Neutrino masses and the matter-antimatter asymmetry of the Universe

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- the matter-antimatter asymmetry of the Universe
- the necessity of a dynamical generation mechanism
- the failure of baryogenesis in the Standard Model
- a link with neutrino masses: baryogenesis via leptogenesis
- scalar triplet leptogenesis and lepton flavour effects
- conclusions

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Introduction

Observational cosmology has made impressive progress over the past 2.5 decades. In particular, the measurement of the anisotropies of the cosmic microwave background (CMB), in addition to validating the hot Big Bang model, confirmed the existence of dark energy, gave support to inflationary cosmology and allowed a precise determination of the cosmological parameters

It remains to understand the origin of these parameters in terms of fundamental physics. Two of them seem to require a particle physics interpretation: dark matter and the matter-antimatter asymmetry (or baryon asymmetry) of the Universe

There are very solid reasons to believe that the latter should be generated by some dynamical mechanism (baryogenesis). While the Standard Model of particle physics contains all the ingredients of baryogenesis, it fails to generate the observed asymmetry. An attractive possibility, known as leptogenesis, is that neutrino masses and the matter-antimatter asymmetry of the Universe share a common origin

The observational evidence

How do we know that there is (almost) no antimatter in the Universe?

Mere observation: the structures we observe in the Universe are made of matter (p, n, e-). No significant presence of antimatter (anti-p, anti-n, e+):

* solar system: no presence of antimatter

* milky way: $\bar{p}/p \approx 10^{-4}$ in cosmic rays - fully understood in terms of

$$p\,(\mathrm{primary\,CR}) + p\,(\mathrm{interstellar\,gas}) \to 3p + \bar{p}$$

* clusters of galaxies: would observe strong γ-ray emission from matter-antimatter annihilations, such as $p + \bar{p} \to \pi^0 + X \to \gamma\gamma + X$

Could there be matter/antimatter separation over larger scales?

Would require violation of causality (the causal horizon before annihilation freeze-out contained only a tiny fraction of our visible Universe) in a non-inflationary Universe. Also problematic if inflation

The matter-antimatter asymmetry of the Universe is measured by the baryon-to-photon ratio:

$$\eta \equiv \frac{n_B}{n_\gamma} \simeq \frac{n_B - n_{\bar{B}}}{n_\gamma}$$

Since the photon density is not preserved in the early Universe, one also considers:

$$Y_B \equiv \frac{n_B - n_{\bar{B}}}{s}$$

s = entropy density = 7.04 n_γ today

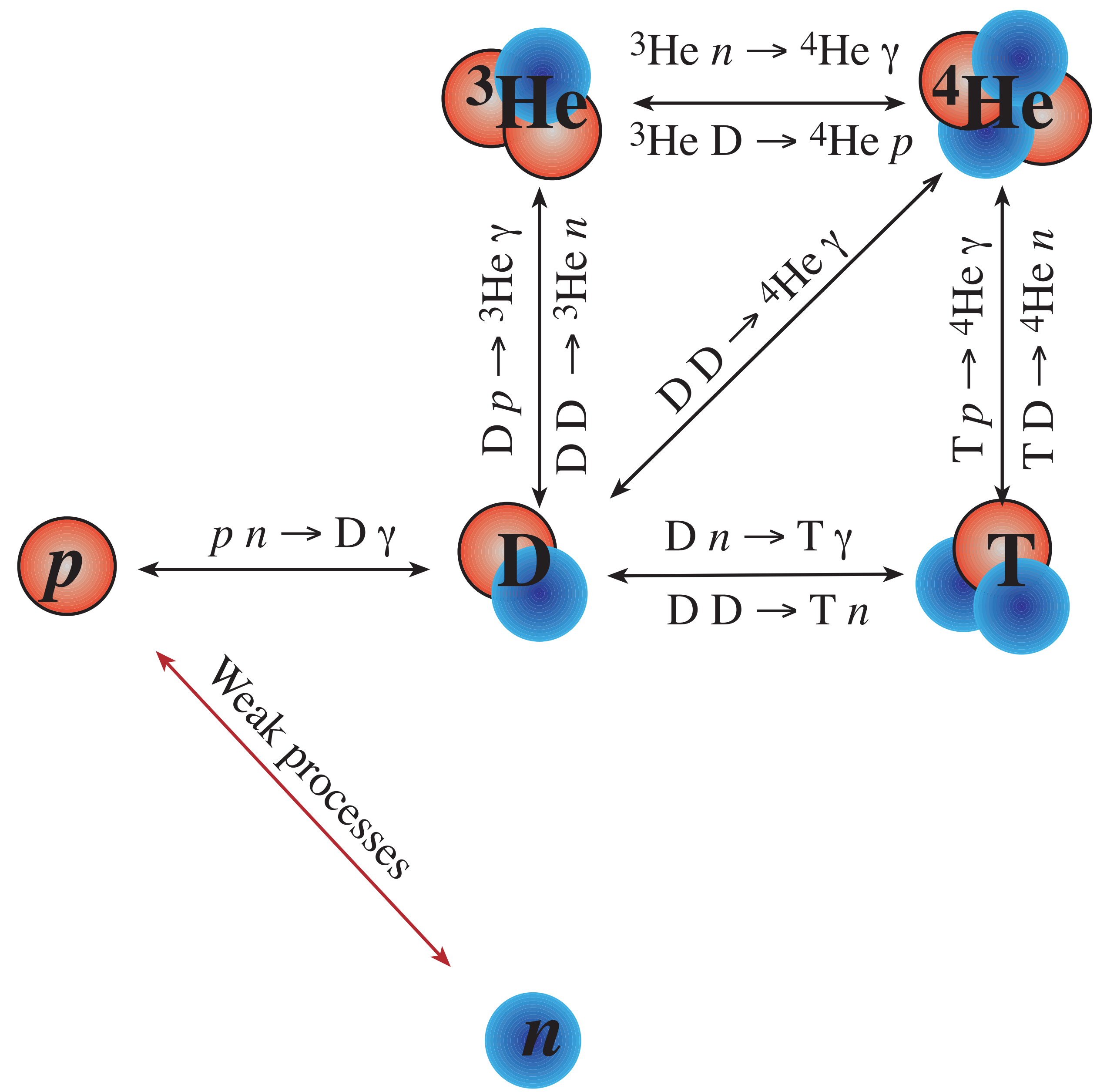
2 independent determinations of Y_B:

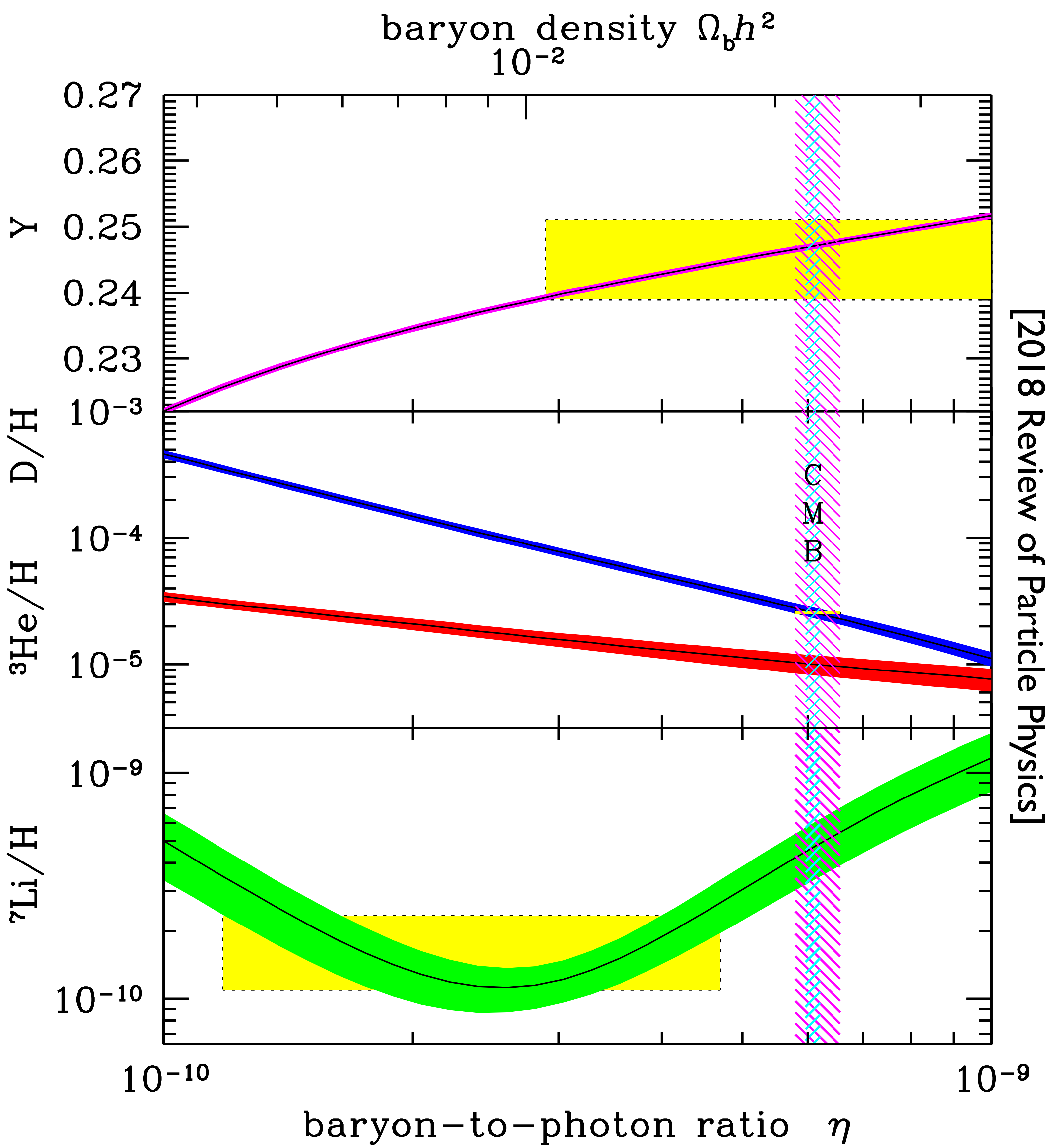
(i) light element abundances

(ii) anisotropies of the cosmic microwave background (CMB)

Big Bang nucleosynthesis (BBN) predicts the abundances of the light elements (D, ^{3}He, ^{4}He and ^{7}Li) as a function of η:

The abundances of D and ^{3}He are very sensitive to η, since a larger η accelerates the synthesis of D and ^{3}He, which are themselves needed for the synthesis of ^{4}He, resulting in final lower abundances for D and ^{3}He





There is a range of values for η consistent with all observed abundances ("concordance", up to a factor of 2 for Li)
→ major success of Big Bang cosmology

$$\eta = (5.8 - 6.6) \times 10^{-10}$$
$$(95\% \text{ C.L.})$$

- curves = BBN prediction (95% C.L.)
- boxes = observed abundances

The cosmic microwave background (CMB) is a remnant of the era of last scattering (of the photons off electrons), after the recombination epoch (p + e- $\rightarrow$ H atoms), where the Universe became transparent to photons

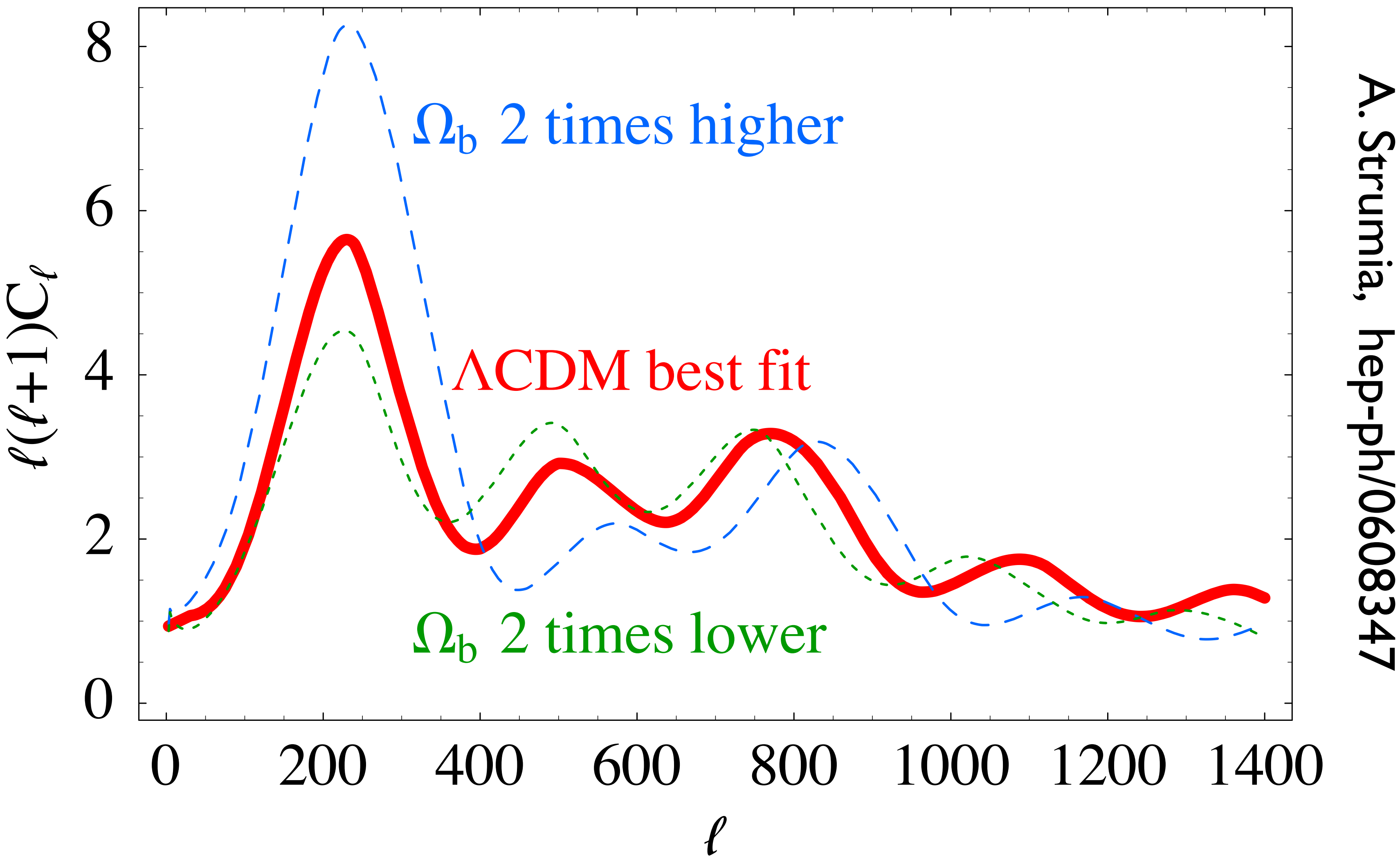
$\Rightarrow$ blackbody spectrum with T = 2.725 K and small ($\delta T/T \sim 10^{-5}$) temperature anisotropies

Most of the cosmological information contained in the anisotropies can be extracted from the temperature 2-point function. The latter is studied by expanding the temperature distribution on the sky in spherical harmonics, then computing the variance of the coefficients a_{lm} :

$$\frac{\delta T}{T}(\theta,\phi) \;=\; \sum_{l=1}^{\infty}\sum_{m=-l}^{+l} a_{lm}Y_{lm}(\theta,\phi)$$

$$\langle a_{lm}a^{*}_{l'm'}\rangle = C_l\delta_{ll'}\delta_{mm'}$$

The C_l are then plotted as a function of the multipole l



Information on the cosmological parameters can be extracted from the temperature anisotropies

In particular, the anisotropies are affected by the oscillations of the baryon-photon plasma before recombination, which depend on η (or $\Omega_b h^2$)

$$\Rightarrow \quad \eta = (6.13 \pm 0.08) \times 10^{-10} \qquad \text{(Planck 2018, 95\% C.L.)}$$

$\Rightarrow$ remarkable agreement between the CMB and BBN determinations of the baryon asymmetry: another success of Big Bang cosmology

$$\eta = (5.8 - 6.6) \times 10^{-10} \qquad \text{(BBN)}$$

$$\eta = (6.13 \pm 0.08) \times 10^{-10} \qquad \text{(Planck 2018)}$$

Although this number might seem small, it is actually very large:

in a baryon-antibaryon symmetric Universe, annihilations would leave a relic abundance $n_B/n_\gamma = n_{\bar{B}}/n_\gamma \approx 5 \times 10^{-19}$

The necessity of a dynamical generation

In a baryon-antibaryon symmetric Universe, annihilations would leave a relic abundance $n_B/n_\gamma = n_{\bar{B}}/n_\gamma \approx 5 \times 10^{-19}$

Since at high temperatures $n_q \sim n_{\bar{q}} \sim n_\gamma$, one would need to fine-tune the initial conditions in order to obtain the observed baryon asymmetry as a result of a small primordial excess of quarks over antiquarks:

$$\frac{n_q - n_{\bar{q}}}{n_q} \approx 3 \times 10^{-8}$$

Furthermore, there is convincing evidence that our Universe underwent a phase of inflation, which exponentially diluted the initial conditions

$\Rightarrow$ need a mechanism to dynamically generate the baryon asymmetry

Baryogenesis!

Conditions for baryogenesis

Sakharov's conditions [1967]:

(i) baryon number (B) violation
(ii) C and CP violation
(iii) departure from thermal equilibrium

(i) is obvious

(ii) C and CP violation

C (charge conjugation) exchanges a particle with its antiparticle. If it were conserved, any processes creating n baryons would occur at the same rate as the C-conjugated process creating n antibaryons, resulting in a vanishing net baryon asymmetry

CP [C combined with a parity transformation, $(t, \vec{x}) \to (t, -\vec{x})$] also reverses the impulsion of the particle. If it were conserved, even with C violated, processes creating baryons and antibaryons would balance each other once integrated over phase space

(iii) departure from thermal equilibrium

At thermal equilibrium, any process creating baryons occurs at the same rate than the inverse process which destroys baryons, resulting in a vanishing net baryon asymmetry

Quite remarkably, the Standard Model (SM) of particle physics satisfies all three Sakharov's conditions:

(i) B is violated by non-perturbative processes known as sphalerons

(ii) C and CP are violated by SM interactions (CP violation due to quark mixing: phase of the Cabibbo-Kobayashi-Maskawa matrix, responsible for CP violation in kaon decays)

(iii) departure from thermal equilibrium can occur during the electroweak phase transition, during which particles acquire their masses

→ ingredients of electroweak baryogenesis

Particle content of the Standard Model

FERMIONS
matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

Electroweak symmetry = gauge symmetry that dictates the form of electromagnetic and weak interactions

Must be broken in order for fermions (q, l) and W, Z gauge bosons to acquire their masses.

This is done by the vev of a scalar field, the Higgs boson

BOSONS
force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin =1

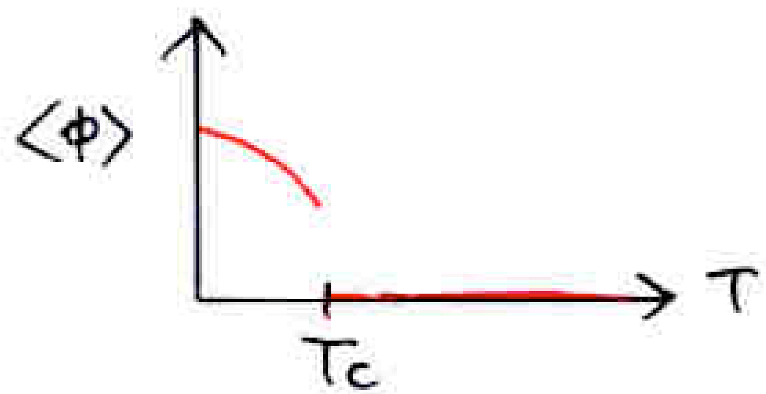
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

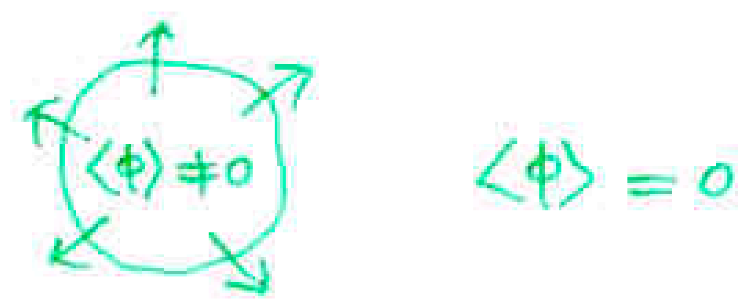
Baryogenesis in the Standard Model: rise and fall of electroweak baryogenesis

The order parameter of the electroweak phase transition is the Higgs vev:

- $T > T_{EW}, \langle \phi \rangle = 0$ unbroken phase
- $T < T_{EW}, \langle \phi \rangle \neq 0$ broken phase

If the phase transition is first order, the two phases coexist at T = Tc and the phase transition proceeds via bubble nucleation





[Cohen, Kaplan, Nelson]

Sphalerons are in equilibrium outside the bubbles, and out of equilibrium inside the bubbles (rate exponentially suppressed by $E_{sph}(T) / T$)

CP-violating interactions in the wall together with unsuppressed sphalerons outside the bubble generate a B asymmetry which diffuses into the bubble

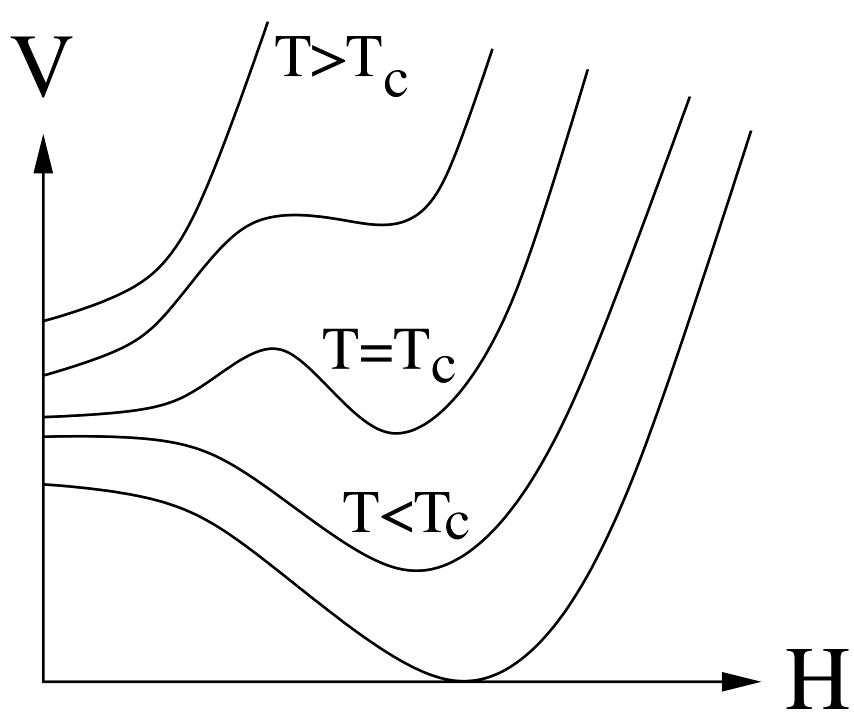
For the mechanism to work, it is crucial that sphalerons are suppressed inside the bubbles (otherwise will erase the generated B asymmetry)

$$\Gamma(T < T_{EW}) \;\propto\; e^{-E_{sph}(T)/T} \quad \text{with} \quad E_{sph}(T) \;\approx\; (8\pi/g)\,\langle\phi(T)\rangle$$

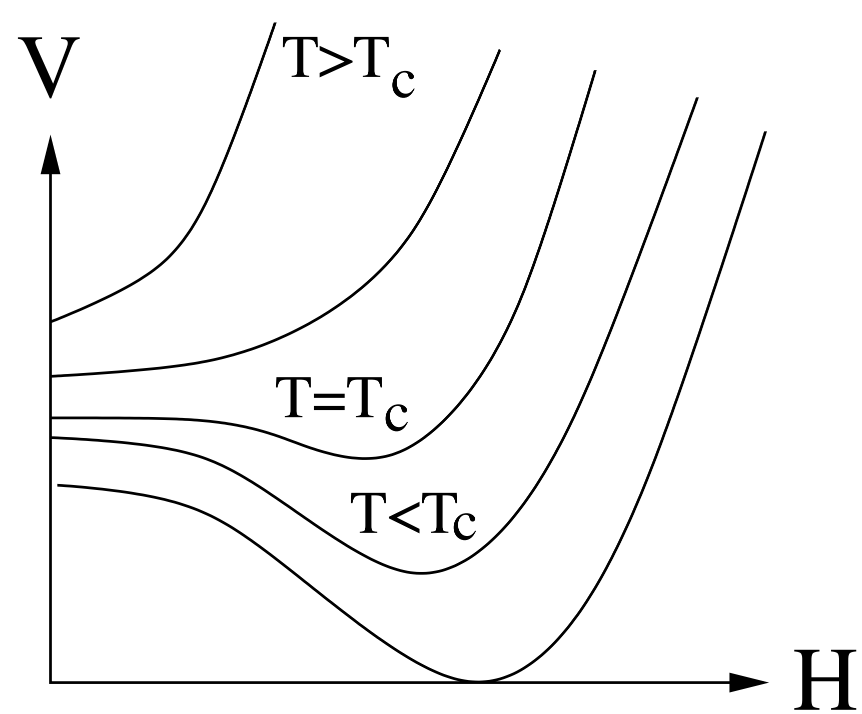
The out-of-equilibrium condition is $\dfrac{\langle\phi(T_c)\rangle}{T_c} \gtrsim 1$

$\Rightarrow$ strongly first order phase transition required!

To determine whether this is indeed the case, need to study the 1-loop effective potential at finite temperature



first order



second order

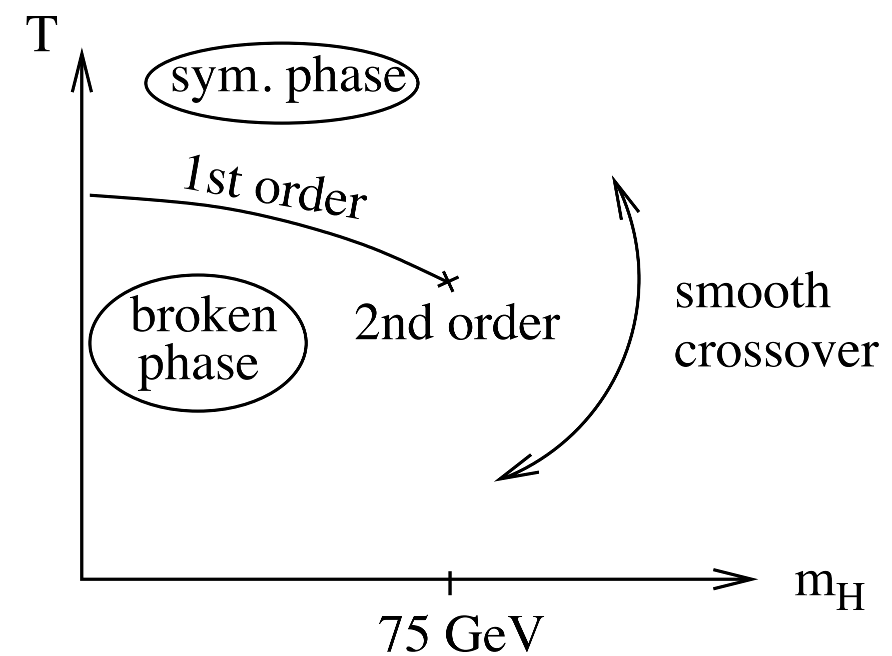
One obtains $\phi(T_c) \propto v^2 T_c / m_H^2$

The out-of-equilibrium condition $\Phi(T_c)/T_c > 1$ then translates into:

$m_H \lesssim 40\,\mathrm{GeV}$ condition for a strong first order transition

$\Rightarrow$ excluded by the LHC, which measured $m_H = 125\,\mathrm{GeV}$

Kajantie et al.
(hep-ph/9605228)



It is also generally admitted that CP-violating effects are too small in the SM for successful electroweak baryogenesis [Gavela, Hernandez, Orloff, Pène]

$\Rightarrow$ standard electroweak baryogenesis fails: the observed baryon asymmetry requires new physics beyond the Standard Model

The observed baryon asymmetry requires new physics beyond the SM

⇒ <u>2 approaches:</u>

1) modify the dynamics of the electroweak phase transition [+ new source of CP violation needed] by adding new scalar fields coupling to the Higgs (2 Higgs doublet model, additional Higgs singlet…)

2) generate a B-L asymmetry at $T > T_{EW}$ (sphaleron processes violate baryon [B] and lepton [L] numbers, but preserve the combination B-L)

Leptogenesis (the generation of a lepton asymmetry in out-of-equilibrium decays of heavy states, which is partially converted into a B asymmetry by sphaleron processes) belongs to the second class

Intestingly, the existence of such heavy states is also suggested by neutrino oscillations, which require neutrinos to be massive

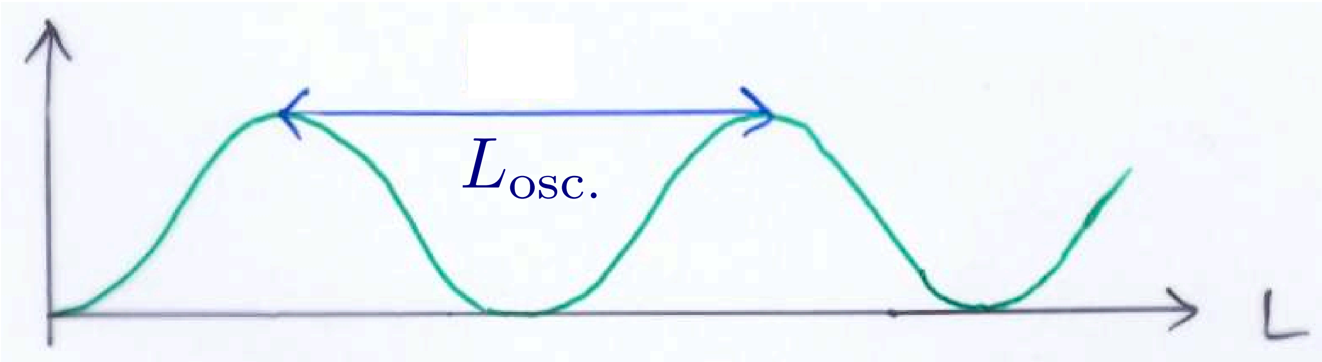
A link with neutrino masses: Baryogenesis via leptogenesis

The observation of neutrino oscillations from different sources (solar, atmospheric and accelerator/reactor neutrinos) has led to a well-established picture in which neutrinos have sub-eV masses and mix among different flavours $(\nu_e, \nu_\mu, \nu_\tau)$

solar neutrinos: $\nu_e \to \nu_\mu, \nu_\tau$ atmospheric neutrinos: $\nu_\mu \to \nu_\tau$

2-flavour oscillations: $P(\nu_\mu \to \nu_e) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$

$\sin^2 2\theta$



$L_{\rm osc.} \propto E/\Delta m^2$

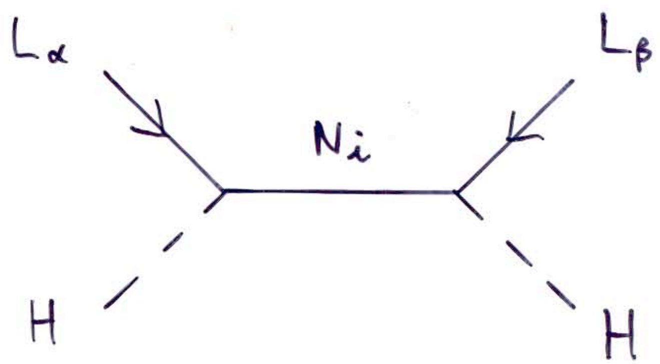
Neutrino oscillations imply neutrino mass! $(0.05\,\mathrm{eV} \lesssim m_\nu \lesssim 0.15\,\mathrm{eV})$

Neutrinos are massless in the Standard Model

Their tiny masses can be interpreted in terms of a high scale (the scale of the physics that generate their masses):

[Weinberg] $$\frac{1}{\Lambda} LLHH \quad \Rightarrow \quad m_\nu = \frac{v^2}{\Lambda} \qquad\qquad \Lambda \sim 10^{14}\,\mathrm{GeV}$$

The simplest realization of the Weinberg operator involves heavy Majorana neutrinos coupling to the Standard Model leptons and Higgs boson

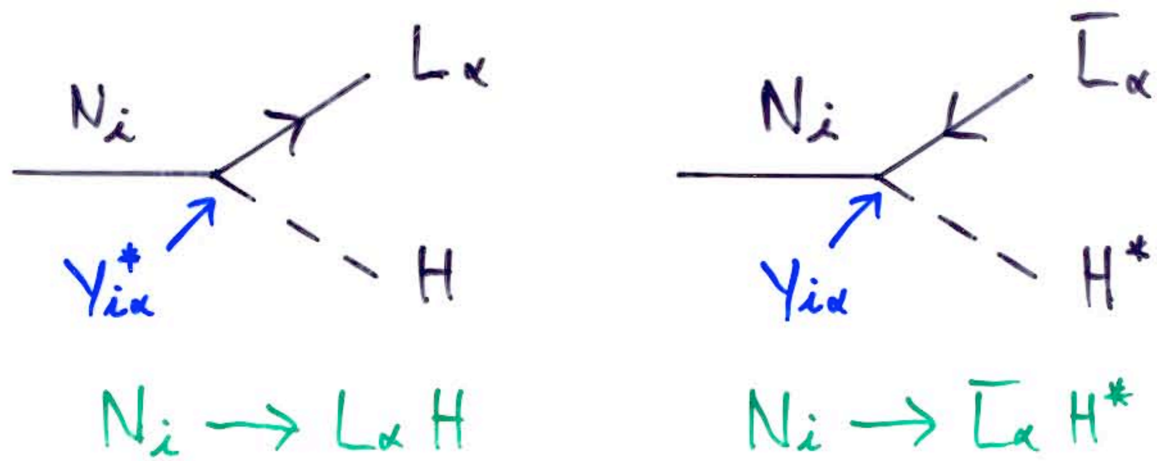


$$\Longrightarrow \qquad m_\nu = \frac{y^2 v^2}{M}$$

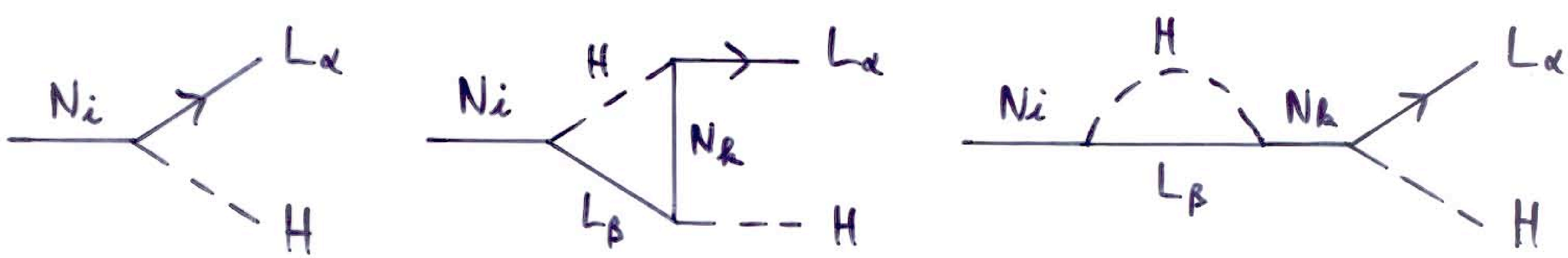
Minkowski - Gell-Mann, Ramond, Slansky
Yanagida - Mohapatra, Senjanovic

Interestingly, this mechanism contains all required ingredient for baryogenesis: out-of-equilibrium decays of the heavy Majorana neutrinos can generate a lepton asymmetry (L violation replaces B violation and is due to the Majorana neutrinos) if their couplings to SM leptons violate CP

<u>CP violation</u>: being Majorana, the heavy neutrinos are CP-conjugated and can decay both into l^+ and into l^-

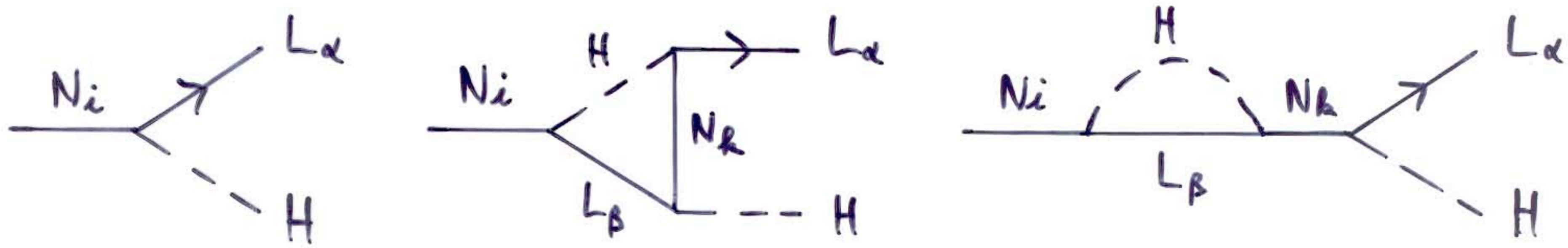


The decay rates into l^+ and into l^- differ due to quantum corrections



$$\Rightarrow \quad \Gamma(N_i \rightarrow LH) \neq \Gamma(N_i \rightarrow \bar{L}H^\star)$$

CP asymmetry due to interference between tree and 1-loop diagrams:



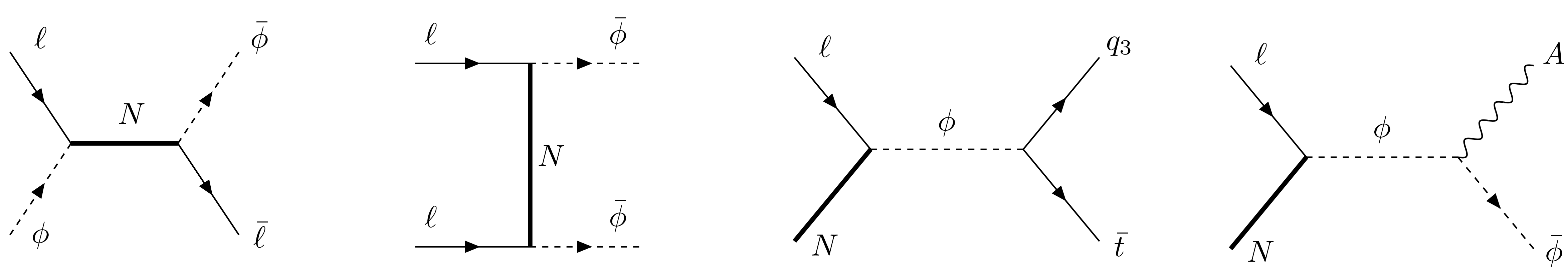
$$\Rightarrow \quad \Gamma(N_i \to LH) \neq \Gamma(N_i \to \bar{L}H^\star)$$

Covi, Roulet, Vissani '96
Buchmüller, Plümacher '98

CP asymmetry in N1 decays (hierarchical case $M_1 \ll M_2, M_3$) $\Rightarrow$ generation of a lepton asymmetry proportional to $\epsilon_{N_1} \equiv \dfrac{\Gamma(N_1 \to LH) - \Gamma(N_1 \to \bar{L}H^\star)}{\Gamma(N_1 \to LH) + \Gamma(N_1 \to \bar{L}H^\star)}$

The generated asymmetry is partly washed out by L-violating processes:

- inverse decays $LH \to N_1$
- ΔL=2 N-mediated scatterings $LH \to \bar{L}\bar{H}\,, \quad LL \to \bar{H}\bar{H}$
- ΔL=1 scatterings involving the top or gauge bosons

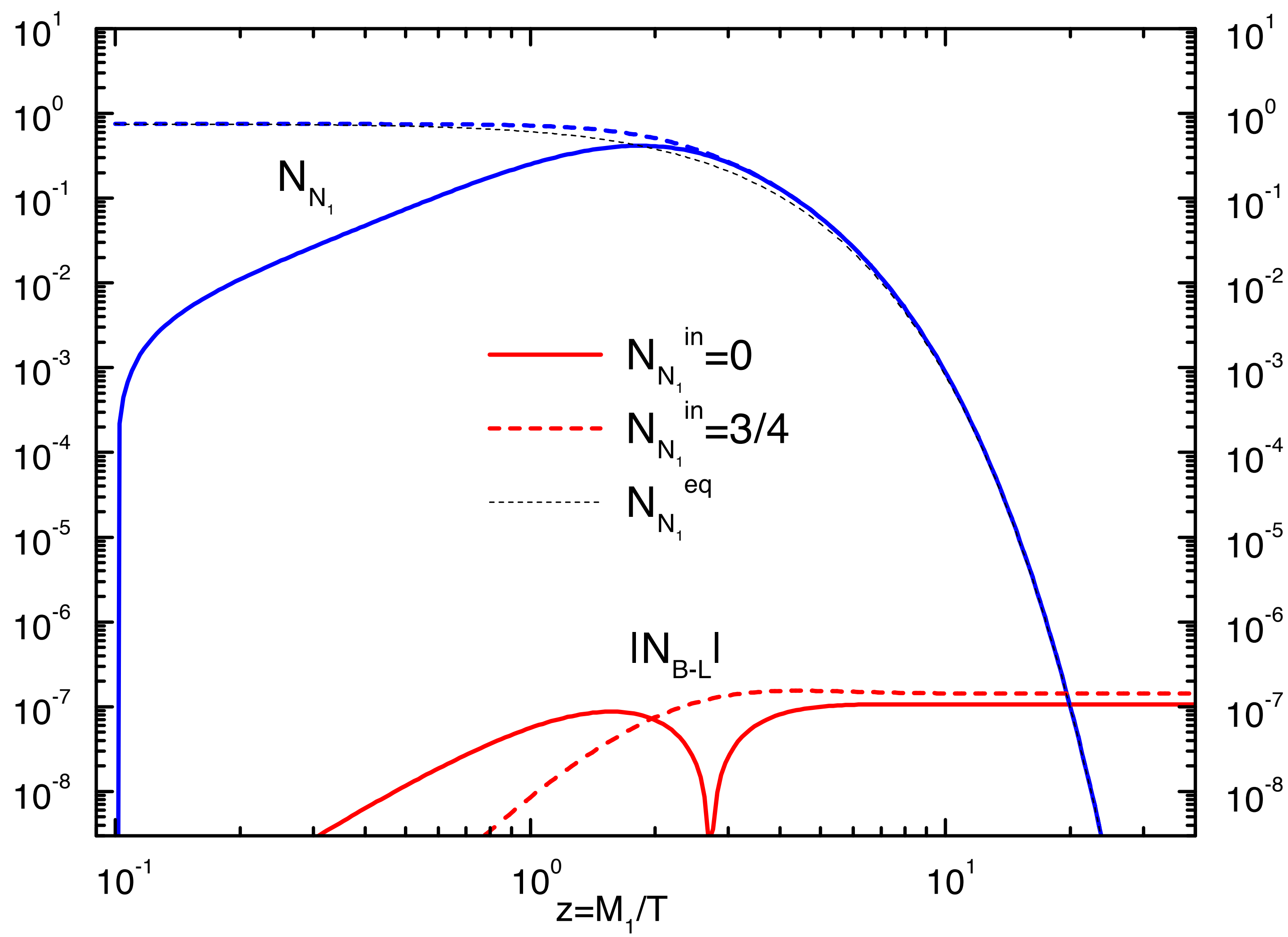


The evolution of the lepton asymmetry is described by the Boltzmann eq.

$$sHz\,\frac{dY_L}{dz} = \left(\frac{Y_{N_1}}{Y_{N_1}^{\rm eq}} - 1\right)\gamma_D\,\epsilon_{N_1} - \frac{Y_L}{Y_\ell^{\rm eq}}\left(\gamma_D + \gamma_{\Delta L=1} + \gamma_{\Delta L=2}\right)$$

$$Y_X \equiv \frac{n_X}{s} \qquad Y_L \equiv Y_\ell - Y_{\bar\ell} \qquad z \equiv \frac{M_1}{T}$$

Typical evolution:



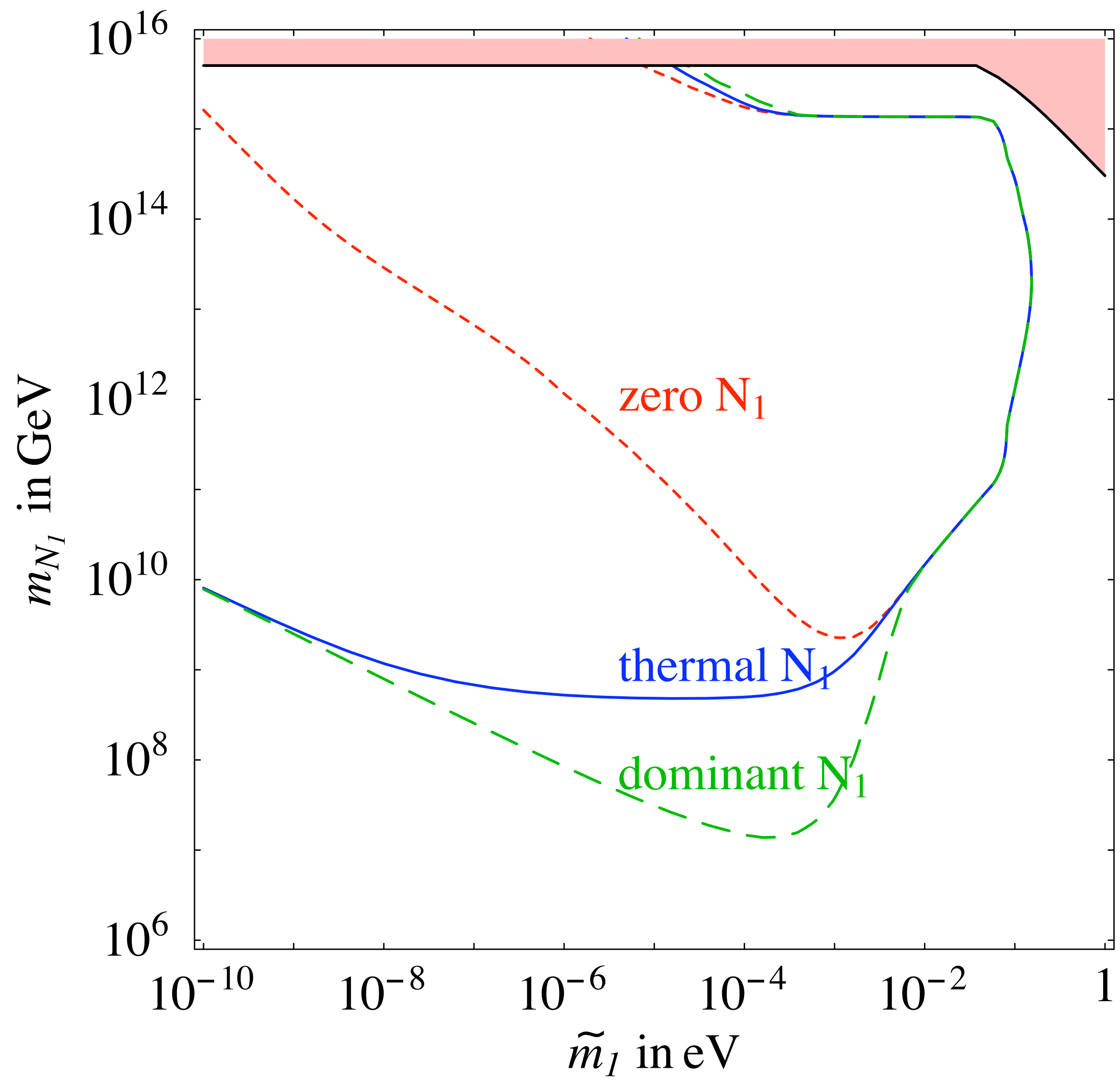
[Buchmüller, Di Bari, Plümacher '02]

Leptogenesis can explain the observed baryon asymmetry

region of successful leptogenesis in the $(\tilde{m}_1, M_1)$ plane

$$\tilde{m}_1 \equiv \frac{(YY^\dagger)_{11} v^2}{M_1}$$ controls washout

[Giudice, Notari, Raidal, Riotto, Strumia '03]



$\Rightarrow\ M_1 \geq (0.5 - 2.5) \times 10^9\,\mathrm{GeV}$ depending on the initial conditions

[Davidson, Ibarra '02]

A lot of theoretical progress on leptogenesis over the past 15 years:

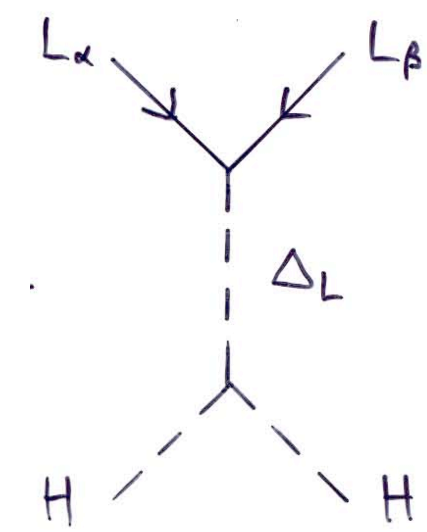
- refinement of the calculation of the generated baryon asymmetry in the standard scenario with RH neutrinos (finite temperature corrections, spectator processes, lepton flavour effects, quantum Boltzmann equations)

- alternative scenarios to the standard one, including low-scale scenarios such as the ARS mechanism (CP-violating oscillations of sterile neutrinos around the EW scale) [Akhmedov, Rubakov, Smirnov '98]

- attempts to relate leptogenesis to measurable parameters, in particular to CP violation in neutrino oscillations (no direct connection in general)

Scalar triplet leptogenesis

Alternative to heavy Majorana neutrinos: the SM neutrino masses may be generated by a heavy scalar (electroweak) triplet

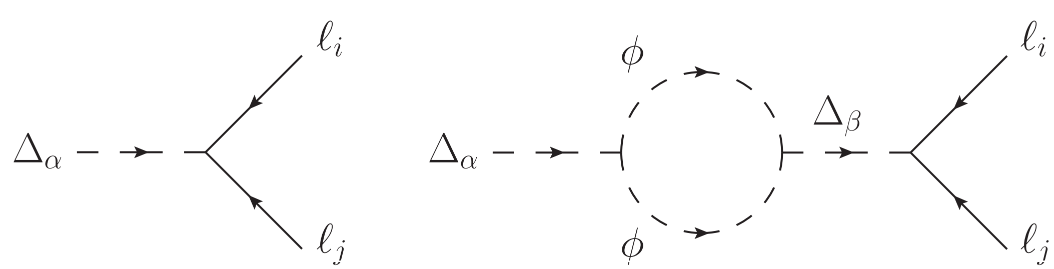


$$\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$$ electroweak triplet

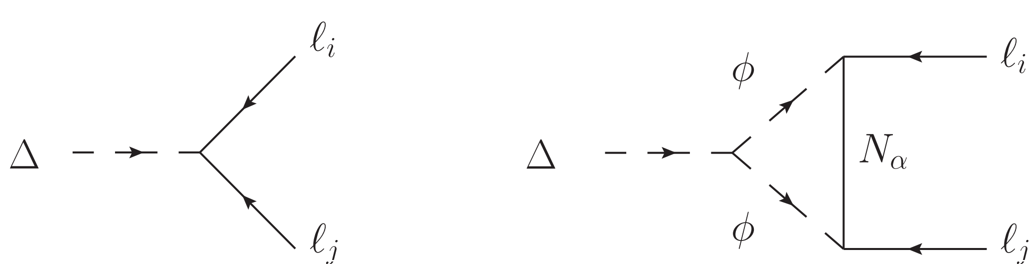
generates a neutrino mass $m_\nu = \dfrac{\mu \lambda_\ell}{2M_\Delta^2} v^2$

Also leads to leptogenesis if another heavy state couples to leptons

$\Rightarrow$ CP asymmetry in triplet decays [Ma, Sarkar '98 - Hambye, Senjanovic '03]



additional triplets



RH neutrinos

Lepton flavour effects in scalar triplet leptogenesis

The lepton asymmetry is the sum of the asymmetries stored in each lepton flavour (e, μ, τ) $\Rightarrow$ coupled evolution of the different flavour asymmetries

The proper description of flavour effects involves a 3x3 matrix in flavour space:

$(\Delta_\ell)_{\alpha\beta}$
- diagonal entries = flavour asymmetries $\Delta_{\ell_\alpha} \equiv Y_{\ell_\alpha} - Y_{\bar{\ell}_\alpha}$
- off-diagonal entries = quantum correlations between flavours

Boltzmann equation for $(\Delta_\ell)_{\alpha\beta}$:

$$sHz\frac{d(\Delta_\ell)_{\alpha\beta}}{dz} = \left(\frac{\Sigma_\Delta}{\Sigma_\Delta^{\rm eq}} - 1\right)\gamma_D\, \underbrace{\mathcal{E}_{\alpha\beta}}_{\text{CP-asymmetry matrix}} - \underbrace{\mathcal{W}^D_{\alpha\beta} - \mathcal{W}^{\ell H}_{\alpha\beta} - \mathcal{W}^{4\ell}_{\alpha\beta} - \mathcal{W}^{\ell\Delta}_{\alpha\beta}}_{\text{washout terms}}$$

All terms on the RHS of the Boltzmann equation for $(\Delta_\ell)_{\alpha\beta}$ transform covariantly under $\ell \to U\ell$:

$$\mathcal{M} \to U^* \mathcal{M} U^T \qquad \mathcal{M} = \{\mathcal{E}, \mathcal{W}^D, \mathcal{W}^{\ell H}, \mathcal{W}^{4\ell}, \mathcal{W}^{\ell\Delta}\}$$

Correlation between different flavour asymmetries play an important role in scalar triplet leptogenesis

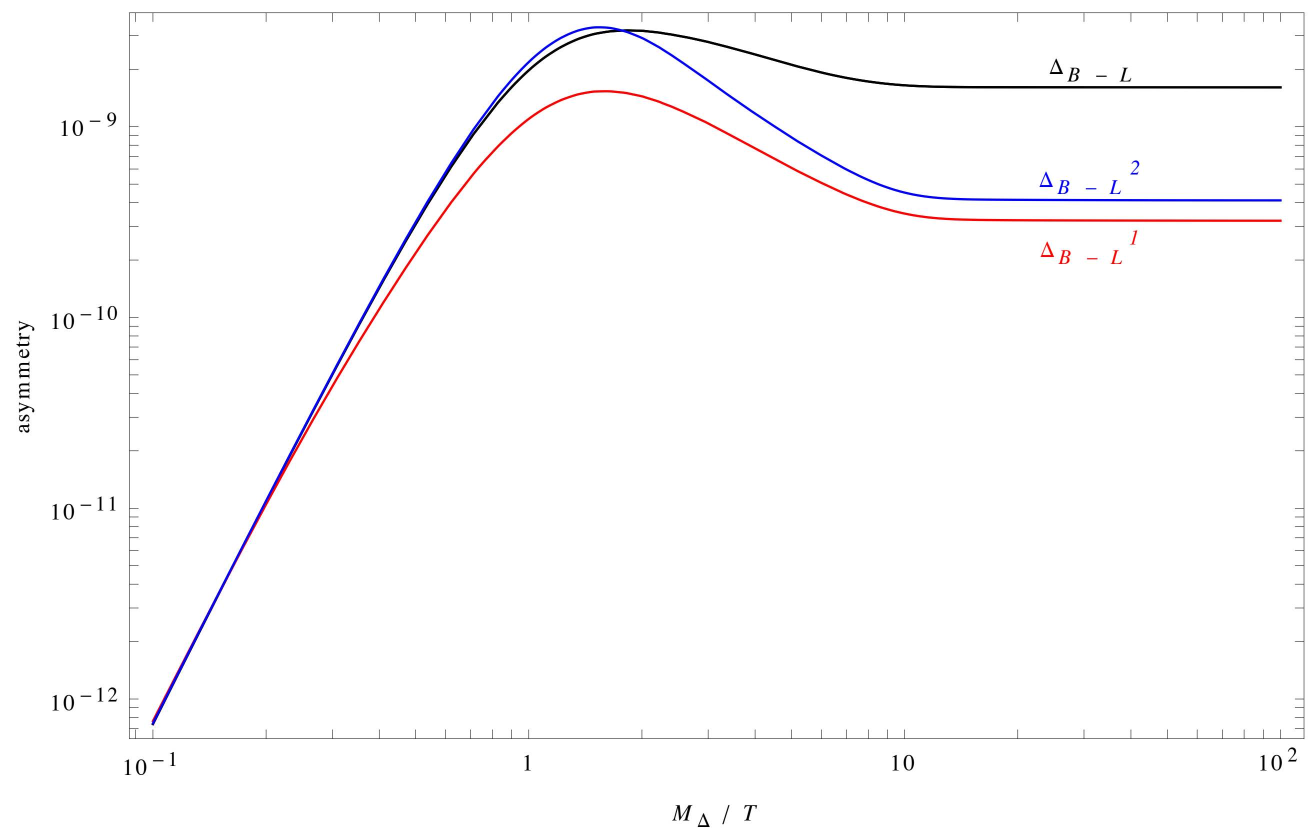
Generated baryon asymmetry computed in three different ways: flavour-covariant computation with the matrix of flavour asymmetries; Boltzmann equations for individual flavour asymmetries (results depend on the basis choice: neutrino vs charged lepton mass eigenstates)

matrix of flavour asymmetries

neutrino mass eigenstate basis

charged lepton eigenstate basis

$$(M_\Delta = 5 \times 10^{12}\,\mathrm{GeV})$$



[SL, Schmauch '15]

$m_\Delta = i m_\nu$ $\qquad\qquad$ $m_{\Delta i} \neq m_{\nu_i}$

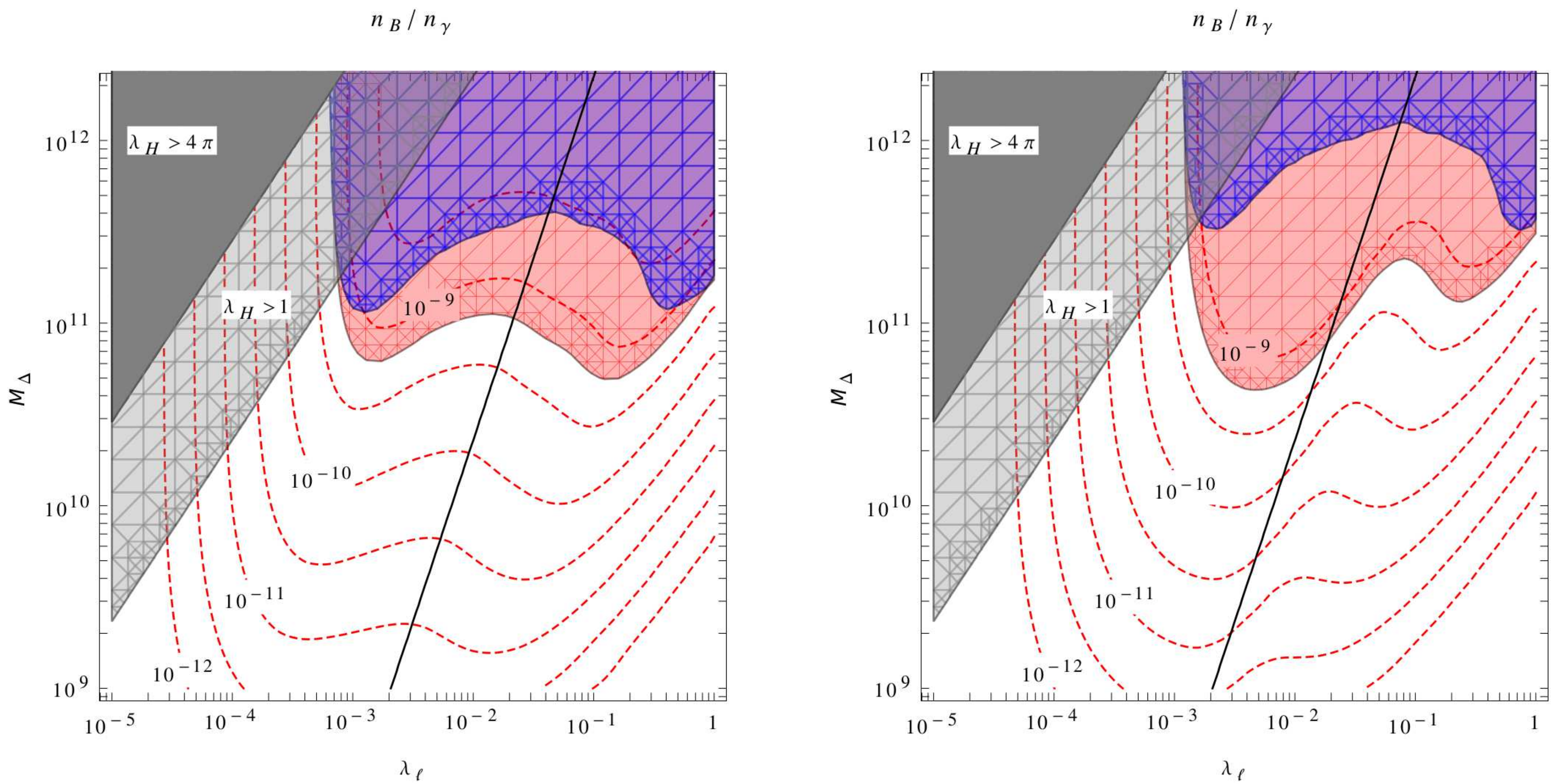


Figure 11: Isocurves of the baryon-to-photon ratio n_B/n_γ in the (λ_ℓ, M_Δ) plane obtained performing the full computation, assuming Ansatz 1 (left panel) or Ansatz 2 with $(x, y) = (0.05, 0.95)$ (right panel). The coloured regions indicate where the observed baryon asymmetry can be reproduced in the full computation (light red shading) or in the single flavour approximation with spectator processes neglected (dark blue shading). The solid black line corresponds to $B_\ell = B_H$. Also shown are the regions where λ_H is greater than 1 or 4π.

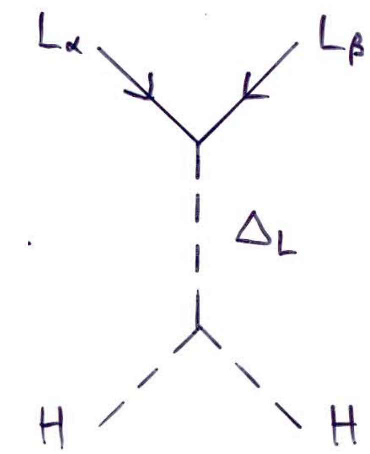
$M_\Delta > 4.4 \times 10^{10}\,\mathrm{GeV}$ $\qquad$ $(1.2 \times 10^{11}\,\mathrm{GeV}$ without flavour effects$)$

[SL, Schmauch '15]

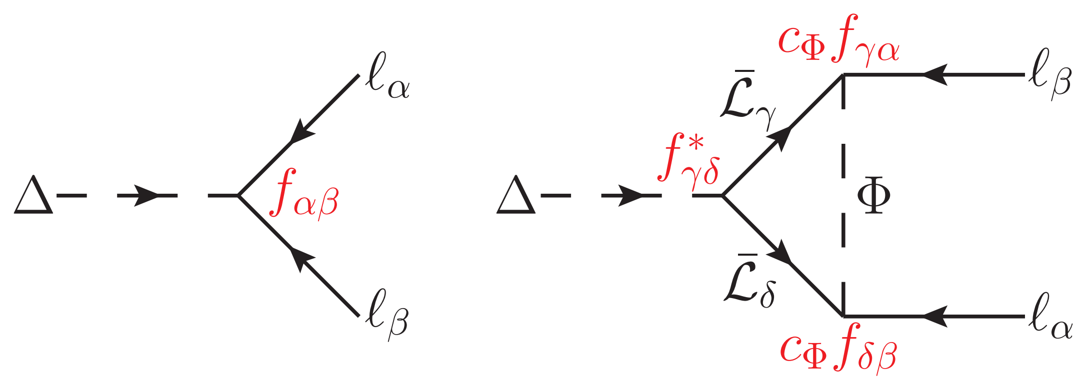
A predictive scheme for scalar triplet leptogenesis

Non-standard SO(10) model that leads to pure type II seesaw mechanism $\Rightarrow$ neutrinos masses proportional to triplet couplings to leptons:

$$(M_\nu)_{\alpha\beta} = \frac{\lambda_H f_{\alpha\beta}}{2M_\Delta}\, v^2$$



This model also contains heavy (non-standard) leptons that induce a CP asymmetry in the heavy triplet decays



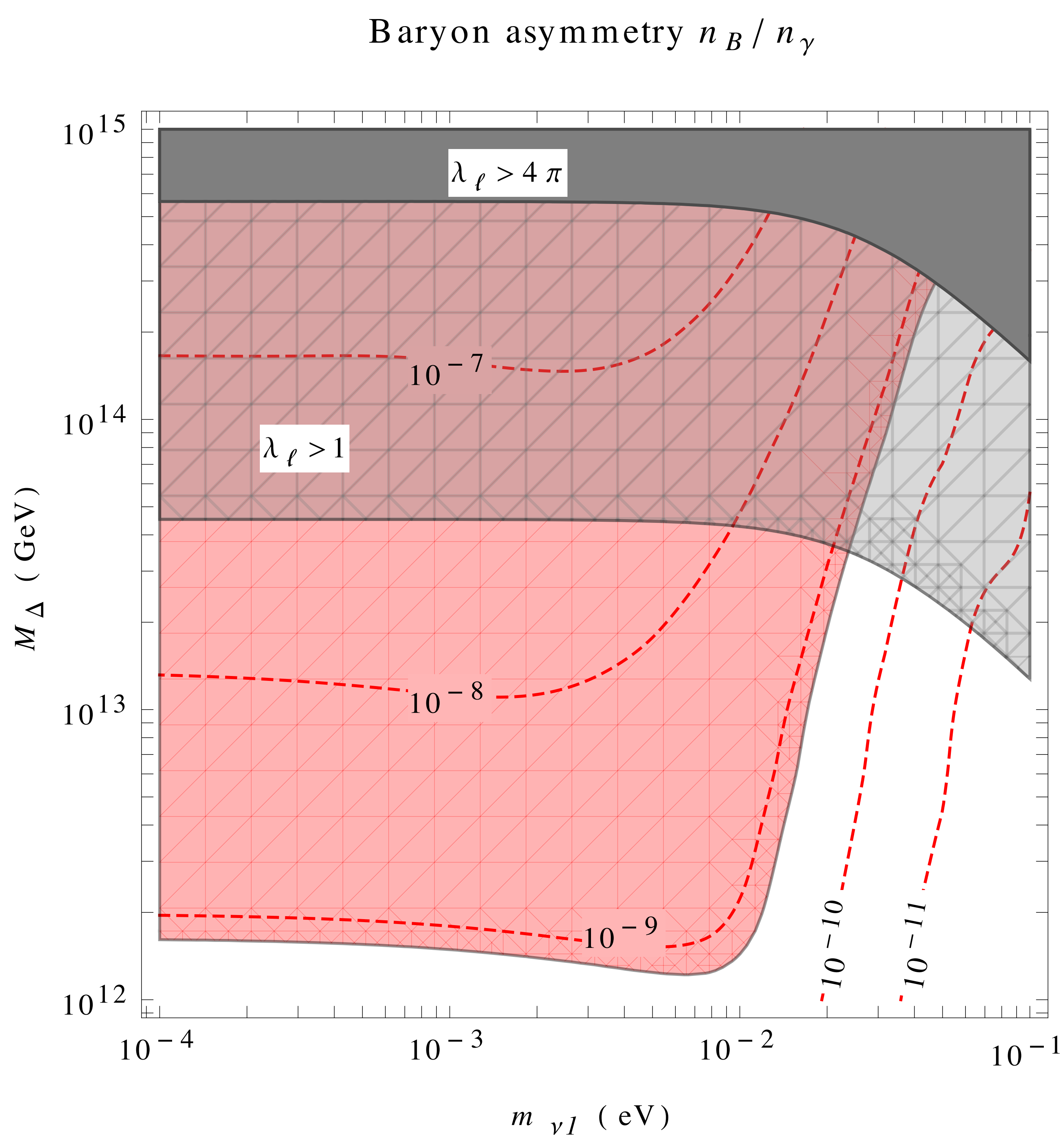
$$\Phi = S, T \in 54$$

The SM and heavy lepton couplings are related by the SO(10) gauge symmetry, implying that the CP asymmetry in triplet decays can be expressed in terms of (measurable) neutrino parameters

→ important difference with other triplet leptogenesis scenarios

[Frigerio, Hosteins, SL, Romanino ’08]

Parameter space allowed by successful leptogenesis: normal hierarchy



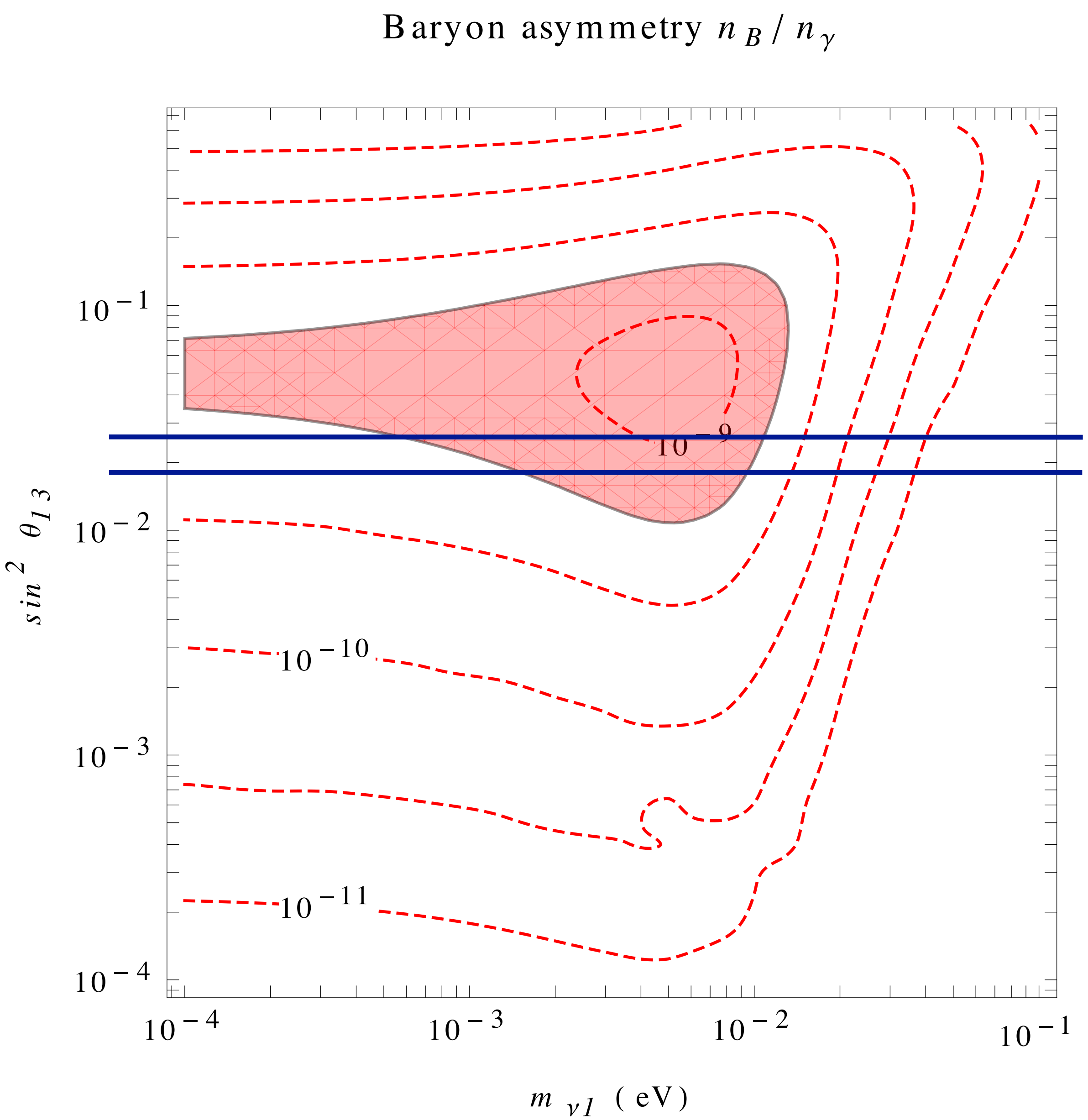
$\lambda_H = 0.2$

→ excludes a quasi-degenerate spectrum

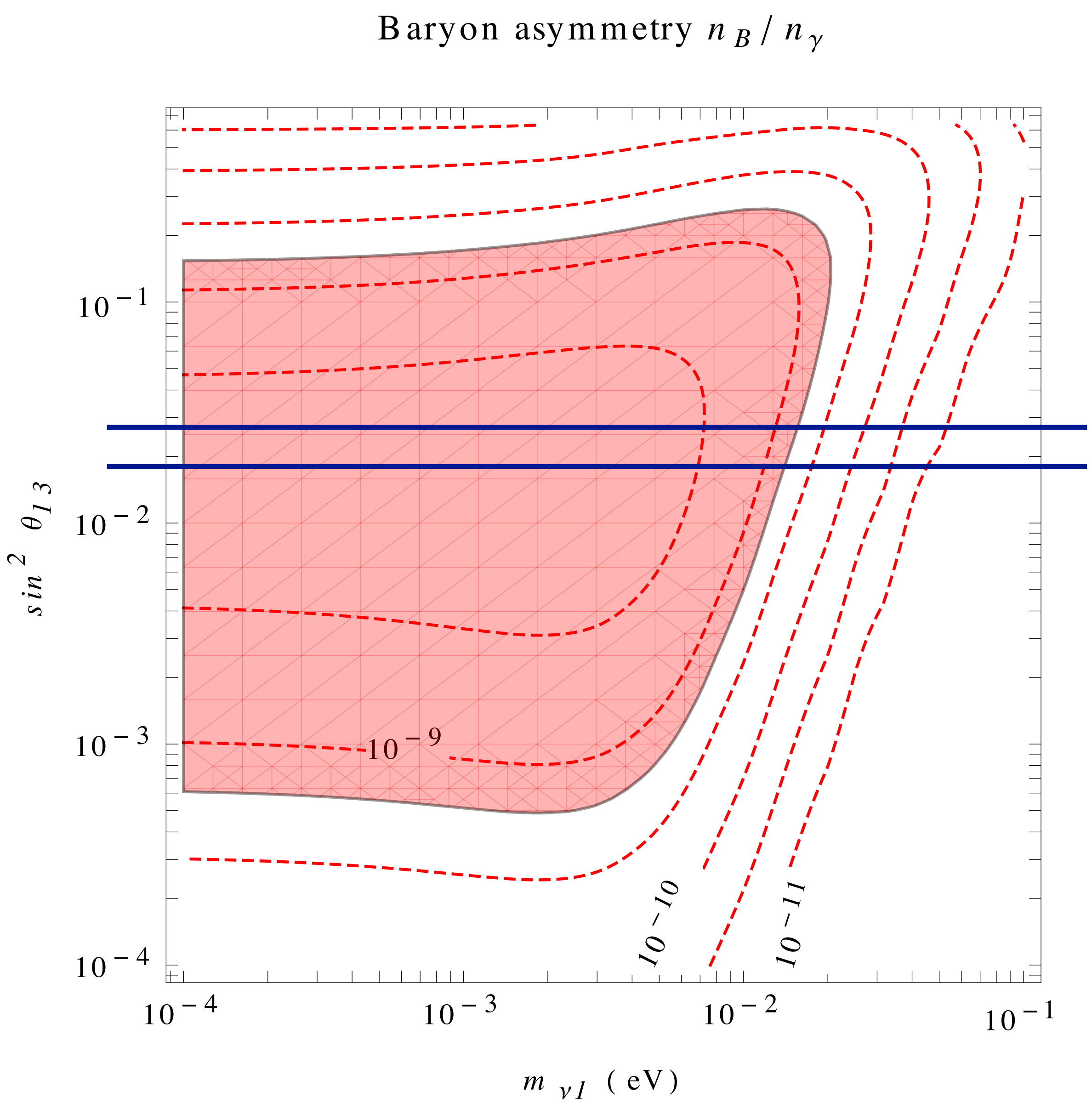
[SL, Schmauch, en préparation]

θ_{13} dependence

$$M_\Delta = 1.5 \times 10^{12}\,\mathrm{GeV}$$



$$M_\Delta = 5 \times 10^{12}\,\mathrm{GeV}$$

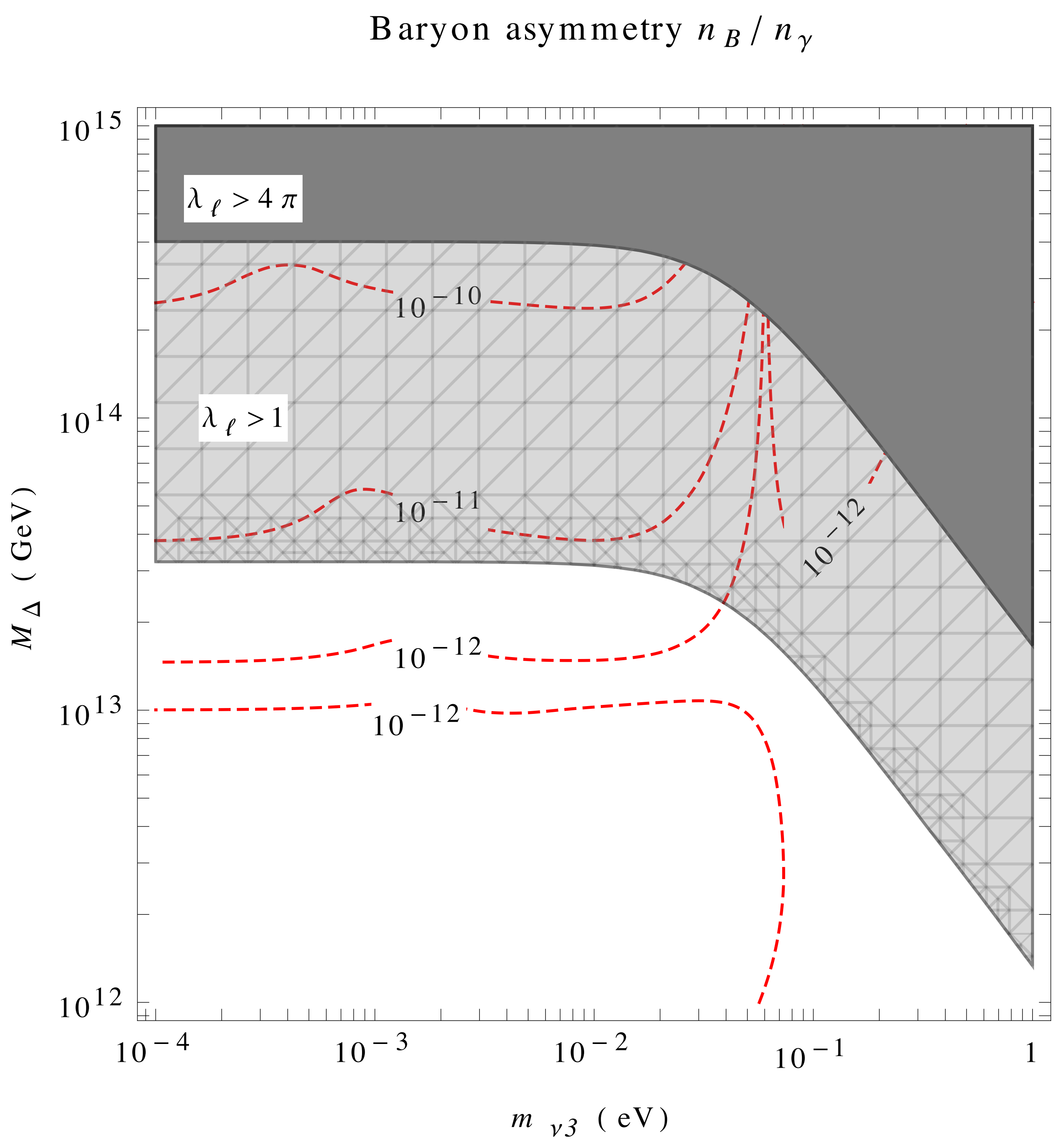


(3σ range)

$$\lambda_H = 0.2$$

[SL, Schmauch, en préparation]

Inverted hierarchy case



$\lambda_H = 0.2$

→ inverted hierarchy disfavoured

[SL, Schmauch, en préparation]

Conclusions

The observed baryon asymmetry of the Universe cannot be generated by standard electroweak baryogenesis, the only available mechanism within the Standard Model.

To explain its origin, new physics beyond the Standard Model must be invoked. Leptogenesis, which relates neutrino masses to the baryon asymmetry, is a very interesting possibility.

Although difficult to test, leptogenesis would gain support from:

- observation of neutrinoless double beta decay: $(A,Z) \rightarrow (A,Z+2)\ e^- \ e^-$ [proof of the Majorana nature of neutrinos - necessary condition]
- observation of CP violation in the lepton sector, e.g. in neutrino oscillations [neither sufficient nor necessary though]
- non-observation of other light scalars (which are present in many non-standard electroweak baryogenesis scenarios) than the Higgs boson at high-energy colliders