Leptogenesis and low-energy CP violation in a type-II-dominated left-right seesaw model

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Baryon asymmetry of the Universe (BAU)

Observations: More matter than antimatter!

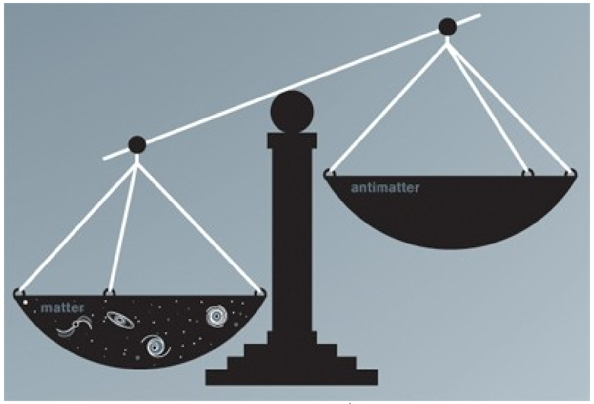
- No annihilation radiation

$$p\overline{p} \rightarrow \ldots\pi^0 \rightarrow \ldots 2\gamma$$

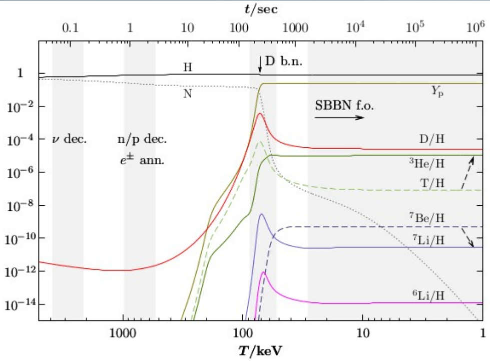
→ exclude up to ~20Mpc

- No γ-rays and no CMB distortions

→ exclude up to ~1Gpc



[https://www.quantumdiaries.org/tag/cpv/]



[Pospelov & Pradler,2010]

Two independent measurements:

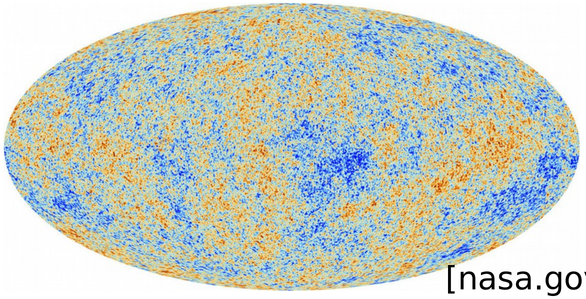
- Light element abundance: $\eta = \dfrac{n_B - n_{\overline{B}}}{n_\gamma}$

$\rightarrow \mathrm{T} \lesssim 1\ \mathrm{MeV}$

$$5.8 \cdot 10^{-10} < \eta < 6.6 \cdot 10^{-10}$$

- CMB anisotropies: $\eta = 274 \cdot \Omega_B h^2 \cdot 10^{-10}$

$\rightarrow \mathrm{T} \lesssim 1\ \mathrm{eV}$



[nasa.gov]

Convenient quantity: $Y_{\Delta B} = \dfrac{n_B - n_{\overline{B}}}{s}$ Conserved!

$$\eta = (6.13 \pm 0.04) \cdot 10^{-10}$$

[Planck 2018]

Theoretical requirements for baryogenesis

Inflation forbids fine-tuned initial conditions → dynamical explanation

Sakharov condition: [Sakharov, 1967]

1) B violation

2) C and CP violation

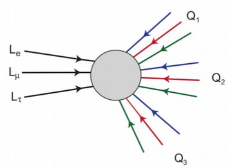
3) Out of equilibrium decay

→ new sources of CP violation and modification of EWPT/thermal departure mechanism

Within the standard model:

1) Triangle anomaly

→ sphalerons



2) Weak interactions

→ CP violation, but **too small**

3) Electroweak phase transition

→ **not sufficiently** first order

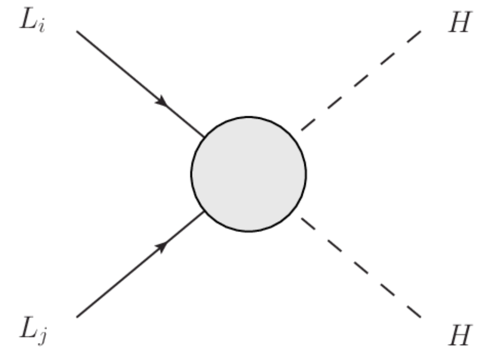
Various scenarios on the market:

- GUT baryogenesis
- Electroweak baryogenesis
- Affleck-Dine mechanism
- Spontaneous baryogenesis
- **Leptogenesis**
- Etc...

Neutrino masses and leptogenesis

Neutrino masses are first real hint for BSM physics!

- Realizations of dim-5 Weinberg operator [Weinberg, 1979]
  - Tree-level: seesaw mechanisms
  - Loop-level: scotogenic model, Zee-Babu

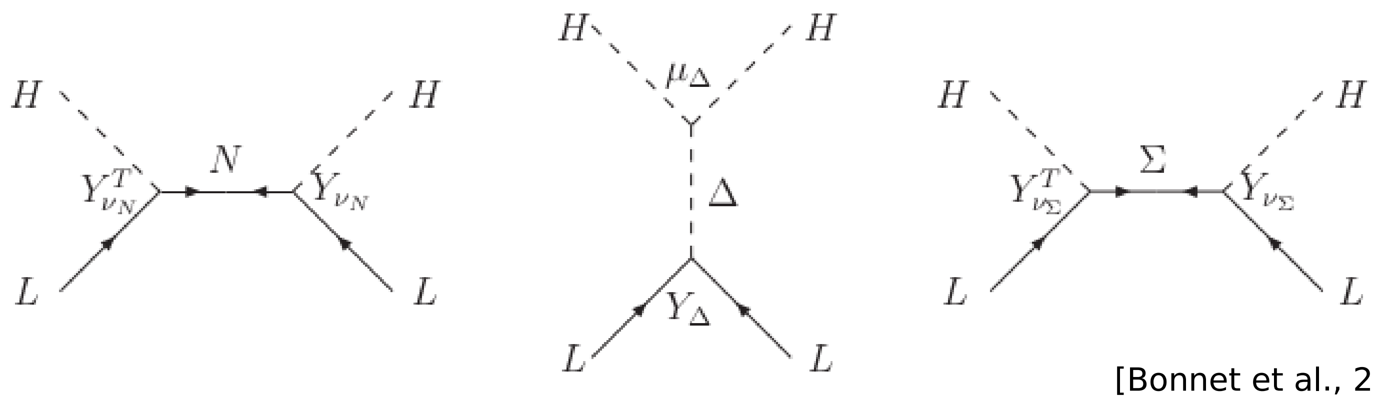


$$\Delta\mathcal{L}_{\text{eff}} = \frac{1}{4}\frac{\kappa_{\alpha\beta}}{\Lambda}\,(\ell_\alpha^T i\sigma^2 H)\,C\,(H^T i\sigma^2 \ell_\beta) + \text{h.c.}$$

- New physics at higher scales could create particle asymmetry
  - New (complex) couplings

    → C and CP violation
  - Out of equilibrium decay of heavy states
    → expansion of the universe

→ natural link between neutrino mass and cosmology !



[Bonnet et al., 2012]

Type-I leptogenesis

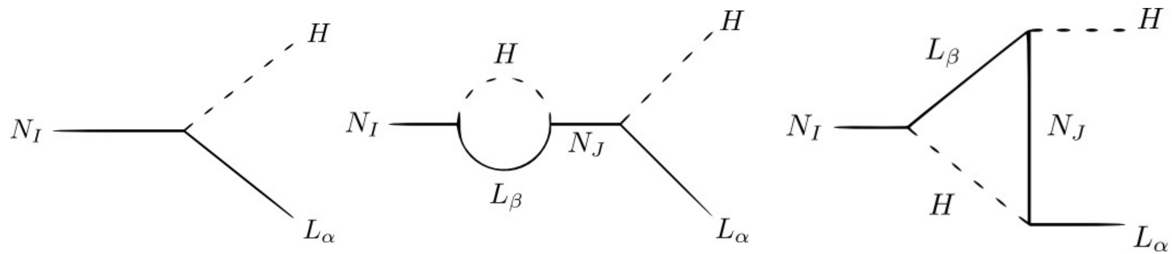
Add ≥2 RH singlet fermions

$$\mathcal{L}_I \supset -\left(\frac{1}{2} M_i \overline{N^c_{R_i}} N_{R_i} + \epsilon_{\alpha\beta} Y_{\alpha i} \overline{N_{R_i}} l^a_\alpha H^b + \text{h.c.}\right) \longrightarrow m_I \simeq -v^2 Y \frac{1}{M} Y^T$$

1) EW sphalerons

2) New complex Yukawas

3) Lifetime of N not much shorter than age of universe

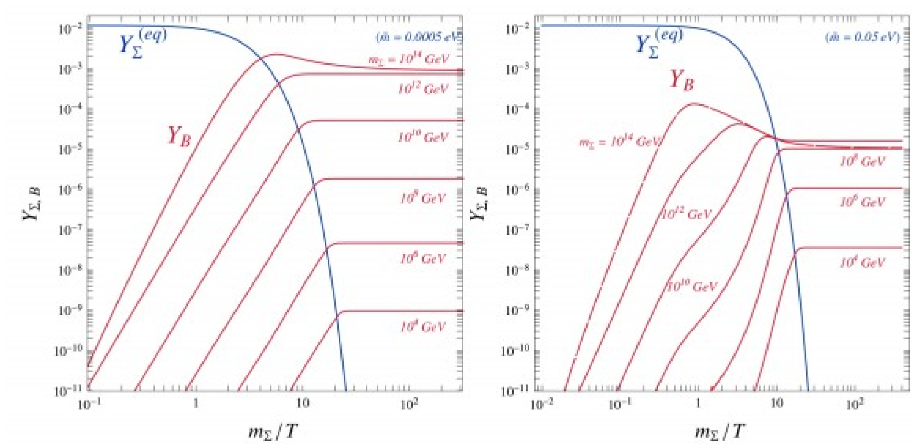


$$\epsilon_i = \sum_\alpha \epsilon_{i\alpha} = \frac{1}{8\pi} \frac{1}{(Y^\dagger Y)_{ii}} \sum_{j \neq i} Im\left[\left(Y^\dagger Y\right)^2_{ji}\right] g\left(\frac{M_j^2}{M_i^2}\right)$$

Evolution of lightest RH density Y_{N1} and $Y_{\Delta L}$

$$\frac{dY_{N_1}}{dz} = -D_1\left(Y_{N_1} - Y^{eq}_{N_1}\right),$$

$$\frac{dY_{\Delta L}}{dz} = \epsilon_1 D_1\left(Y_{N_1} - Y^{eq}_{N_1}\right) - W_1 Y_{\Delta L}$$



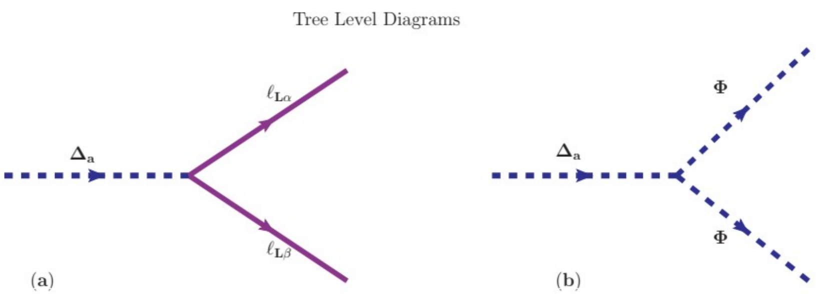
[T. Hambye, 2012]

Type-II leptogenesis

Add ≥1 scalar $SU(2)_L$ triplet(s)

$$\mathcal{L}_{II} \supset -m_\Delta^2 tr\left[\Delta_L^\dagger \Delta_L\right] - \left(f_{ij} L_i^T C i\sigma_2 \Delta_L^\dagger L_j + \mu H^T i\sigma_2 \Delta^\dagger H + \text{h.c.}\right) \longrightarrow m_{II} = f v_L = f\frac{\mu v^2}{m_\Delta^2}$$

- Sakharov conditions equivalent to type-I
- CP asymmetry: two decay channels!



[Lavignac & Schmauch, 2015]

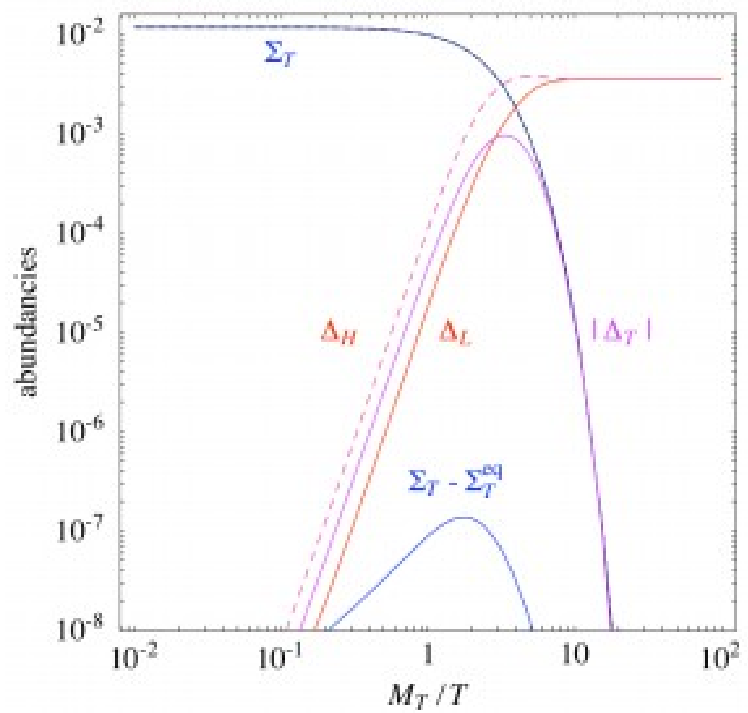
Evolution describes of four quantities:

$$\frac{d\Sigma_\Delta}{dz} = -D\left(\Sigma_\Delta - \Sigma_\Delta^{eq}\right) - 2A\left(\Sigma_\Delta^2 - \Sigma_\Delta^{2eq}\right)$$

$$\frac{d\Delta_L}{dz} = -D\epsilon_L\left(\Sigma_\Delta - \Sigma_\Delta^{eq}\right) + \mathcal{W}_\mathcal{L}^\mathcal{D}$$

$$\frac{d\Delta_\Delta}{dz} = -\frac{1}{2}\left(\mathcal{W}_L^D - \mathcal{W}_L^H\right)$$

$$\left(\frac{d\Delta_H}{dz} = -D\epsilon_L\left(\Sigma_\Delta - \Sigma_\Delta^{eq}\right) + \mathcal{W}_\mathcal{L}^\mathcal{H}\right)$$



Minimal model in left-right symmetric context

Assume: just one scalar triplet

- 11 quantities: f, m_Δ, μ
- Minimal flavor structure: $m_\nu \sim f$
- Mass scale set by $\mathbf{v}_L$

→ perfect minimal model, but..

- Triplet not self-conjugate
  → no vertex diagram
- Self-energy diagram real
  → no CP violation
- More loops suppressed anyway

→minimal models in larger context!

Idea: $SU(2)_L$ x $SU(2)_R$ models [Mohapatra & Senjanovic, 1975]

- Natural embedding of type-I and type-II seesaw $$m_\nu = m_I + m_{II}$$
- Connection between RH and LH neutrino masses possible!
- Outlook: implementation into **SO(10)** GUTs
  - $\mathbf{126}_S$ contains both Δ_L and Δ_R
  - $\Delta_L \gg \Delta_R$ vs. $\Delta_L \ll \Delta_R$

Type-II dominated Left-right leptogenesis

Assumptions for our model: $\Delta_L \ll \Delta_R$ [Joshipura, Paschos, Rodejohann, 2001]

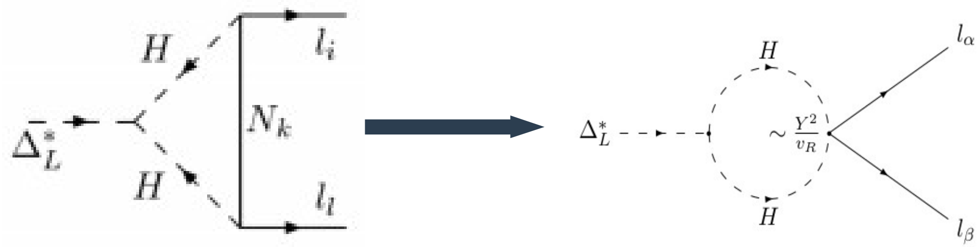
1) LR context & type-II dominance

→ same mass hierarchy between LH and RH particles

$$SU(2)_L \times SU(2)_R \times U(1)_{\tilde{Y}} \rightarrow SU(2)_L \times U(1)_Y$$

2) One $SU(2)_L$ triplet

→ Triplet solely generates BAU



3) GUT-inspired Dirac mass hierarchy

$$m_D \simeq \mathrm{diag}(m_u, m_c, m_t) \simeq \frac{v_{EW}}{\sqrt{2}}\mathrm{diag}(0,0,1)$$

4) (perturbativity bound

→ maximal possible BAU)

$$\sqrt{\mathrm{Tr}(\mathrm{f}^\dagger \mathrm{f})} = \frac{\bar{m}}{v_L} \lesssim \mathcal{O}(1)$$

→ **Framework**: Flavoured semi-classical Boltzmann equation [Lavignac & Schmauch, 2015]

Type-II dominated light neutrino masses

Assume: $\Delta_L \ll \Delta_R$

- RH neutrinos much heavier than scalar triplet $m_\nu = m_I + m_{II} \simeq m_{II}$
- RH VEV $\boldsymbol{v}_R$ induces Majorana neutrino mass

$$\rightarrow m_N = f \cdot v_R = \left(\frac{m_{II}}{v_L}\right) \cdot v_R \approx \frac{v_R}{v_L} m_\nu$$

- Diagonalizing m_ν diagonalizes m_N $\rightarrow$ $D_N \approx \frac{v_R}{v_L} D_\nu$
  - Heavy and light neutrinos exhibit same mass hierarchy!
  - Connected by ratio of different scales! $r \equiv \frac{v_L}{v_R}$
- GUT-inspired structure for Dirac neutrino mass

$$\rightarrow \quad \bar{m}_I \equiv \sqrt{\mathrm{Tr}\left(m_I^\dagger m_I\right)} = \frac{r v_{\mathrm{ew}}^2}{2} \sqrt{\sum_{i,j} \frac{U_{\tau i}^2 U_{\tau j}^{2*}}{m_i m_j}} \equiv \frac{r v_{\mathrm{ew}}^2}{2\tilde{m}}$$

- Type-II mass scale:

$$\bar{m}_{II} \equiv \sqrt{\mathrm{Tr}\left(m_{II}^\dagger m_{II}\right)} = \lambda_l v_L \simeq \bar{m}, \text{ with } \lambda_l \equiv \sqrt{\mathrm{Tr}\left(\mathrm{f}^\dagger \mathrm{f}\right)}$$

Quantifying type-II dominance

Type-II dominance is realized if $\boxed{R = \frac{\bar{m}_I}{\bar{m}_{II}} \simeq \frac{r v_{\rm ew}^2}{2\bar{m}\tilde{m}} \ll 1}$

Constraints on parameter space:

- Ratio of scales:

$$r \ll \frac{2\bar{m}\tilde{m}}{v_{\rm ew}^2} \sim 10^{-26} \left(\frac{\tilde{m}}{0.01\ \mathrm{eV}}\right) \left(\frac{\bar{m}}{0.05\ \mathrm{eV}}\right)$$

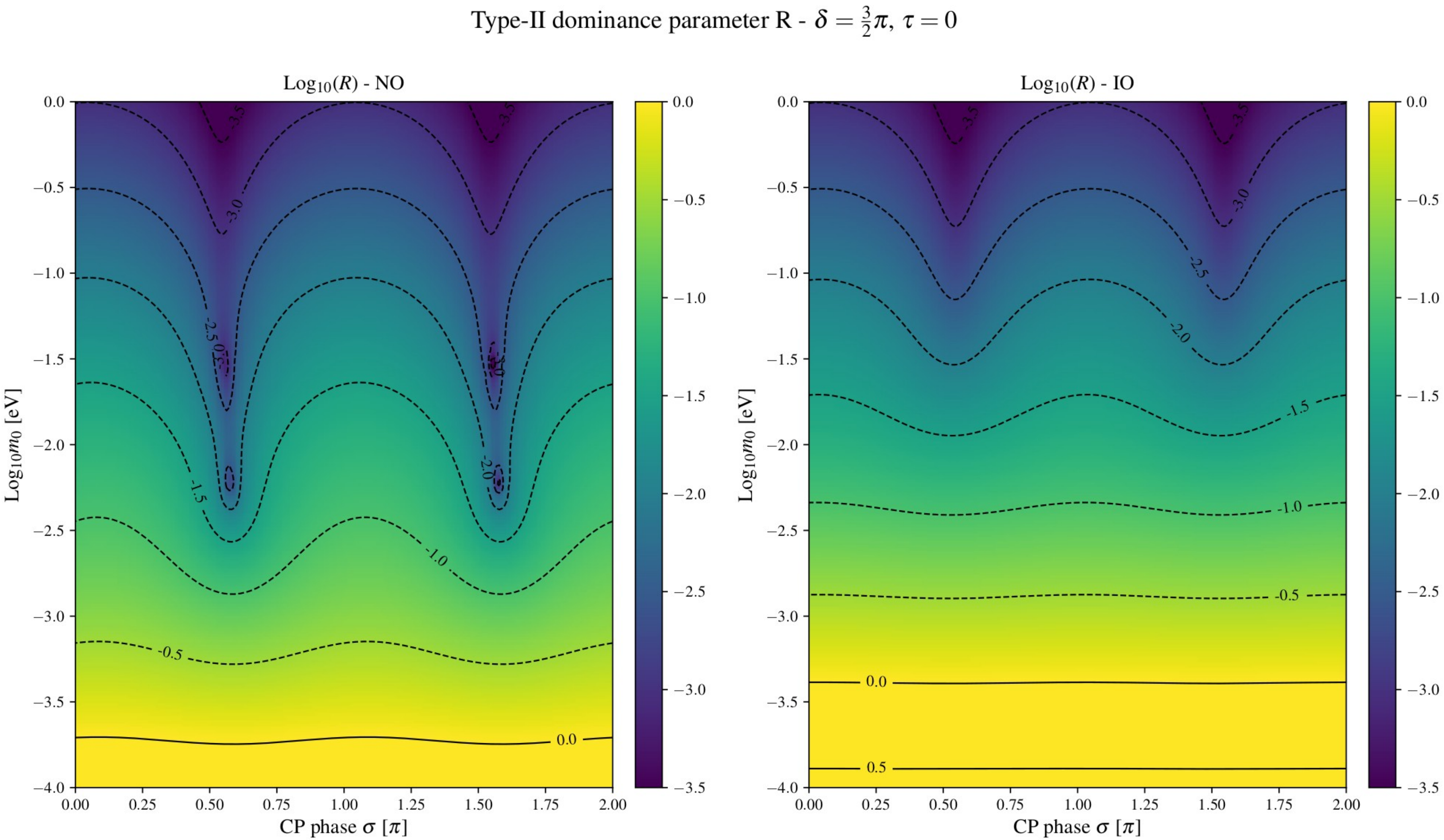
- LH mass scale

$$v_L \ll \frac{2\bar{m}\tilde{m} v_R}{v_{\rm ew}^2} \sim 0.1\ \mathrm{eV} \left(\frac{\tilde{m}}{0.01\ \mathrm{eV}}\right) \left(\frac{\bar{m}}{0.05\ \mathrm{eV}}\right) \left(\frac{v_R}{10^{16}\ \mathrm{GeV}}\right)$$

- Tri-linear scalar coupling

$$\mu \ll \frac{\bar{m}\tilde{m} M_\Delta^2 v_R}{v_{\rm ew}^4} \sim 10^{10}\ \mathrm{GeV} \left(\frac{\tilde{m}}{0.01\ \mathrm{eV}}\right) \left(\frac{\bar{m}}{0.05\ \mathrm{eV}}\right) \left(\frac{M_\Delta}{10^{12}\ \mathrm{GeV}}\right)^2 \left(\frac{v_R}{10^{16}\ \mathrm{GeV}}\right)$$

Quantifying type-II dominance



Available parameter space

Low energy observables:

- Light neutrino mass scale: **m**
- CP phases of PMNS matrix: **δ, σ, τ**
- LH VEV: $v_L \to \bar{m}$ (perturb. bound)

Experiments:
- GERDA/Majorana, ...
- KATRIN

Cosmology

High energy quantities:

- Triplet mass : $\mathbf{m_\Delta}$
- Tri-linear scalar coupling: μ

  → fixed by LH VEV v_L
- Lepton-triplet coupling matrix: f

  → fixed by LR symmetry and type-II dominance
- RH VEV: fixed at high value: $v_R \sim 10^{16}$ GeV

Constrain with correct BAU

$$\eta \sim 6.1 \cdot 10^{-10}$$

Higher order washout effects

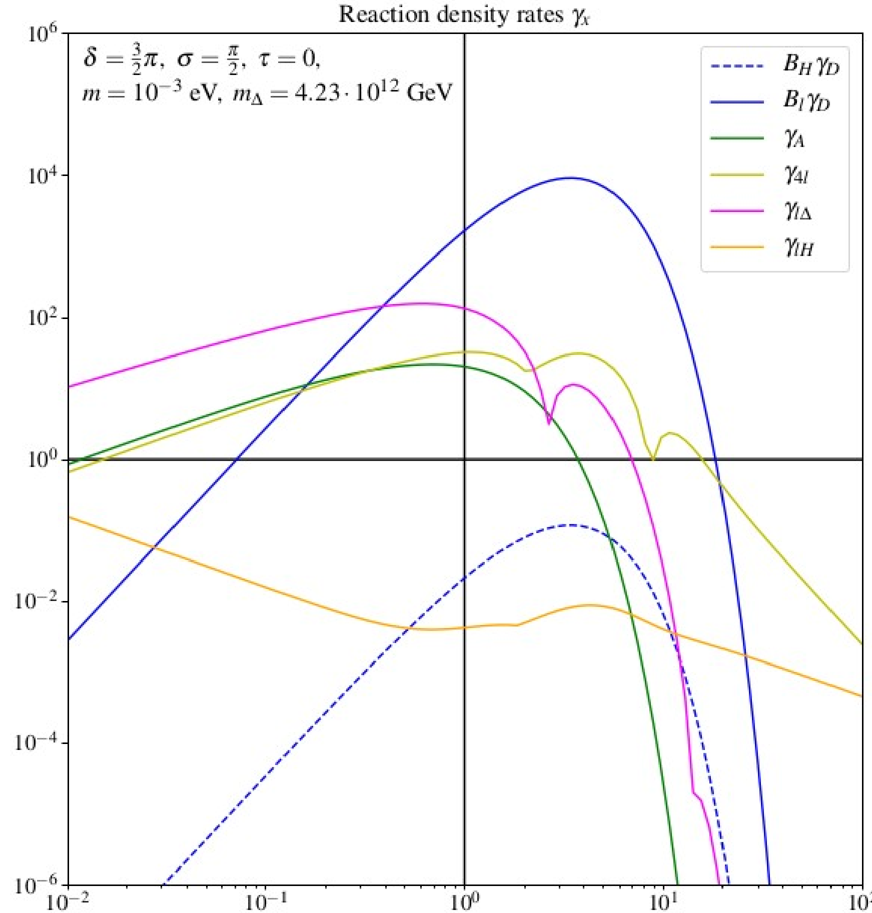
→ **(2-2)-scatterings contribute further washout!**

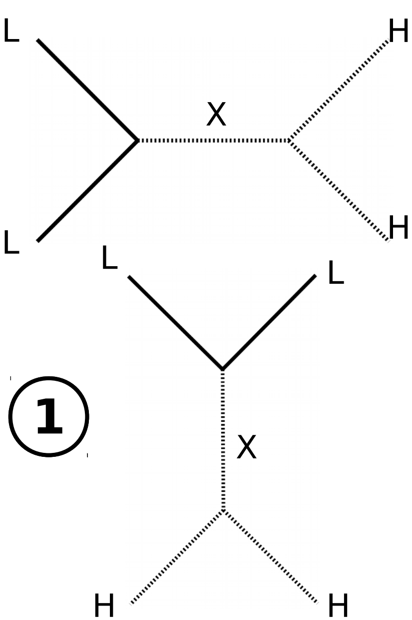
1) Lepton-Higgs scattering
2) 4-lepton scattering
3) Lepton-Triplet scattering

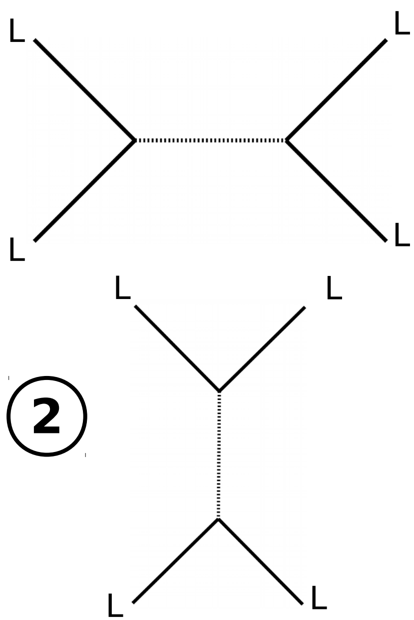
} Vanish in unflavoured regime

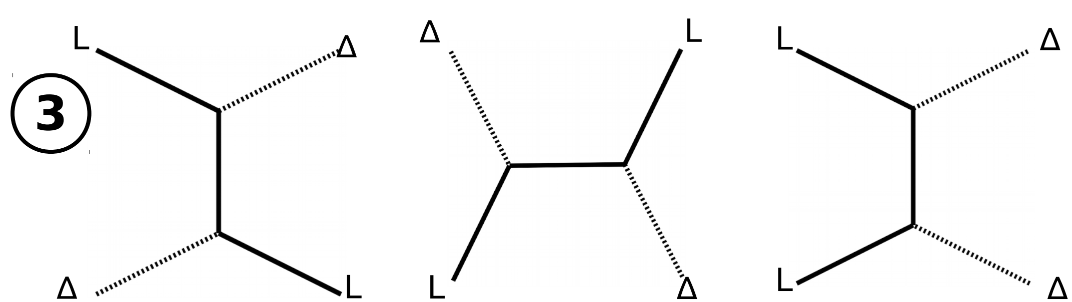
→ redistribute asymmetries among different flavors

→ in general small: **O(1)** effect



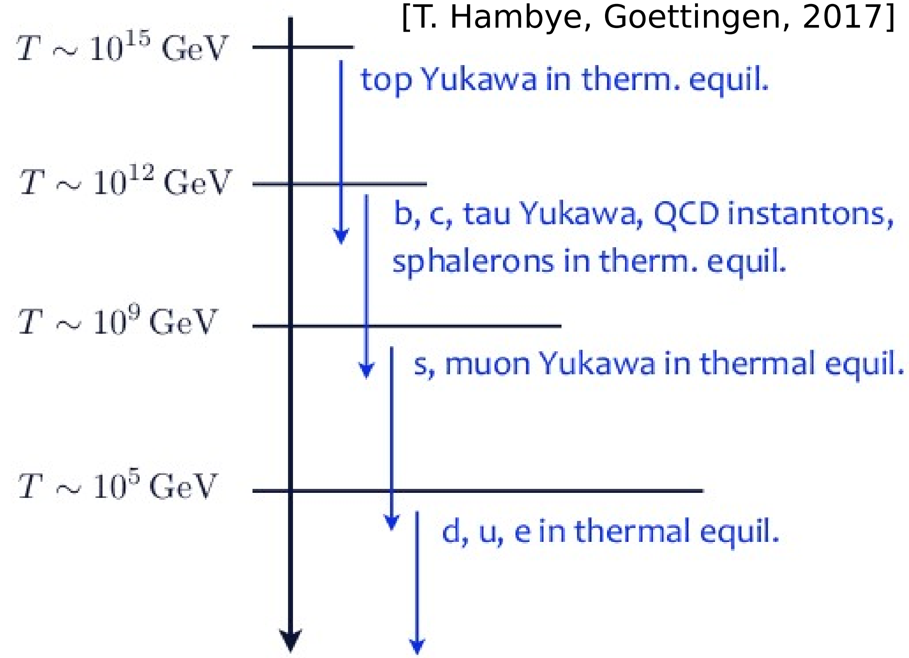






Flavour and spectator processes

[T. Hambye, Goettingen, 2017]



→ Yukawa interactions become effective as Universe cools: Γ~H

- Yukawa interactions are sensitive to flavor → break quantum coherence!
- Corresponding density matrix elements vanish → different regimes: 1-/2-/3-flavour
- Different viewpoint: hide asymmetry from washout!

→ strong effect on BAU evolution: ~ **O(10)**

→ Spectator processes have indirect effects!

- Modify particle densities that influence washout terms

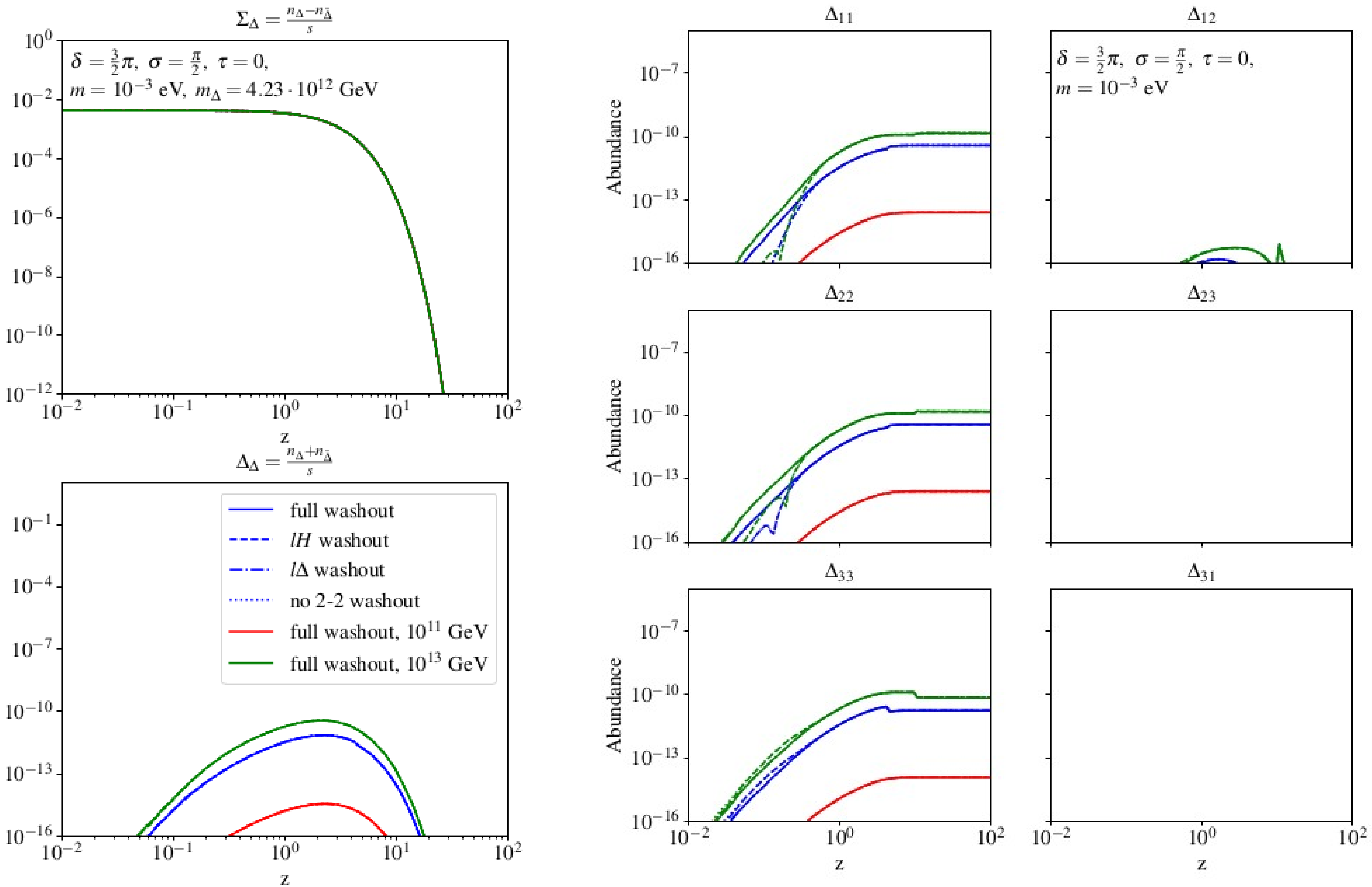
Δ_L, Δ_H

→ re-express lepton and Higgs doublet densities

in terms of relevant quantities

- Equilibrium regimes are well understood, transitions more subtle ...

Generating BAU in the early Universe



A detailed example:

→ Overview of relevant quantities (assume NO, 3-flavor description)

Lightest neutrino m_0	0.01 eV
Dirac phase δ	1.5π
Majorana phase σ	0.5π
Majorana phase τ	0.0
Triplet mass m_Δ	$1.492 \cdot 10^{13}$ GeV

↓ Neutrino mass quantities

Neutrino mass scale $\overline{m}$	0.054 eV
Eff. Majorana mass $m_{\beta\beta}$	0.002 eV
β-decay mass m_{ee}	0.013 eV
Sum of all masses	0.074 eV

Relevant quantities for leptogenesis

- R parameter: 0.013
- RH VEV: $v_R \sim 10^{16}$ GeV
- LH VEV: $\mathbf{v_L << 0.83}$ **eV**
- Tri-linear coupling: $\mu << 1.85 \cdot 10^{13}$ GeV
- $\mathbf{B_L}$ = 0.9998 vs. B_H = 0.0002

Baryon-to-photon ratios η [10^{-10}]:
- Full washout: 6.16
- Just lepton-Higgs: 6.15
- 4lepton & lepton-triplet: 6.71
- No 2→2 washout: 6.71

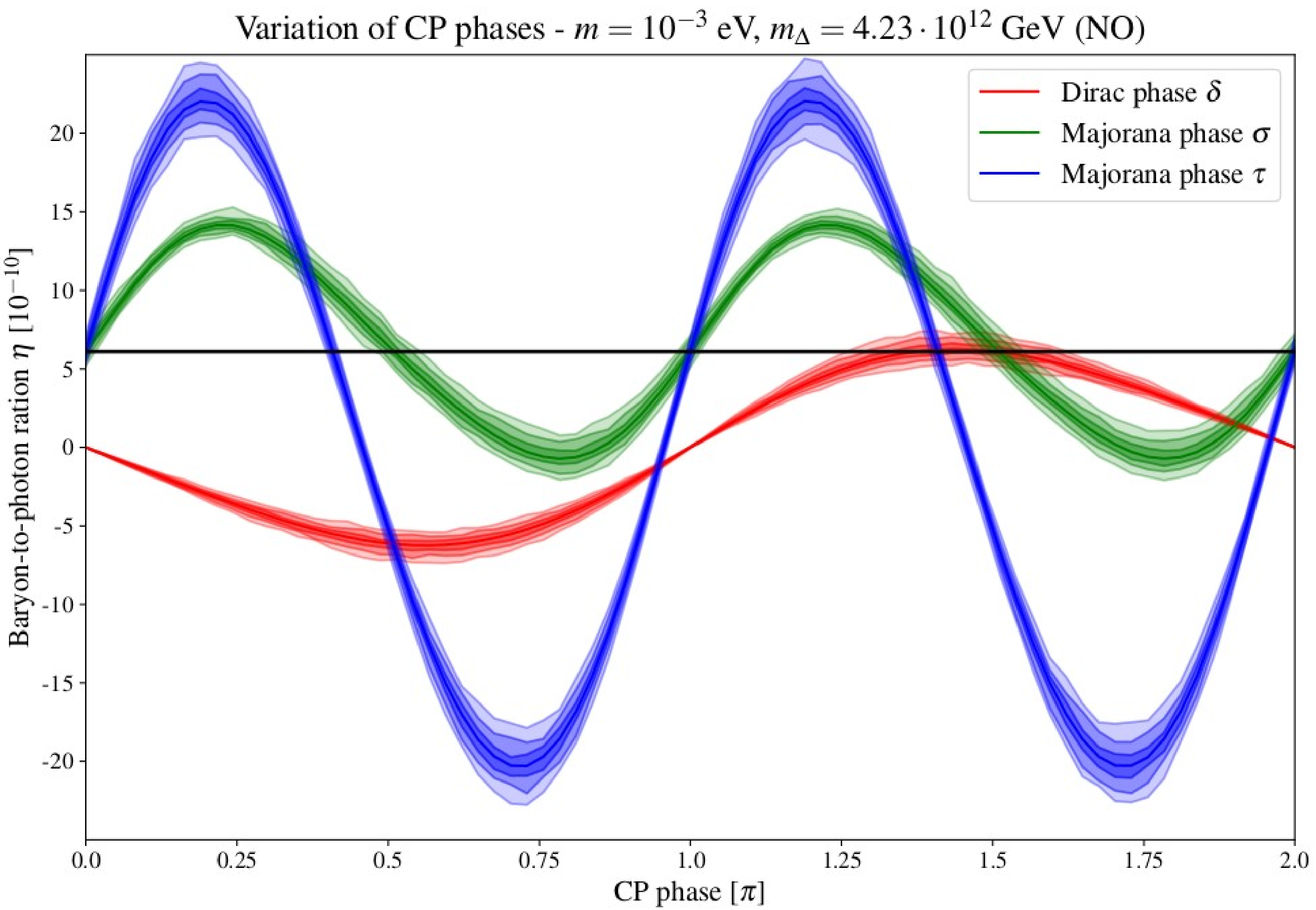
(assuming thermal initial abundance for triplet)

[1-Flavor approximation: 9.35 (full) vs. 9.78 (none)]

Influence of experimental uncertainties

→ **Vary experimental inputs within error regions**

$\left(\Delta\mathrm{m}^2_{\mathrm{ij}}, \sin^2\theta_{\mathrm{ij}}\right)$

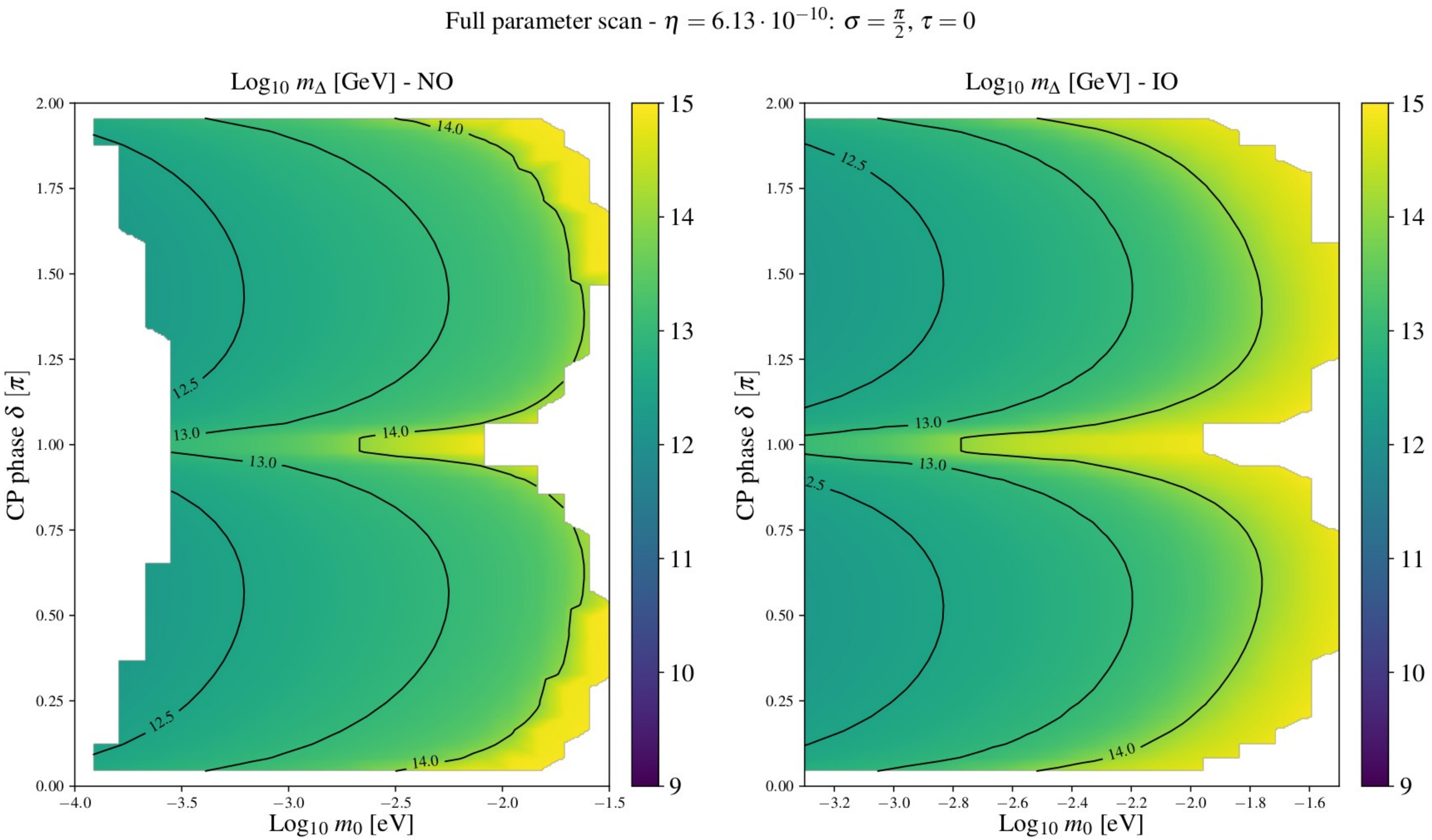


Normal Ordering (best fit)	
bfp $\pm1\sigma$	3σ range
$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$
$0.580^{+0.017}_{-0.021}$	$0.418 \to 0.627$
$49.6^{+1.0}_{-1.2}$	$40.3 \to 52.4$
$0.02241^{+0.00065}_{-0.00065}$	$0.02045 \to 0.02439$
$8.61^{+0.13}_{-0.13}$	$8.22 \to 8.99$
215^{+40}_{-29}	$125 \to 392$
$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
$+2.525^{+0.033}_{-0.032}$	$+2.427 \to +2.625$

Inverted Ordering ($\Delta\chi^2 = 4.7$)	
bfp $\pm1\sigma$	3σ range
$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$
$0.584^{+0.016}_{-0.020}$	$0.423 \to 0.629$
$49.8^{+1.0}_{-1.1}$	$40.6 \to 52.5$
$0.02264^{+0.00066}_{-0.00066}$	$0.02068 \to 0.02463$
$8.65^{+0.13}_{-0.13}$	$8.27 \to 9.03$
284^{+27}_{-29}	$196 \to 360$
$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
$-2.512^{+0.034}_{-0.032}$	$-2.611 \to -2.412$

[Esteban et al., 2018]

Constraining parameter space with correct BAU



Conclusion

- Leptogenesis allows natural connection to neutrino masses
- LR symmetric models incorporate type-I and type-II seesaw mechanism

  → minimal type-II leptogenesis scenario valid again!
- Our minimal predictive model: **type-II dominated LR-symmetric seesaw**
  - Type-II dominance
  - LR-symmetry
  - GUT-inspired neutrino Dirac mass
- Separation of parameter space:

Low-E observables: m, δ, σ, τ	⟷	High-E parameters: m_Δ , (μ)

- Future neutrino experiments will determine low-E parameters

  → potential window into high-energy regions!

Stay tuned !

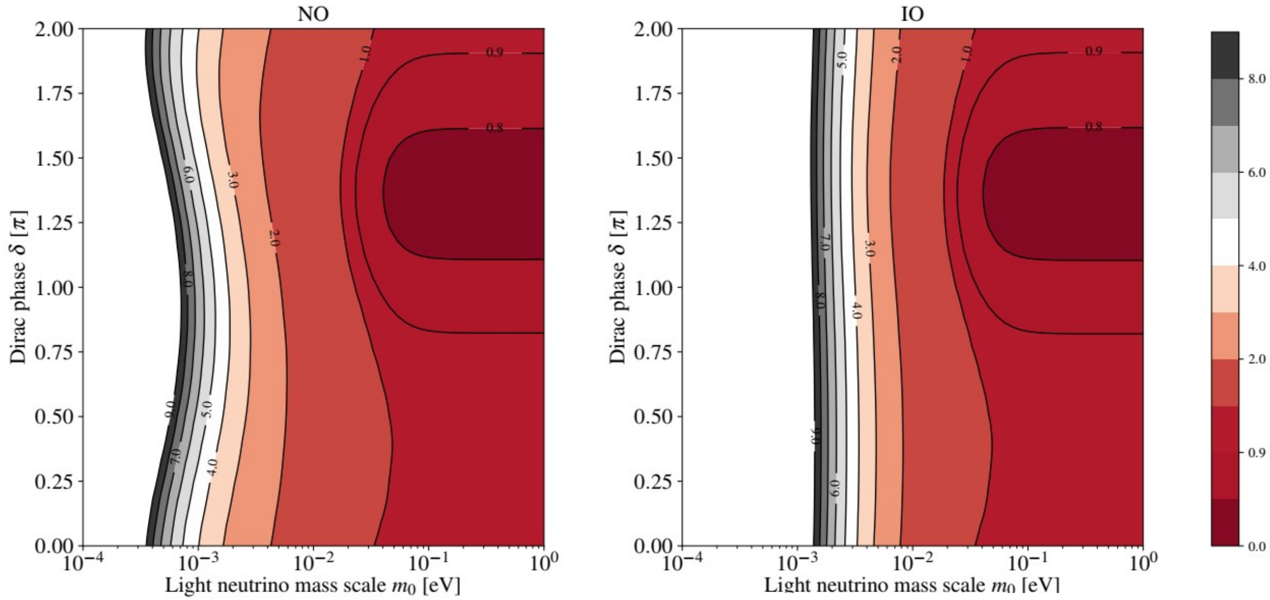
Thank you for your attention!

Type-II dominated CP asymmetry

→ Single flavour CP asymmetry with top Yukawa dominated Dirac mass

$$\epsilon_\Delta = \frac{1}{4\pi}\left(B_\Delta^l B_\Delta^h\right)^{1/2} \frac{m_\Delta}{v_{EW}^2 \bar{m}_{II}} \mathrm{Im}\ \mathrm{Tr}\left[\mathrm{m}_{\mathrm{II}}^\dagger \mathrm{m}_{\mathrm{I}}\right] \longrightarrow \epsilon_\Delta = -A \cdot B$$

A_{max} as a function of m_0 and δ



Low energy behaviour:

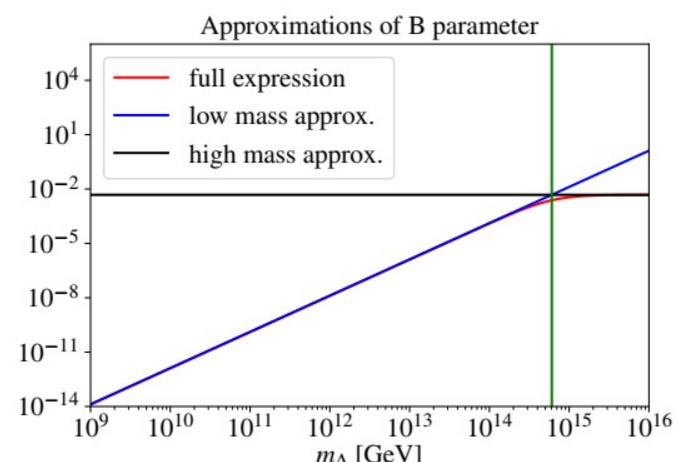
$$A = \sum_{i,j} \frac{m_i}{m_j} \mathrm{Im}\left[\left(U_{\tau i} U_{\tau j}\right)^2\right]$$

$$\Big\downarrow$$

$$A_{\max}(m_0, \delta) = \max_{\sigma,\tau} \left|A(m_0, \delta, \sigma, \tau)\right|$$

High energy behaviour:

$$B = \frac{\lambda_H}{1+\lambda_H^2} \frac{M_\Delta}{4\pi v_R}$$



Benchmark point $m_\Delta^0 \simeq 3 \cdot 10^{14}\ \mathrm{GeV} \left(\frac{0.05\ \mathrm{eV}}{\bar{m}}\right)$

1-flavour vs. 3-flavour description