Baryogenesis from the Weak Scale to the GUT Scale

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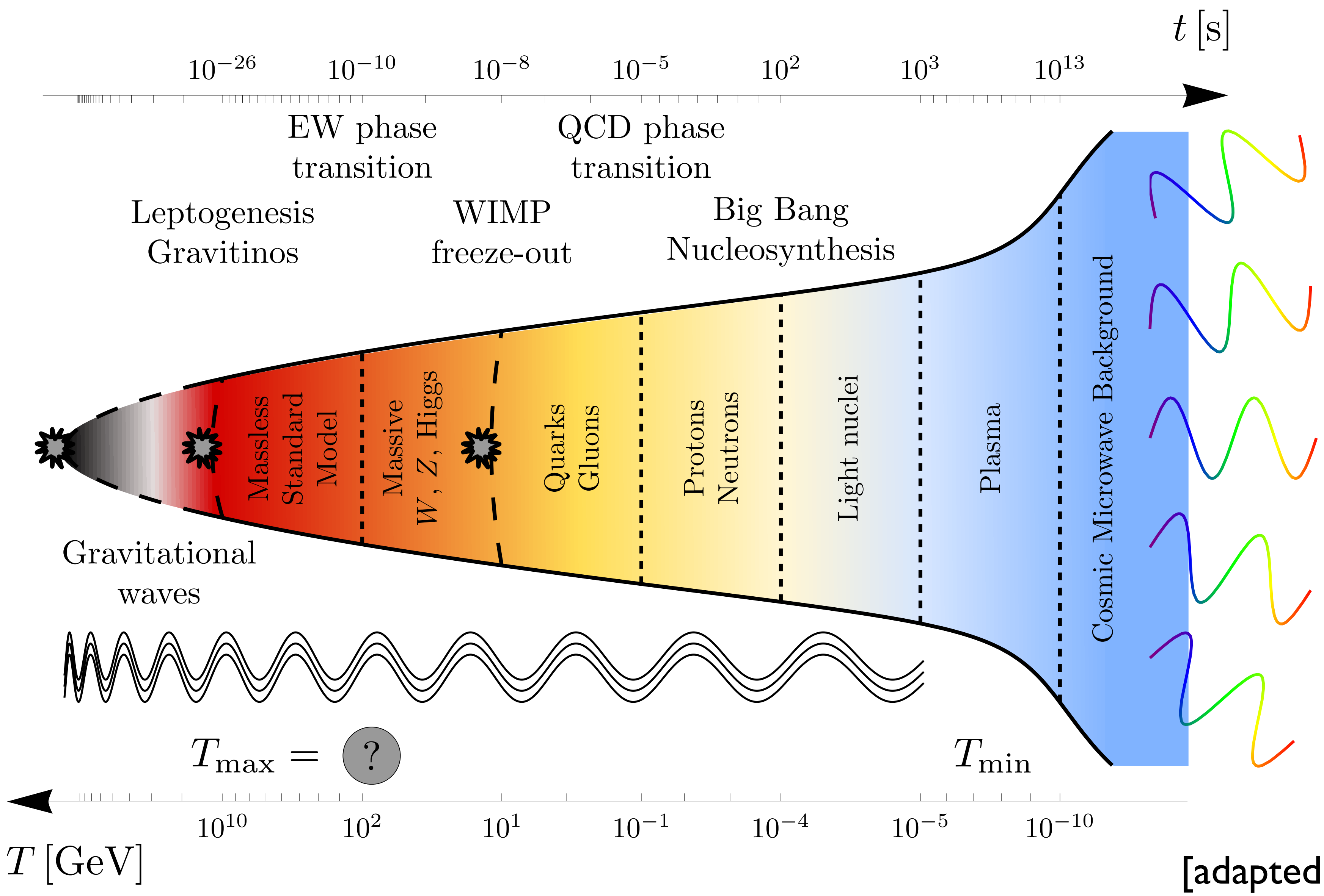
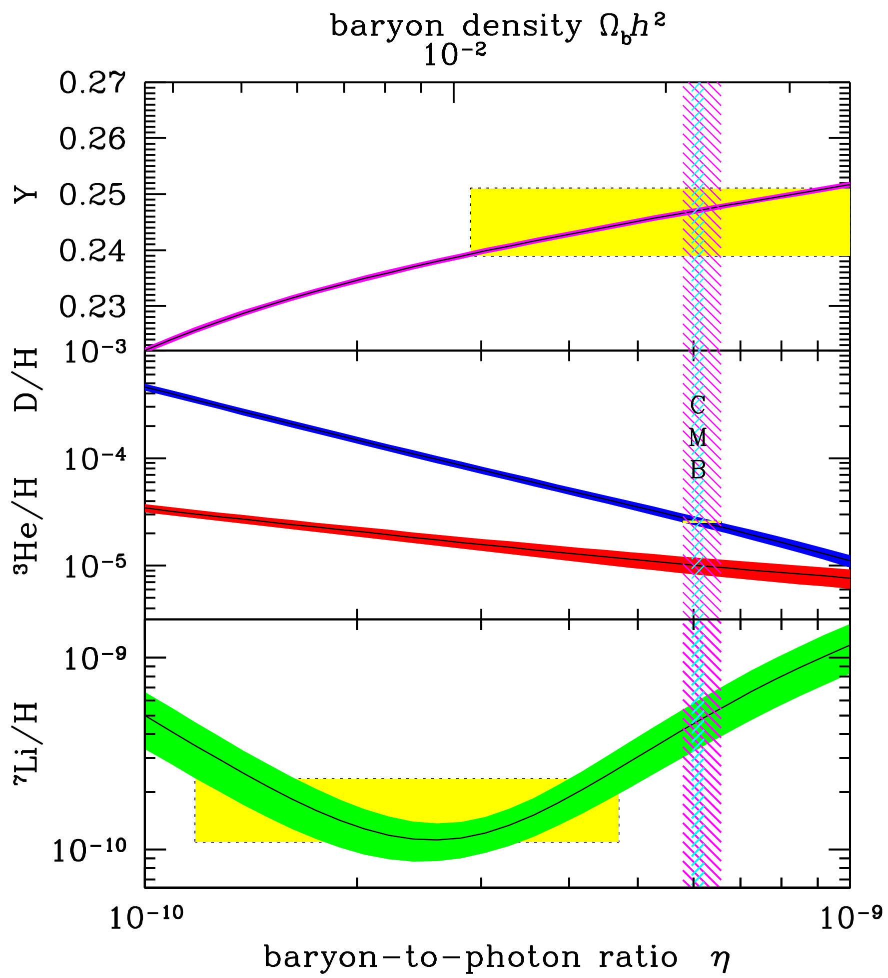
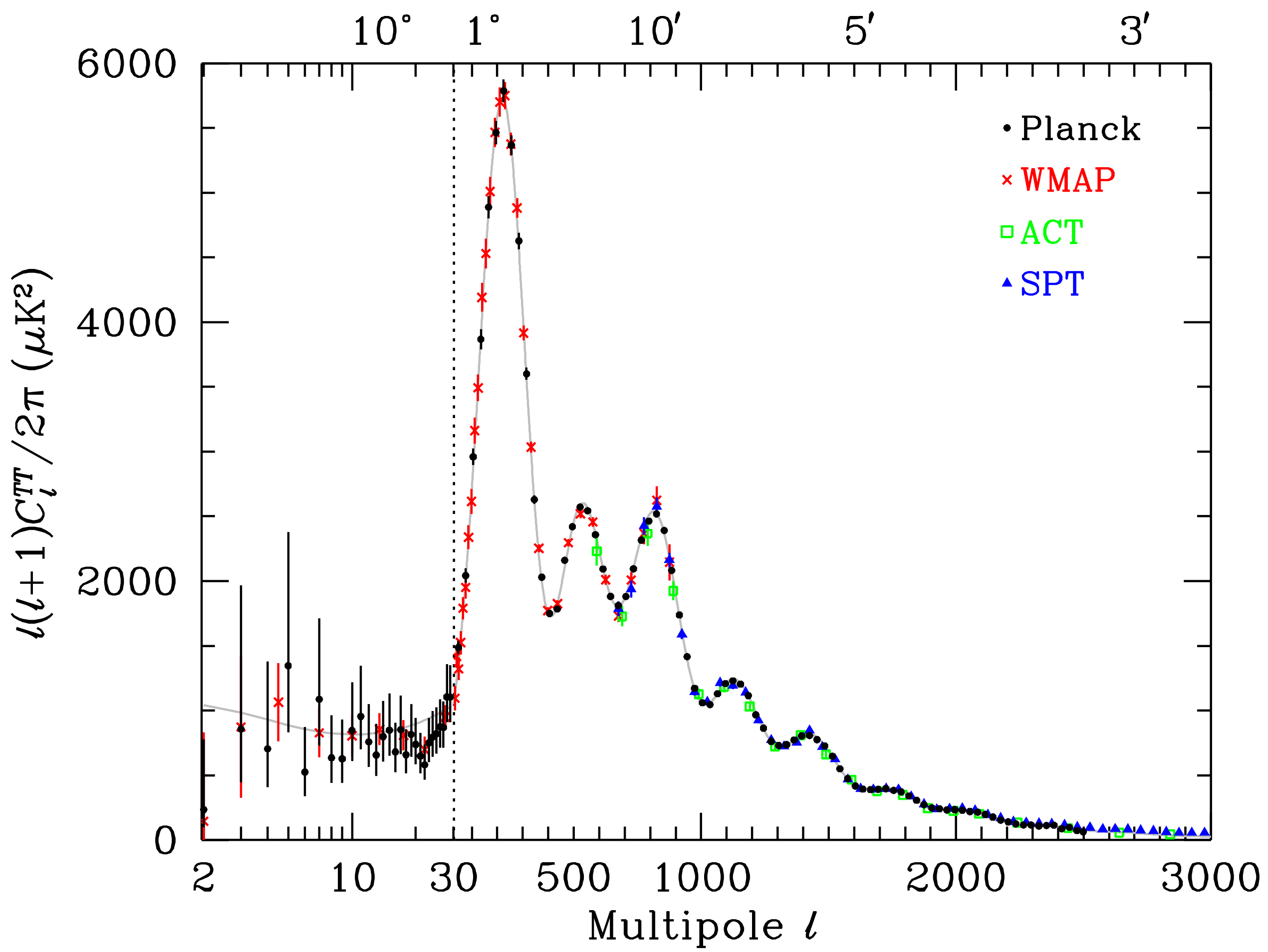


[adapted from Schmitz '12]

- Beautiful connection between particle physics and early universe
- Different stages of evolution: inflation, matter-antimatter asymmetry, dark matter, dark energy, ...
- How are these phases related to extensions of the Standard Model?

Matter-antimatter asymmetry





Quantum field theory predicts existence of antimatter; astrophysics: no antimatter in the universe; abundance of matter:

$$\frac{n_B}{n_\gamma} = \{0.03\ (\text{visible});\ 5.8 - 6.6\ (\text{BBN});\ 6.09 \pm 0.06\ (\text{CMB})\} \times 10^{-10}$$

Independent measurements at very different times!

Outline

- Basics
- Electroweak baryogenesis
- Leptogenesis
- Other models

Baryogenesis

What is the origin of matter and why is the baryon-to-photon ratio so small,

$$\eta_B = \frac{n_B}{n_\gamma} = (6.09 \pm 0.06) \times 10^{-10}$$

? ? ? ?

Initial condition after inflation: B=0, present value has to be explained

Key references

A. D. Sakharov, JETP Lett. 5 (1967) 24
G. 't Hooft, Phys. Rev. Lett. 37 (1976) 8
V. A. Kuzmin, V. A. Rubakov and M. E. Shaposhnikov, Phys. Lett. B 155 (1985) 36
J. A. Harvey and M. S. Turner, Phys. Rev. D 42 (1990) 3344

Violation of *CP* invariance, *C* asymmetry, and baryon asymmetry of the universe

A. D. Sakharov

(Submitted 23 September 1966)
Pis'ma Zh. Eksp. Teor. Fiz. **5**, 32–35 (1967) [JETP Lett. **5**, 24–27 (1967).
Also S7, pp. 85–88]

Usp. Fiz. Nauk **161**, 61–64 (May 1991)

Из эффекта С. Окубо
При большой температуре
Для Вселенной сшита шуба
По ее кривой фигуре

Literal translation: *Out of S. Okubo's effect*
At high temperature
A fur coat is sewed for the Universe
Shaped for its crooked figure.

The theory of the expanding universe, which presupposes a superdense initial state of matter, apparently excludes the possibility of macroscopic separation of matter from antimatter; it must therefore be assumed that there are no antimatter bodies in nature, i.e., the universe is asymmetrical with respect to the number of particles and antiparticles (*C* asymmetry). In particular, the absence of antibaryons and the proposed absence of baryonic neutrinos implies a nonzero baryon charge (baryonic asymmetry). We wish to point out a possible explanation of *C* asymmetry in the hot model of the expanding universe (see Ref. 1) by making use of effects of *CP* invariance violation (see Ref. 2). To explain baryon asymmetry, we propose in addition an approximate character for the baryon conservation law.

We assume that the baryon and muon conservation laws are not absolute and should be unified into a "combined" baryon-muon charge $n_c = 3n_B - n_\mu$. We put

for antimuons μ_+ and $\nu_\mu = \mu_0$: $n_\mu = -1$, $n_c = +1$.

for muons μ_- and $\nu_\mu = \mu_0$: $n_\mu = +1$, $n_c = -1$.

for baryons P and N: $n_B = +1$, $n_c = +3$.

for antibaryons $\bar{P}$ and $\bar{N}$: $n_B = -1$, $n_c = -3$.

negative in the excess of μ neutrinos over μ antineutrinos).

According to our hypothesis, the occurrence of *C* asymmetry is the consequence of violation of *CP* invariance in the nonstationary expansion of the hot universe during the superdense stage, as manifest in the difference between the partial probabilities of the charge-conjugate reactions. This effect has not yet been observed experimentally, but its existence is theoretically undisputed (the first concrete example, Σ_+ and Σ_- decay, was pointed out by S. Okubo as early as 1958) and should, in our opinion, have much cosmological significance.

We assume that the asymmetry has occurred in an earlier stage of the expansion, in which the particle, energy, and entropy densities, the Hubble constant, and the temperatures were of the order of unity in gravitational units (in conventional units the particle and energy densities were $n \sim 10^{98}$ cm^{-3} and $\varepsilon \sim 10^{114}$ erg/cm^3).

M. A. Markov (see Ref. 3) proposed that during the early stages there existed particles with maximum mass of the order of one gravitational unit ($M_0 = 2\times10^{-5}$ g in ordinary units), and called them maximons. The presence of such particles leads unavoidably to strong violation of thermodynamic equilibrium. We can visualize that neutral spinless maximons (or photons) are produced at $t < 0$ from contracting matter having an excess of antiquarks, that they

...proton lifetime
~ 10^50 yr ...

Discovery of CPV in K-decays in 1964 [Christenson, Cronin, Fitch, Turlay]

Sakharov's conditions

Necessary conditions for generating a matter-antimatter asymmetry:

- baryon number violation
- C and CP violation
- deviation from thermal equilibrium

Check of 3rd condition:

$$\begin{aligned}\langle B\rangle = \mathrm{Tr}(e^{-\beta H}B) &= \mathrm{Tr}(\Theta\Theta^{-1}e^{-\beta H}B)\\ &= -\mathrm{Tr}(e^{-\beta H}B)\,, \quad \Theta = CPT\end{aligned}$$

Alternative mechanisms: dynamics of scalar fields, e.g. Affleck-Dine baryogenesis, heavy moduli decay, ...

Sphaleron processes

Baryon and lepton number not conserved in Standard Model,

$$J_\mu^B = \frac{1}{3} \sum_{generations} \left(\overline{q_L}\gamma_\mu q_L + \overline{u_R}\gamma_\mu u_R + \overline{d_R}\gamma_\mu d_R\right) \ ,$$

$$J_\mu^L = \sum_{generations} \left(\overline{l_L}\gamma_\mu l_L + \overline{e_R}\gamma_\mu e_R\right) \ ,$$

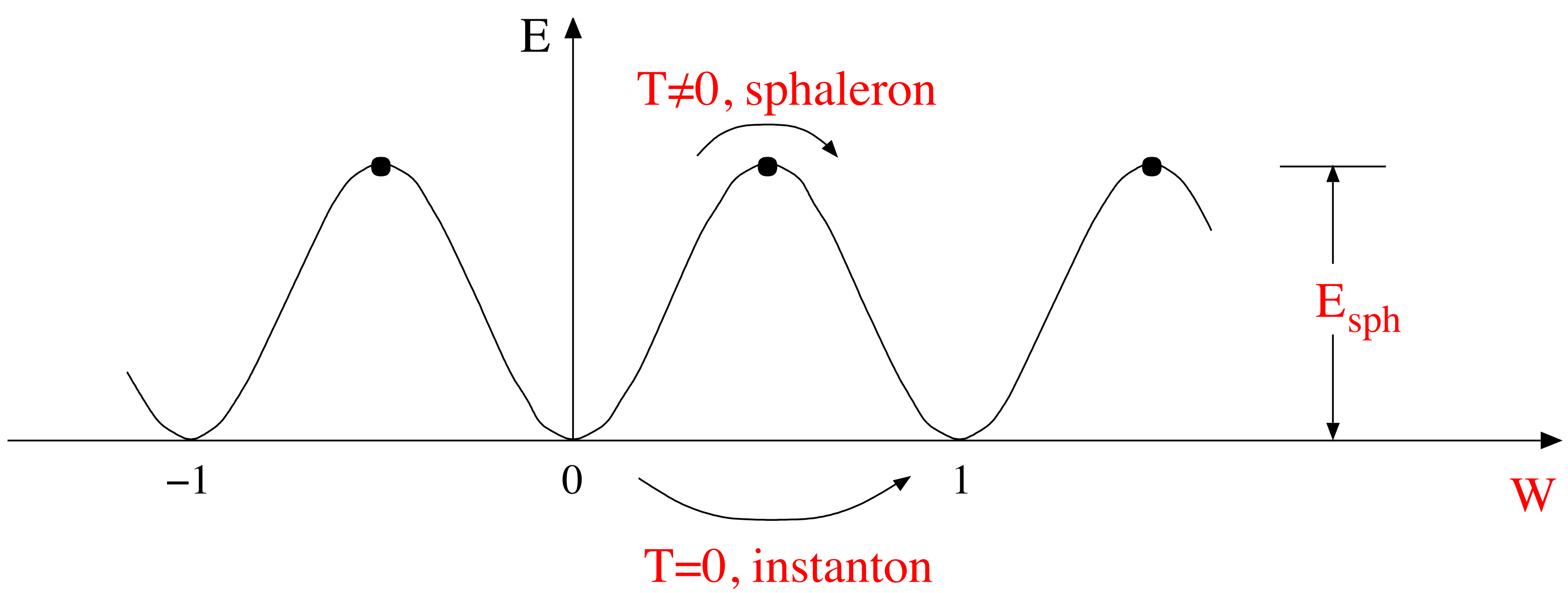
divergence given by triangle anomaly,

$$\begin{aligned} \partial^\mu J_\mu^B &= \partial^\mu J_\mu^L \\ &= \frac{N_f}{32\pi^2}\left(-g^2 W_{\mu\nu}^I \widetilde{W}^{I\mu\nu} + g'^2 B_{\mu\nu}\widetilde{B}^{\mu\nu}\right) \ ; \end{aligned}$$

N_f: number of generations; W_μ^I, B_μ: $SU(2)$ and $U(1)$ gauge fields, gauge couplings g and g'.

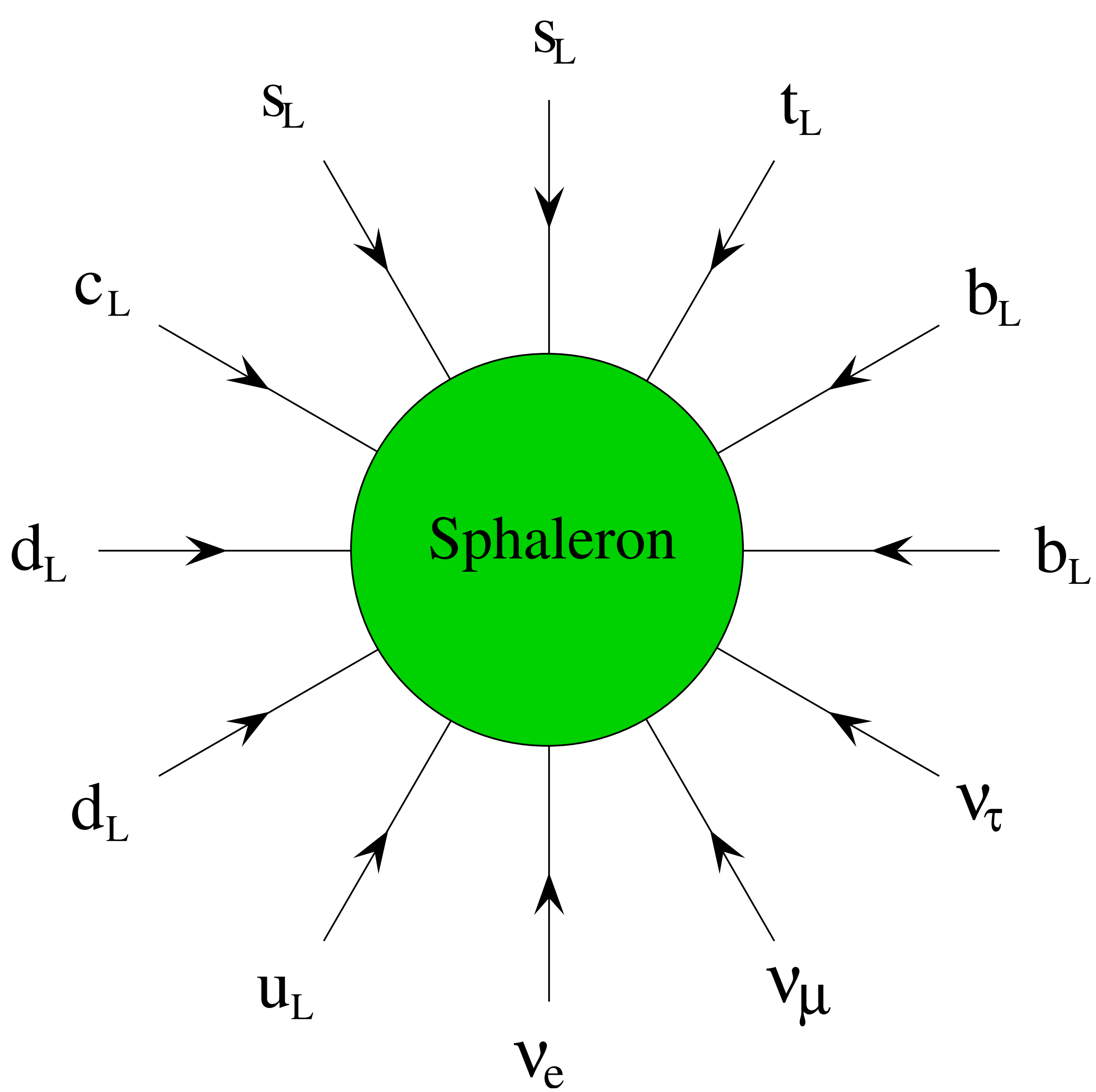
Change in baryon and lepton number related to the change in topological charge the gauge field,

$$B(t_f) - B(t_i) = \int_{t_i}^{t_f} dt \int d^3x \partial^\mu J_\mu^B$$
$$= N_f [N_{cs}(t_f) - N_{cs}(t_i)] \ , \quad \text{with}$$
$$N_{cs}(t) = \frac{g^3}{96\pi^2} \int d^3x \epsilon_{ijk} \epsilon^{IJK} W^{Ii} W^{Jj} W^{Kk}$$



Non-abelian gauge theory: $\Delta N_{cs} = \pm 1, \pm 2, \ldots$. Jumps in Chern-Simons associated with changes of baryon and lepton number,

$$\Delta B = \Delta L = N_f \Delta N_{cs} \ .$$



In SM, effective 12-fermion interaction

$$O_{B+L} = \prod_i (q_{Li} q_{Li} q_{Li} l_{Li}) \ , \quad \Delta B = \Delta L = 3$$

$$u^c + d^c + c^c \to d + 2s + 2b + t + \nu_e + \nu_\mu + \nu_\tau$$

Sphaleron rate crucially depends on temperature, only relevant in early universe:

$$\textit{zero temperature:} \quad \Gamma \sim e^{-S_{\text{inst}}} = e^{-\frac{4\pi}{\alpha}} = \mathcal{O}\left(10^{-165}\right)$$

$$\textit{EW phase transition:} \quad \frac{\Gamma_{B+L}}{V} = \kappa \frac{M_W^7}{(\alpha T)^3} \exp\left(-\beta E_{\text{sph}}(T)\right),$$

$$\text{with} \quad E_{\text{sph}}(T) \simeq \frac{8\pi}{g} v(T)$$

$$\textit{high temperature phase:} \quad \frac{\Gamma_{B+L}}{V} = \kappa_s \alpha^5 T^4 \sim 10^{-6}$$

"consensus" among theorists: B+L violating processes in thermal equilibrium in temperature range:

$$T_{EW} \sim 100 \text{ GeV} < T < T_{sph} \sim 10^{12} \text{ GeV}$$

... but no direct experimental evidence for instanton or sphaleron processes ...

Chemical potentials

In SM, with Higgs doublet H and N_f generations, there are $5N_f + 1$ chemical potentials (q_i, ℓ_i, u_i, d_i, e_i); for non-interacting gas of massless particles μ_i give asymmetries in particle and antiparticle number densities,

$$n_i - \overline{n}_i = \frac{gT^3}{6} \begin{cases} \beta\mu_i + \mathcal{O}\left((\beta\mu_i)^3\right) \ , & \text{fermions} \\ 2\beta\mu_i + \mathcal{O}\left((\beta\mu_i)^3\right) \ , & \text{bosons} \end{cases}$$

Relations between the various chemical potentials:

$SU(2)$ *instantons:*

$$\sum_i (3\mu_{qi} + \mu_{li}) = 0$$

QCD *instantons:*

$$\sum_i (2\mu_{qi} - \mu_{ui} - \mu_{di}) = 0$$

vanishing hypercharge of plasma:

$$\sum_i \left(\mu_{qi} + 2\mu_{ui} - \mu_{di} - \mu_{li} - \mu_{ei} + \frac{2}{N_f}\mu_H \right) = 0$$

Yukawa interactions:

$$\mu_{qi} - \mu_H - \mu_{dj} = 0 \;, \quad \mu_{qi} + \mu_H - \mu_{uj} = 0 \;,$$
$$\mu_{li} - \mu_H - \mu_{ej} = 0$$

Relations determine B and L in terms of B-L :

$$B = \sum_i (2\mu_{qi} + \mu_{ui} + \mu_{di}) \;, \quad L = \sum_i (2\mu_{li} + \mu_{ei})$$

$$B = c_s(B - L)\,, \quad L = (c_s - 1)(B - L)\,, \quad c_s = \frac{8N_f + 4}{22N_f + 13}$$

Electroweak baryogenesis and leptogenesis fundamentally different!
In EWBG B-L conserved, generation of B in strong phase transition;
in LG generation of B from initial generation of B-L (then unaffected by sphaleron processes)

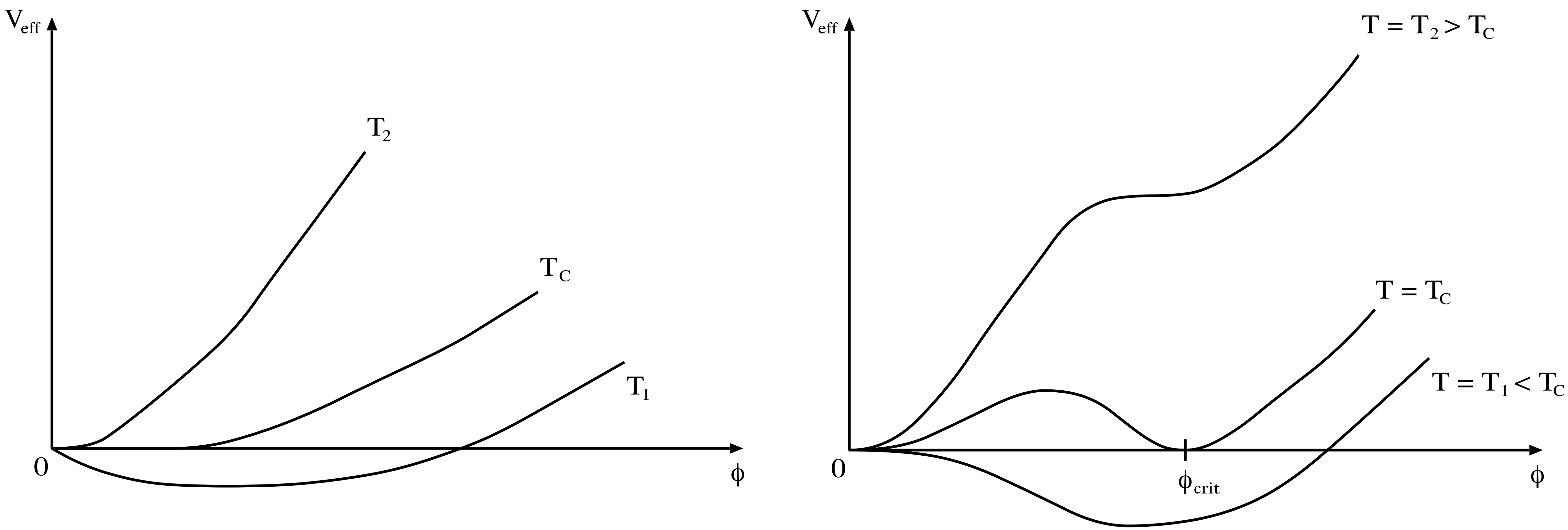
I. Electroweak Baryogenesis

Key references

D. A. Kirzhnits and A. D. Linde, Phys. Lett. B 42 (1972) 471
A. G. Cohen, D. B. Kaplan and A. E. Nelson, Phys. Lett. B 336 (1994) 41

Reviews

W. Bernreuther, Lect. Notes Phys. 591 (2002) 237
D. E. Morrissey and M. J. Ramsey-Musolf, New J. Phys. 14 (2012) 125003
T. Konstandin, Physics - Uspekhi 56 (8) 747 (2013)



2nd order vs 1st order (electroweak) phase transition, as universe cools down. What determines the shape of the effective potential? How does the phasetransition proceed in an expanding universe? How can the complicated nonequilibrium process be calculated, where all masses are generated?

Finite-temperature effective potential

Massive scalar field:

$$S_\beta = \int_\beta \left(\frac{1}{2}(\partial_\tau \phi)^2 + \frac{1}{2}(\partial_i \phi)^2 + V(\phi) \right)$$

$$V(\phi) = \frac{1}{2}\mu^2 + \frac{\lambda}{4}\phi^4 , \quad \int_\beta = \int_0^\beta d\tau \int d^3x , \quad \beta = \frac{1}{T}$$

Euclidean field theory with finite time range β; add source term, calculate free energy (constant source, volume Ω):

$$Z_\beta[j] = \int_\beta D\phi \exp\left(-S_\beta[\phi] - \int_\beta j\phi\right) = \exp\left(-\beta\Omega W_\beta(j)\right),$$

$$\frac{\partial W_\beta}{\partial j} = \frac{1}{\beta\Omega} \langle \int_\beta \phi(x) \rangle \equiv \varphi$$

Legendre transformation yields effective potential:

$$V_\beta(\varphi) = W_\beta(j) - \varphi j\,, \quad j = -\frac{\partial V_\beta}{\partial \phi}$$

explicit calculation, high temperature expansion:

$$V_\beta(\varphi) = V_{T=0}(\varphi) - \frac{\pi^2}{90}T^4 + \frac{1}{24}m^2(\varphi)T^2 - \frac{1}{12\pi}m^3(\varphi)T + \ldots$$

$$m^2(\varphi) = m^2 + 3\lambda\varphi^2\,, \quad \frac{m(\varphi)}{T} \ll 1$$

$$= \frac{1}{2}(m^2 + \frac{\lambda}{4}T^2)\varphi^2 + \frac{\lambda}{4}\varphi^2 + \ldots$$

2nd term is free energy of massless boson; thermal bath generates "thermal mass" of boson; usefull concept to understand some effects in thermal field theory qualitatively, but different from kinematic mass; in gauge theories problem of gauge invariance ...

Higgs model & symmetry breaking

In (Abelian) Higgs symmetry "broken" in ground state:

$$S_\beta = \int_\beta \left((D_\mu \phi)^* D_\mu \phi + \mu^2 |\phi|^2 + \lambda |\phi|^4 \right) \;,$$

$$D_\mu = \partial_\mu + igA_\mu \,, \quad \mu^2 < 0 \,, \quad \mathrm{Re}\ \phi_0 = \left(-\mu^2/\lambda\right)^{1/2} \equiv \varphi_0/\sqrt{2} \,,$$

$$m_A = g\varphi_0 \,, \quad m_H = \sqrt{2\lambda}\, \varphi_0$$

finite-temperature potential (with "barrier temperature", where the barrier dissappears):

$$V_\beta(\varphi) = \frac{a}{2}(T^2 - T_b^2)\varphi^2 - \frac{b}{3} T\varphi^3 + \frac{\lambda}{4}\varphi^4 + \ldots$$

$$\left.\frac{\partial^2 V_\beta}{\partial^2 \varphi}\right|_{\varphi=0} = 0 \;:\; T_b^2 = -\frac{\mu^2}{a} \,, \quad a = \frac{3g^2}{16} + \frac{\lambda}{2}$$

Note: potential not convex, even complex! (interpretation -> E. Weinberg)

Departure from thermal equilibrium: cooling below critical temperature, then jump of Higgs vev:

$$V_{\beta_c}(\varphi_c) = V_{\beta_c}(0) \ : \ \frac{T_c^2 - T_b^2}{T_c^2} \simeq \frac{b^2}{a\lambda} > 0 \,,$$
$$\frac{\varphi_c}{T_c} = \frac{2b}{3\lambda}$$

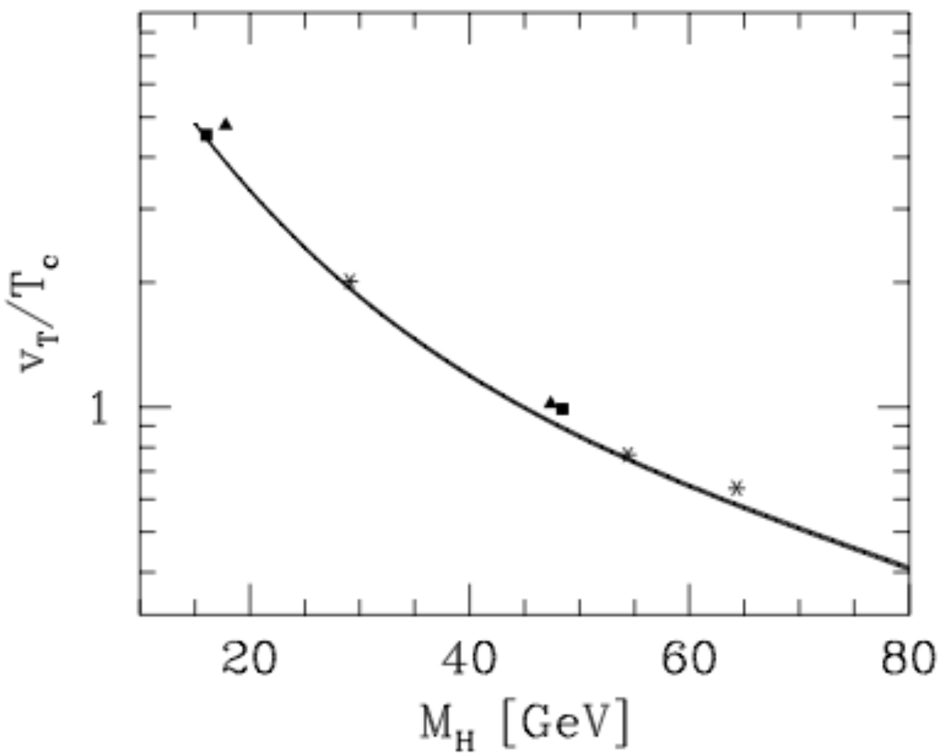
phase transition weak for large Higgs mass (small coupling λ); Standard Model and extensions: "a" and "b" in effective potential more complicated functions of gauge and Yukawa couplings.

Much work on effective potential (mostly mid-nineties): loop corrections, gauge dependence, infrared divergencies, treatment of Goldstone bosons, resummations, nonperturbative effects (gap equations, rigorous lattice studies!), beautiful work ... Baryogenesis needs strong phase transition:

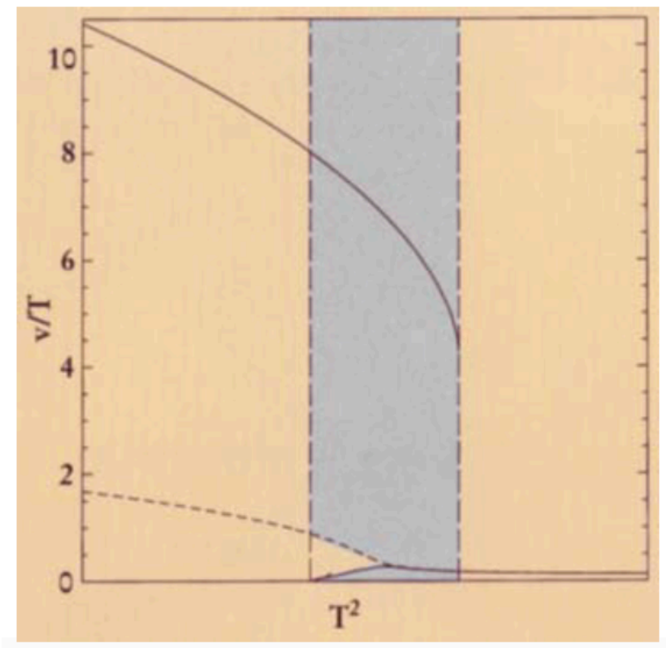
$$\frac{\varphi_c}{T_c} > 1$$

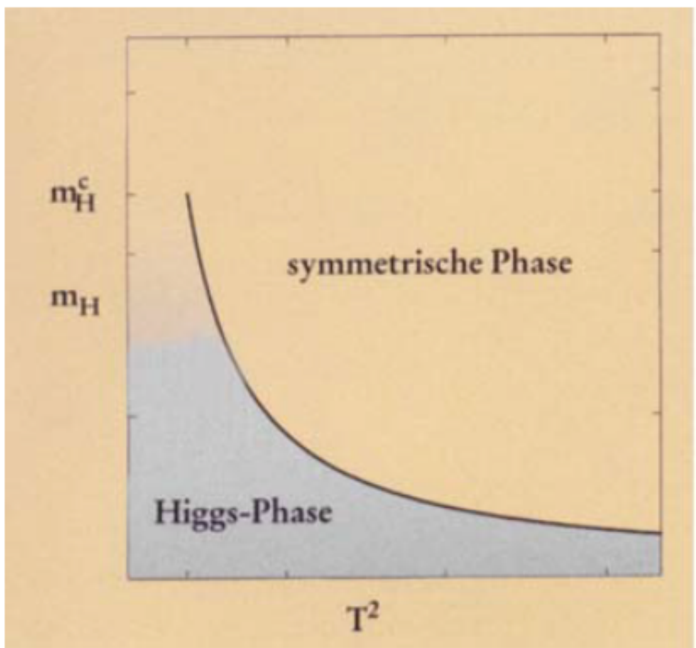
not possible in SM, but possible in extensions ...

Phase diagram



[Jansen '96]





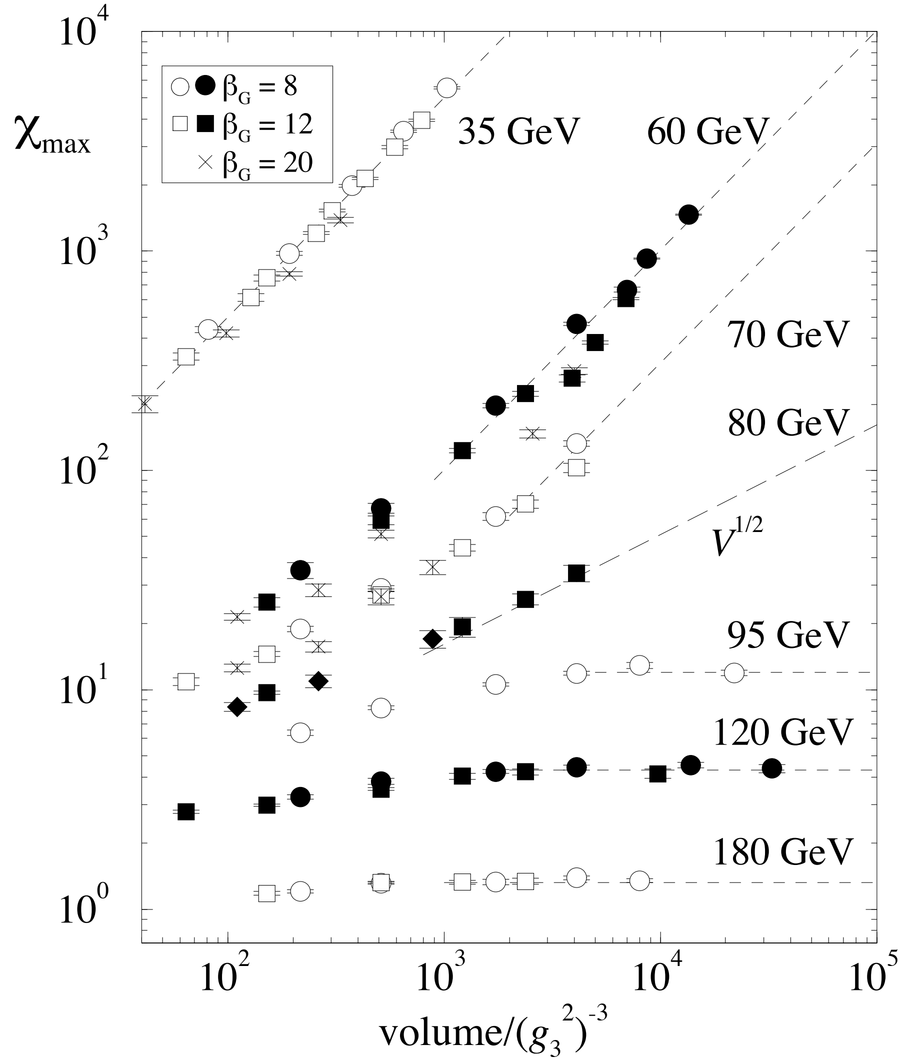
[WB, Philipsen '95,'97]

$$\textit{critical endpoint, lattice: } R_{HW} = \frac{m_H}{m_W}\,, \quad m_H^c = 72.1 \pm 1.4 \text{ GeV}$$

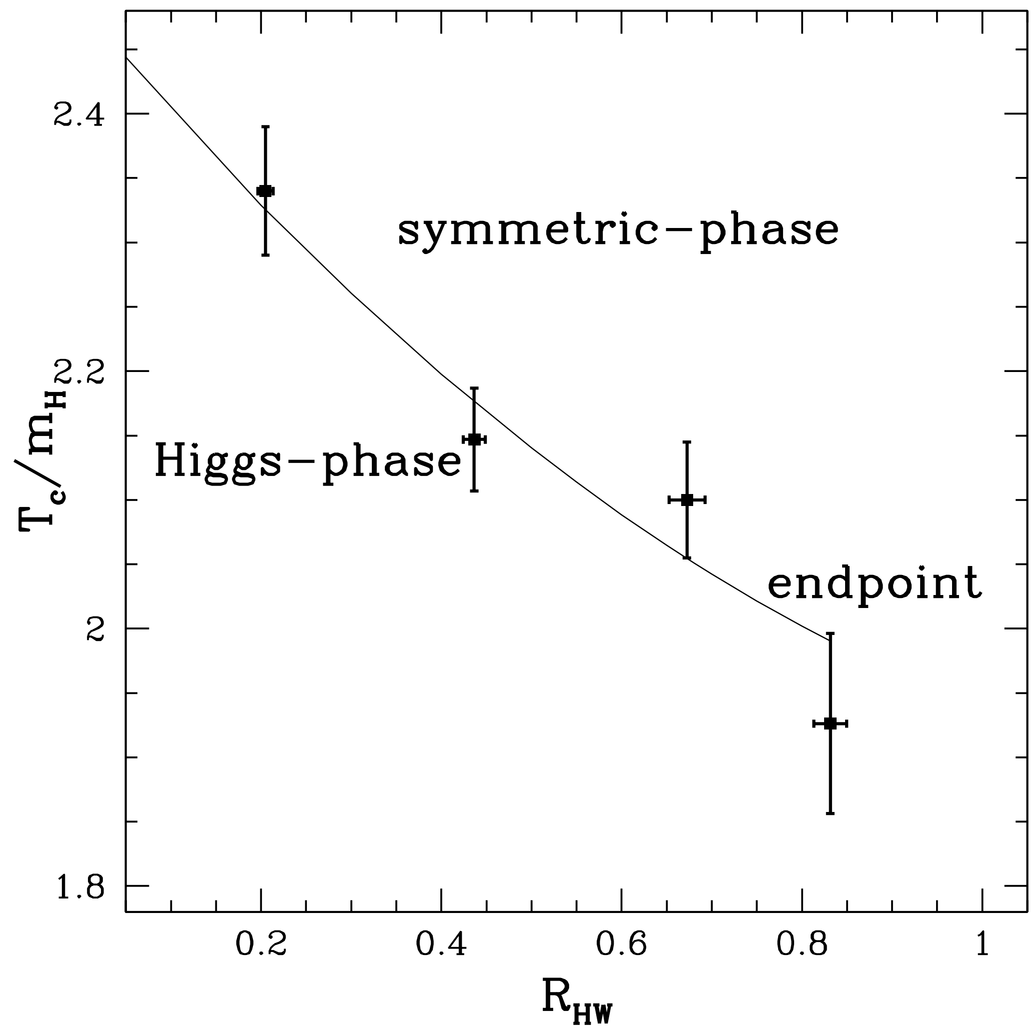
$$\textit{gap equations, magnetic mass: } m_H^c = \left(\frac{3}{4\pi C}\right)^{1/2} \simeq 74 \text{ GeV}\,,$$

$$m_{SM} = C g^2 T\,, \quad C \simeq 0.35$$

crucial effect: thermal magnetic mass for non-Abelian gauge theory!



[Kajantje, Laine, Rummukainen, Shaposhnikov '96]

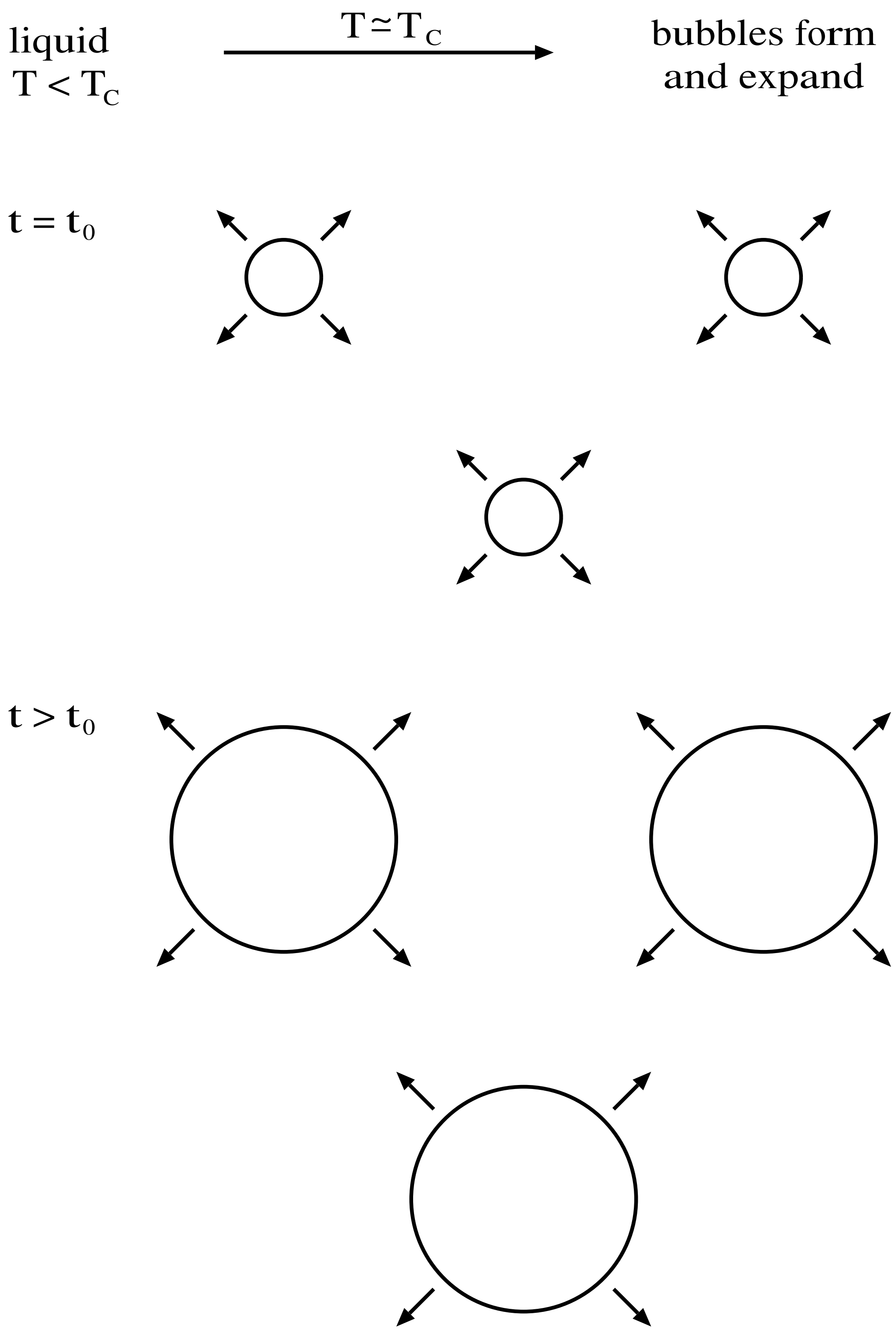


[Csikor, Fodor, Heitger '98]

Solid evidence for crossover from lattice simulations, volume dependence of Higgs-field susceptibility:

$$\chi \propto V\langle(\phi^\dagger\phi - \langle\phi^\dagger\phi\rangle)^2\rangle \to \mathrm{const}$$

Bubble nucleation & growth

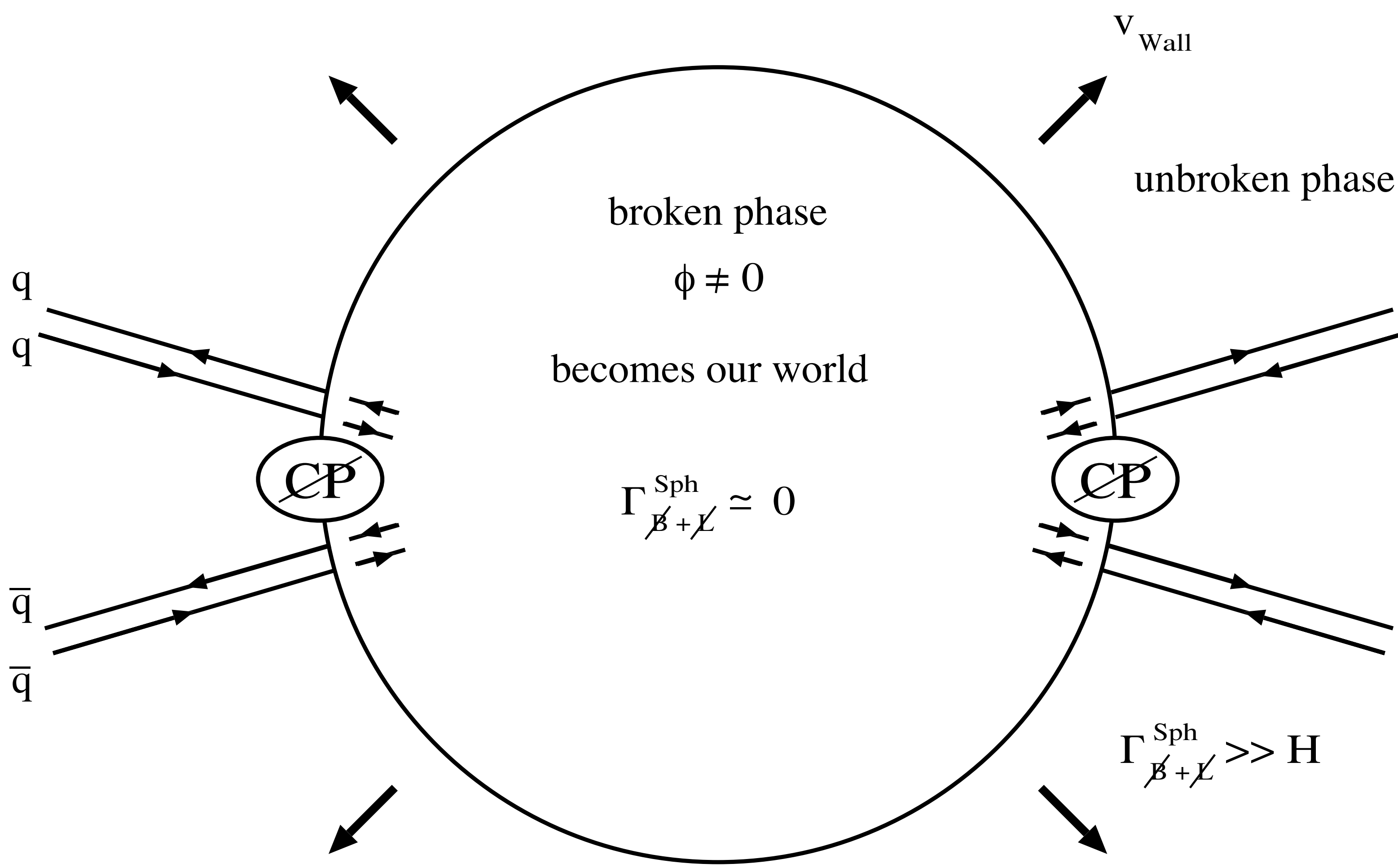


no 1st-order phase transition in SM, but in extensions (singlet model, 2HDM,...)

nucleation rate per volume:

$$\frac{\Gamma}{V} = A \ \exp\left(-\Gamma_{eff}[\overline{\Phi}]\right),$$

$\overline{\Phi}$: *saddle point of effective action, interpolating between the two phases, Langer's theory, ...*



CP violating scatterings at bubble wall (one-dimensional approximation):

$$\mathcal{L}_f = -\sum_{\psi} y_\psi \bar{\psi}_L \psi_R \phi \,, \quad \phi(z) = \frac{\rho(z)}{\sqrt{2}} e^{i\theta(z)} \,, \quad \rho(z) = \frac{v_c}{2}\left(1 - \tanh\frac{z}{L_w}\right)$$

Calculating the baryon asymmetry

very difficult, series of approximations: Schwinger-Keldysh → Boltzmann equations → diffusion equations ... ; CP violating interactions with bubble wall generate in front of wall excess of left-handed “tops”, converted to baryon asymmetry by sphaleron processes; in frame of wall chemical potentials only depend on distance from wall:

$$\textit{chemical potentials:} \quad \mu_{q_L}(z) = 3(\mu_{q_1}(z) + \mu_{q_2}(z) + \mu_{q_3}(z))$$

$$\textit{baryon number density:} \quad \frac{\partial n_B}{\partial t} = \frac{3}{2}\frac{\Gamma_{\rm sph}}{T}\left(\mu_{q_L} - \kappa_{\rm cs}\frac{n_B}{T^2}\right)$$

$$\textit{diffusion equations:} \quad v_w \partial_z \mu_i - \sum_j \Gamma_{ij}\mu_j + \cdots = S_i$$

$$\textit{final result:} \quad n_B = \frac{3}{2}\frac{\Gamma_{\rm sph}}{v_w T}\int_0^\infty \mu_{q_L}(z) e^{-k_B z}\,, \qquad k_B = \frac{3\kappa_{\rm cs}}{2 v_w}\frac{\Gamma_{\rm sph}}{T^3}$$

important parameters: critical Higgs vev, bubble wall velocity, bubble wall width, diffusion parameters, ...

Example 1: 2 Higgs-doublet model (2HDM)

Higgs potential with complex parameters:

$$V_{\rm tree}(\Phi_1,\Phi_2) = -\,\mu_1^2\Phi_1^\dagger\Phi_1 - \mu_2^2\Phi_2^\dagger\Phi_2 - \frac{1}{2}\left(\mu^2\Phi_1^\dagger\Phi_2 + \text{H.c.}\right) + \\ + \frac{\lambda_1}{2}\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger\Phi_2\right)^2 + \lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \\ + \lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right) + \frac{1}{2}\left[\lambda_5\left(\Phi_1^\dagger\Phi_2\right)^2 + \text{H.c.}\right] \ ,$$

$$\langle\Phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v\cos\beta \end{pmatrix}, \qquad \langle\Phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v\sin\beta\, e^{i\theta} \end{pmatrix} \ ,$$

$$\delta_1 = \text{Arg}[(\mu^2)^2\lambda_5^*],$$
$$\delta_2 = \text{Arg}(v_1 v_2^*\,\mu^2\lambda_5^*) \ .$$

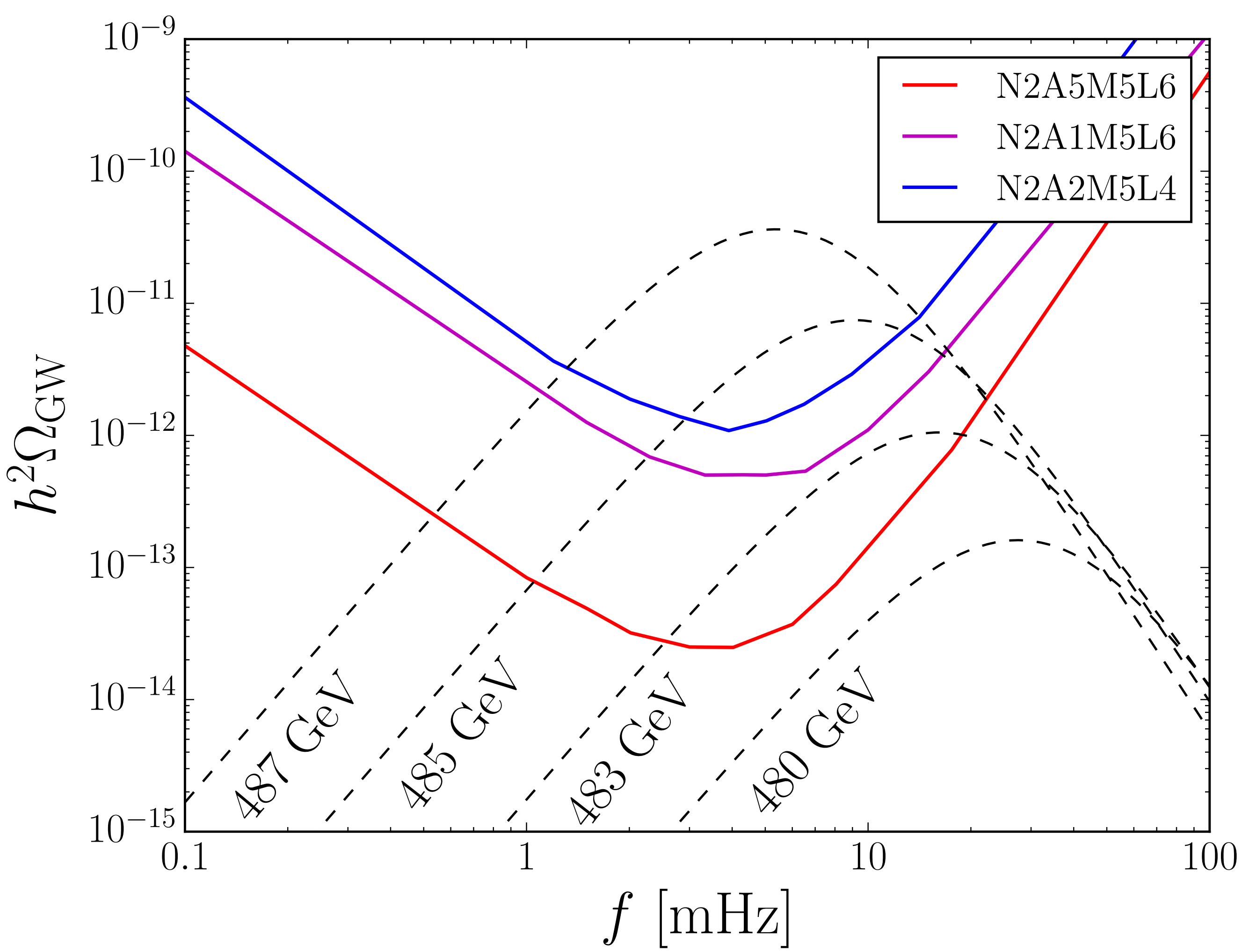
Strong 1st order phase transition and EWBG possible for large couplings; also CP violation in Higgs sector large enough

Gravitational waves from electroweak phase transition:

$$ds^2 = a^2(\tau)(\eta_{\mu\nu} + h_{\mu\nu})dx^\mu dx^\nu \ , \quad \bar{h}_{\mu\nu} = h_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu}h^\rho_\rho$$

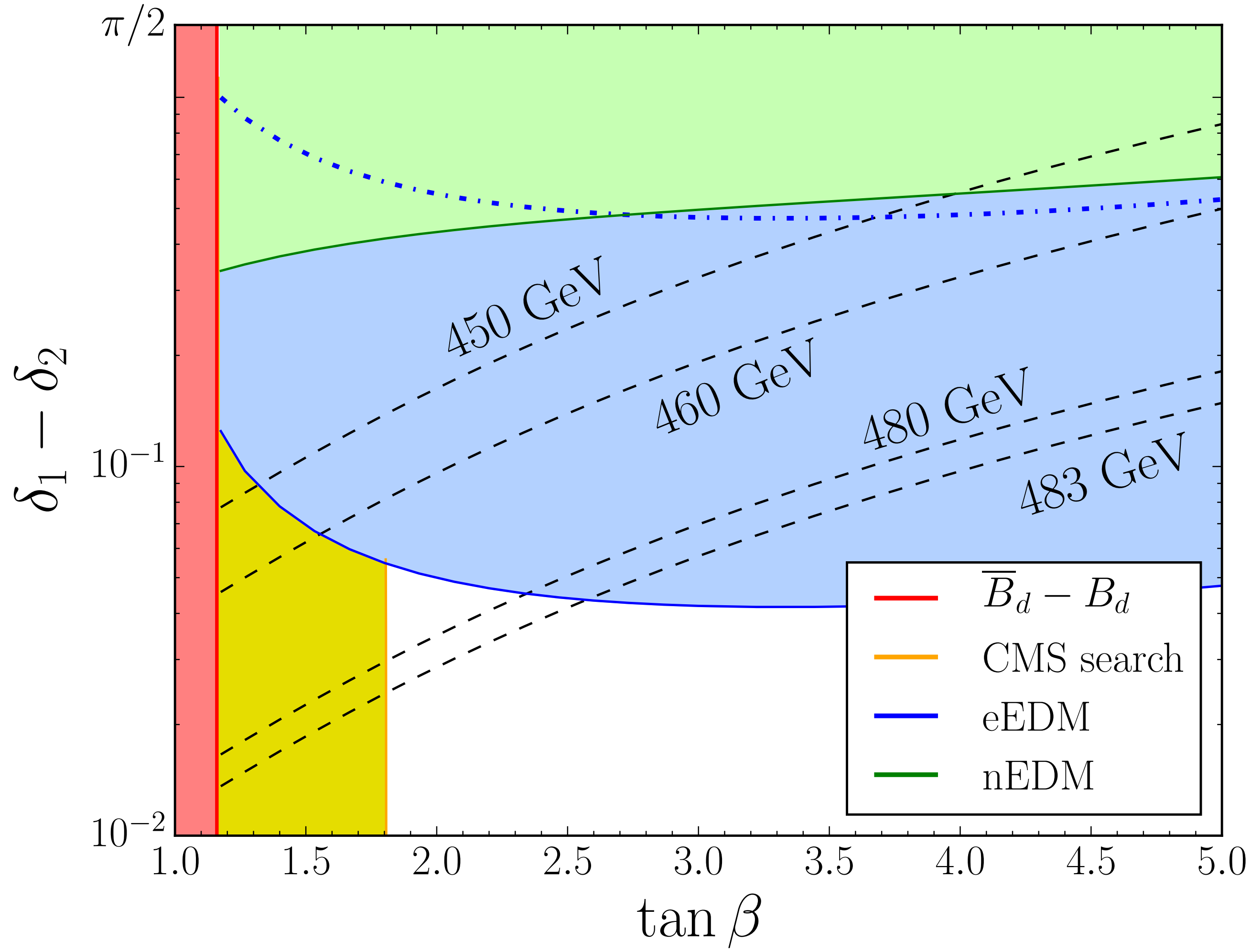
$$\bar{h}''_{\mu\nu}(\mathbf{x},\tau) + 2\frac{a'}{a}\bar{h}'_{\mu\nu}(\mathbf{x},\tau) - \nabla^2_{\mathbf{x}}\bar{h}_{\mu\nu}(\mathbf{x},\tau) = 16\pi G T_{\mu\nu}(\mathbf{x},\tau)$$

$$\int_{-\infty}^{\infty}\frac{dk}{k}\Omega_{GW}(k,\tau) = \frac{1}{32\pi G\rho_c}\langle\dot{h}_{ij}(\mathbf{x},\tau)\dot{h}^{ij}(\mathbf{x},\tau)\rangle$$



nice correlation between strong 1st order phase transition and gravitational waves in the LISA frequency range

Severe constraints from electric dipole moments (correlation between CP phase and tanβ for given pseudoscalar Higgs mass):



EWBG consistent with electron ACME I bound, but model **ruled out** by ACME II bound (October 2018):

$$|d_e^{\mathrm{ACMEI}}| < 8.7 \times 10^{-29}\ e \cdot \mathrm{cm}$$

$$|d_e^{\mathrm{ACMEII}}| < 1.1 \times 10^{-29}\ e \cdot \mathrm{cm}$$

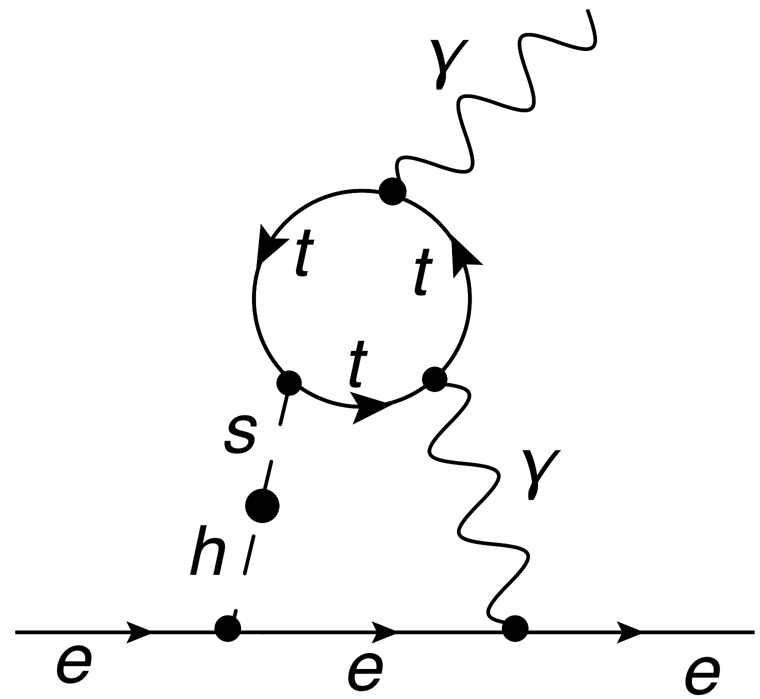
Note: baryogenesis in MSSM popular for many years, now also **ruled out**

Example 2: Standard Model with singlet

Motivation: non-minimal composite Higgs models, additional singlet in low energy effective Lagrangian; strong first-order phase transition from tree-level potential, thermal instability for singlet and Higgs; CP violation via additional dim5-operator: [Espinosa, Gripaios, Konstandin, Riva '12]

$$
\begin{aligned}
V &= V^{\text{even}} + V^{\text{odd}} \ , \\
V^{\text{even}} &= -\mu_h^2 |H|^2 + \lambda_h |H|^4 \\
&\quad - \ \frac{1}{2}\mu_s^2 s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{2}\lambda_m s^2 |H|^2, \\
V^{\text{odd}} &= \frac{1}{2}\mu_m s |H|^2 + \mu_1^3 s + \frac{1}{3}\mu_3 s^3 \ , \\
\mathbf{Z}_2 &: \ s \to -s \ .
\end{aligned}
$$

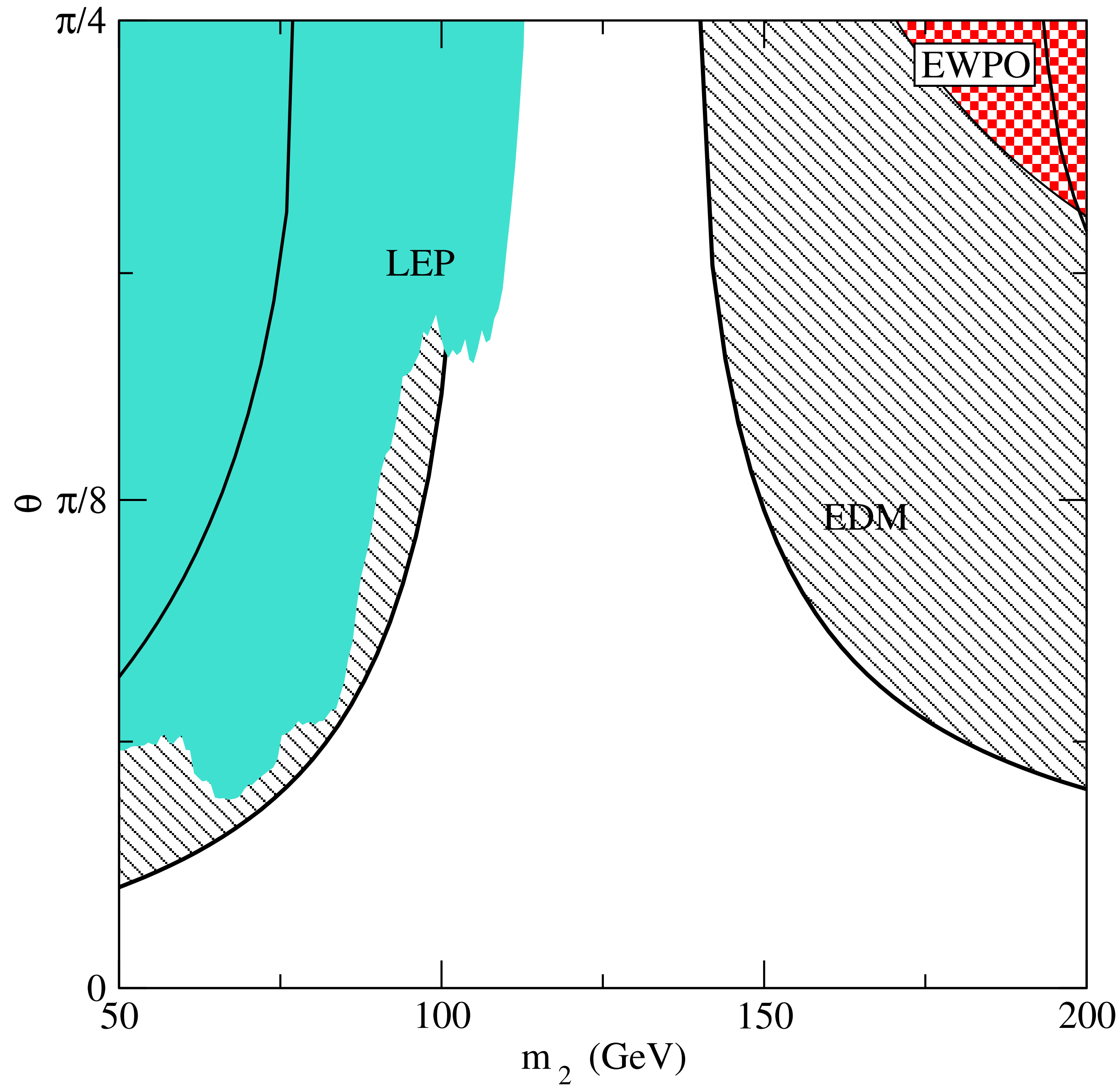
$\mathbf{Z}_2$ symmetry explicitly broken; non-zero vev of singlet at zero temperature



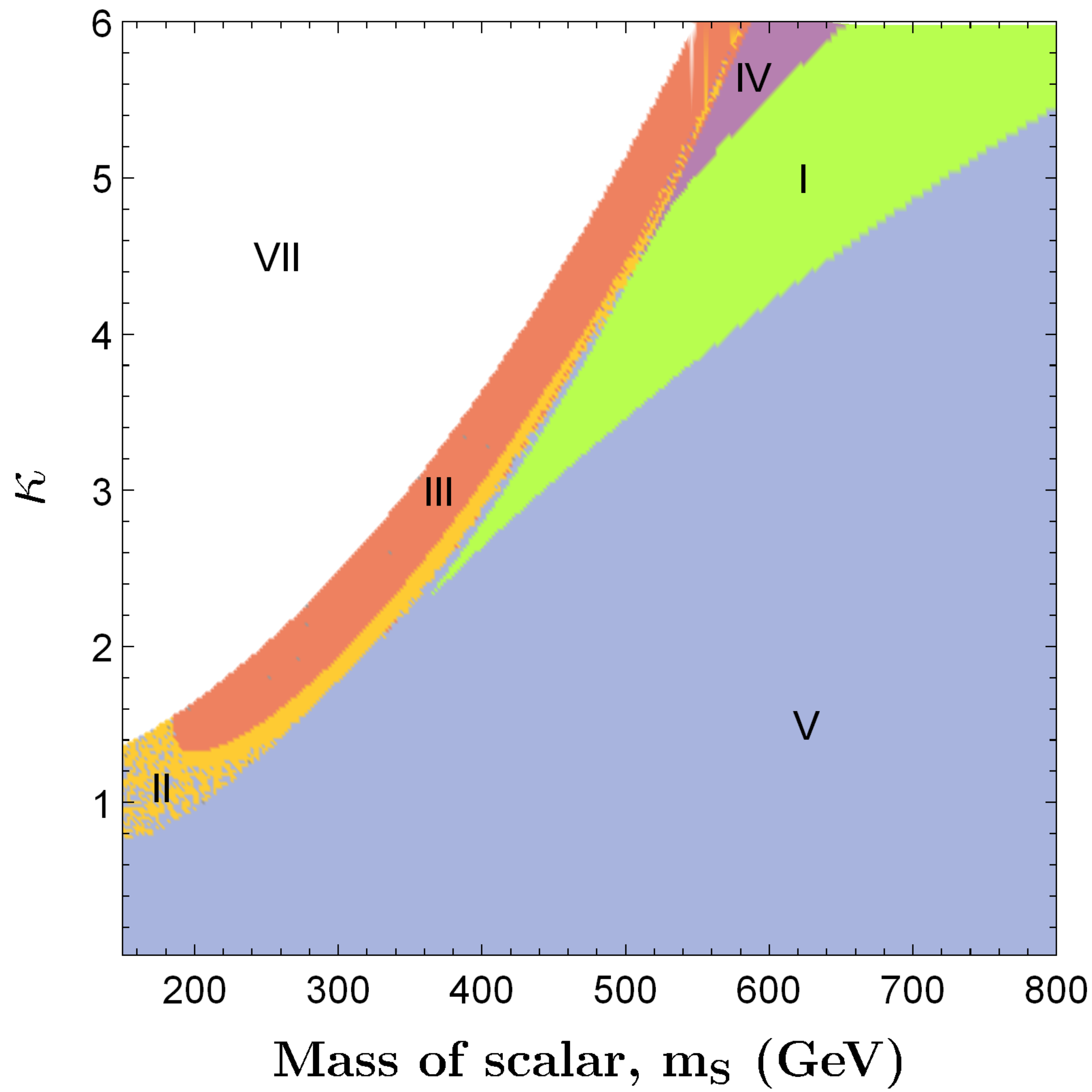
$$\mathcal{L}_{tHs} = \frac{s}{f} H \bar{q}_{L3}(a + ib\gamma_5)t_R + \mathrm{h.}c.$$

CP violation for baryogenesis implies EDMs for electron and neutron; predictions close to upper experimental bound! Energy scale f/b ~ 1 TeV, i.e. low compositeness scale - other resonances due to compositeness should be in LHC range! CP violations for baryogenesis and EDMs are correlated; analysis carried out for

$$\frac{d_e}{e} < 1.05 \times 10^{-27}\mathrm{cm}$$



Model strongly constrained by LEP (Higgs-singlet mixing), electroweak precision observables and EDMs for electron and neutron; singlet mass naturally light (compared to TeV strongly interacting particles), comparable to Higgs mass [θ: Higgs-singlet mixing angle; band: theoretical uncertainty]



[Kurup, Perelstein '17]

Strong ACME II bound requires "decoupling" of higgs physics and EDMs from electroweak phase transition; achieved in $\mathbf{Z}_2$ limit, with "tuned" tiny singlet vev and "tuned" strongly 1st order phase transition for strong coupling [green domain, $\kappa \equiv \lambda_m$] ("nightmare scenario")

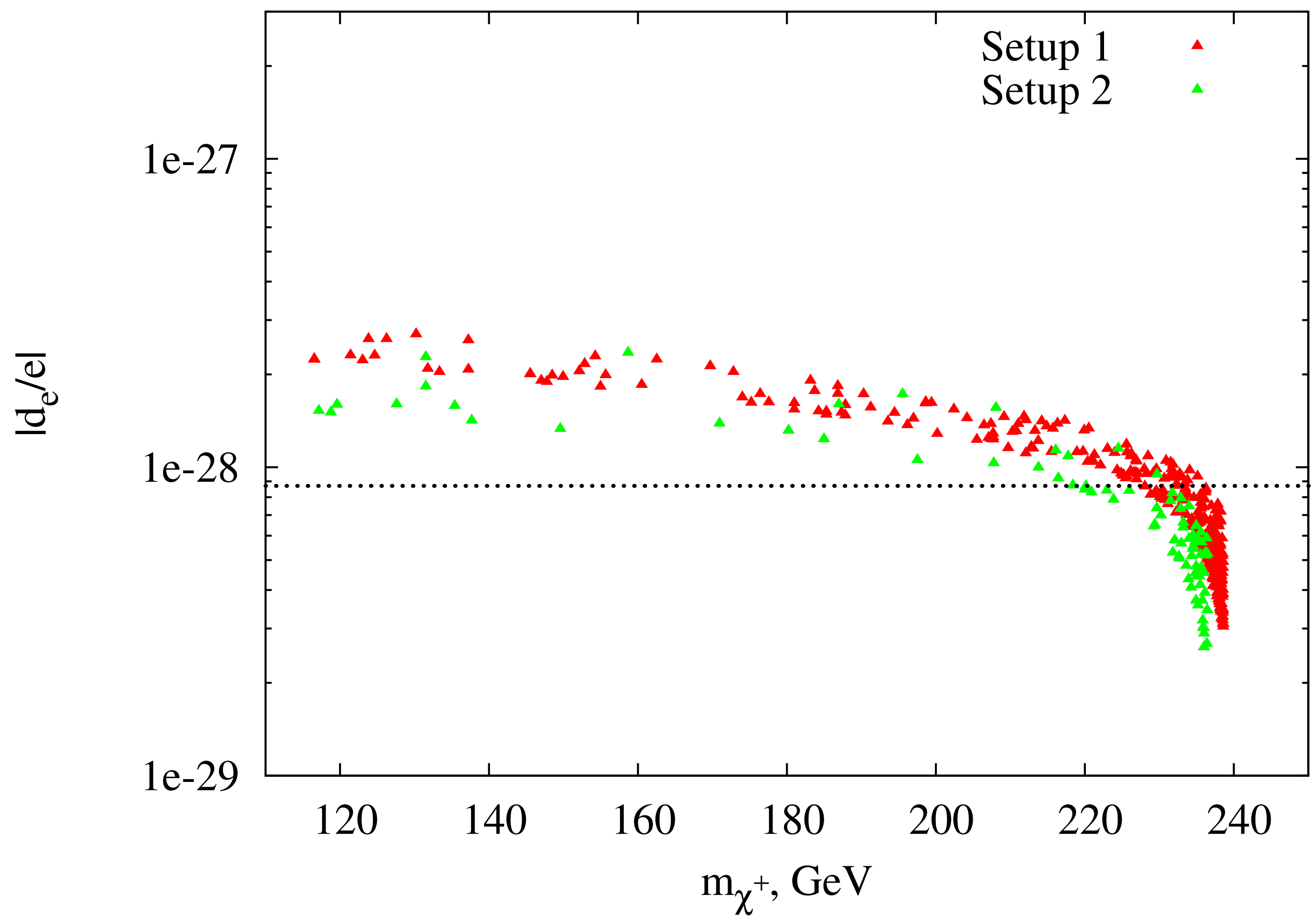
Theoretically well motivated model: **Split NMSSM**

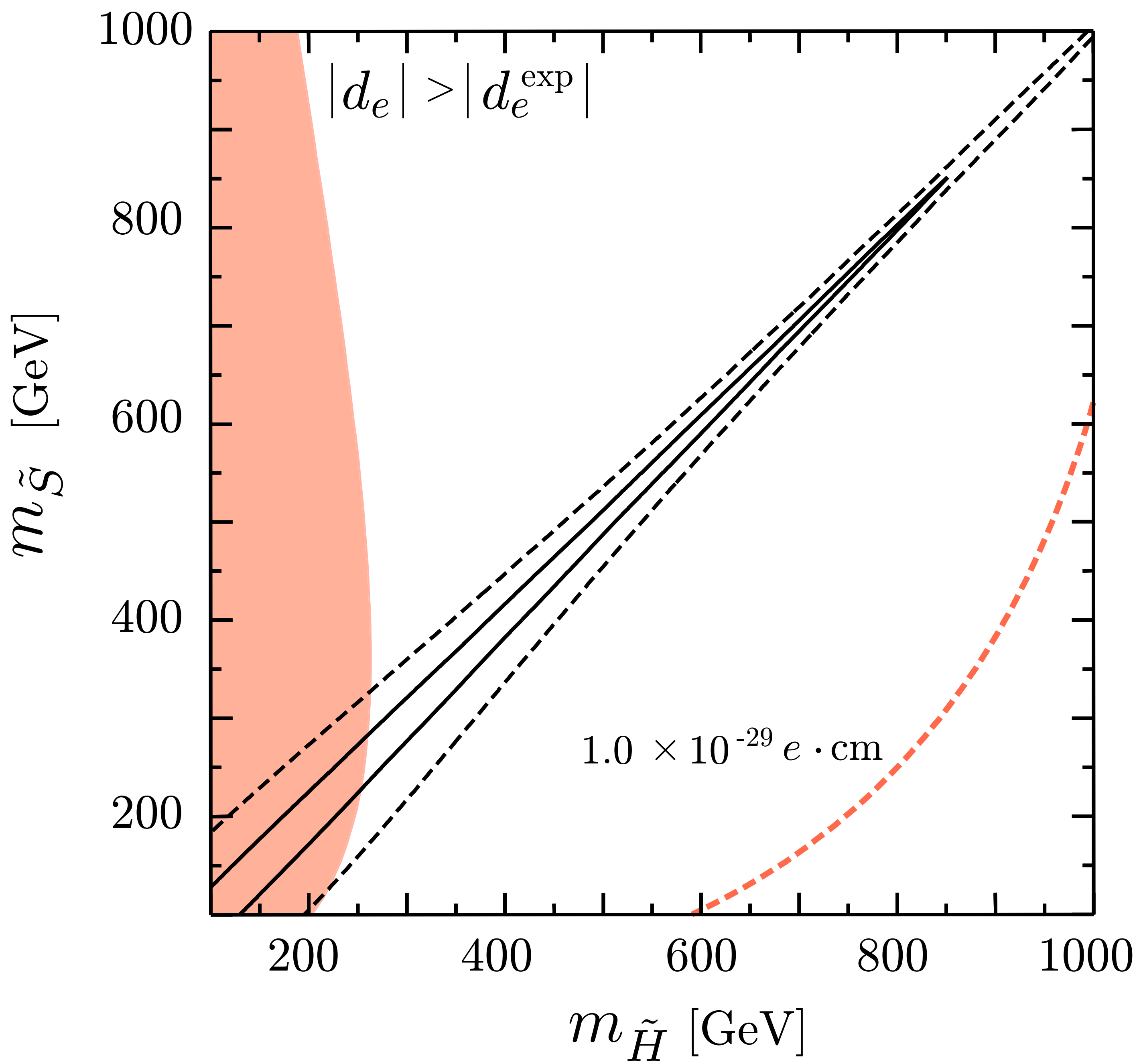
[Demidov, Gorbunov, Kirpichnikov '16]

Superpotential for Higgs doublets and singlets:

$$W = \lambda \hat{N} \hat{H}_u \epsilon \hat{H}_d + \frac{1}{3} k \hat{N}^3 + \mu \hat{H}_u \epsilon \hat{H}_d + r \hat{N}$$

EWBG consistent with ACME I bound on electron EDM, but model ruled out by ACME II bound





[Fuyuto, Hisano, Senaha '15]

General analysis of EWBG and EDMs in extensions of SM with 2 Higgs doublets and singlet and additional fermions with electroweak interactions; baryon asymmetry: $Y/Y_{\rm obs} = 1(0.1)$ for full (dashed) black lines

EWBG in dynamical composite model

[Bruggisser, von Harling, Matsedonskyi, Servant '18]

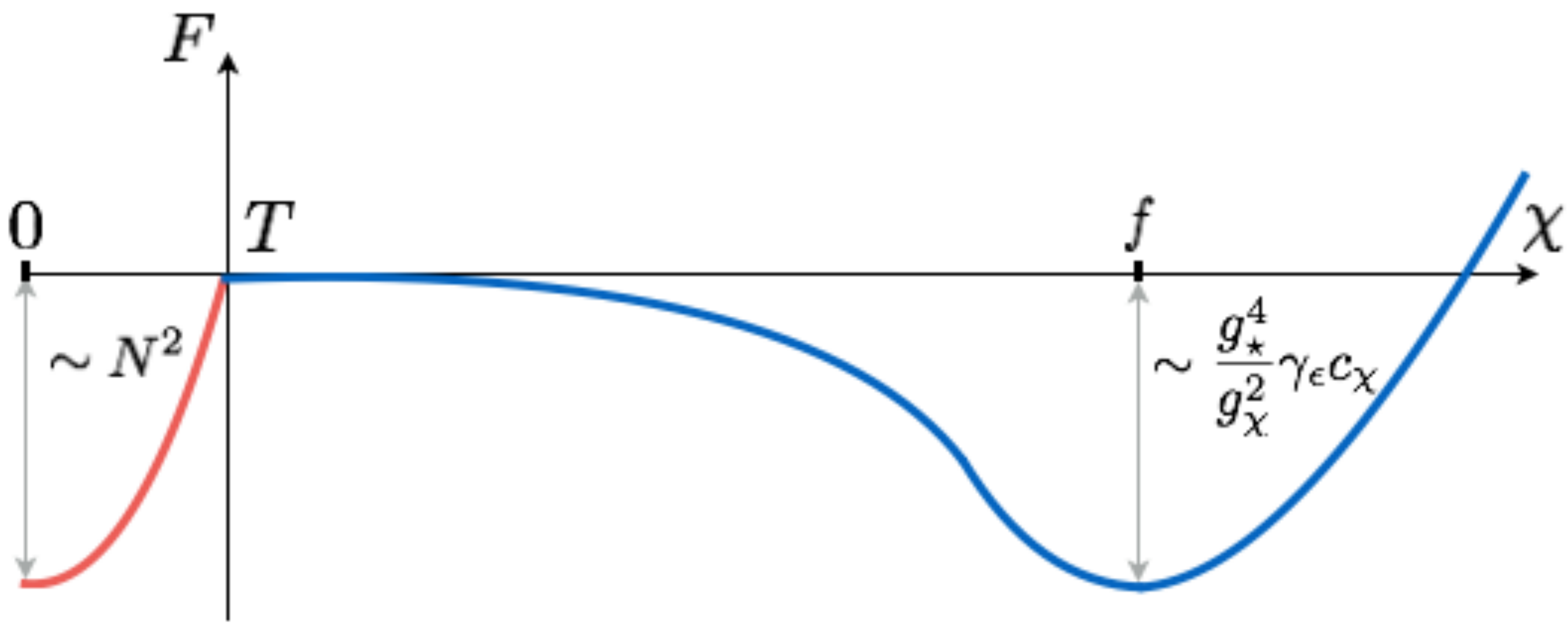
Basic idea: Higgs as pseudo-Nambu-Goldstone boson from broken global symmetry together with dilaton as pseudo-Nambu-Goldstone boson from broken conformal symmetry of strongly coupled sector in framework of partial compositeness; electroweak phase transition together with confinement phase transition of strongly coupled sector; enhancement of CP violation from varying Yukawa couplings

Higgs as PNGB (e.g. SO(5)/SO(4); shift symmetry):

$$V[h,\chi] \;\sim\; f^4\left[\alpha \sin^2(h/f) + \beta \sin^4(h/f)\right] + V_\chi + \Delta V_T \;,$$

$$\alpha[y] \;\sim\; c_\alpha \sum_{n_f} g_\star^2 \frac{N_c\, y^2[\chi]}{(4\pi)^2}\left(\frac{g_\chi}{g_\star}\chi\right)^4 \;, \quad y_i[\chi] \;\simeq\; y_{0,i}\;\left(\frac{\chi}{\chi_0}\right)^{\gamma_i} \;,$$

$$\beta[y] = c_\beta \sum_{n_f} g_\star^2 \frac{N_c\, y_i^2[\chi]}{(4\pi)^2}\left(\frac{g_\chi}{g_\star}\chi\right)^4\left(\frac{y}{g_\star}\right)^{p_\beta} \;.$$



dilaton free energy, couplings and mass scales:

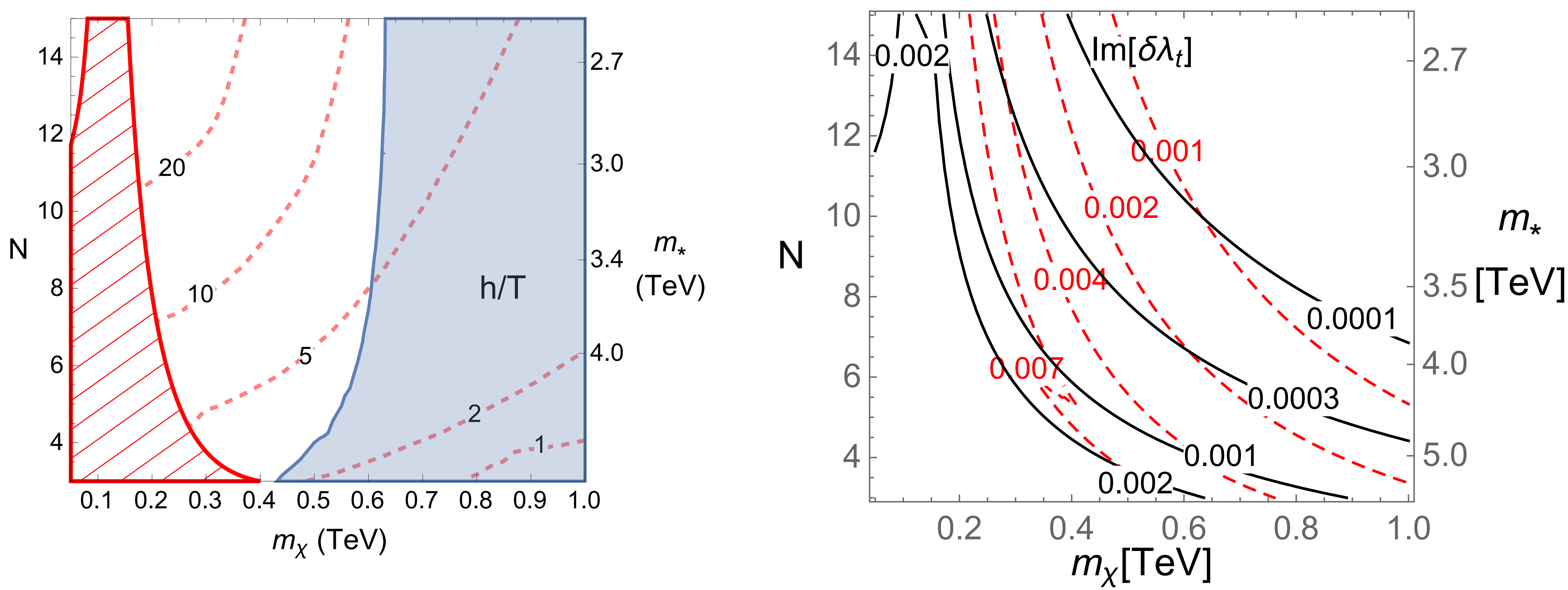
$$g_* f = g_\chi \chi_0 \ , \quad f = 0.8 \text{ TeV} \ ,$$

$$g_* = 4\pi/\sqrt{N} \ , \quad m_* = g_* f \ \text{(heavy resonances)}$$

$$m_\chi = g_\chi f \ , \quad g_\chi = 4\pi/N \ \text{(glueball-like)} \quad g_\chi = 4\pi/\sqrt{N} \ \text{(meson-like)} \ ,$$

$$F_{\rm CFT}[\chi = 0] \ \simeq \ -\frac{\pi^2 N^2}{8} T^4 \, (N = \text{number of 'hyper colours'})$$

$$T_c \ \simeq \ 2 \left(\frac{g_\star^2}{4\pi g_\chi N} \right)^{1/2} (2\gamma_\epsilon c_\chi)^{1/4} f \ \text{(critical temperature)}$$



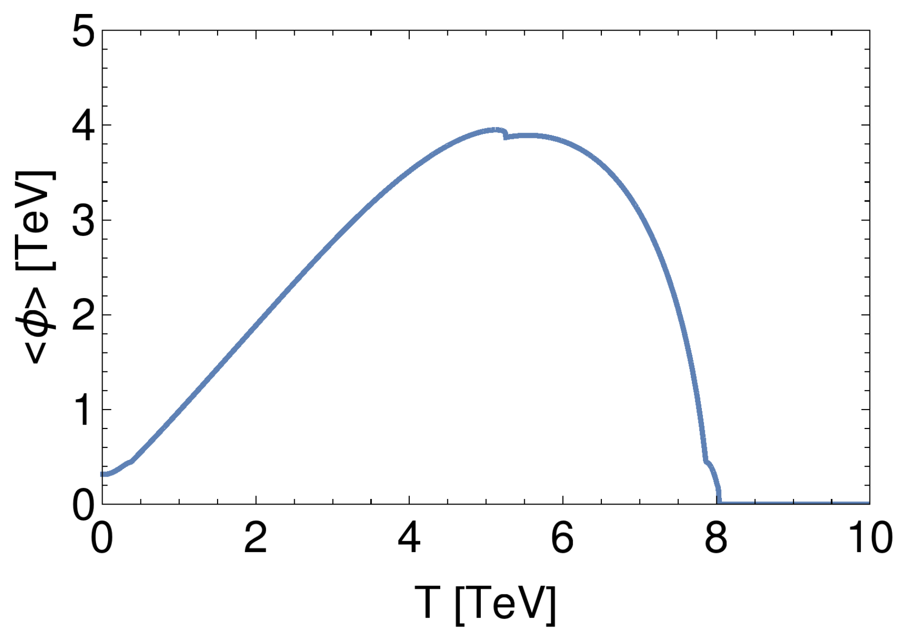
Strong 1st EWPT, avoiding washout of symmetry, and EWBG possible; predictions: light dilaton at LHC, electron EDM from varying Yukawa couplings:

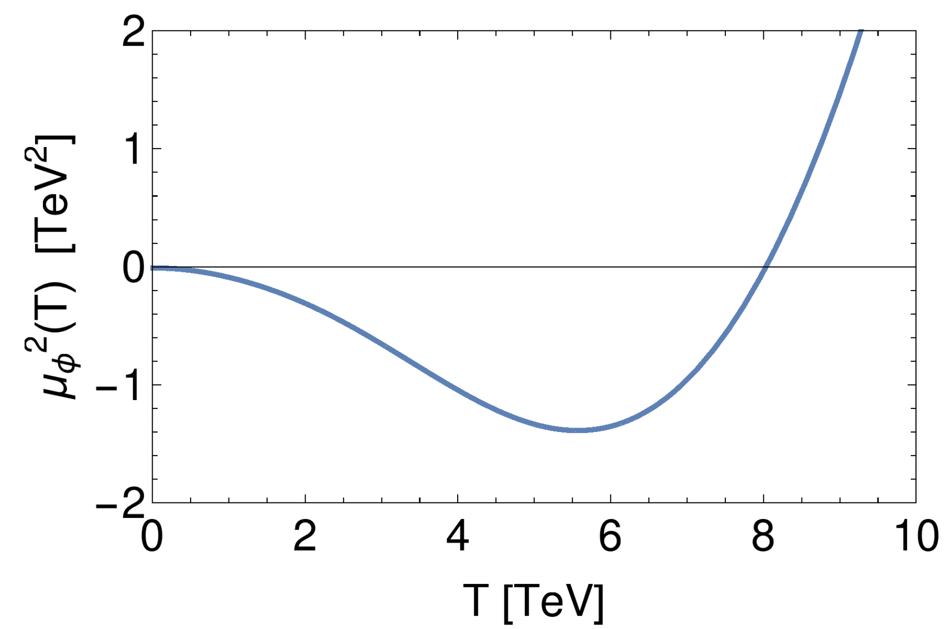
$$\text{ACME I} : \text{Im}[\delta\lambda_t] \lesssim 2 \cdot 10^{-2}\,\text{OK}$$

$$\text{ACME II} : \text{Im}[\delta\lambda_t] \lesssim 2 \cdot 10^{-3}\,\text{currently tested}$$

High-scale EWBG & symmetry non-restauration

[Baldes, Servant '18]





$$V(\phi,\chi) = \frac{\mu_S^2}{2}S^2 + \frac{\mu_\chi^2}{2}\sum_i \chi_i^2 + \frac{\mu_\phi^2}{2}\phi^2 + \frac{\lambda_\phi}{4}\phi^4$$
$$+ \frac{\lambda_\chi}{4}\sum_i \chi_i^4 + \frac{\lambda_S}{4}S^4 + \frac{\lambda_{\phi\chi}}{4}\phi^2\sum_i \chi_i^2 + \frac{\lambda_{\phi S}}{4}\phi^2 S^2 \ ,$$

$$\mu_\phi^2(T) = \mu_\phi^2 + c_\phi T^2 > (<)\ 0\ , \quad T > (<)\ \mu_S\ ; \quad \lambda_{\phi\chi} < 0$$

With many new heavy degrees of freedom, EWSB can take place at high scale; 1st order phase transition and EWBG can be arranged; **decoupling** of EWBG from LHC physics and EDMs

Summary: electroweak baryogenesis

- Very interesting topic in nonequilibrium QFT, huge activity during the past past 30 years since closely related to Higgs mechanism

- Baryon asymmetry determined by parameters of Higgs sector (various theoretical uncertainties):

$$\frac{n_B}{s} \sim \frac{\Gamma_{\rm sph}}{T^4} \frac{1}{L_w T_c} \frac{\delta_{\rm CP}}{4\pi} e^{-m_\psi/T_c} \left(\frac{v_c}{T_c}\right)^\gamma \kappa_d \lesssim 10^{-9} ,$$

$$\Gamma_{\rm sph}/T^4 \sim 10^{-6} , \quad \gamma = 3 \ldots 4 , \quad \kappa_d = 10^{-2} \ldots 10^{-1}$$

$$\simeq 6.2 \cdot 10^{-10}$$

- Very strong bound from electron EDM! Renormalizable models excluded (2HDM, MSSM, NMSSM, ...)

- Strongly interacting Higgs sector with dilaton still viable; hope: discovery of EDMs & dilaton at LHC; falsification of EWBG mechanism not possible, EWBG can be decoupled from low energy physics

II. Leptogenesis

Key references

M. Fukugita and T. Yanagida, Phys. Lett. B 174 (1986) 45
G. Lazarides and Q, Shafi, Phys. Lett. B 258 (1991) 305
A. Pilaftsis, T. E. J. Underwood, Nucl. Phys. B692 (2004) 303
W. Buchmuller, P. Di Bari, M. Plumacher, Annals Phys. 315 (2005) 305

Reviews

W. Buchmuller, R. D. Peccei, T. Yanagida, Ann. Rev. Nucl. Parti. Sci. 55 (2005) 311
S. Davidson, E. Nardi, and Yossi Nir, Phys. Rept. 466 (2008) 105
B. Garbrecht, A. Molinaro, eds, Int. J. Mod. Phys. A Vol. 33, Nos. 5 & 6 (2018)
[6 review articles]

GUT-scale seesaw

Grand Unified Theories (GUTs) predict right-handed neutrinos:

$$G_{SM} = U(1) \times SU(2) \times SU(3) \subset SU(5) \subset SO(10) \subset \ldots$$
$$SO(10): \ \mathbf{16} = \ (d_R^c, l_L, q_L, u_R^c, e_R^c, \nu_R^c)$$

RH neutrinos can have large Majorana masses M, not predicted by SM gauge symmetry; electroweak symmetry breaking yields Dirac neutrino masses $m_D = hv_F$; result 3 heavy and 3 light mass eigenstates (seesaw mechanism):

$$N \simeq \nu_R + \nu_R^c \ : \qquad m_N \simeq M \ ,$$
$$\nu \simeq \nu_L + \nu_L^c \ : \qquad m_\nu = -m_D \frac{1}{M} m_D^T$$

For hierarchical right-handed neutrinos and 3rd generation Yukawa couplings $\mathcal{O}(1)$, light neutrino masses related to mass scale of grand unification:

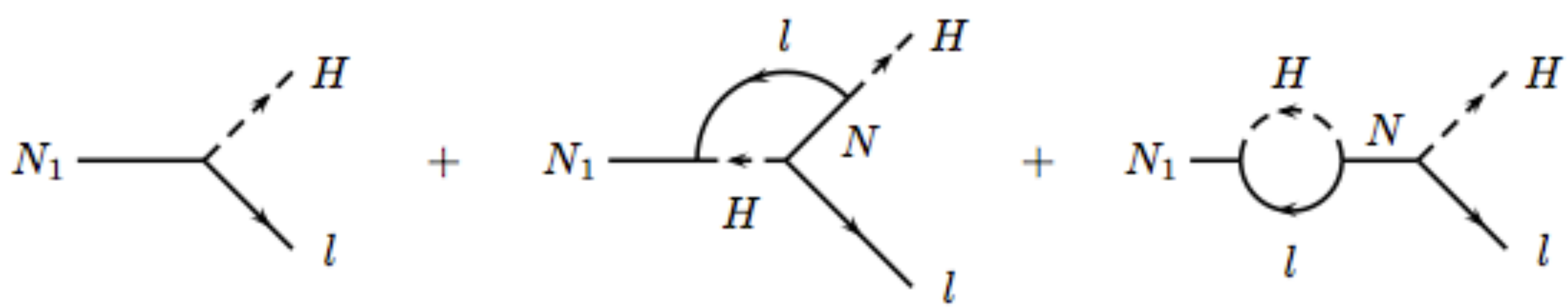
$$M_3 \sim \Lambda_{\mathrm{GUT}} \sim 10^{15} \ \mathrm{GeV} \ , \quad m_3 \sim \frac{v^2}{M_3} \sim \ 0.01 \ \mathrm{eV}$$

Lepton asymmetry, and subsequently baryon asymmetry is caused by CP violation in heavy Majorana neutrino decays, magnitude determined by neutrino masses (quantum interference!):

$$\varepsilon_1 = \frac{\Gamma\left(N_1 \to H + l_L\right) - \Gamma\left(N_1 \to H^\dagger + l_L^\dagger\right)}{\Gamma\left(N_1 \to H + l_L\right) + \Gamma\left(N_1 \to H^\dagger + l_L^\dagger\right)}$$

$$\simeq \; -\frac{3}{16\pi}\frac{M_1}{(hh^\dagger)_{11} v_F^2} \mathrm{Im}\left(h^* m_\nu h^\dagger\right)_{11}$$

Covi, Roulet, Vissani '96



Self-energy diagram gives "resonant enhancement" of CP asymmetry for quasi-degenerate N's

Rough estimate of CP asymmetry in terms of neutrino masses, assuming dominance of largest eigenvalue, phases $\mathcal{O}(1)$ and seesaw relation,

$$\varepsilon_1 \sim \frac{3}{16\pi} \frac{M_1 m_3}{v^2} \sim 0.1 \; \frac{M_1}{M_3} \; ,$$

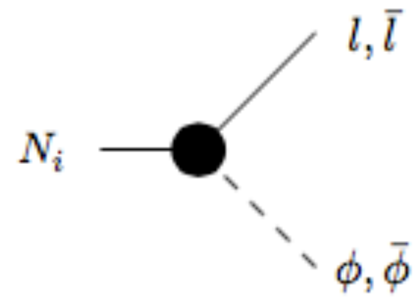
CP asymmetry determined by heavy neutrino mass hierarchy; mass ratios like for quarks or charged leptons, $M_1/M_3 \sim 10^{-4} \ldots 10^{-5}$, yield estimate $\epsilon_1 \sim 10^{-5} \ldots 10^{-6}$. Final baryon asymmetry:

$$\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} = -d c_s \varepsilon_1 \kappa_f \sim 10^{-9} \ldots 10^{-10}$$

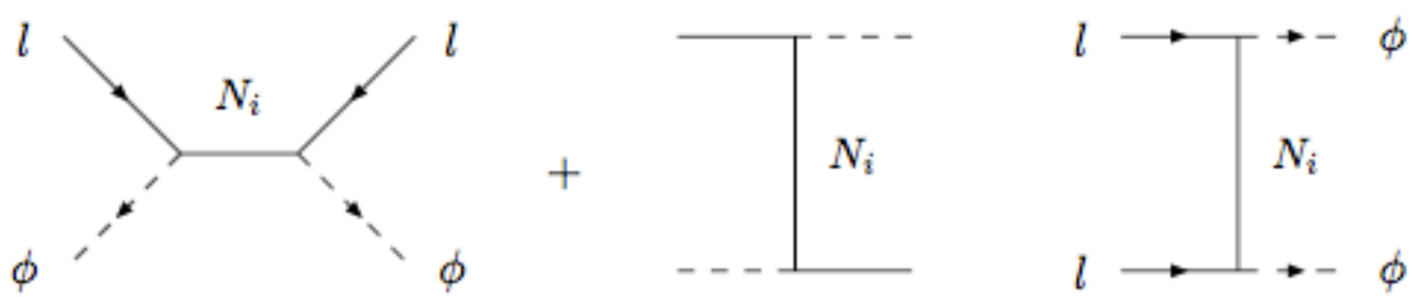
with "dilution factor" $d \sim 10^{-2}$ and "washout factor" $\kappa_f \sim 10^{-2}$ (Boltzmann equations); observed value of baryon asymmetry consequence of **hierarchical heavy neutrino masses** and kinematical factors!

Decays (D) and inverse decays (ID)

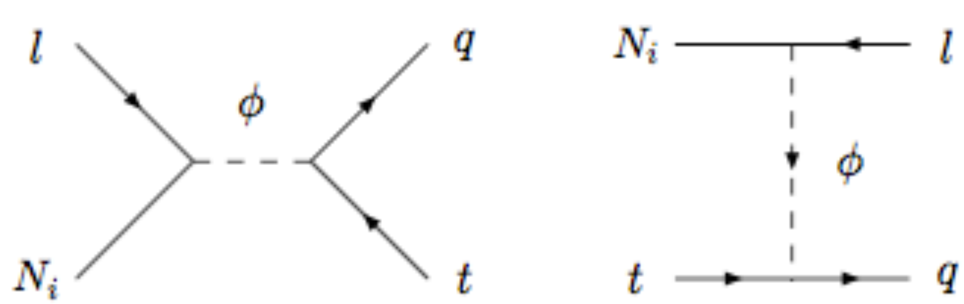
$N_i \leftrightarrow l\,\phi\,,\ \bar{l}\,\bar{\phi}$



$\Delta L = 2$ processes (N_i virtual)



$\Delta L = 1$ processes (N_i real, ϕ virtual)



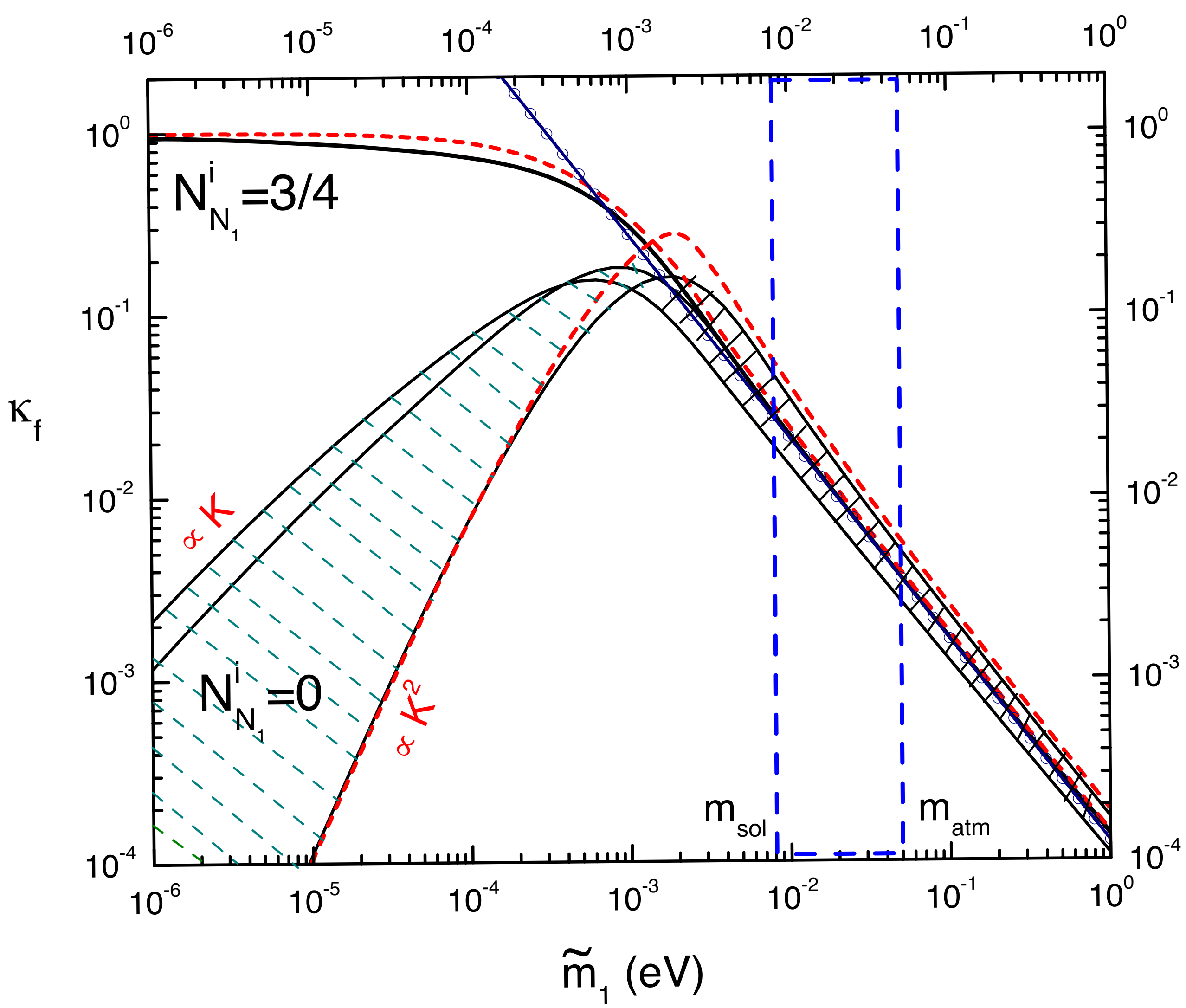
Luty ’92, Plumacher ’96

basic decay and scattering processes of heavy neutrinos in plasma

further important: interactions with gauge bosons!

Quantitative description via Boltzmann equations (decays "D", scatterings "S", washout "W"; simple for sum over lepton flavours):

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



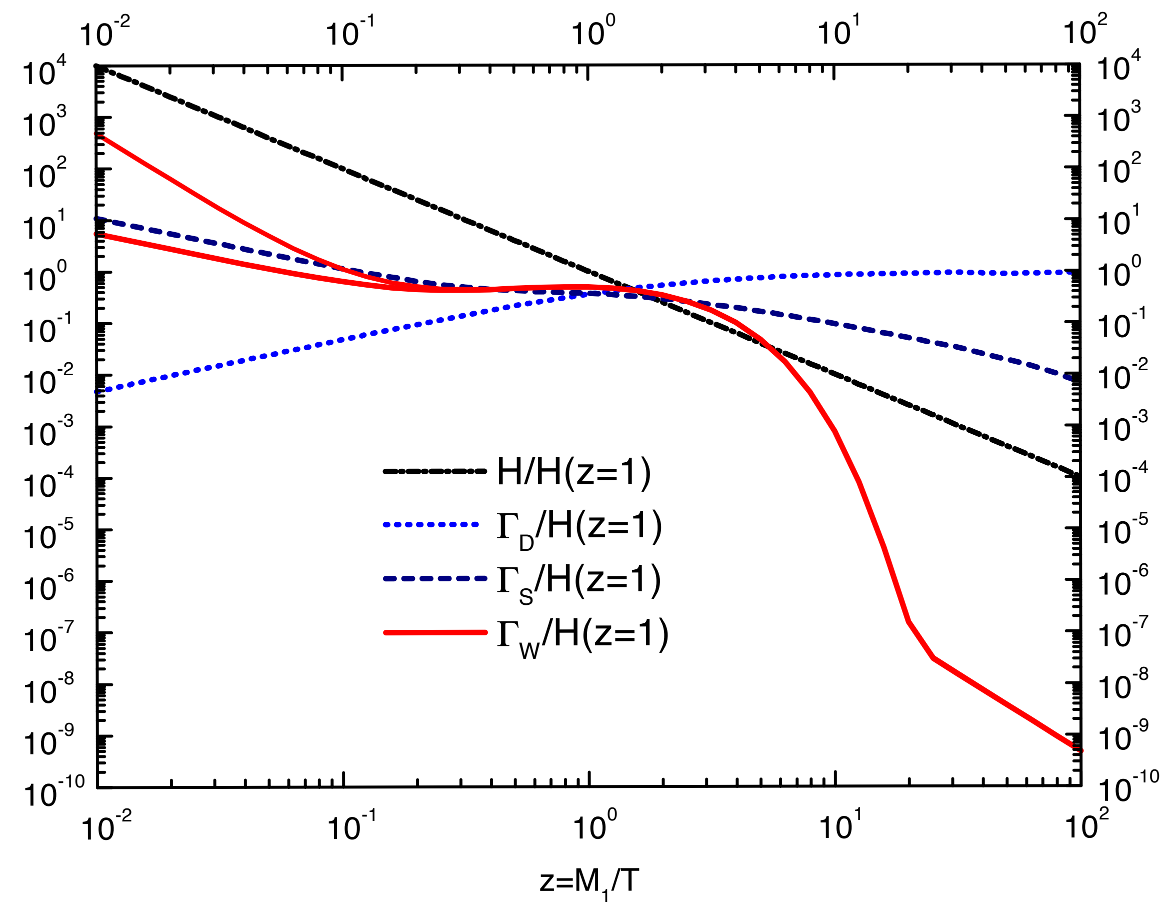
In "strong washout regime,"

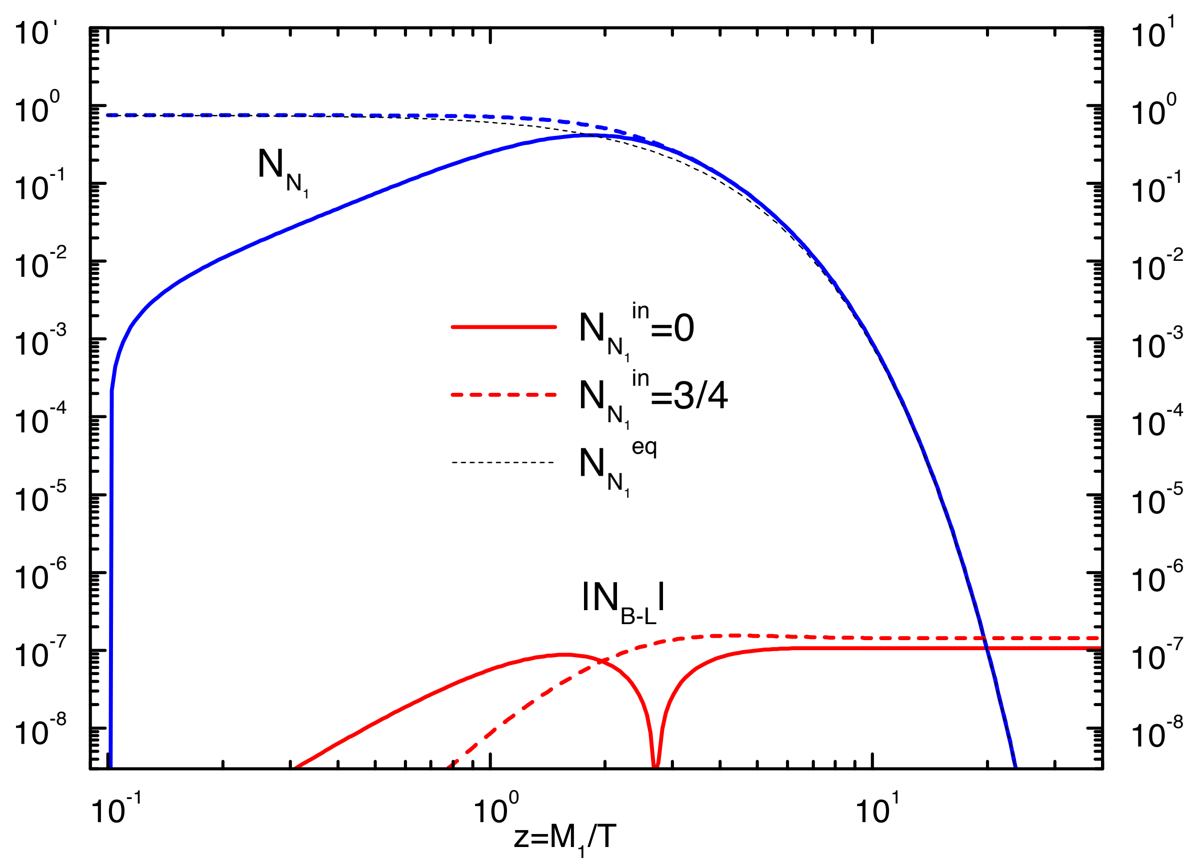
$$\widetilde{m} > m_* \sim 10^{-3}\ \mathrm{eV}$$

baryon asymmetry rather independent of initial conditions (but flavour effects!); efficiency factor:

$$\kappa_{\rm f} = (2\pm 1)\, 10^{-2}\, \left(\frac{0.01\,\mathrm{eV}}{\widetilde{m}}\right)^{1.1\pm 0.1}$$

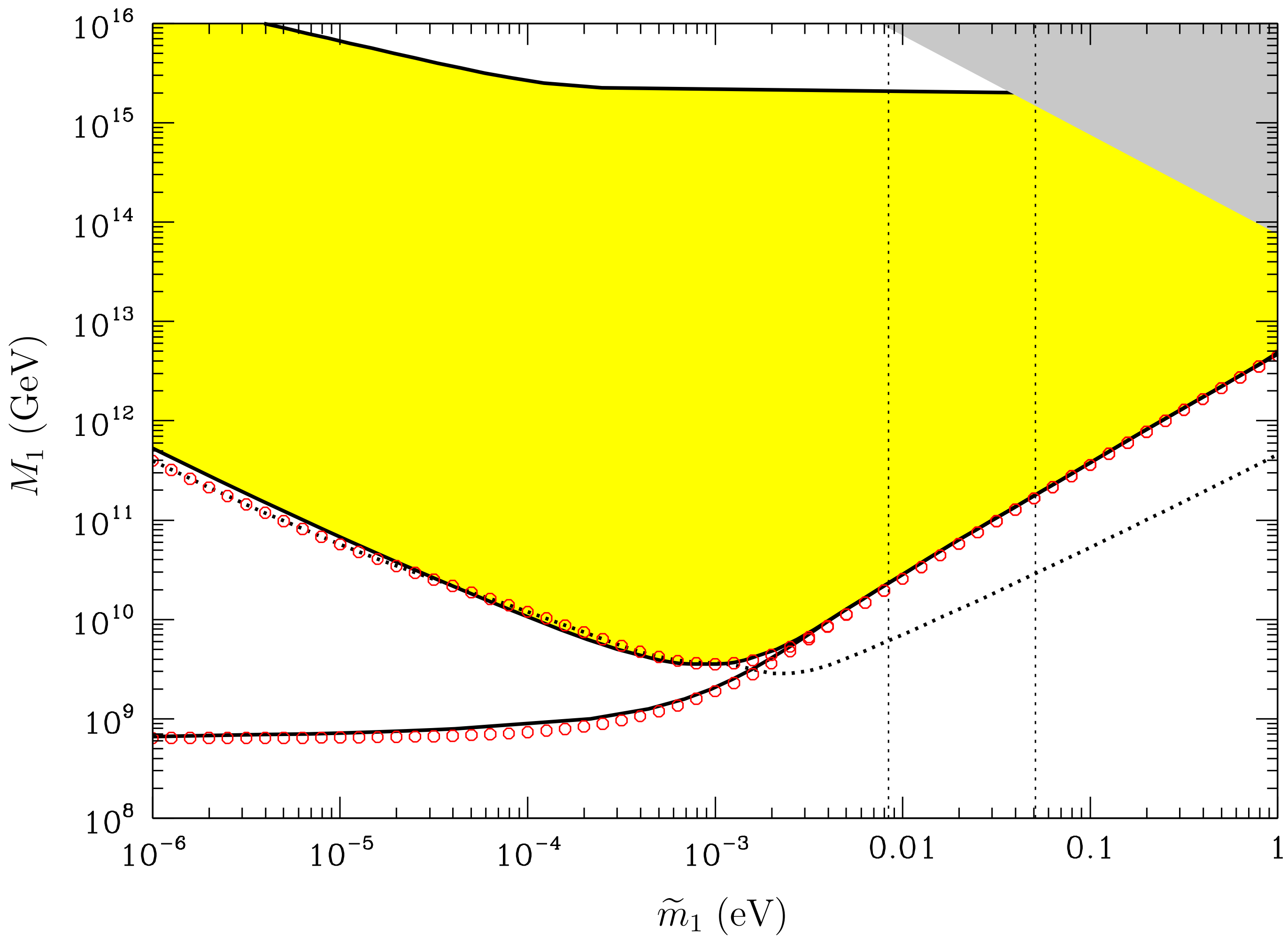
$$\widetilde{m} = \frac{(m_D m_D^\dagger)_{11}}{M_1}$$





upper: comparison of decay/scattering/washout rates with Hubble parameter. It is amazing that leptogenesis works at all!

lower: heavy neutrino densities & baryon asymmetry; leptogenesis process close to equilibrium



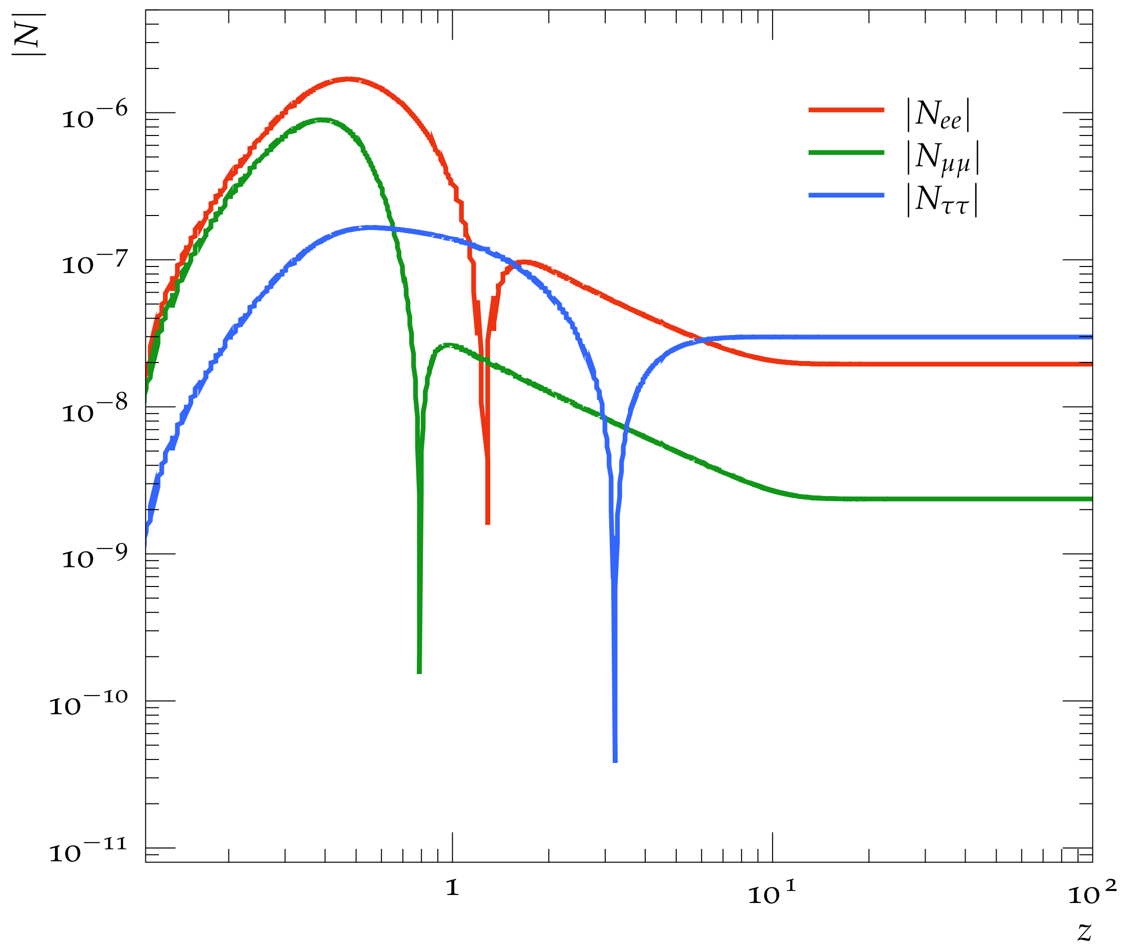
Upper bound on CP asymmetry [Davidson, Ibarra '02] and detailed study of Boltzmann equations [WB, Di Bari, Plumacher '02-'04] leads to bounds on light and heavy neutrino masses (and reheating temperature); in simplest approximation (sum over lepton flavours):

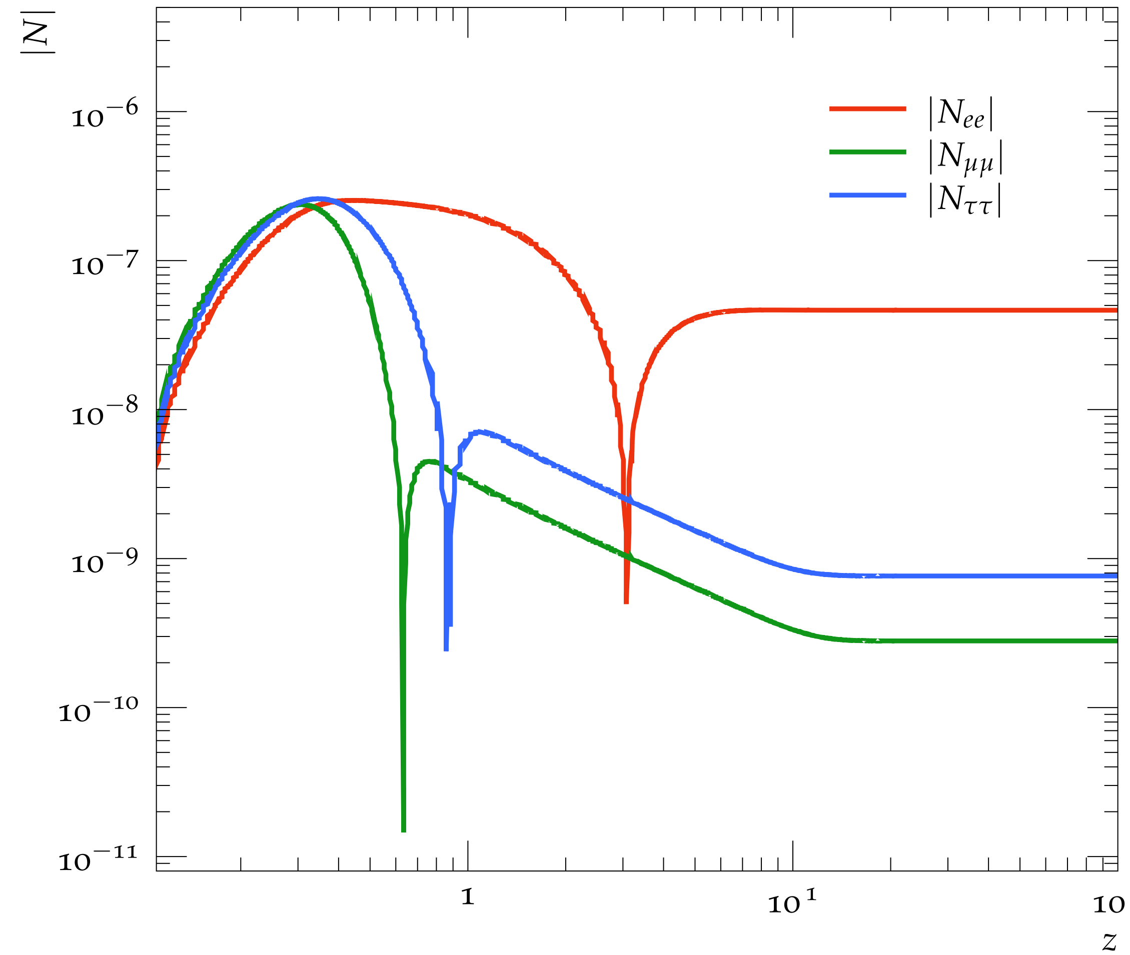
$$m_i < 0.1\,\mathrm{eV}\ , \quad M_1 > 4 \times 10^8\ \mathrm{GeV}$$

Preferred neutrino mass range ("strong washout regime", independence of initial conditions):

$$10^{-3}\ \mathrm{eV} < m_i < 0.1\ \mathrm{eV}$$

modifications: lepton flavour effects (bounds relaxed by about one order of magnitude ?! [Davidson, Nardi, Nir '08; Blanchet, Di Bari '12]); also effects from neutrino mass degeneracies ....[Nardi et al '05, Abada et al '06]





	m_1 (eV)	M_1 (GeV)	M_2 (GeV)	M_3(GeV)
S_2	0.079	$10^{6.5}$	10^{7}	$10^{7.5}$
S_3	0.114	$10^{6.5}$	$10^{7.2}$	$10^{7.9}$

[Mofat, Pascoli, Petcov, Schulz, Turner '18]

Flavour effects: leptogenesis scale can be lowered (some fine tuning), maximal asymmetry in different flavours; light neutrino masses satisfy "upper bound"

TeV-scale seesaw

Pilaftsis et al '03, ...

Basic idea: enhance CP asymmetry by mass degeneracy of heavy neutrinos, lower scale of B-L breaking, look for signatures at the LHC

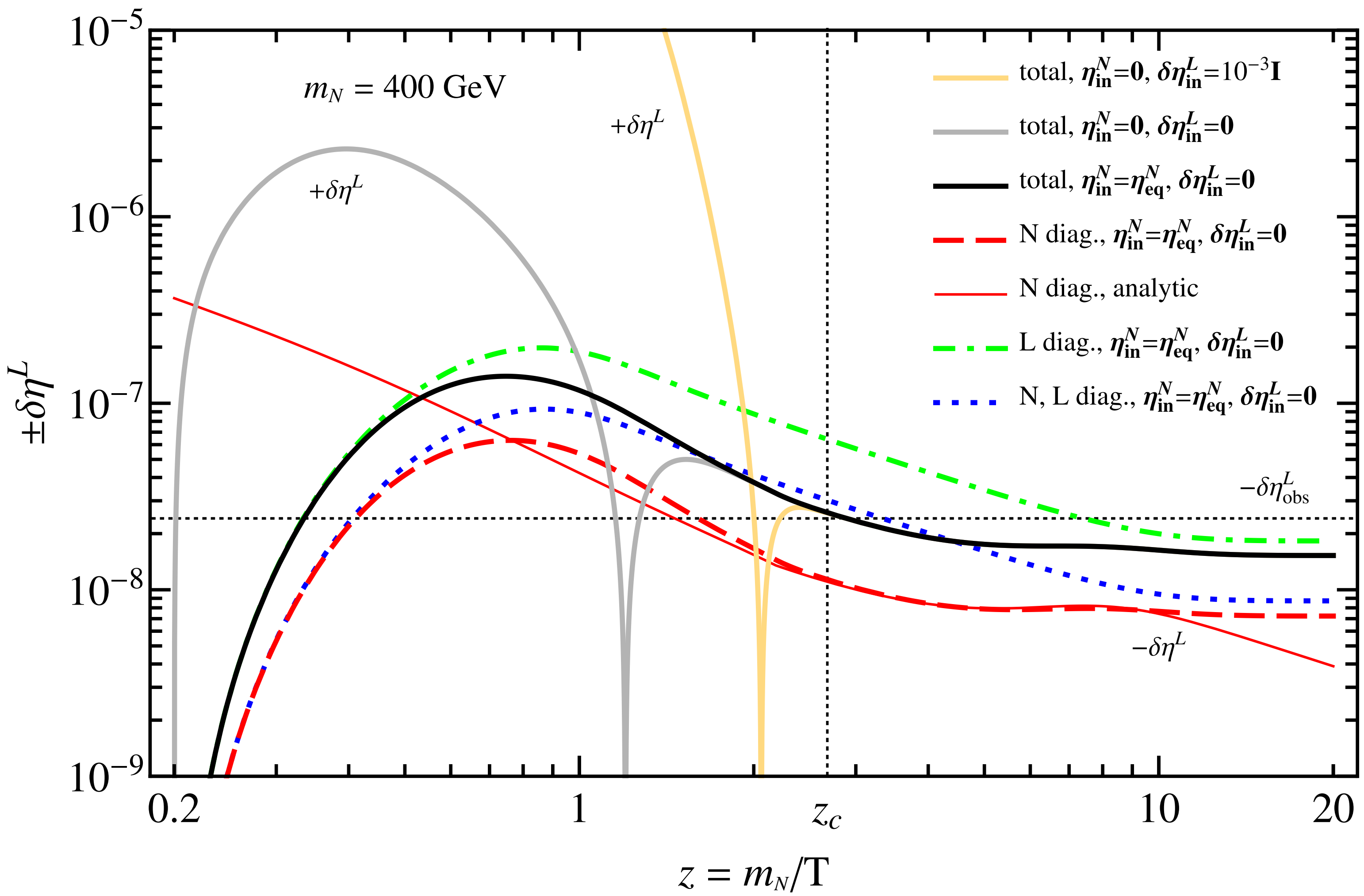
$$\Gamma_{\alpha l} \;=\; \Gamma(N_\alpha \to l_L^- + W^+) \;+\; \Gamma(N_\alpha \to \nu_{lL} + Z, H)$$

Leptonic asymmetries for individual lepton flavour in terms of the resummed neutrino Yukawa couplings:

$$\delta_{\alpha l} \;\equiv\; \frac{\Gamma_{\alpha l} \;-\; \Gamma^C_{\alpha l}}{\sum\limits_{l=e,\mu,\tau} \left(\Gamma_{\alpha l} \;+\; \Gamma^C_{\alpha l}\right)} \;=\; \frac{\left|\overline{\mathbf{h}}^\nu_{l\alpha}\right|^2 \;-\; \left|\overline{\mathbf{h}}^{\nu C}_{l\alpha}\right|^2}{\left(\overline{\mathbf{h}}^{\nu\dagger}\,\overline{\mathbf{h}}^\nu\right)_{\alpha\alpha} \;+\; \left(\overline{\mathbf{h}}^{\nu C\dagger}\,\overline{\mathbf{h}}^{\nu C}\right)_{\alpha\alpha}}$$

Leptonic asymmetries $\delta_{\alpha l}$ enhanced for degeneracy of heavy neutrinos (2-heavy neutrino mixing):

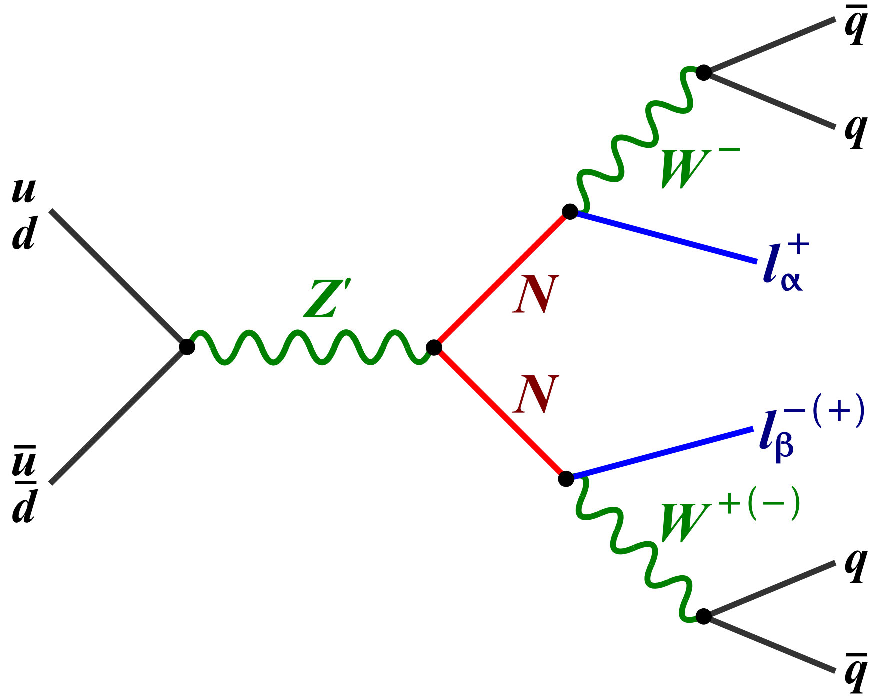
$$\delta_{\alpha l} \;\approx\; \frac{\mathrm{Im}\big[\,(\mathbf{h}^{\nu\dagger}_{\alpha l}\mathbf{h}^\nu_{l\beta})\,(\mathbf{h}^{\nu\dagger}\mathbf{h}^\nu)_{\alpha\beta}\big]}{(\mathbf{h}^{\nu\dagger}\mathbf{h}^\nu)_{\alpha\alpha}\,(\mathbf{h}^{\nu\dagger}\mathbf{h}^\nu)_{\beta\beta}}\;\frac{(m^2_{N_\alpha} - m^2_{N_\beta})\,m_{N_\alpha}\,\Gamma^{(0)}_{N_\beta}}{(m^2_{N_\alpha} - m^2_{N_\beta})^2 \;+\; m^2_{N_\alpha}\,\Gamma^{(0)2}_{N_\beta}}$$



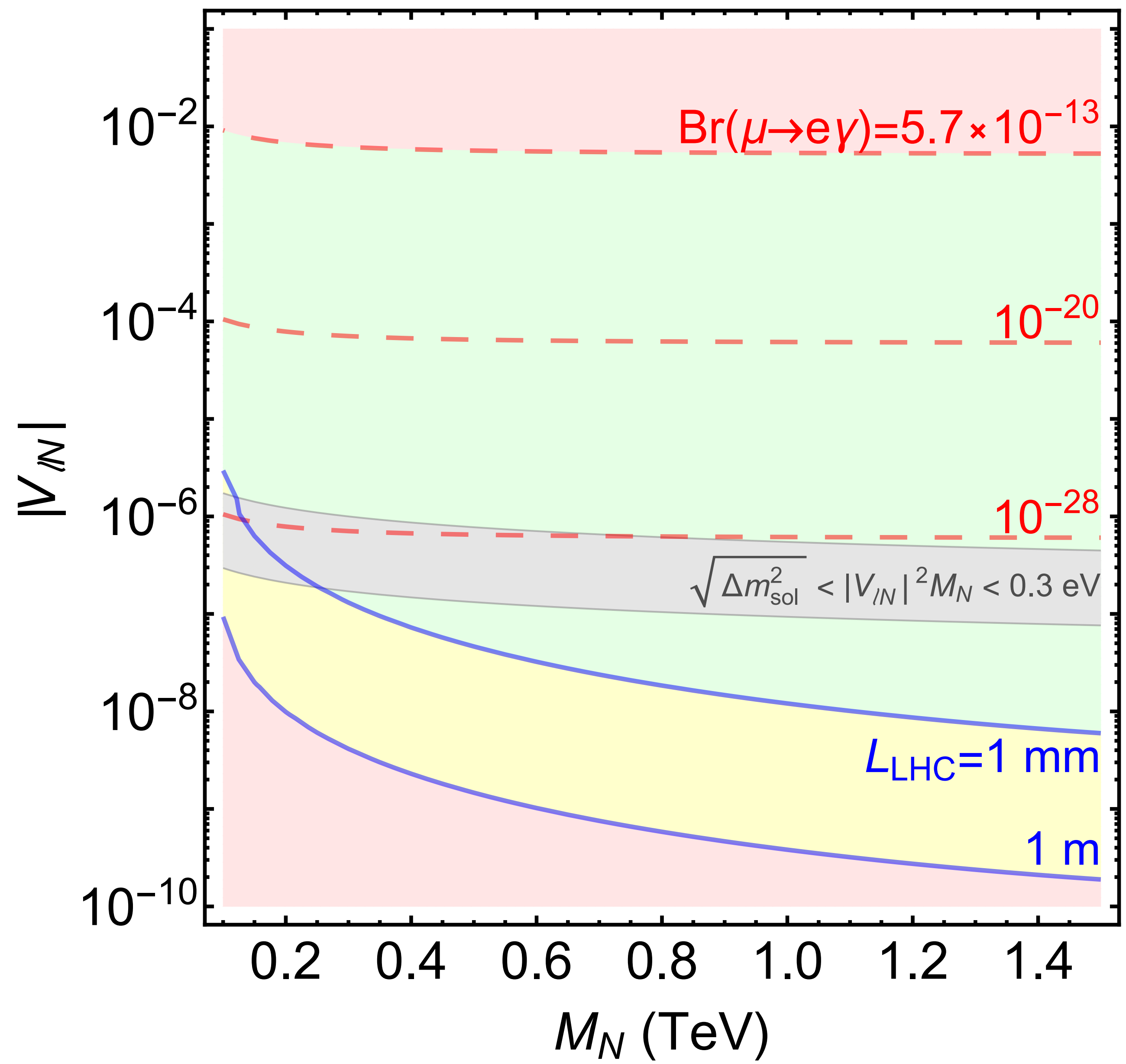
Parameter	Value
m_N	400 GeV
c	2×10^{-7}
$\frac{\Delta M_1}{m_N}$	-3×10^{-5}
$\frac{\Delta M_2}{m_N}$	$(-1.21 + 0.10\,i) \times 10^{-9}$
a	$(4.93 - 2.32\,i) \times 10^{-3}$
b	$(8.04 - 3.79\,i) \times 10^{-3}$
ϵ_e	$5.73\,i \times 10^{-8}$
ϵ_μ	$4.30\,i \times 10^{-7}$
ϵ_τ	$6.39\,i \times 10^{-7}$

[Dev, Millington, Pilaftsis, Teresi '15]

Resonant leptogenesis: strong enhancement of CP asymmetry, and baryon asymmetry, due to close degeneracy of heavy neutrino masses; flavour effects included; careful adjustment of parameters required



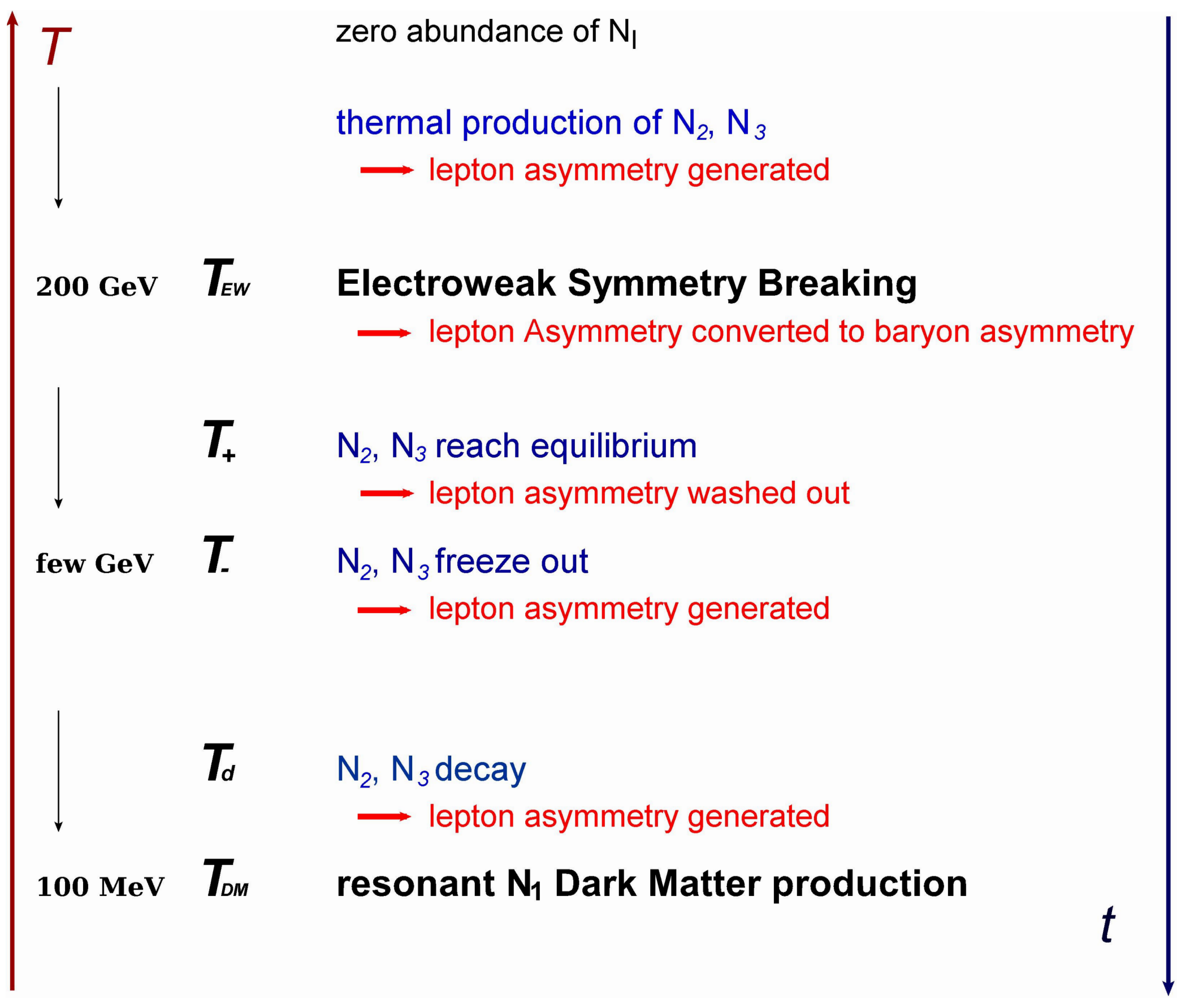
[Depisch, Dev, Pilaftsis '15]



Direct test: heavy neutrino production at the LHC (assume additional vector bosons), with lepton-flavour violation, displaced vertices; strong constraints from out-of-equilibrium condition in leptogenesis

GeV-scale seesaw

Canetti, Drewes & Shaposhnikov '13



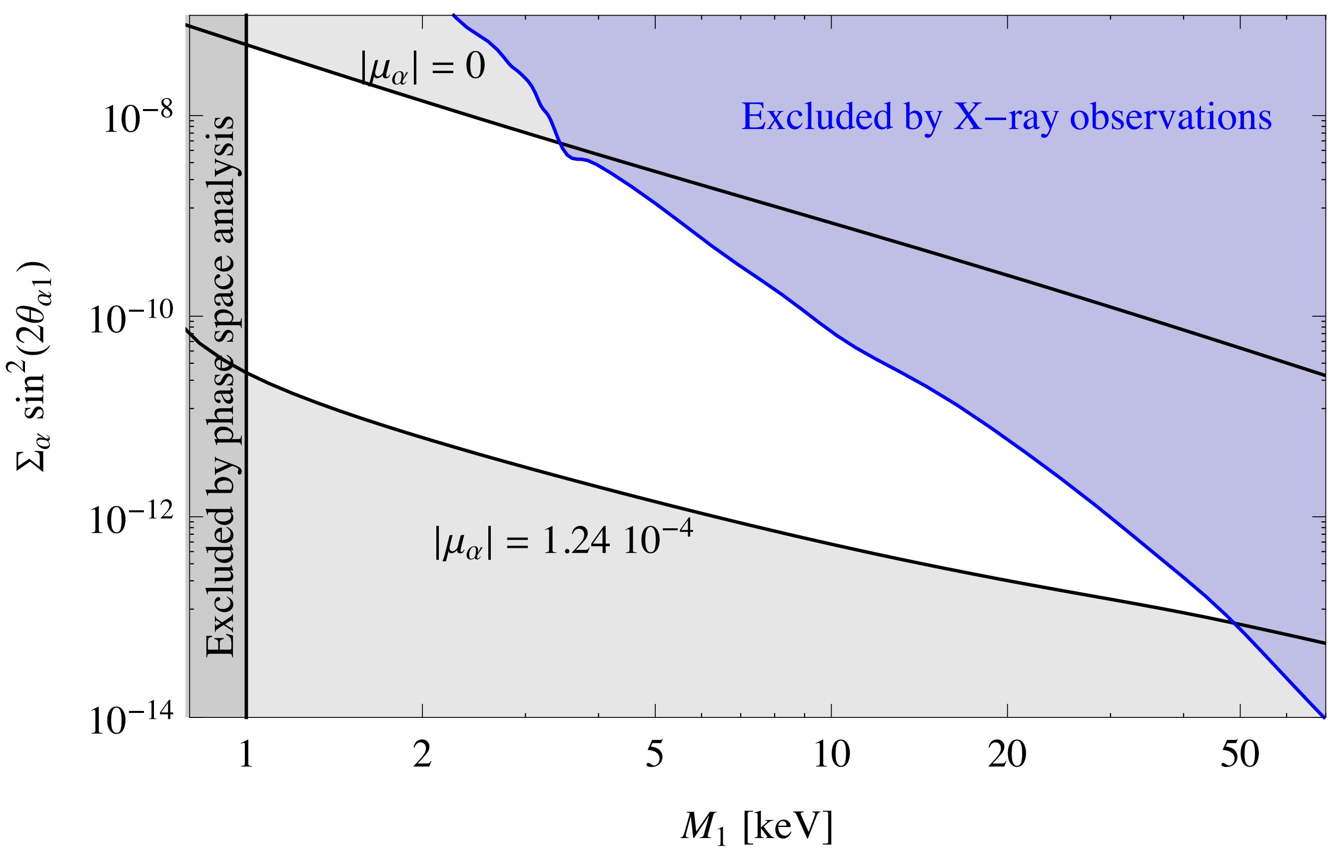
νM(inimal)S(tandard)M(odel) [Asaka, Blanchet, Shaposhnikov '05]: NO's, DM and baryon asymmetry just from SM with 3 N's; baryon asymmetry from N-oscillations [Akhmedov, Rubakov, Smirnov '98] and sphaleron conversion; resonant enhancement of CP asymmetry:

$$\delta = \frac{|M_2 - M_3|}{|M_2 + M_3|} \sim 10^{-13}$$

thermal history:

$$T \sim 100 \text{ GeV} : |\mu_\alpha| \sim 10^{-10}$$

$$T \sim 100 \text{ MeV} : |\mu_\alpha| \gtrsim 8 \times 10^{-6}$$



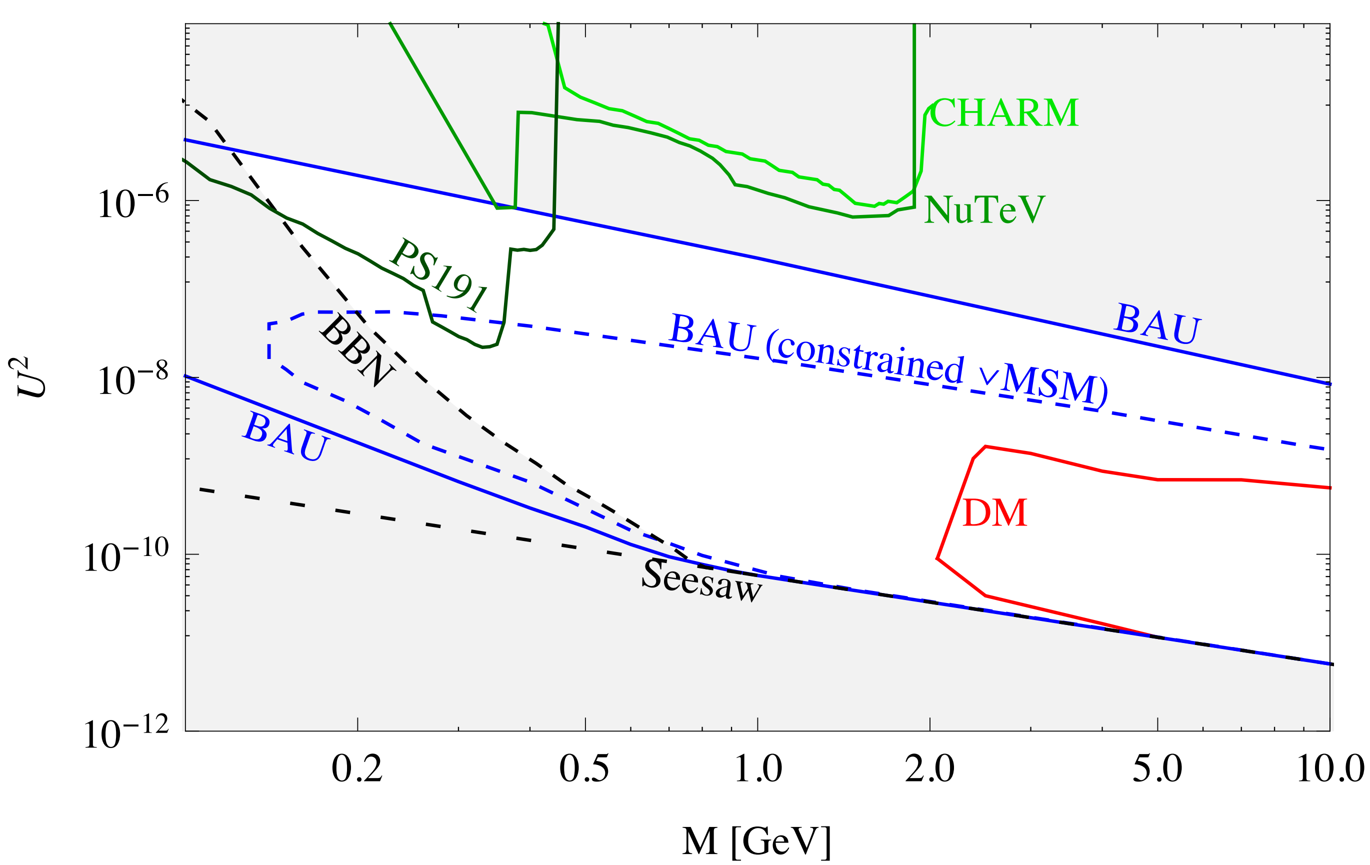
Dark Matter (keV mass, small active-sterile mixing):

$$1\ \text{keV} < M_1 < 50\ \text{keV}$$

$$\theta = m_D M^{-1}, \quad U^2 = \text{tr}(\theta^\dagger \theta)$$

$$10^{-13} \lesssim \sin^2(2\theta_{\alpha 1}) \lesssim 10^{-7}$$

3.5 keV line welcome!(?)



Lower bound on masses of heavier RH neutrinos:

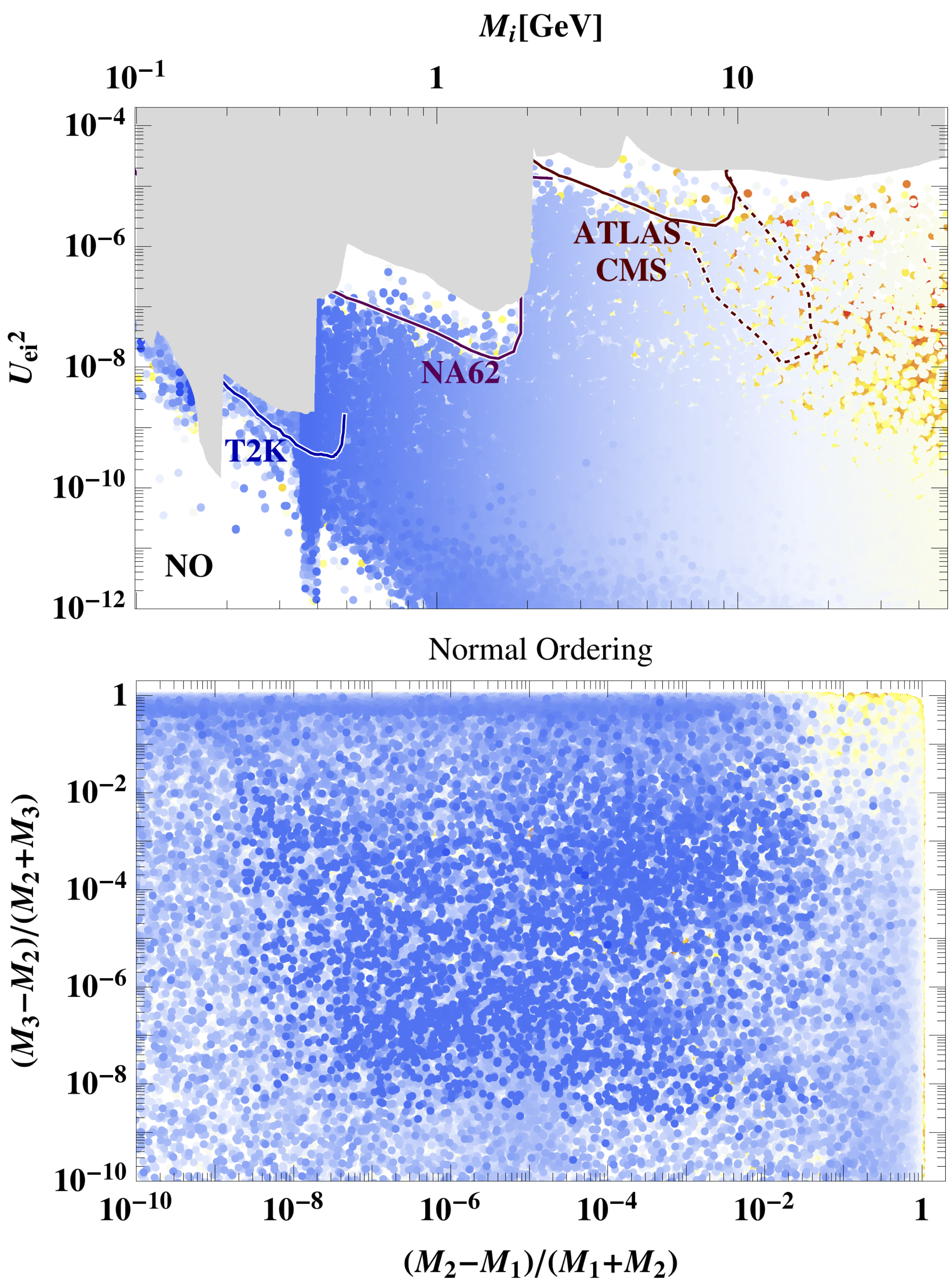
$$M_{2,3} \gtrsim 2\ \text{GeV}$$

can be searched for at SHiP

Prediction for lightest ν-mass:

$$m_1 \simeq 0$$

GeV-scale leptogenesis with 3 heavy neutrinos



[Abada, Arcadi, Domcke, Drewes, Klaric, Lucente '18]

Give up dark matter explanation; for 3 N's, with 2 mass differences, oscillations of GeV N's can generate baryon asymmetry with much smaller mass-degeneracies and much larger active-sterile mixing angles; observable effects in various experiments. What is the theoretical motivation for GeV sterile neutrinos? Scenario testable in collider experiments.

Leptogenesis - piece of a puzzle

Can "standard thermal leptogenesis" (GUT scale) be tested? RH neutrinos very heavy! Compare with grand unification:

grand unification	**GUT-scale leptogenesis**
fermion reps of SM	connection of B & L
gauge coupling unification (large GUT scale)	small neutrino masses (GUT seesaw scale)
relations between Yukawa couplings	relation between baryon and lepton asymmetries
proton decay	Majorana neutrinos
proton decay branching ratios	ν masses and mixings

- Majorana nature of neutrinos; lepton flavour violating processes (in supersymmetric GUTs, $\mu \to e\gamma$, ...); connection with dark matter

- light neutrino masses and phases, using relations between quark and lepton mass matrices; key observables: ν-less $\beta\beta$-decay, absolute neutrino mass scale, magnitude and sign of baryon asymmetry

Anarchy with U(1) flavour symmetry

[Lu, Murayama '14]

Instructive example: leptogenesis by Monte Carlo; input: anarchy & U(1) flavour symmetry:

$$\Delta\mathcal{L} \supset -\epsilon^{ab}\bar{L}_a H_b^\dagger y_\nu \nu_R - \frac{1}{2}\bar{\nu}_R^c m_R \nu_R + h.c.$$

$$y_\nu \sim O(1)\ , \quad m_R \sim \mathcal{M}\begin{pmatrix} \epsilon^4 & \epsilon^3 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & \epsilon \\ \epsilon^2 & \epsilon & 1 \end{pmatrix}$$

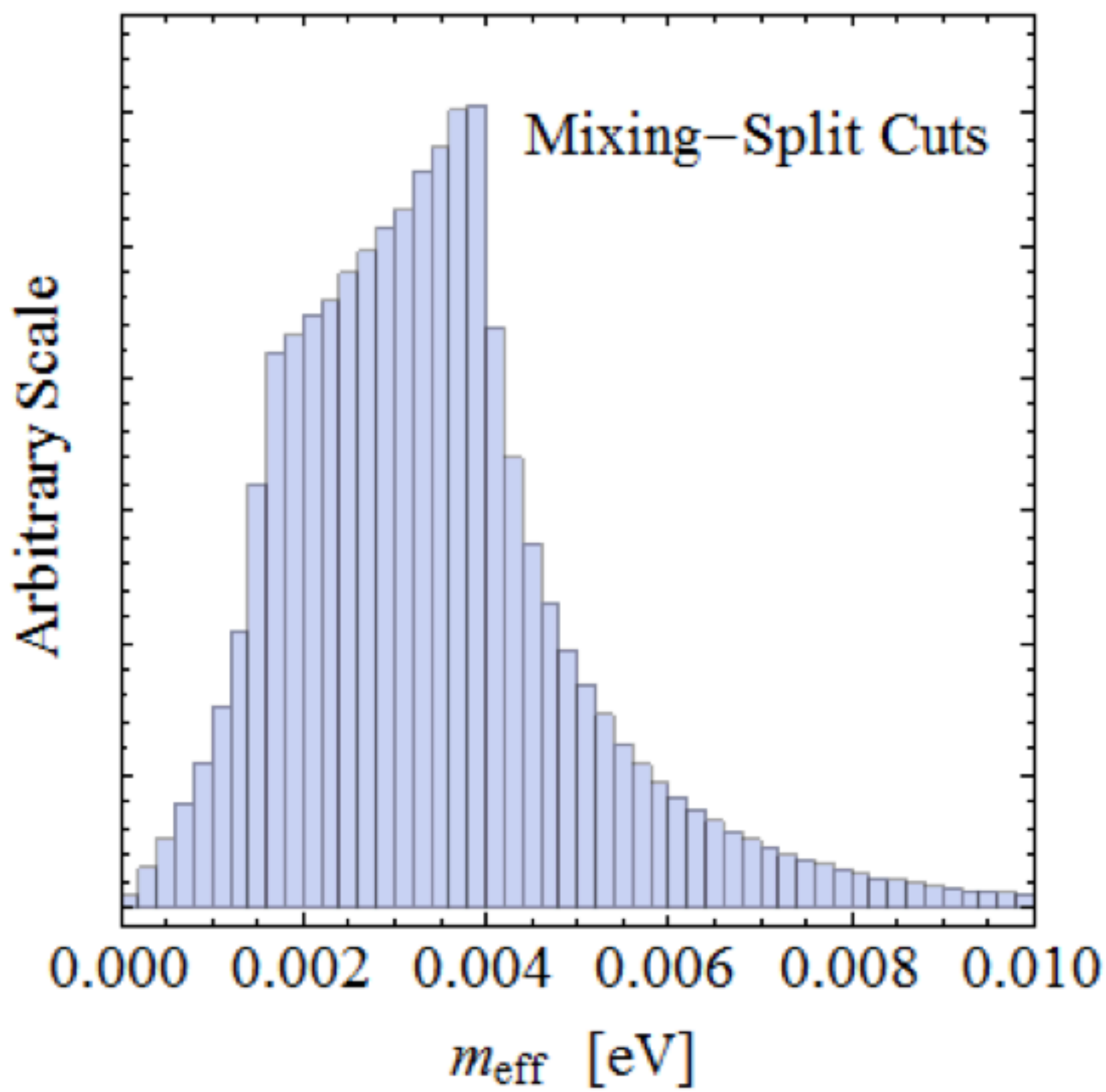
with $\epsilon \simeq 0.1$ and $\mathcal{M}$ fixed by $\Delta m_l^2 = 2.5\times 10^{-3}\ \mathrm{eV}^2$; random coefficients (Gaussian measure, independent of basis); data (mixing-split cuts):

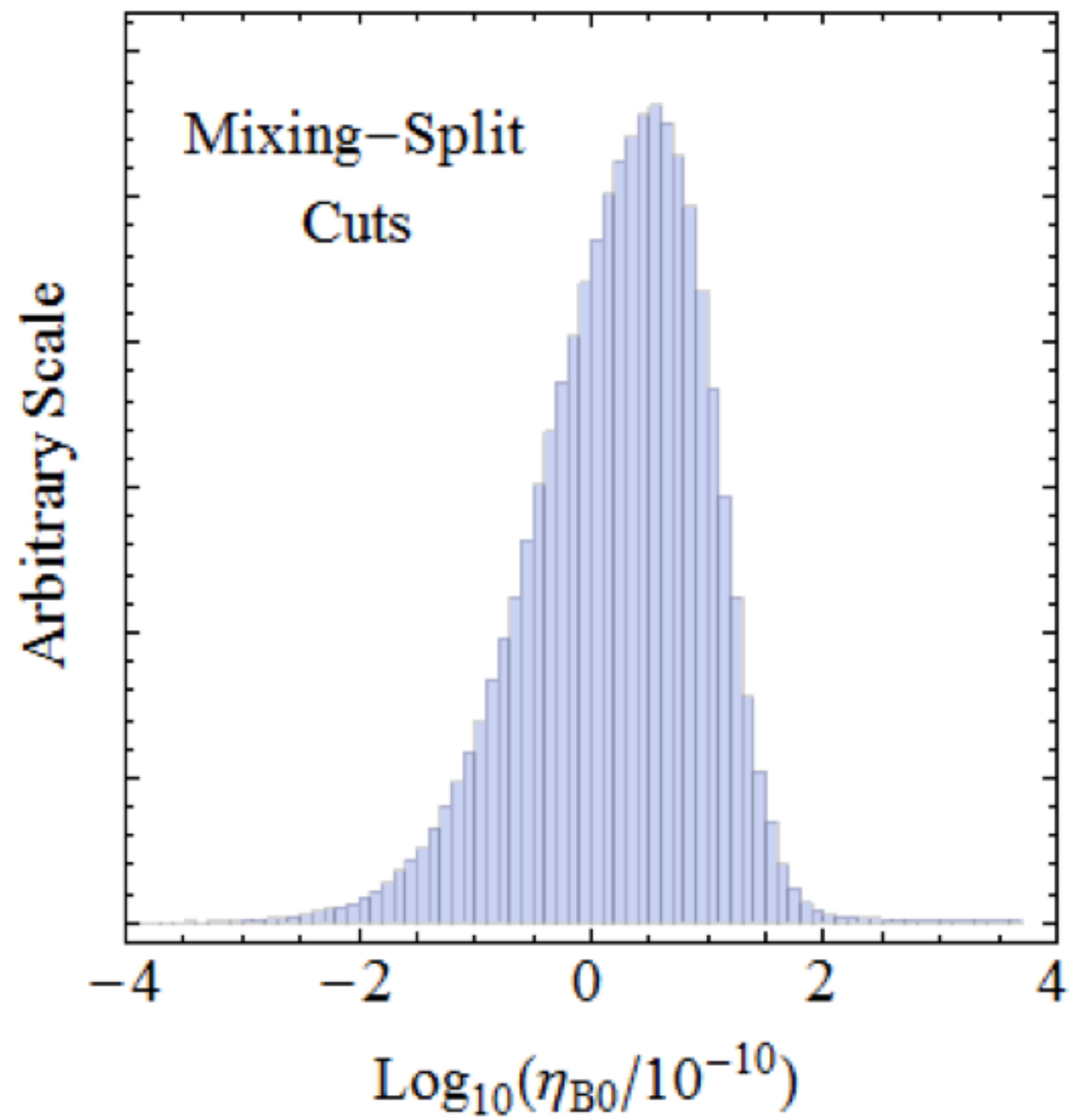
$$\sin^2 2\theta_{23} = 1.0$$

$$\sin^2 2\theta_{12} = 0.857$$

$$\sin^2 2\theta_{13} = 0.095$$

$$R = \frac{\Delta m_s^2}{\Delta m_l^2} \in R_{\mathrm{exp}} \times (1-0.05, 1+0.05)$$





$$m_{\mathrm{eff}} \equiv \left| \sum_i m_i U^2_{v,ei} \right|$$

Normal hierarchy dominant, inverted hierarchy only 0.1%; ν-less ββ-decay: $m_{\mathrm{eff}} \sim 2 - 4\ \mathrm{meV}$; baryon asymmetry peaks at observed value!

Semi-Anarchy with U(1) flavour symmetry

[WB, Domcke, Schmitz '12]

For comparison: semi-anarchy & U(1) flavour symmetry; input:

$$h^{(\nu)} \sim \eta^a \begin{pmatrix} \eta^{d+1} & \eta^{c+1} & \eta^{b+1} \\ \eta^d & \eta^c & \eta^b \\ \eta^d & \eta^c & \eta^b \end{pmatrix} , \quad M_R \sim \begin{pmatrix} \eta^{2d} & 0 & 0 \\ 0 & \eta^{2c} & 0 \\ 0 & 0 & \eta^{2b} \end{pmatrix} ,$$

$$\to m_\nu \sim \eta^{2a} \begin{pmatrix} \eta^2 & \eta & \eta \\ \eta & 1 & 1 \\ \eta & 1 & 1 \end{pmatrix} , \quad h^{(e)} \sim \eta^a \begin{pmatrix} \eta^3 & \eta^2 & \eta \\ \eta^2 & \eta & 1 \\ \eta^2 & \eta & 1 \end{pmatrix}$$

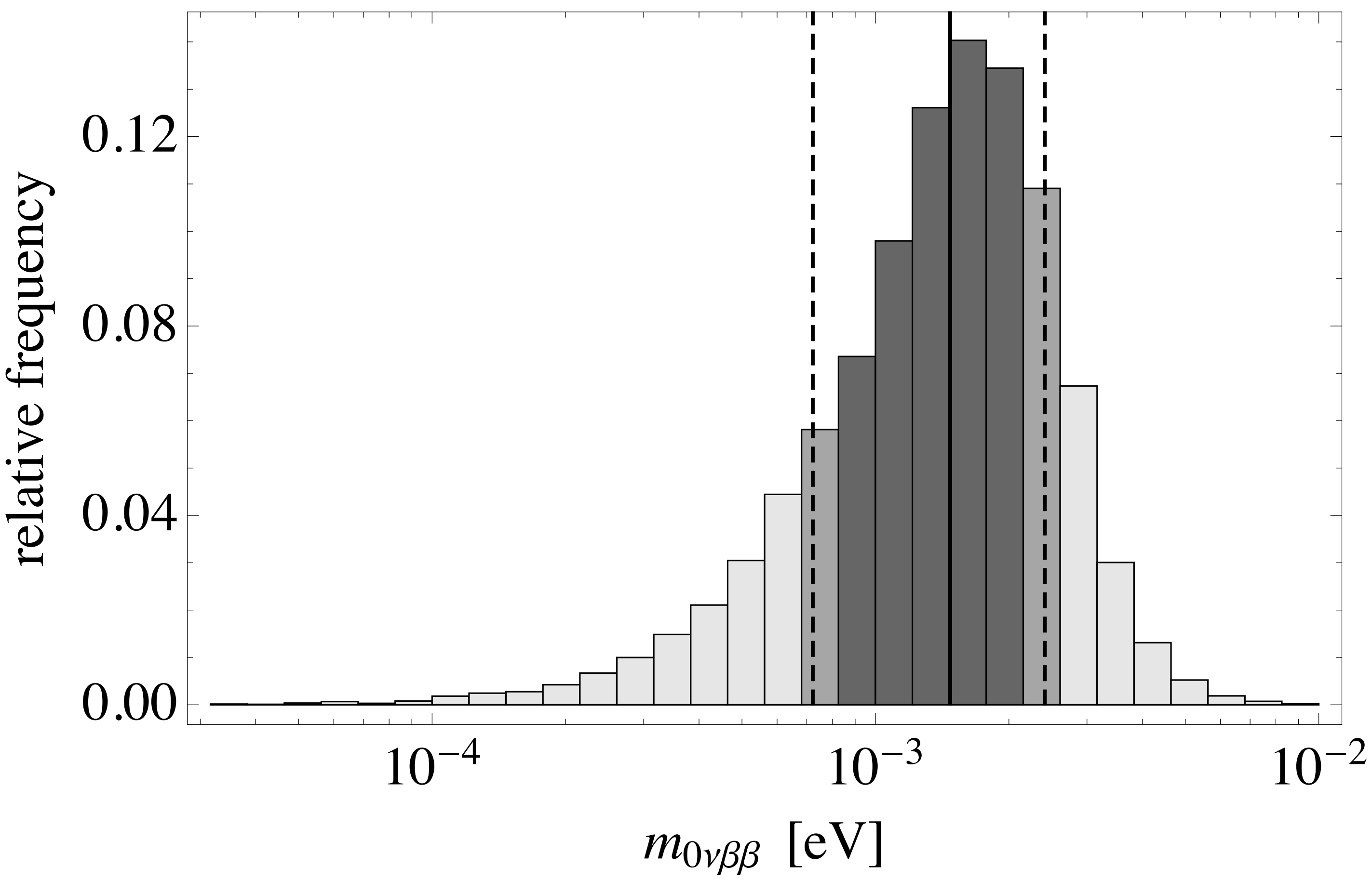
with $0 \leq a \leq 1$ $(\tan\beta)$; $b \leq c \leq d$; $a + d = 2$; 39 real parameters, random numbers O(1), uniform on logarithmic scale; data:

$$2.07 \times 10^{-3}\,\mathrm{eV}^2 \leq |\Delta m^2_{\mathrm{atm}}| \leq 2.75 \times 10^{-3}\,\mathrm{eV}^2 ,$$

$$7.05 \times 10^{-5}\,\mathrm{eV}^2 \leq \Delta m^2_{\mathrm{sol}} \leq 8.34 \times 10^{-5}\,\mathrm{eV}^2 ,$$

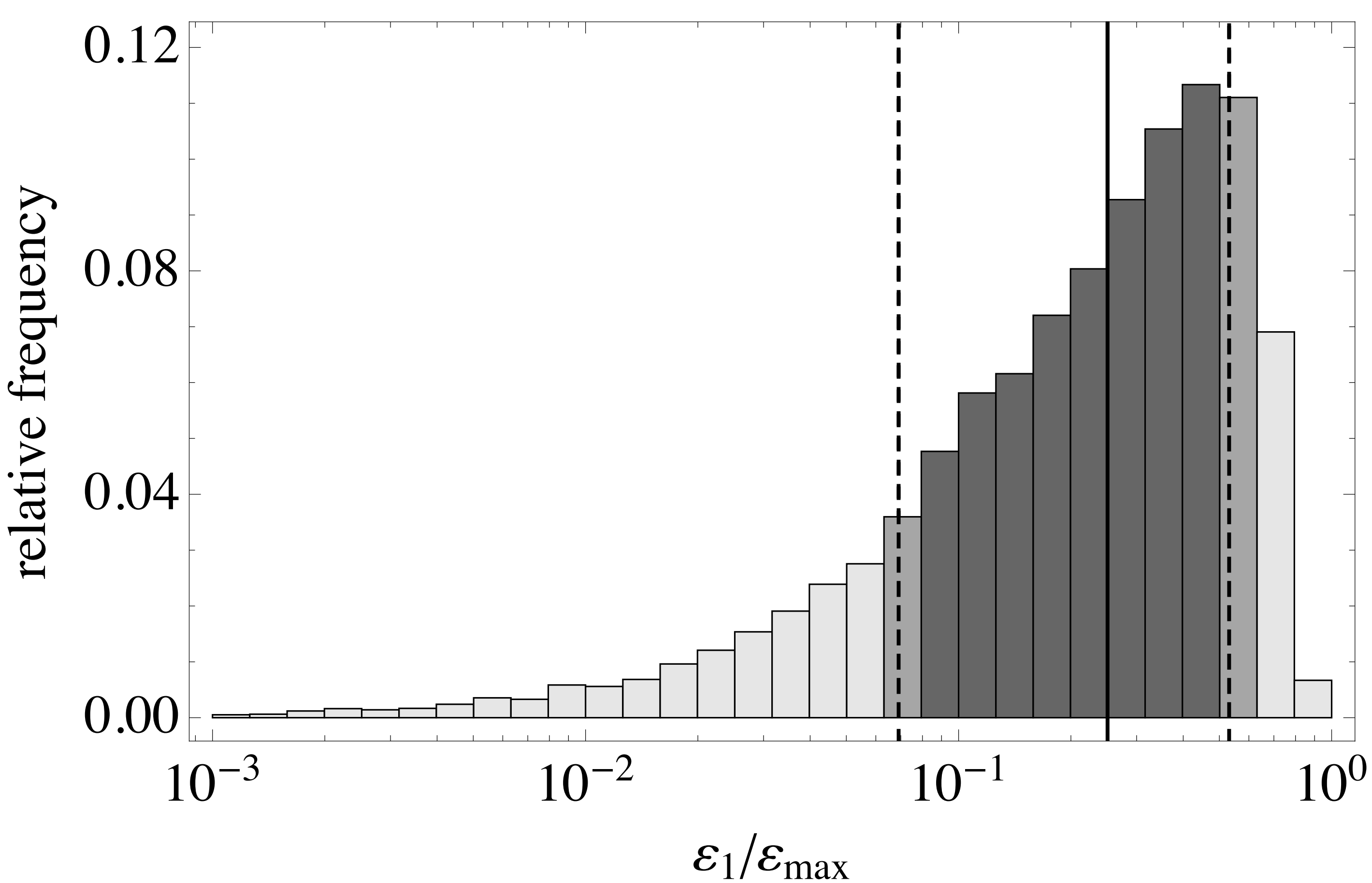
$$0.75 \leq \sin^2(2\theta_{12}) \leq 0.93 ,$$

$$0.88 \leq \sin^2(2\theta_{23}) \leq 1$$



effective neutrino mass:

$$m_{0\nu\beta\beta} = 1.5^{+0.9}_{-0.8}\ \mathrm{meV}$$



mean corresponds to

$$\eta_B \sim 5 \times 10^{-10}$$

observed baryon asymmetry obtained for hierarchical heavy neutrinos (strong washout regime favoured)!

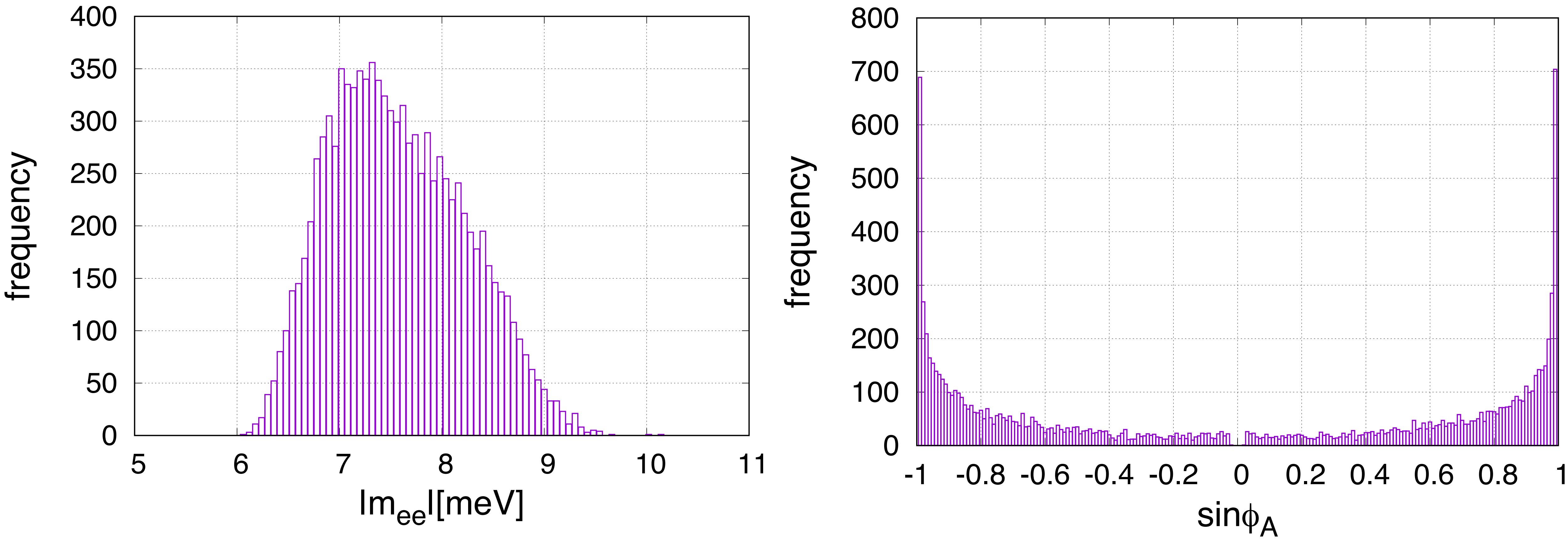
Occam's razor

[Kaneta, Shimizu, Tanimoto, Yanagida'16]

More ambitious: predict sign of baryon asymmetry! Ansatz: restrict mass matrices by "texture zeros"; light-neutrino mass matrix can be completely reconstructed from experiment, includes 2 phases which determine sign of baryon asymmetry (vary parameters consistent with present data)

$$M_E = \begin{pmatrix} m_e & 0 & 0 \\ 0 & m_\mu & 0 \\ 0 & 0 & m_\tau \end{pmatrix}_{LR} , \quad m_D = \begin{pmatrix} 0 & A & 0 \\ A' & 0 & B \\ 0 & B' & C \end{pmatrix}_{LR} ,$$

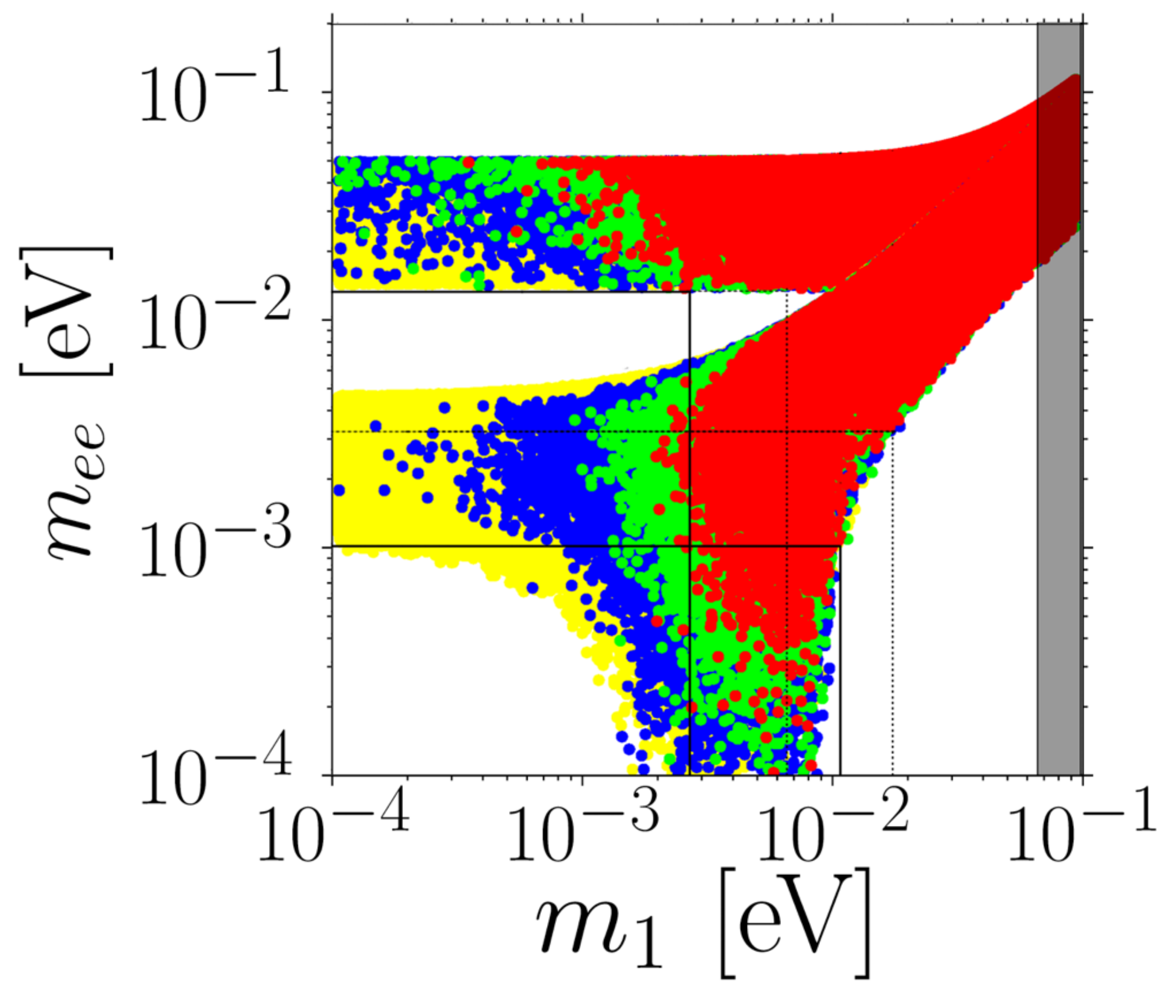
$$M_R = \begin{pmatrix} M_1 e^{-i\phi_A} & 0 & 0 \\ 0 & M_2 e^{-i\phi_B} & 0 \\ 0 & 0 & M_3 \end{pmatrix}_{RR}$$

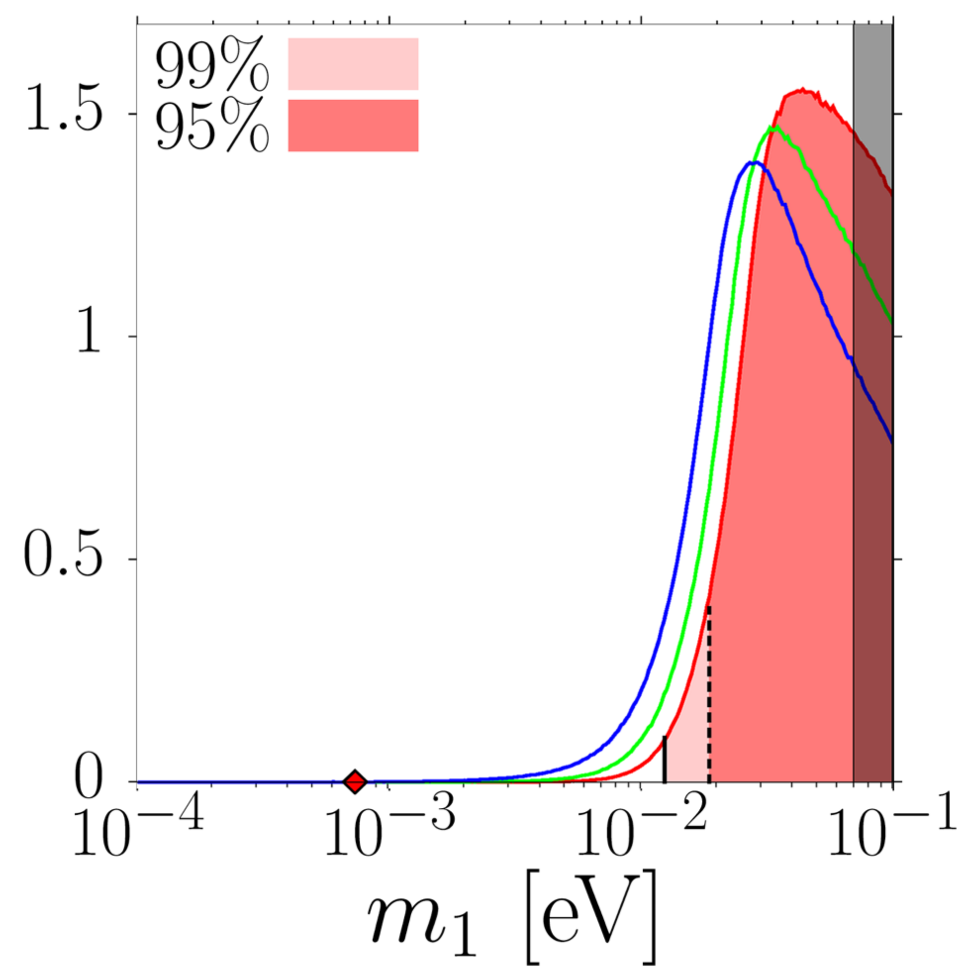


Results of Monte Carlo analysis (random numbers, linear scale):
neutrino mass for ν-less ββ-decay: $m_{ee} \simeq 7 - 8\ \mathrm{meV}$
sign of baryon asymmetry: $\mathrm{sign}[\eta_B] = \mathrm{sign}[\sin\phi_A]$
improved measurements will eventually resolve ambiguity

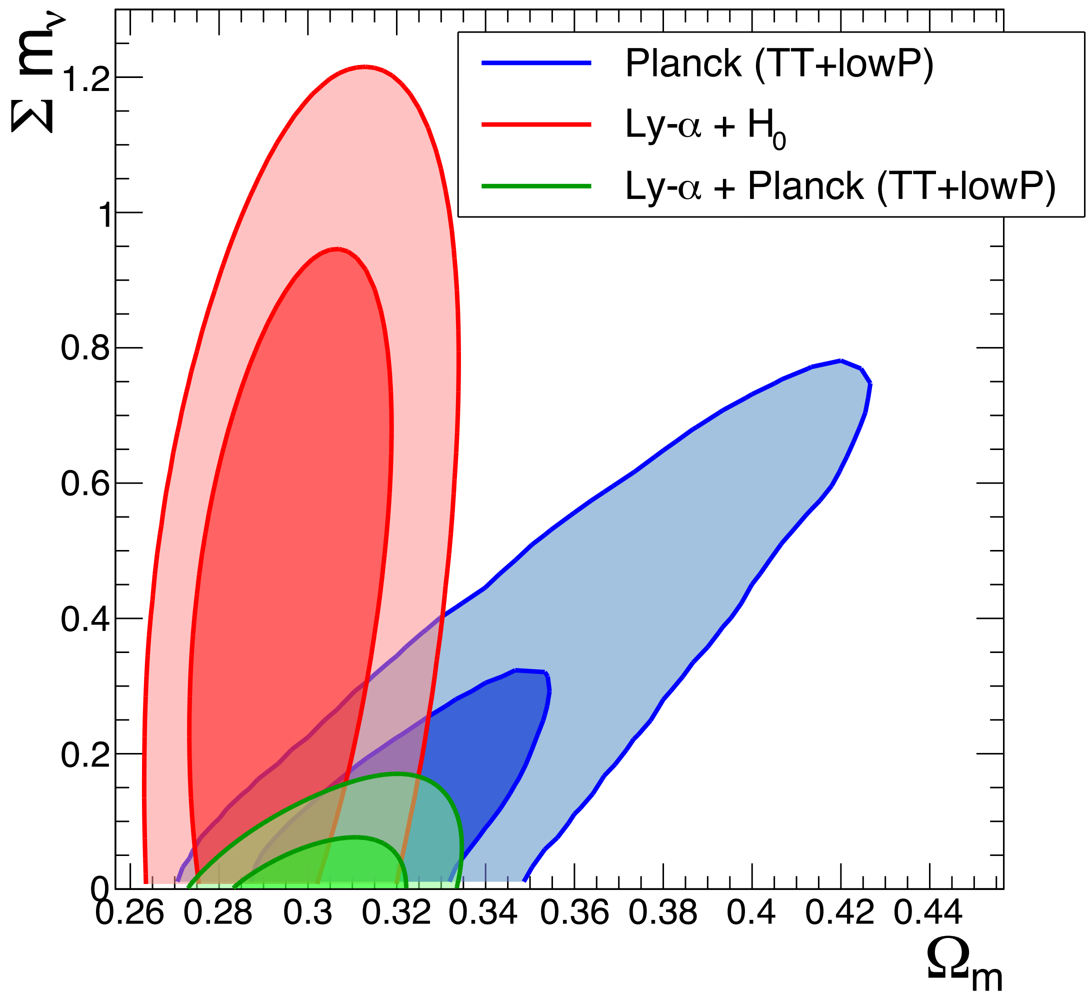
Independence of initial conditions

[Di Bari, King, Fiorentin '14]





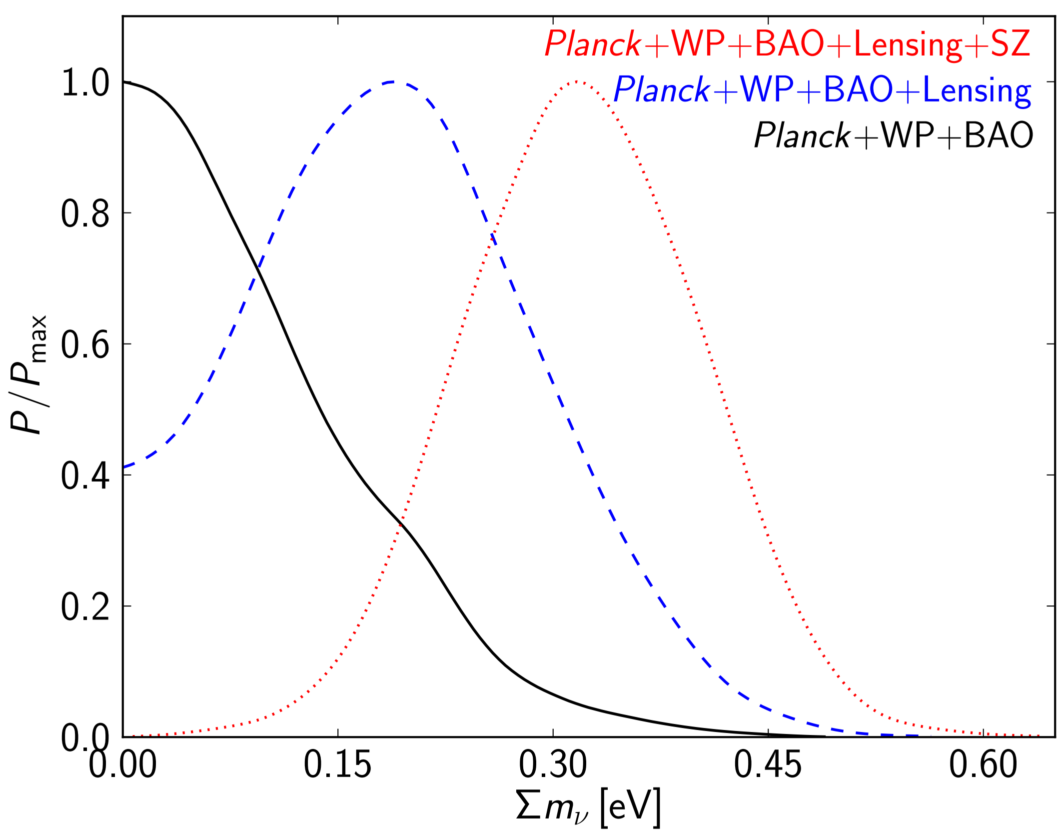
Red: demand washout of initial B+L asymmetry $\eta_B^i \sim 10^7 \eta_B$("independence" of initial B+L asymmetry); NH: for 99% of scatter points $m_1 \gtrsim 10\ \mathrm{meV}$!! (IH less restrictive); experimental progress: soon $\sum m_\nu = 90 \pm 10\ \mathrm{meV}$?? Would exclude seesaw with 2 N's, νMSM and Affleck-Dine leptogenesis !!



[Palanque-Delabrouille et al '15]

CMB & Lyman-alpha:

$$m_{\rm tot} \;<\; 0.12\ \mathrm{eV}$$



[Battye & Moss '14]

CMB, BAO, lensing & galaxy counts (PRL) :

$$m_{\rm tot} \;=\; (0.320 \pm 0.081)\ \mathrm{eV}$$

thermal leptogenesis ruled out ??

Leptogenesis, inflation & dark matter

[WB, Domcke, Kamada, Schmitz '13, '14]

Leptogenesis & gravitinos: for thermal leptogenesis and typical superparticle masses, thermal production yields observed amount of dark matter:

$$\Omega_{3/2}h^2 = C\left(\frac{T_R}{10^{10}\,\mathrm{GeV}}\right)\left(\frac{100\,\mathrm{GeV}}{m_{3/2}}\right)\left(\frac{m_{\tilde{g}}}{1\,\mathrm{TeV}}\right)^2 , \quad C \sim 0.5$$

$\Omega_{3/2}h^2 \sim 0.1$ is natural value; but why is reheating temperature close to minimal LG temperature?

Simple observation: heavy neutrino decay width (for typical LG parameters)

$$\Gamma_{N_1} = \frac{\widetilde{m}_1}{8\pi}\left(\frac{M_1}{v_\mathrm{F}}\right)^2 \sim 10^3\ \mathrm{GeV}\ , \quad \widetilde{m}_1 \sim 0.01\ \mathrm{eV}\ , \quad M_1 \sim 10^{10}\ \mathrm{GeV}$$

yields reheating temperature (for gas of decaying heavy neutrinos)

$$T_R \sim 0.2 \cdot \sqrt{\Gamma^0_{N_1} M_P} \sim 10^{10}\ \mathrm{GeV}$$

wanted for gravitino DM. *Intriguing hint or misleading coincidence?*

Example: **cosmological B-L breaking after inflation**; consider supersymmetric SM with right-handed neutrinos:

$$W_M = h^u_{ij}\mathbf{10}_i\mathbf{10}_j H_u + h^d_{ij}\mathbf{5}^*_i\mathbf{10}_j H_d + h^\nu_{ij}\mathbf{5}^*_i n^c_j H_u + h^n_i n^c_i n^c_i S_1$$

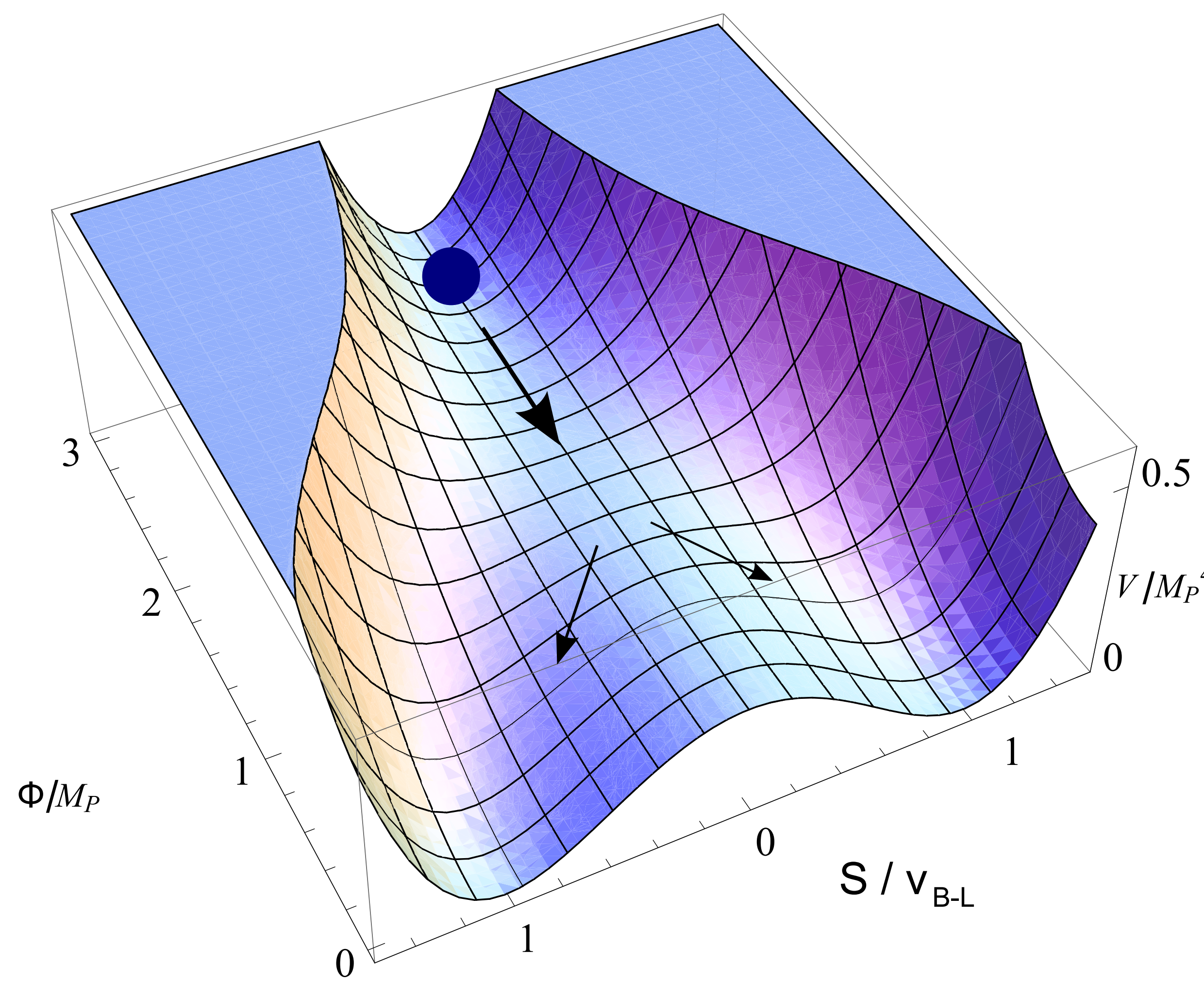
in SU(5) notation: $\mathbf{10} \supset (q, u^c, e^c),\ \mathbf{5}^* \supset (d^c, l),\ n^c \supset (\nu^c)$; B-L breaking:

$$W_{B-L} = \lambda\Phi\left(\frac{1}{2}v^2_{B-L} - S_1 S_2\right)$$

$\langle S_{1,2}\rangle = v_{B-L}/\sqrt{2}$ yields heavy neutrino masses.

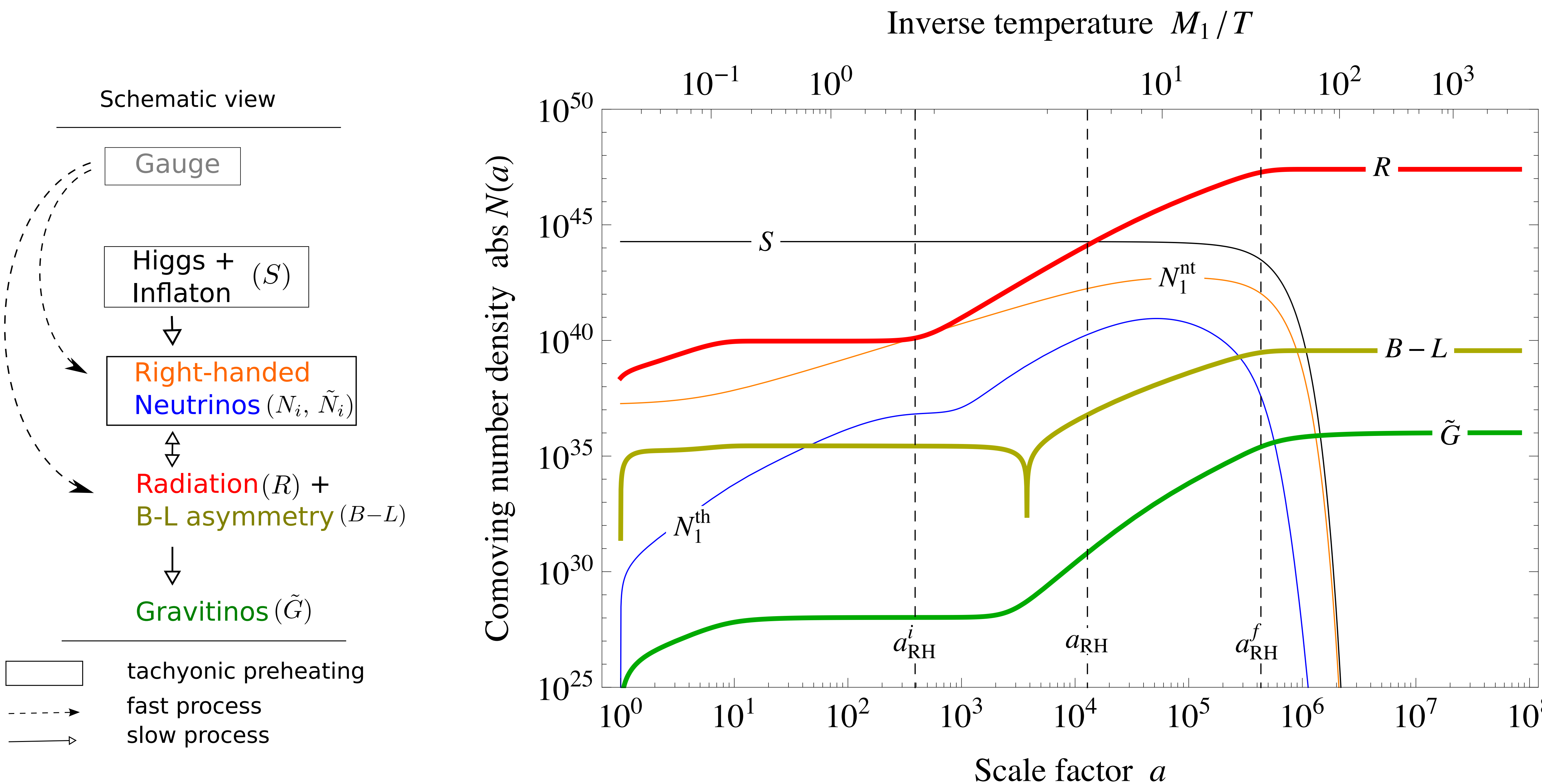
Lagrangian is determined by low energy physics: quark, lepton, neutrino masses etc, but it *contains all ingredients wanted in cosmology*: inflation, leptogenesis, dark matter, ..., all related!

Technically: Abelian Higgs model in unitary gauge; inflation ends with phase transition (“tachyonic preheating”, “spinodal decomposition”)



time-dependent masses of B-L Higgs, inflaton, heavy neutrinos ... (bosons and fermions):

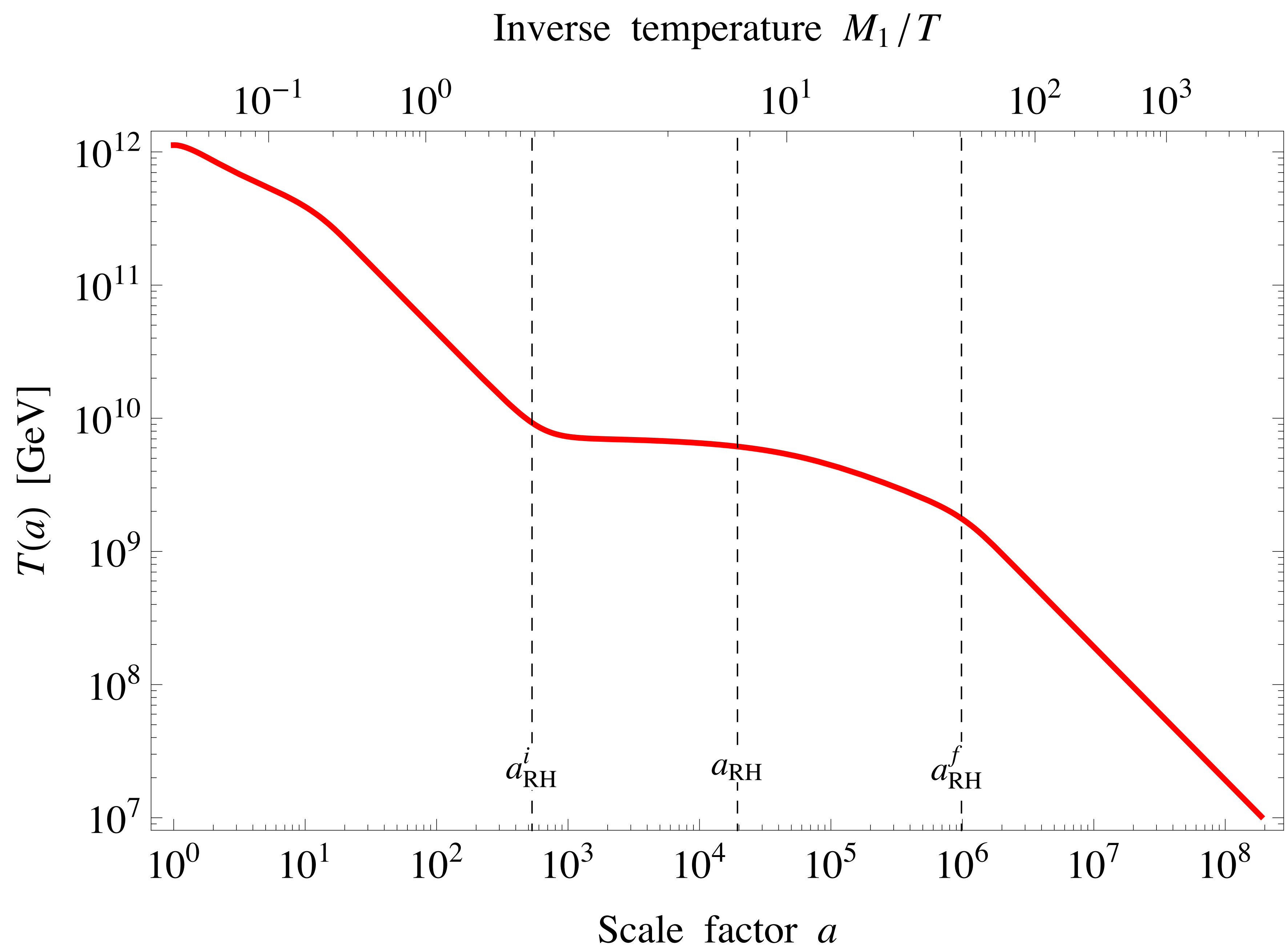
$$m_\sigma^2 = \frac{1}{2}\lambda(3v^2(t) - v_{B-L}^2)\ , \quad m_\phi^2 = \lambda v^2(t)\ , \quad M_i^2 = (h_i^n)^2 v^2(t)\ \ldots$$



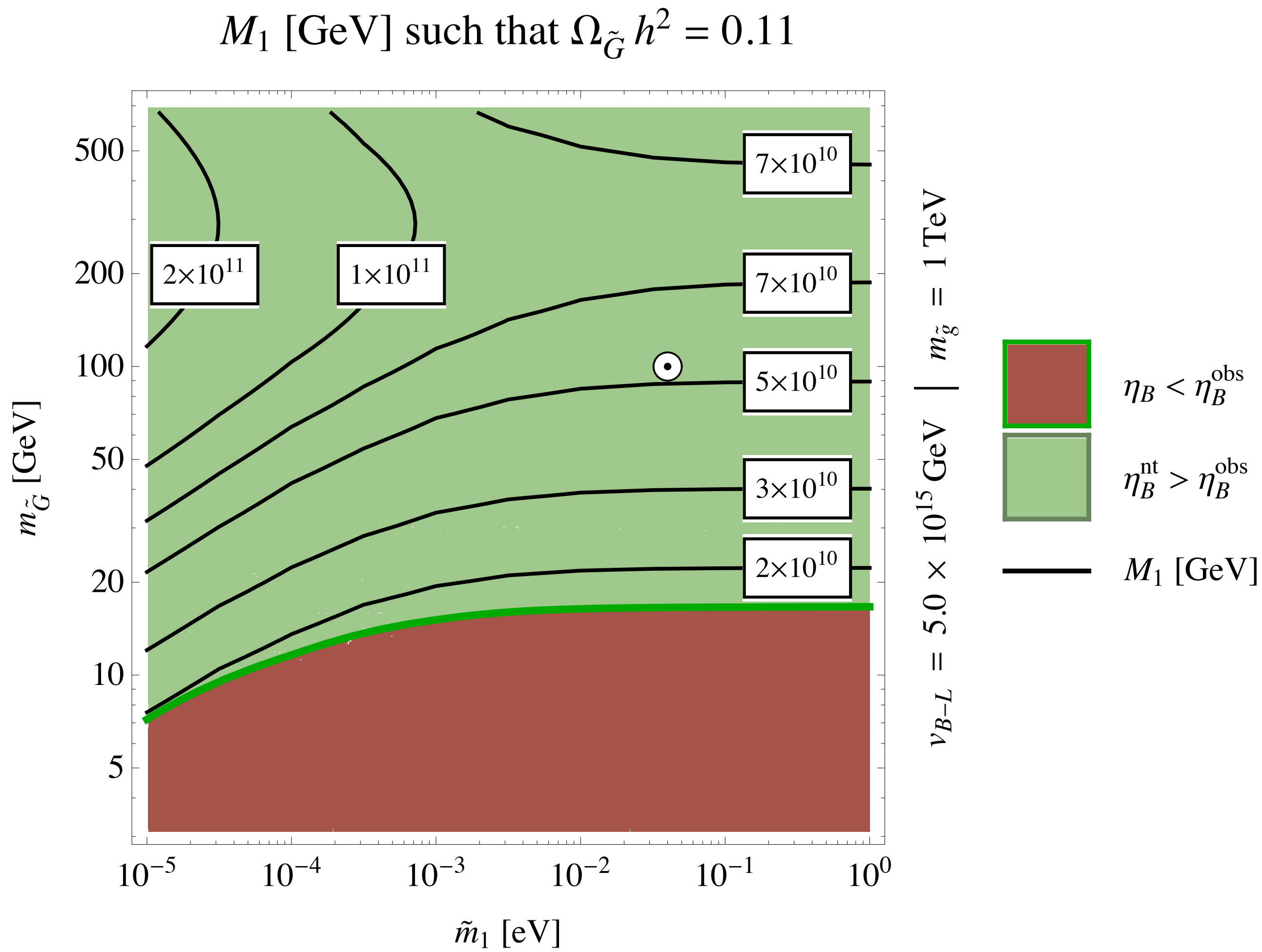
Transition from end of inflation to hot early universe (typical parameters), calculated by means of Boltzmann equations:

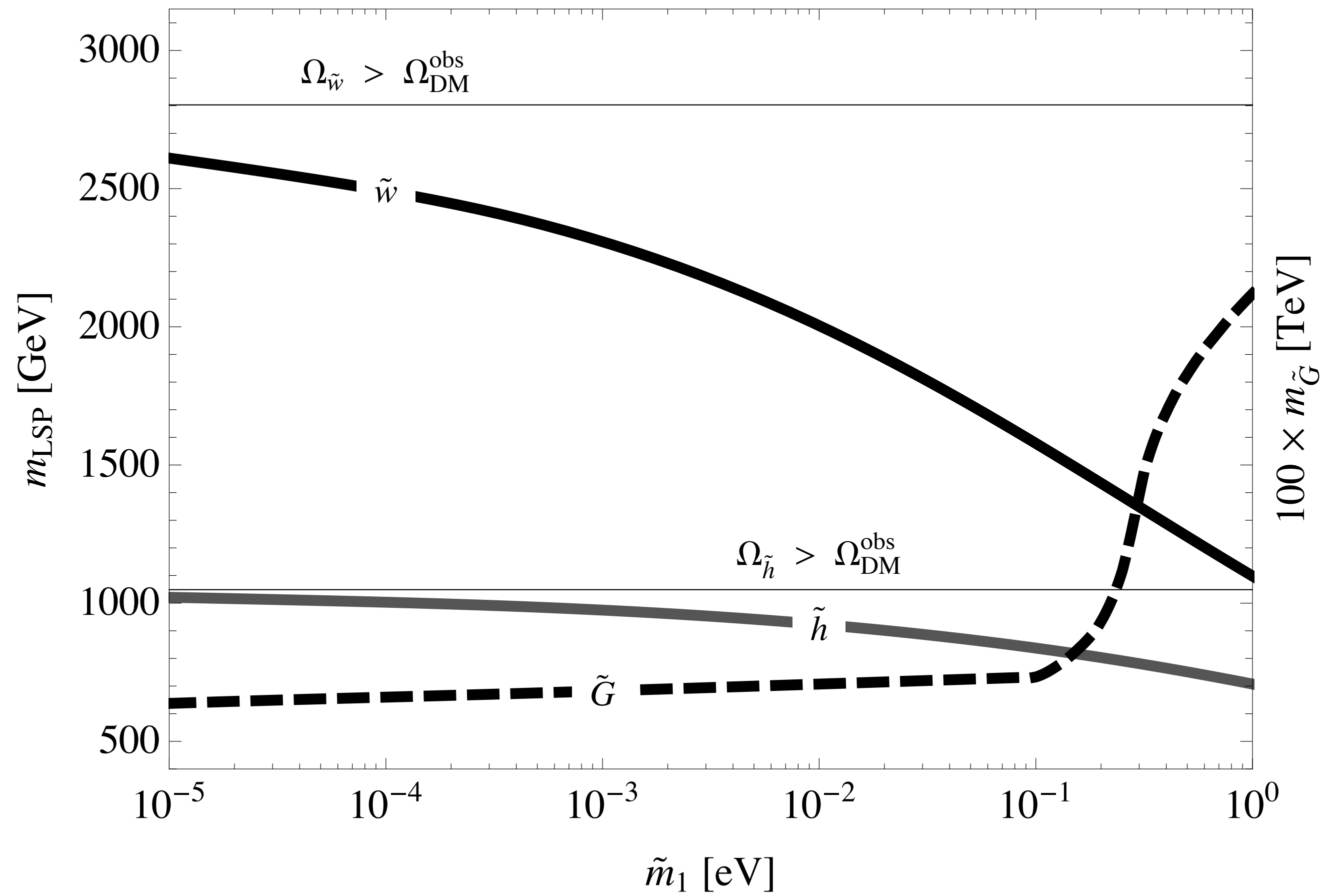
$$E\left(\frac{\partial}{\partial t} - Hp\frac{\partial}{\partial p}\right) f_X(t,p) = \sum_{i'j'..}\sum_{ij..} C_X(Xi'j'.. \leftrightarrow ij..)$$

yields *correct baryon asymmetry* and *dark matter abundance*

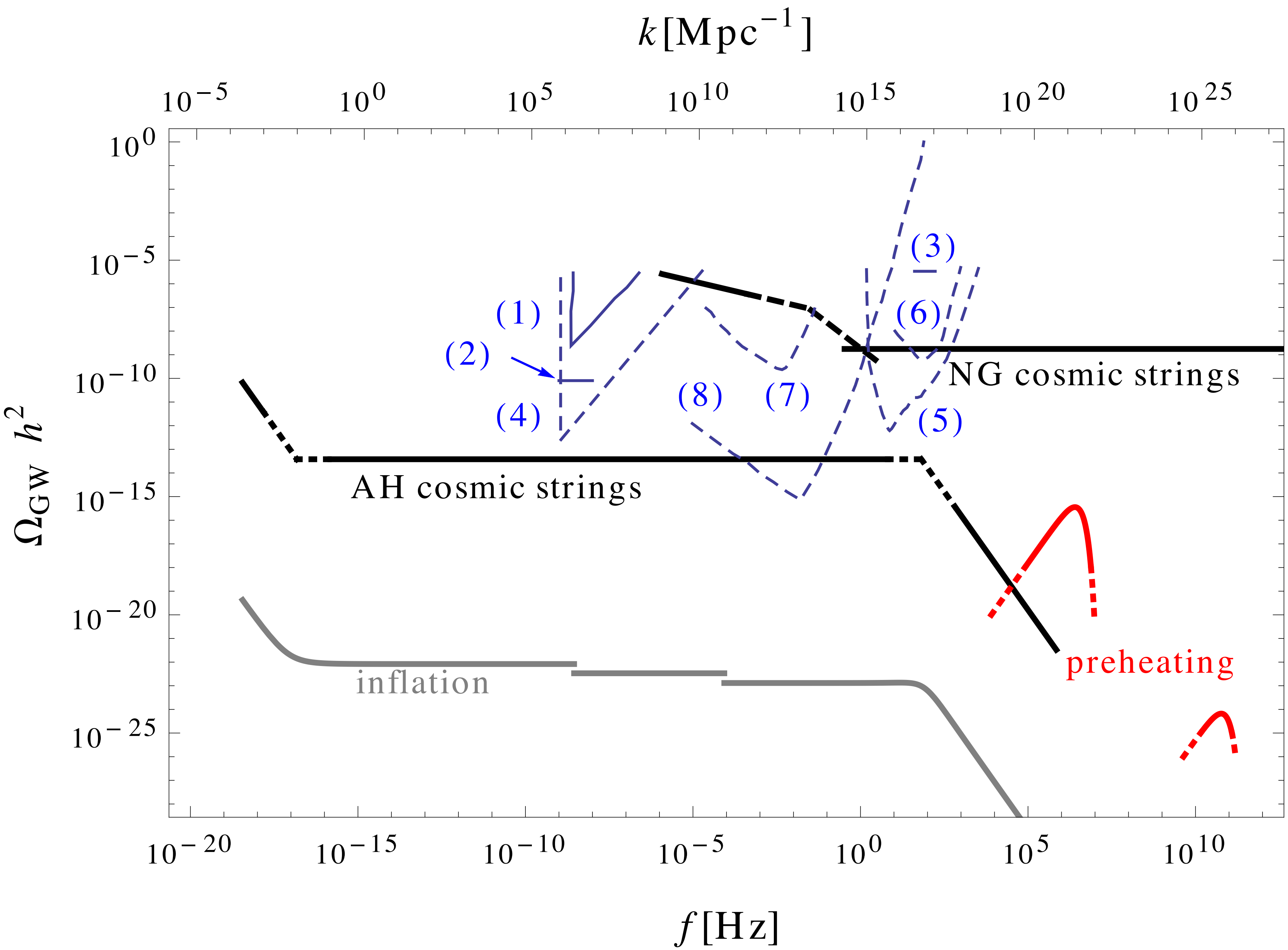


Time evolution of temperature: intermediate plateau ("maximal temperature"), determined by neutrino properties! Yields correct *gravitino abundance* when combined with 'standard formula'





Predictions for LHC (parameter scans): successful leptogenesis and *gravitino DM* (left) or *neutralino DM* (right, upper bounds) [non-thermally produced in decays of thermally produced gravitinos] constrains neutrino and superparticle masses



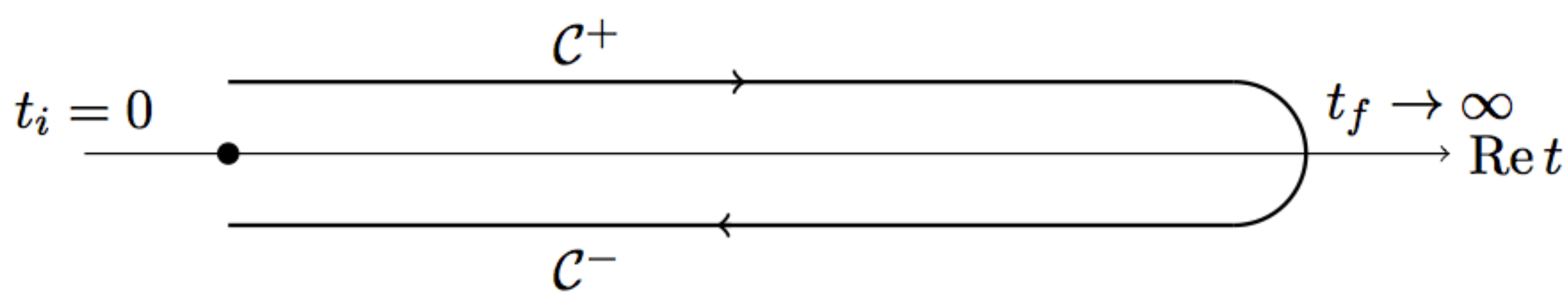
Observational prospects (for typical parameters); 'soon': Advanced Ligo (6) [100 Hz], eLISA [0.01 Hz]; 'later': Einstein Telescope [100 Hz], BBO/DECIGO [0.01 Hz]; eventually determination of reheating temperature (leptogenesis)?!

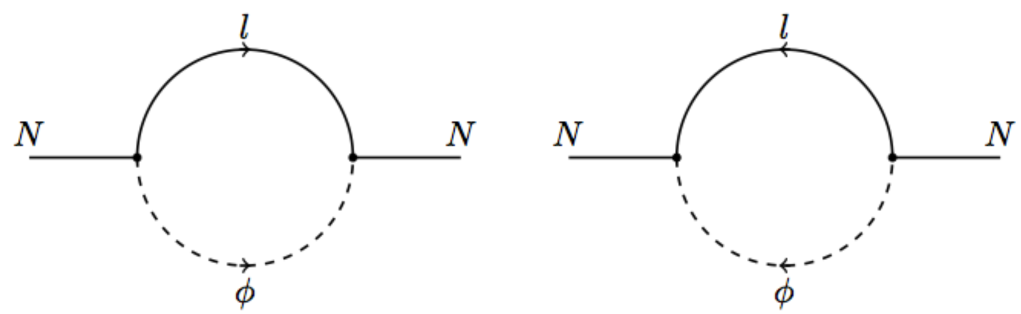
Towards a theory of leptogenesis

Leptogenesis is "simple" nonequilibrium process: weakly coupled heavy neutrino in large SM thermal bath, close to thermal equilibrium; rigrous treatment in nonequilibrium QFT? [Bodeker et al; Garbrecht et al; Garny et al; Iso et al; Ramsey-Musolf et al; Hutig, Mendizabal, Philipsen '13 - '17]; Schwinger-Keldysh formalism for spectral functions and statistical propagators of lepton doublets and heavy Majorana neutrino:

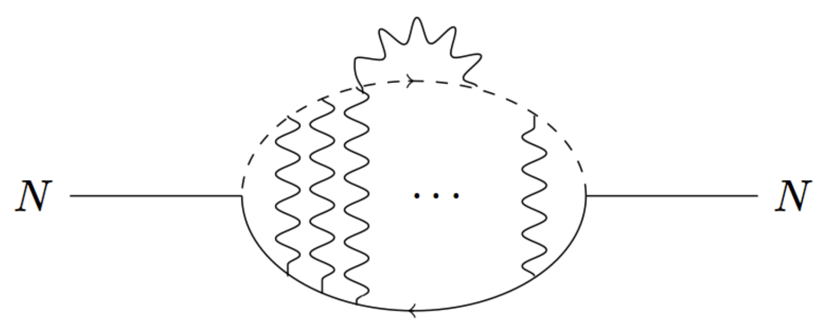
$$(\partial_{t_1}^2 + \omega_{\mathbf{q}}^2)\Delta_{\mathbf{q}}^-(t_1 - t_2) = -\int_{t_2}^{t_1} \mathrm{d}t'\, \Pi_{\mathbf{q}}^-(t_1 - t')\Delta_{\mathbf{q}}^-(t' - t_2)$$

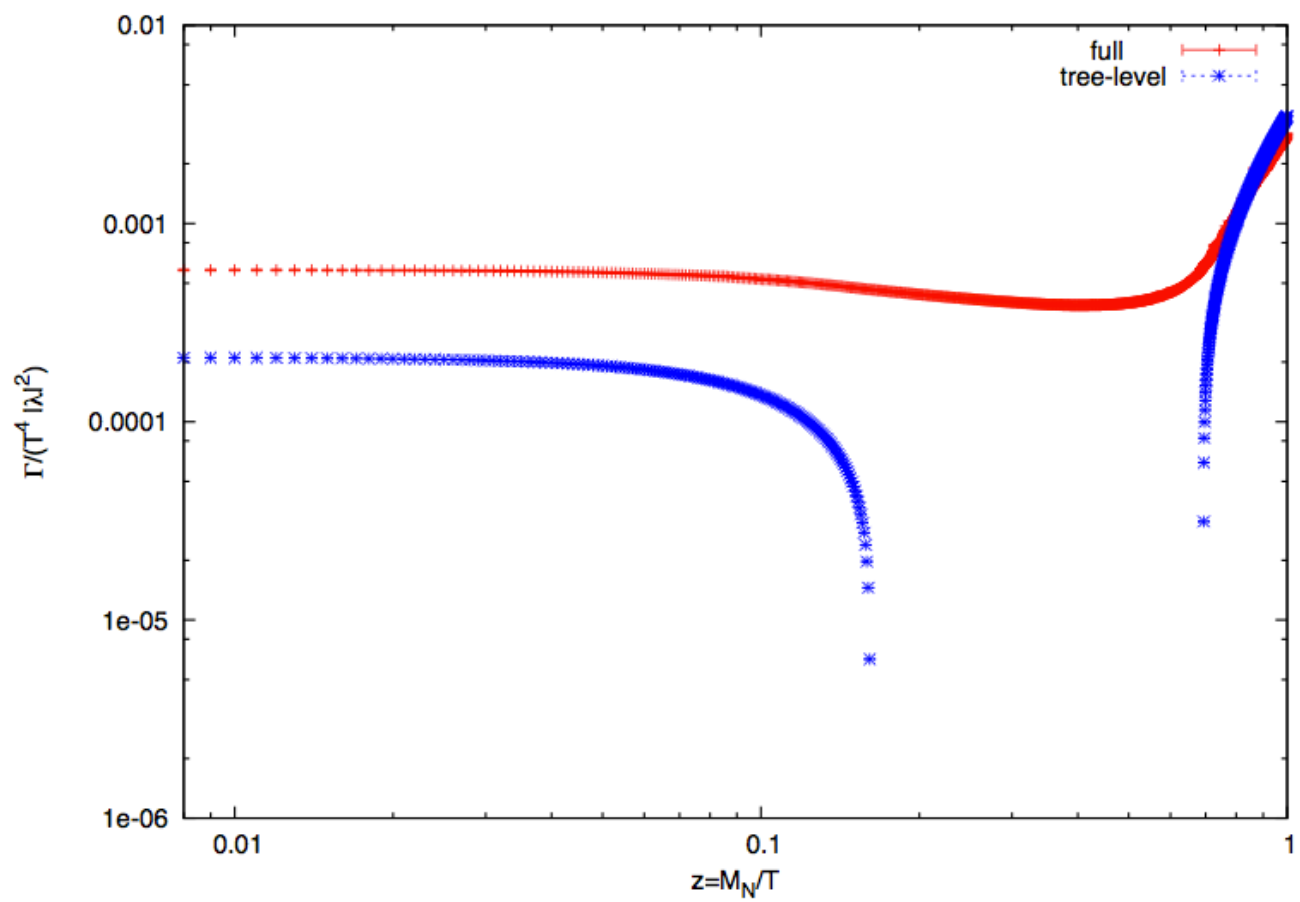
$$\begin{aligned}(\partial_{t_1}^2 + \omega_{\mathbf{q}}^2)\Delta_{\mathbf{q}}^+(t_1, t_2) = &\int_{t_i}^{t_2} \mathrm{d}t'\, \Pi_{\mathbf{q}}^+(t_1 - t')\Delta_{\mathbf{q}}^-(t' - t_2) \\ &- \int_{t_i}^{t_1} \mathrm{d}t'\, \Pi_{\mathbf{q}}^-(t_1 - t')\Delta_{\mathbf{q}}^+(t', t_2)\,,\end{aligned}$$



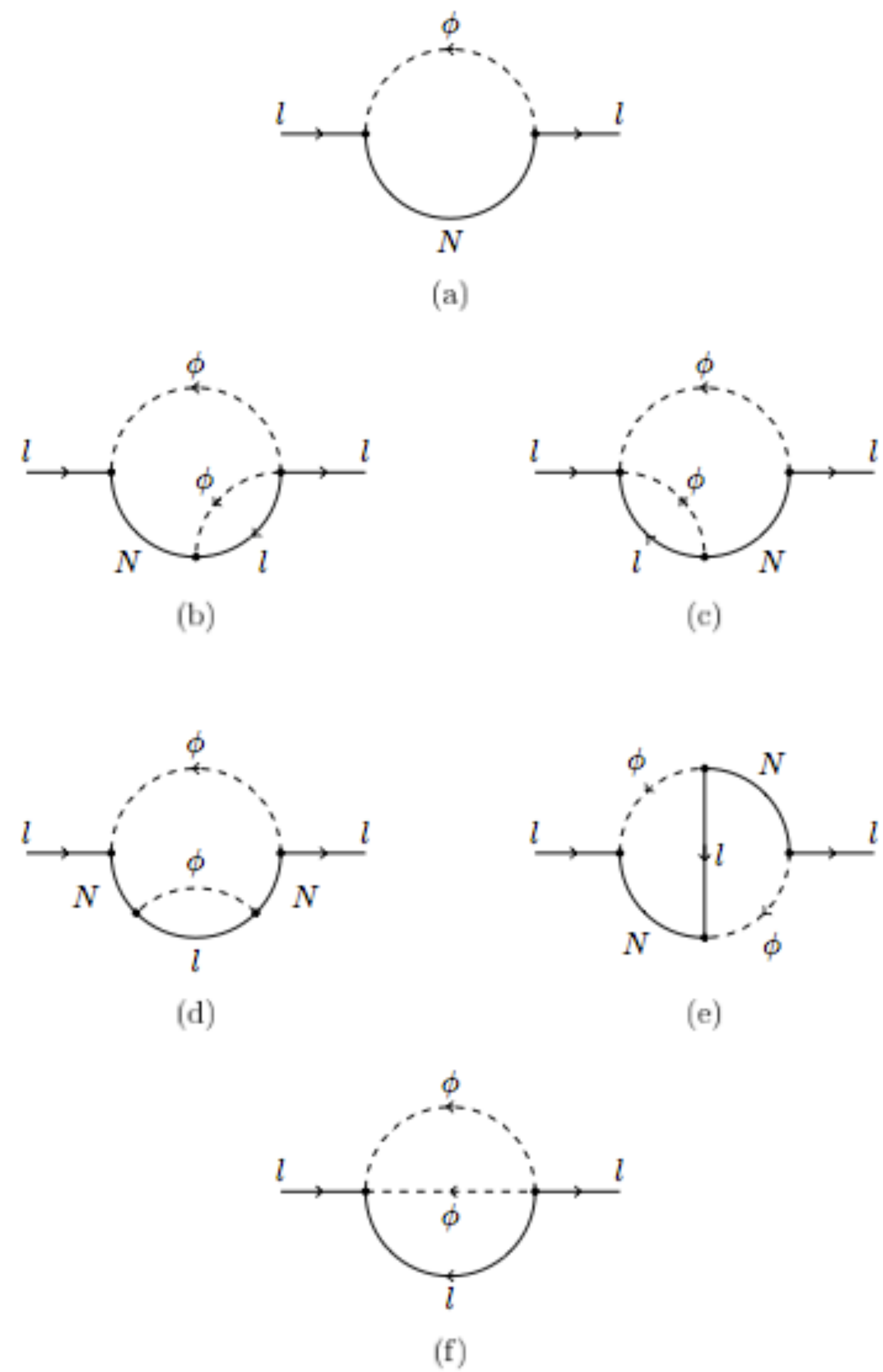


(a) (b)

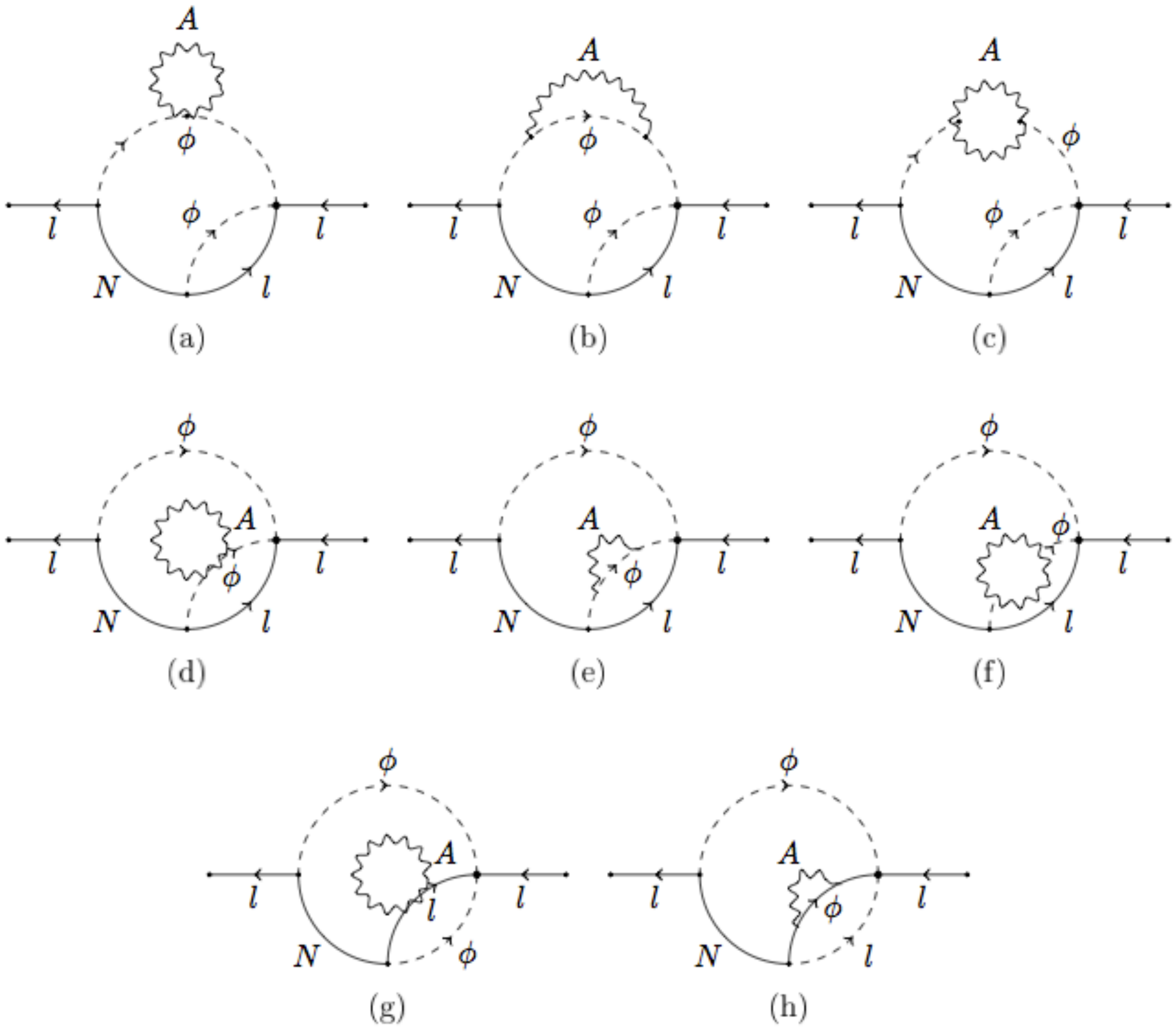


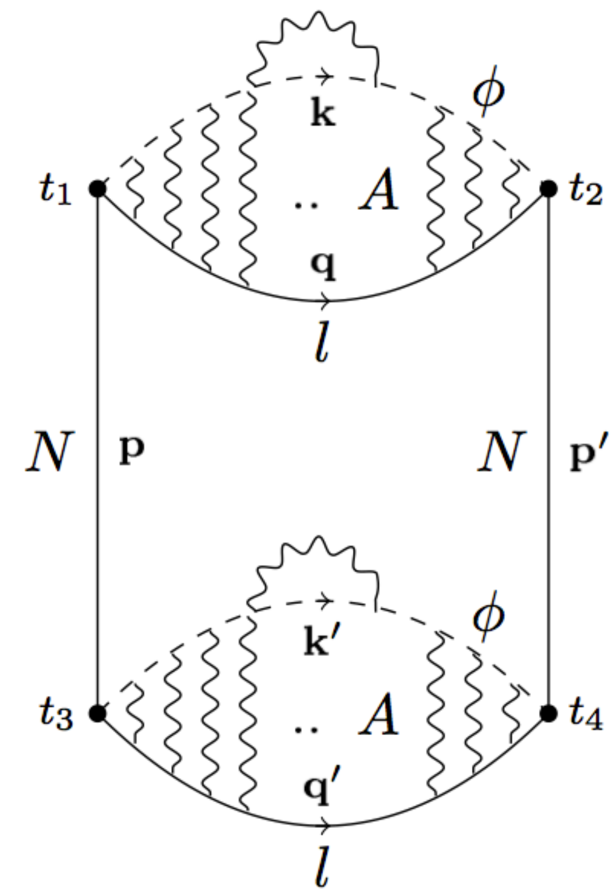


thermal production of heavy neutrinos (Higgs decay, production from lepton-Higgs pair, soft gauge bosons ...); resummation of soft gauge bosons; result very different from naive estimate with thermal masses!

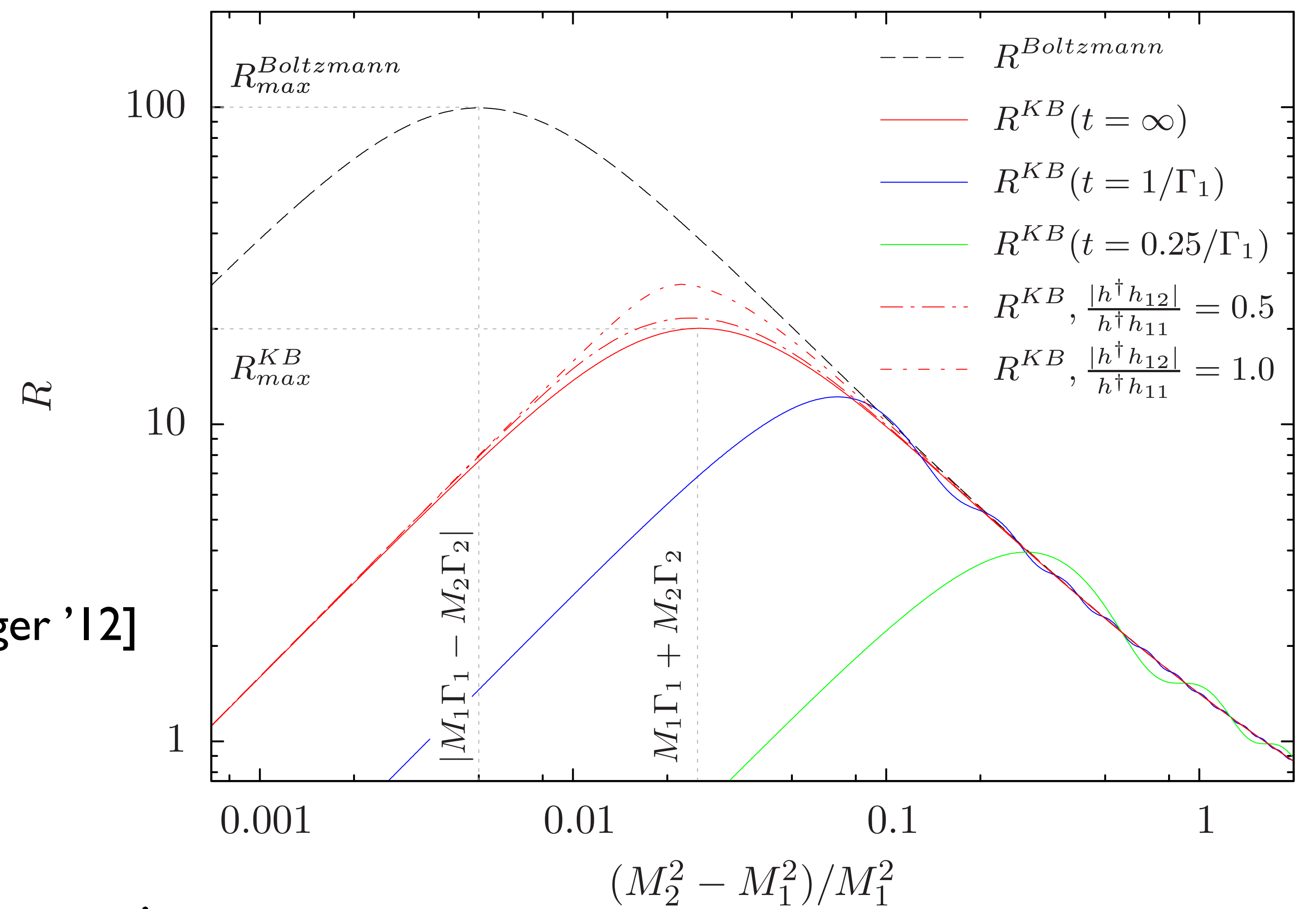


generation of lepton asymmetry (CP violation!) starts at two loops;
cut: interference of tree-level and one-loop diagrams





difficult problem: resummation of soft gauge bosons; compact analytical expressions obtained, numerical analysis in progress; expected result: thermal damping in the bath leads to local (in time) equation for lepton density matrix, including corrections from quantum statistics and propagator effects; systematic expansion in couplings...; it is important to obtain **rigorous prediction** for baryon asymmetry with error bar!



[Garny, Kartavtsev, Hohenegger '12]

Solve Kadanoff-Baym equations,

$$\Box_{1,\mathbf{q}}\Delta^-_{\mathbf{q}}(t_1,t_2) = -\int_{t_2}^{t_1} dt'\Pi^-_{\mathbf{q}}(t_1,t')\Delta^-_{\mathbf{q}}(t',t_2)\ ,\ldots$$

Compare for *resonant leptognesis* enhancement predicted by Boltzmann eqs. and Kadanoff-Baym eqs.,

$$R^{Boltzmann}_{max} = \frac{M_1M_2}{2|M_1\Gamma_1 - M_2\Gamma_2|}\ ,\quad R^{KB}_{max} = \frac{M_1M_2}{2(M_1\Gamma_1 + M_2\Gamma_2)}\ ,$$

$\rightarrow$ enhancement suppressed!

Summary: leptogenesis

- GUT-scale leptogenesis elegant and natural mechanism for explanation of baryon asymmetry, supported by small neutrino masses

- TeV-scale (resonant) leptogenesis testable and LHC, interesting signatures

- GeV-scale leptogenesis (ARS mechanism) possible without much fine-tuning, testable at colliders; theoretical motivation for neutrino masses?

- Very important: measurement of CP violation, $0\nu\beta\beta$ decay and **absolute neutrino mass scale**

- Interesting connection between leptogenesis, dark matter and inflation

- Much progress towards rigorous treatment of thermal leptogenesis based on thermal QFT

III. Other models

- Affleck-Dine mechanism: generic possibility (particularly attractive for flat directions in MSSM)
- Heavy moduli decay (can simultaneously predict dark matter, very model dependent)
- Cold baryogenesis
- Baryogenesis from strong CP violation and the QCD axion
- Baryogenesis from B-meson oscillations
- ....
- Important: baryogenesis consequence of theoretically motivated extension of Standard Model

Conclusions & Outlook

Two routes beyond the Standard Model:

- **new strong interactions at TeV-scale**
  Renormalizable models of electroweak baryogenesis appear to be ruled out by electron EDM constraints; EWBG possible with strong interactions, hope: discovery of dilaton at LHC and discovery of electron EDM; EWBG not falsifiable by laboratory experiments ("nightmare scenario")

- **weakly coupled extrapolation of SM to GUT-scale**
  GUT-scale leptogenesis robust and natural explanation of baryon asymmetry; TeV- or GeV- scale leptogenesis also possible (theoretical motivation of energy scale?) Leptogenesis not falsifiable by laboratory experiments in model-independent way. Hope: in addition to light neutrino masses further support by measurement of CP violation, $0\nu\beta\beta$ decay and absolute neutrino mass scale