Testing Leptogenesis

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DESY, Hamburg

Symposium, University of Tokyo, May 2016

Leptogenesis

Fukugita, Yanagida '86

This year: 30th aniversary, opened new field of research!

Key idea: CP violating decays and scatterings of heavy Majorana neutrinos generate lepton asymmetry which is partially transformed into baryon asymmetry via sphaleron processes [Kuzmin, Rubakov, Shaposhnikov '85]; observed baryon asymmetry perfectly consistent with neutrino properties!

Many versions of leptogenesis: thermal, nonthermal, resonant, soft, axion oscillations, Higgs relaxation, gravitational, ...; (historically) interesting: main activity started with about 10 years delay ...

This talk: focus on aspects most relevant to neutrino physics and testability of leptogenesis; classify models according to seesaw mass scale

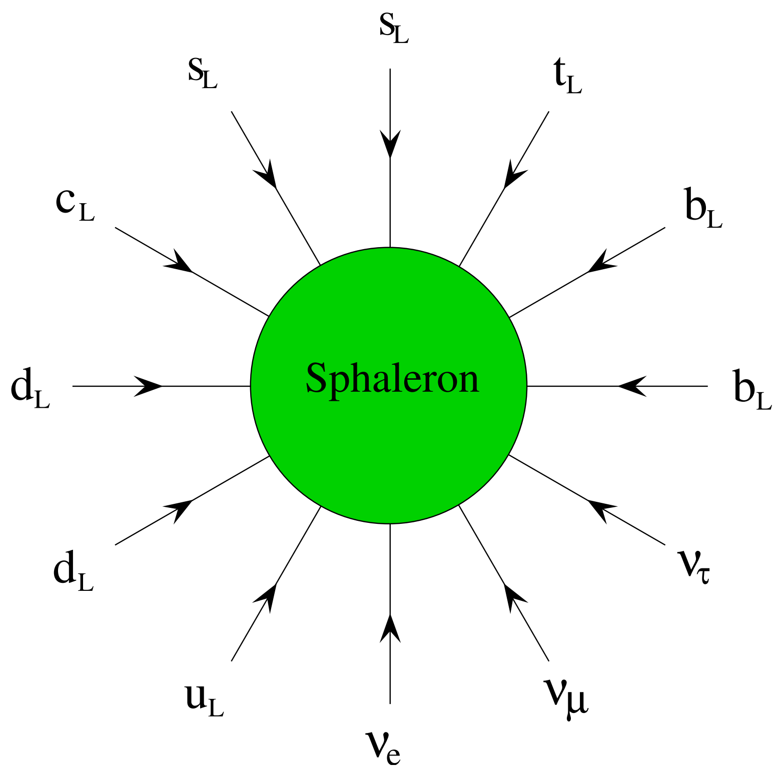
Matter in the Universe

What is the origin of matter, i.e., the baryon-to-photon ratio

$$\eta_B = \frac{n_B}{n_\gamma} = (6.1 \pm 0.1) \times 10^{-10}$$

? ? ? ?

Leptogenesis: quantum effect, requires CP violation, small Majorana neutrino masses, connection between baryon and lepton number, and an expanding universe (Sakharov's conditions OK)



GUT-scale seesaw

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

$$G_{SM} = U(1) \times SU(2) \times SU(3) \subset SU(5) \subset SO(10) \subset \ldots$$

$$SO(10): \ \mathbf{16} = \ (d^c_R, l_L, q_L, u^c_R, e^c_R, \nu^c_R)$$

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):

$$N \simeq \nu_R + \nu^c_R \ : \qquad m_N \simeq M \ ,$$

$$\nu \simeq \nu_L + \nu^c_L \ : \qquad m_\nu = -m_D \frac{1}{M} m^T_D$$

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

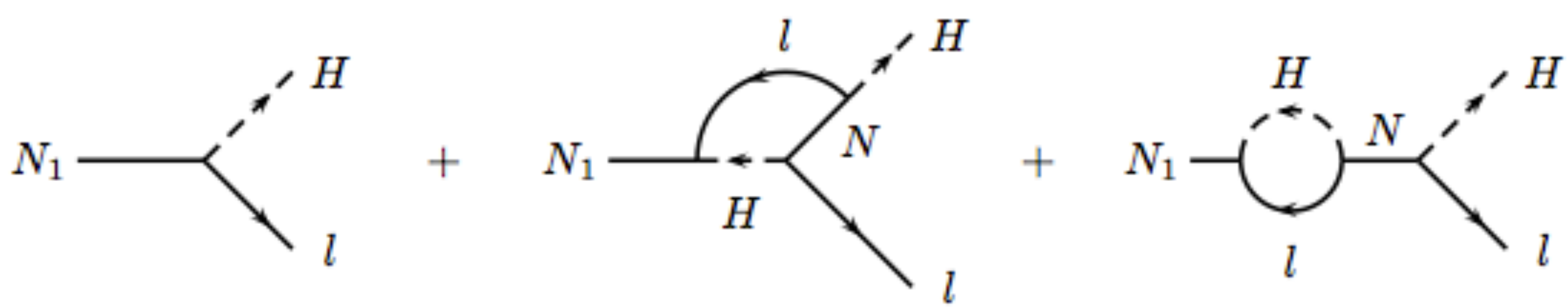
$$M_3 \sim \Lambda_{\rm GUT} \sim 10^{15} \ {\rm GeV} \ , \quad m_3 \sim \frac{v^2}{M_3} \sim \ 0.01 \ {\rm eV}$$

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,

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

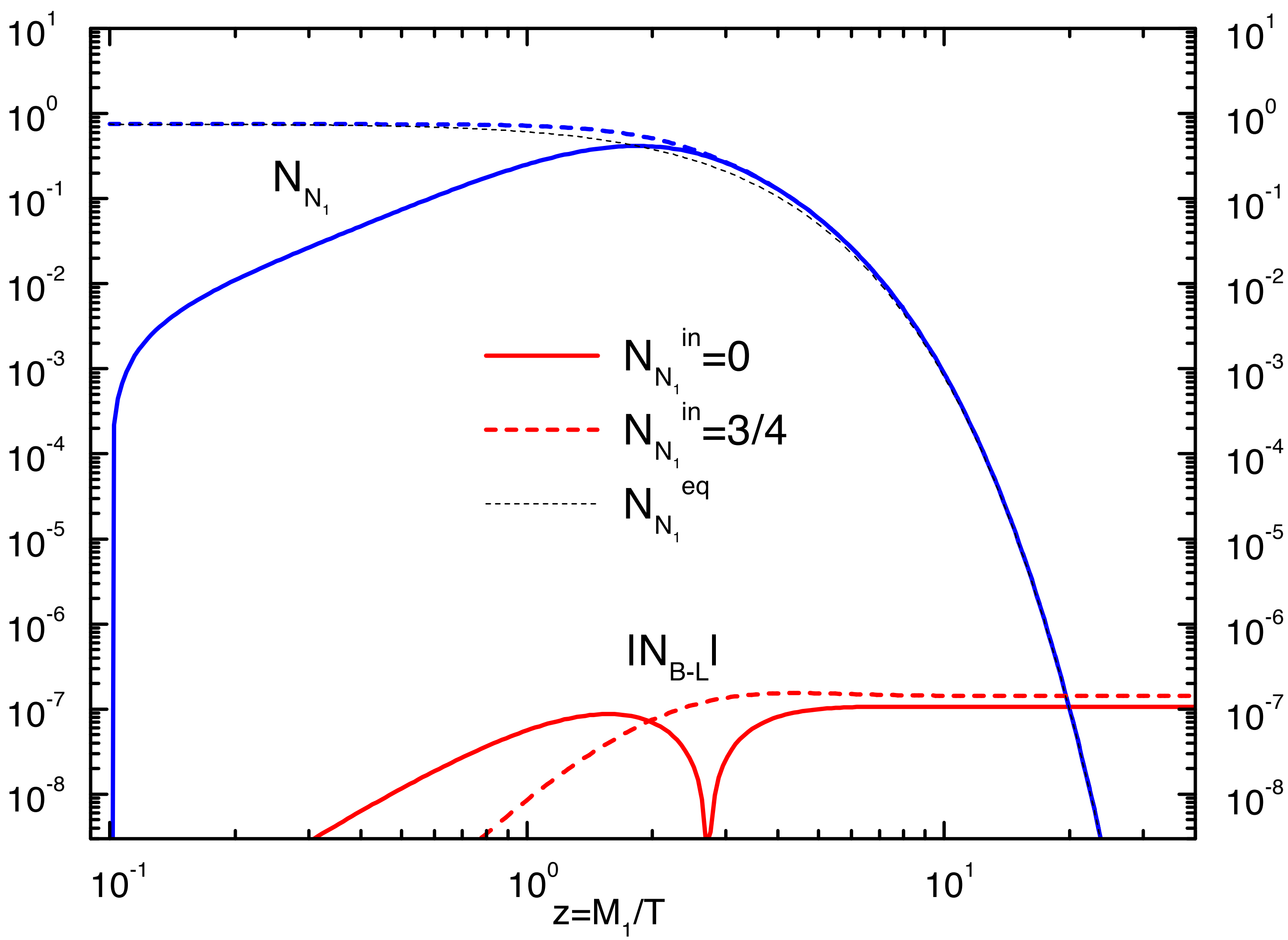
CP asymmetry determined by heavy neutrino mass hierarchy; mass ratios like for quarks or charged leptons, $M_1/M_3 \sim 10^{-4}\ldots 10^{-5}$, yield estimate $\epsilon_1 \sim 10^{-5}\ldots 10^{-6}$. Final baryon asymmetry:

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

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!

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

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

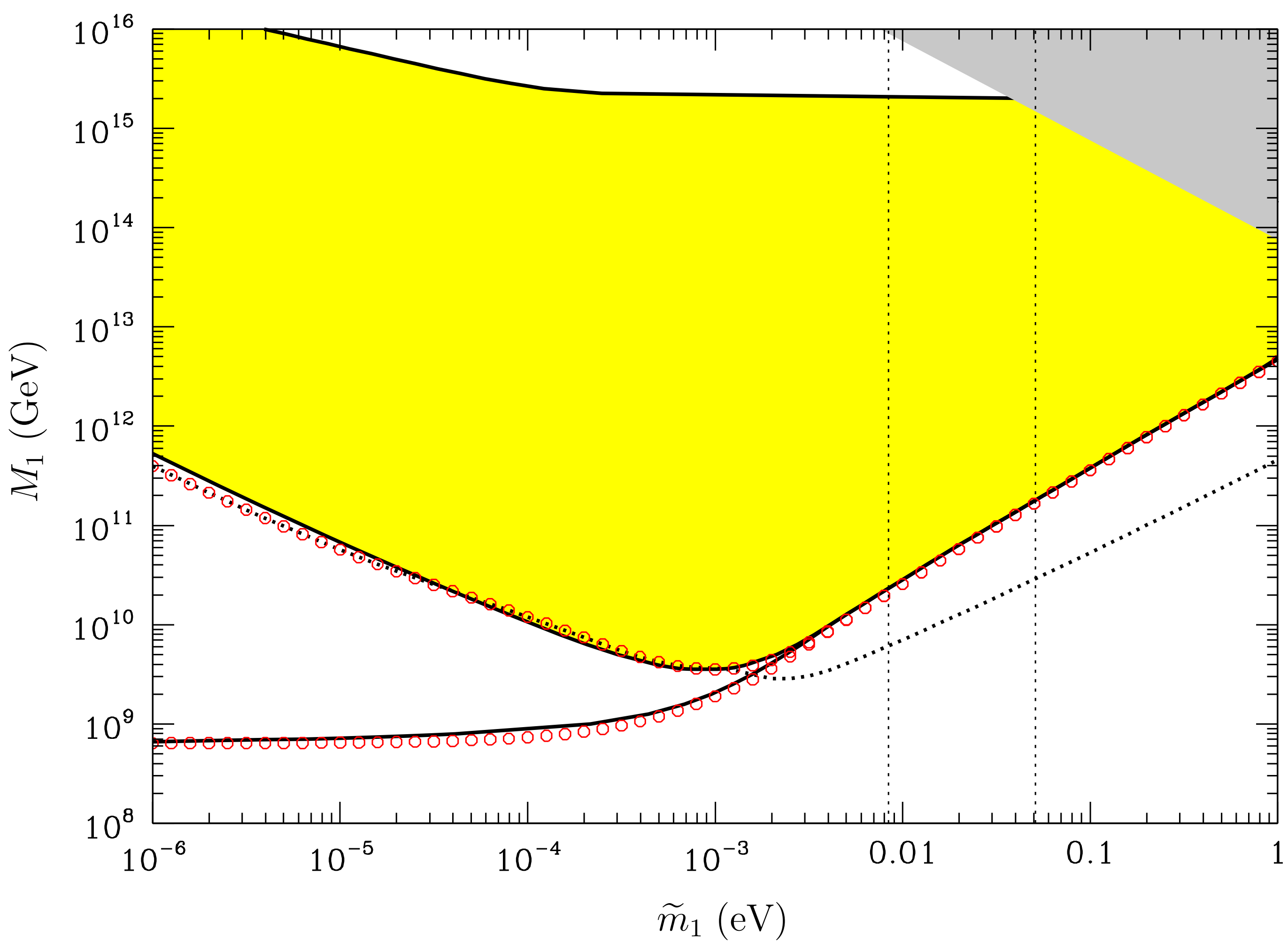


In "strong washout regime,"

$$\tilde m_1 > m_* \sim 10^{-3}\ {\rm eV}$$

$$\tilde m_1 = \frac{(m_D m_D^\dagger)_{11}}{M_1}$$

baryon asymmetry rather independent of initial conditions (abundance of heavy neutrinos & initial baryon asymmetry)



WB, Di Bari, Plumacher '04

Detailed study of Boltzmann equations leads to bounds on light and heavy neutrino masses (and reheating temperature); in simplest approximation (sum over lepton flavours):

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

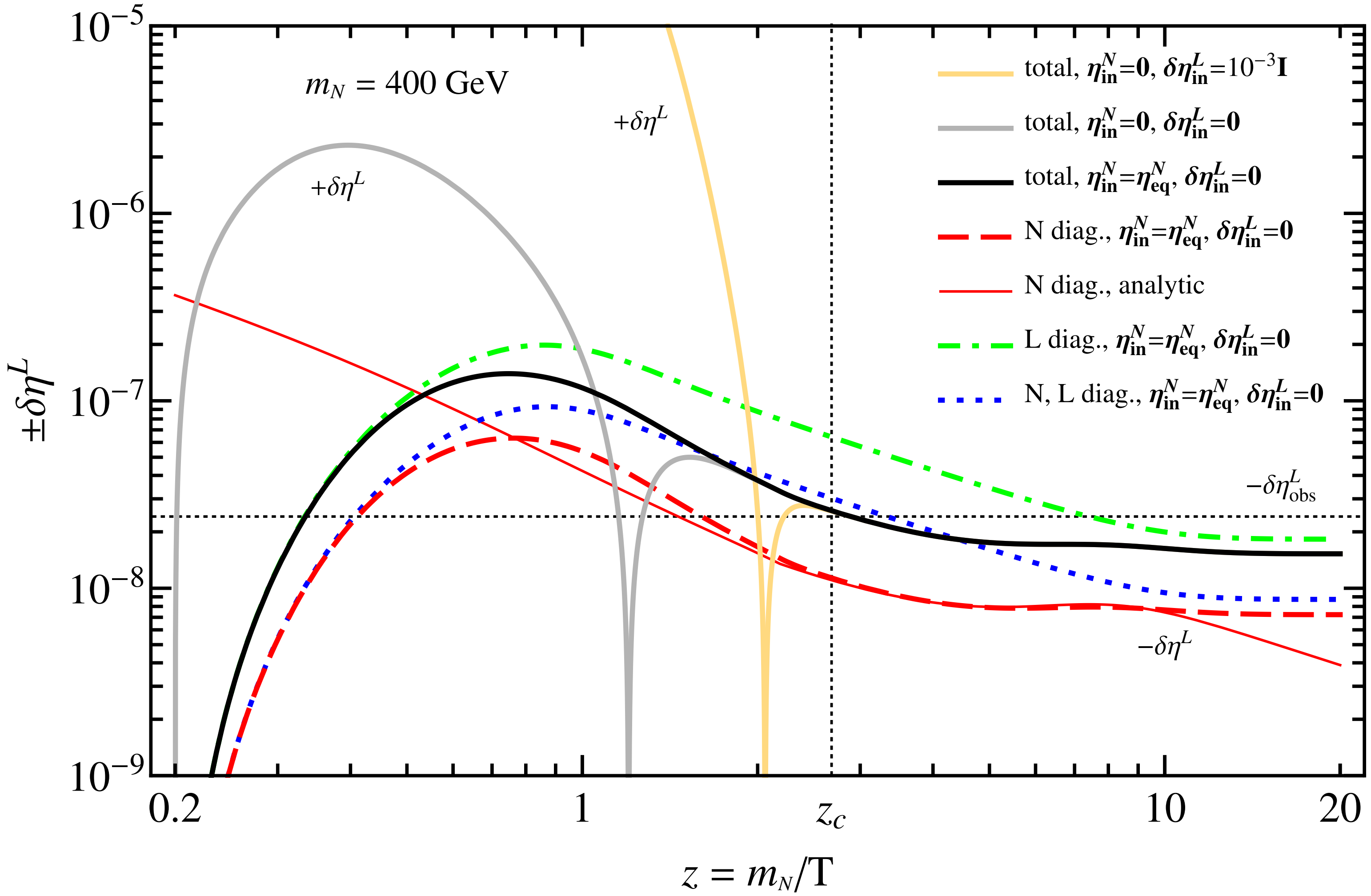
Preferred neutrino mass range ("strong washout regime", independence of initial conditions):

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

modifications: lepton flavour effects (bounds relaxed by about one order of magnitude ?! [Davidson, Nardi, Nir '08; Blanchet, Di Bari '12]); furthermore effects from possible neutrino mass degeneracies

TeV-scale seesaw

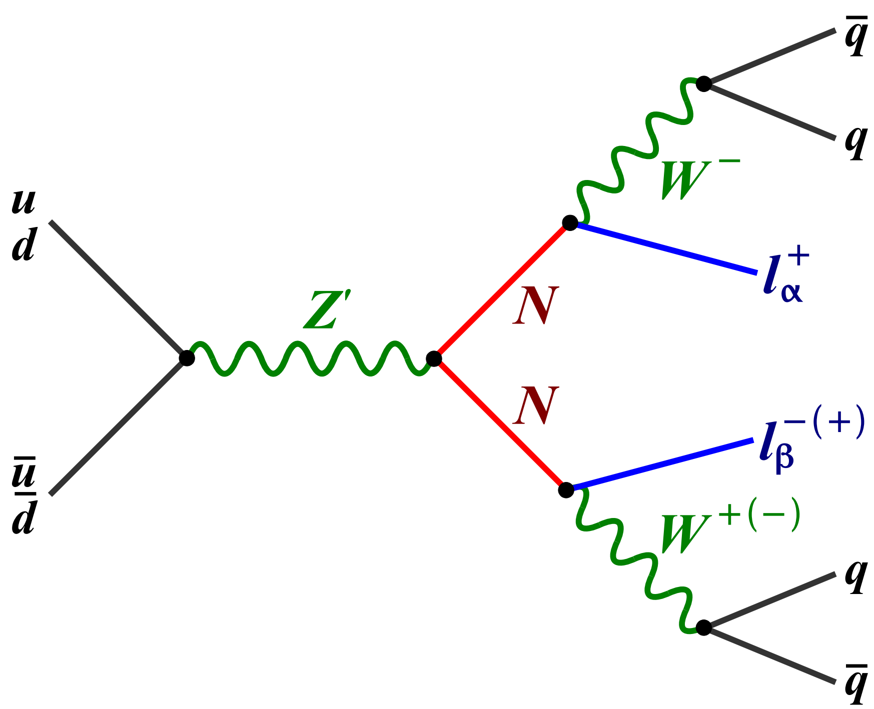
Pilaftsis et al ’03, ...



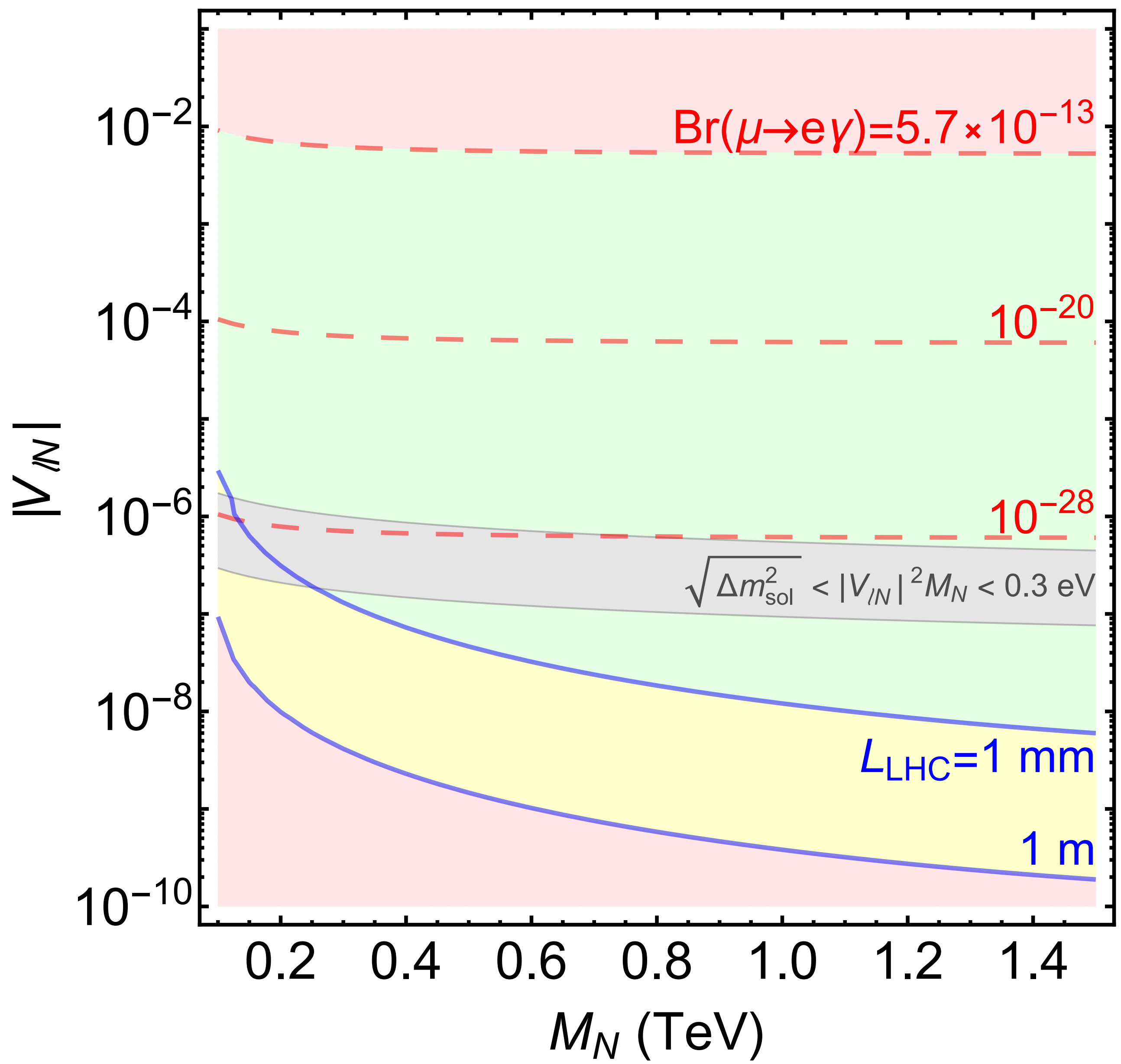
Parameter	Value
m_N	400 GeV
c	2×10^{-7}
$\frac{\Delta M_1}{m_N}$	-3×10^{-5}
$\frac{\Delta M_2}{m_N}$	$(-1.21 + 0.10\,i) \times 10^{-9}$
a	$(4.93 - 2.32\,i) \times 10^{-3}$
b	$(8.04 - 3.79\,i) \times 10^{-3}$
ϵ_e	$5.73\,i \times 10^{-8}$
ϵ_μ	$4.30\,i \times 10^{-7}$
ϵ_τ	$6.39\,i \times 10^{-7}$

[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



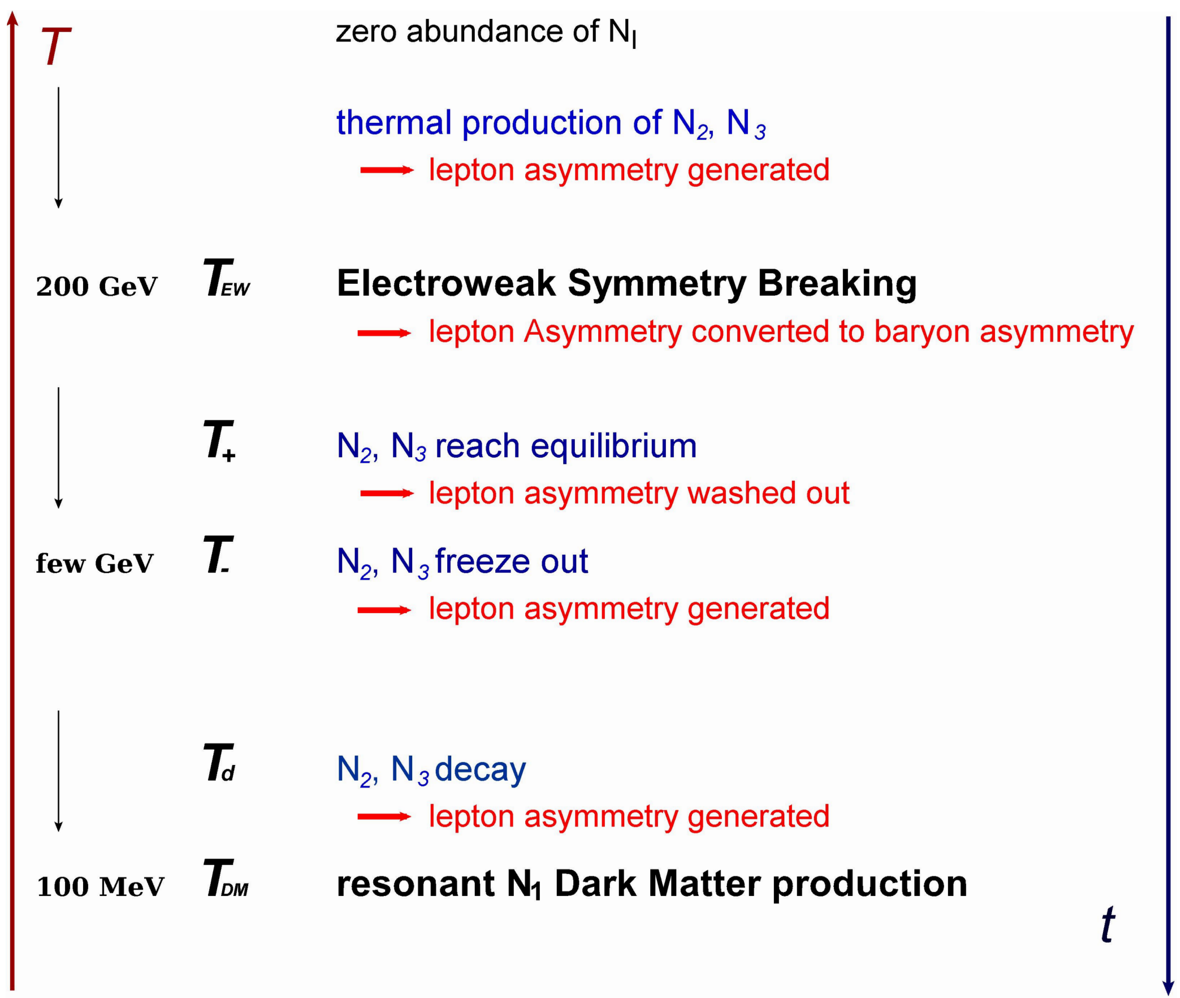
[Depisch, Dev, Pilaftsis '15]



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



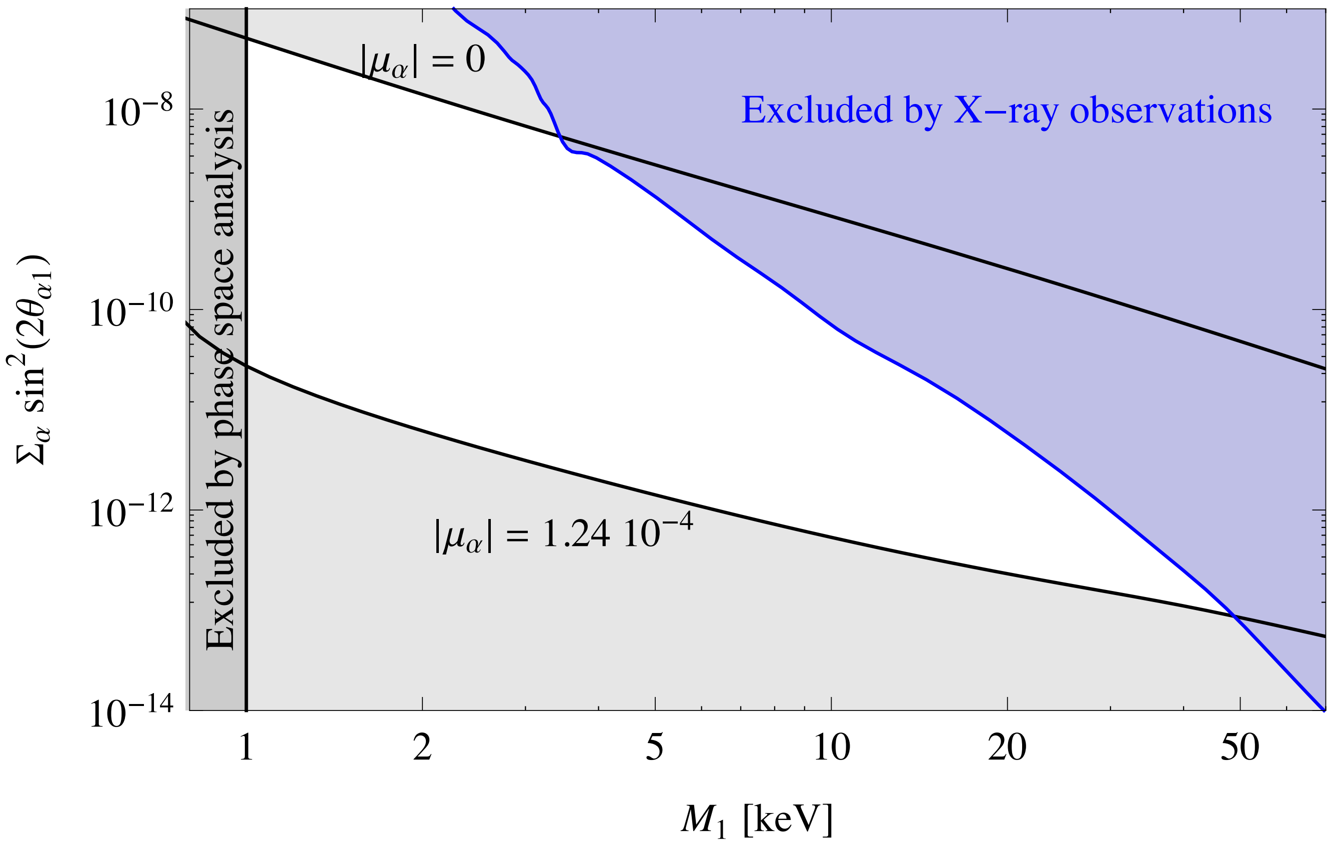
νM(inimal)S(tandard)M(odel) [Asaka, Blanchet, Shaposhnikov '05]: NO's, DM and baryon asymmetry just from SM with 3 N's; baryon asymmetry from N-oscillations and sphaleron conversion; resonant enhancement of CP asymmetry:

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

thermal history:

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

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



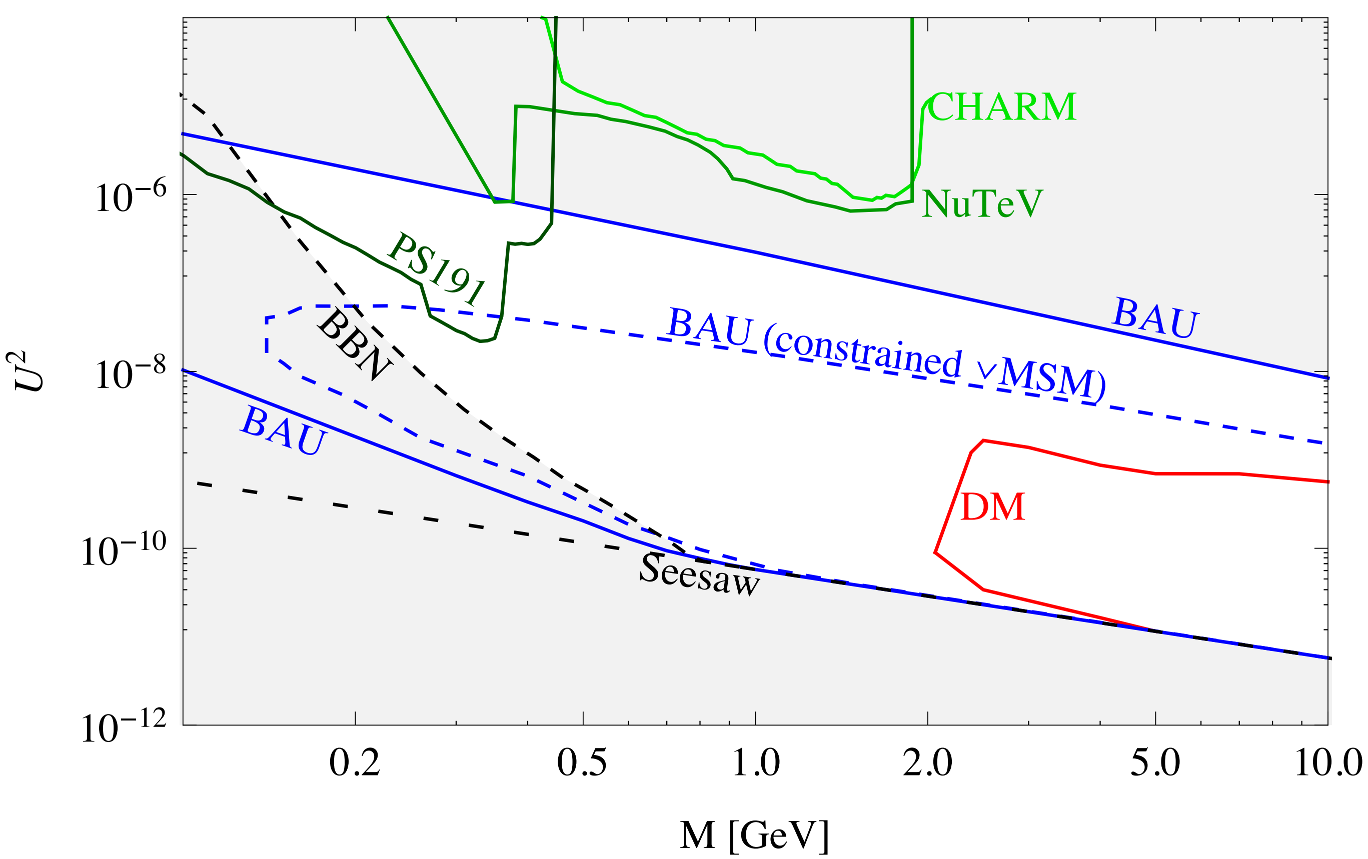
Dark Matter (keV mass, small active-sterile mixing):

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

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

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

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:

$$m_1 \simeq 0$$

Leptogenesis - piece of a puzzle

For GUT scale seesaw, RH neutrinos very heavy, cannot be produced in laboratory experiments (in principle direct tests possible in cosmology via gravitational waves!). Indirect tests:

- Majorana nature of neutrinos

- lepton flavour violating processes (e.g. in supersymmetric GUTs, $\mu \to e\gamma$, ...)

- connection with dark matter

- properties of light neutrino masses, using relations between quark, charged lepton and neutrino mass matrices; key observables:
  neutrino mass differences and mixings, CP violation
  ν-less ββ-decay: $m_{0\nu\beta\beta} = |\sum_i U_{ei}^2 m_i| \ (\lesssim 0.2 \text{ eV})$
  absolute neutrino mass scale: $m_{\text{tot}} = \sum_i m_i \ (\lesssim 0.5 \text{ eV})$
  baryon asymmetry, magnitude and sign: $\epsilon, \ |\eta_B|, \ \text{sign}[\eta_B]$

Anarchy with U(1) flavour symmetry

Lu, Murayama '14

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

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

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

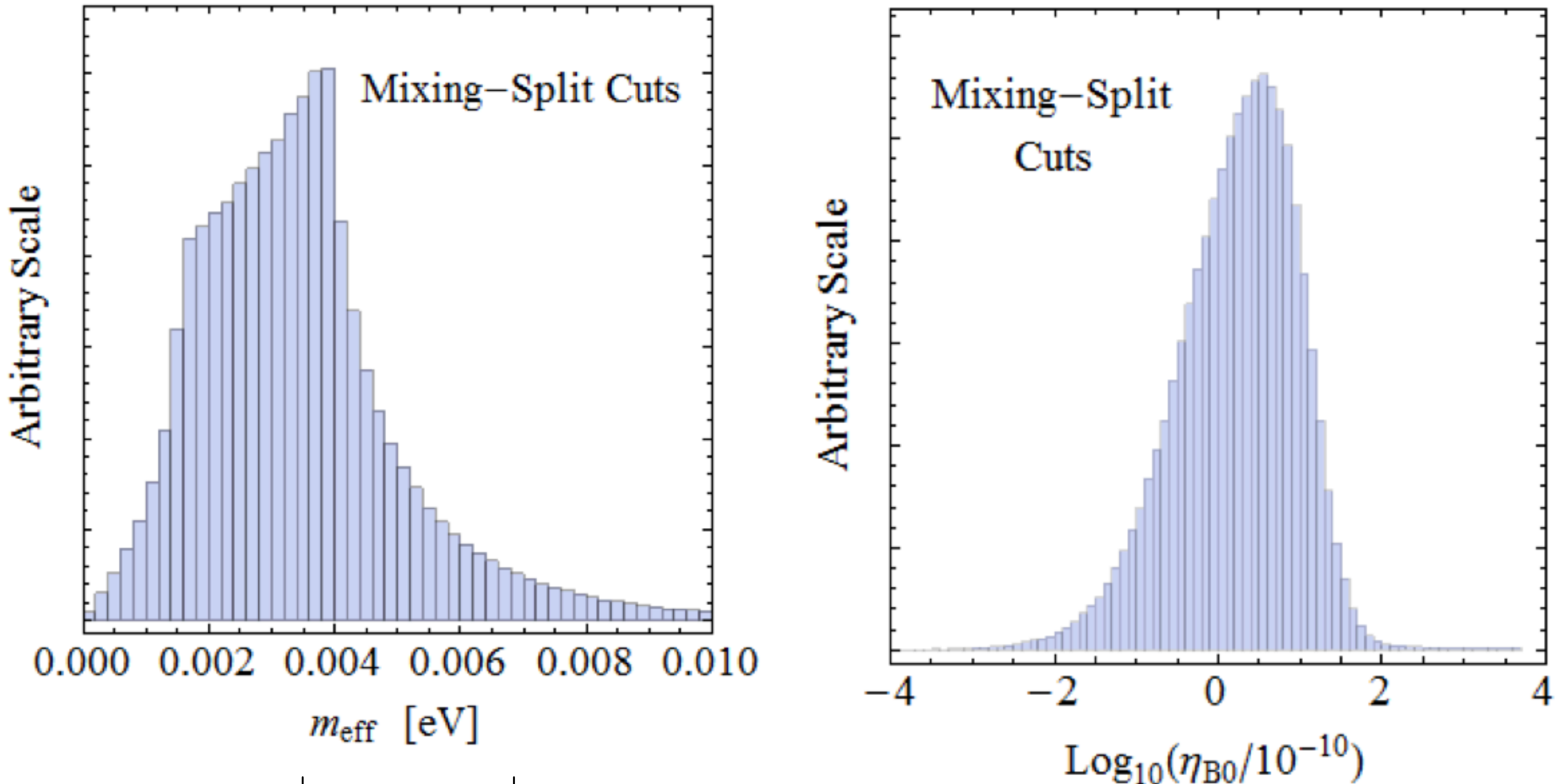
with $\epsilon \simeq 0.1$ and $\mathcal{M}$ fixed by $\Delta m_l^2 = 2.5\times 10^{-3}\ \mathrm{eV}^2$; random coefficients (Gaussian measure, independent of basis); data (mixing-split cuts):

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

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

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

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



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

Normal hierarchy dominant, inverted hierarchy only 0.1%; ν-less ββ-decay: $m_{\rm eff} \sim 2 - 4$ 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:

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

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

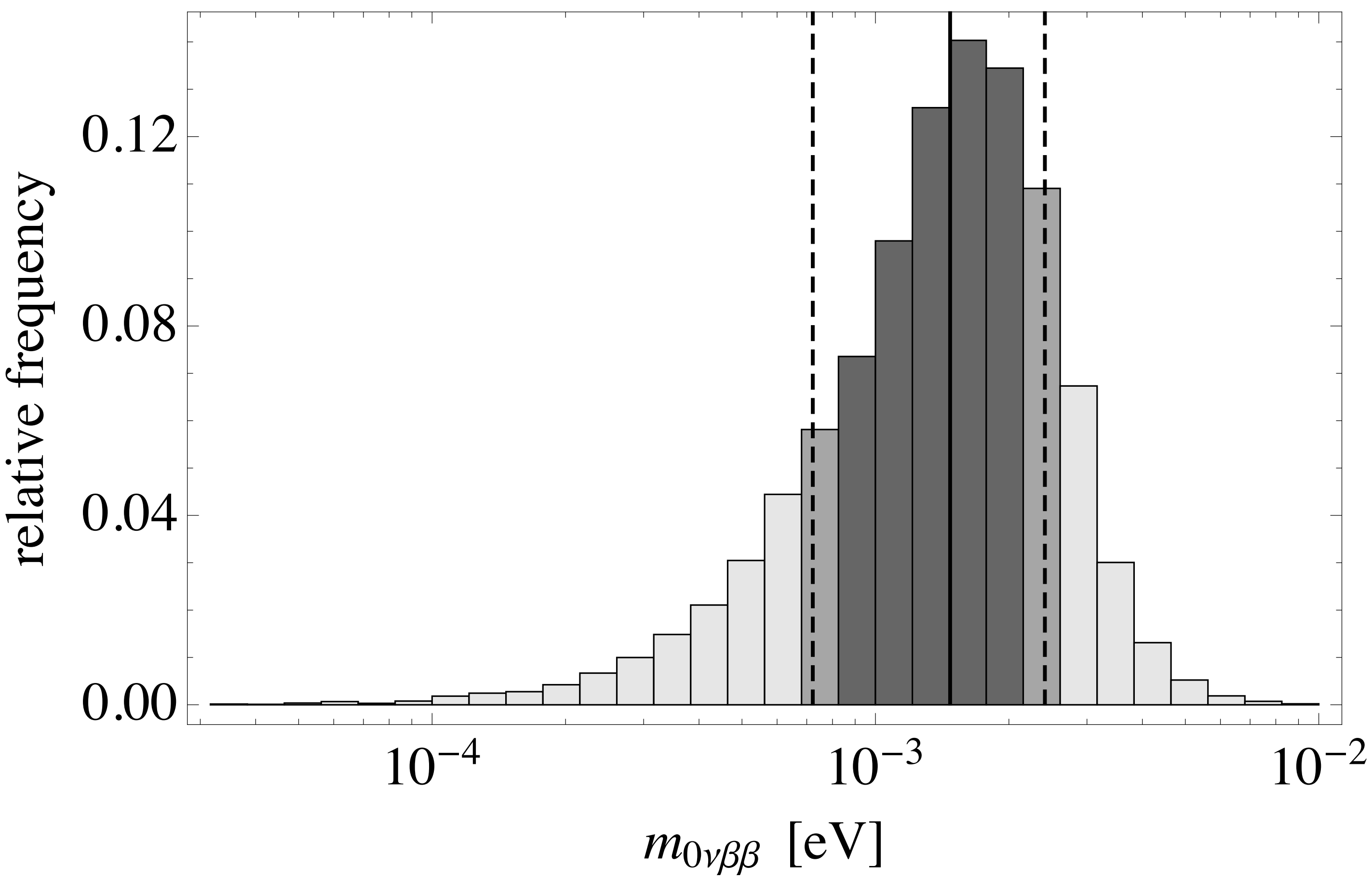
with $0 \leq a \leq 1 \ (\tan\beta); \ b \leq c \leq d; \ a + d = 2$; 39 real parameters, random numbers O(1), uniform on logarithmic scale; data:

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

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

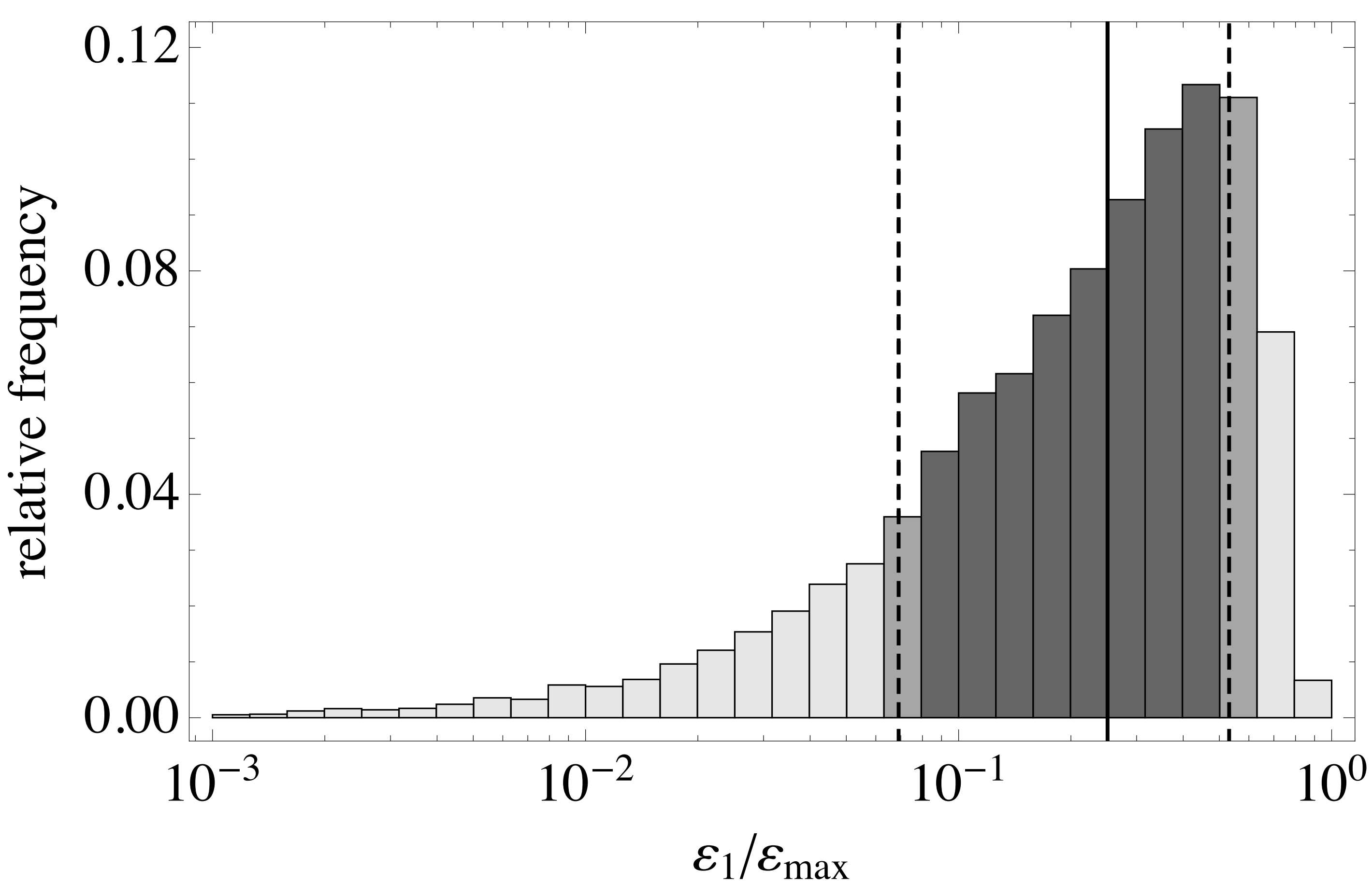
$$0.75 \leq \sin^2(2\theta_{12}) \leq 0.93 ,$$

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



effective neutrino mass:

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



mean corresponds to

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

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

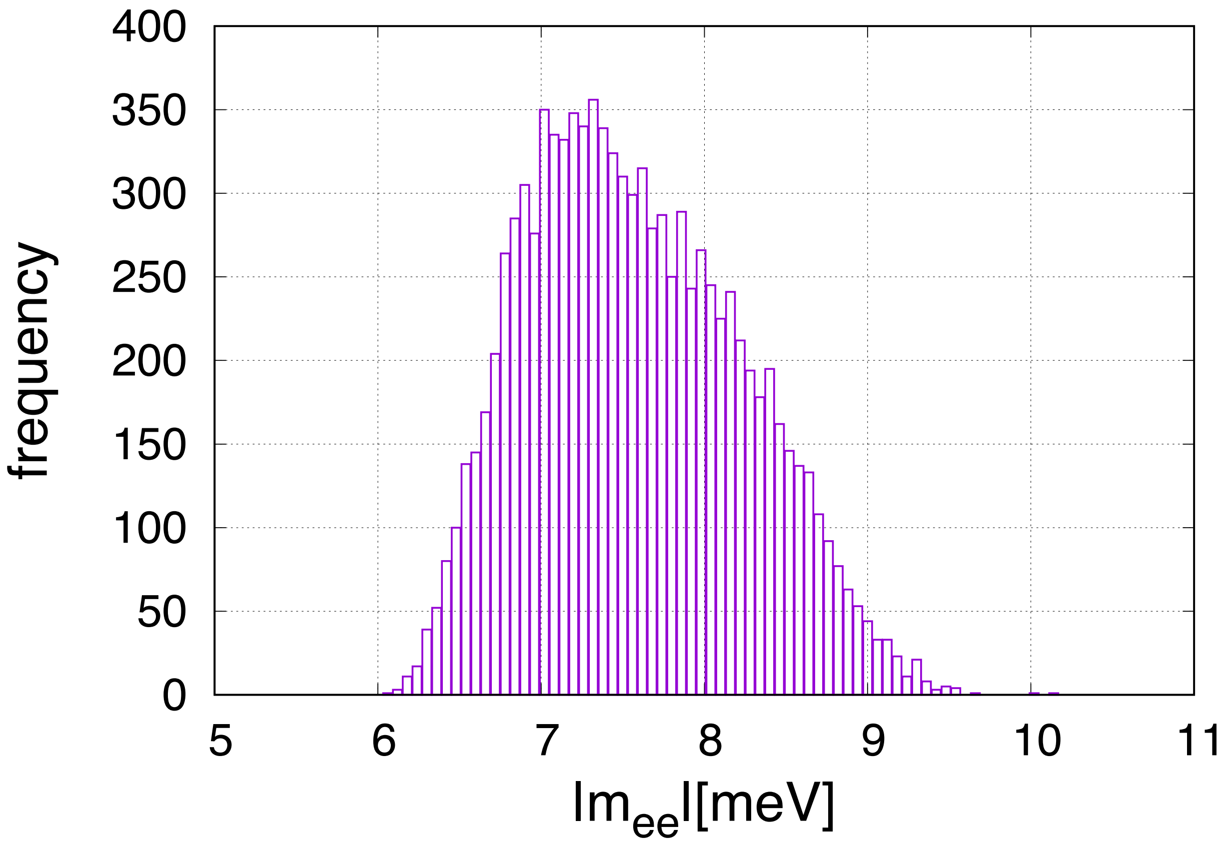
Occam's razor

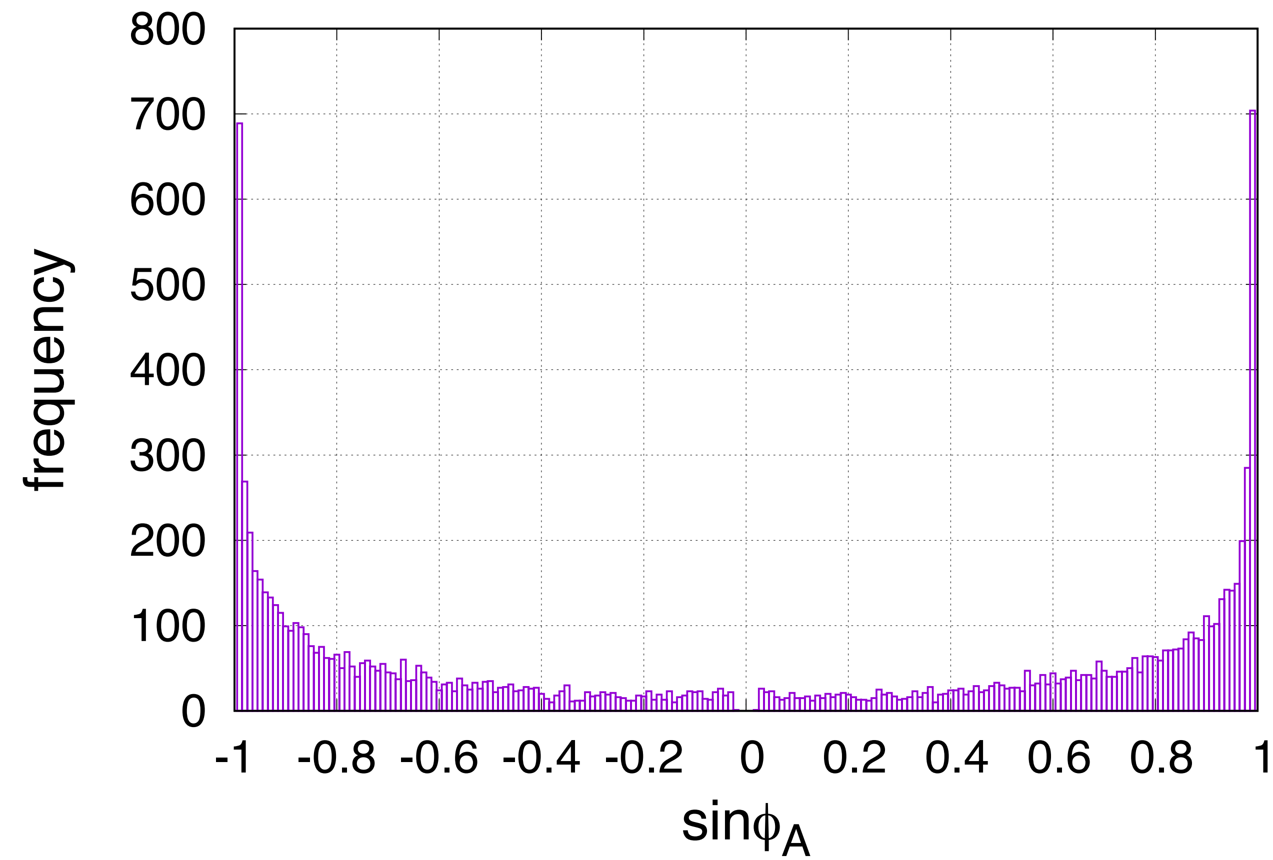
Kaneta, Shimizu, Tanimoto, Yanagida'16

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)

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

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

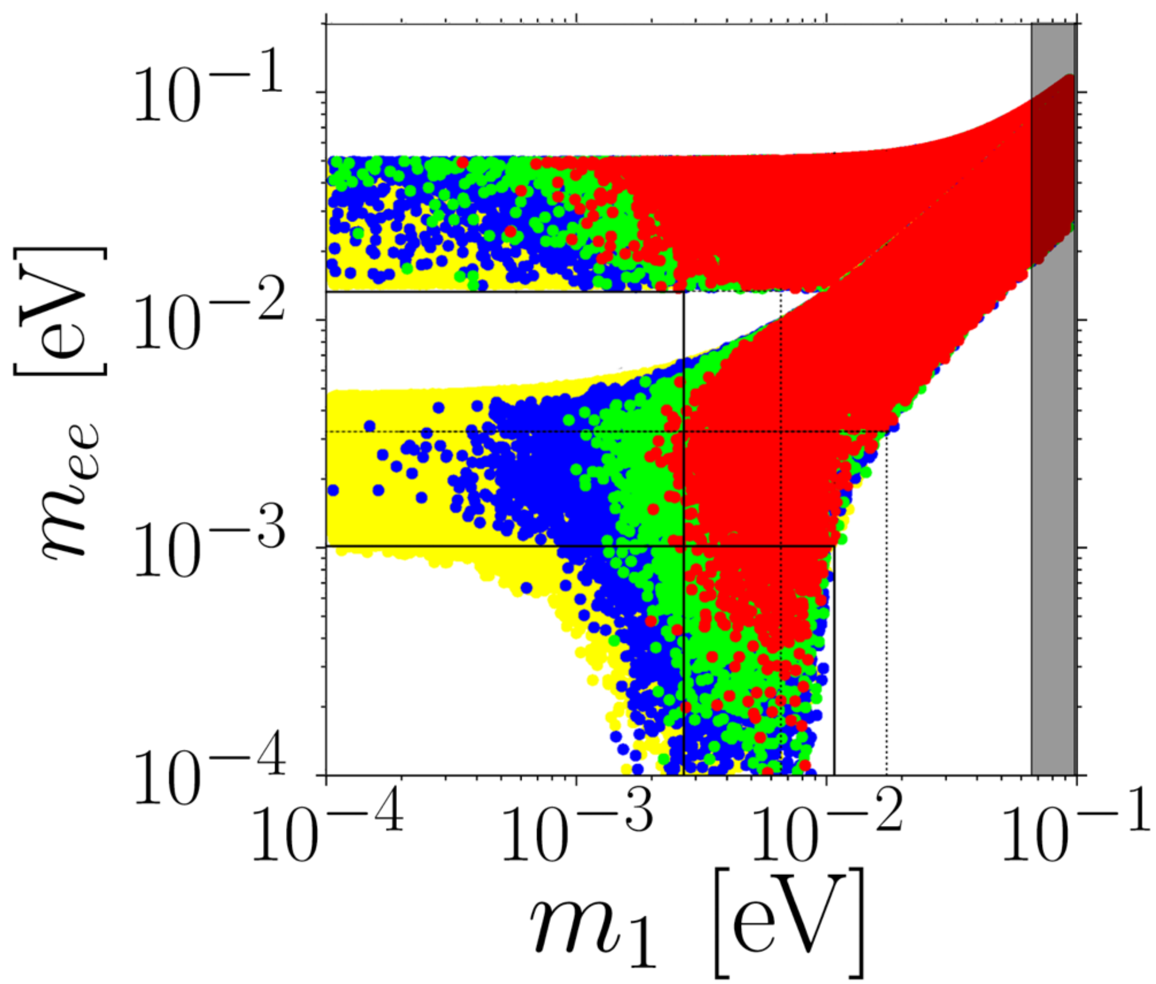


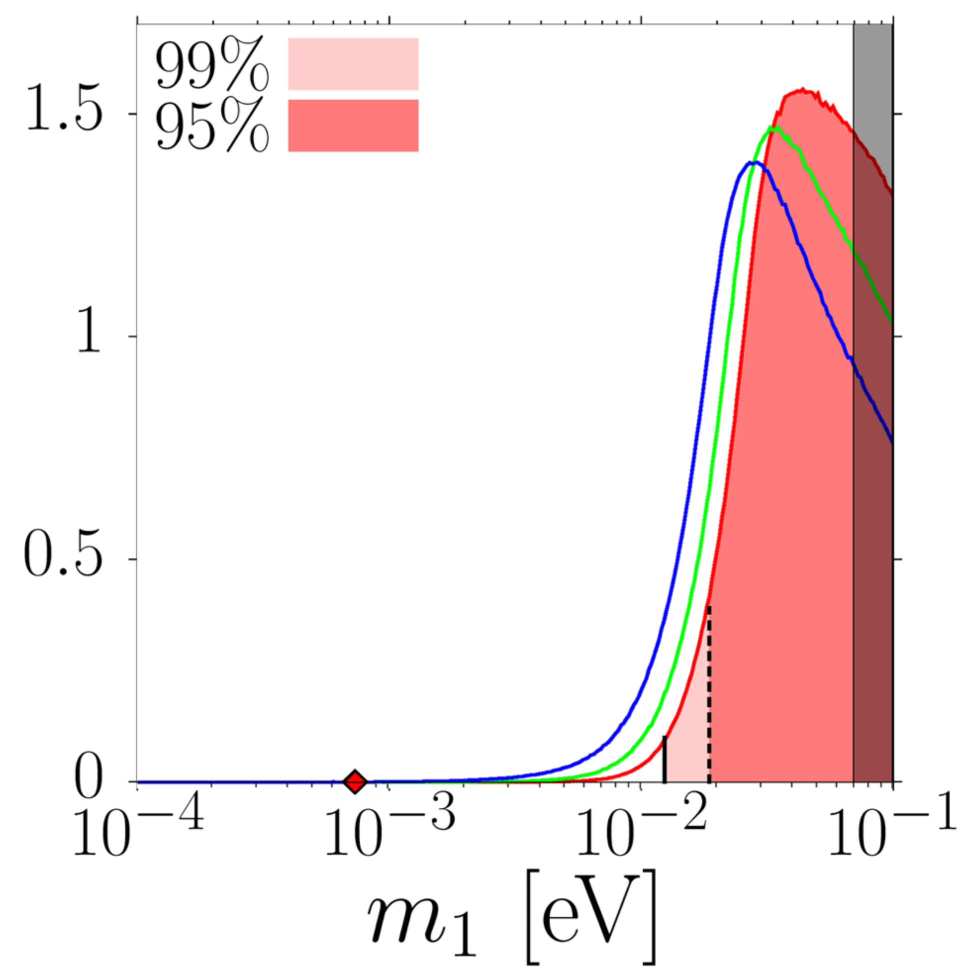


Results of Monte Carlo analysis (random numbers, linear scale):
neutrino mass for ν-less ββ-decay: $m_{ee} \simeq 7 - 8 \text{ meV}$
sign of baryon asymmetry: $\text{sign}[\eta_B] = \text{sign}[\sin\phi_A]$
improved measurements will eventually resolve ambiguity

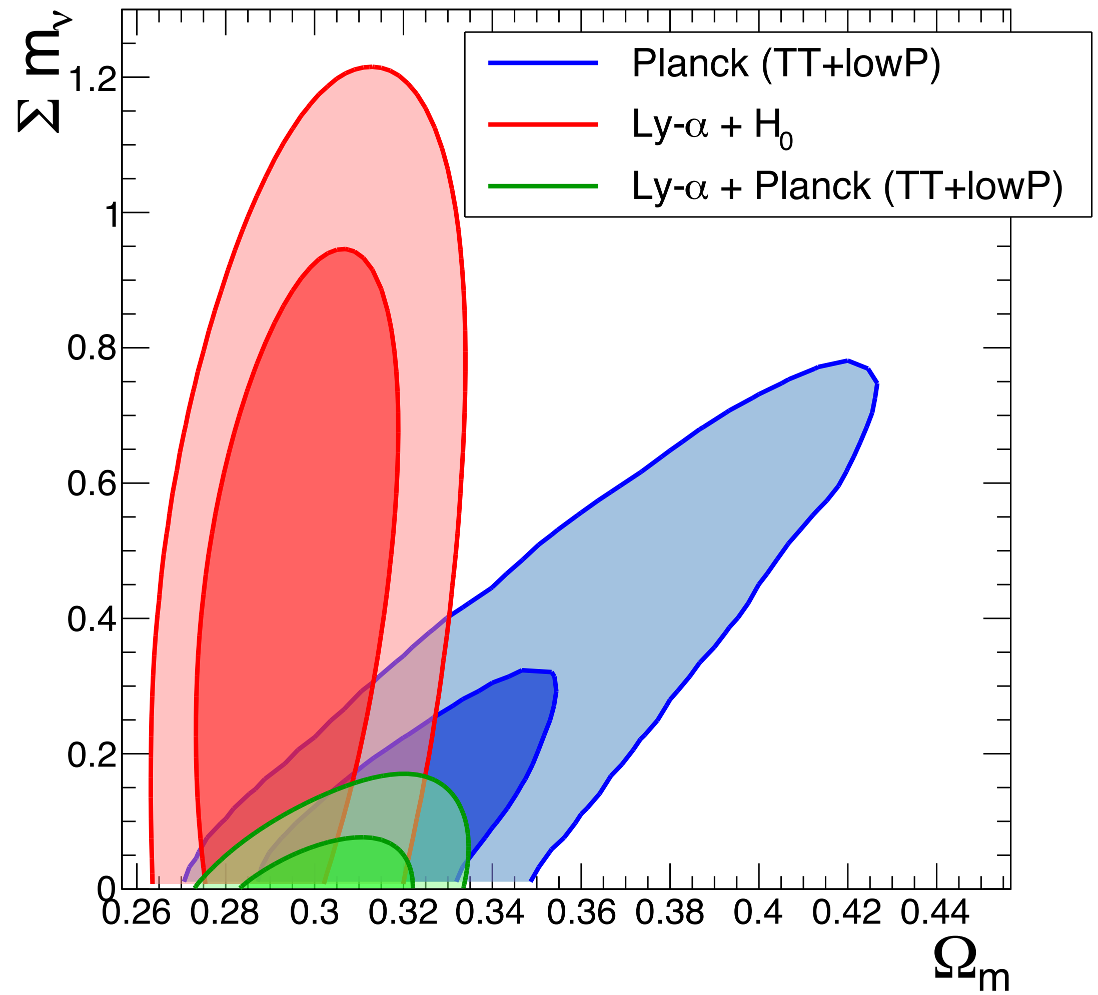
Independence of initial conditions

Di Bari, King, Fiorentin '14





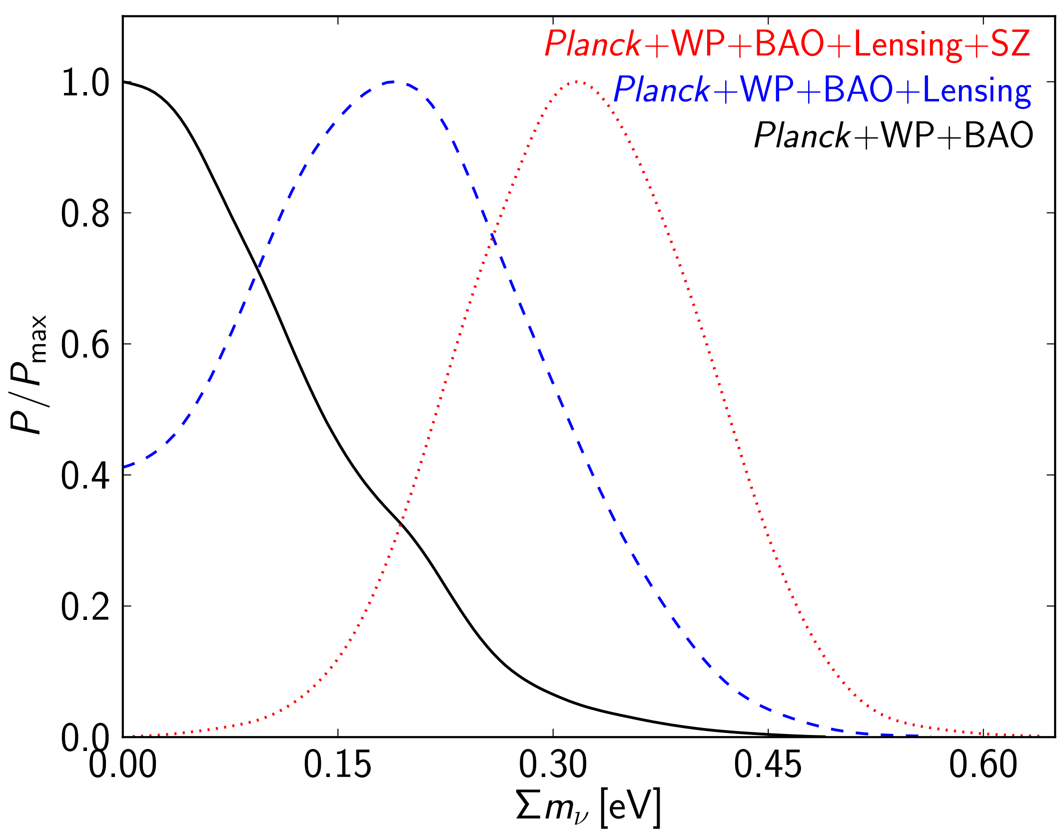
Red: demand washout of initial B+L asymmetry $\eta_B^i \sim 10^7 \eta_B$("independence" of initial B+L asymmetry); NH: for 99% of scatter points $m_1 \gtrsim 10$ meV !! (IH less restrictive); experimental progress: soon $\sum m_\nu = 90 \pm 10$ meV ?? Would exclude seesaw with 2 N's, νMSM and Affleck-Dine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



Palanque-Delabrouille et al '15

CMB & Lyman-alpha:

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



Battye & Moss '14

CMB, BAO, lensing & galaxy counts :

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

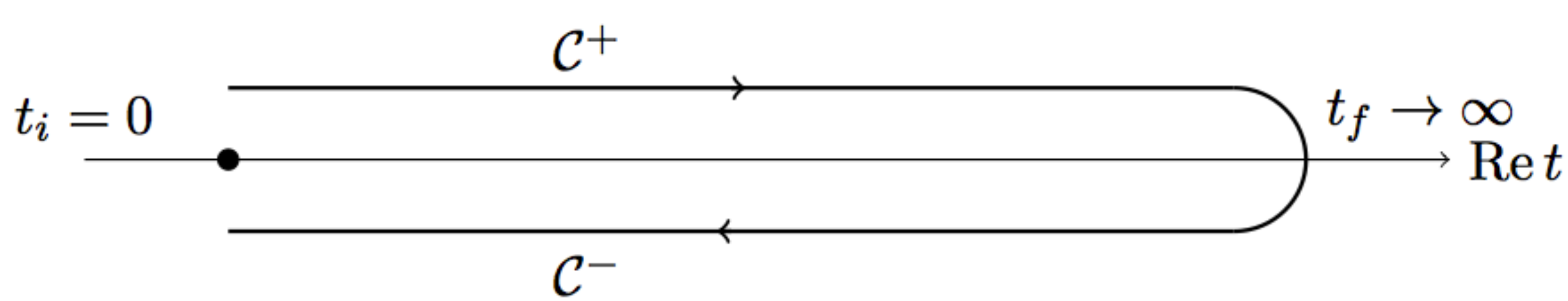
thermal leptogenesis ruled out ??

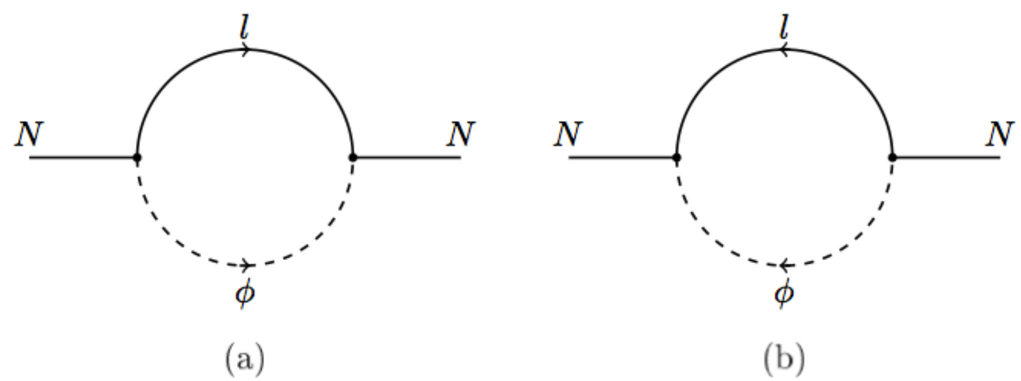
Towards a theory of leptogenesis

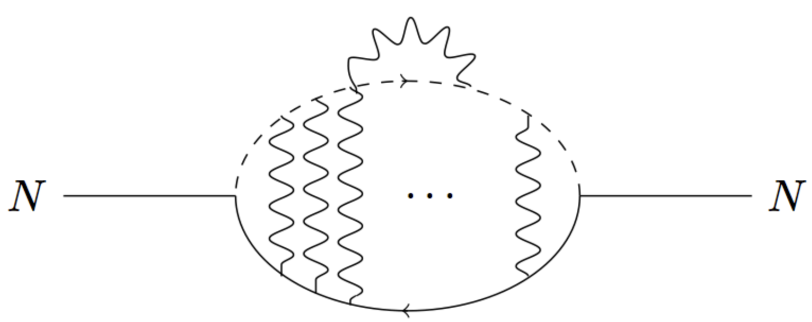
Leptogenesis is "simple" nonequilibrium process: weakly coupled heavy neutrino in large SM thermal bath, close to thermal equilibrium; rigrous treatment in nonequilibrium QFT? [Bodeker et al; Garbrecht et al; Garny et al; Iso et al; Ramsey-Musolf et al; Hutig, Mendizabal, Philipsen '13]; Schwinger-Keldysh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

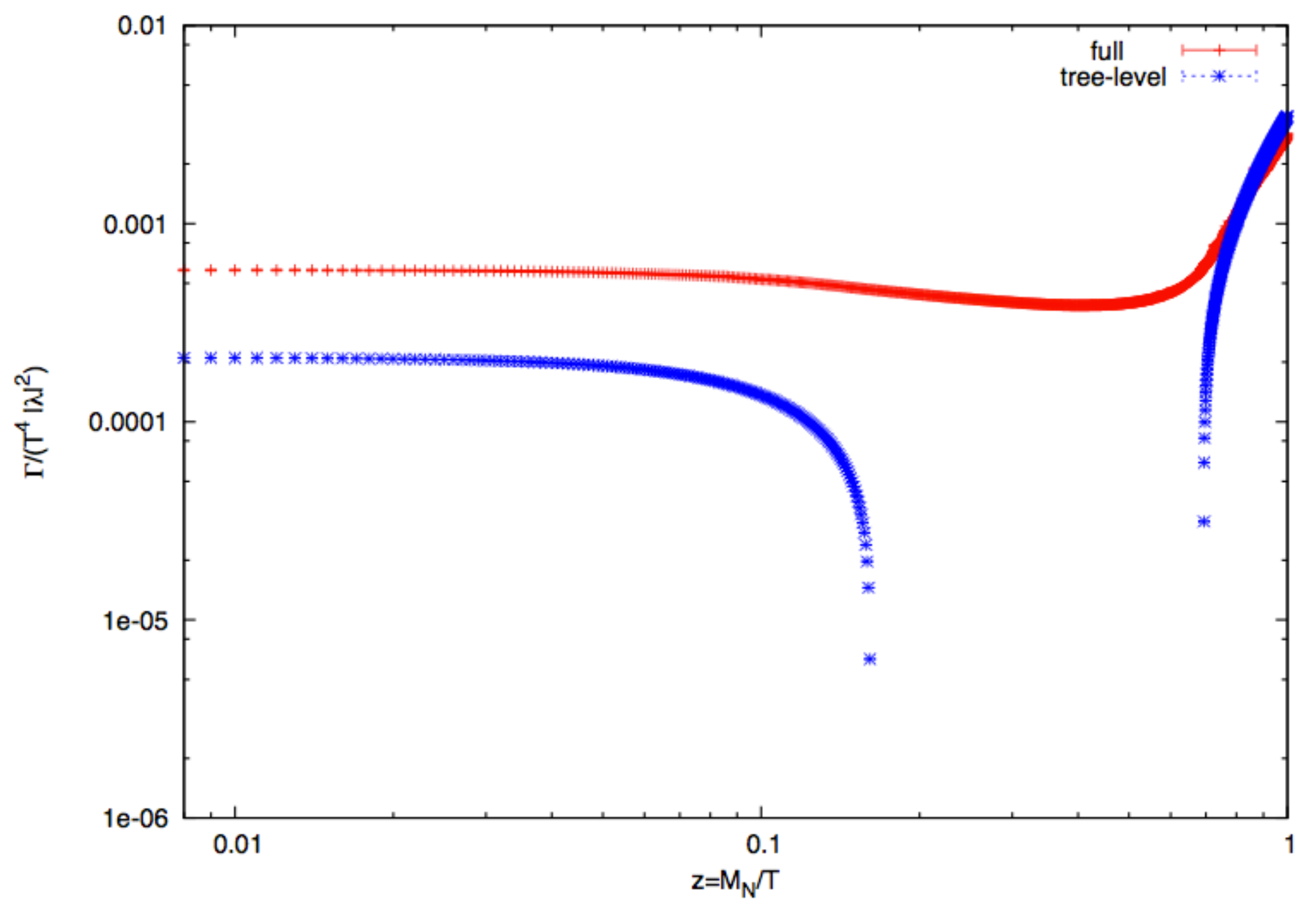
$$(\partial_{t_1}^2 + \omega_{\mathbf{q}}^2)\Delta_{\mathbf{q}}^-(t_1 - t_2) = -\int_{t_2}^{t_1} \mathrm{d}t'\, \Pi_{\mathbf{q}}^-(t_1 - t')\Delta_{\mathbf{q}}^-(t' - t_2)$$

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

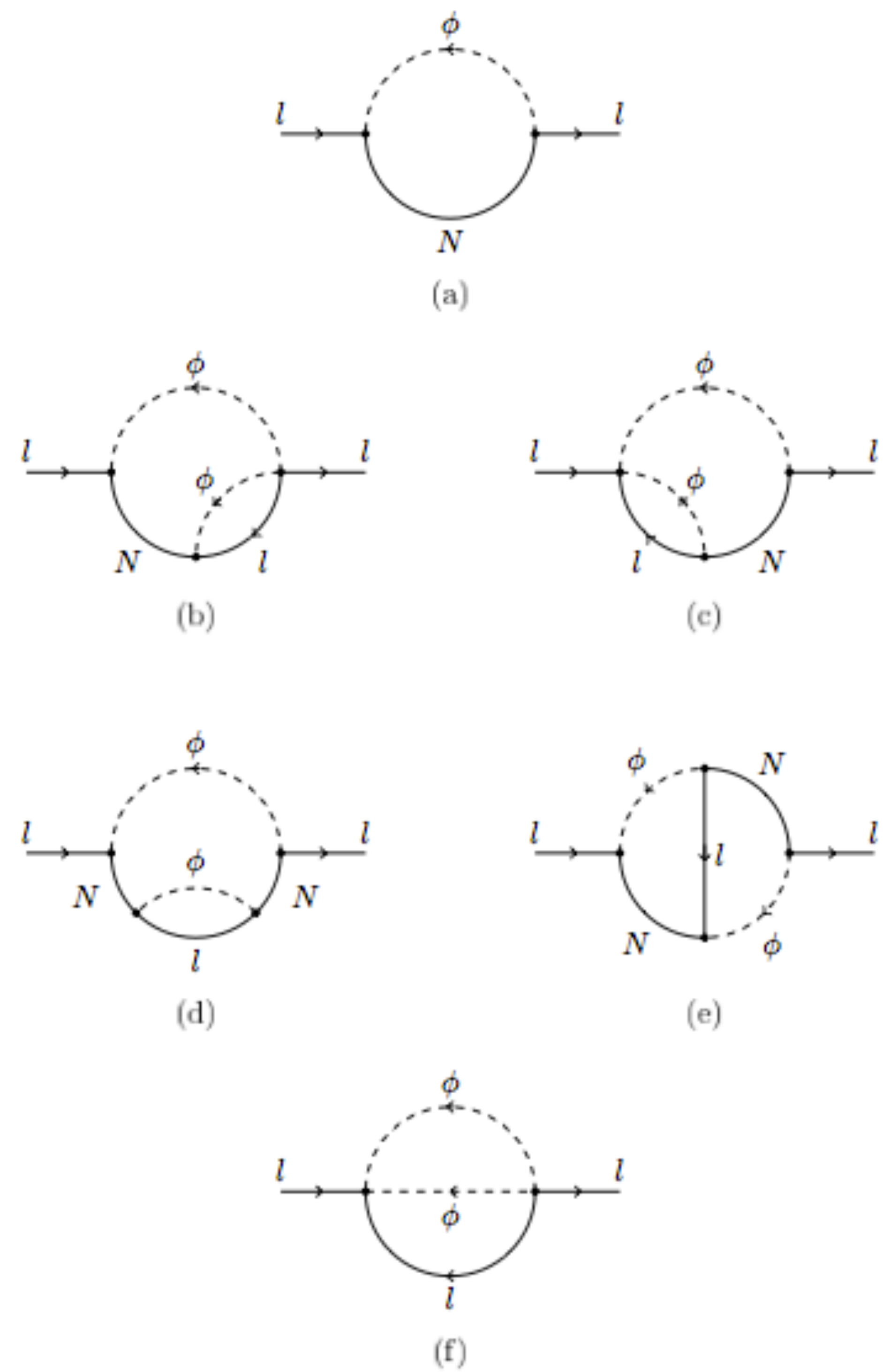




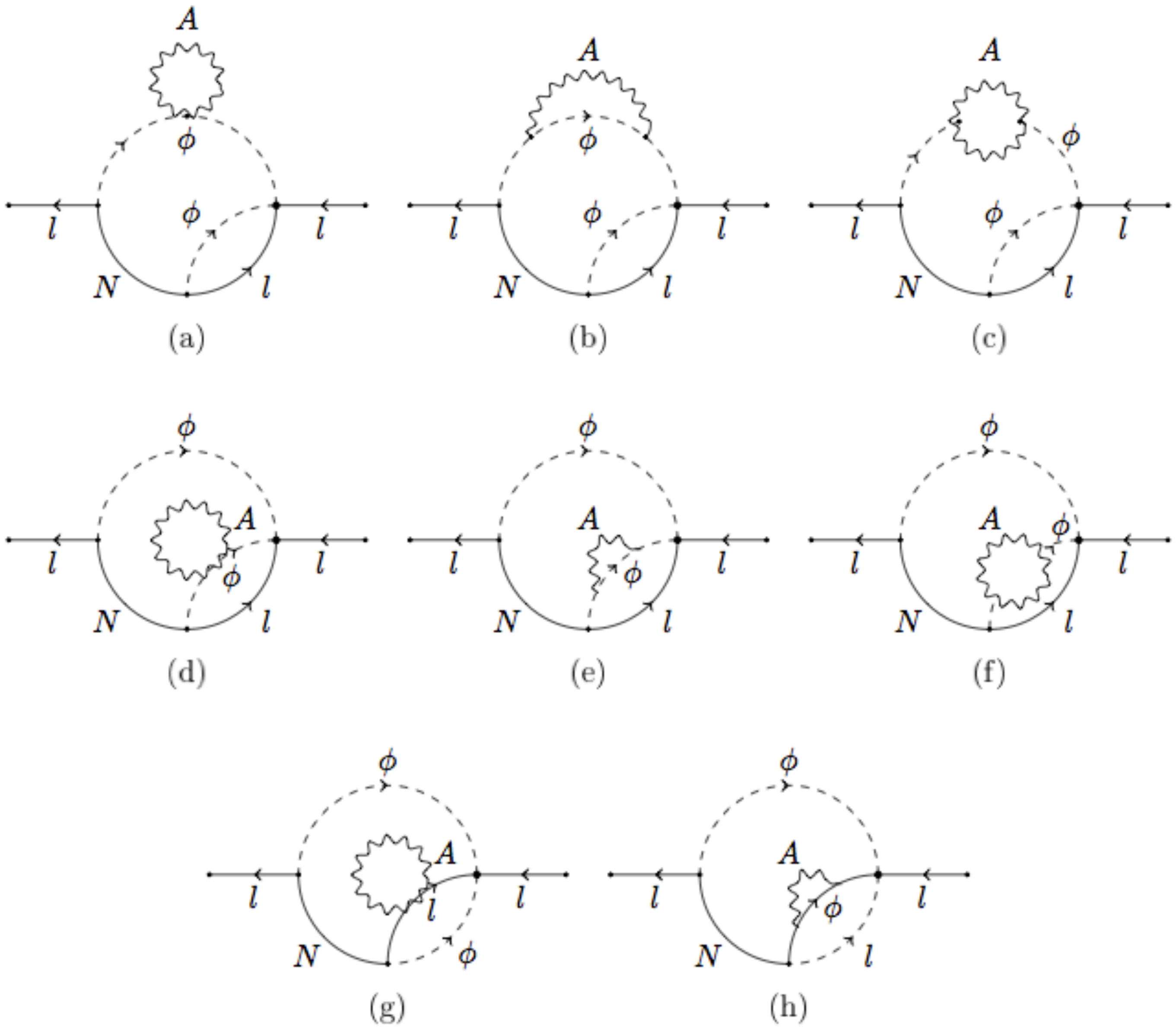


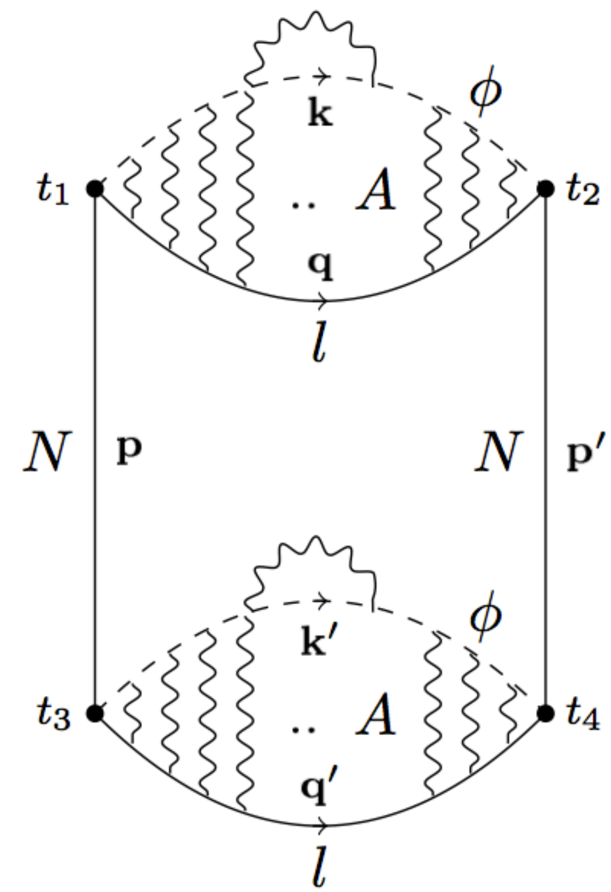


thermal production of heavy neutrinos (Higgs decay, production from lepton-Higgs pair, soft gauge bosons ...); resummation of soft gauge bosons; result very different from naive estimate with thermal masses!



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!

Conclusions & Outlook

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

- Low-scale leptogenesis (TeV or GeV seesaw scale) possible; potentially interesting signature: lepton-number violation at LHC; problem: scenarios rather fine-tuned (theoretical motivation?)

- Very important: more precise measurement of neutrino masses and mixings, CP violation, in particular $0\nu\beta\beta$ decay and absolute neutrino mass scale,

- Cosmological determination of absolute neutrino mass scale would rule out several classes of leptogenesis scenarios and support GUT-scale thermal leptogenesis

- Rigorous treatment of thermal leptogenesis in thermal QFT within reach