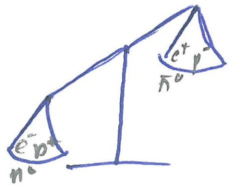
3) Leptogenesis



Baryon Asymmetry of the Universe

→ Observations and thermal history:

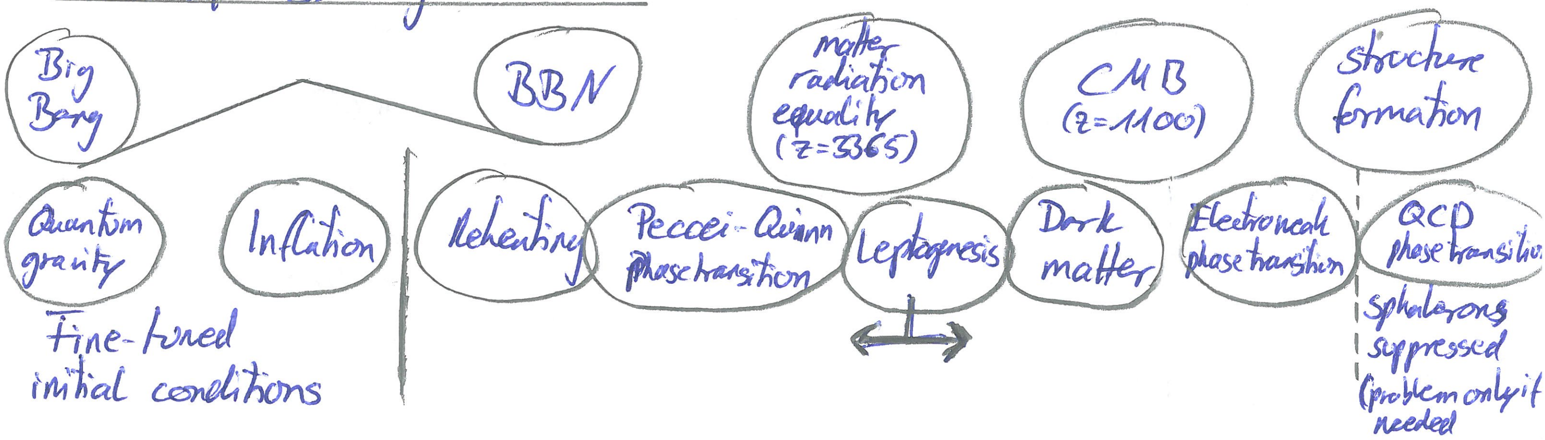
We observe more matter than antimatter in our universe! → BAU

Indications:
- no $p\bar{p} \to \dots \pi^0 \to 2\gamma$ → exclude large amounts of antimatter up to ~ 20 Mpc
- no extragal. γ-rays, nor CMB distortions → exclude antimatter up to 1 Gpc

Two independent measurements:
- Light element abundance ($T \lesssim 1\,\text{MeV}$): baryon-to-photon ratio $\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma}$
  → $5.8 \cdot 10^{-10} < \eta < 6.6 \cdot 10^{-10}$
- CMB ($T \lesssim 1\,\text{eV}$): $\Omega_B h^2 \to \eta \simeq 274 \cdot \Omega_B h^2 \cdot 10^{-10}$
  → $\eta = (6.13 \pm 0.04) \cdot 10^{-10}$

↳ useful quantity: $Y = \frac{n_B - n_{\bar{B}}}{s} = \frac{\eta}{7.04}$ → conserved

Time of BAU generation:



→ Successful baryogenesis: Sakharov conditions

① Baryon number violation:
- needed to evolve from state with $B=0$ to state with $B \neq 0$
- naturally in GUTs (@ tree-level), also in SM @ loop-level
  → non-perturbative instantons

↳ $B = \int d^3x\, J_0^B(x)$ and $L = \int d^3x\, J_0^L(x)$ accidental symmetries that are violated @ quantum level → triangle anomalies

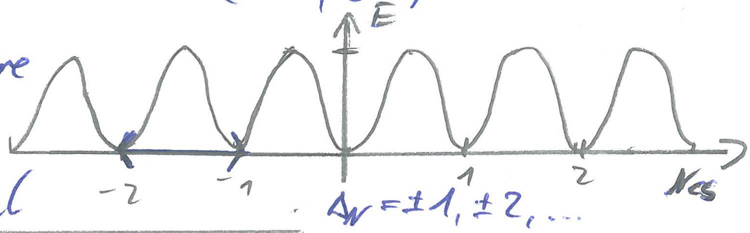
currents:
$$J_\mu^B = \frac{1}{3} \sum_i \left(\bar{q}_{L_i} \gamma_\mu q_{L_i} + \bar{u}_{R_i} \gamma_\mu u_{R_i} + \bar{d}_{R_i} \gamma_\mu d_{R_i} \right)$$
$$J_\mu^L = \sum_i \left(\bar{L}_{L_i} \gamma_\mu L_{L_i} + \bar{e}_{R_i} \gamma_\mu e_{R_i} \right)$$

↳ currents are not conserved: $\partial_\mu J^\mu_B = \partial_\mu J^\mu_L = \frac{N_f}{32\pi}\left(g^2 W^a_{\mu\nu}\tilde{W}^{a\mu\nu} - g'^2 B_{\mu\nu}\tilde{B}^{\mu\nu}\right)$

$\Rightarrow \partial_\mu\left(J^\mu_B - J^\mu_L\right) = 0 \quad \longrightarrow \quad (B-L)$ conserved!

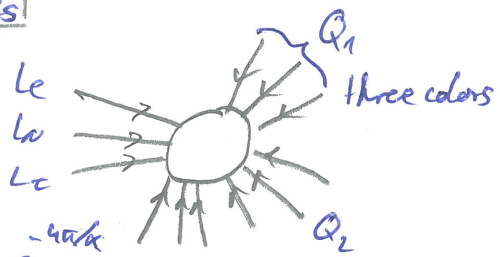
$\partial^\mu\left(J^B_\mu + J^L_\mu\right) = 2N_F\,\partial_\mu K^\mu$ with $K^\mu(W^{\mu\nu}, B^{\mu\nu})$

- violation is due to vacuum structure of non-abelian gauge theories:



B and L are related to topological charges $\to N_{CS}$ $\Rightarrow \boxed{\Delta B = \Delta L = N_f\,\Delta N_{CS}}$

↳ SU(2) instantons generate eff. 12 fermion operator $O_{B+L} = \prod_{i=1,2,3} q_{Li}\,q_{Li}\,q_{Li}\,l_{Li}$



- instanton tunnelling @ $T=0$ highly suppressed: $\Gamma \sim e^{-4\pi/\alpha} \sim O(10^{-165})$

@finite T: no tunnelling but T-fluctuation $\longrightarrow$ sphalerons

$T < T_{EW}$: $\frac{\Gamma_{B+L}}{V} \sim e^{-M_W/(\alpha k T)}$ → suppression

$T > T_{EW}$: $\frac{\Gamma_{B+L}}{V} \sim \alpha^5 \ln \alpha^{-1}\, T^4$ → Boltzmann factor disappears

$\Rightarrow$ sphalerons link lepton and baryon asymmetry:

$B = c_s (B-L)\,, \quad L = (c_s - 1)(B-L)\,,$

with $c_s = \frac{8N_f + 4N_H}{22N_f + 13N_H}$ $\quad N_f$: #(generations), N_H: #(Higgs doublets)

2 C and CP violation:

- if C and CP ~~were~~ conserved: $\Gamma(b \to \ldots) = \Gamma(\bar{b} \to \ldots)$ no generation of asymmetry

↳ asymmetry parameter $\varepsilon = \frac{\Gamma(X \to \psi\bar{\chi}) - \Gamma(\bar{X} \to \bar{\psi}\chi)}{\Gamma(X \to \text{any}) + \Gamma(\bar{X} \to \text{any})}$

- condition: ① complex coupling $\lambda \neq \lambda^*$ (necessary)
② no removal of phase possible (sufficient)

e.g. $X \to \psi \chi$

$$\lambda \bar{\psi} \not{X} \chi + \lambda^* \bar{\chi} \not{X} \psi \xrightarrow{CP} \lambda^* \bar{\psi} \not{X} \chi + \lambda \bar{\chi} \not{X} \psi$$

gauge boson

- interference between tree and loop amplitudes generates CP asymmetry

$M = M_0 + M_1 = c_0 A_0 + c_1 A_1$

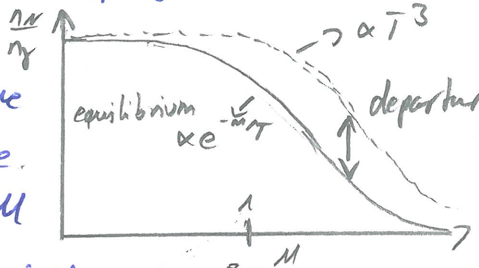
$$\varepsilon \propto \frac{\int |c_0 A_0 + c_1 A_1|^2 - \int |c_0^* A_0 + c_1^* A_1|^2}{2\int |c_0 A_0|^2} \sim \frac{\mathrm{Im}[c_0 c_1^*]}{|c_0|^2} \cdot \frac{2\int \mathrm{Im}[A_0 A_1^*]}{\int |A_0|^2}$$

③ Departure from thermal equilibrium

- in therm equilibrium: $\Gamma(X \to \psi A) = \Gamma(\bar{A}\bar{\psi} \to X)$ $\longrightarrow$ $\boxed{\text{no net } \Delta B \text{ develops since inverse processes wash out produced asym.}}$

↳ three options for departure: ① Out-of-equilibrium decay of heavy particle ←
② Electroweak phase transition
③ Dynamics of topological defects

Out-of-equilibrium decay:



- if $\Gamma < H$ (@$T \sim M$): particle cannot decay within time scales of expansion $\Rightarrow$ remains in initial abundance.
$n_X \sim n_{\bar{X}} \sim n_\gamma \sim T^3$ for $T \lesssim M$

(other point of view: @ $T \gg M$ particles interact so weakly that they cannot catch up with exp.)

- particles decouple from thermal bath while still being relativistic ($n_X \sim T^3$) and populate universe @ $T \simeq M$ with with much larger abundance than in equilibrium (compare: $n_X = n_{\bar{X}} \simeq n_\gamma$ for $T \gtrsim M$, $n_X = n_{\bar{X}} \simeq (M_X T)^{3/2} e^{-M/T} \ll n_\gamma$ for $T \lesssim M$)

$\longrightarrow$ out-of-equilibrium condition: $\frac{\Gamma}{H} \propto \frac{1}{M} < 1$

$\boxed{\begin{array}{l} \text{gauge bosons}: M_X \gtrsim 10^{15/16}\,\text{GeV} \\ \text{scalars}: M_X \gtrsim 10^{10-16}\,\text{GeV} \\ \text{Majorana } \nu: M_X \sim 10^9\,\text{GeV} \end{array}}$

$\longrightarrow$ Type-I leptogenesis ① EW sphalerons ② new Yukawas ③ heavy ν_R decay

- useful: Casas-Ibarra-parametrization $\to$ parametrizes our ignorance by separating high E from low-E quantities

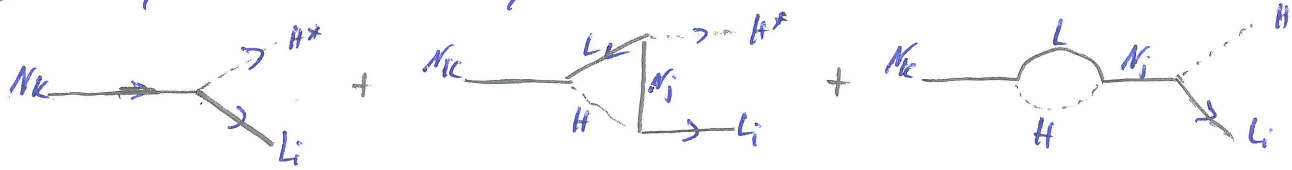
$$m_I = m_D^T m_R^{-1} m_D = h^T m_R^{-1} h v^2 \Longrightarrow m = \frac{m_I}{v^2} = h^T m_R^{-1} h \quad (m_R \text{ diagonal})$$

$$\longrightarrow \boxed{h = \sqrt{D_N}\, R \sqrt{D_m}\, U^+_{PMNS} = \frac{1}{v} \sqrt{D_N}\, R \sqrt{D_{m_I}}\, U^+_{PMNS}}$$

R: complex rotation matrix
low-E: D_{m_I}, U
high-E: D_N, R

(in general: no connection between (D_{m_I}, U) and (D_N, R))

$\longrightarrow$ heavy RH neutrino decay ($\nu_R = N$): $N \to H L$



@ tree-level: $\Gamma(N_k \to H^* L_i) = \Gamma(N_k \to \bar{H}^* \bar{L}_i) = \frac{1}{8\pi} (hh^+)_{ii} M_i$ $\to$ no net $\cancel{CP}$

@ loop-level: $\varepsilon_1 \simeq \frac{1}{8\pi} \frac{1}{(hh^+)_{11}} \sum_{i=2,3} \text{Im}\left[(hh^+)^2_{1i}\right] \left(f\left(\frac{m_i^2}{m_1^2}\right) + g\left(\frac{m_i^2}{m_1^2}\right)\right)$

with loop functions $f(x) = \sqrt{x}\left[1 - (1-x)\ln\left(\frac{1+x}{x}\right)\right]$, $g(x) = \frac{\sqrt{x}}{1-x}$

↳ assume: $m_1 \ll m_{2,3}$: $x \gg 1$ $\to$ simplify loop terms

$$\varepsilon_1 \simeq -\frac{3}{16\pi} \frac{1}{(hh^+)_{11}} \sum_{i=2,3} \text{Im}\left[(hh^+)^2_{1i}\right] \frac{m_1}{m_i}$$

↳ other option: resonant leptogenesis (degenerate masses lead to resonant enhancement of self-energy diagram)
→ lowers bound on M_K

- successful scenario: prevent generated asymmetry from washout, i.e. out-of-equilibrium $\Gamma_D < H|_{T=M_1}$

two quantities: ① eff. light ν-mass $\quad \tilde{m}_1 \equiv \sum_\alpha \frac{(hh^+)_{\alpha 1} v^2}{M_1} = 8\pi \frac{v^2}{M_1^2} \Gamma_D$

② equilibrium ν-mass $\quad m_* \equiv 8\pi \frac{v^2}{M_1^2} H|_{T=M_1} \simeq 1.1 \cdot 10^{-3}\,\mathrm{eV}$

⟹ condition ("$\Gamma_D < H$") translates into [redacted] $\tilde{m}_1 < m_* \simeq 1.1 \cdot 10^{-3}\,\mathrm{eV}$

- final lepton asymmetry: depends on washout

$$Y_L = \frac{n_L - \bar{n}_L}{s} = \kappa \cdot \frac{\varepsilon_1}{g_*}, \quad g_* = 106.75 \qquad Y_B = \frac{n_B - \bar{n}_B}{s} = c\, Y_{B-L} = \frac{c}{c-1} Y_L$$

κ: parametrisation of washout; c: sphalerons

→ "Davidson - Ibarra" bound: ν-mass from leptogenesis

↳ assume: strong hierarchy among RH neutrinos

- rewrite ε by using Casas-Ibarra-parametrisation:

$$\varepsilon_1 \lesssim \frac{3}{16\pi} \cdot \frac{M_1 (m_2 - m_1)}{v^2} \simeq \frac{3}{16\pi} \frac{M_1 m_3}{v^2} \quad \text{for NO}$$

$$\Leftrightarrow M_1 \gtrsim \eta \frac{1-c}{c} \left[\text{[redacted]} \frac{3}{16\pi} \frac{m_3}{v^2} \frac{\kappa}{g_*} \right]^{-1}$$

example: $\eta = 6.1 \cdot 10^{-10}$, $m_3 \simeq \sqrt{\Delta m_{31}^2}$, $\kappa \simeq 1$,

$$\boxed{M_1 \gtrsim 2 \cdot 10^9\,\mathrm{GeV}}$$

- properties of Casas-Ibarra param ($RR^T = R^T R = \mathbb{1}$) demand: $m_1 \leq \tilde{m}_1 \leq m_3$

- assuming weak washout ($\tilde{m}_1 \simeq 0.1 - 0.2$): $\boxed{10^{-3} \lesssim m_i \lesssim 0.1\,\mathrm{eV}}$

⟹ leptogenesis conspiracy: successful leptogenesis requires ν-mass of similar order as indicated by "experiments"

→ Washout processes:

↳ efficiency of washout determined by $\frac{\Gamma_1}{H|_{T=M_1}} \to \frac{\tilde{m}_1}{m_*} \equiv r$

Weak washout:

↳ $r \ll 1$ for $T_D \lesssim M_1$

- inverse decays and scatterings can be ignored
- @ $T = T_D$: $n_X \simeq n_{\bar{X}} = n_\gamma$

$n_L = \varepsilon_1 n_\gamma$

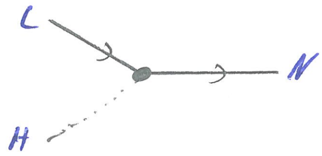
Strong washout:

↳ $r \gg 1$

- no departure from thermal equilibrium
- net lepton asymmetry vanishes

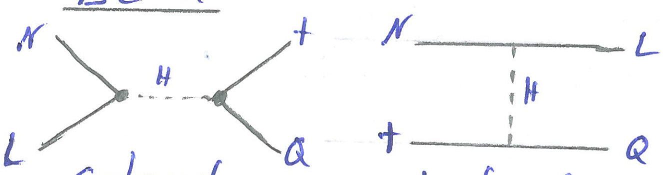
↳ for $1 < r < 10$ sizeable asymmetry: solve Boltzmann equations

↳ reactions: ① Inverse decays $\overset{(-)}{\ell} + \overset{(-)}{H} \to N$



② $(2\to 2)$ scatterings:

$\Delta L = 1$



s-channel

$N_1 L \leftrightarrow tQ$

t-channel

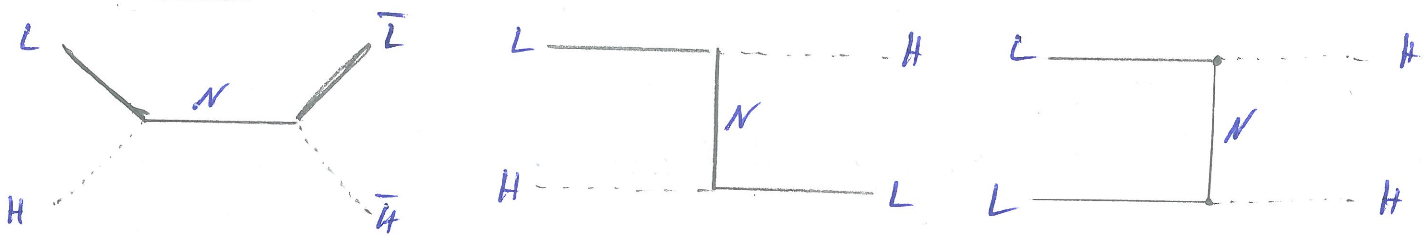
$N_1 t \leftrightarrow LQ$

Interplay:

@ $T \gtrsim M_1$: strong enough to keep N in equilibrium

@ $T \lesssim M_1$: weak enough to generate asymmetry

$\Delta L = 2$

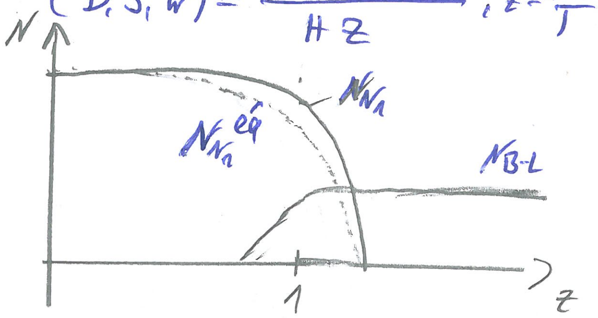


⇒ Boltzmann equations:

$$\frac{dN_{N_1}}{dz} = -(D+S)(N_{N_1} - N_{N_1}^{eq})$$

$$\frac{dN_{B-L}}{dz} = -\varepsilon_1 D(N_{N_1} - N_{N_1}^{eq}) - W N_{B-L}$$

with $(D, S, W) \equiv \frac{(\Gamma_D, \Gamma_S, \Gamma_W)}{H z}$, $z = \frac{M}{T}$



↳ N_1 abundance affected by decays, inverse decays and $(\Delta L = 1)$ scattering

↳ N_1 decays are source of $(B-L)$; washout by inverse decays and $\Delta L = 1$ scatterings

→ Corrections to vanilla scenario*:

↳ Flavor effects:

- total asymmetry: $\varepsilon_1 = \sum_{\alpha=e,\mu,\tau} \varepsilon^{\alpha\alpha}$
- @ highest T: charged lepton Yukawa interactions are out-of-equilibrium
  → three flavors indistinguishable: $L = L_e + L_\mu + L_\tau$ coherent superposition
- as T drops: Yukawa interactions reach equilibrium @ different T
  ↳ corresponding lepton flavor becomes distinguishable
  ⟹ BEs for different lepton flavors (→ matrix equations)
  washout not universal any more → hide asymmetry!
- Temperature regimes: $\Gamma_f > H$ (necessary), $\Gamma_f > \Gamma_{ID}$ (sufficient)
  $T > 10^{12}$ GeV: all lepton Yukawas out of equilibrium "$L = L_e + L_\mu + L_\tau$"
  $10^{12}\,\text{GeV} > T > 10^{9}\,\text{GeV}$: τ Yukawa in equilibrium (L_τ, "$L_\tau^{\pm} = L_e + L_\mu$")
  $10^{9}\,\text{GeV} > T$: μ Yukawa in equilibrium (L_τ, L_μ, L_e)

⟹ potential enhancement of BAU generation (washout less efficient → effective only for certain flavors)

↳ spectator effects:

- processes that do not directly affect BAU generation, but change particle densities on which washout depends, e.g. asymmetry of lepton and Higgs doublets
- general: as T drops, more spectators reach equilibrium and washout becomes less effective
- examples: gauge & top-Yukawa interactions @ $T > 10^{13}$ GeV
  strong sphalerons @ $T \sim 10^{13}$ GeV
  b- and τ-Yukawa @ $10^{13} > T > 10^{12}$ GeV

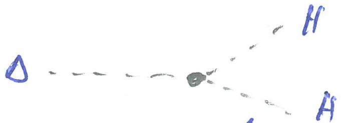
↳ thermal effects:

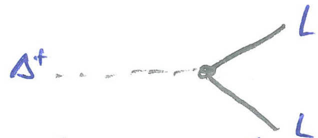
- interactions with thermal bath lead to corrections concerning masses, couplings and distributions

→ type-II leptogenesis: *

→ heavy $SU(2)_L$ triplet decays:

@ tree level:

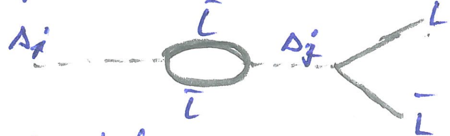


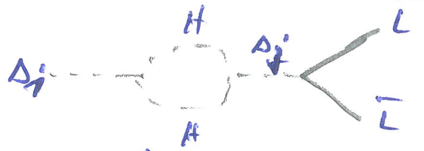


two decay modes $\Gamma(\Delta \to HH) = \frac{1}{8\pi} \frac{|\mu|^2}{M_\Delta}$ $\qquad \Gamma(\Delta^+ \to LL) = \frac{1}{8\pi}\, tr(YY^\dagger) M_\Delta$

@ loop-level: model-dependence

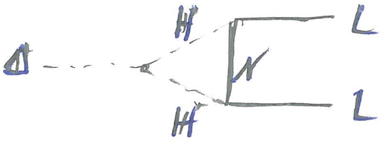
① several triplets:



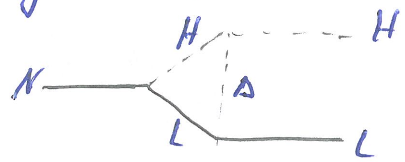


(for $\varepsilon \neq 0$, another triplet is needed (self-energy))

→ ② another heavy state, e.g. RH neutrino N



$+$



→ works with a single $SU(2)_L$ triplet
↳ inspired by $SO(10)$ or Left-right symmetry

⇒ general: $\varepsilon_\Delta = -\frac{1}{16\pi^2} \frac{M_\Delta^3}{\Gamma_\Delta^{tot} v^4} \mathrm{Im}\left[tr(m_\nu^\Delta m_\nu^{H\dagger})\right]$

type-II mass $\qquad$ ↳ ν-mass from heavier state, e.g. type-I

↳ model-independent bound (ε purely from triplet decay):

$|\varepsilon_\Delta| \leq \frac{1}{2\pi} \frac{M_\Delta}{v^2} \sqrt{B_L B_H \sum_i m_i^2}$ → stronger bounds if contributions of triplet and heavier state to ν-mass are known precisely

(m_i: light ν-mass)

↳ perturbativity bound: $\varepsilon_\Delta \leq 2 \min[B_L, B_H]$

→ Boltzmann equations: four dynamical quantities $\Sigma_\Delta = \frac{n_\Delta + n_{\bar\Delta}}{s}$, $\Delta_X = \frac{\Delta_X - \Delta_{\bar X}}{s}$ with $X = \{\Delta, L, H\}$

↳ hypercharge conservation: $2\Delta_\Delta + \Delta_H - \Delta_L = 0$

→ only three independent equations

$$sHz \frac{d\Sigma_\Delta}{dz} = -\left(\frac{\Sigma_\Delta}{\Sigma_\Delta^{eq}} - 1\right)\gamma_D - 2\left(\left(\frac{\Sigma_\Delta}{\Sigma_\Delta^{eq}}\right)^2 - 1\right)\gamma_A$$

flavoured case

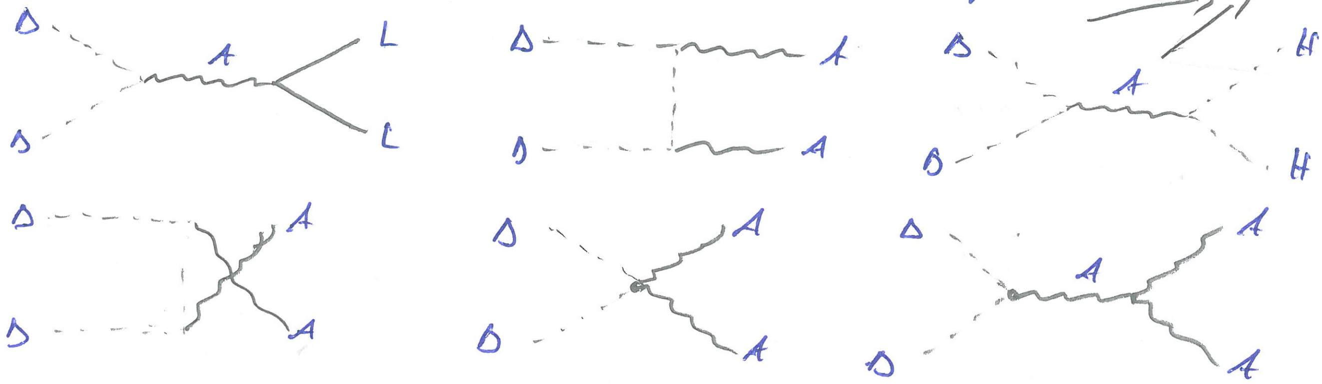
$$sHz \frac{d\Delta_L}{dz} = \left(\frac{\Sigma_\Delta}{\Sigma_\Delta^{eq}} - 1\right)\gamma_D \varepsilon_\Delta + W_L^D(\Delta_L, \Delta_H) + W^{LH}(\Delta_L, \Delta_H) + \overbrace{W^{4L} + W^{L\Delta}}$$

$$sHz \frac{d\Delta_\Delta}{dz} = \frac{1}{2}\left[W_L^D(\Delta_L, \Delta_H) - W_H^D(\Delta_H, \Delta_\Delta)\right]$$

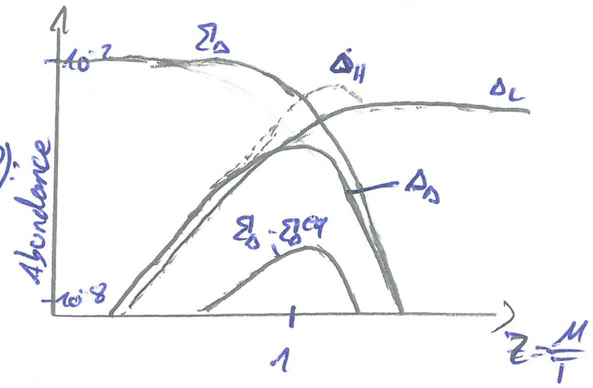
with $\Delta_L(\Delta_{B-L}, \dots)$, $\Delta_H(\Delta_{B-L}, \Delta_\Delta, \dots)$

- differences to type-I case: triplet has three degrees of freedom
  triplet is not self-conjugate → add equation
  triplet undergoes gauge scattering → γ_A

A: gauge boson

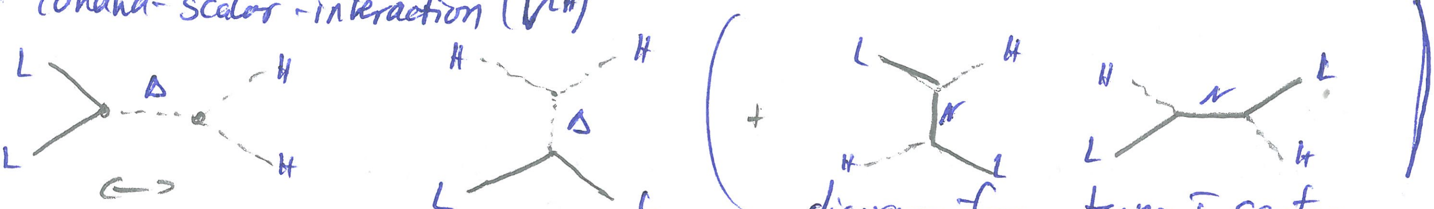


→ washout:



- Yukawa and scalar-induced inverse decay (W^D):

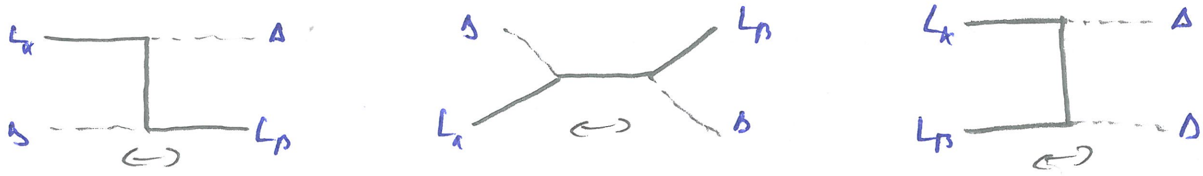
- Yukawa-scalar-interaction (W^{LH})



diagrams from type-I sector

- 4-lepton interaction (W^4): ONLY within flavoured scenario

- lepton-triplet interaction ($W^{L\Delta}$): ONLY within flavoured scenario



↳ Comment on flavoured framework:

modified flavour regimes since charged lepton Yukawa interactions have to be faster than inverse decays ($\Gamma_f > \Gamma_{ID}$) → not always the case for fast gauge scatterings (lepton doublet inverse decay before charged Yukawa interaction takes place)

→ Connection between leptogenesis and ν-oscillations:*

- generally no connection between low-E CP violation and leptogenesis
  ⇒ extra phases and mixing angles in heavy N sector (compare with Casas-Ibarra parametrisation)
- connections in specific cases possible:
  ① reduction of inter-family couplings: only two RH N's
  ② CP violation from same origin

<u>examples</u> ① Frampton, Glashow, Yanagida model

- only two RH N's: m_D – (3×2)-matrix → six complex parameter (→ 6 phases)
- absorb 3 phases in charged lepton fields [redacted]
  ⇒ one phase related to high-E sector + two phases related to low-E
- further assume two "texture zeros" (m_D has two entries set to zero):
  only <u>one</u> CP phase within Yukawa matrix
  ⇒ connection between low-E and high-E!

$$\mathcal{L} \supset (N_1\, N_2)\begin{pmatrix} a & a' & 0 \\ 0 & b & b' \end{pmatrix}\begin{pmatrix} l_1 \\ l_2 \\ l_3 \end{pmatrix} H + h.c.$$

<u>example</u> ② Minimal left-right symmetric model with spontaneous CP violation

$$G_{LR} = SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times P \xrightarrow{\langle \Delta_R \rangle} SU(3)_c \times SU(2)_L \times U(1)_Y$$

with bi-doublet ϕ and LH/RH doublet $\Delta_{L,R}$

↳ EWSB through bi-doublet ϕ

$$\langle \phi \rangle = \begin{pmatrix} \kappa & 0 \\ 0 & \kappa' e^{i\alpha_{\kappa'}} \end{pmatrix}, \quad \langle \Delta_L \rangle = \begin{pmatrix} 0 & 0 \\ v_L e^{i\alpha_L} & 0 \end{pmatrix} \quad \langle \Delta_R \rangle = \begin{pmatrix} 0 & 0 \\ v_R & 0 \end{pmatrix}$$

(matter fields already rephased to remove phase from RH components)

<u>Yukawa sector:</u>

$$-\mathcal{L}_Y = \overline{Q}_{i,R}(F_{ij}\phi + G_{ij}\tilde{\phi})Q_{j,L} + \overline{L}_{i,R}(P_{ij}\phi + R_{ij}\tilde{\phi})L_{j,L} + i f_{ij}(L^T_{i,L} C\sigma_2 \Delta_L L_{j,L} + L^T_{i,R} C\sigma_2 \Delta_R L_{j,R}) + h.c.$$

$F_{ij}, G_{ij}, P_{ij}, R_{ij}, f_{ij}$ are real

$$M_u = \kappa F_{ij} + \kappa' e^{-i\alpha_{\kappa'}} G_{ij}, \qquad M_d = \kappa' e^{i\alpha_{\kappa'}} F_{ij} + \kappa G_{ij}$$

→ relative phase between bidoublet VEVs gives rise to CP violation in CKM matrix!

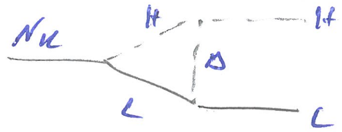
$M_e = \kappa' e^{i\alpha_{\kappa'}} P_{ij} + \kappa R_{ij}$ $\qquad$ $M_\nu^D = \kappa P_{ij} + \kappa' e^{-i\alpha_{\kappa'}} R_{ij}$

$M_\nu^R = v_R f_{ij}$ $\qquad$ $M_\nu^L = v_L e^{i\alpha_L} f_{ij} = m_\nu^{II}$

$\Rightarrow m_\nu^I = (M_\nu^D)^T (M_\nu^R)^{-1} (M_\nu^D)$

- three low-E phases in PMNS matrix are all functions of α_L
  leptonic Jarlskog $J^l_{CP} \propto \mathrm{Im}(U^* U U U^*) \propto \sin\alpha_L$

- Leptogenesis via



$\to \varepsilon^{\Delta_L} \propto \sin\alpha_L$

$\Rightarrow$ connection between low-E and high-E CP violation
J^l_{CP} and ε^{Δ_L} are proportional to $\sin\alpha_L$ (phase of $\langle \Delta_L \rangle$)
(additional U(1): lowering LR breaking scale + link between CP violation of quark and lepton sector)

$\to$ Summary:

- leptogenesis is a successful explanation of observed BAU: create particle-antiparticle asymmetry in lepton sector via CP violating out-of-equilibrium decay of heavy particle and convert it into baryon sector via EW sphalerons
  $\to$ natural connection between light ν-masses and cosmology!
  (not only in seesaw models)
- well established and studied subject: flavour, spectator and thermal corrections; also more formal treatments on the market
- experimentally hard to test: heavy N_R and small h
  $\hookrightarrow$ indirectly: leptonic CP violation (ν-beams) $\to$ 2nd Sakharov cond.
  L violation ($0\nu\beta\beta$) $\to$ Majorana nature & 1st Sakharov cond.
  ν-mass scale (KATRIN/cosmology) $\to$ probe generic ν-mass ranges

$\Rightarrow$ aim: map high-E parameters to low-E observables

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