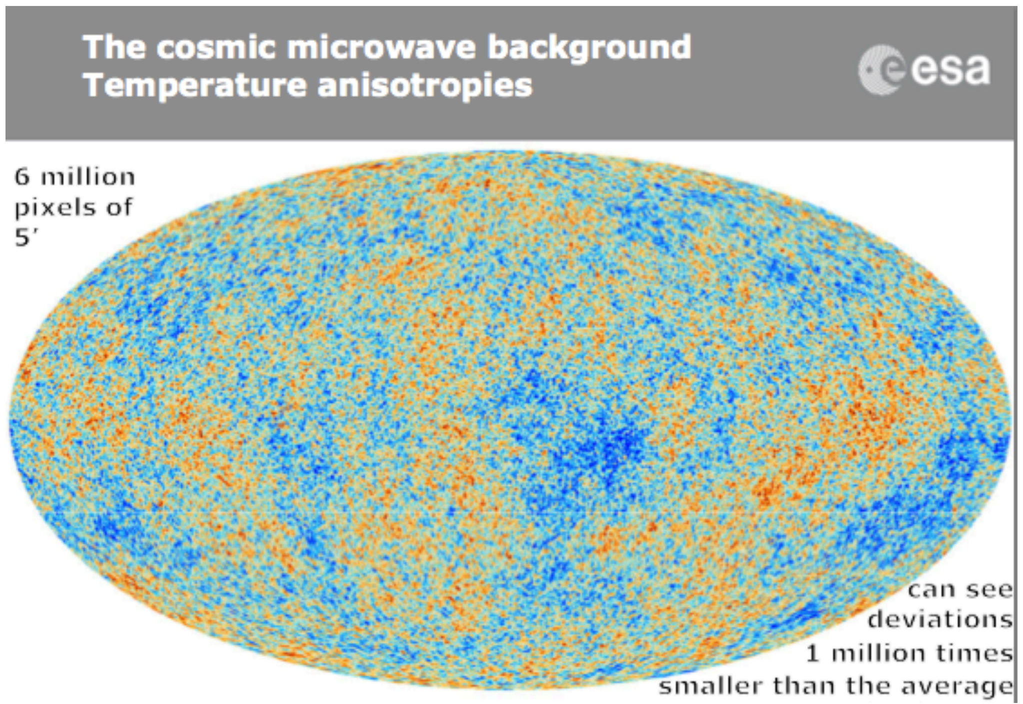
Baryogenesis - piece of a puzzle

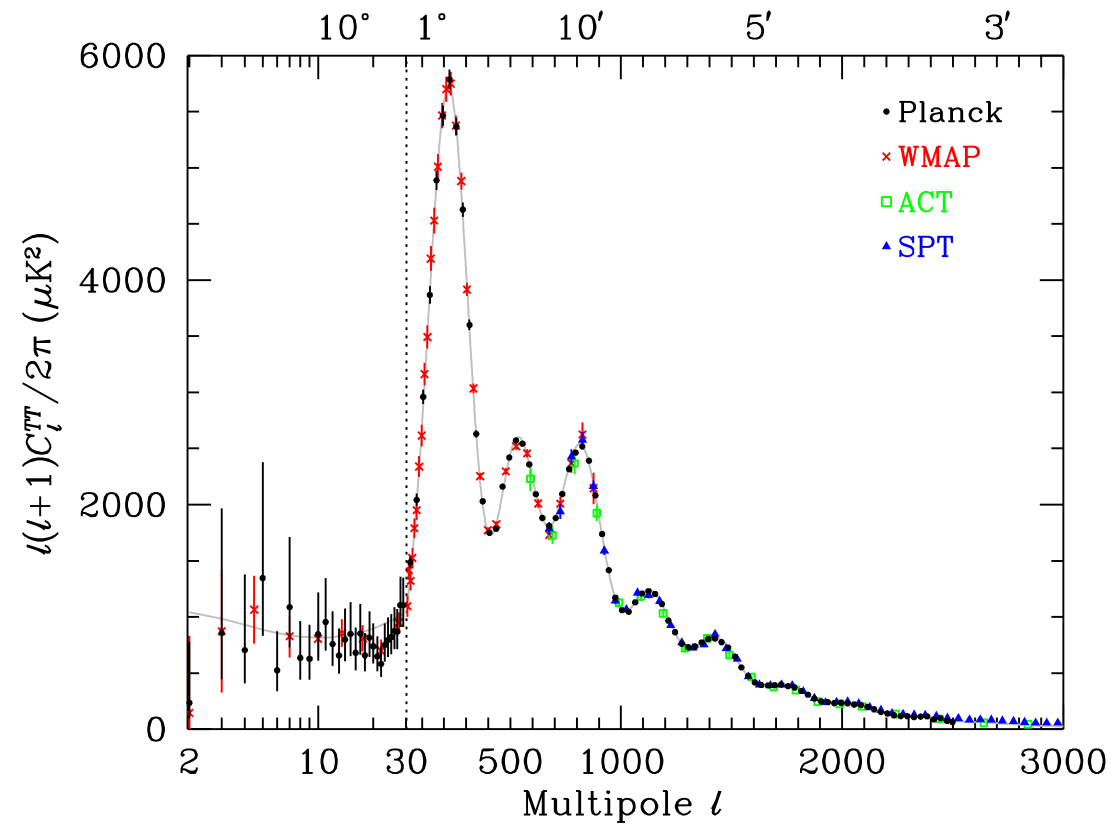
Wilfried Buchmüller

based on work with Dietrich Bödeker, arXiv:2009.07294

DESY, Hamburg, November 2020

Cosmic microwave background



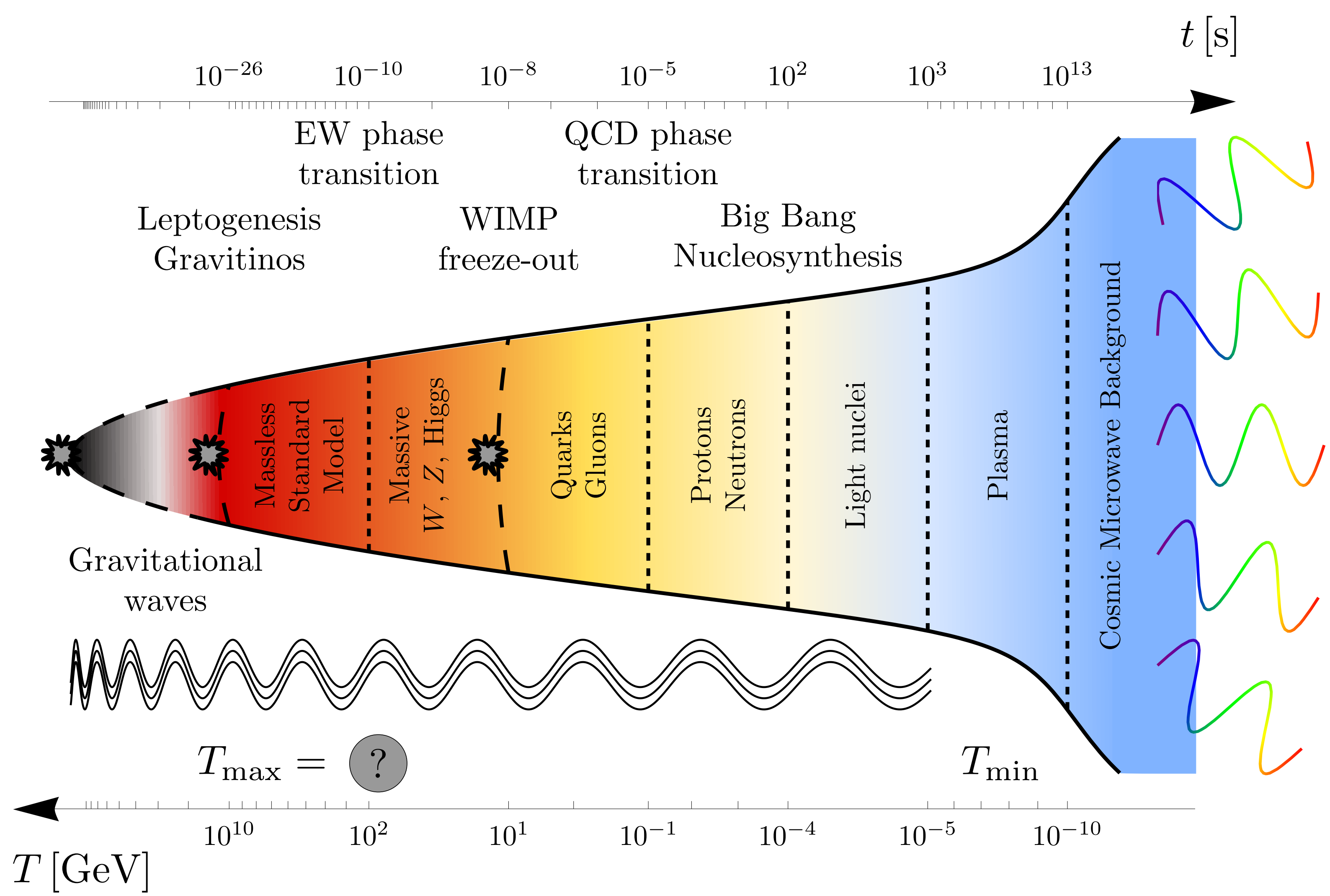


approximate homogeneity of CMB requires "inflation"; small anisotropies determine baryon/matter-antimatter asymmetry:

$$\eta_B \equiv \frac{n_B}{n_\gamma} = \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.12 \pm 0.04) \times 10^{-10}$$

big bang nucleosynthesis (BBN): $(5.8 - 6.6) \times 10^{-10}$

independent measurements at very different times consistent!



hot phase of early universe: $\frac{n_q + n_{\bar{q}}}{n_\gamma} \sim 36$

η_B corresponds to tiny asymmetry $\boxed{\frac{n_q - n_{\bar{q}}}{n_\gamma} \sim 10^{-10}}$, must have

generated after inflation and before BBN: **baryogenesis**

The early days

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 $\nu_\mu = \mu_0$: $n_\mu = -1$, $n_x = +1$.

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

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

for antibaryons P and N: $n_B = -1$, $n_x = -3$.

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

two years after discovery of CP violation in K-decays [Christenson, Cronin, Fitch, Turlay '64], one year after discovery of CMB [Penzias, Wilson '65], early universe at Planck era, prediction of proton lifetime $\sim 10^{50}$ yr …

Sakharov's conditions

Necessary conditions for generating a matter-antimatter asymmetry:

- baryon number violation
  otherwise, a state with $B = 0$ could not evolve into a state with $B \neq 0$

- C and CP violation
  exchanging particles and anti-particles would not change reaction rates

- deviation from thermal equilibrium
  this holds for a thermal system (considered by Sacharov), which is stationary; departure from thermal equilibrium defines an error of time

  (alternative mechanisms: dynamics of scalar fields, e.g. Affleck-Dine baryogenesis, spontaneous baryogenesis, heavy moduli decay, …)

Milestones

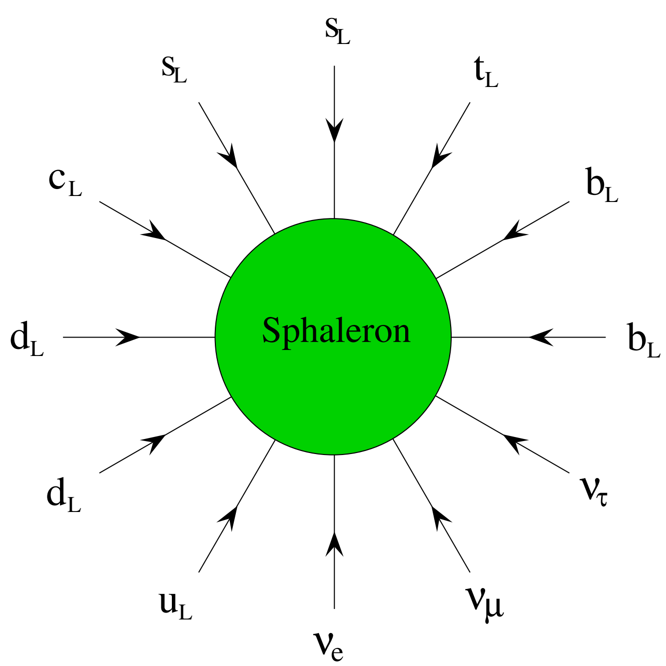
- 1978: SU(5) GUT baryogenesis
  [Yoshimura; Dimopoulos, Susskind; Touissant, Treiman, Wilczek, Zee; Weinberg]
  CP-violating decays of leptoquarks (problematic); detailed calculations based on Boltzmann equations [Kolb, Wolfram]

- 1985: Affleck-Dine baryogenesis
  scalar dynamics in supersymmetric models

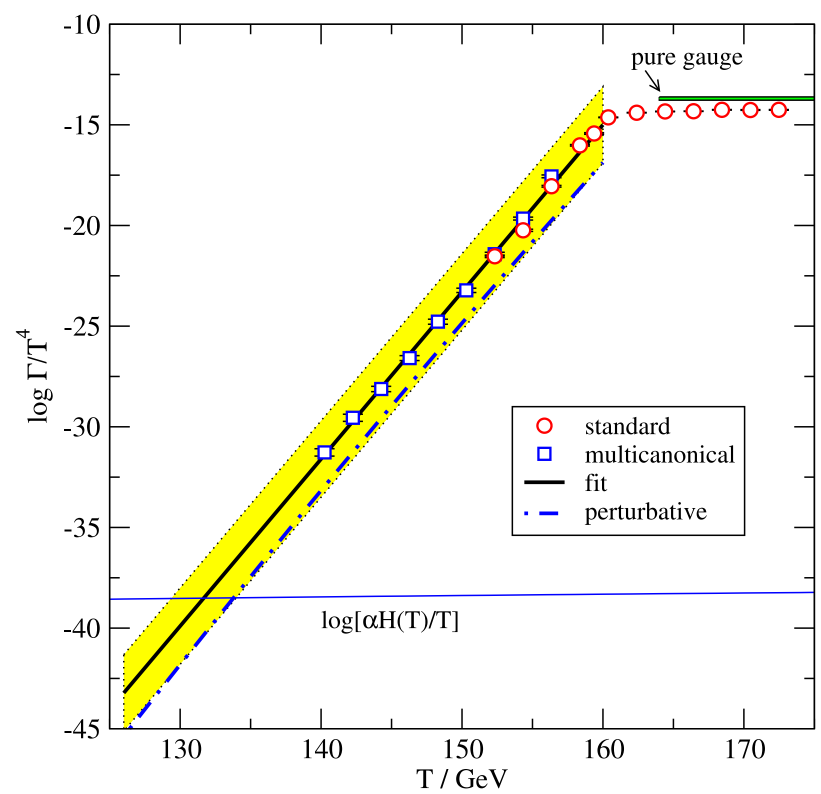
- 1985: sphaleron processes
  [Kuzmin, Rubakov, Shaposhnikov]; SU(5) GUT baryogenesis excluded; idea of electroweak baryogenesis (appealing mechanism, just SM!)

- 1986: Leptogenesis
  [Fukugita, Yanagida]; CP- violating decays of heavy Majorana neutrinos;
  leptogenesis and invisible axions [Langacker, Peccei, Yanagida]

Sphaleron processes



['t Hooft '76]



sphaleron rate in SM

[D'Onofrio et al '14]

sphaleron induced $B+L$ changing processes:

$$O_{B+L} = \prod_{i=1}^{3}(q_{L_i} q_{L_i} q_{L_i} l_{L_i}) \ , \quad \Delta B = \Delta L = 3 \ , \ldots$$

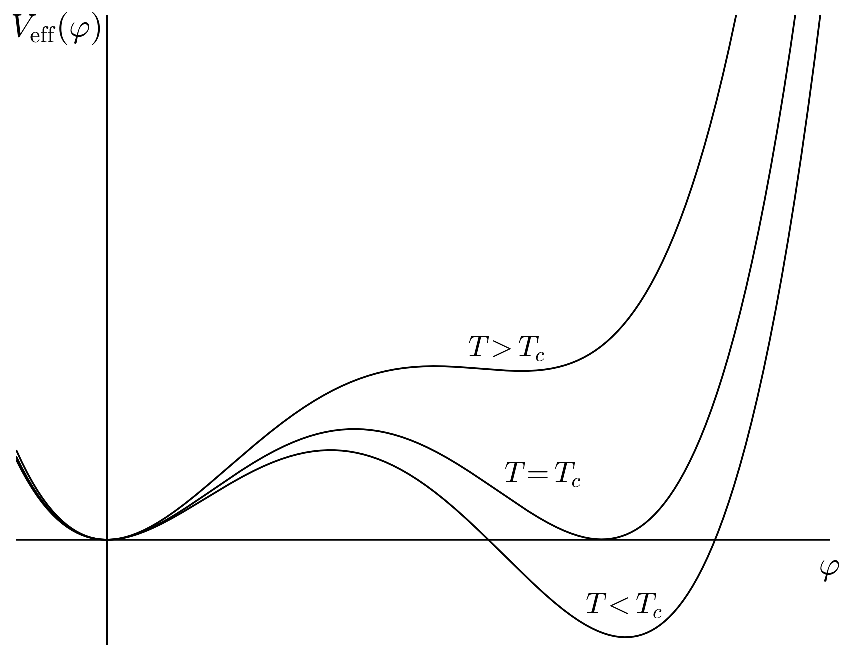
$$u^c + d^c + c^c \to d + 2s + 2b + t + \nu_e + \nu_\mu + \nu_\tau$$

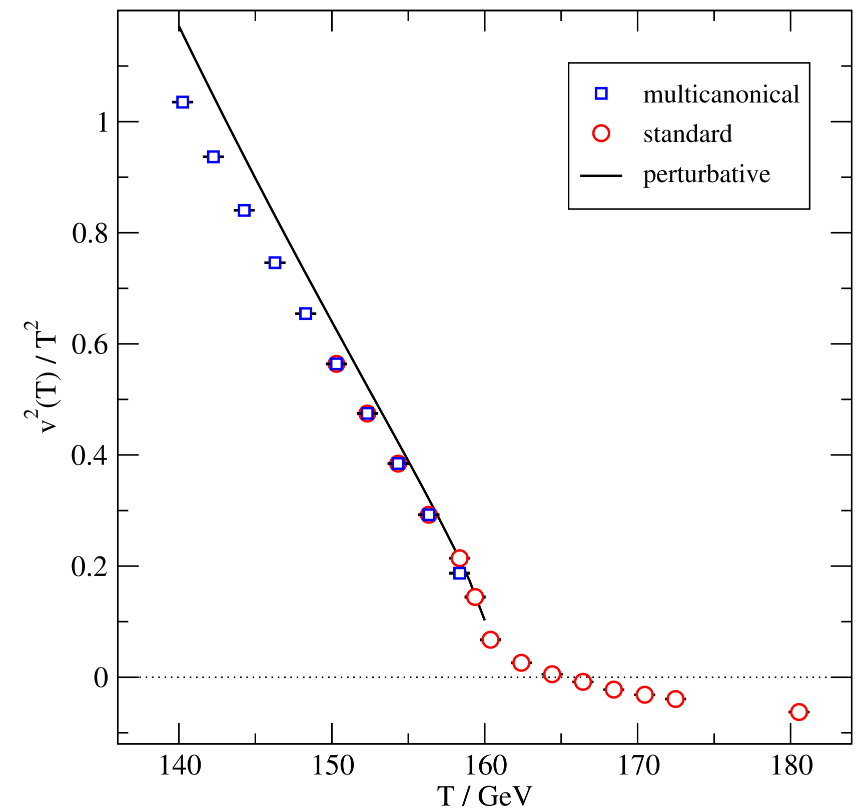
in thermal equilibrium: $T_{EW} \sim 100 \text{ GeV} < T < T_{sph} \sim 10^{12} \text{ GeV}$

(so far purely theoretical; search at LHC -> Ringwald)

Electroweak Baryogenesis

[Kuzmin, Rubakov, Shaposhnikov '86; … Cohen, Kaplan, Nelson '93 … Konstandin … Servant …]

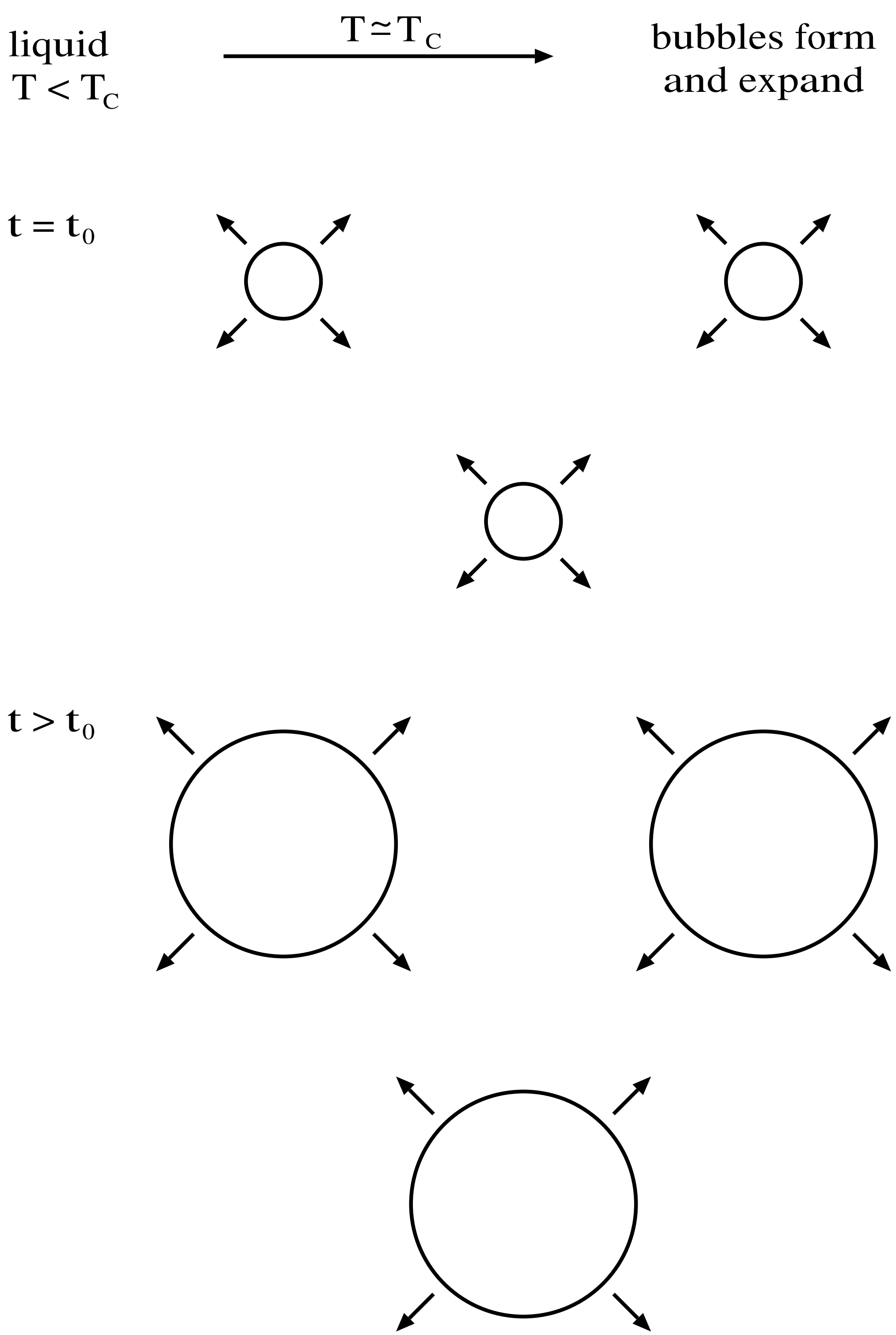




[D' Onofrio et al. '14]

EWBG requires strong 1st order (electroweak) phase transition, as universe cools down; required jump in Higgs field: $\varphi_c/T_c > 1$; for "large" Higgs masses potential nonperturbative, lattice simulations required; in SM only smooth crossover; 1st order phase transition requires extension of SM

Bubble nucleation & growth

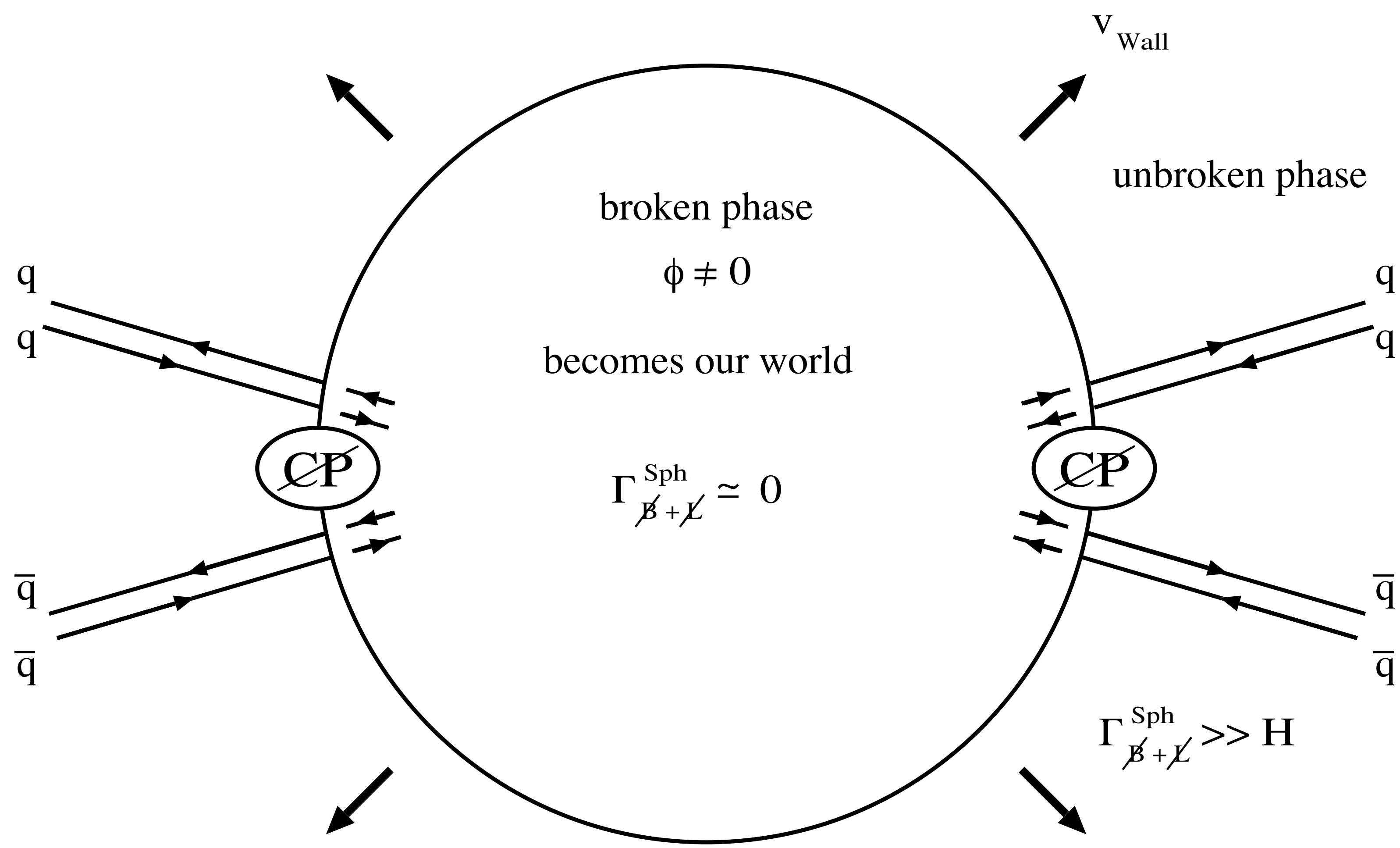


1st-order phase transition in extensions of SM (2HDM, doublet-singlet model,...)

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):

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

[review: Konstandin ’13]

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

[Dorsch, Huber, Konstandin, No '17]

Potential with complex parameters for two Higgs fields Φ_1, Φ_2 :

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

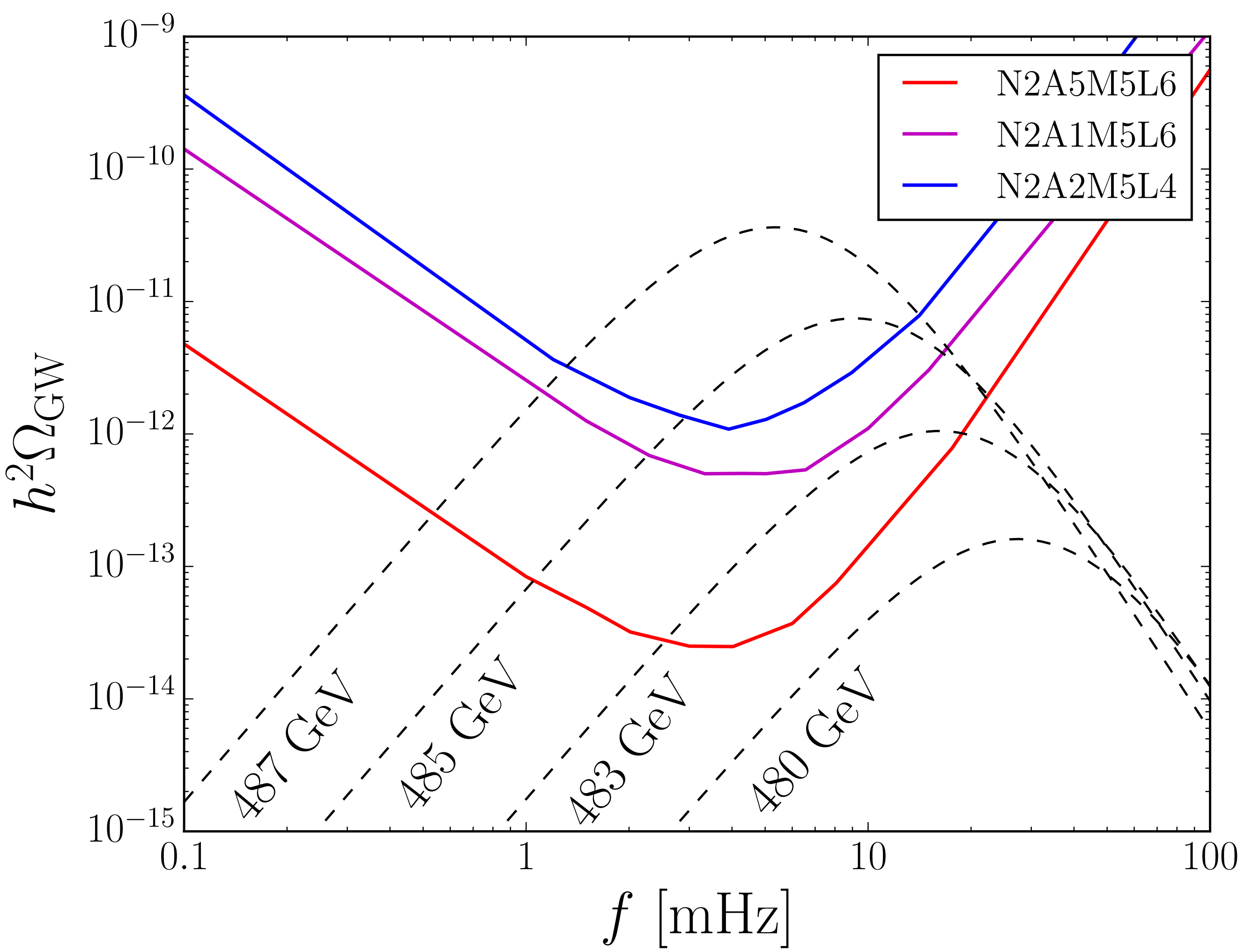
$$
\langle \Phi_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \cos\beta \end{pmatrix}, \qquad \langle \Phi_2 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \sin\beta \, e^{i\theta} \end{pmatrix} ,
$$

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

search for further charged and neutral Higgs bosons at LHC; strong 1st order phase transition and EWBG require large couplings; also CP violation in Higgs sector has to large enough attractive consequence of large couplings: **gravitational waves** from electroweak phase transition:

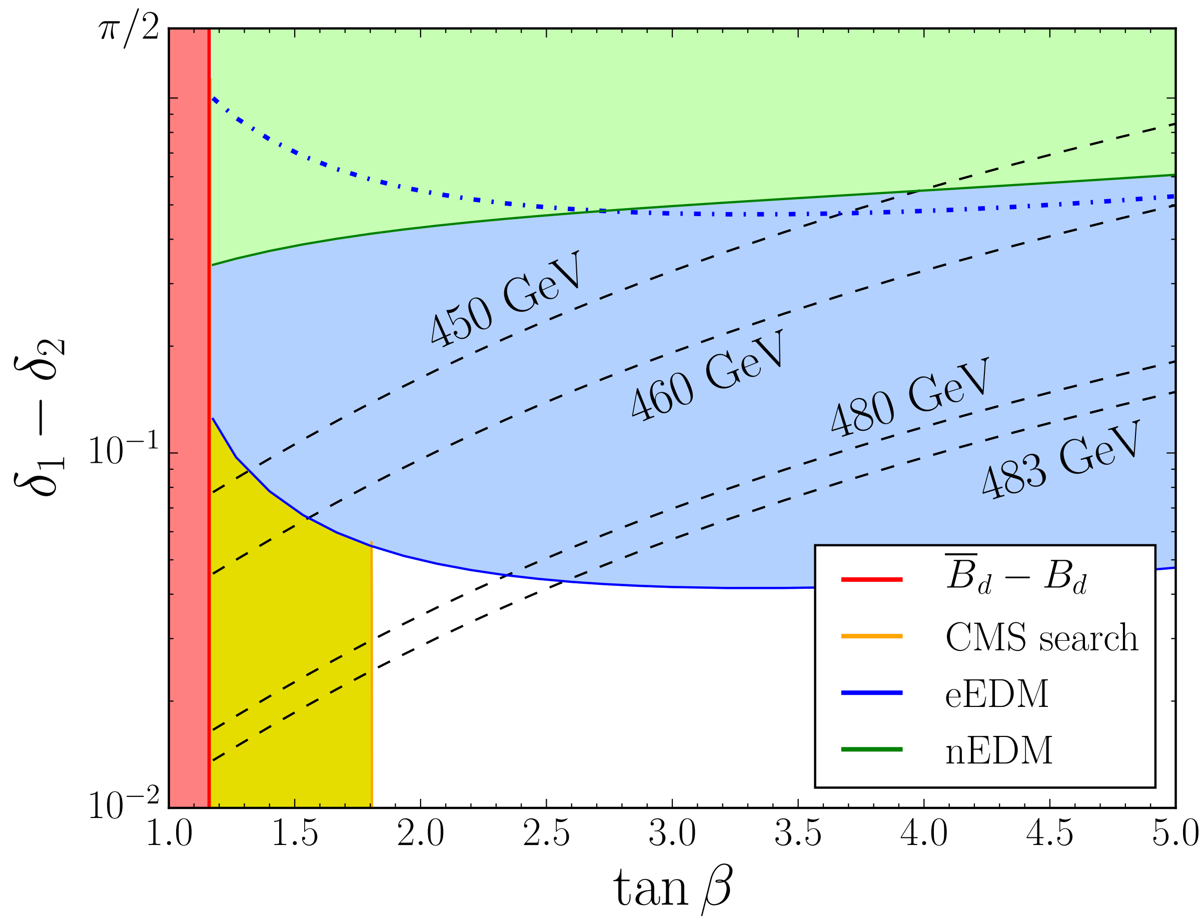
$$ds^2 = a^2(\tau)(\eta_{\mu\nu} + h_{\mu\nu})dx^\mu dx^\nu \ , \quad \bar{h}_{\mu\nu} = h_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu}h^\rho_\rho$$

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



nice correlation between strong 1st order phase transition and gravitational waves in the LISA frequency range; many detailed studies [Caprini et al '19]

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



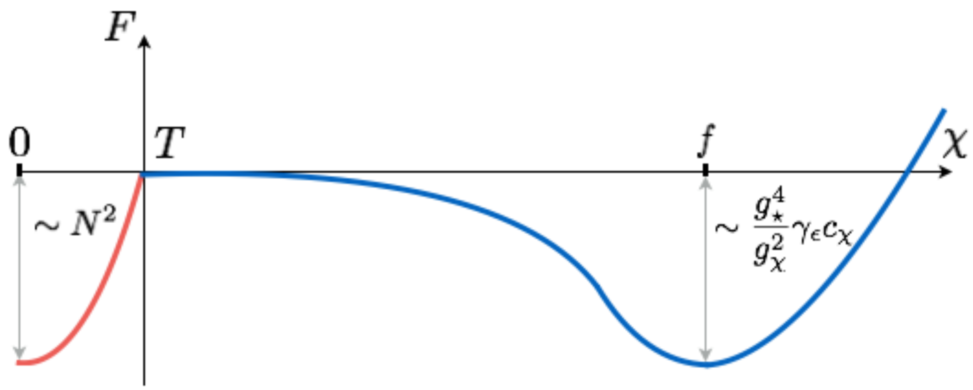
EWBG consistent with electron ACME I bound, but model ruled out by ACME II bound (October 2018):

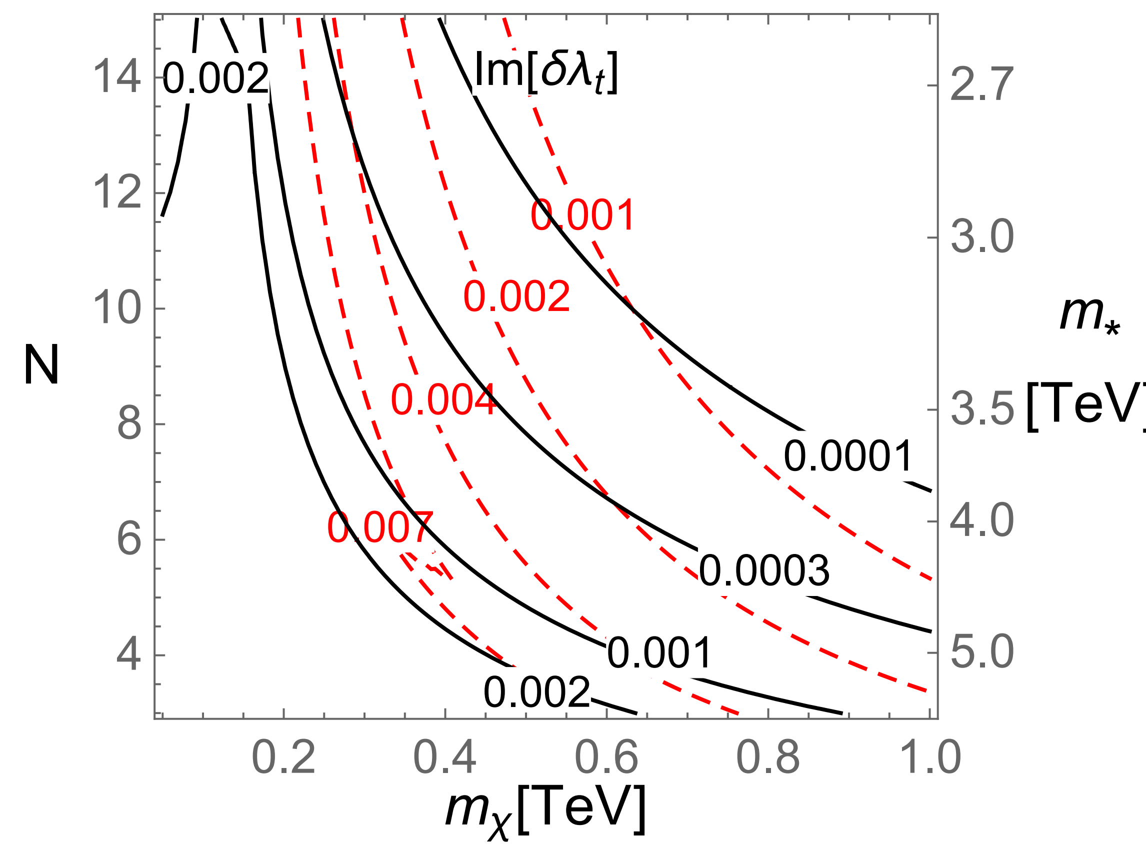
$$|d_e^{\mathrm{ACMEI}}| < 8.7 \times 10^{-29}\ e \cdot \mathrm{cm}$$
$$|d_e^{\mathrm{ACMEII}}| < 1.1 \times 10^{-29}\ e \cdot \mathrm{cm}$$

Note: situation similar in doublet-singlet model, MSSM, split NMSSM, …

Example 2: Light composite Higgs boson

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





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

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

Basic idea: **Higgs** as pseudo-Goldstone boson from broken global symmetry together with **dilaton** χ as pseudo-Goldstone boson from broken conformal symmetry of strongly coupled sector (partial compositeness) [Giudice, Grojean, Pomarol, Rattazzi '07]; EWPT together with confinement phase transition; consistent with constraints from electron edm; light dilaton in reach of **LHC**!!

Leptogenesis

[Garbrecht, Molinaro, eds, Int. J. Mod. Phys. A Vol. 33, Nos. 5 & 6 (2018)]

SM with right-handed neutrinos

$$-\mathcal{L} = h^e_{ij}\overline{e_{Rj}}l_{Li}\tilde{\phi} + h^\nu_{ij}\overline{\nu_{Rj}}l_{Li}\phi + \frac{1}{2}M_{ij}\overline{\nu_{Rj}}\nu^c_{Ri} + \mathrm{h.c.}$$

After electroweak symmetry breaking charged lepton and Dirac neutrino masses, $m_D = h^\nu\langle\phi\rangle \equiv h^\nu v_{\mathrm{EW}}$, and heavy and light Majorana neutrinos as 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:

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

i.e., neutrino mass scale from electroweak scale and GUT scale!

Parameter space: two 3x3 complex matrices $M, \ m_D$!!

Lepton asymmetry from **CP-violating decays** of heavy Majorana neutrinos (quantum interference!):

$$\varepsilon_i = \frac{\Gamma(N_i \to l\phi) - \Gamma(N_i \to \bar{l}\bar{\phi})}{\Gamma(N_i \to l\phi) + \Gamma(N_i \to \bar{l}\bar{\phi})}$$

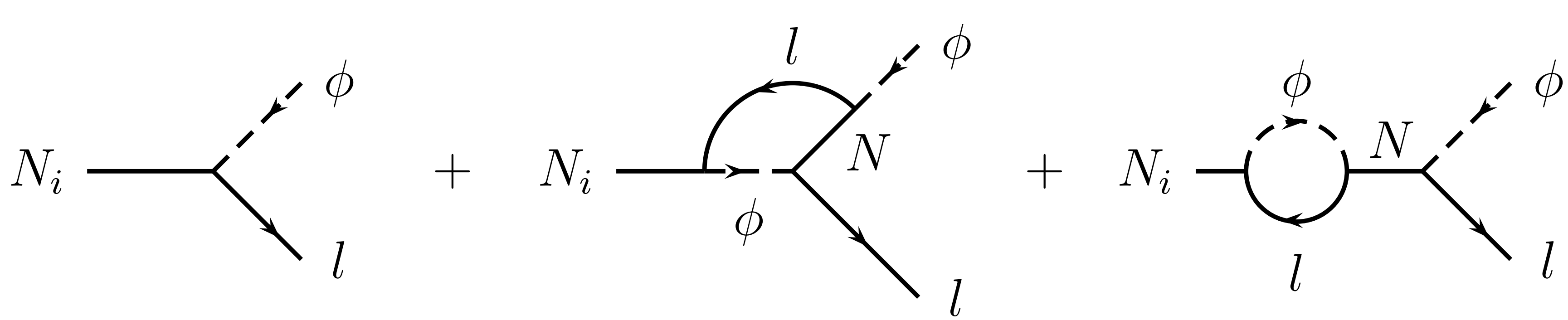
hierarchical heavy Majorana neutrinos N_i:

$$\varepsilon_i = -\frac{3}{16\pi}\frac{M_i}{v_{\mathrm{EW}}^2 \left(h^{\nu\dagger}h^{\nu}\right)_{ii}} \mathrm{Im}\left(h^{\nu\dagger}m_\nu h^{\nu *}\right)_{ii}$$

Covi, Roulet, Vissani '96

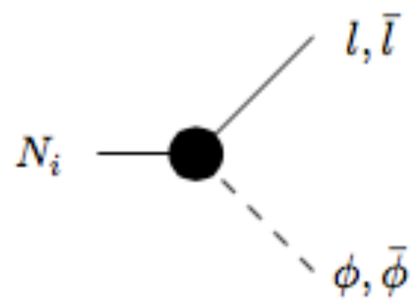
quasi-degenerate heavy Majorana neutrinos N_i:

$$\varepsilon_i = \frac{1}{8\pi}\sum_{i\neq k}\frac{\mathrm{Im}\left(h^{\nu\dagger}h^{\nu}\right)_{ik}^2}{\left(h^{\nu\dagger}h^{\nu}\right)_{ii}}\frac{M_i M_k}{M_k^2 - M_i^2}$$

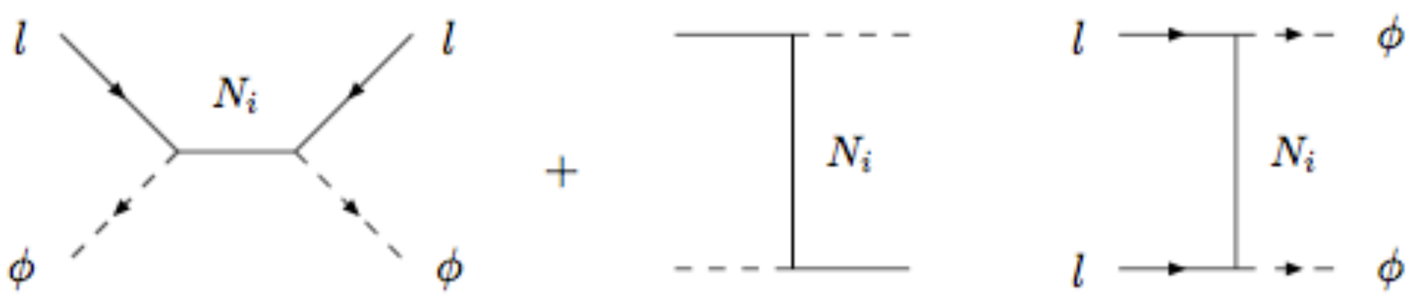


Decays (D) and inverse decays (ID)

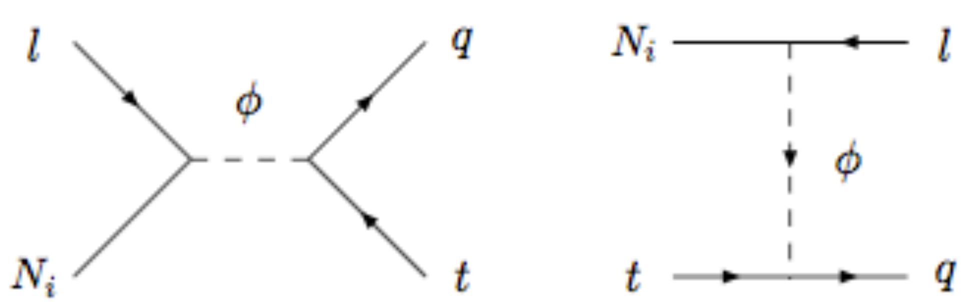
$N_i \leftrightarrow l\,\phi\,,\ \bar{l}\,\bar{\phi}$



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



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



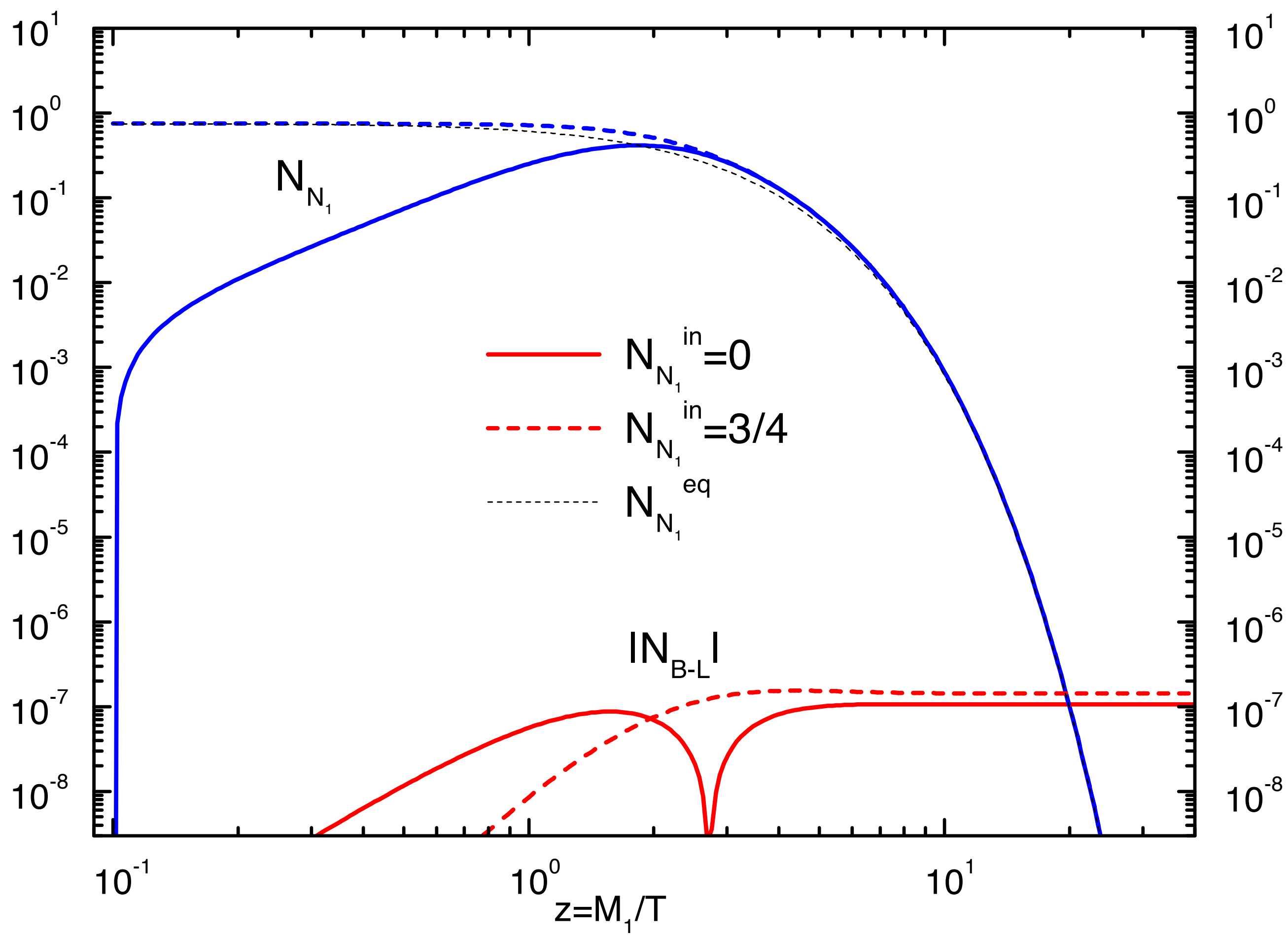
Luty '92, Plumacher '96, …

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, $z = M_{N_1}/T$):

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

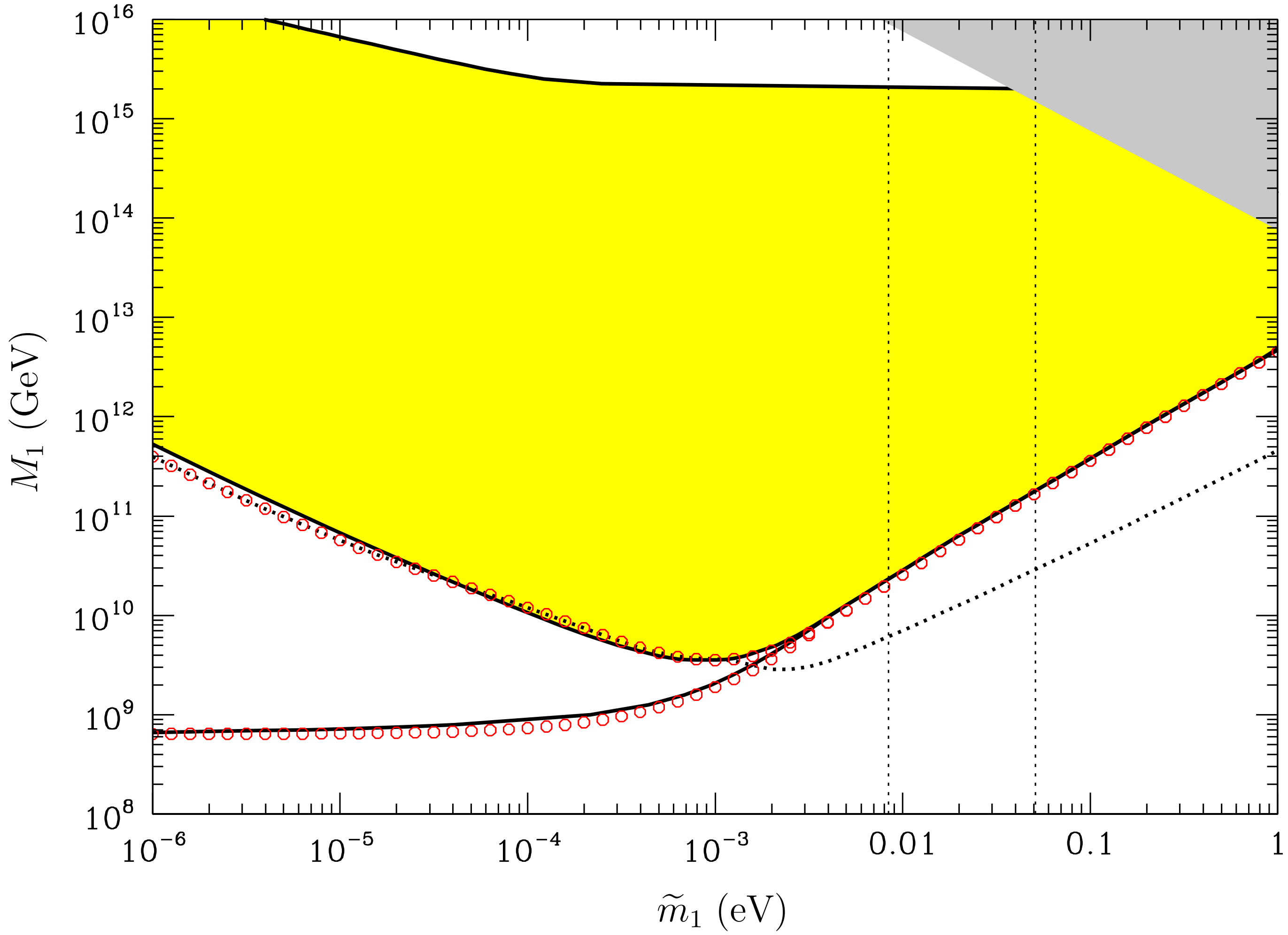


heavy neutrino densities & baryon asymmetry; leptogenesis process close to equilibrium; in "strong washout regime,"

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

baryon asymmetry rather independent of initial conditions (but flavour effects!)

$$\tilde{m} = (h^{\nu\dagger}h^{\nu})_{11} v_{\mathrm{EW}}^2/M_1$$



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):

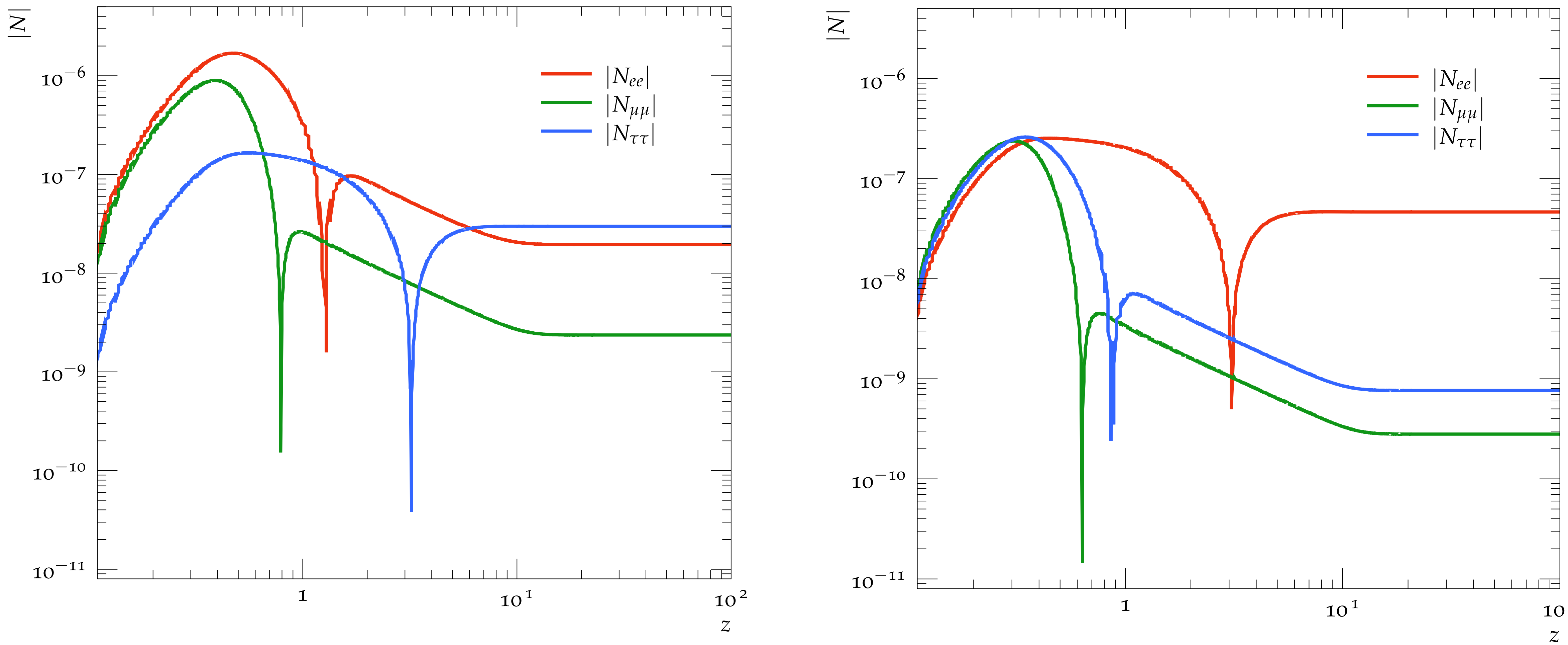
$$m_i < 0.1\,\mathrm{eV}\ , \quad M_1 > 4 \times 10^8\ \mathrm{GeV}$$

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]

Can one lower the leptogenesis scale?



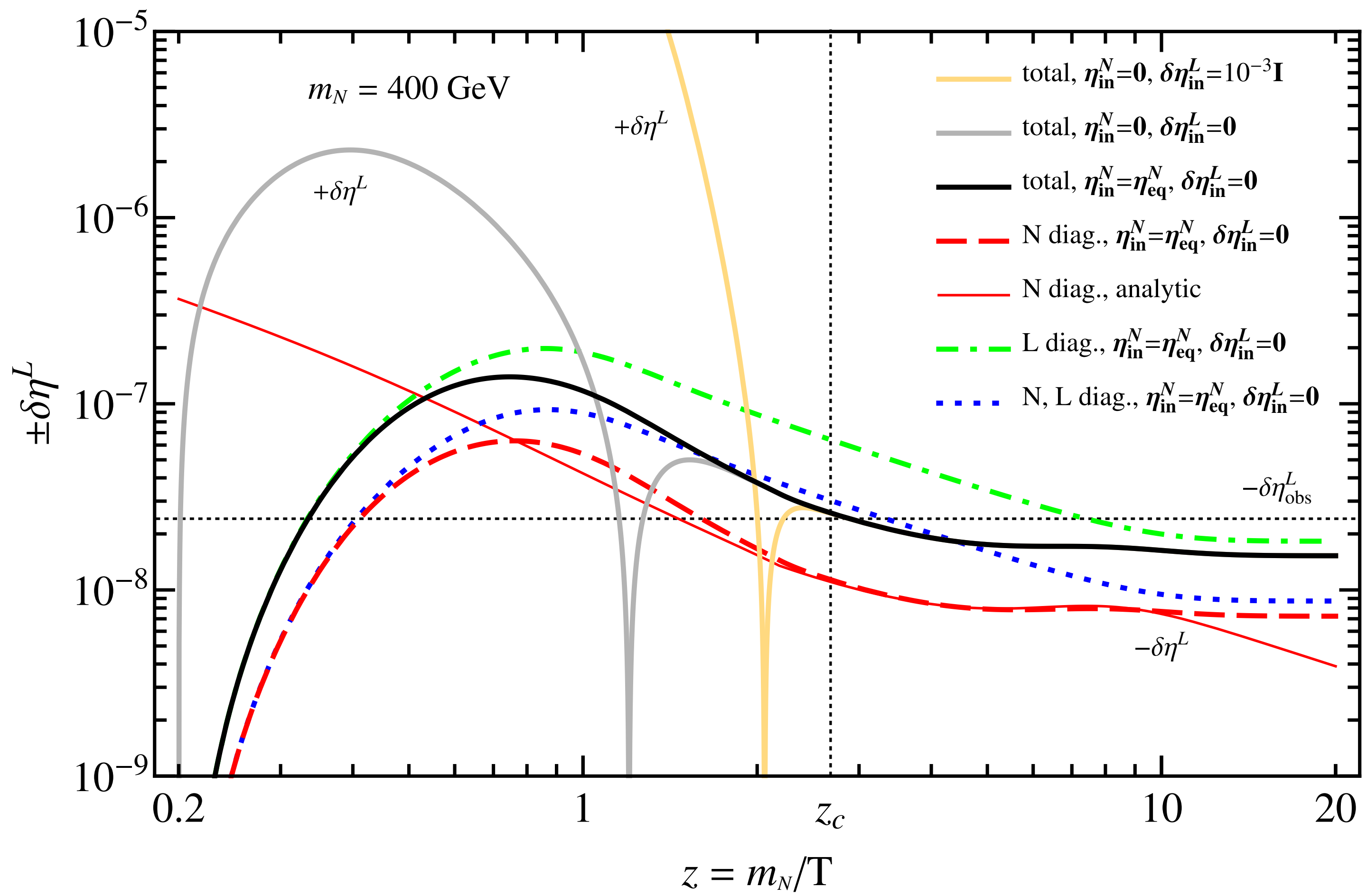
	m_1 (eV)	M_1 (GeV)	M_2 (GeV)	M_3(GeV)
S_2	0.079	$10^{6.5}$	10^{7}	$10^{7.5}$
S_3	0.114	$10^{6.5}$	$10^{7.2}$	$10^{7.9}$

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

Flavour effects: heavy neutrino masses (leptogenesis scale) can be lowered (**fine tuning**!), asymmetries flavour dependent; light neutrino masses satisfy “upper bound”

Resonant leptogenesis

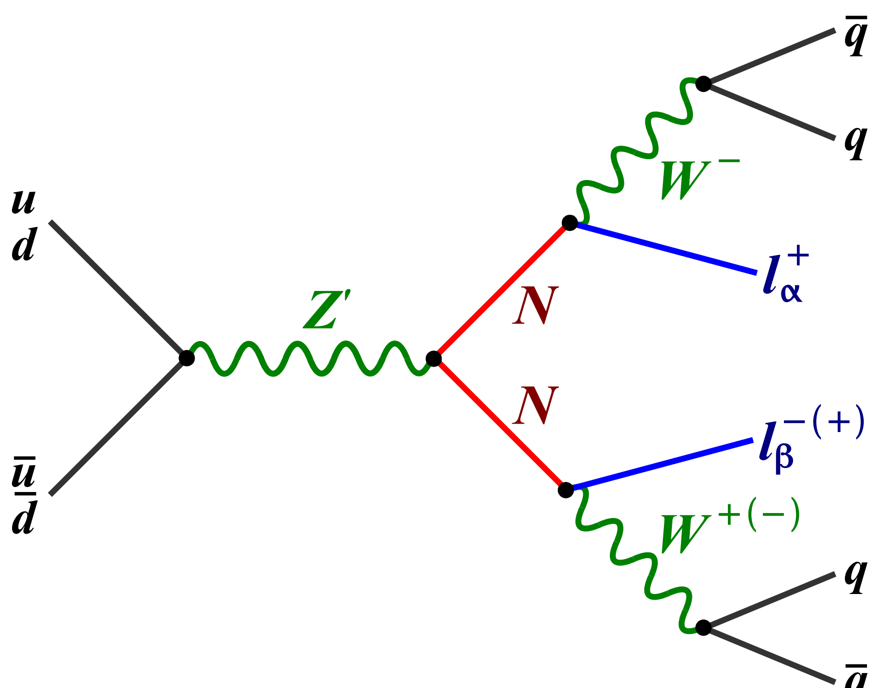
[Pilaftsis …’03]



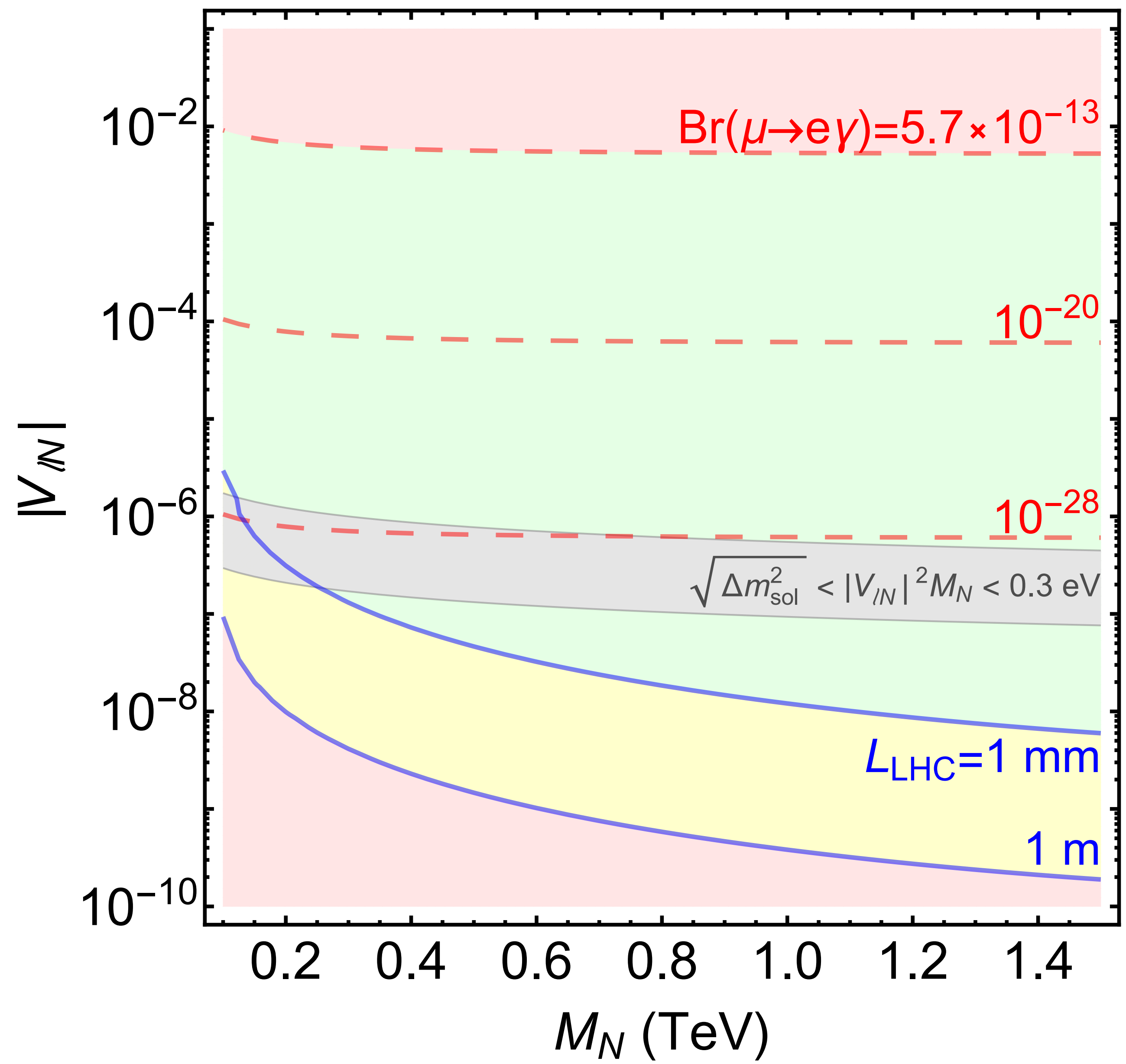
Parameter	Value
m_N	400 GeV
c	2×10^{-7}
$\frac{\Delta M_1}{m_N}$	-3×10^{-5}
$\frac{\Delta M_2}{m_N}$	$(-1.21+0.10\,i)\times10^{-9}$
a	$(4.93-2.32\,i)\times10^{-3}$
b	$(8.04-3.79\,i)\times10^{-3}$
ϵ_e	$5.73\,i\times10^{-8}$
ϵ_μ	$4.30\,i\times10^{-7}$
ϵ_τ	$6.39\,i\times10^{-7}$

[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; motivation: testability at colliders!

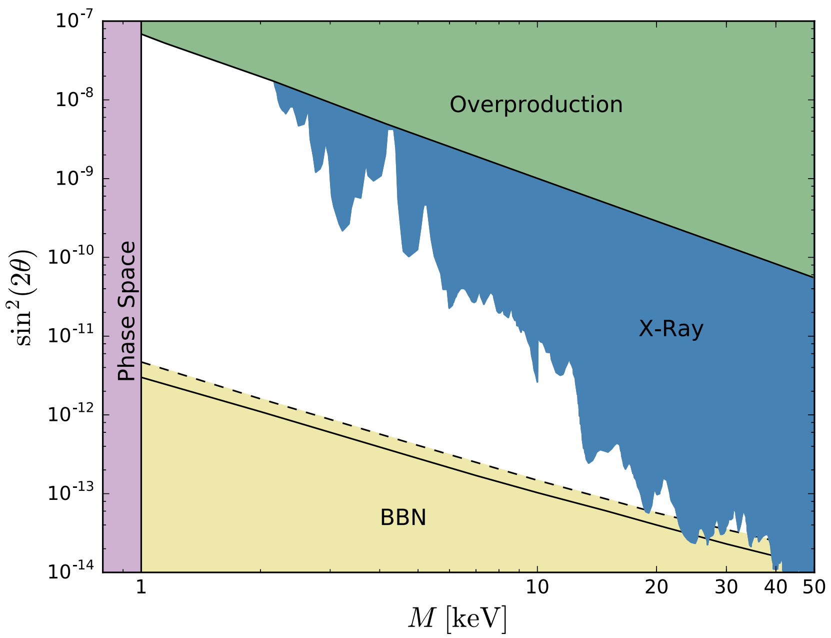


[Depisch, Dev, Pilaftsis ’15]

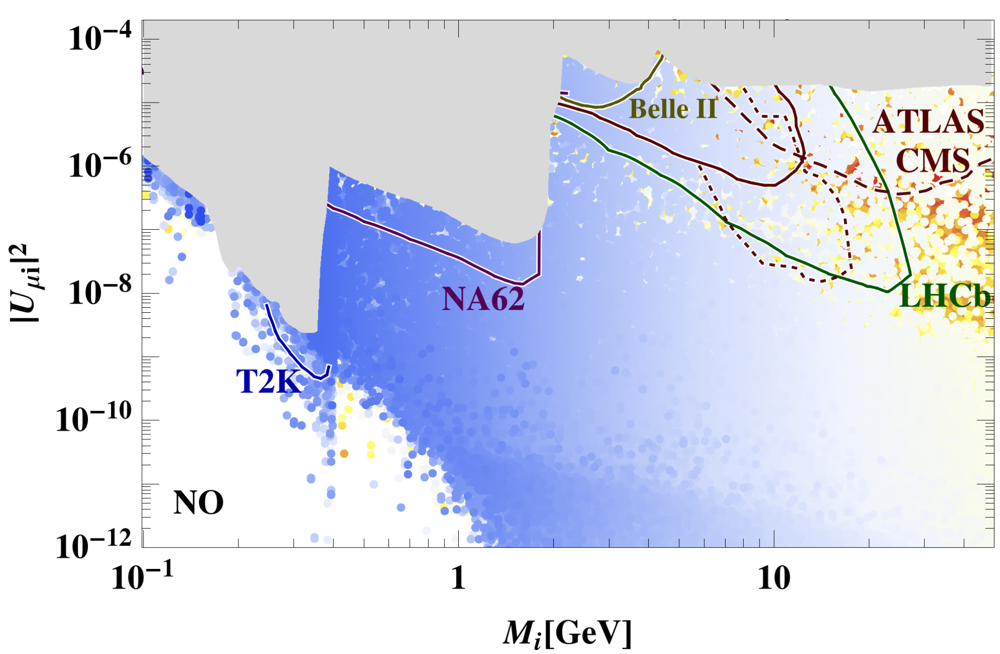


Direct test: heavy neutrino production at the LHC (assume additional vector bosons), with lepton-flavour violation, displaced vertices; strong constraints from out-of-equilibrium condition in leptogenesis

Sterile-neutrino oscillations



[Bodeker, Klaus '20]



[Abada et al, '19]

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:

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

3.5 keV γ-ray line from DM decay?

3 N oscillations: GeV neutrinos at Belle II, LHCb ? (motivation: testability at colliders)

Leptogenesis & grand unification

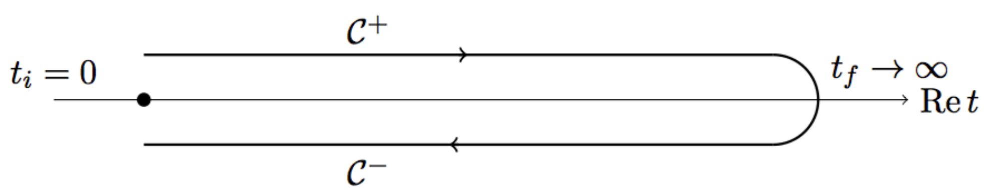
Can GUT-scale leptogenesis be tested? RH neutrinos very heavy! Compare with grand unification:

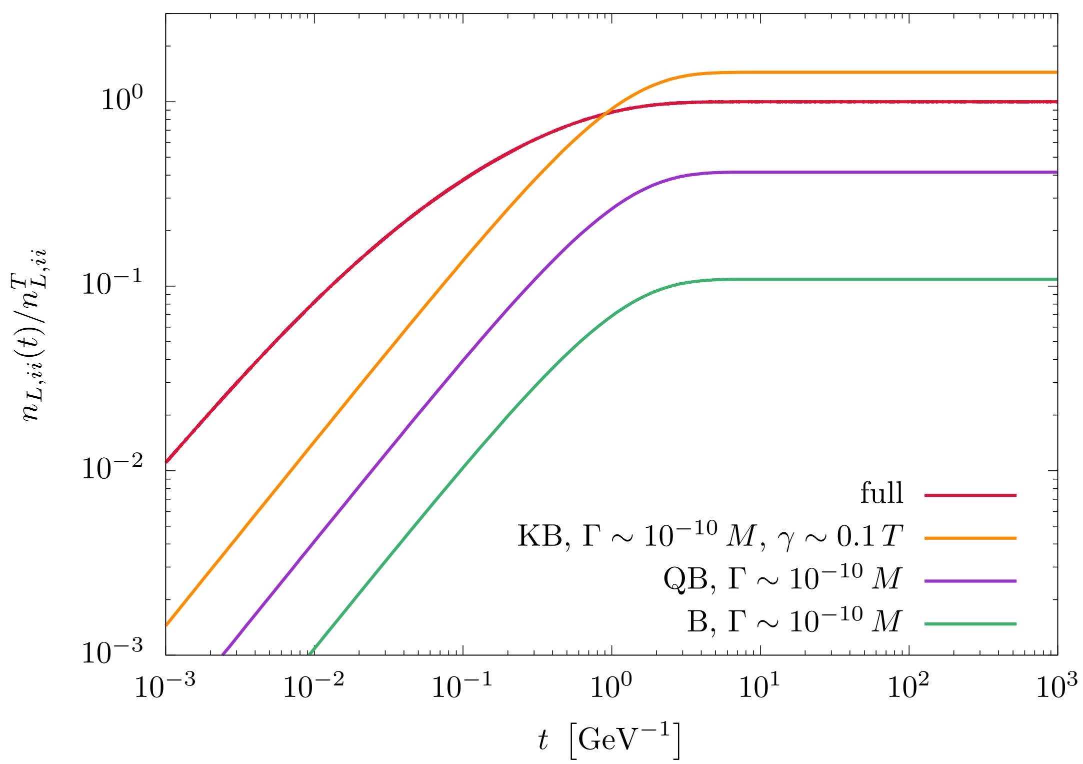
grand unification	**GUT-scale leptogenesis**
fermion reps of SM	connection of B & L
gauge coupling unification (large GUT scale)	small neutrino masses (GUT seesaw scale)
relations between Yukawa couplings	relation between baryon and lepton asymmetries
proton decay	Majorana neutrinos
proton decay branching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

tests only indirect; light neutrino masses and phases, using relations between quark and lepton mass matrices: ν-less ββ-decay, absolute neutrino mass scale consistent with cosmology bound! ; estimate of baryon asymmetry :

$$\varepsilon_1 \sim 0.1\ \frac{m_3 M_1}{v_{\mathrm{EW}}^2} \sim 0.1\ \frac{M_1}{M_3} \sim 10^{-6} \ldots 10^{-5} \rightarrow \eta_B \sim 10^{-10} \ldots 10^{-8}$$

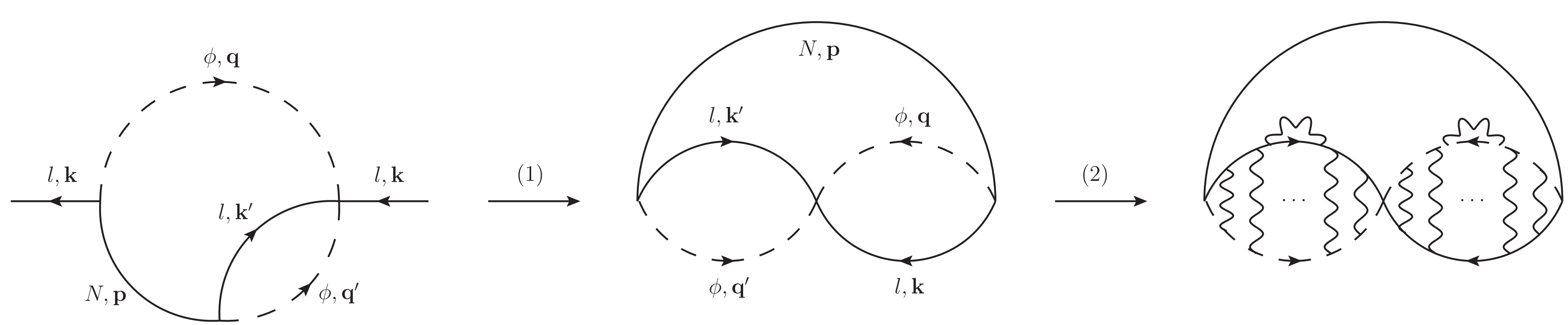
Toward a theory leptogenesis





[Depta, Halsch, Hutig, Mendizabal, Philipsen '20]

Full QFT treatment of leptogenesis: "effective kinetic equations" [Bodeker et al], Kadanoff-Baym equations [...]; recent achievement: full resummation of gauge boson interactions, "complete" QFT treatment of generated baryon asymmetry; theoretical uncertainty factor $\mathcal{O}(1)$



Leptogenesis, inflation & gravitational waves

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

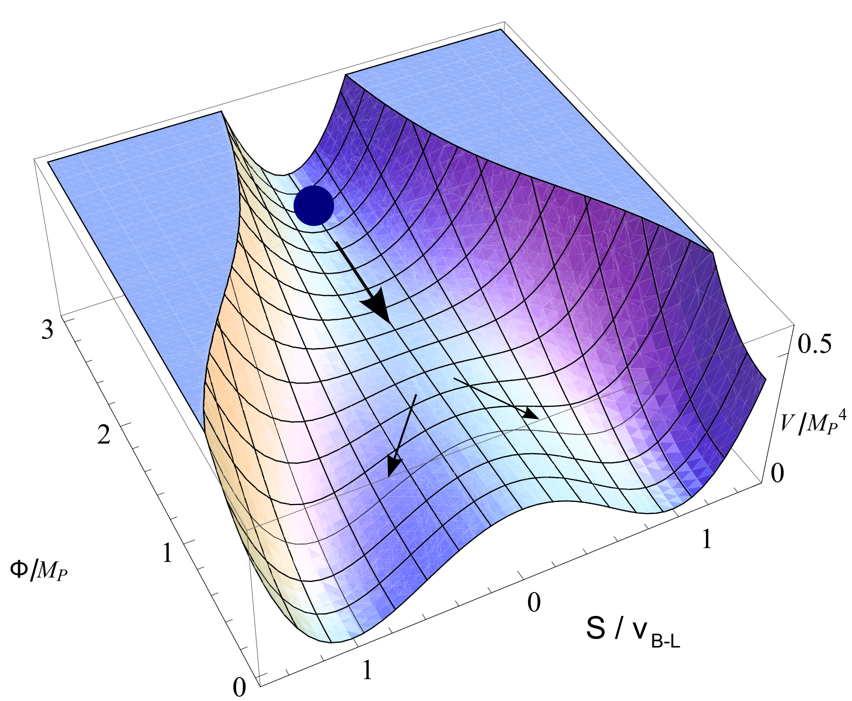
Example: cosmological B-L breaking after inflation in supersymmetric extension of SM with right-handed neutrinos:

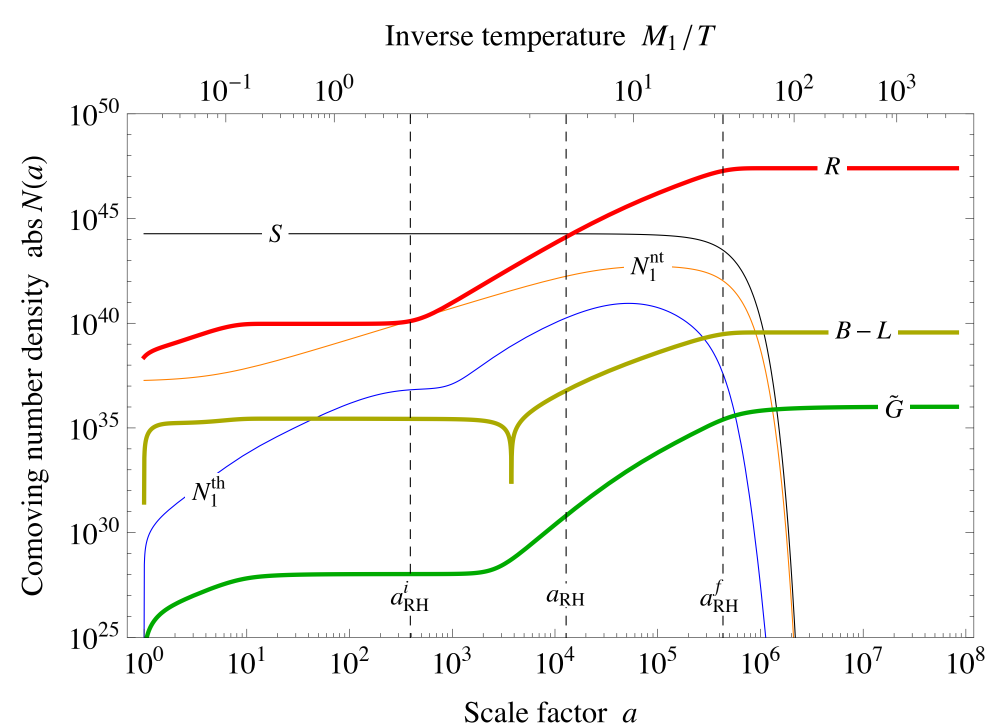
$$W_M = h_{ij}^u \mathbf{10}_i \mathbf{10}_j H_u + h_{ij}^d \mathbf{5}_i^* \mathbf{10}_j H_d + h_{ij}^\nu \mathbf{5}_i^* n_j^c H_u + h_i^n n_i^c n_i^c S_1$$

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:

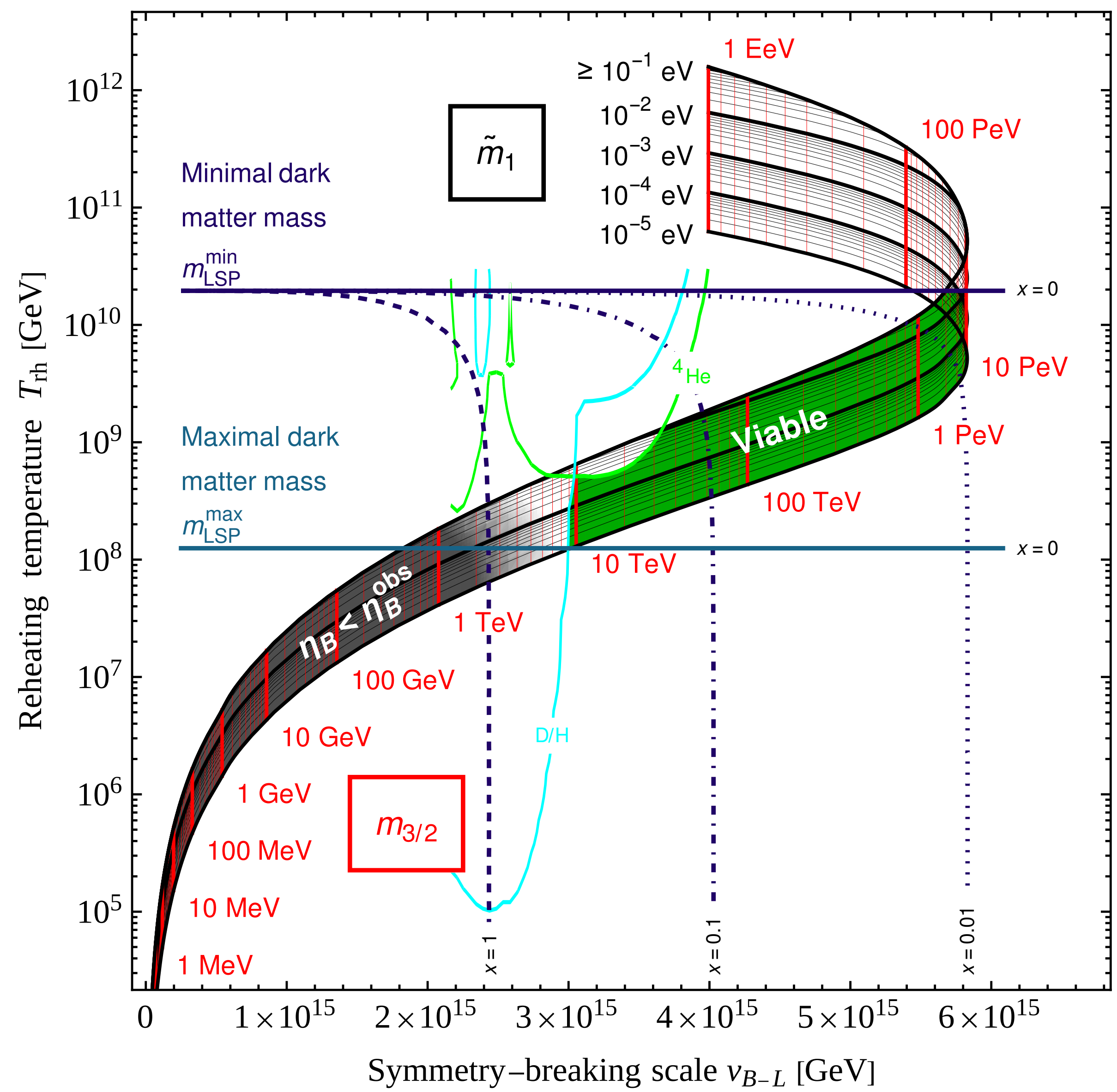
$$W_{B-L} = \lambda \Phi \left(\frac{1}{2} v_{B-L}^2 - S_1 S_2 \right)$$

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





Consistency of leptogenesis, inflation and dark matter:



[WB, Domcke, Murayama, Schmitz '19]

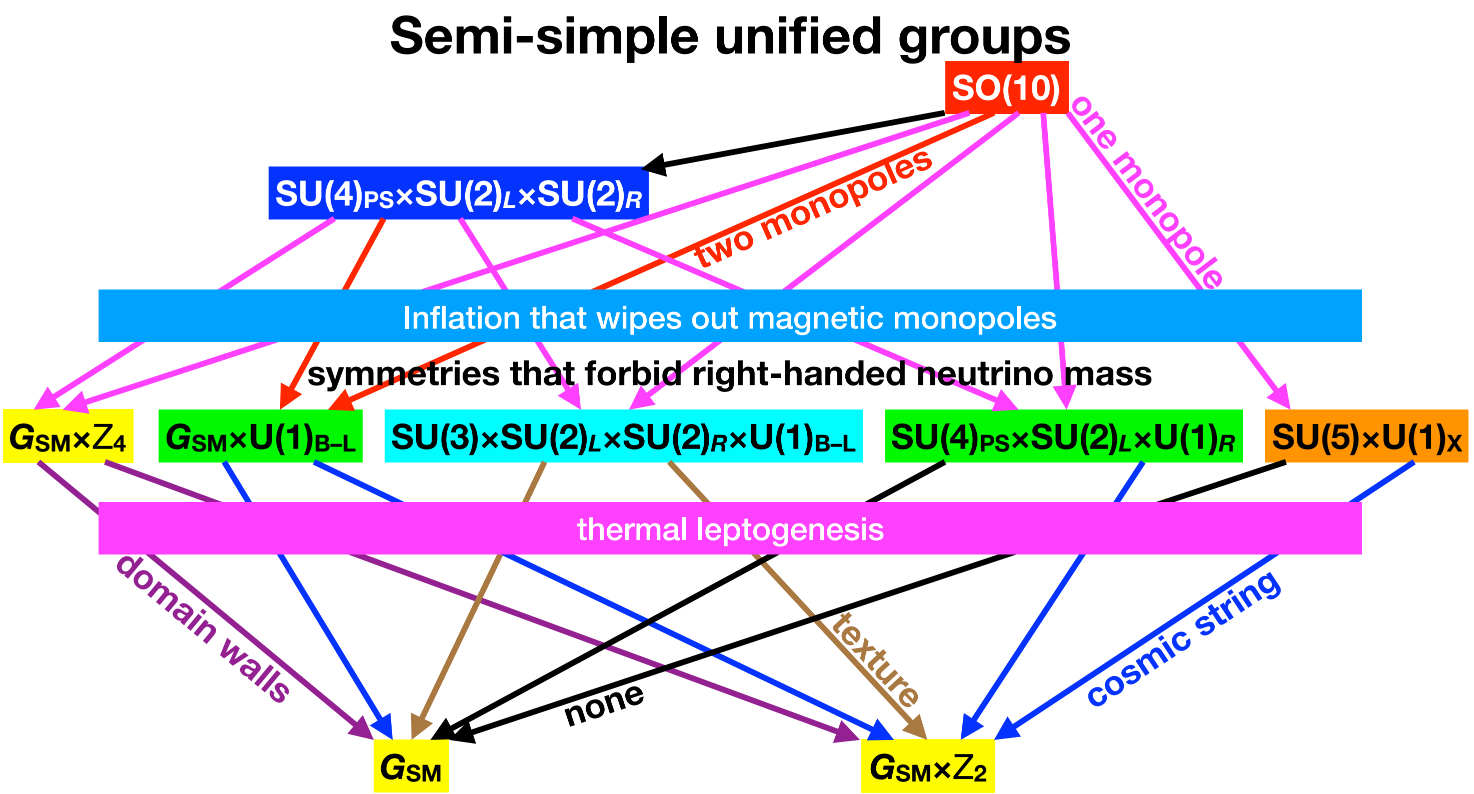
B-L breaking: $v_{B-L} \sim (3\ldots6)\times 10^{15}$ GeV

reheating temperature: $T_{\rm rh} \sim (10^8 \ldots 10^{10})$ GeV

SUSY breaking: $m_{3/2} \sim 10$ TeV $\ldots$ 10 PeV

dark matter: $0.1 \leq m_{h(w)}/\mathrm{TeV} \leq 1.1\ (2.7)$ higgsino (wino)

prediction: cosmic strings and gravitational waves

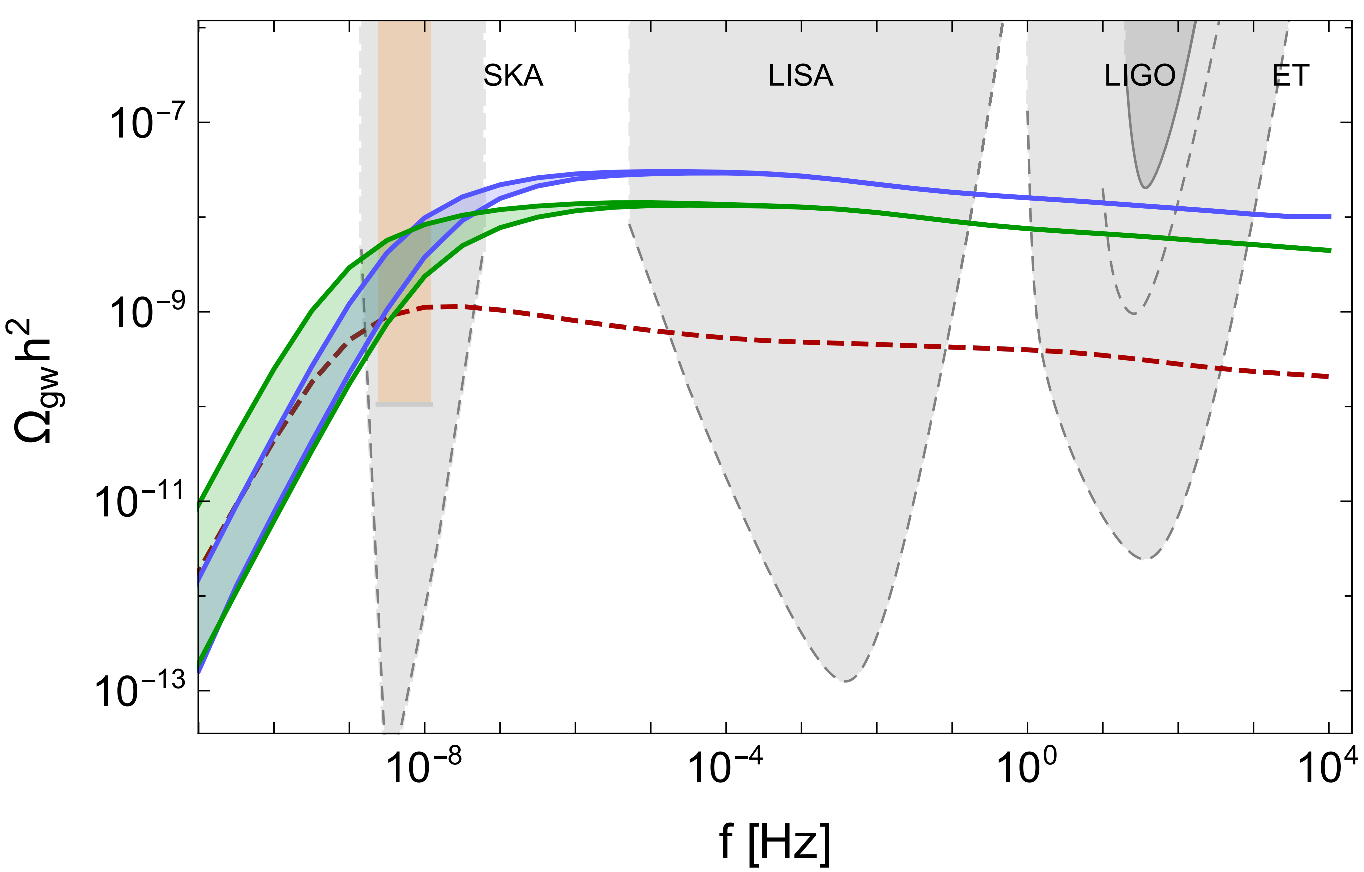


When B-L is properly embedded in GUT group, e.g,

$$G \times U(1)_{B-L} \subset SO(10)$$

strings become metastable (monopoles)

[Dror, Hiramatsu, Kohri, Murayama, White '19]



Decaying string network yields characteristic GW spectrum, prediction for LIGO, consistent with NANOGrav:

$$v_{B-L} \simeq (3\ldots6) \times 10^{15}\ \text{GeV}$$

$$m_{mp} \simeq (3\ldots8) \times 10^{16}\ \text{GeV}$$

[WB, Domcke, Murayama, Schmitz '19, WB, Domcke, Schmitz '20]

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)
- Spontaneous baryogenesis
- Cold baryogenesis
- Baryogenesis from strong CP violation and the QCD axion
- Baryogenesis from B-meson oscillations
- ....

Summary

Baryonasymmetry has to be dynamically explained; closely related to other aspects of particle physics and cosmology, Higgs/LHC, neutrino masses and mixings, inflation, dark matter and SUSY, axions, gravitational waves …
… some discovery will come!