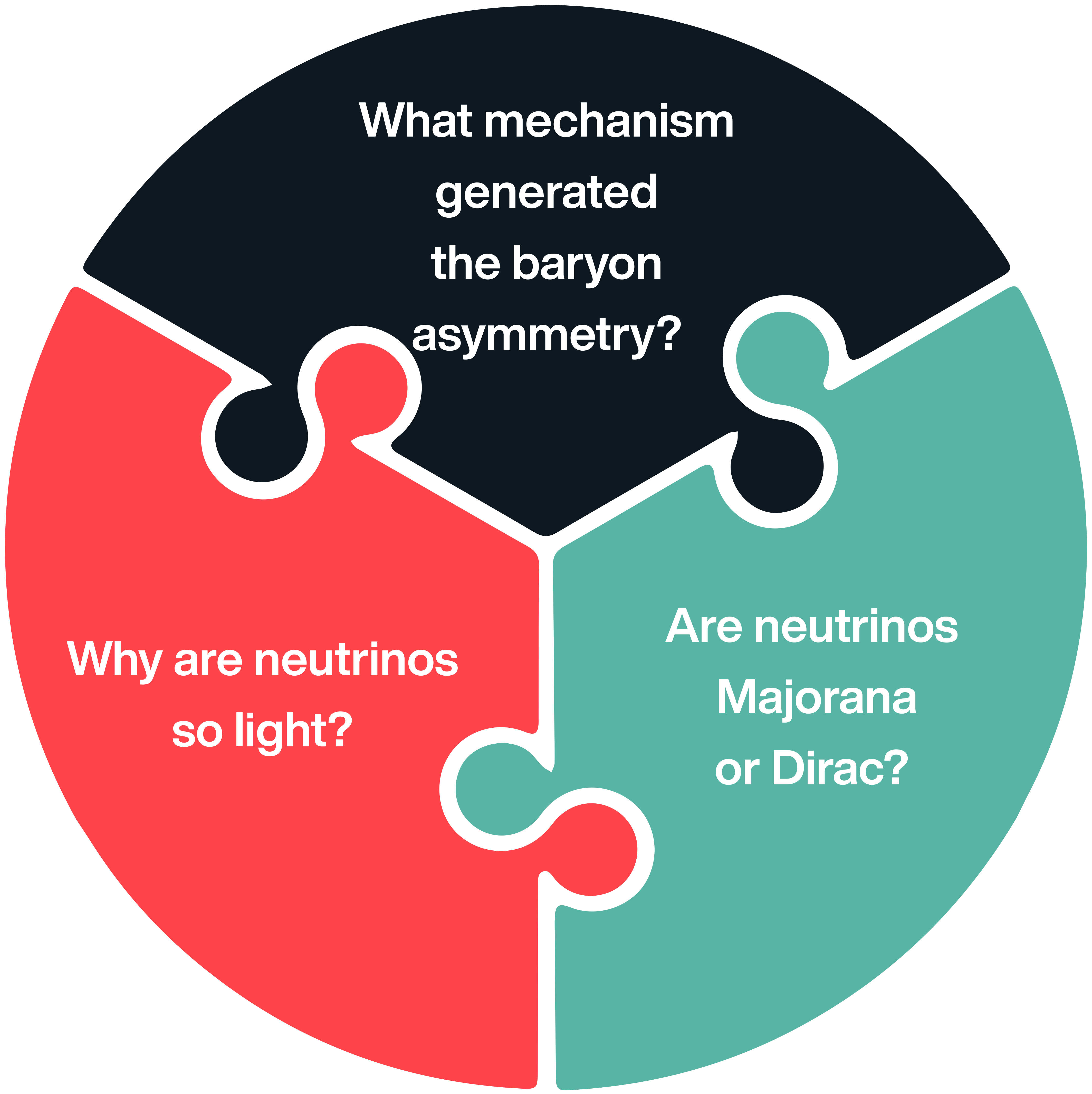
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Seesaw Mechanism

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

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

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

Seesaw Mechanism

$$L^L_{Maj} = -\frac{1}{2} m_L \overline{\nu^C_L} \nu_L$$

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	ν_L	ν_L^C	$\overline{\nu_L^C}$	$\overline{\nu_L^C}\nu_L$
Q	0	0	0	0
T_3	$+1/2$	$-1/2$	$+1/2$	1

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To make L^L_{Maj} gauge singlet we need field with $Q = 0$ and $T_3 = -1$

This is not part of the Higgs doublet so we set $m_L = 0$

Seesaw Mechanism

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Seesaw Mechanism

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

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

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

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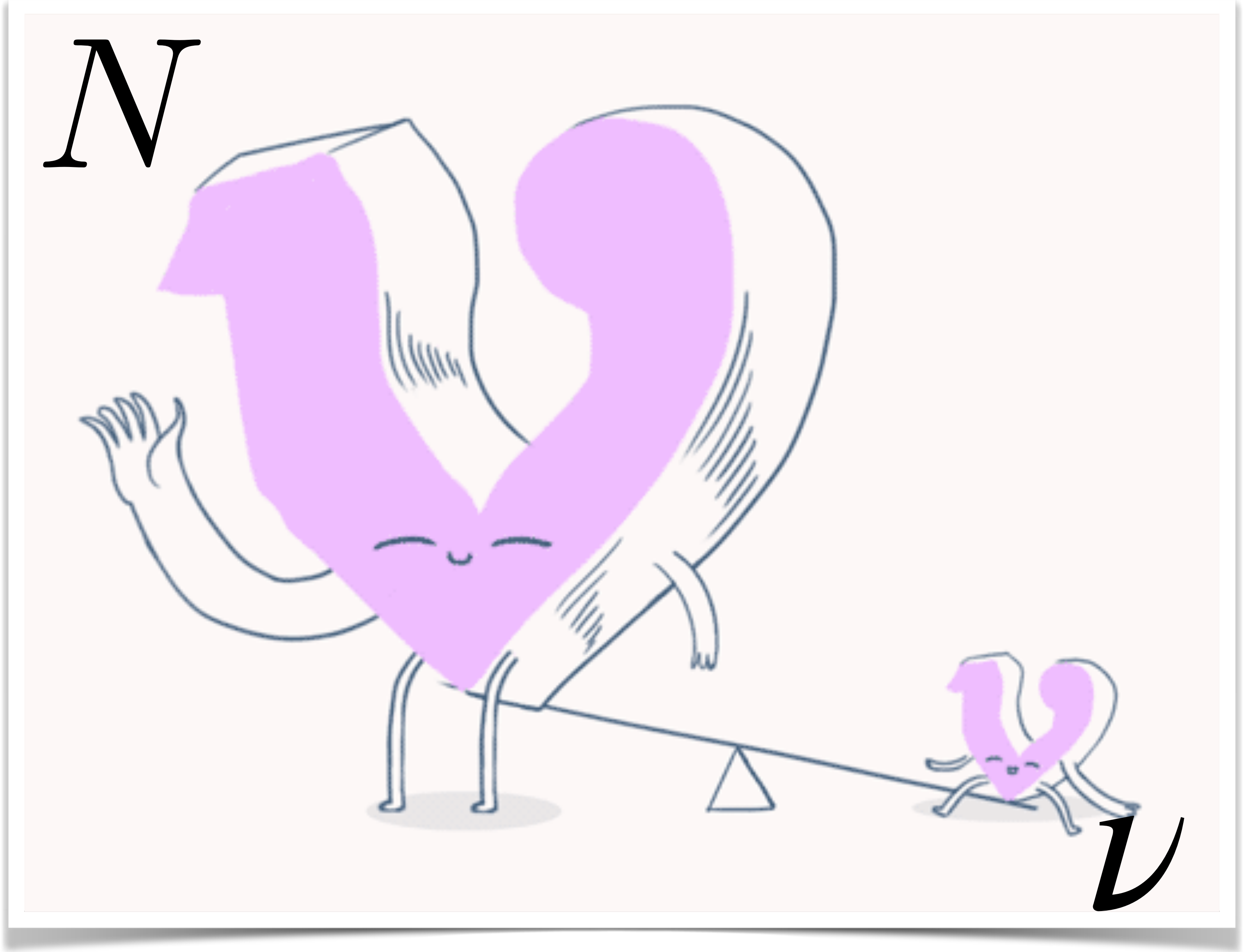
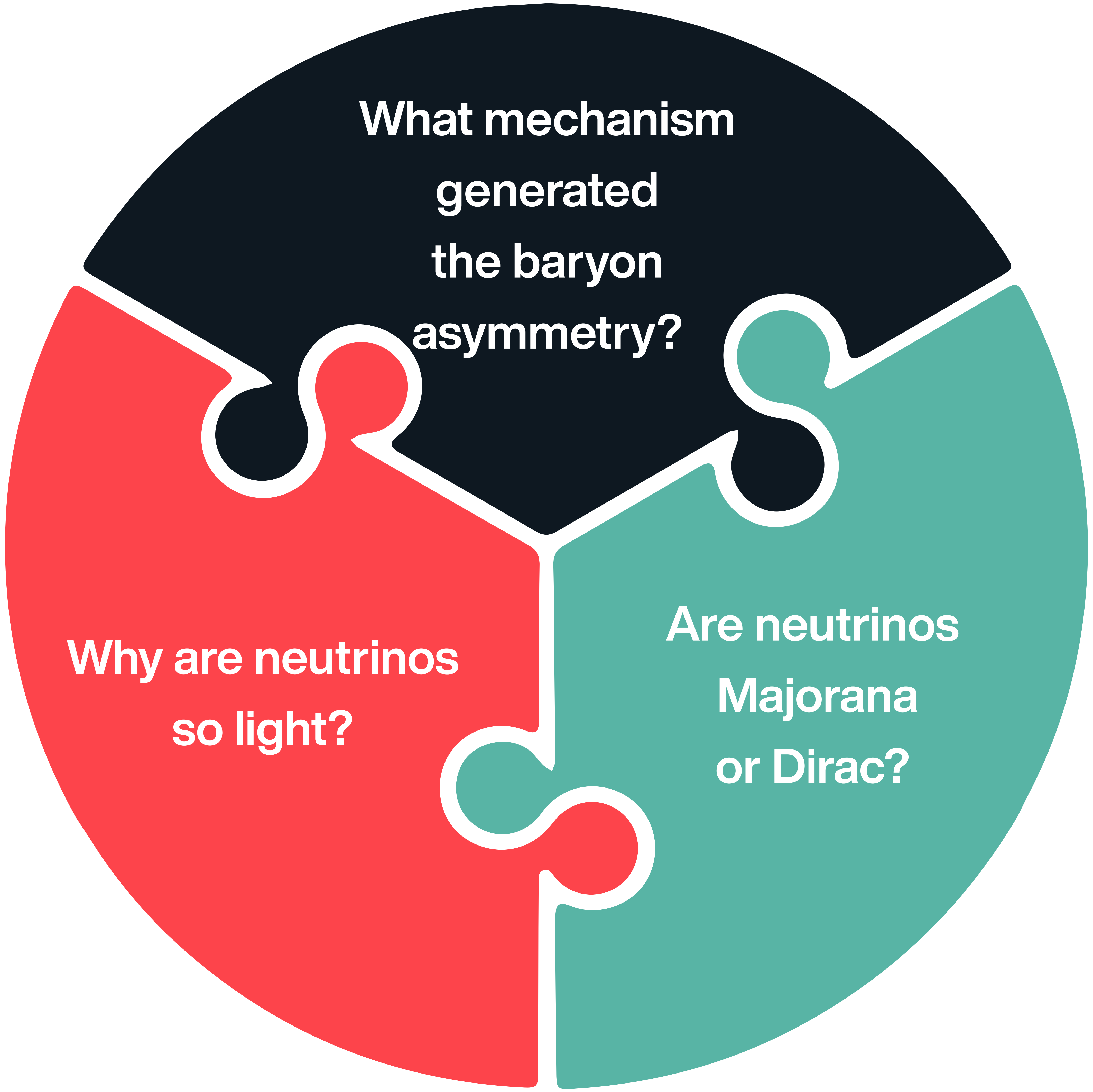


Image courtesy of Symmetry Magazine

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

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

Sakharov's conditions satisfied!


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

Thermal Leptogenesis

Fukugita & Yanagida (1986)

Thermal Leptogenesis

Fukugita & Yanagida (1986)

N

$$N \rightarrow LH$$

$$N \rightarrow \bar{L}H^{\dagger}$$

Anti-Leptons

Leptons

Decays Occurs
when $T \sim M_N$

$$\Gamma_N \sim H$$

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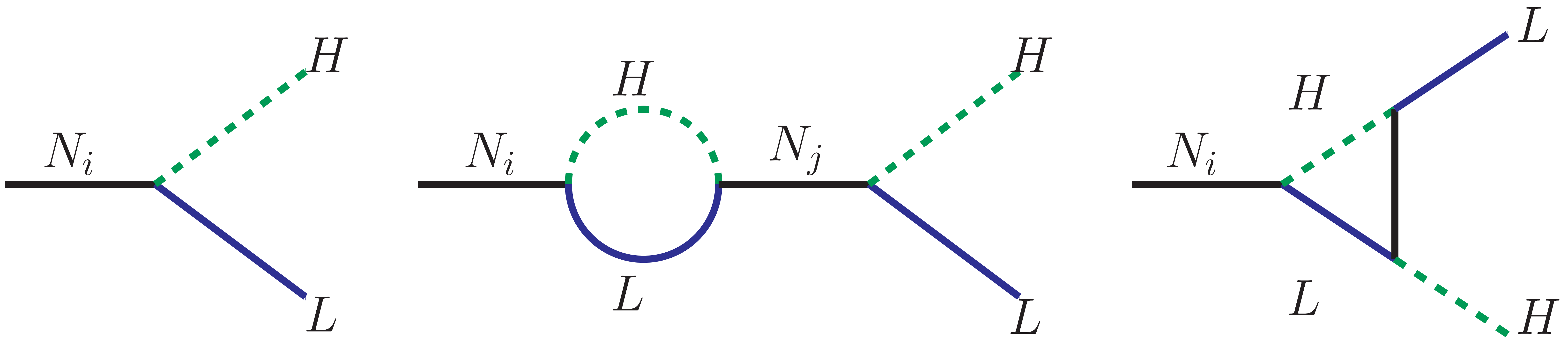
Decay asymmetry from interference between tree and loop level diagrams

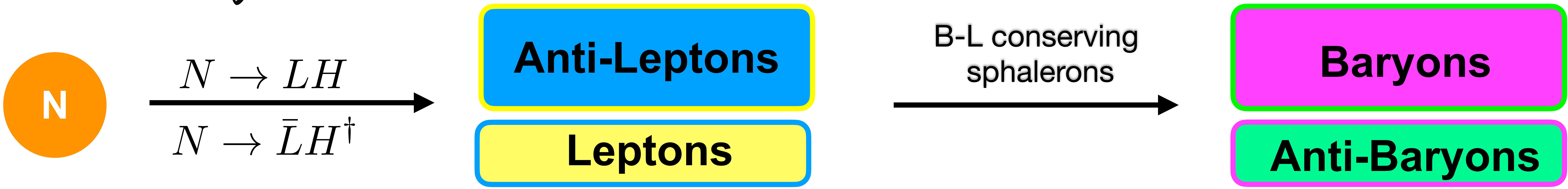
Covi, Roulet, Vissani



$$\epsilon \equiv \frac{\Gamma\left(N_1 \to HL\right) - \Gamma\left(N_1 \to H^\dagger \bar{L}\right)}{\Gamma\left(N_1 \to HL\right) + \Gamma\left(N_1 \to H^\dagger \bar{L}\right)}$$

Thermal Leptogenesis

Fukugita & Yanagida (1986)



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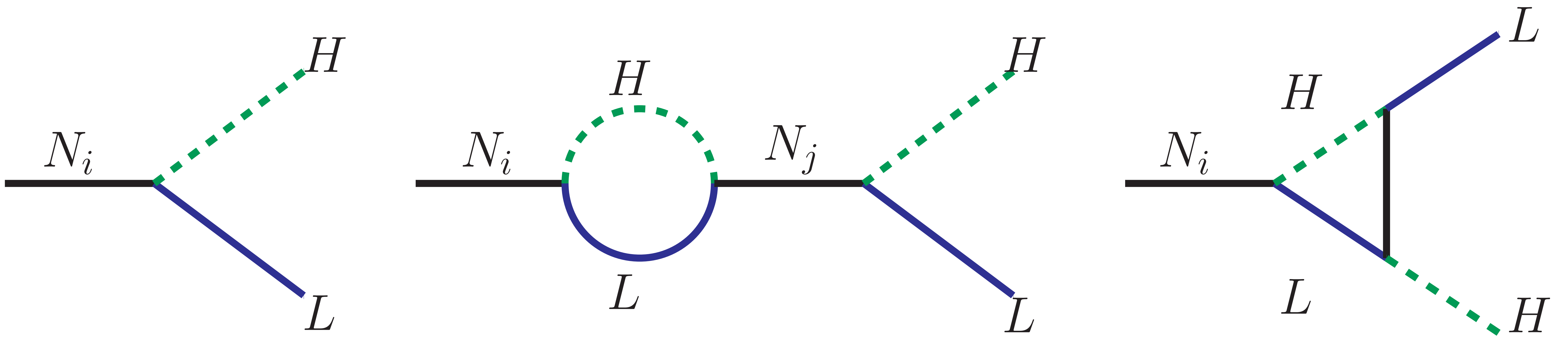

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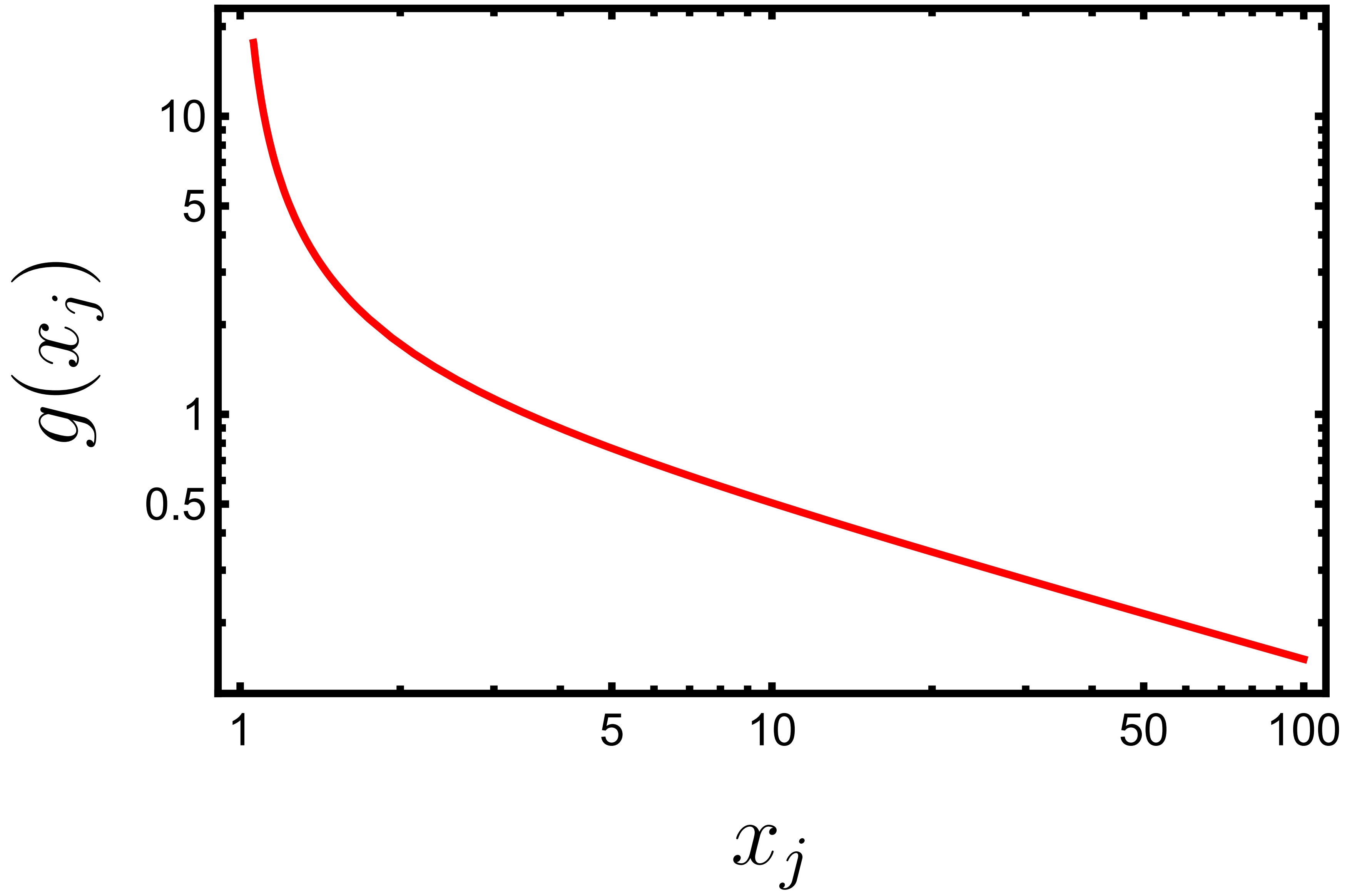
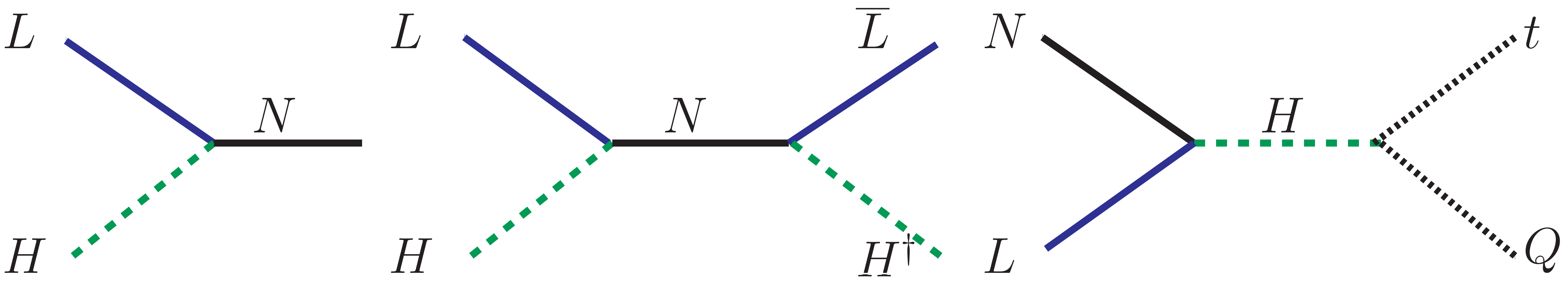
$$\epsilon = \frac{1}{8\pi}\frac{1}{(Y^\dagger Y)_{11}}\sum_j \mathcal{I}m\left\{\left[\left(Y^\dagger Y\right)_{1j}\right]^2\right\} g\left(x_j\right) \qquad x_j \equiv M_j^2/M_1^2$$



Thermal Leptogenesis

Fukugita & Yanagida (1986)

Washout and Scattering Processes



Inverse Decays

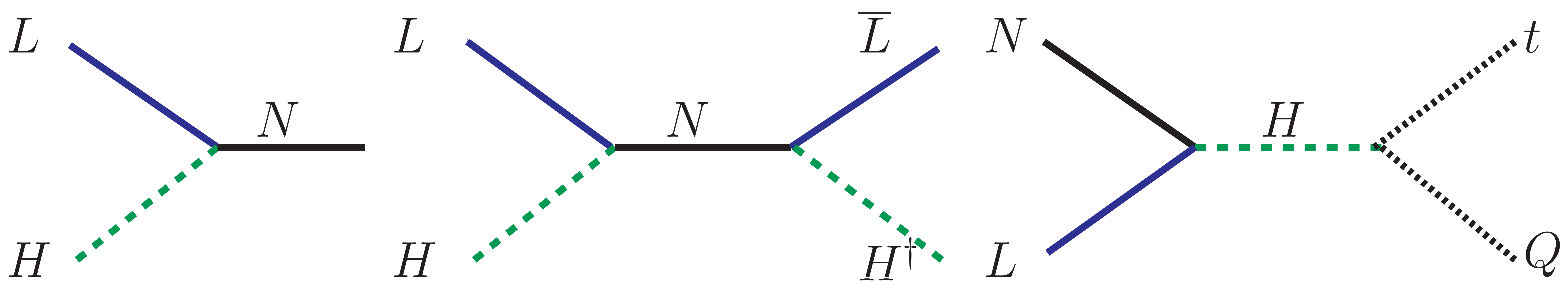
$\Delta L = 2$

$\Delta L = 1$

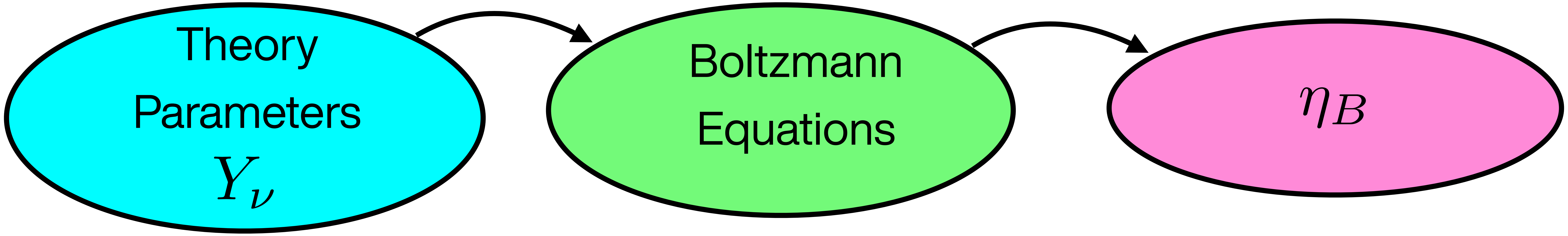
Fukugita & Yanagida (1986)

Thermal Leptogenesis

Washout and Scattering Processes



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



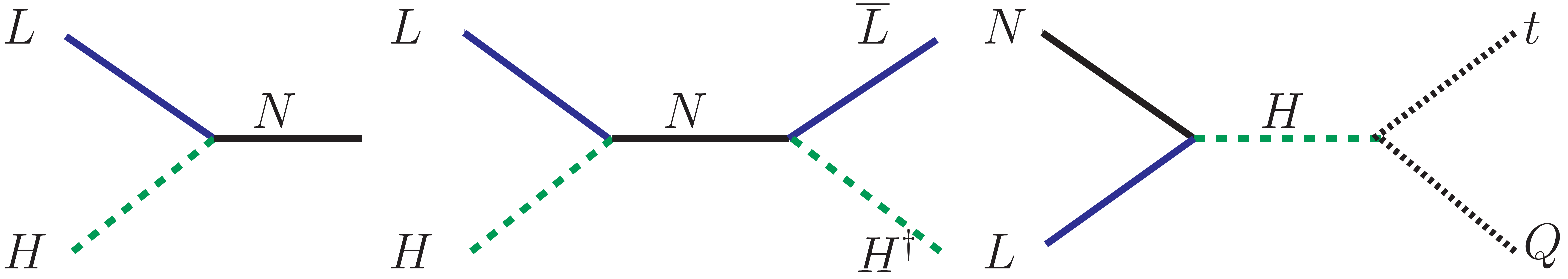
$$\frac{dN_N}{dz} = -D(z)\,(N_N - N_N^{\rm eq})$$

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

Thermal Leptogenesis

Fukugita & Yanagida (1986)

Washout and Scattering Processes



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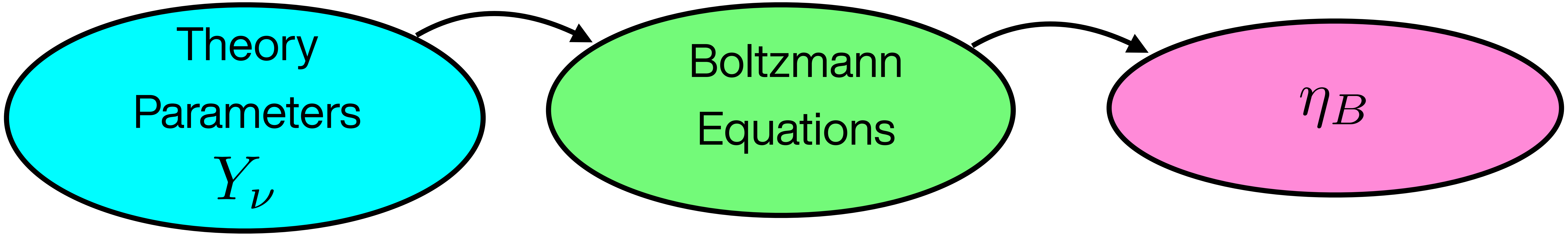
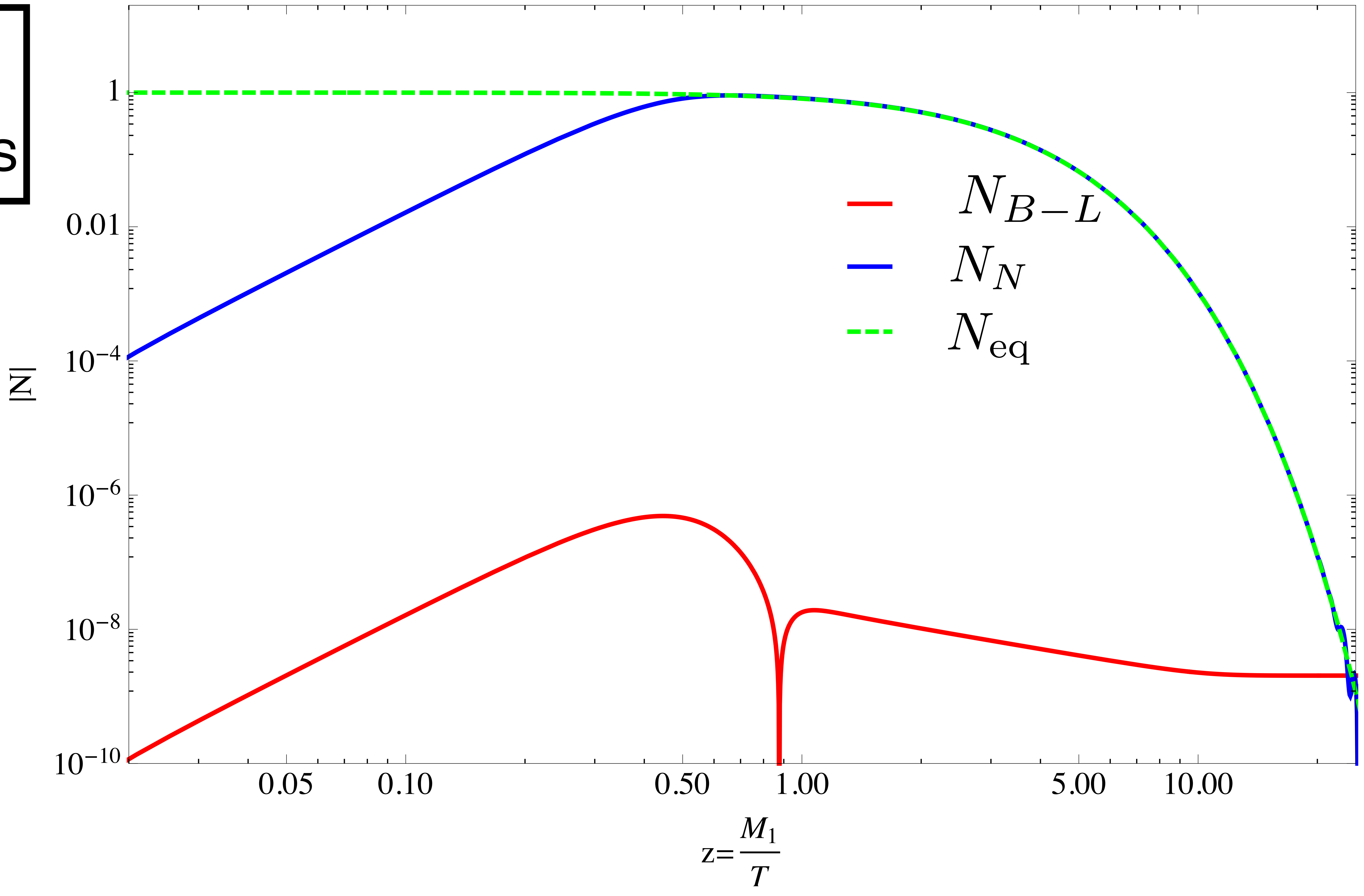


assume zero initial abundance of RHNs



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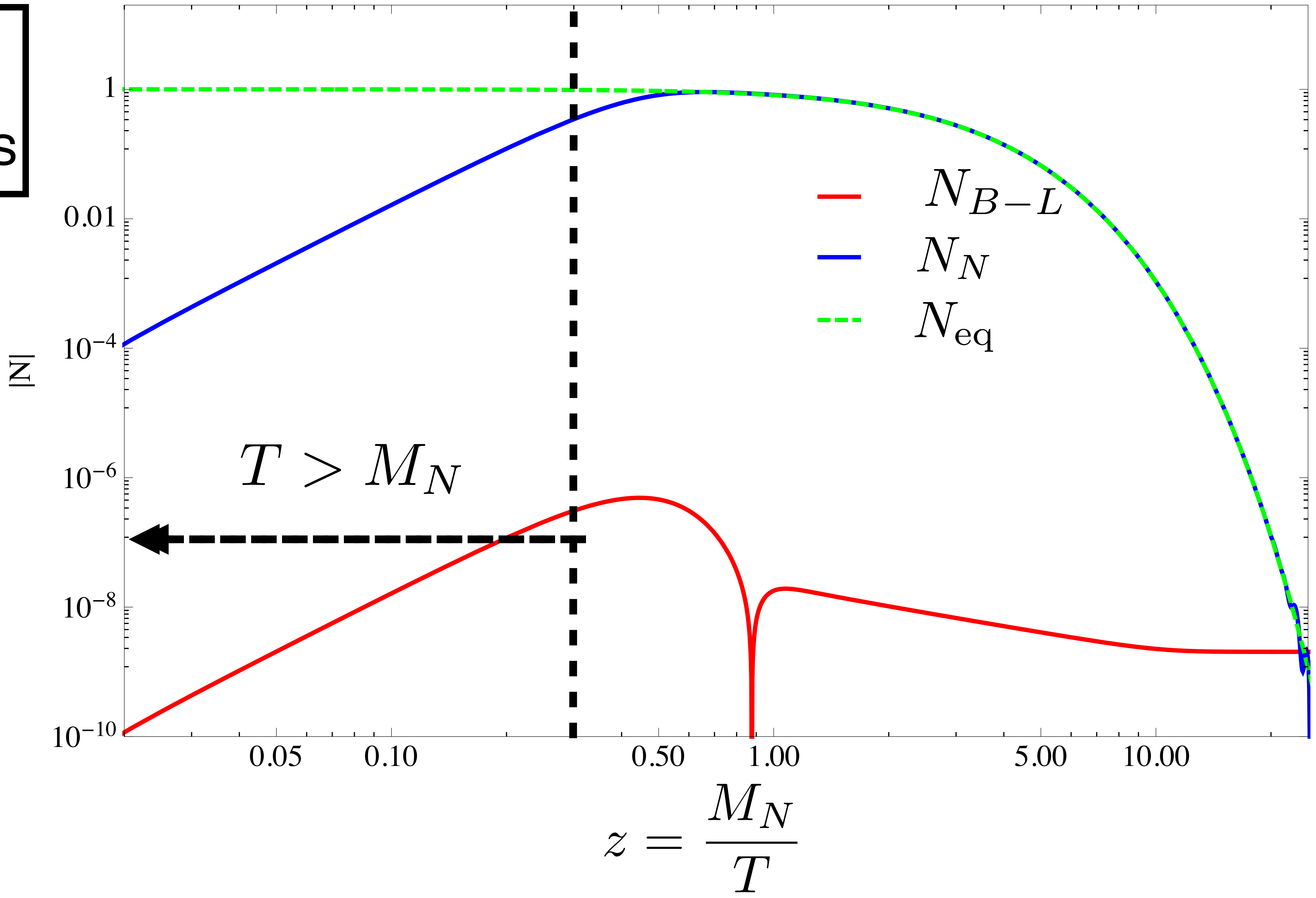

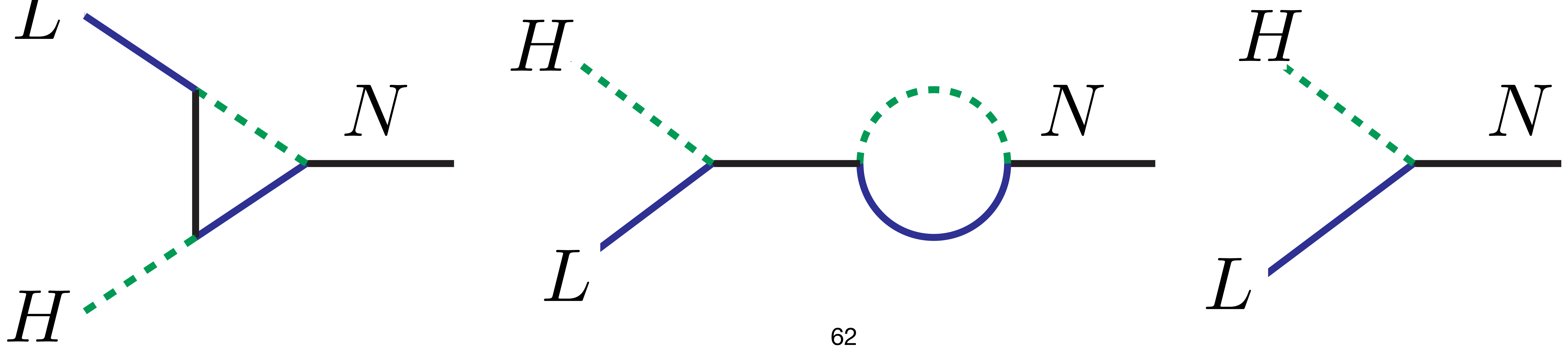

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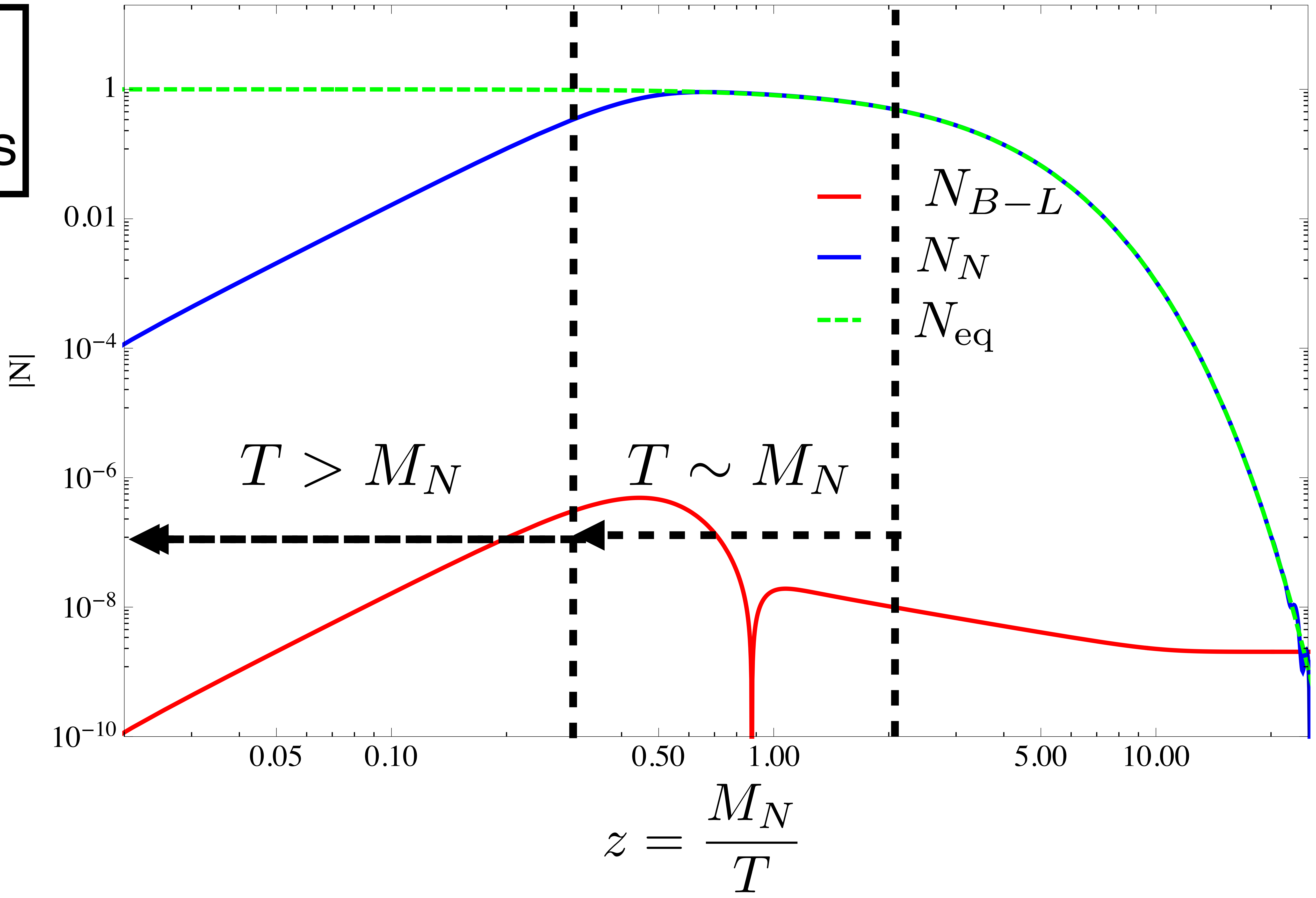

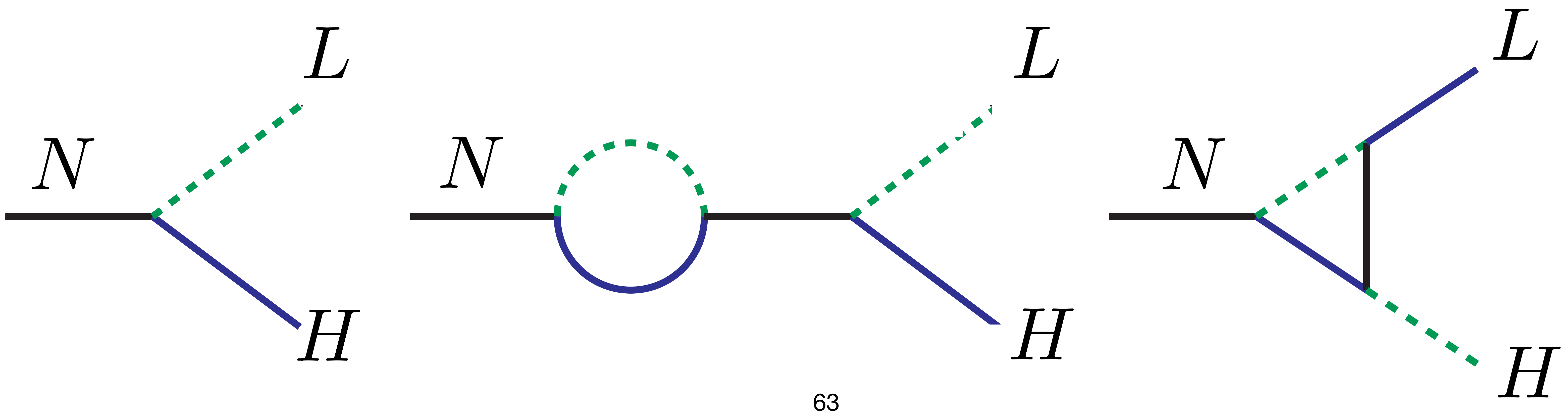

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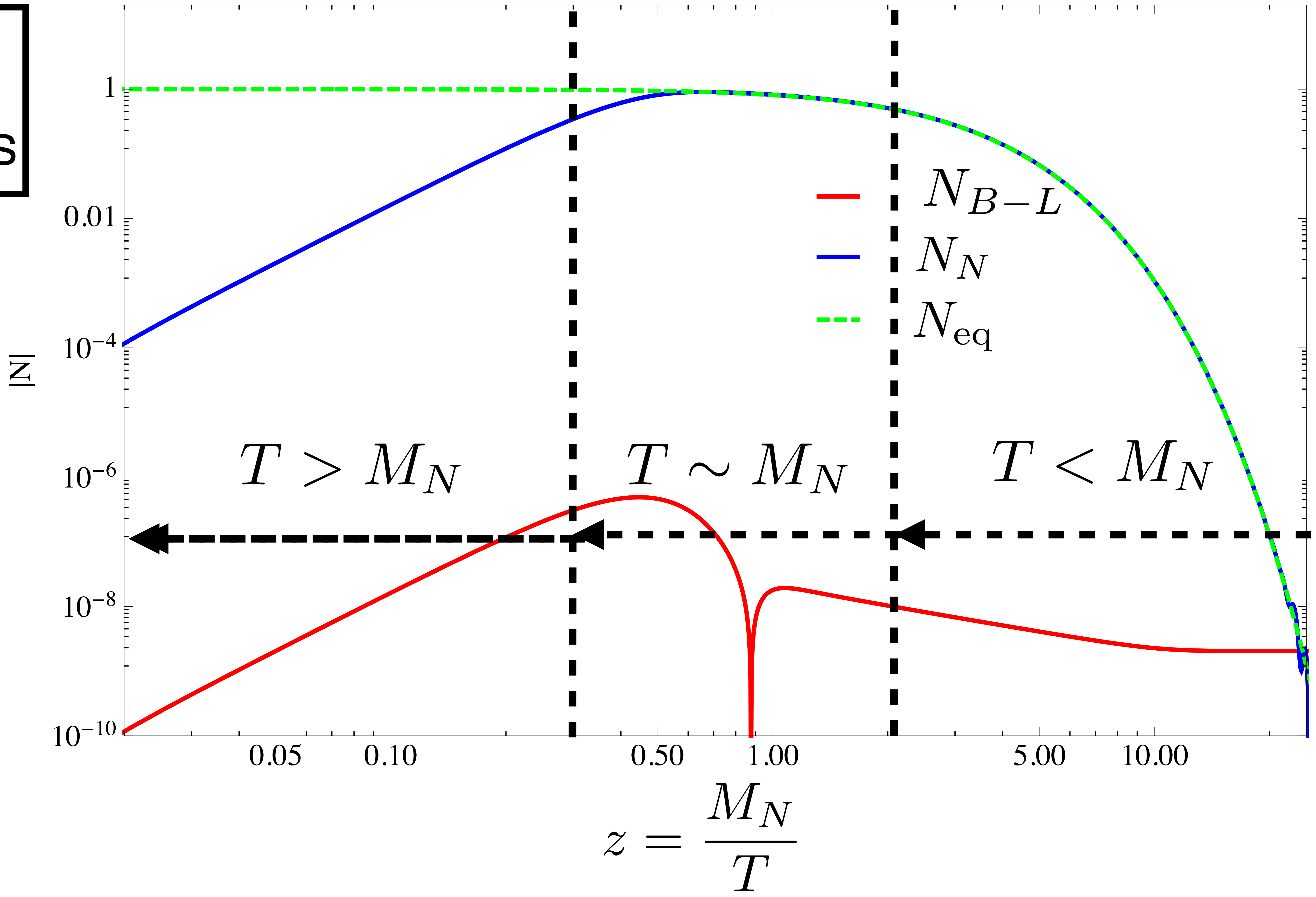
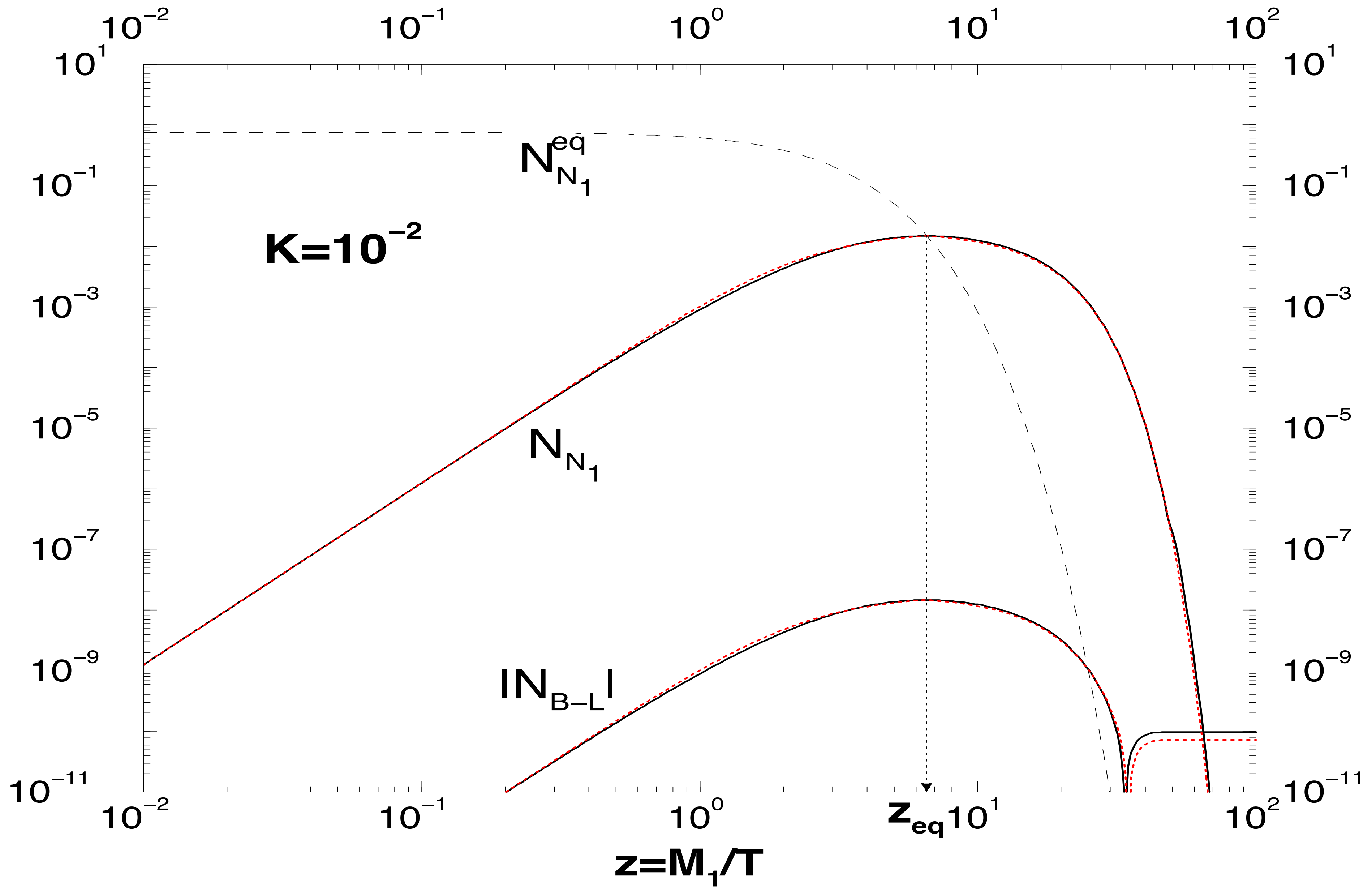


RHN abundance is depleted. Lepton asymmetry freezes out

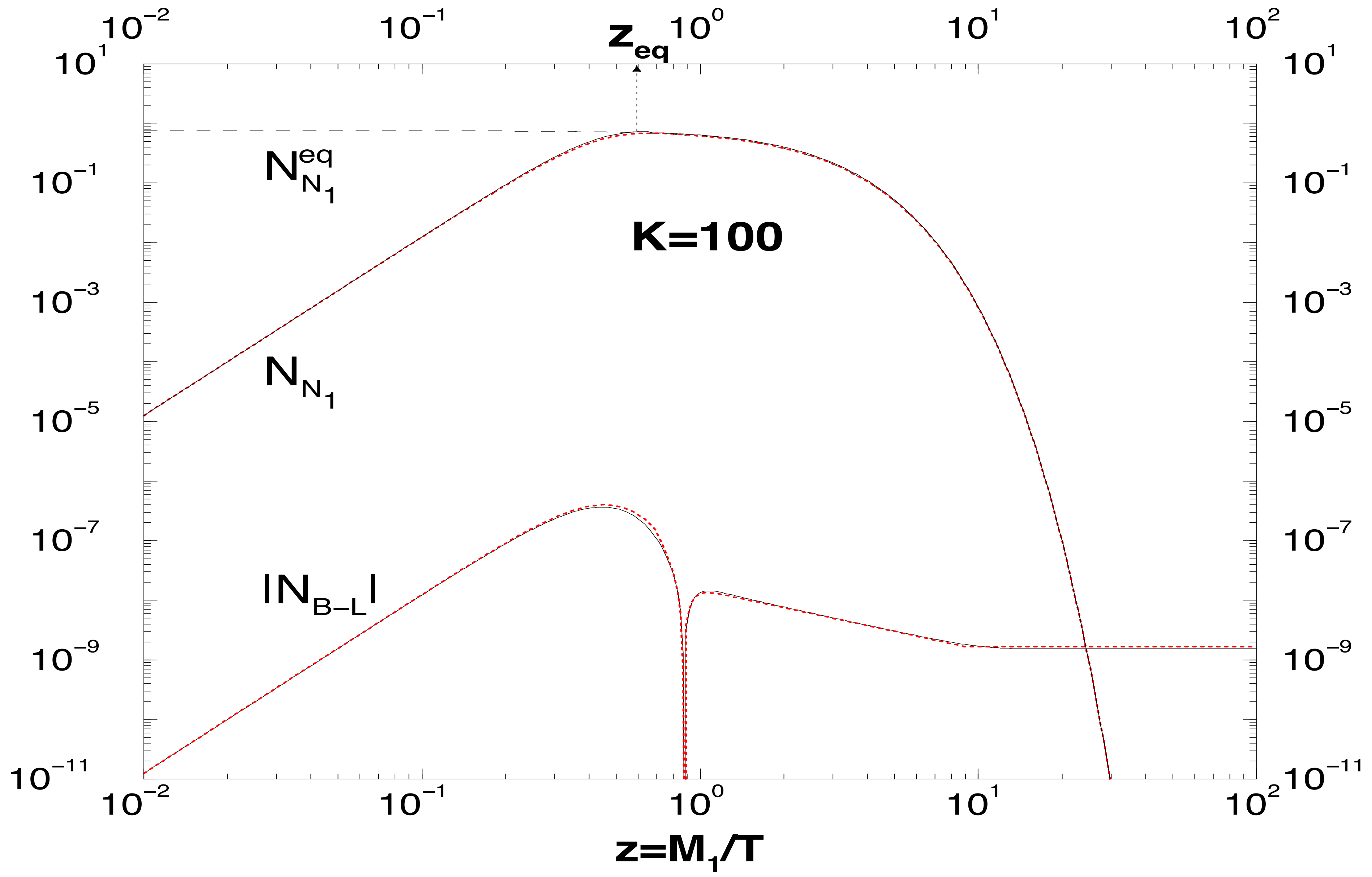
The decay rate of the RHNs compared to the Hubble expansion rate determines whether or not leptogenesis occurs in the **strong** or **weak washout** regimes

$$K = \frac{\Gamma_D}{H(z=1)} \qquad H \simeq \sqrt{\frac{8\pi^3 g_*}{90}} \frac{T^2}{M_{\rm Pl}} \qquad \Gamma_D = \frac{(Y_\nu^\dagger Y_\nu) M_1}{8\pi}$$

$K \ll 1$ Weak washout



$K > 1$ Strong washout



Parameter Space

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

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

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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

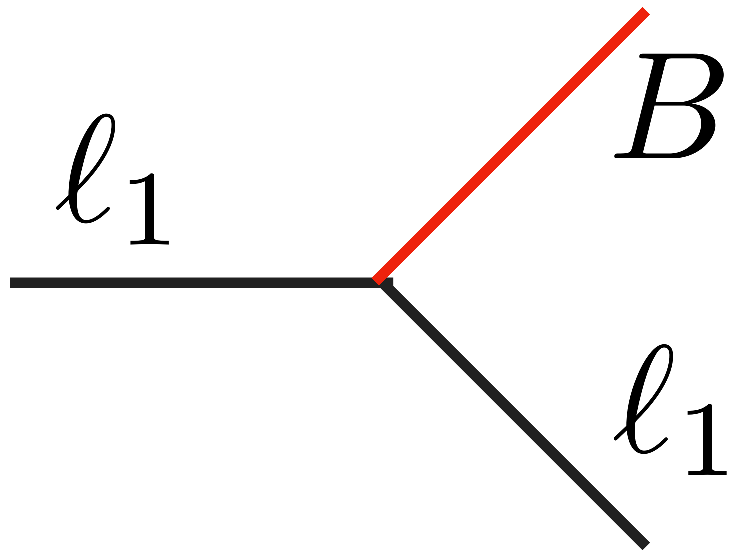
CI model-independent way $m_\nu \leftrightarrow$ leptogenesis

Flavour effects in Leptogenesis

$$\Gamma_\ell < H$$

$$\Gamma_\alpha \sim Y_\alpha^2 T$$

$$T \gtrapprox 10^{13}\text{GeV}$$



$$|\ell_1\rangle = \sum_{\alpha=e,\mu,\tau} c_{1\alpha}|\ell_\alpha\rangle$$

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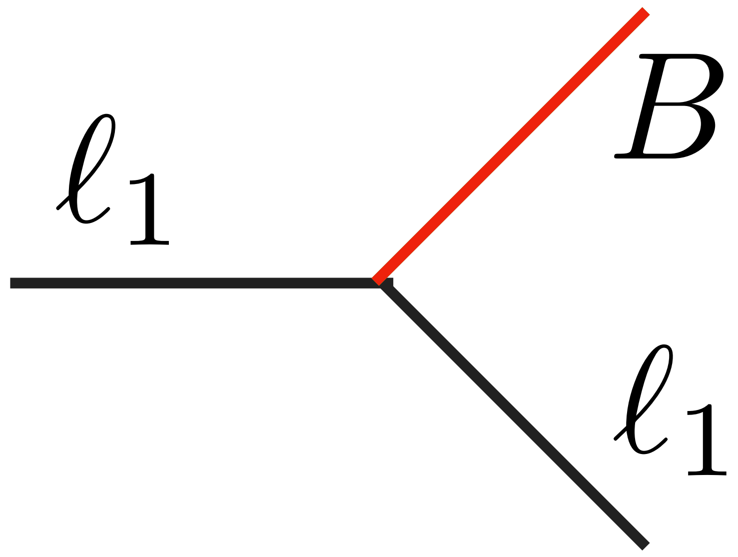
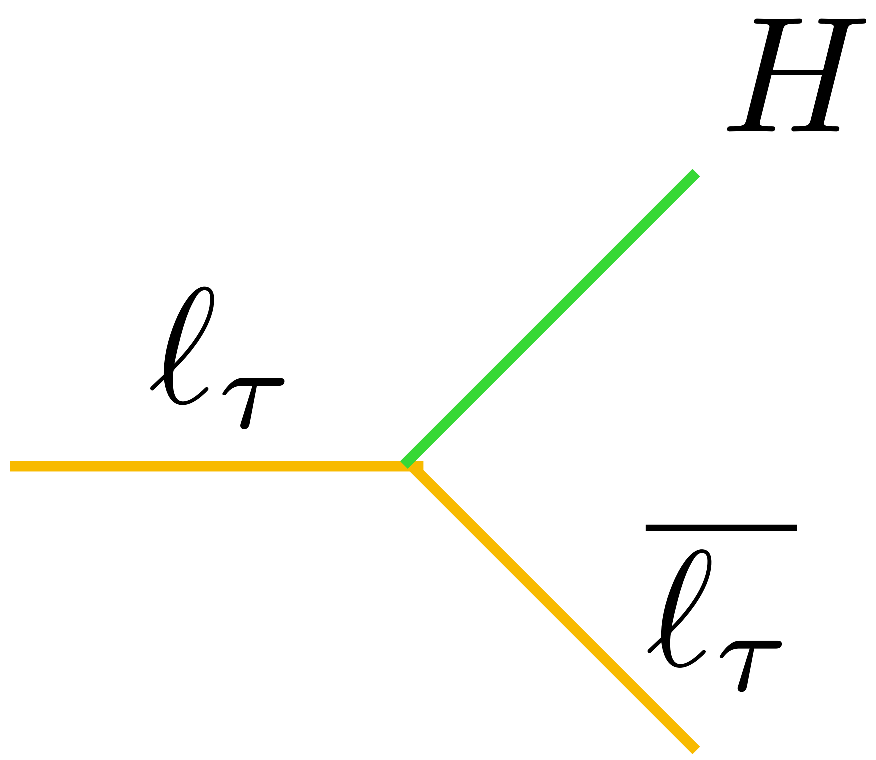
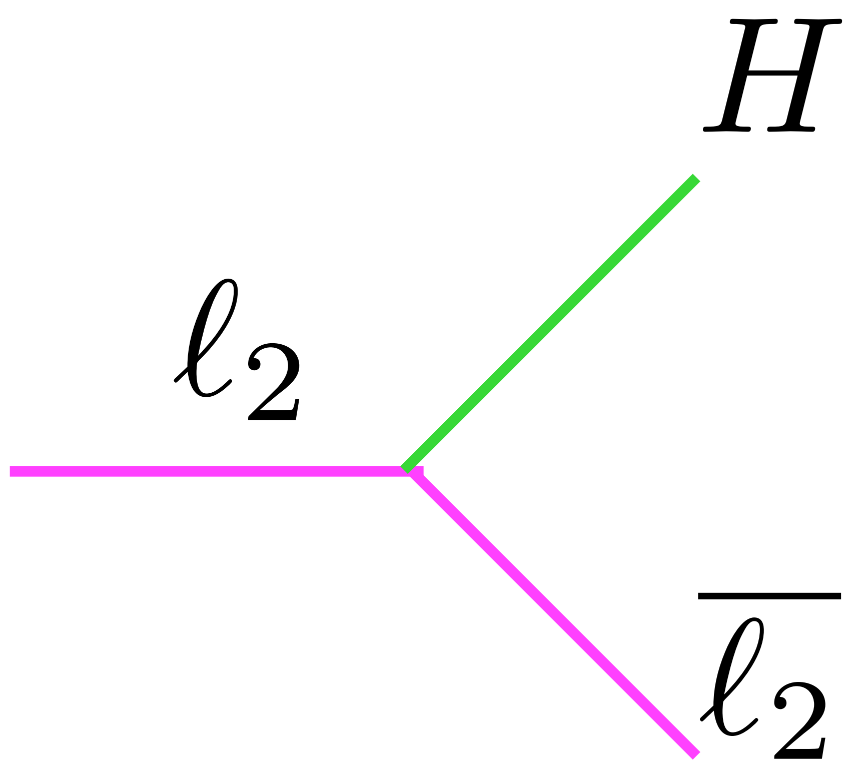


$$|\ell_1\rangle = \sum_{\alpha=e,\mu,\tau} c_{1\alpha}|\ell_\alpha\rangle$$

$$T \sim 10^{11}\mathrm{GeV}$$





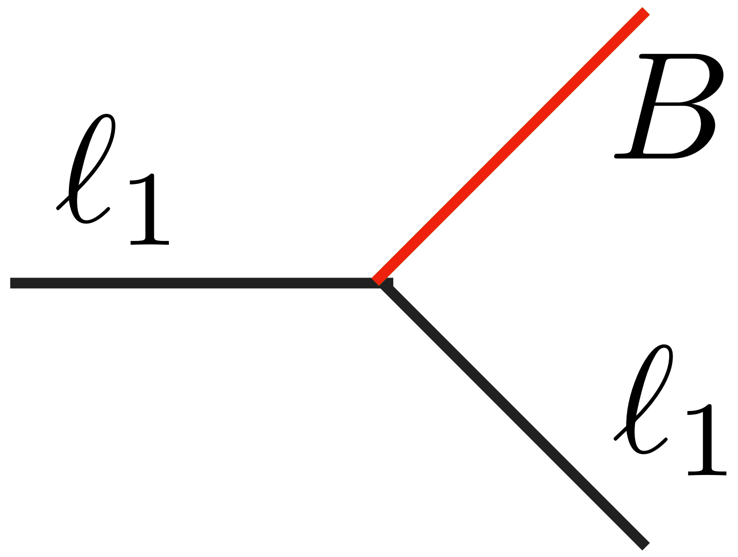
$$\Gamma_\tau > H$$

Flavour effects in Leptogenesis

$$\Gamma_\ell < H$$

$$\Gamma_\alpha \sim Y_\alpha^2 T$$

$$T \gtrapprox 10^{13}\,\mathrm{GeV}$$



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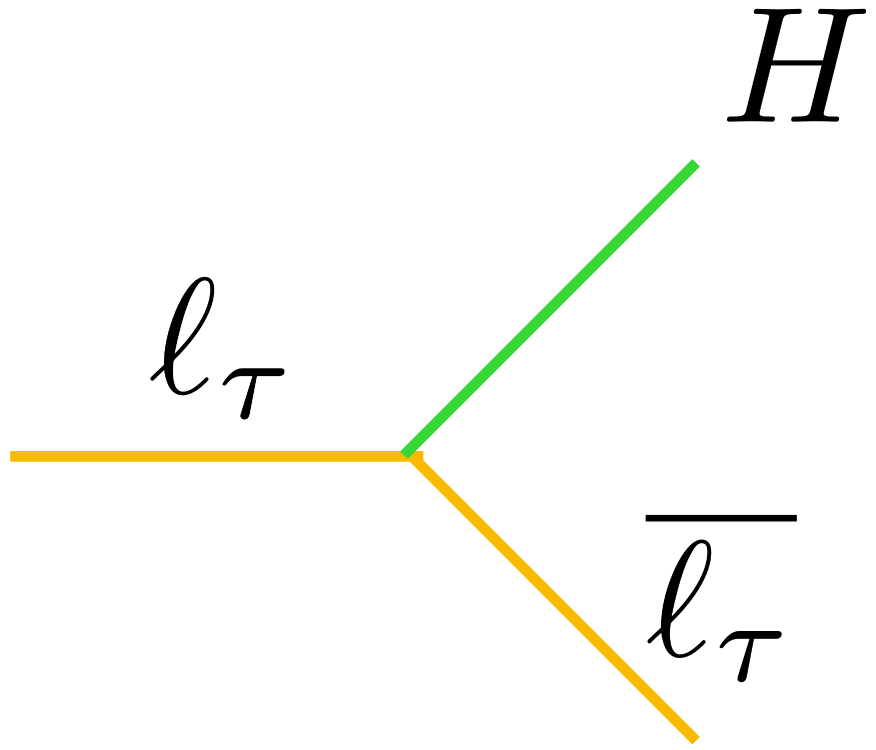
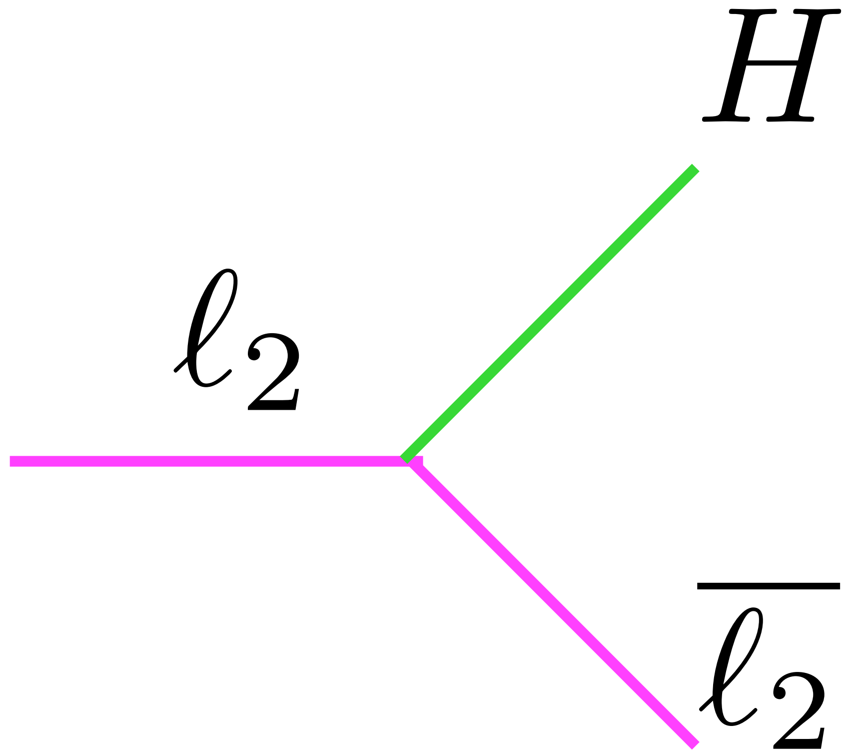
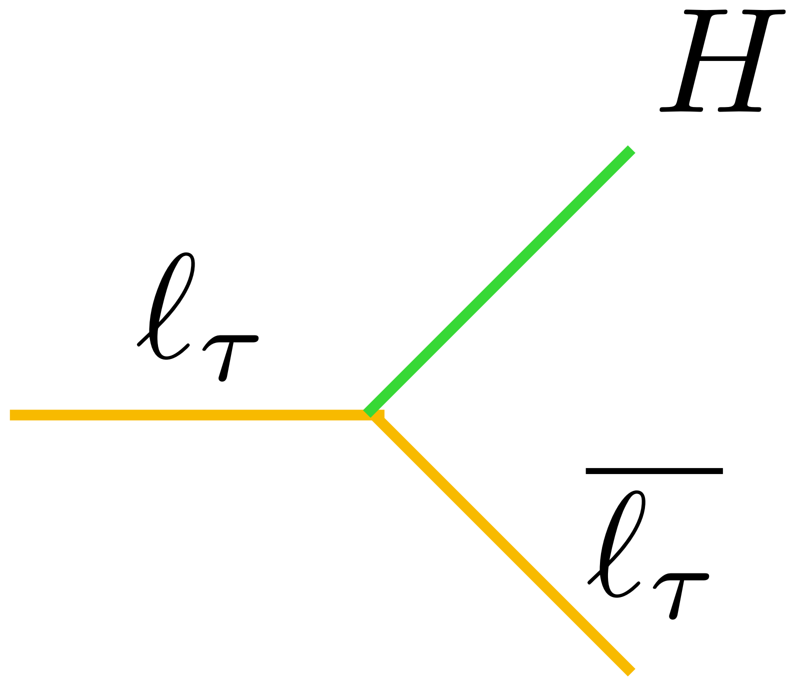
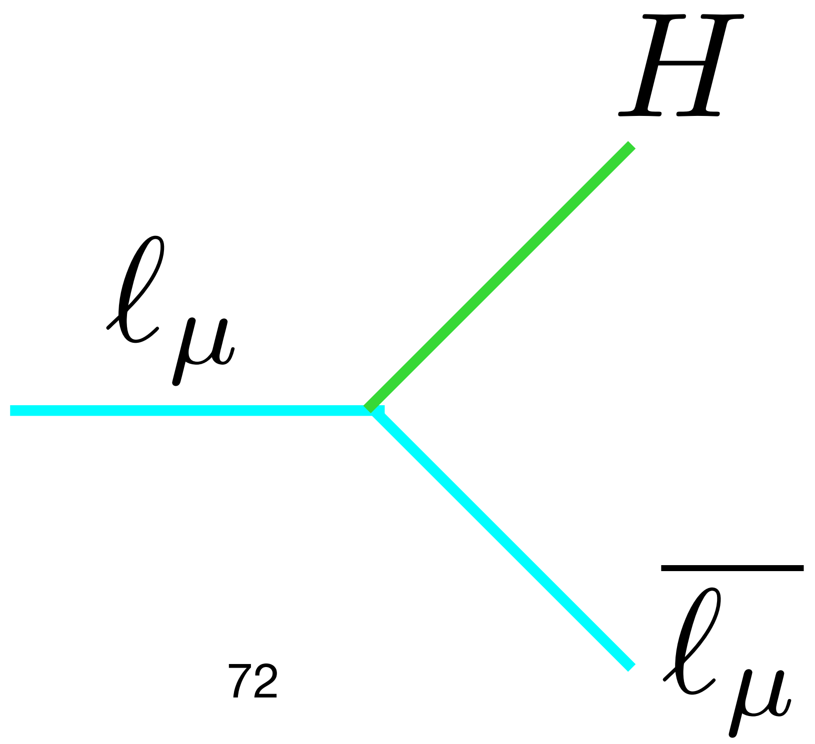


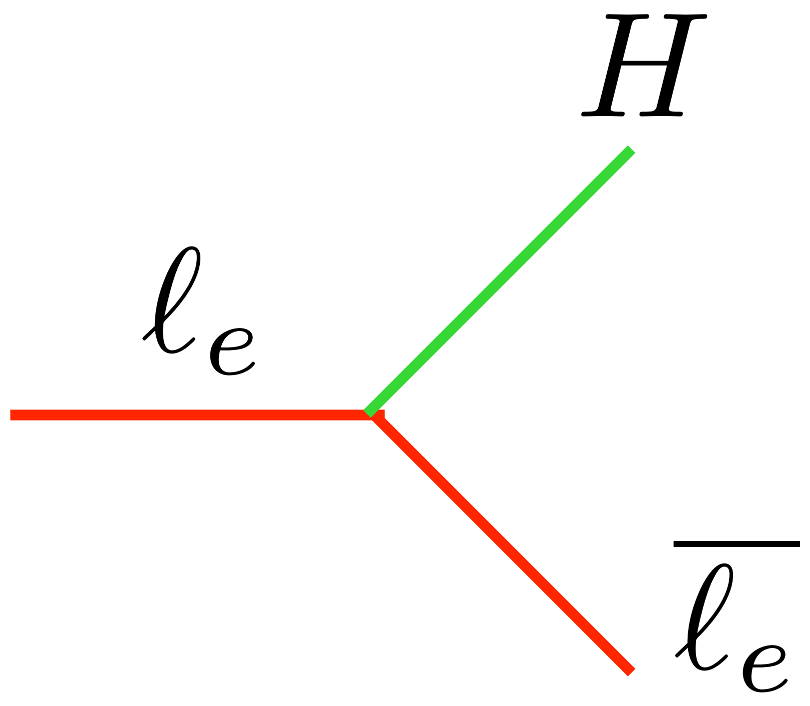


$$\Gamma_\tau > H$$

$$T \sim 10^{9}\,\mathrm{GeV}$$







$$\Gamma_\tau > H$$

$$\Gamma_\mu > H$$

Density Matrix Equations

$$
\begin{aligned}
\frac{dn_{N_i}}{dz} &= -\, D_i(n_{N_i} - n_{N_i}^{\mathrm{eq}}) \\
\frac{dn_{\alpha\beta}}{dz} &= \sum_i \left(\epsilon^{(i)}_{\alpha\beta} D_i(n_{N_i} - n_{N_i}^{\mathrm{eq}}) - \frac{1}{2} W_i \left\{ P^{0(i)}, n \right\}_{\alpha\beta} \right) \\
&\quad - \frac{\Im(\Lambda_\tau)}{Hz} \left[\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \left[\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, n \right] \right]_{\alpha\beta} - \frac{\Im(\Lambda_\mu)}{Hz} \left[\begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \left[\begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}, n \right] \right]_{\alpha\beta},
\end{aligned}
$$

Promote lepton asymmetry number density to matrix:

$$
N = \begin{pmatrix} N_{\tau\tau} & N_{\tau\mu} & N_{\tau e} \\ N_{\mu\tau} & N_{\mu\mu} & N_{\mu e} \\ N_{e\tau} & N_{e\mu} & N_{ee} \end{pmatrix}
$$

Density Matrix Equations

$$\frac{dn_{N_i}}{dz} = -\, D_i(n_{N_i} - n_{N_i}^{\rm eq})$$

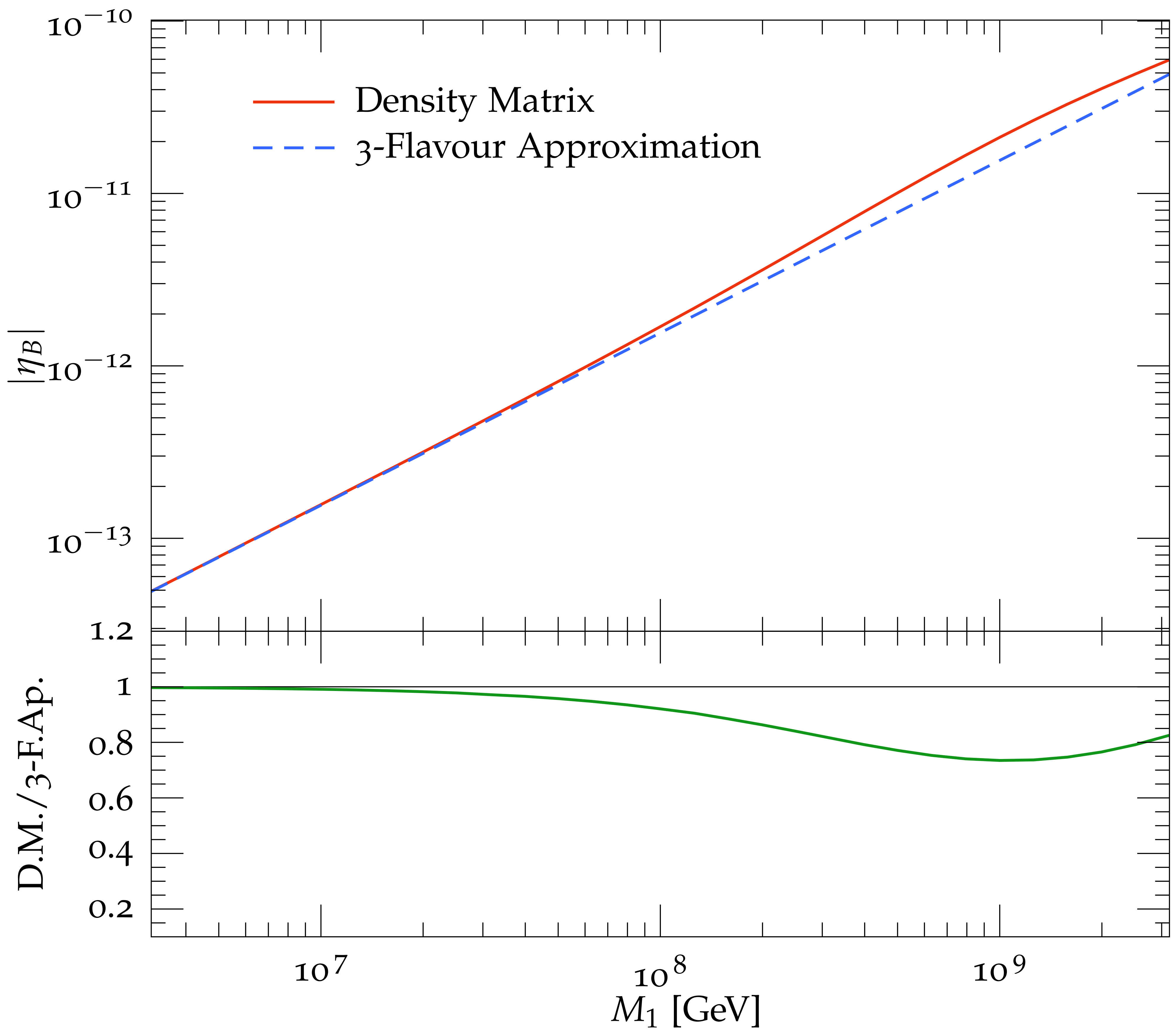
$$\frac{dn_{\alpha\beta}}{dz} = \sum_i \left(\epsilon^{(i)}_{\alpha\beta} D_i (n_{N_i} - n_{N_i}^{\rm eq}) - \frac{1}{2} W_i \left\{ P^{0(i)}, n \right\}_{\alpha\beta} \right)$$

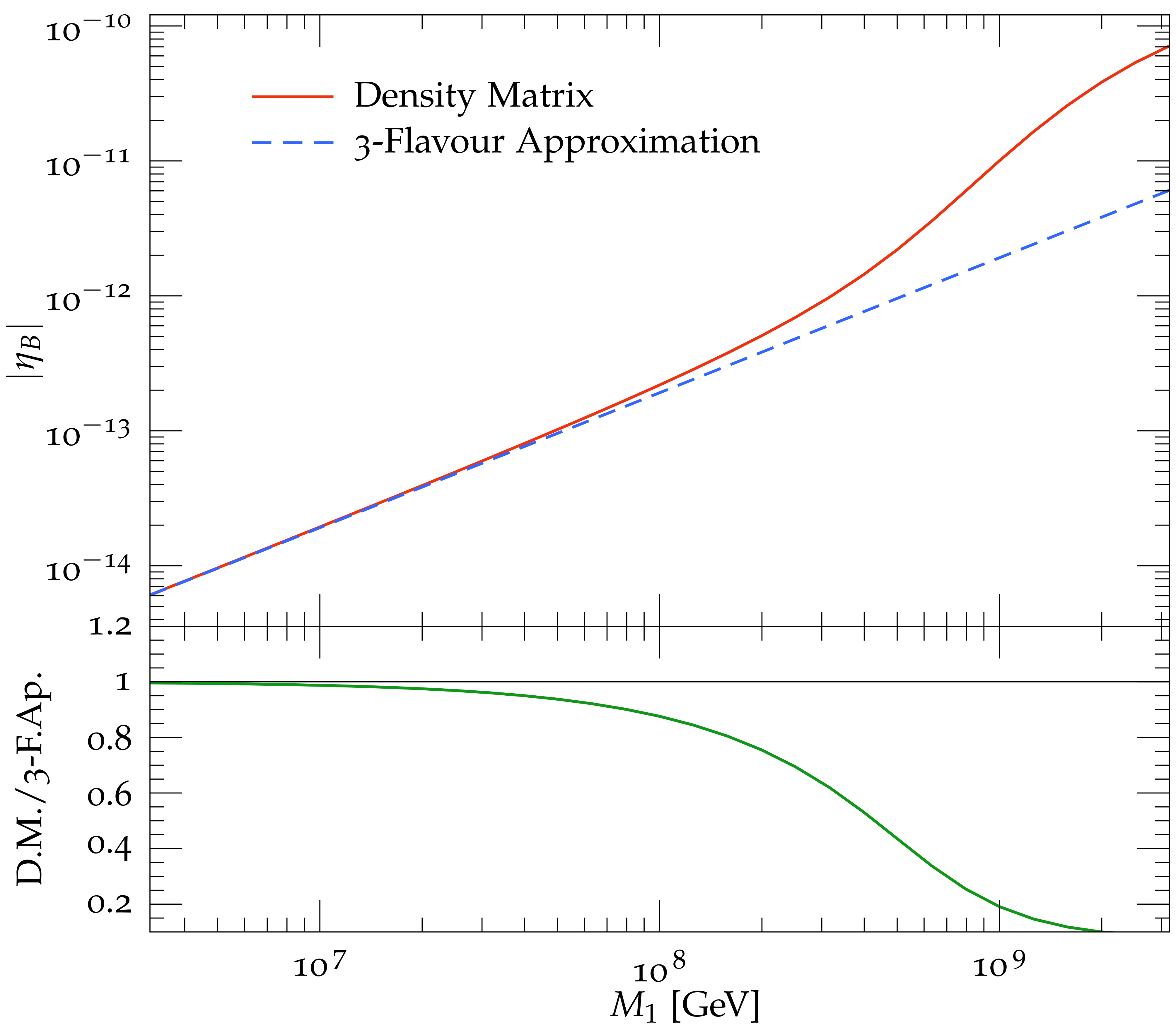
$$- \frac{\Im(\Lambda_\tau)}{Hz} \left[\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \left[\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, n \right] \right]_{\alpha\beta} - \frac{\Im(\Lambda_\mu)}{Hz} \left[\begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \left[\begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}, n \right] \right]_{\alpha\beta},$$

"Classical" BE ignore off-diagonal components of matrix and only take the trace of the matrix

$$N = \begin{pmatrix} N_{\tau\tau} & N_{\tau\mu} & N_{\tau e} \\ N_{\mu\tau} & N_{\mu\mu} & N_{\mu e} \\ N_{e\tau} & N_{e\mu} & N_{ee} \end{pmatrix}$$

Density Matrix Equations versus Classical BEs





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

Fukugida & Yanagida

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

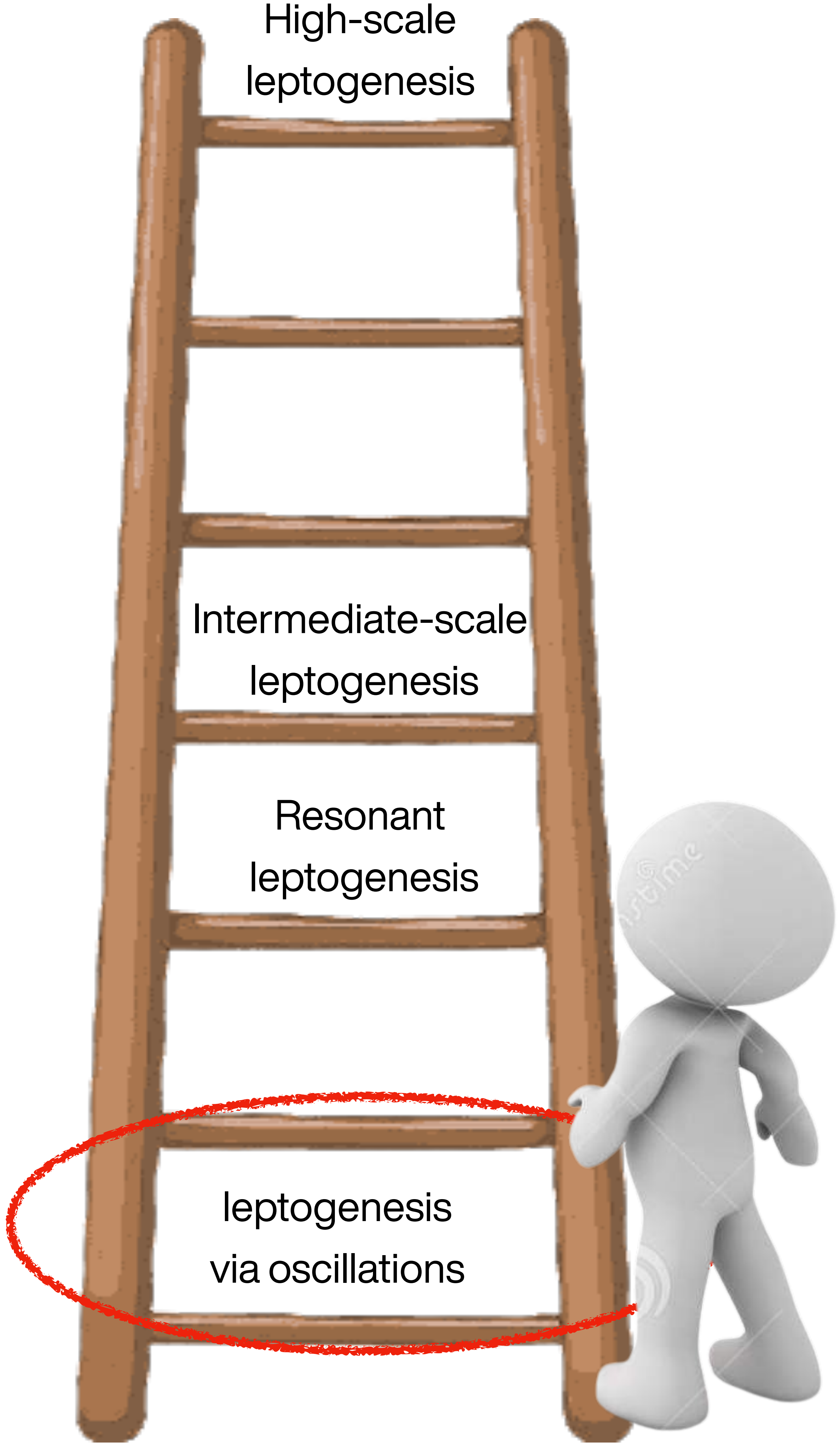
Racker, Rius & Pena

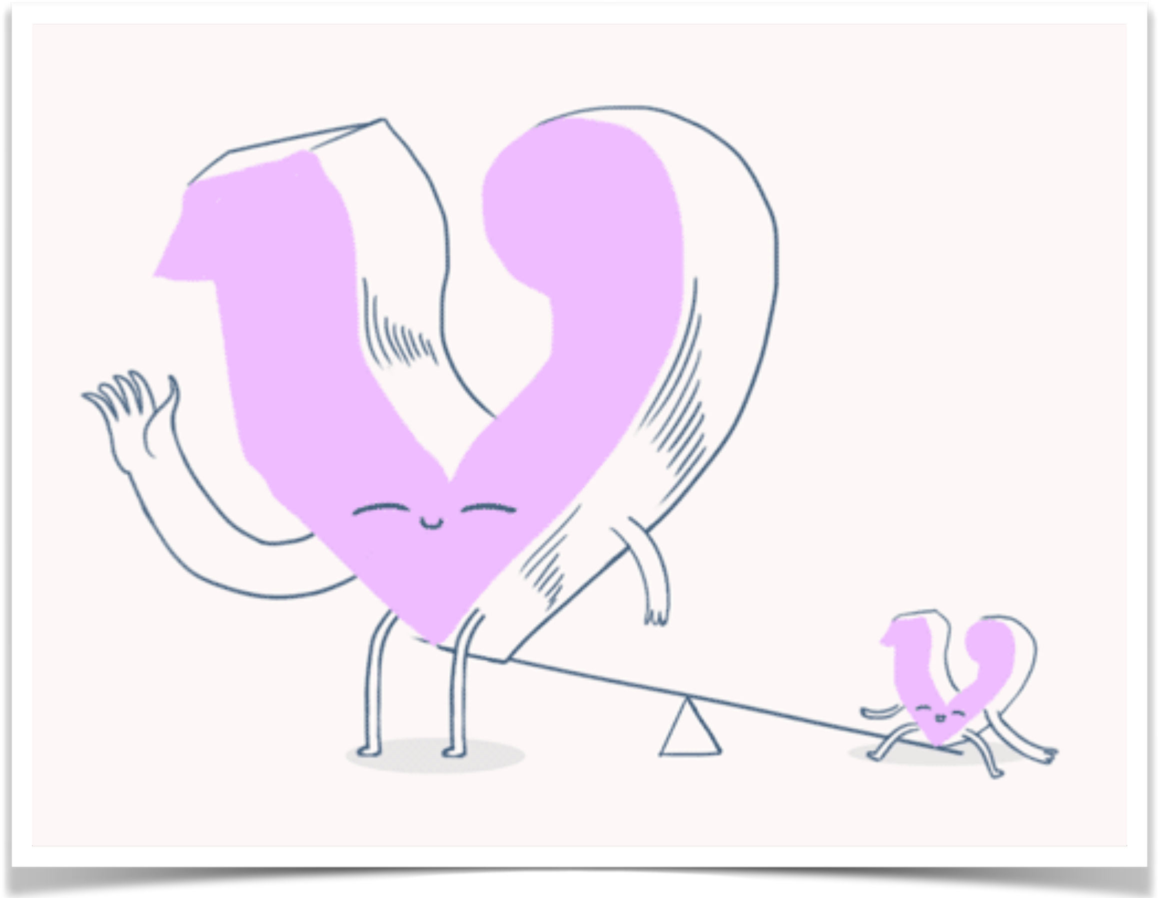
$\mathcal{O}(10^{3})$ GeV

Pilaftis & Underwood

$\mathcal{O}(1)$ GeV

Akhmedov, Rubakov & Smirnov





RHNs GeV mass

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

Leptogenesis via Oscillations

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

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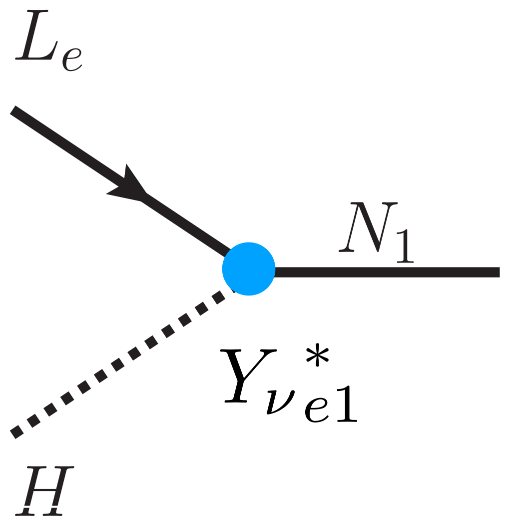
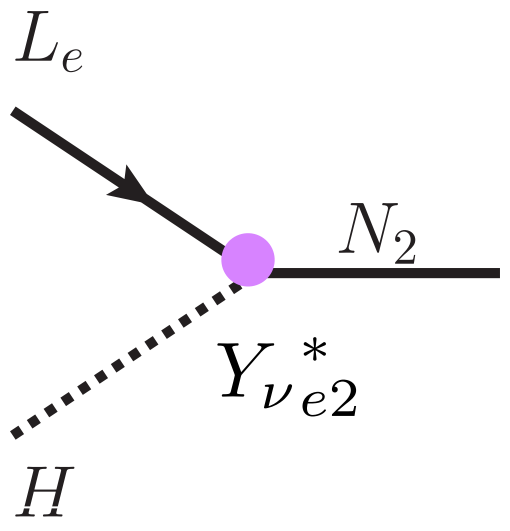


For simplicity, consider two flavour system

(1,2) & (e, μ)



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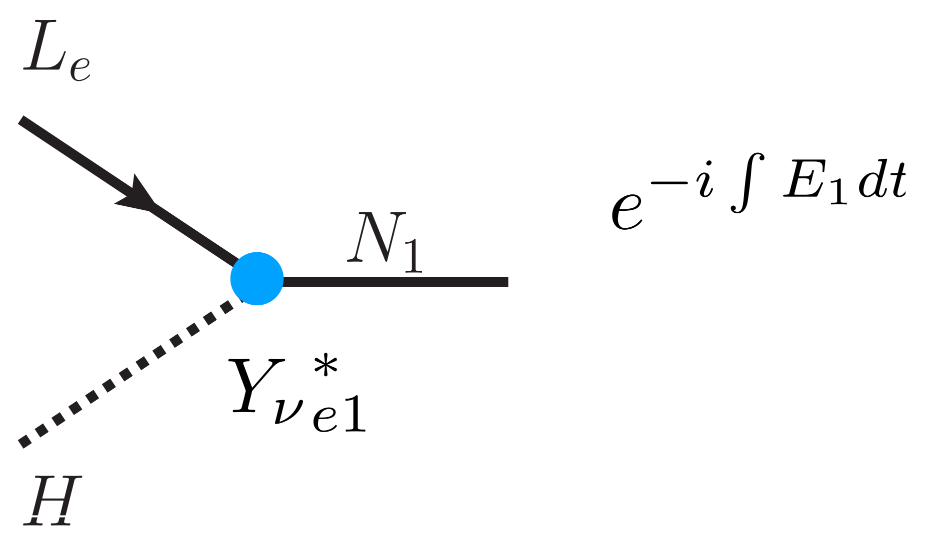

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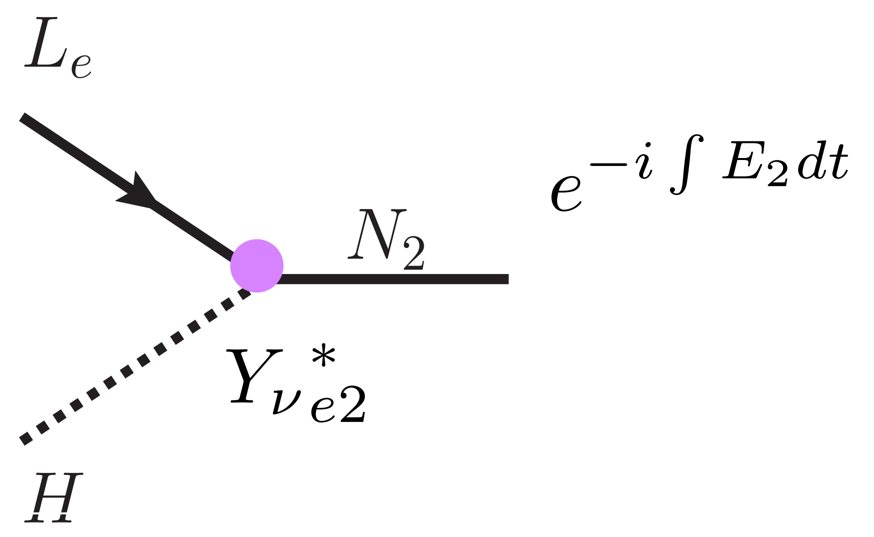

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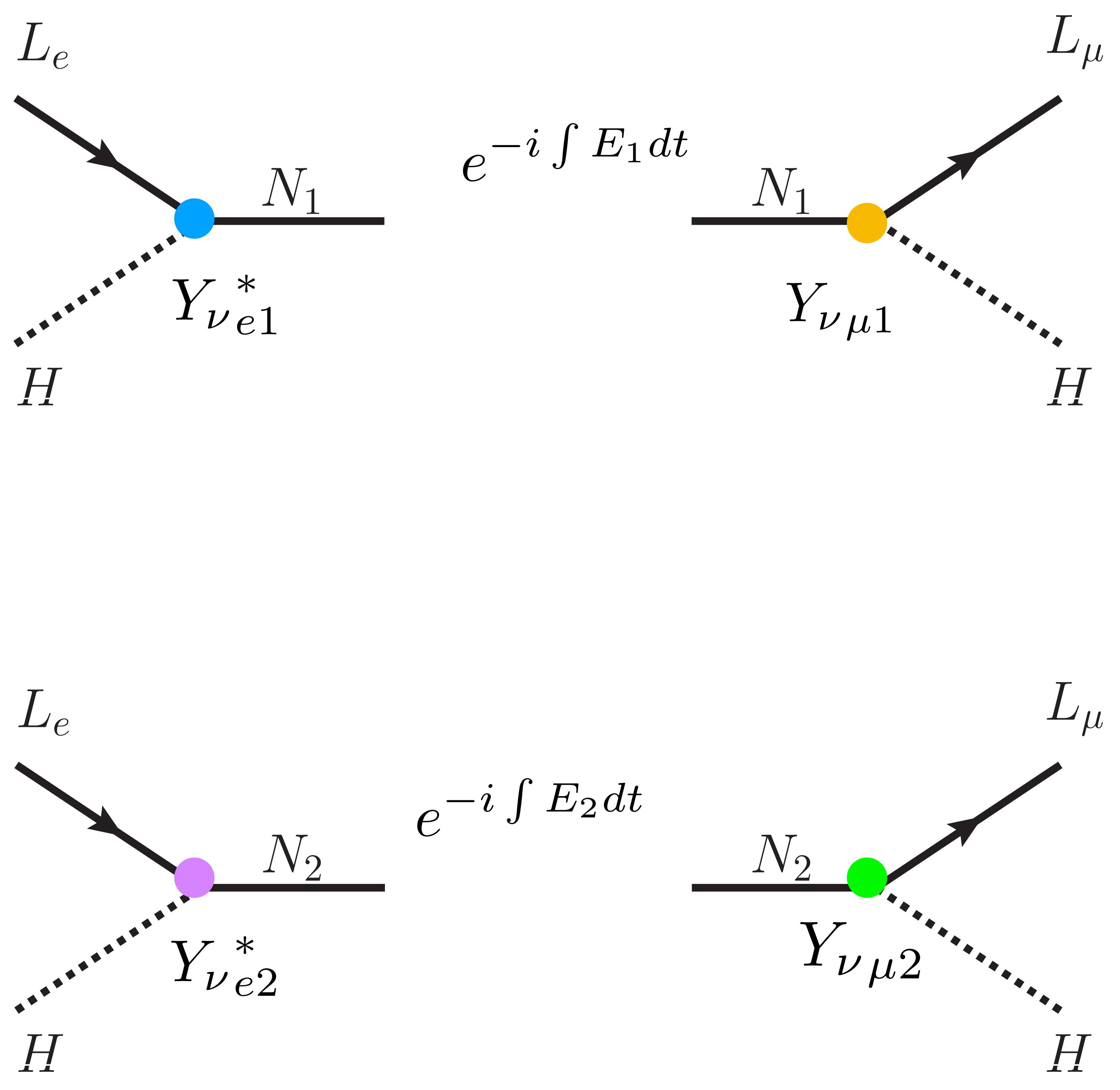

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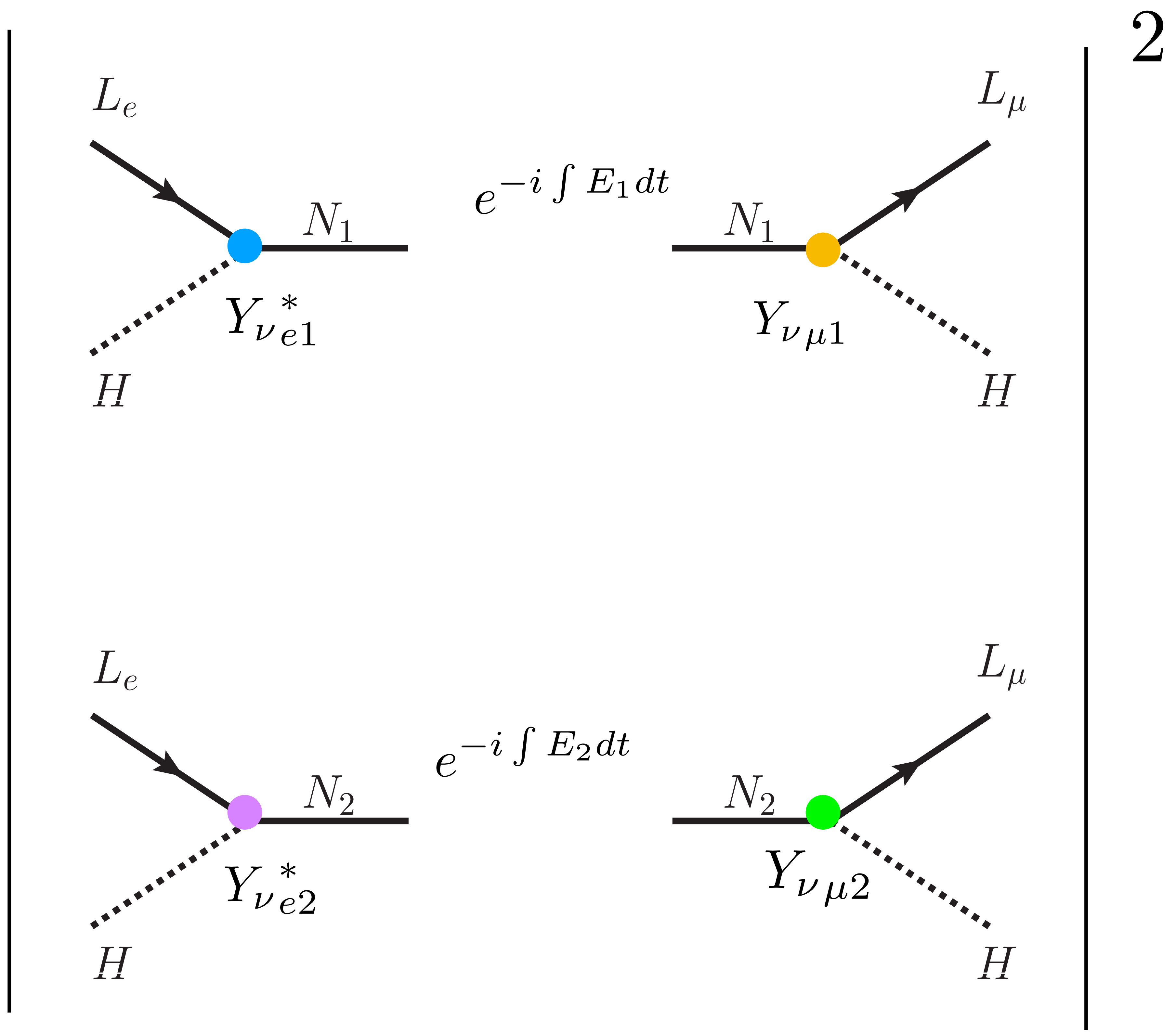
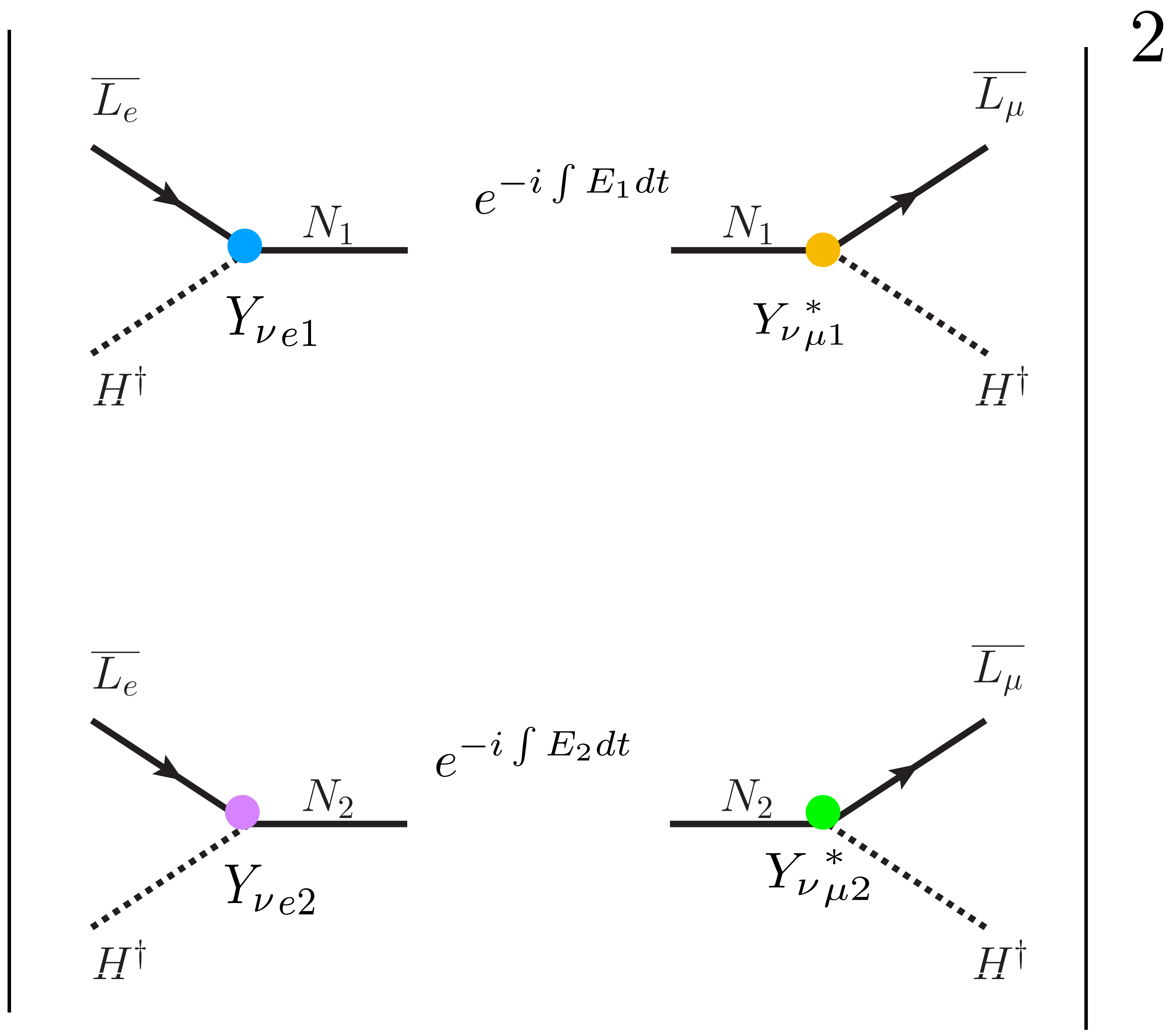


$$\Gamma(L_e \to L_\mu) \propto e^{-i\int \frac{\Delta m^2_{21}}{2|\vec{p}|} dt} \times \left(Y^*_{\nu e1} Y_{\nu\mu 1} Y^*_{\nu e2} Y_{\nu\mu 2}\right)$$

Leptogenesis via Oscillations



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 Oscillations

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

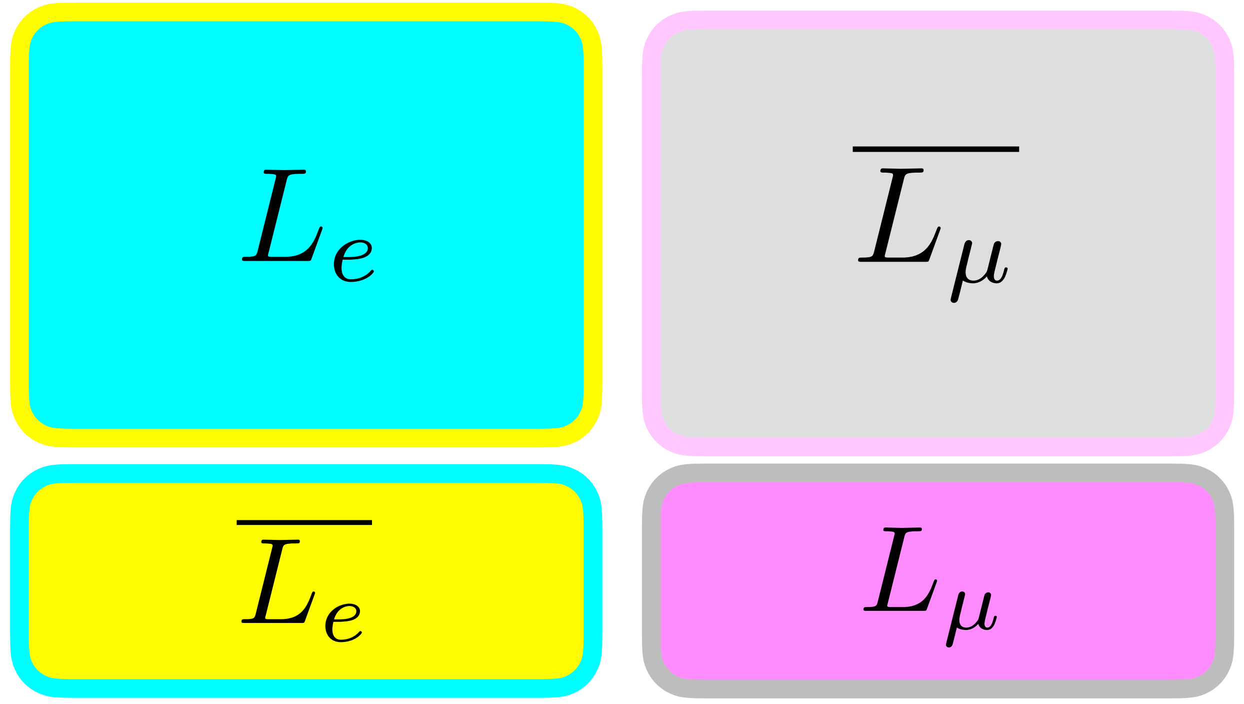
L_e $\overline{L_\mu}$

$\overline{L_e}$ L_μ

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

Leptogenesis via Oscillations

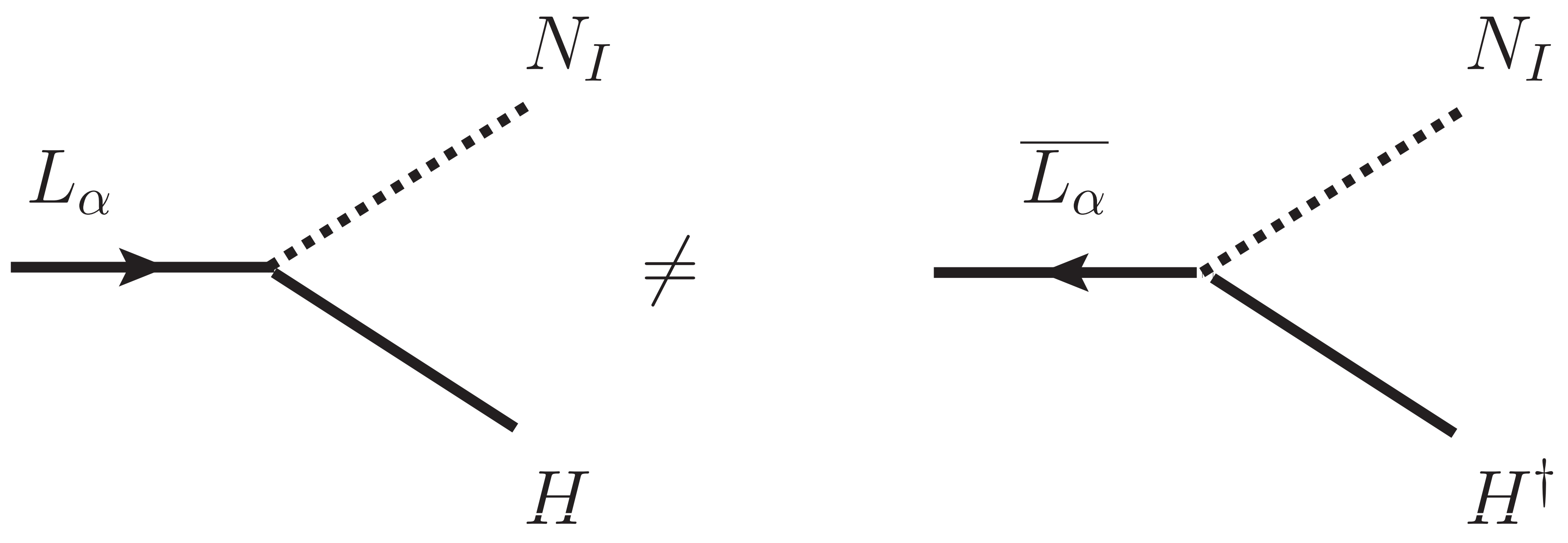
$$\Gamma\left(L_e \to L_\mu\right) - \Gamma\left(\overline{L_e} \to \overline{L_\mu}\right) \propto \sin\left(\int \frac{\Delta m_{21}^2}{2|\vec{p}|}dt\right) \times \mathrm{Im}\left(Y_{\nu e1}Y^*_{\nu\mu 1}Y_{\nu e2}Y^*_{\nu\mu 1}\right)$$



$\Delta L_e \neq 0$

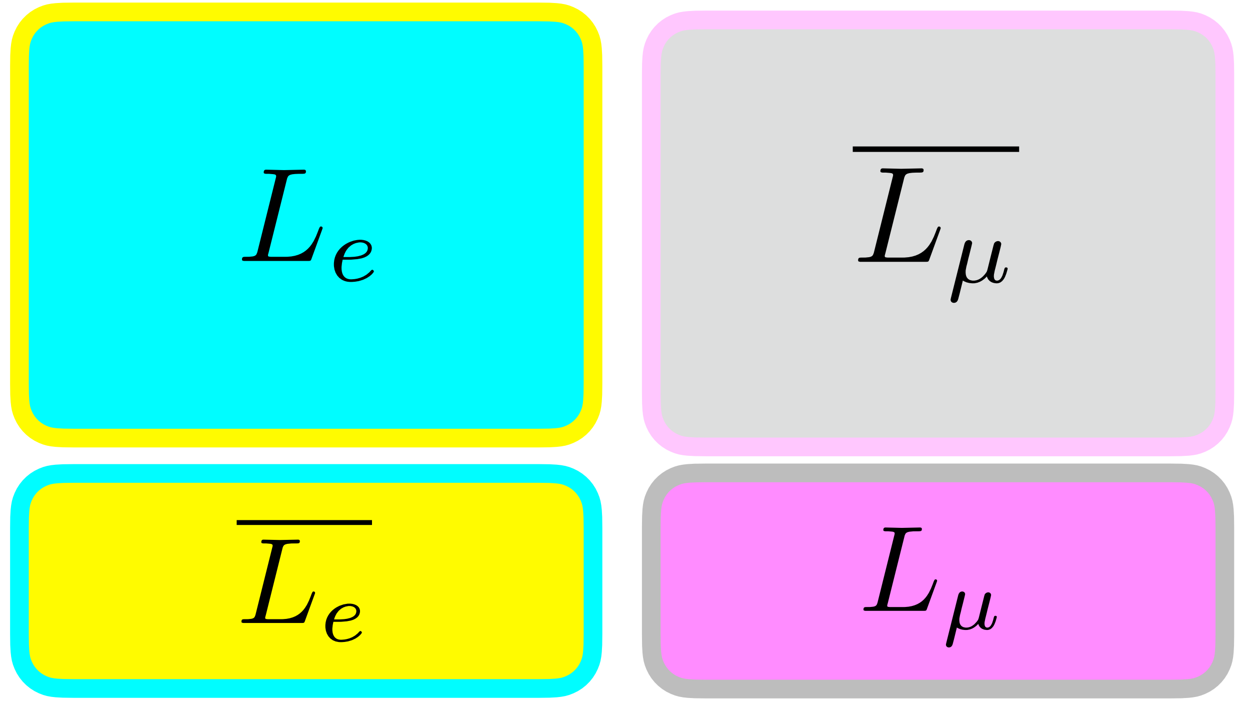
$\Delta L_\mu \neq 0$

$\Delta L = 0$



Leptogenesis via Oscillations

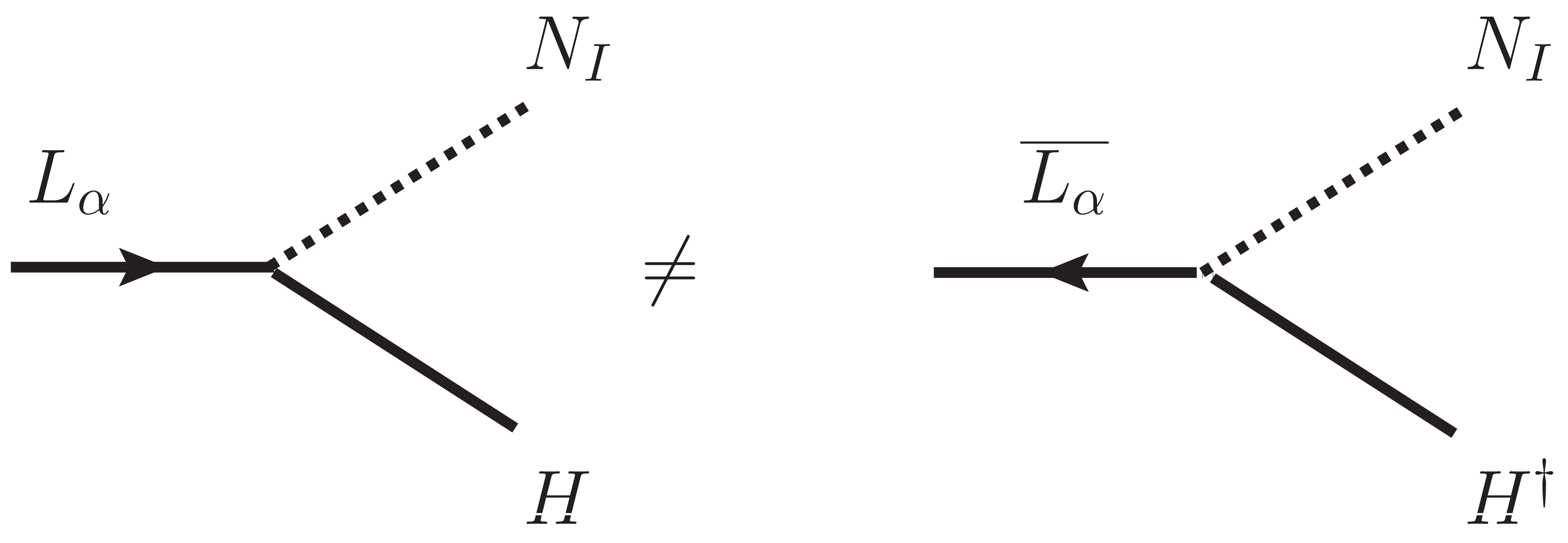
$$\Gamma\left(L_e \to L_\mu\right) - \Gamma\left(\overline{L_e} \to \overline{L_\mu}\right) \propto \sin\left(\int \frac{\Delta m^2_{21}}{2|\vec{p}|} dt\right) \times \mathrm{Im}\left(Y_{\nu e1} Y^*_{\nu\mu 1} Y_{\nu e2} Y^*_{\nu\mu 1}\right)$$



$\Delta L_e \neq 0$

$\Delta L_\mu \neq 0$

$\Delta L = 0$



$\Delta L \neq 0$

EW sphalerons

convert SM lepton asymmetry

to baryon asymmetry

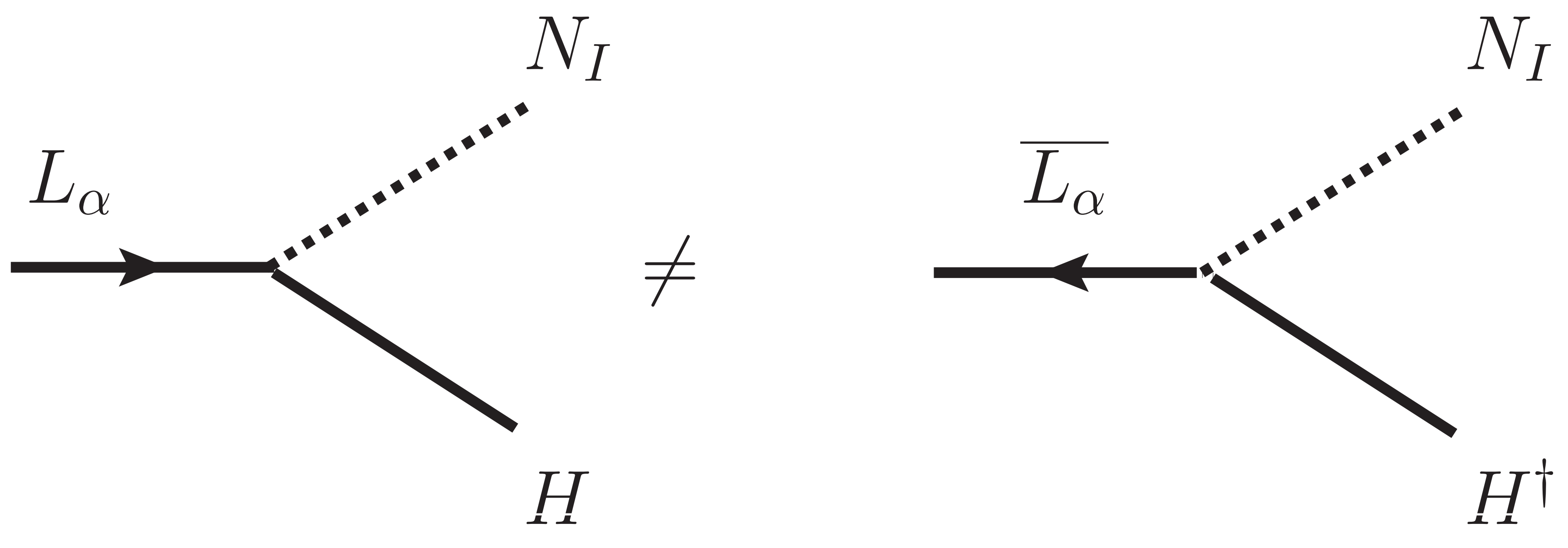
Leptogenesis via Oscillations

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

L_e | $\overline{L_\mu}$

$\overline{L_e}$ | L_μ

$$\Delta L_e \neq 0$$
$$\Delta L_\mu \neq 0$$
$$\Delta L = 0$$



$$\Delta L \neq 0$$

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convert SM lepton asymmetry

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B

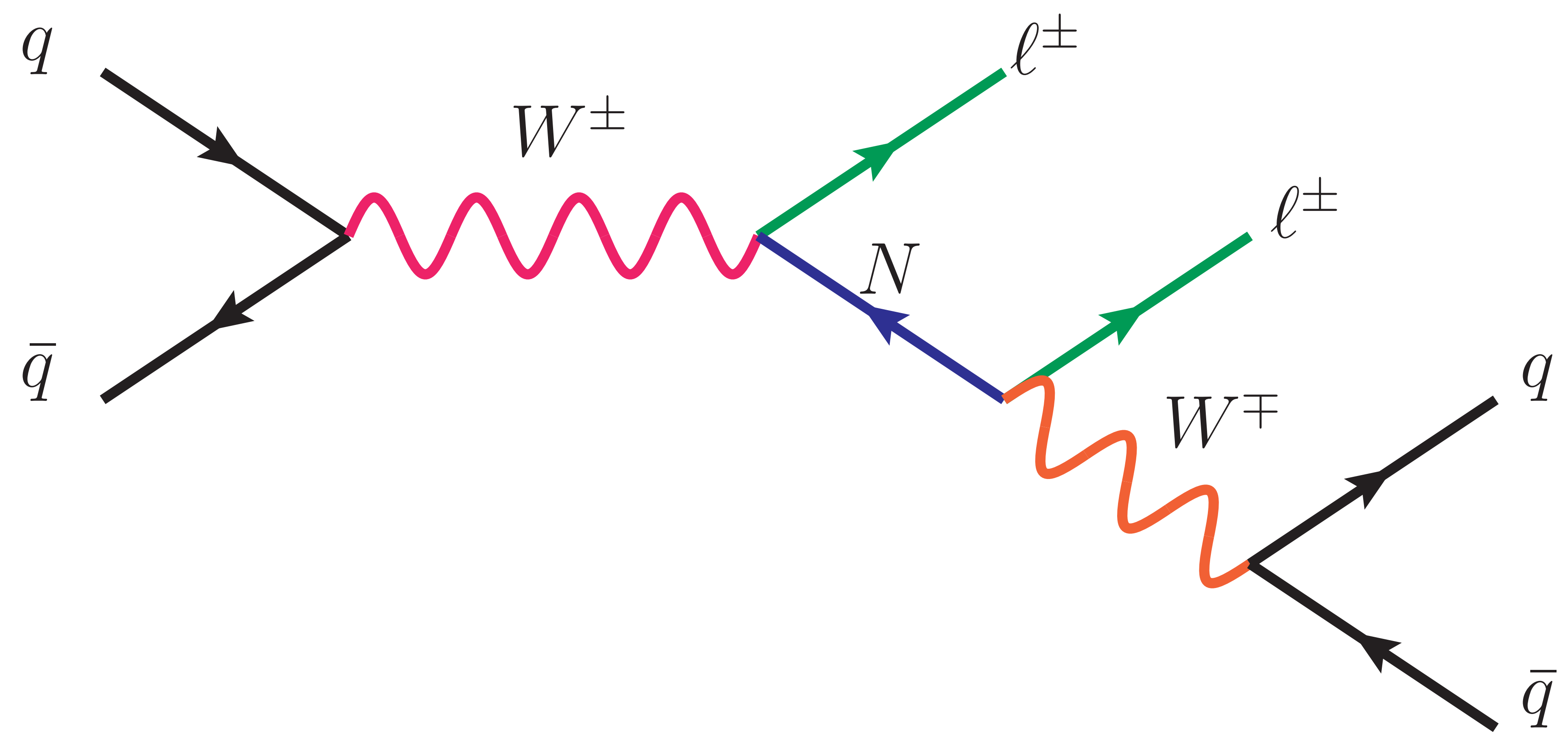
$\overline{B}$

Leptogenesis via Oscillations

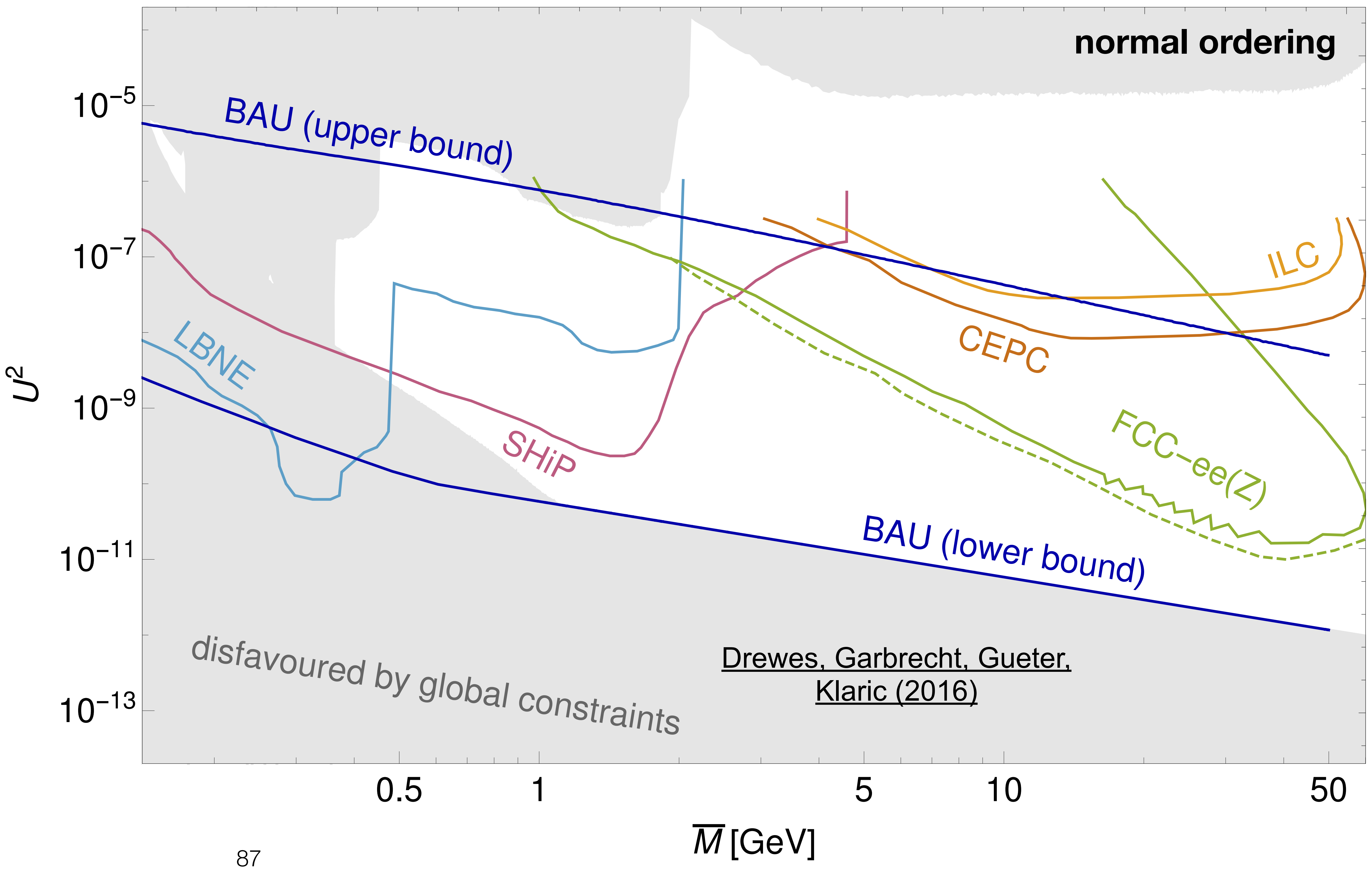
2 RHNs → 4 masses, 4 mixing angles, 3 phases

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

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



Like-sign lepton + dijet



Leptogenesis via Oscillations

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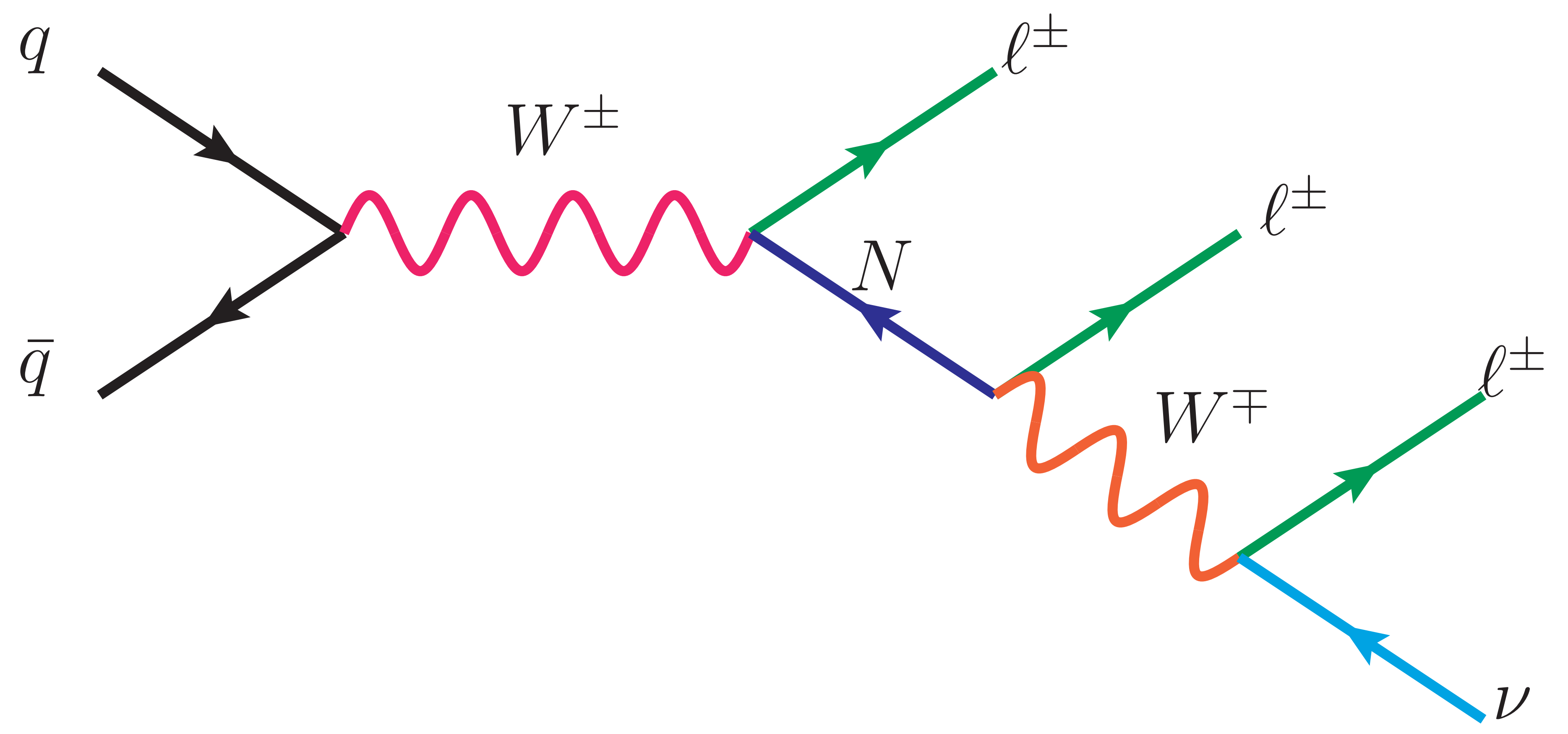
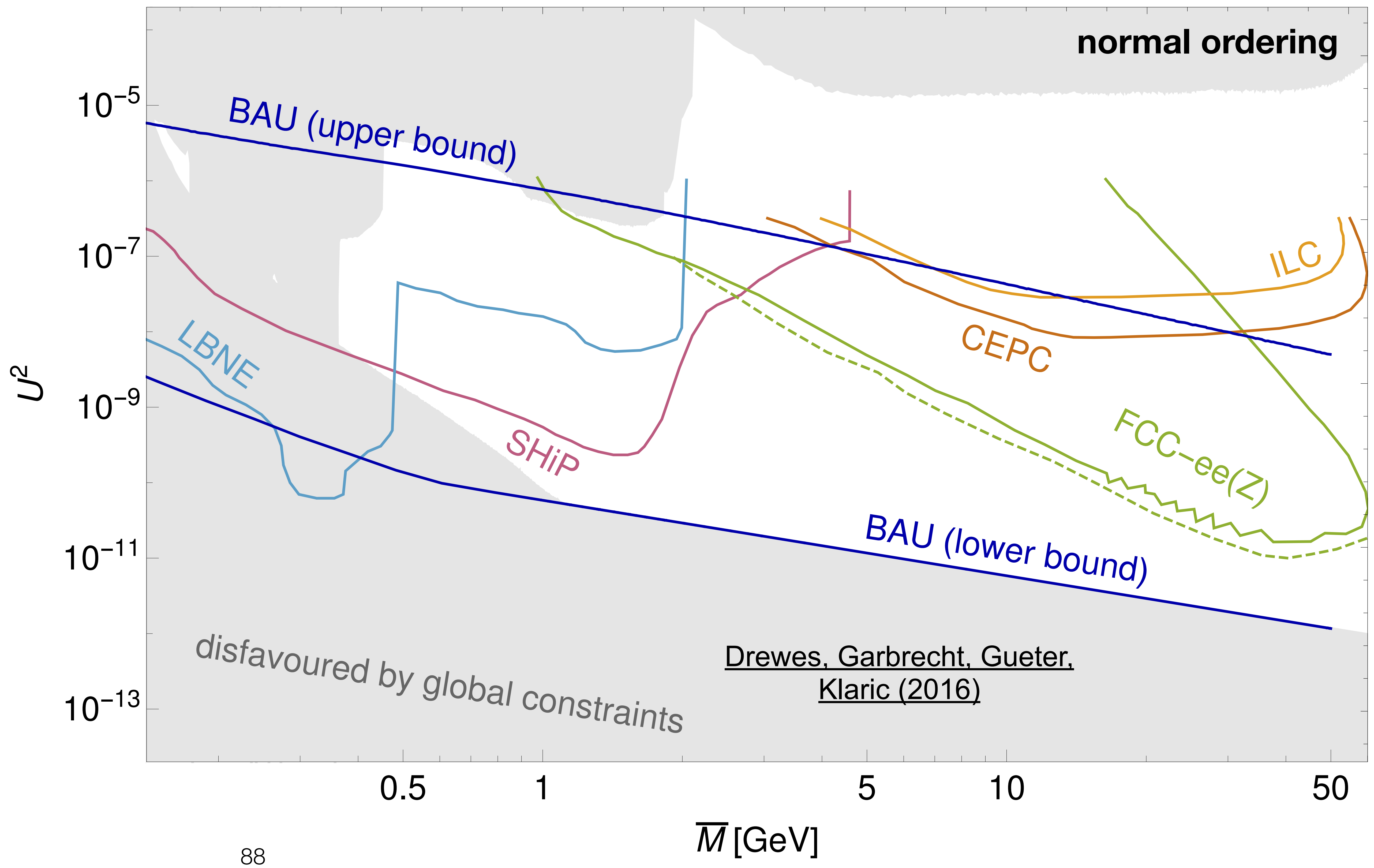


Trilepton



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

Fukugida & Yanagida

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

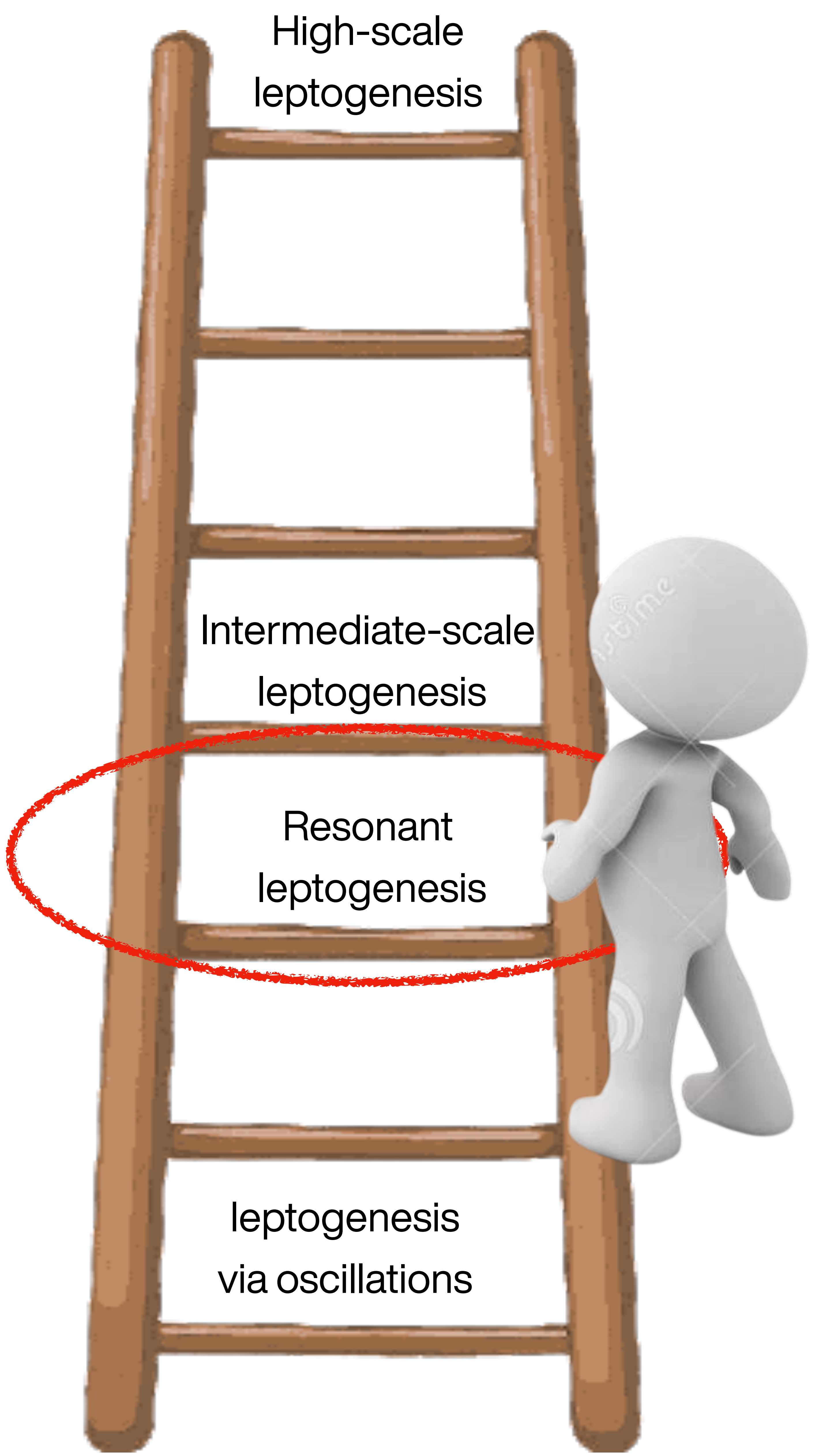
Racker, Rius & Pena

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

Pilaftis & Underwood

$\mathcal{O}(1)$ GeV

Akhmedov, Rubakov & Smirnov



RHNs TeV mass

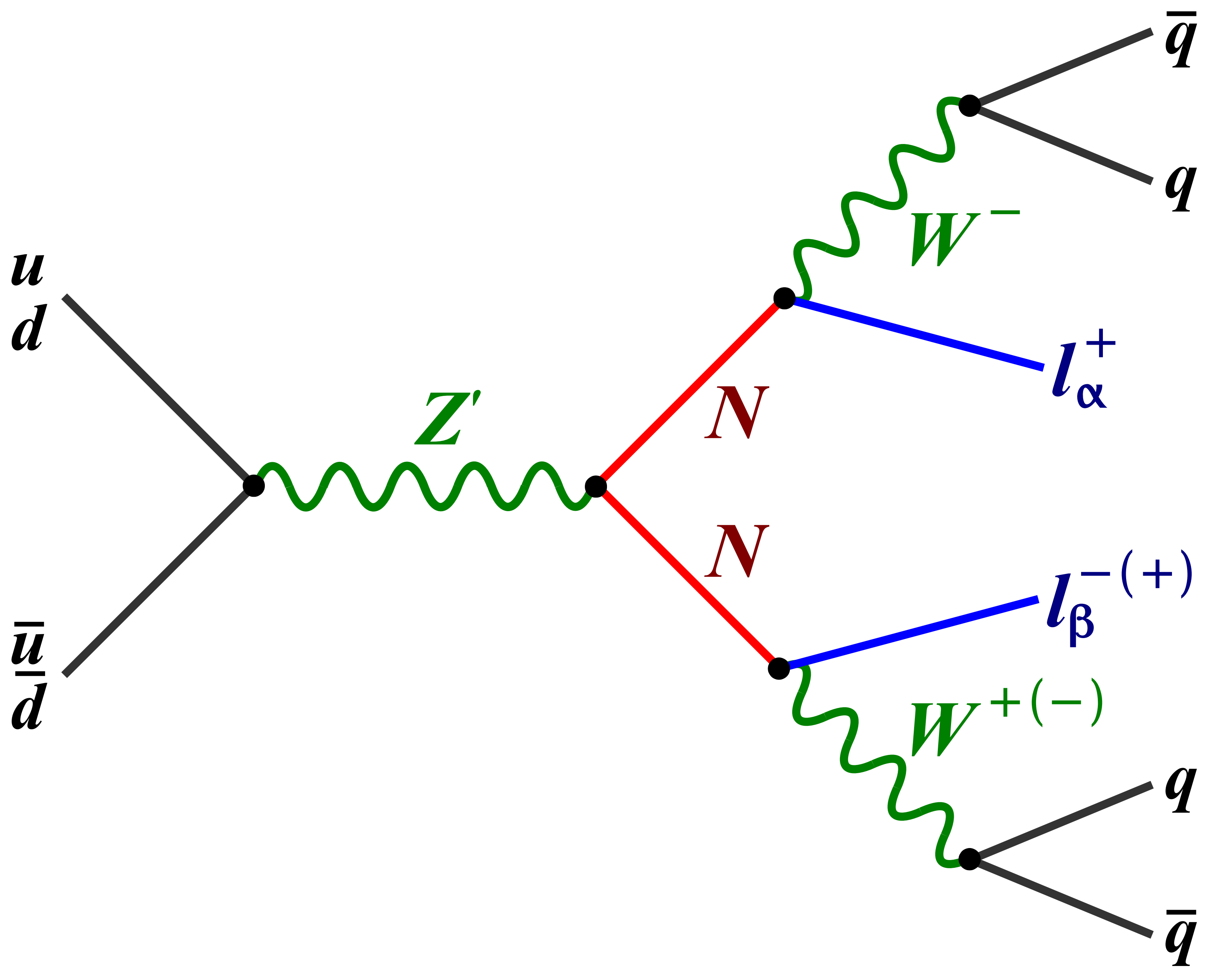
$$\Longrightarrow \; Y_\nu \sim 10^{-5} - 10^{-4}$$

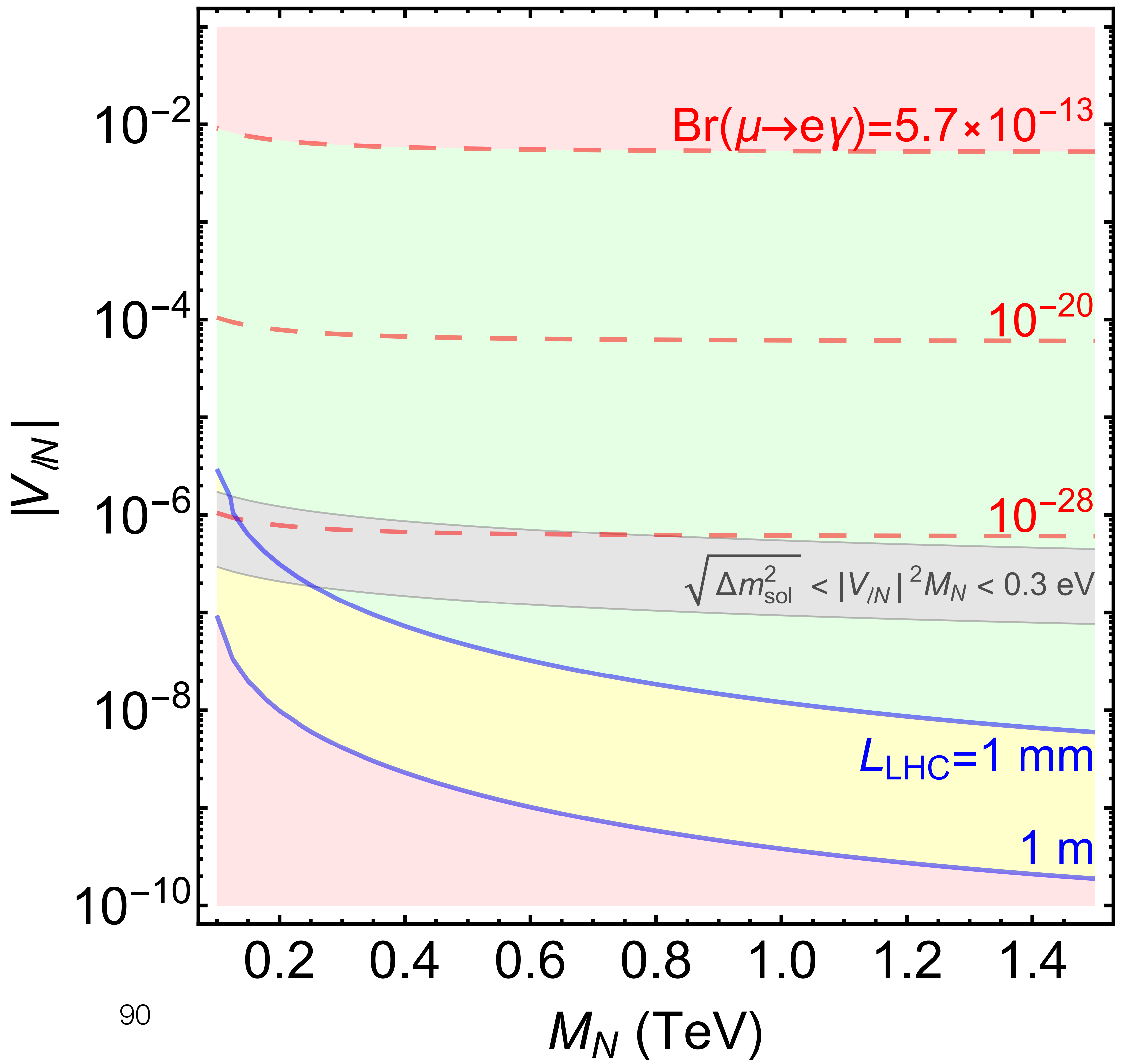
Resonant Leptogenesis

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)

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

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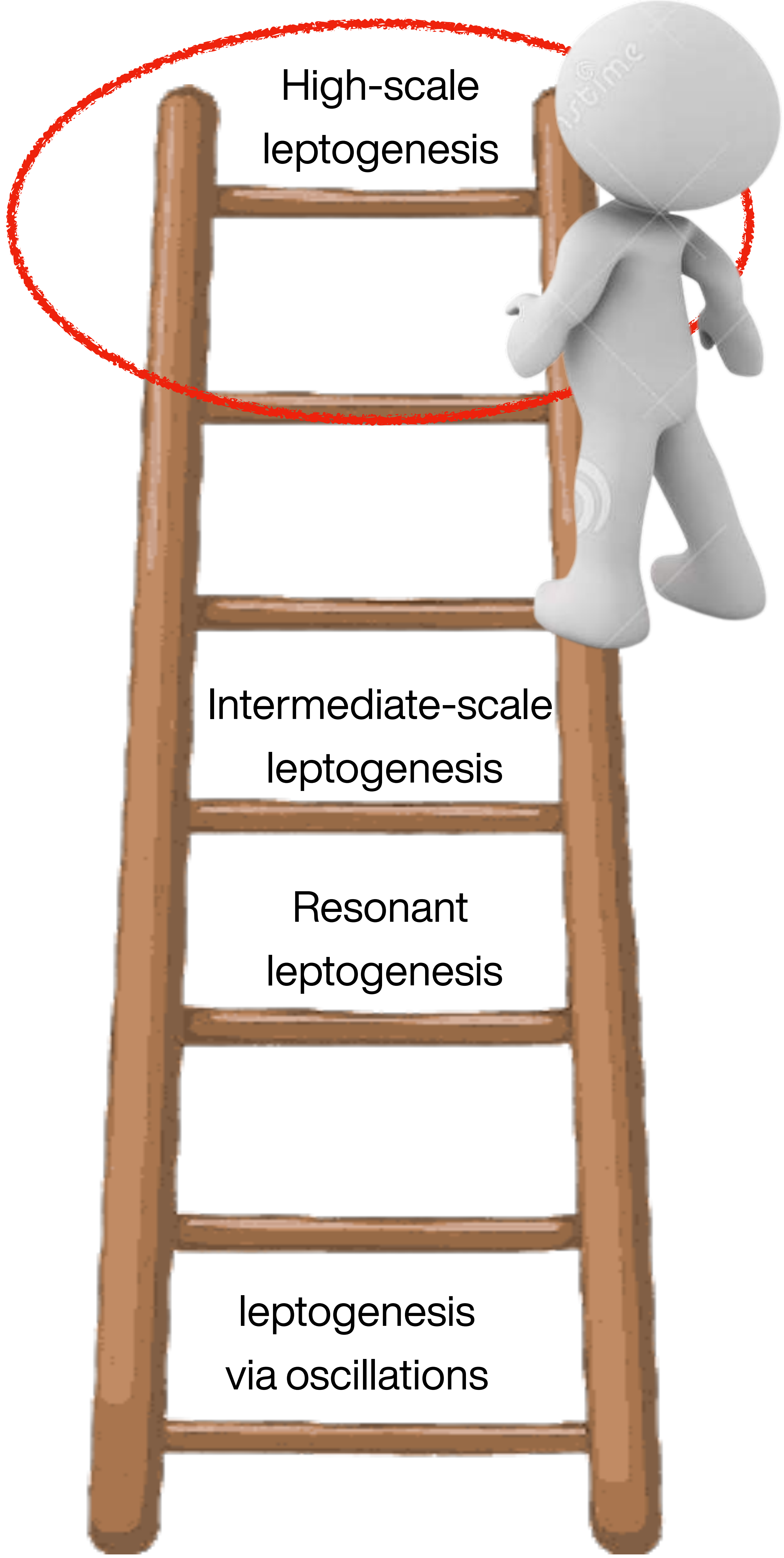
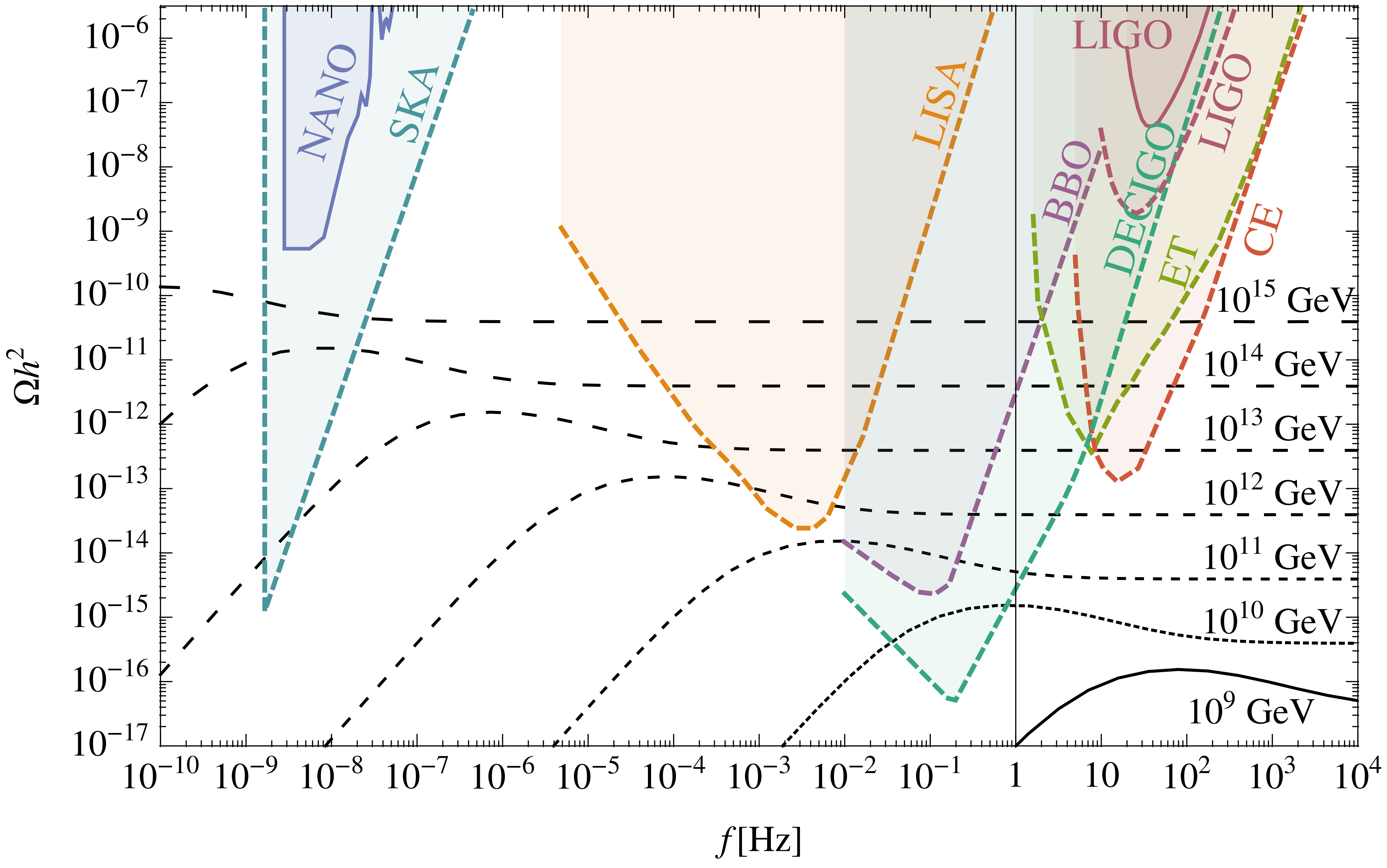


Tough to test but gravitational waves offer an additional probe

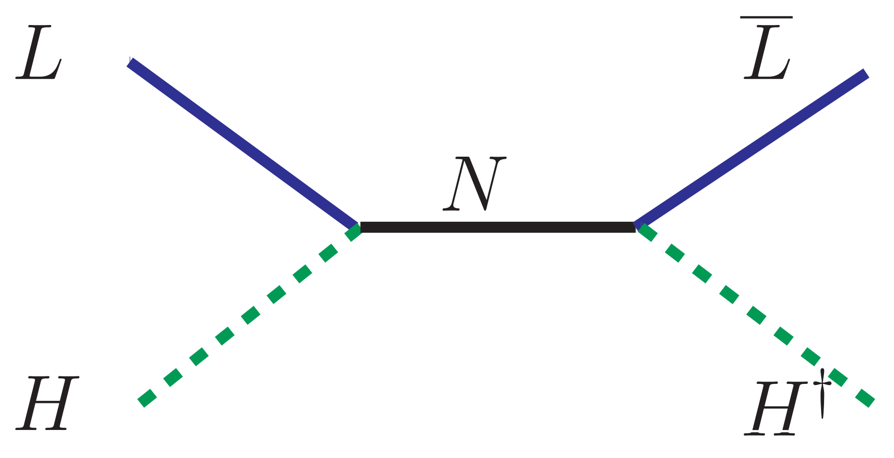
High-Scale Leptogenesis

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

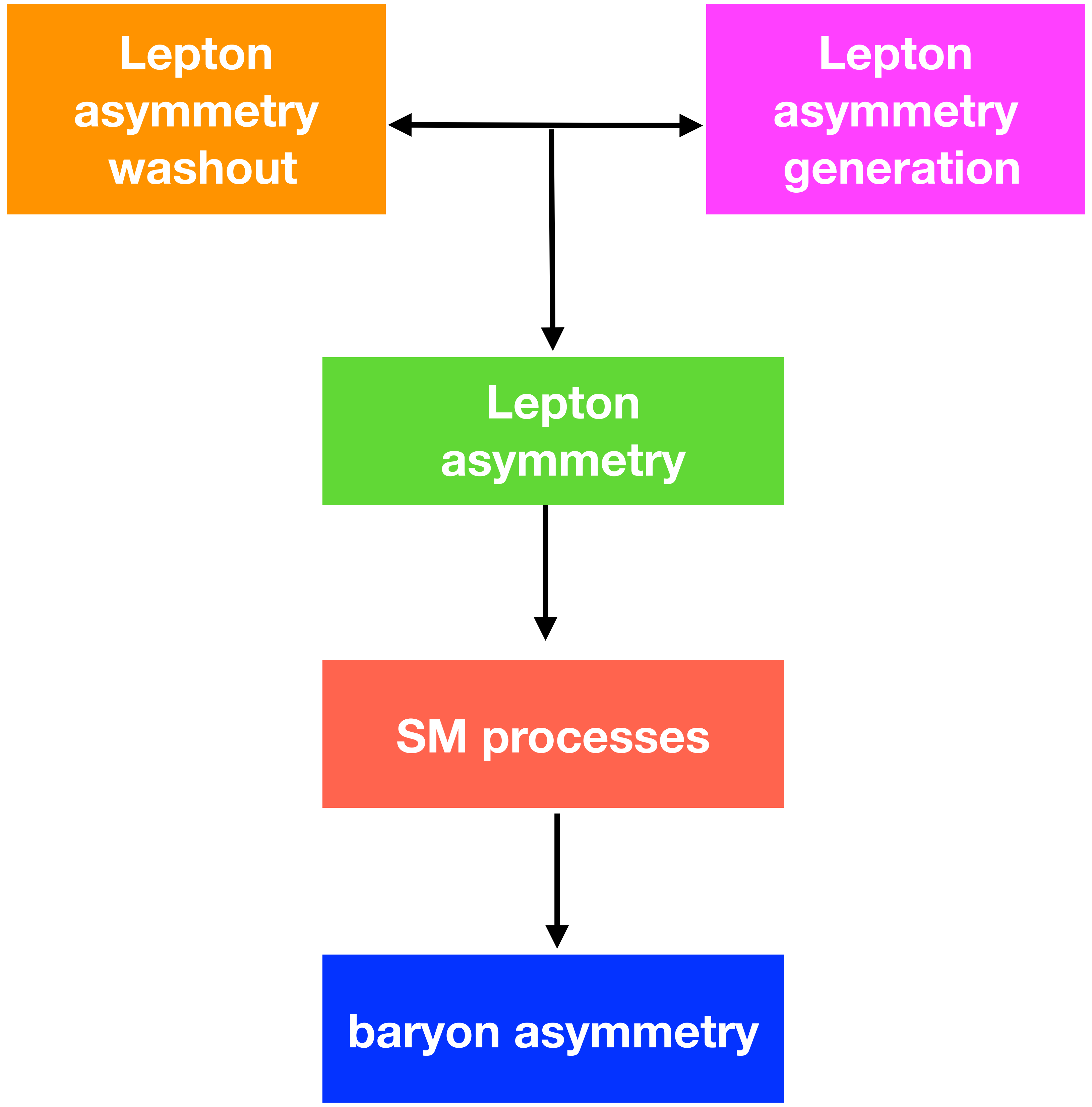


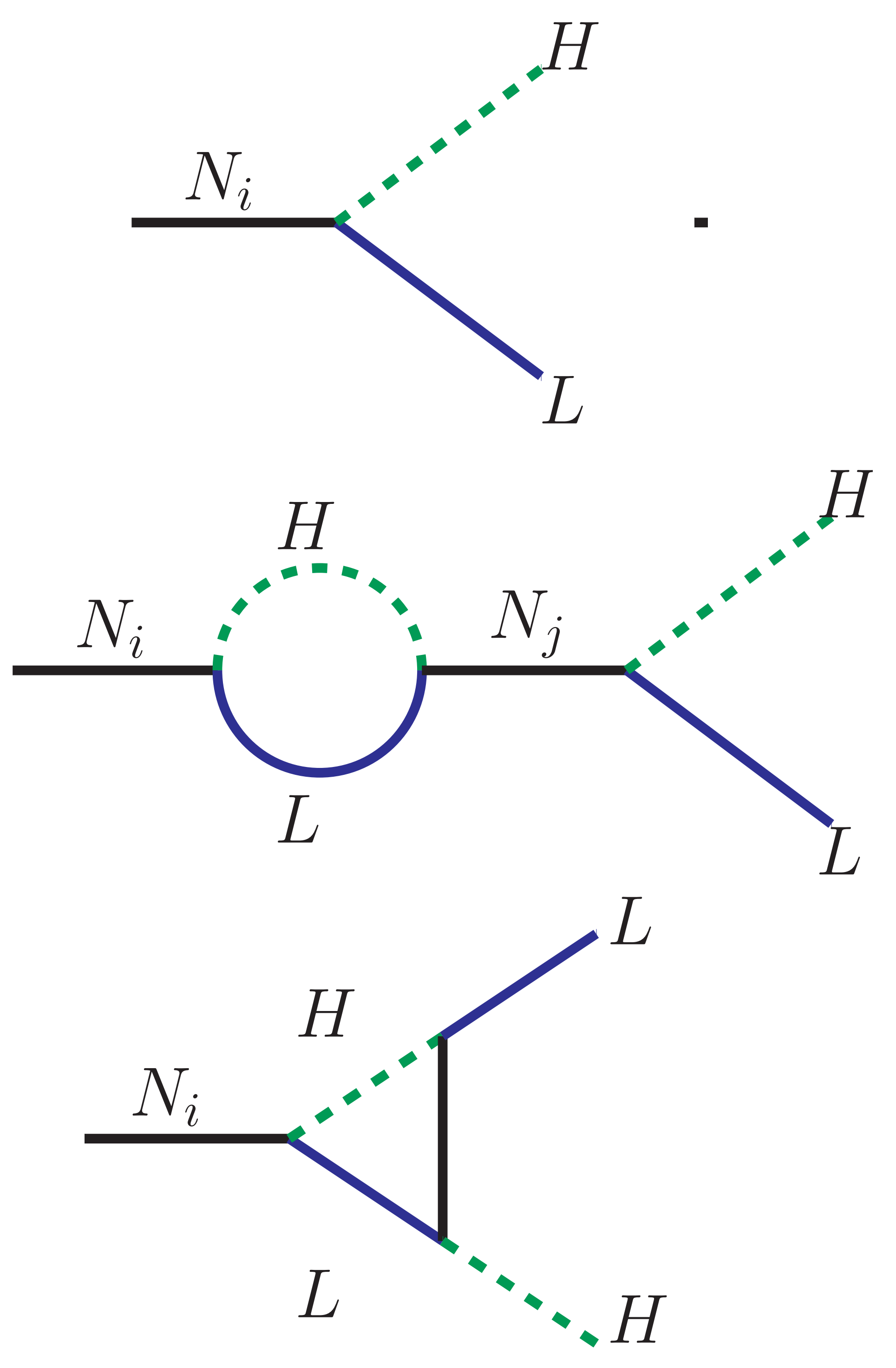
Dror, Hiramatsu, Kohri, Murayama & White (2020)

Falsifying High-Scale Leptogenesis



Γ_W



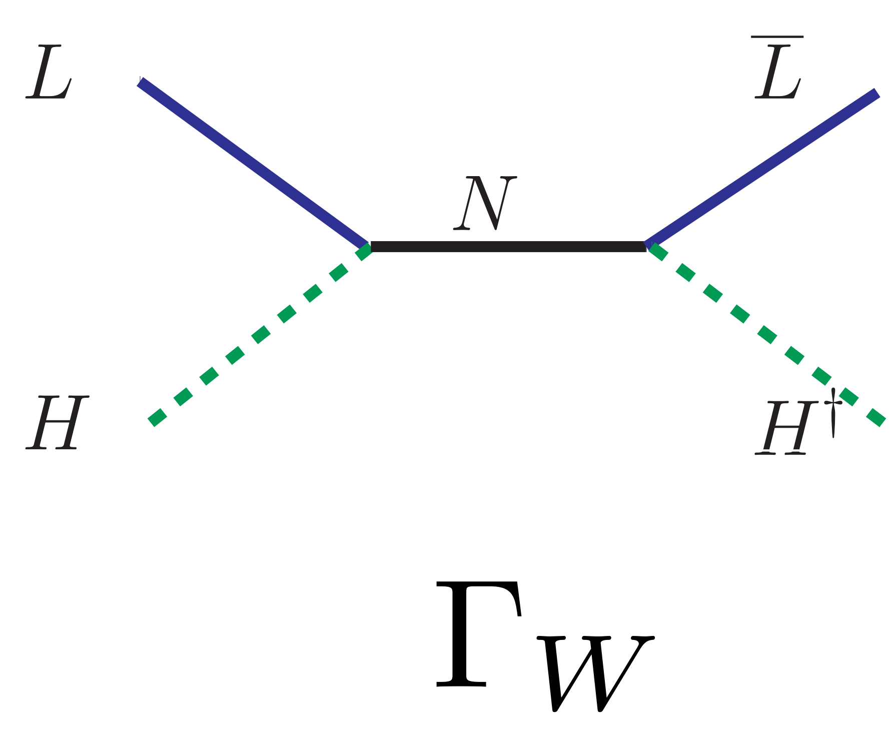


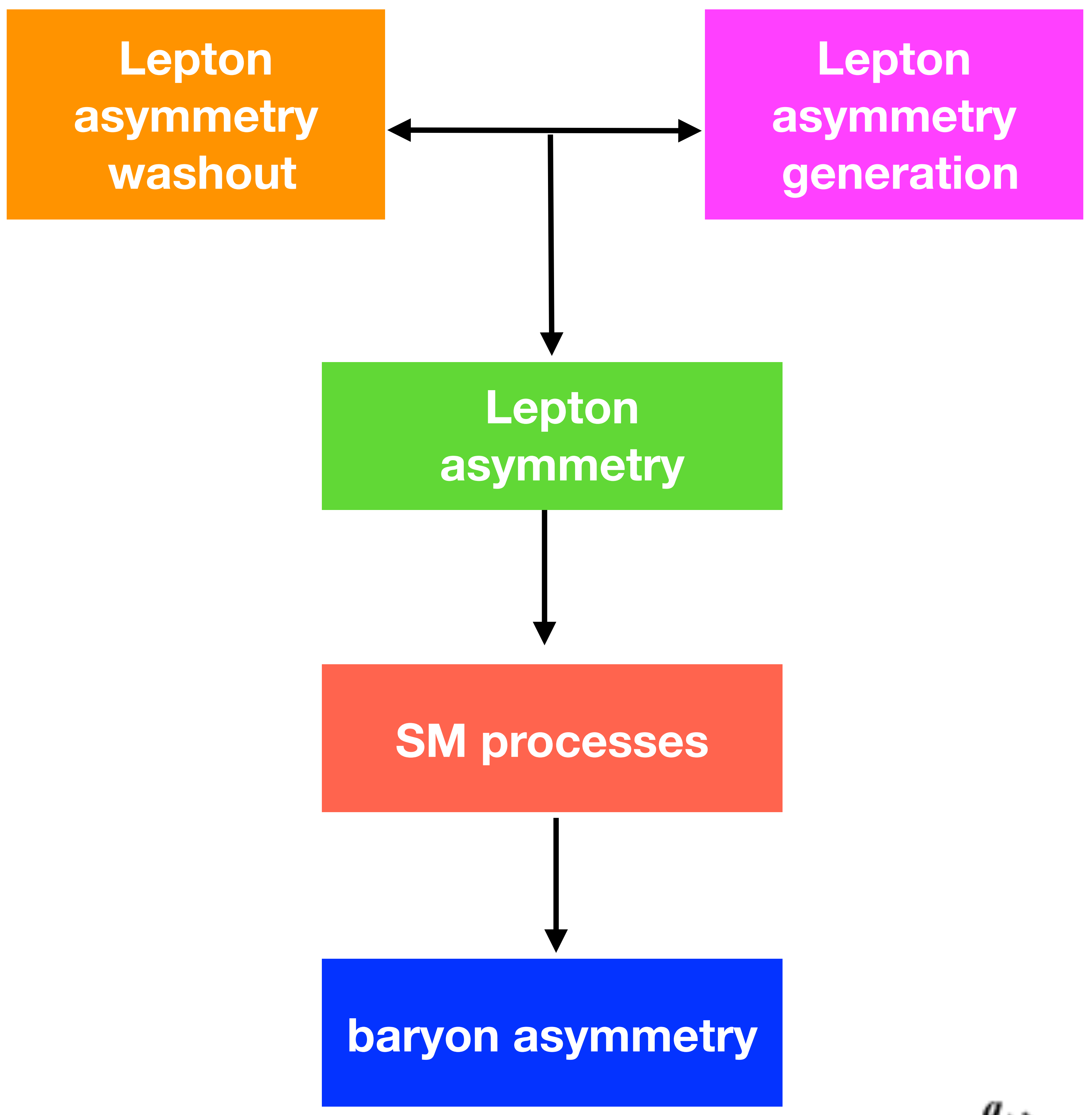
Γ_D

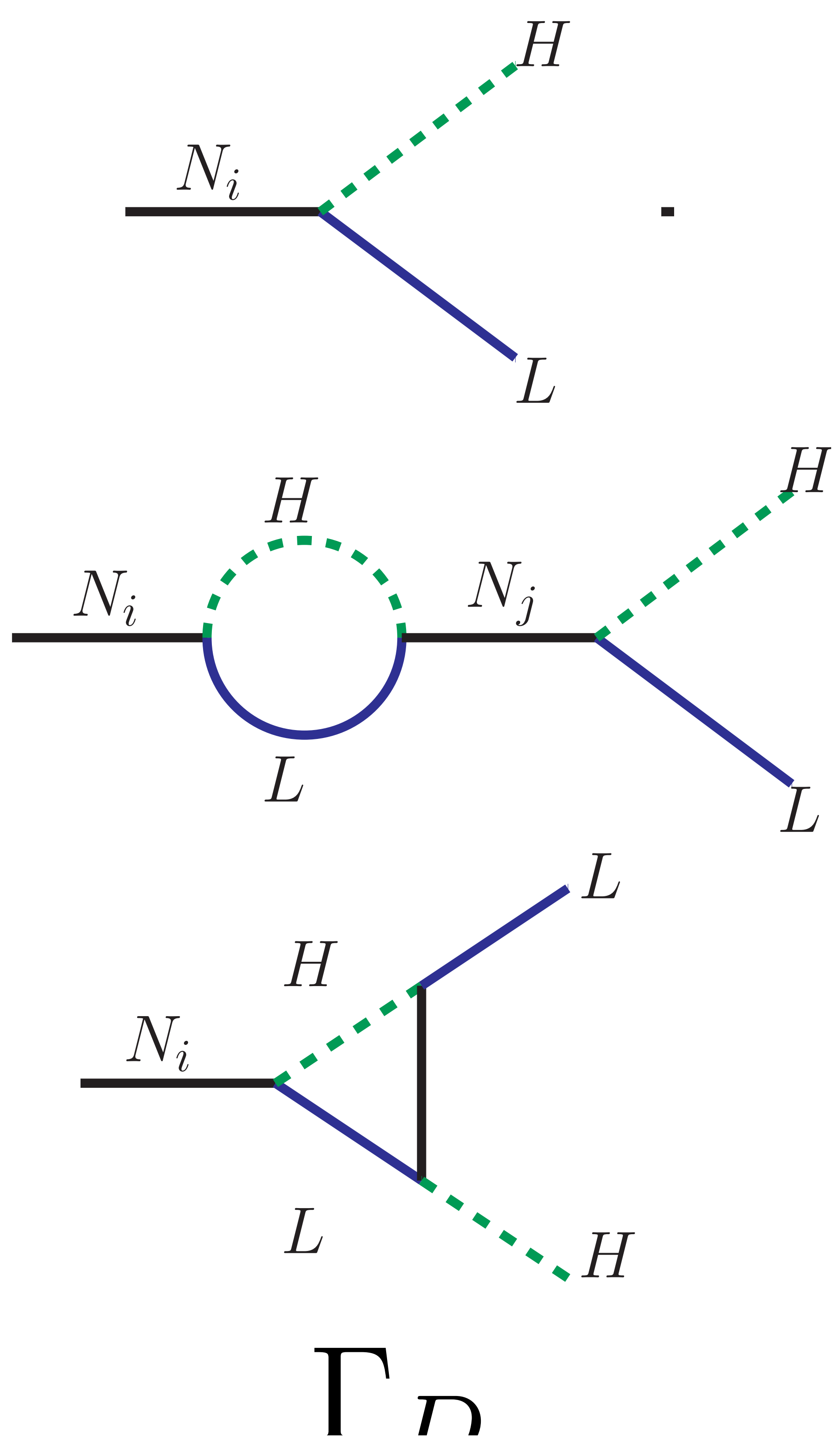
Deppisch & Harz (2014)

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

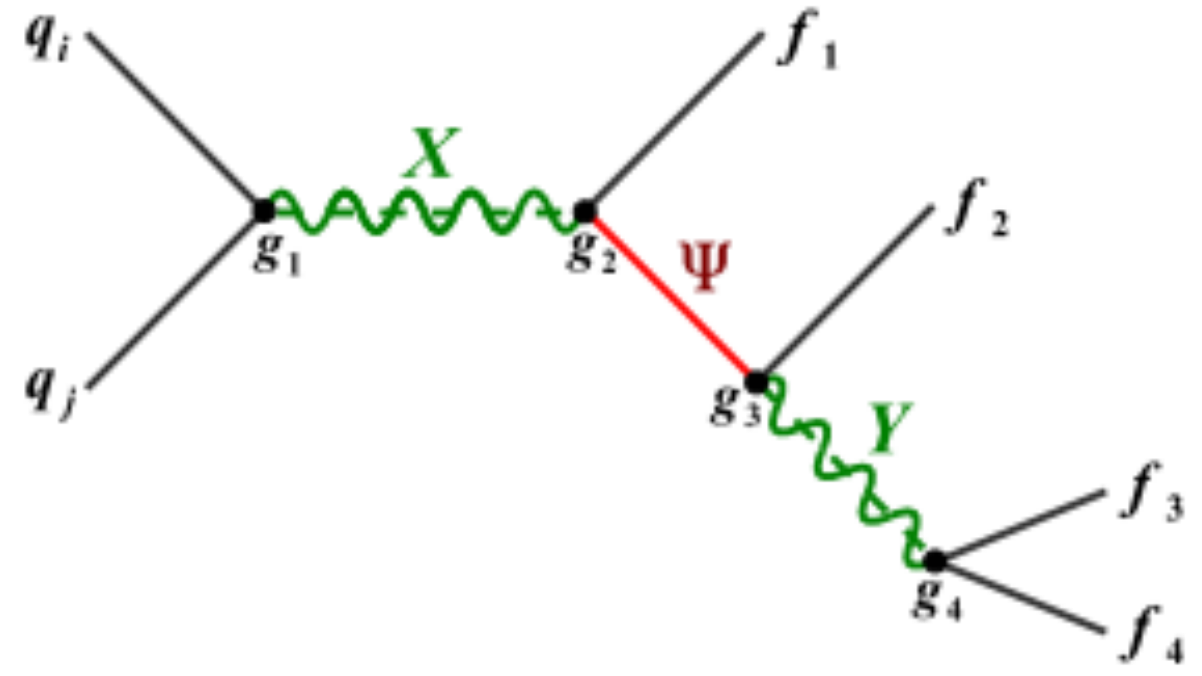
Falsifying High-Scale Leptogenesis







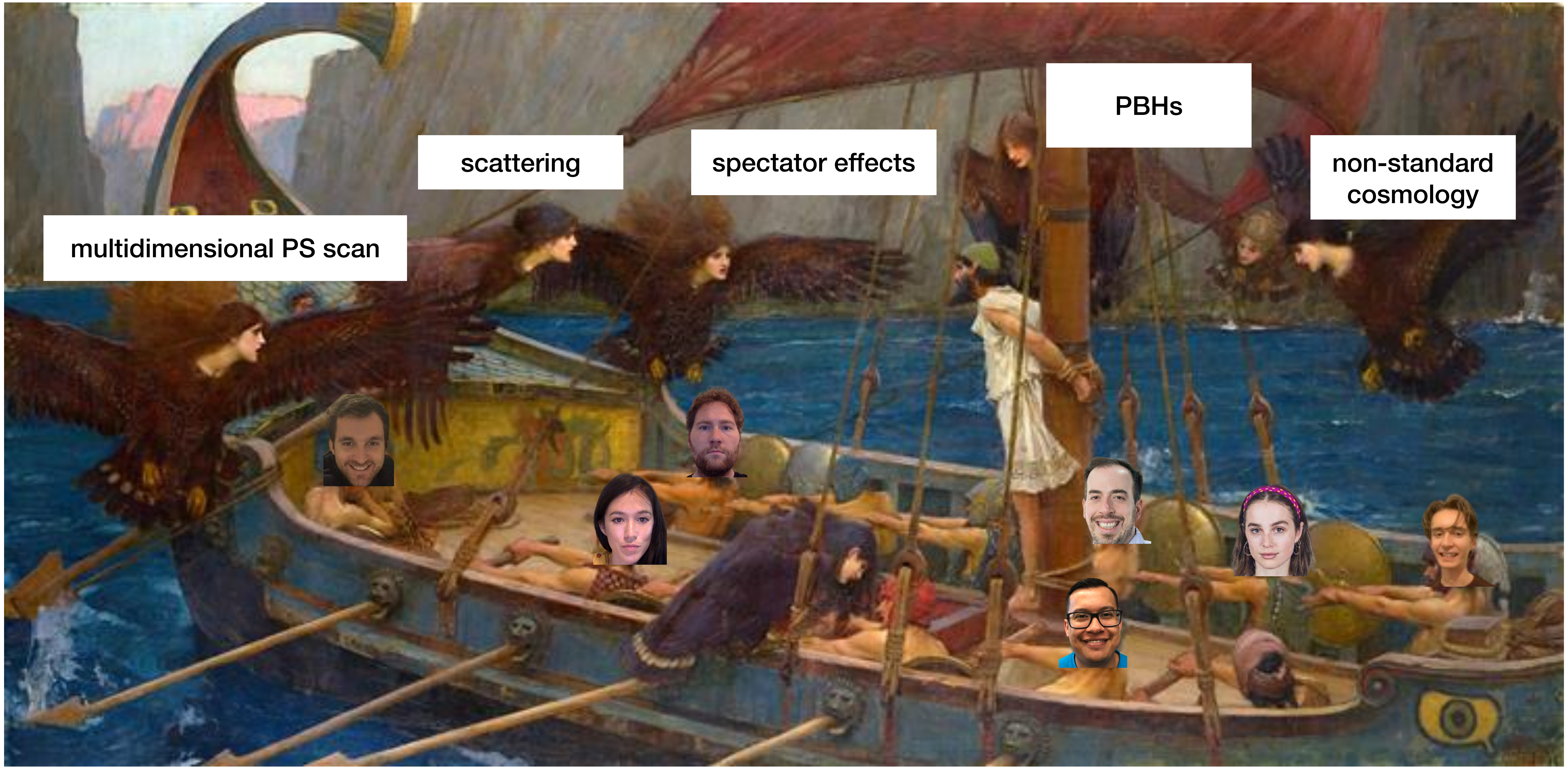
Deppisch & Harz (2014)



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

$pp \to l^{\pm} l^{\pm} + 2$ 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!

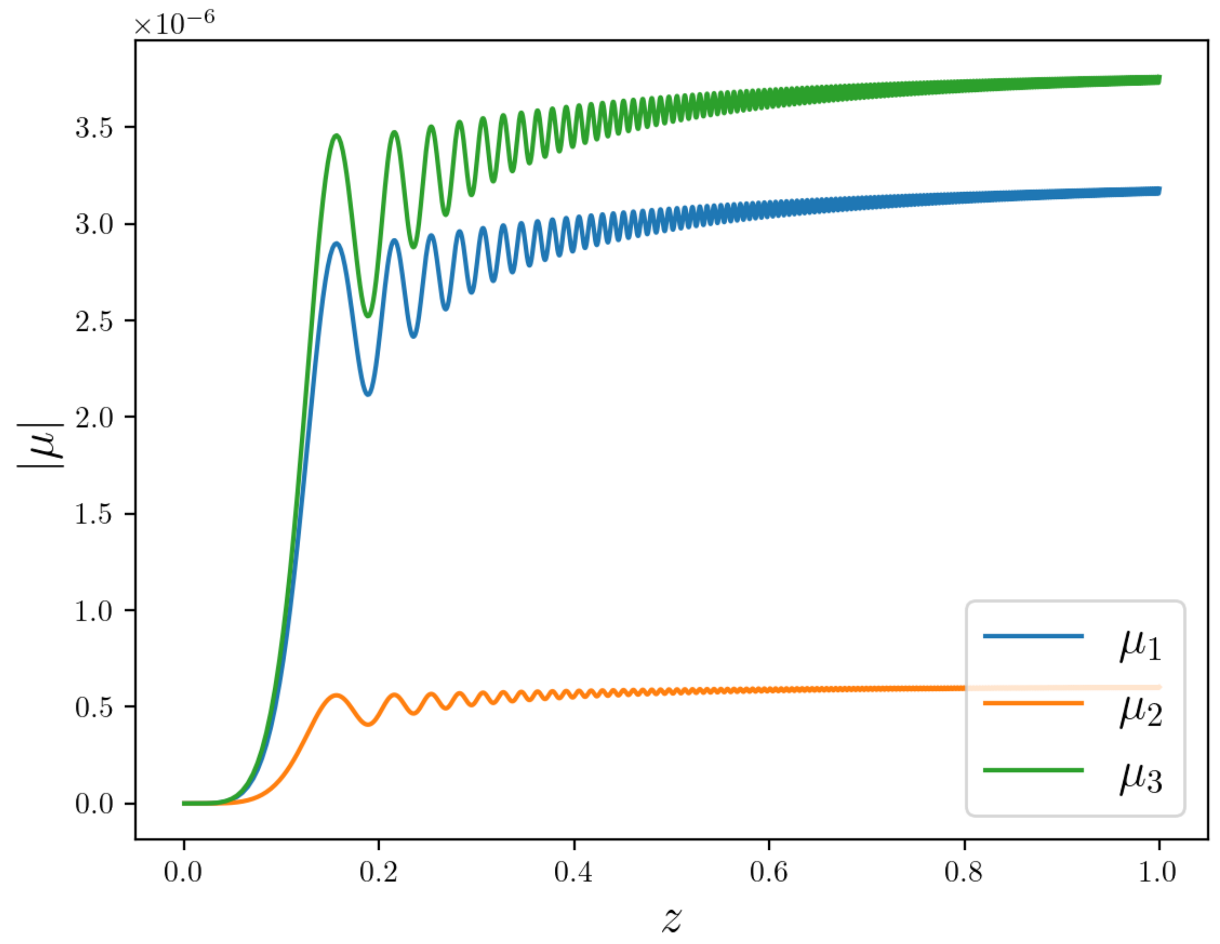
ULYSSES: Universal LeptogeneSiS Equation Solver

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
```

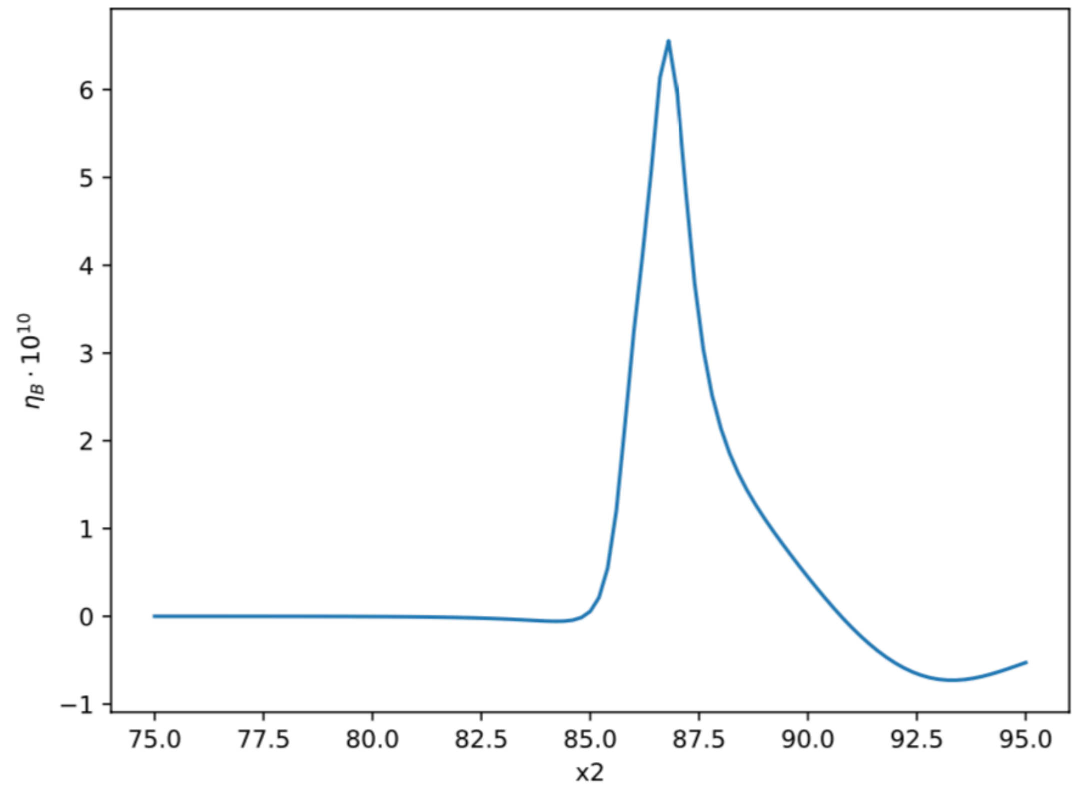
point.txt



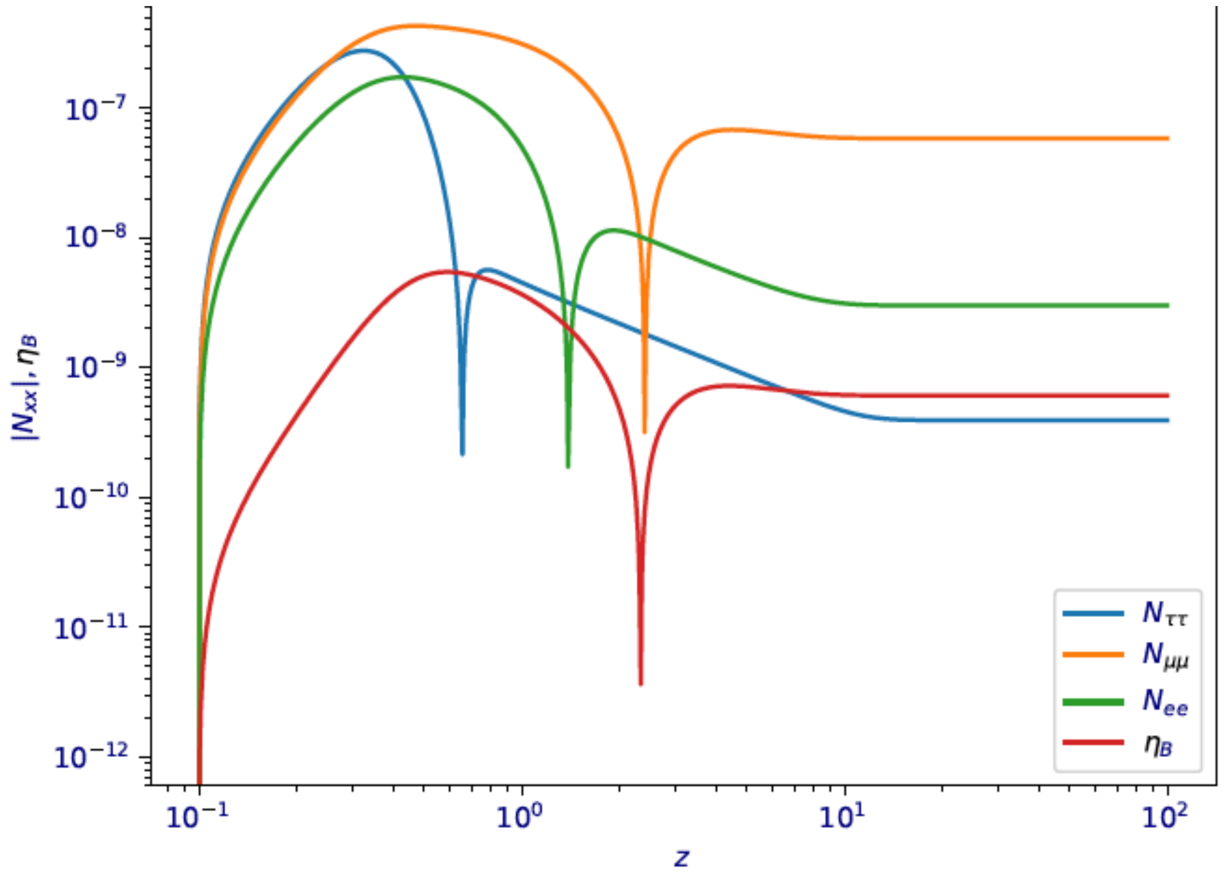
3. Pick a regime to solve `ulc-calc -m 3DME point.txt`

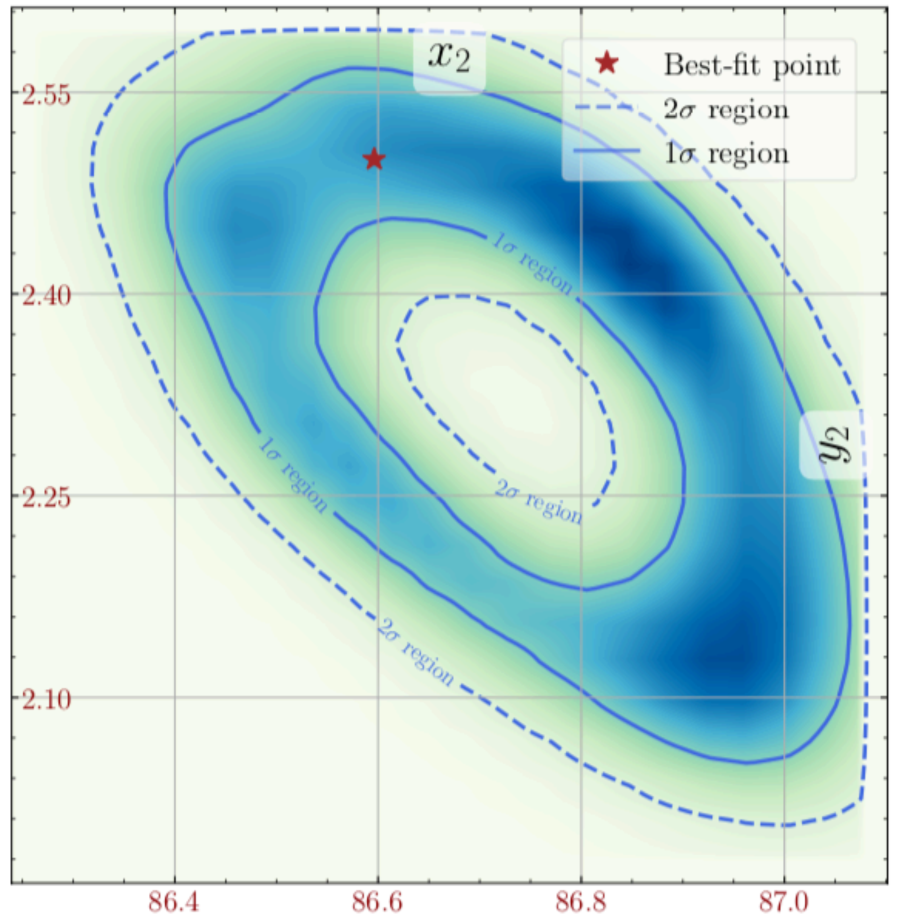
4. Select output including point, scan in 1 or 2D or multidimensional scan

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



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





- 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