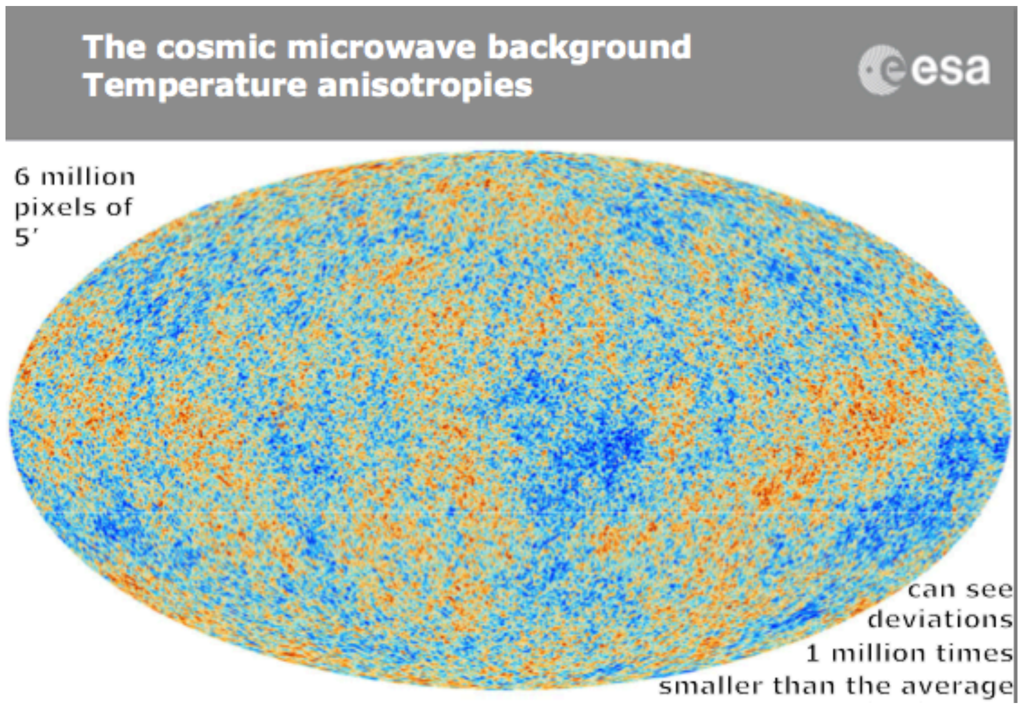
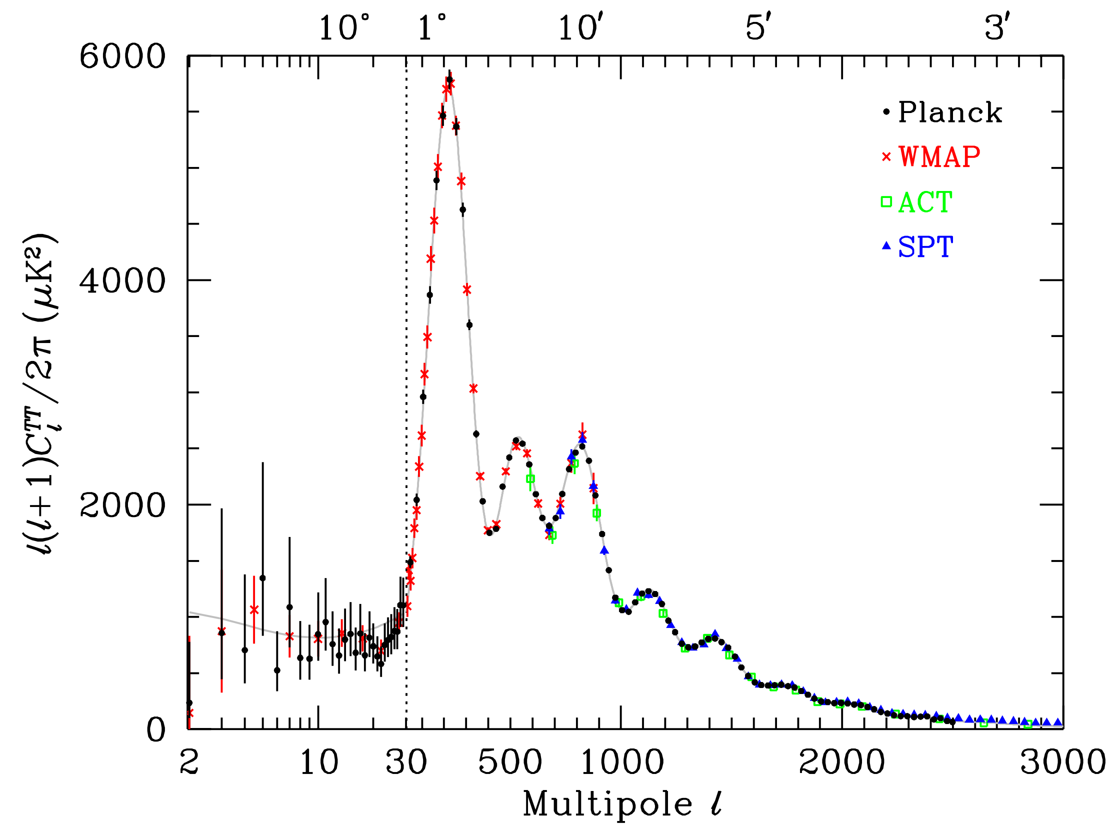
Baryogenesis - a piece of a puzzle

Wilfried Buchmüller

ICRHEP1402, Teheran, November 2023

Cosmic microwave background



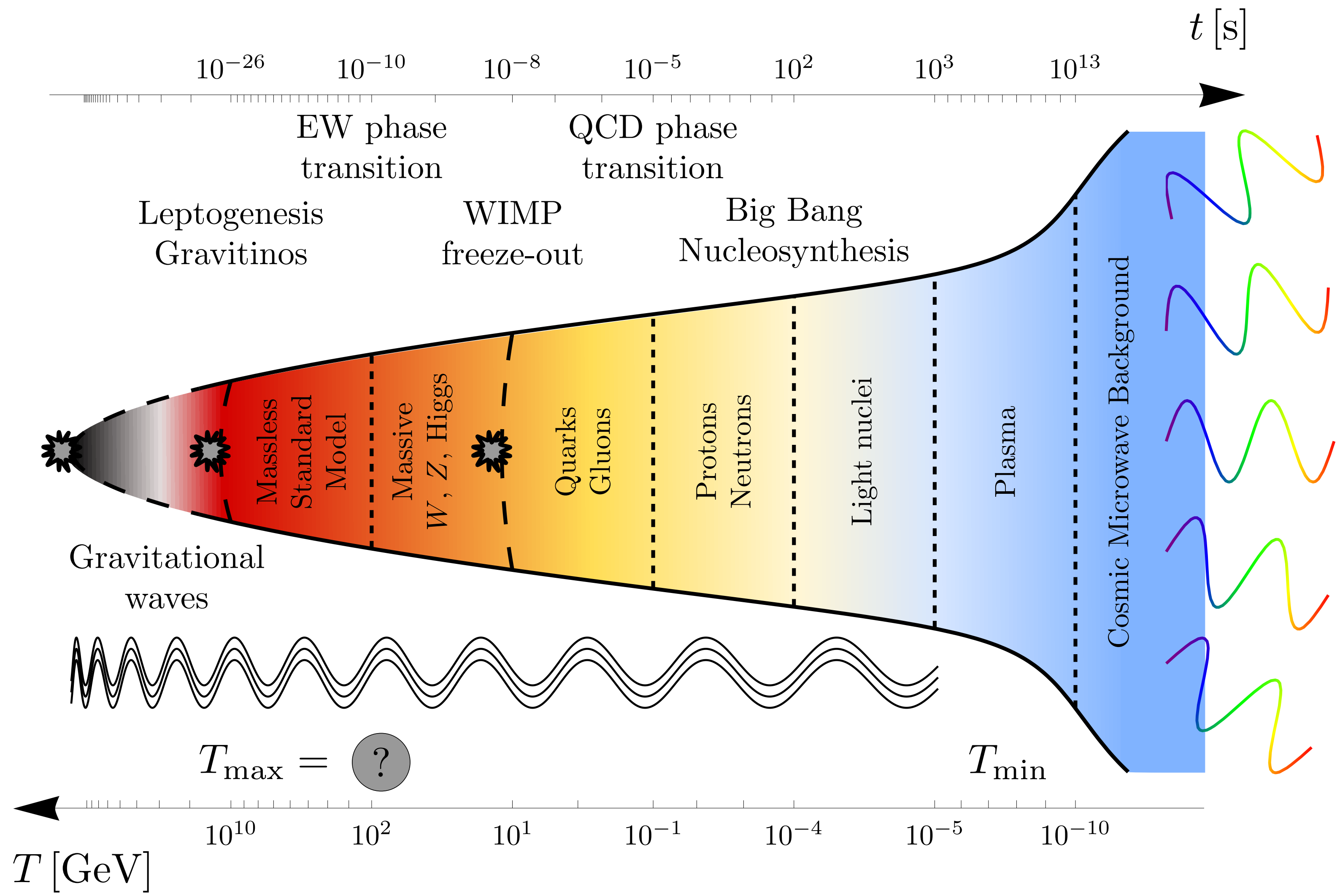


approximate homogeneity of CMB requires "inflation"; small anisotropies determine baryon/matter-antimatter asymmetry:

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

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 $\frac{n_q - n_{\bar{q}}}{n_\gamma} \sim 10^{-10}$, must have

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

[recent review: Bodeker, WB '21]

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

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 P and 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 $n \sim 10^{98}\ \mathrm{cm}^{-3}$ and $\varepsilon \sim 10^{114}\ \mathrm{erg/cm^3}$).

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 ($M_0 = 2\times 10^{-5}$ 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 $\sim 10^{50}\ \mathrm{yr}$ …

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

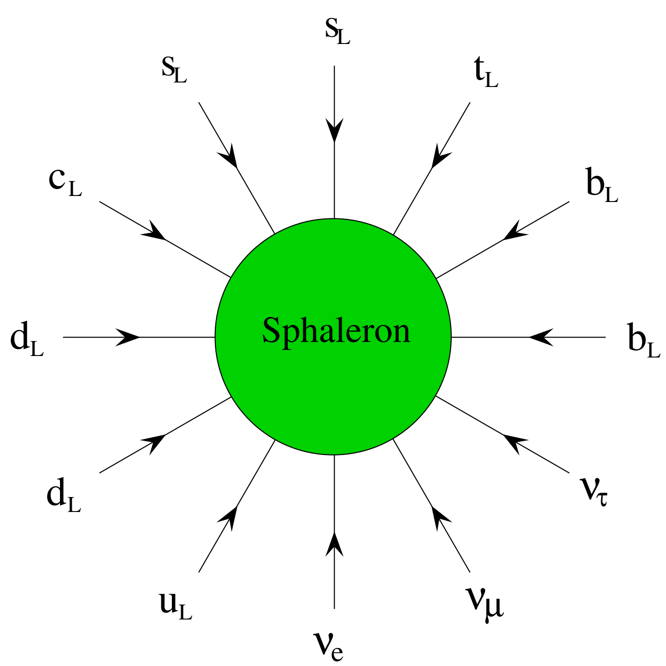
- 1978: SU(5) GUT baryogenesis
  [Yoshimura; Dimopoulos, Susskind; Touissant, Treiman, Wilczek, Zee; Weinberg]
  CP-violating decays of leptoquarks; detailed calculations based on Boltzmann equations [Kolb, Wolfram]

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

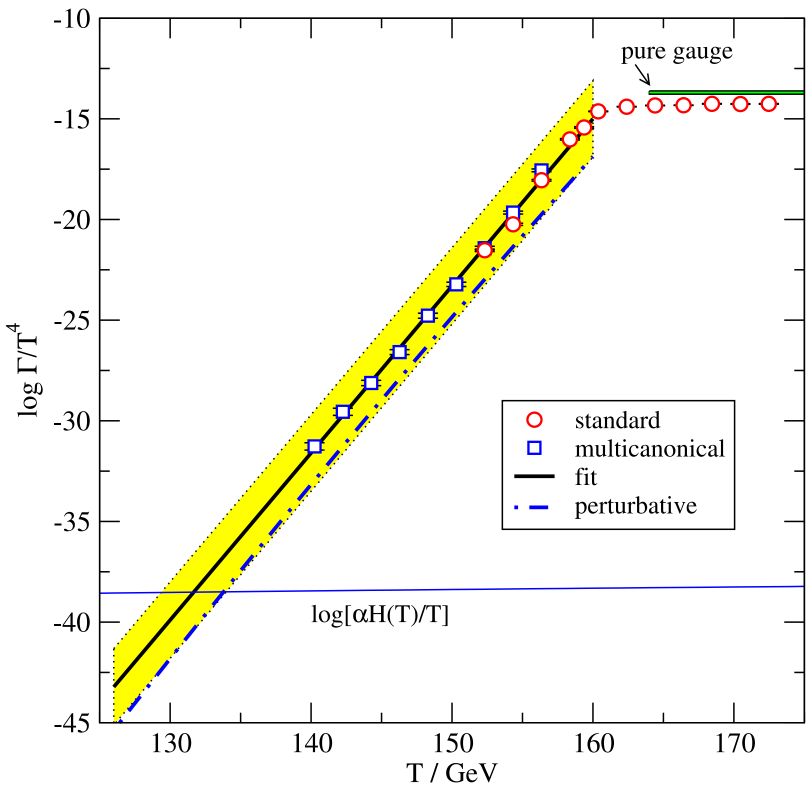
- 1985: sphaleron processes
  [Kuzmin, Rubakov, Shaposhnikov]; SU(5) GUT baryogenesis excluded; idea of electroweak baryogenesis (appealing mechanism, just SM!)

- 1986: Leptogenesis
  [Fukugita, Yanagida]; CP- violating decays of heavy Majorana neutrinos

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

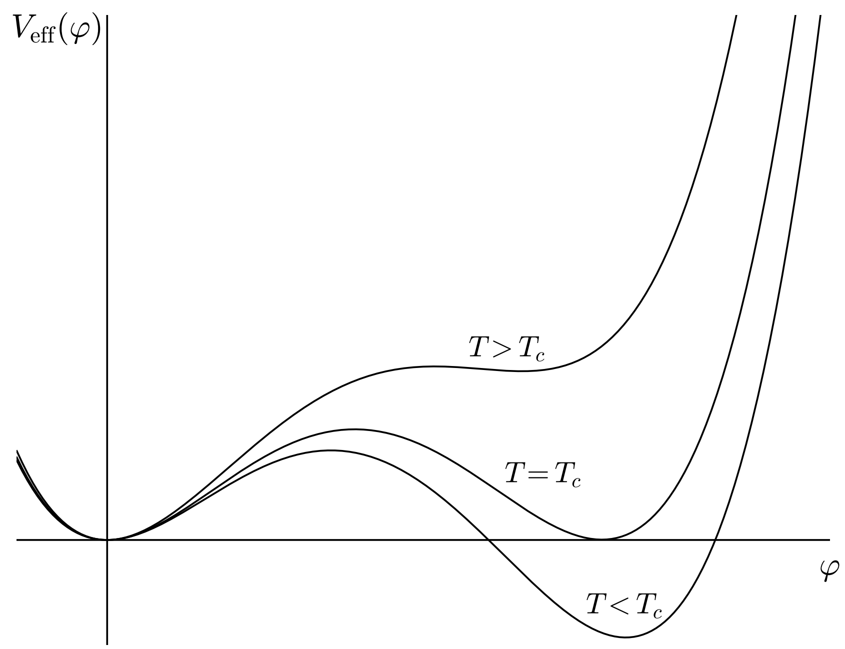
(so far purely theoretical; search at LHC -> Ringwald)

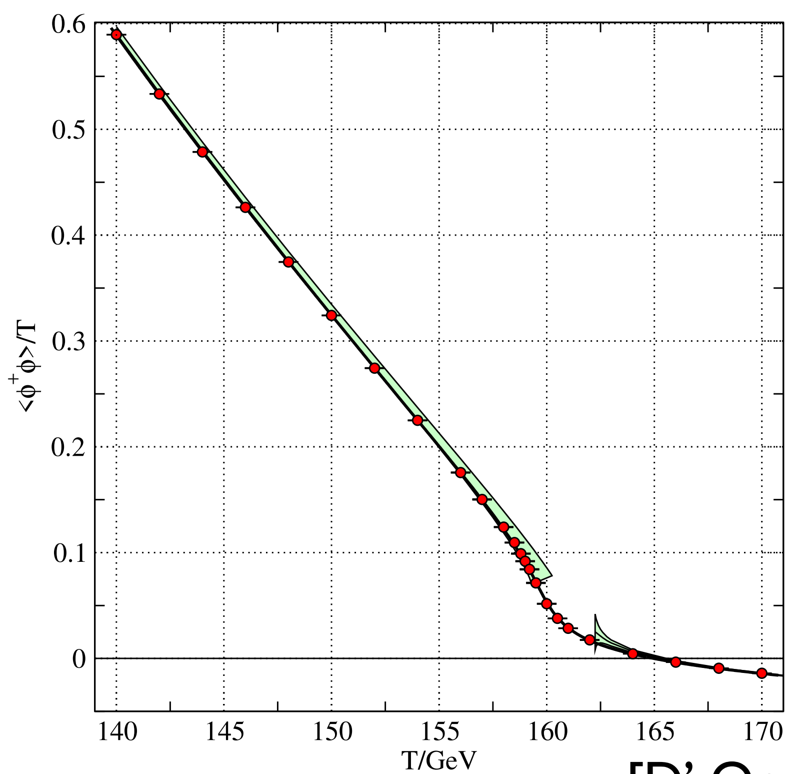
Outline

- Electroweak symmetry breaking: weak coupling
- Electroweak symmetry breaking: strong coupling
- Leptogenesis: high scale
- Leptogenesis: low scale
- Baryon asymmetry and dark matter: modulus decay
- Connection with inflation and gravitational waves
- Other models

Electroweak Baryogenesis

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

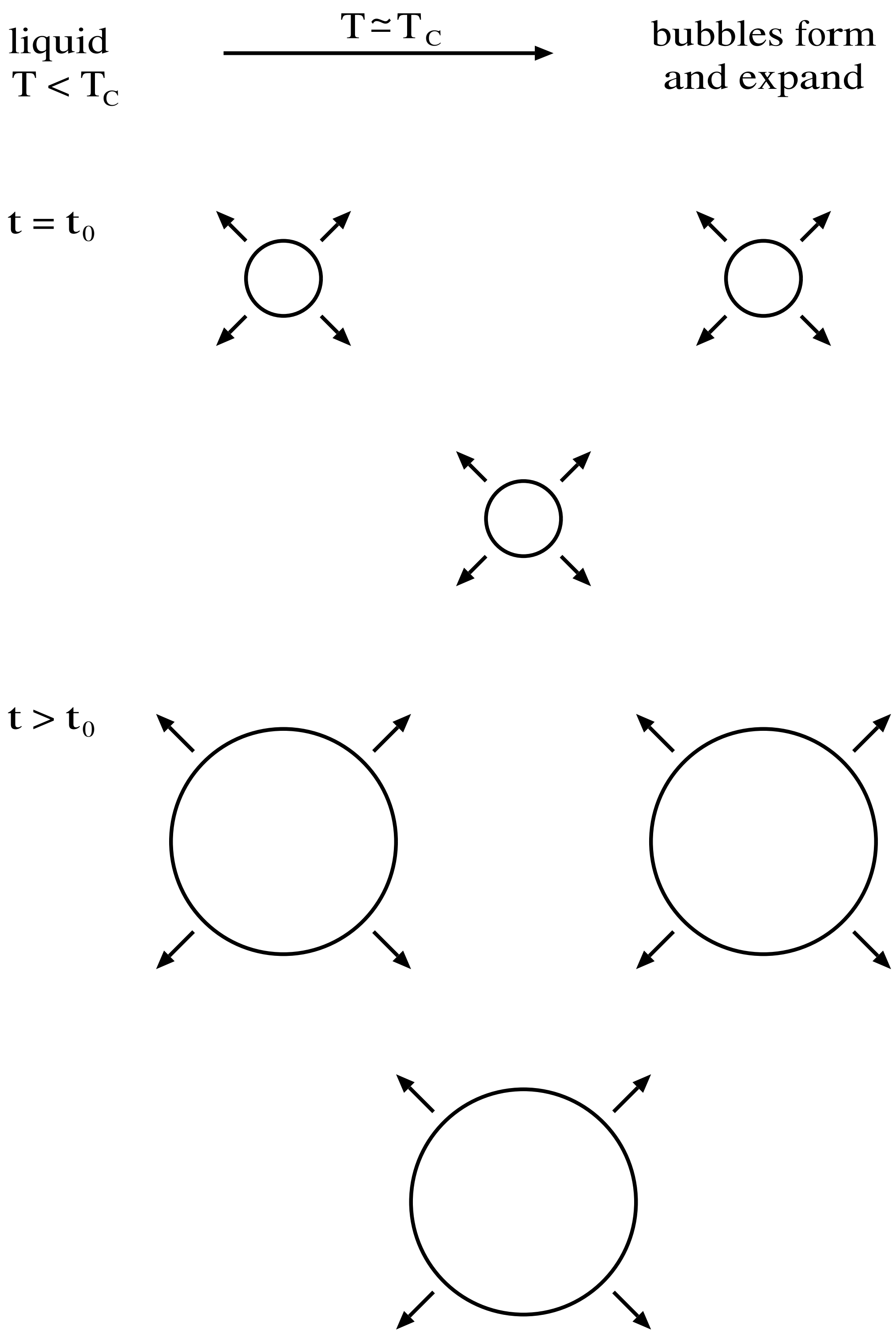




[D' Onofrio et al. '16]

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

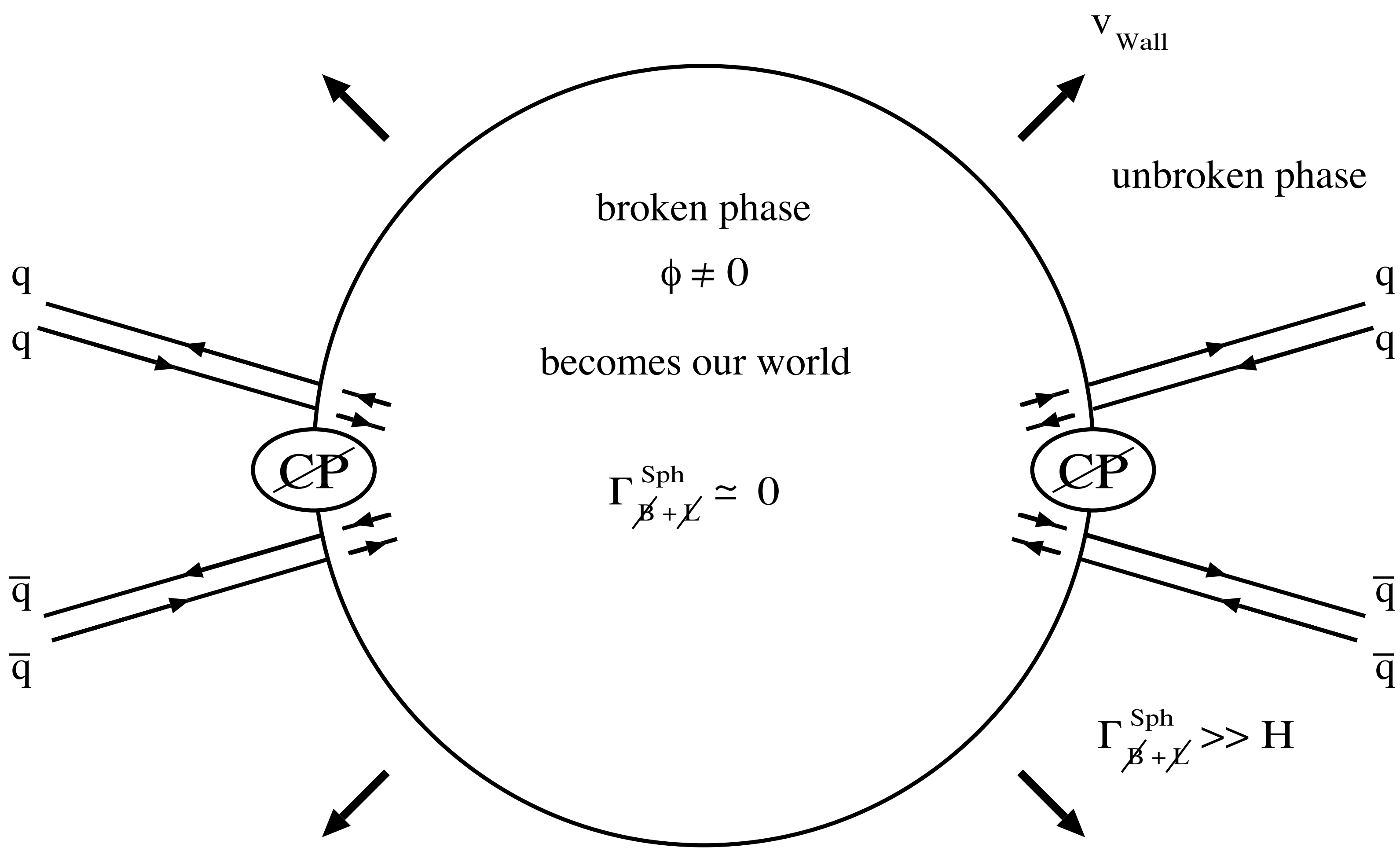


1st-order phase transition in extensions of SM (2HDM, doublet-singlet model,…)

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 :

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

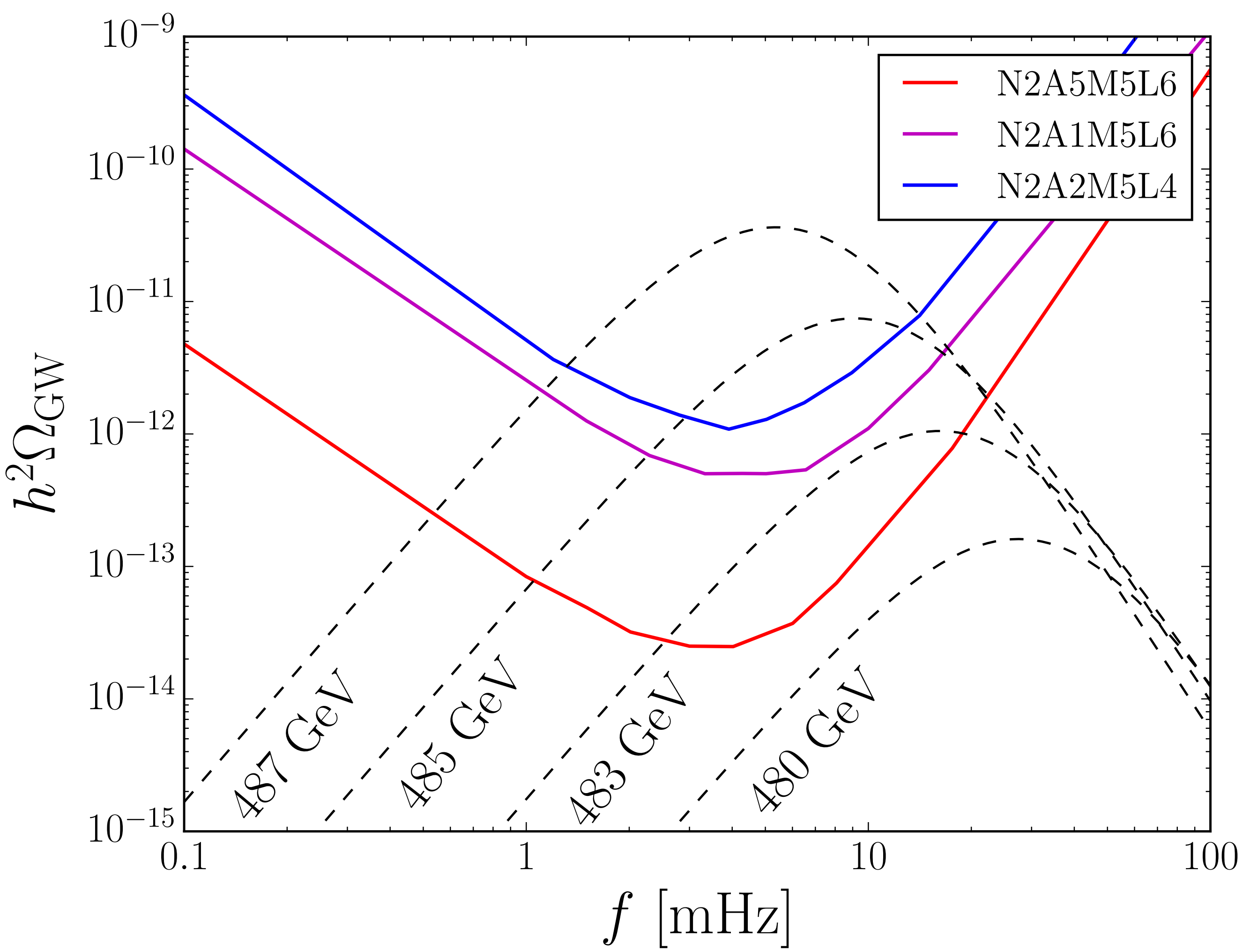
$$\langle\Phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v\cos\beta \end{pmatrix}, \qquad \langle\Phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v\sin\beta\, e^{i\theta} \end{pmatrix} ,$$

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

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:

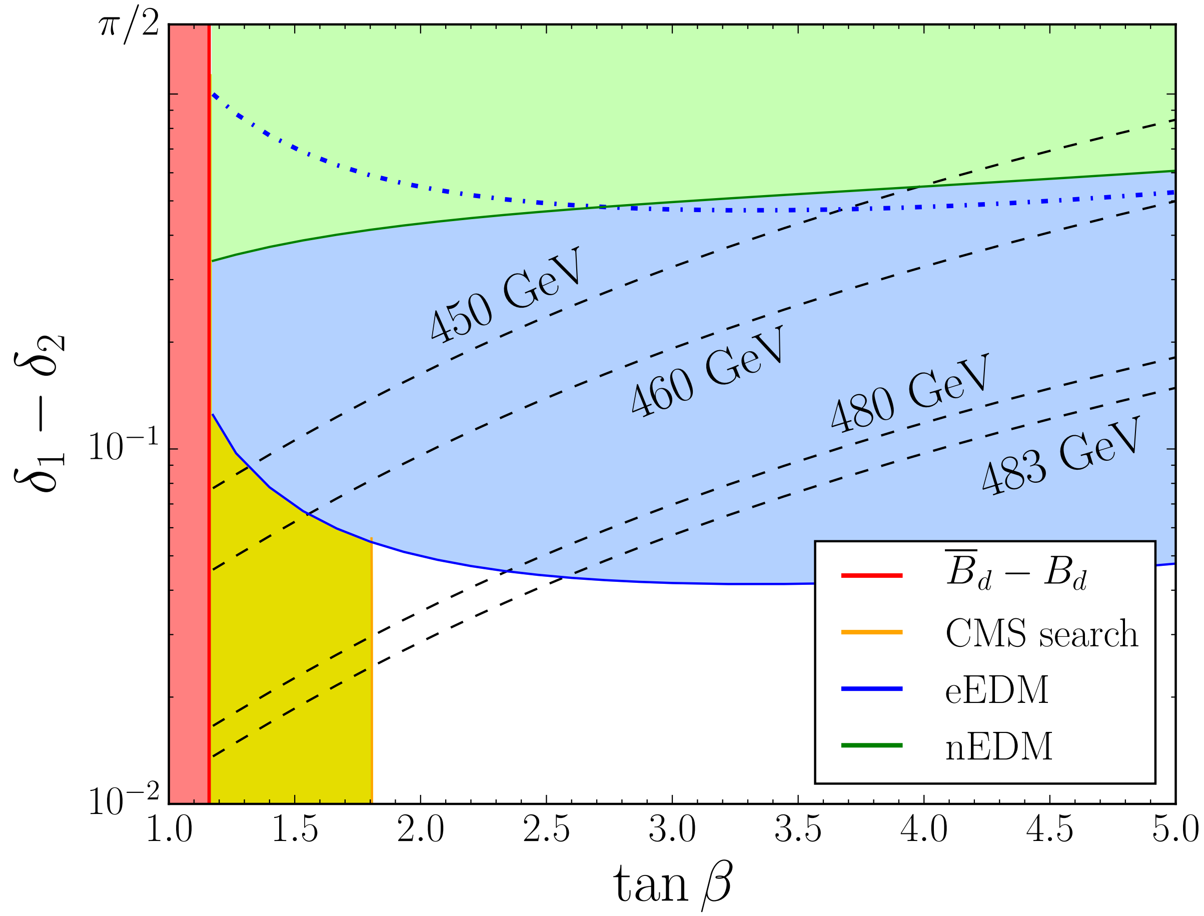
$$ds^2 = a^2(\tau)(\eta_{\mu\nu} + h_{\mu\nu})dx^\mu dx^\nu \ , \quad \bar{h}_{\mu\nu} = h_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu}h^\rho_\rho$$

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



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):



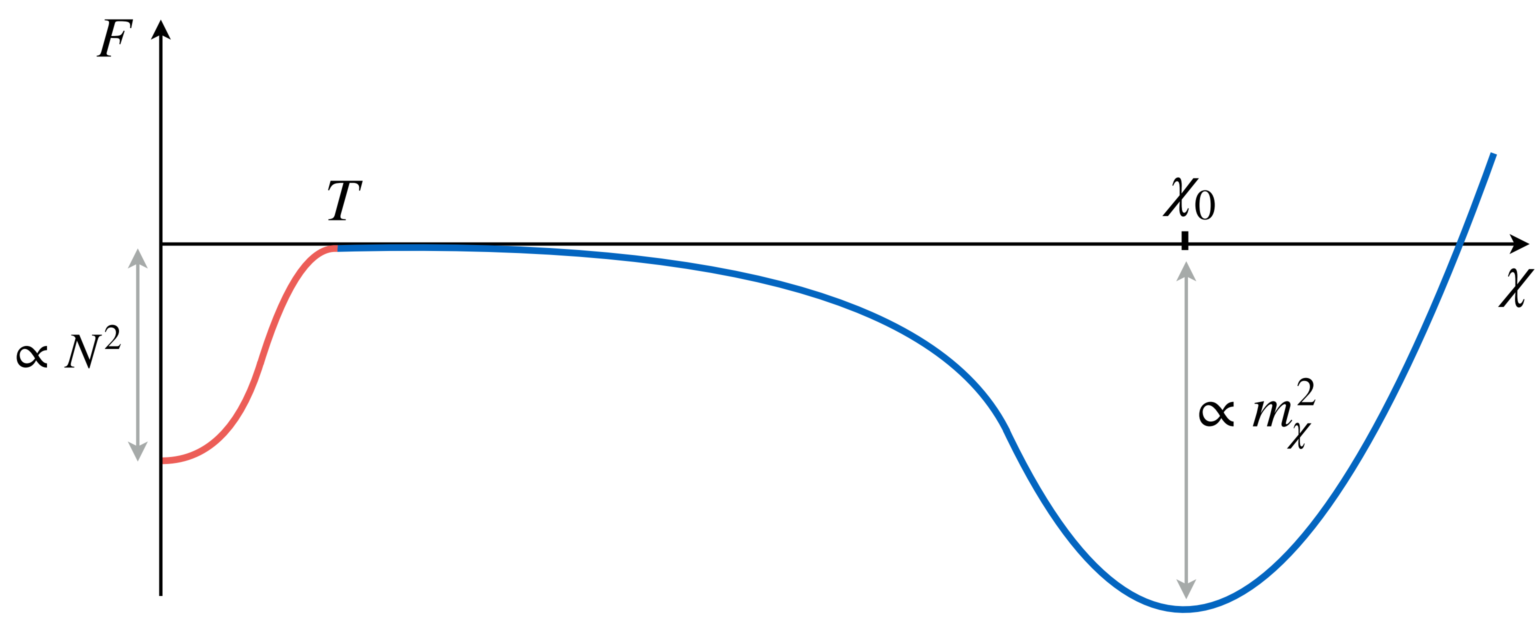
EWBG consistent with electron ACME I bound, but model ruled out by ACME II bound (October 2018):

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

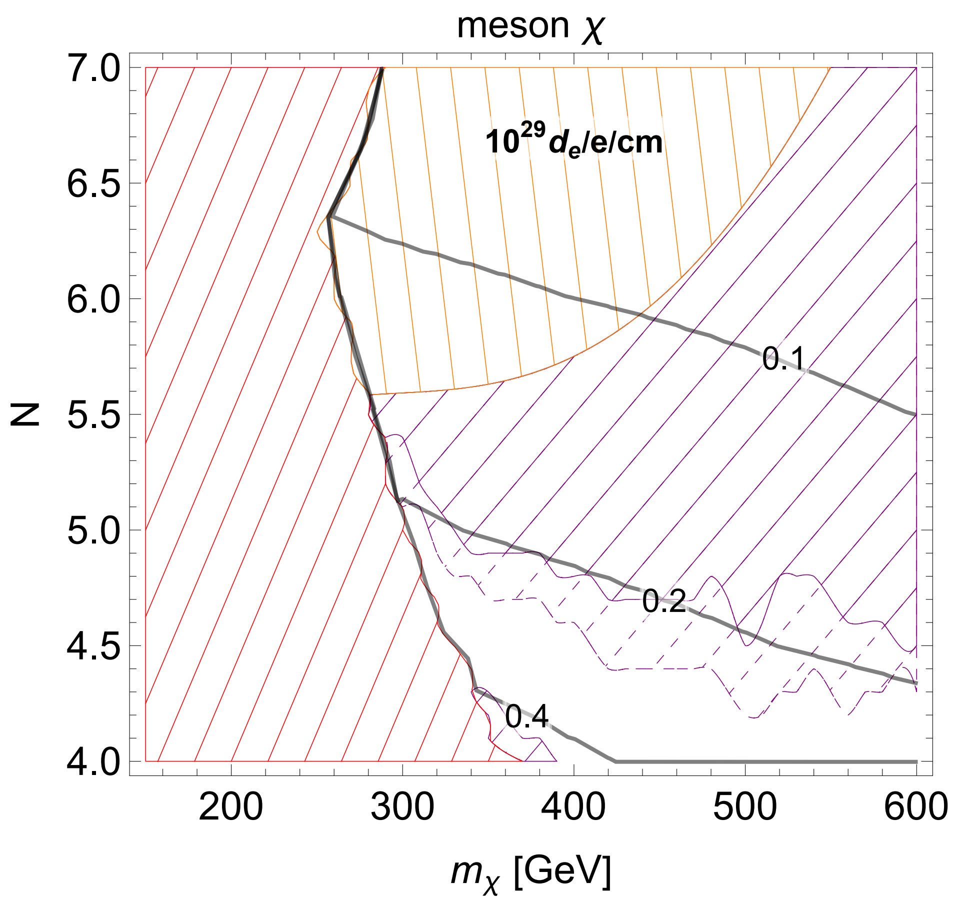
Note: situation similar in doublet-singlet model, MSSM, split NMSSM, …

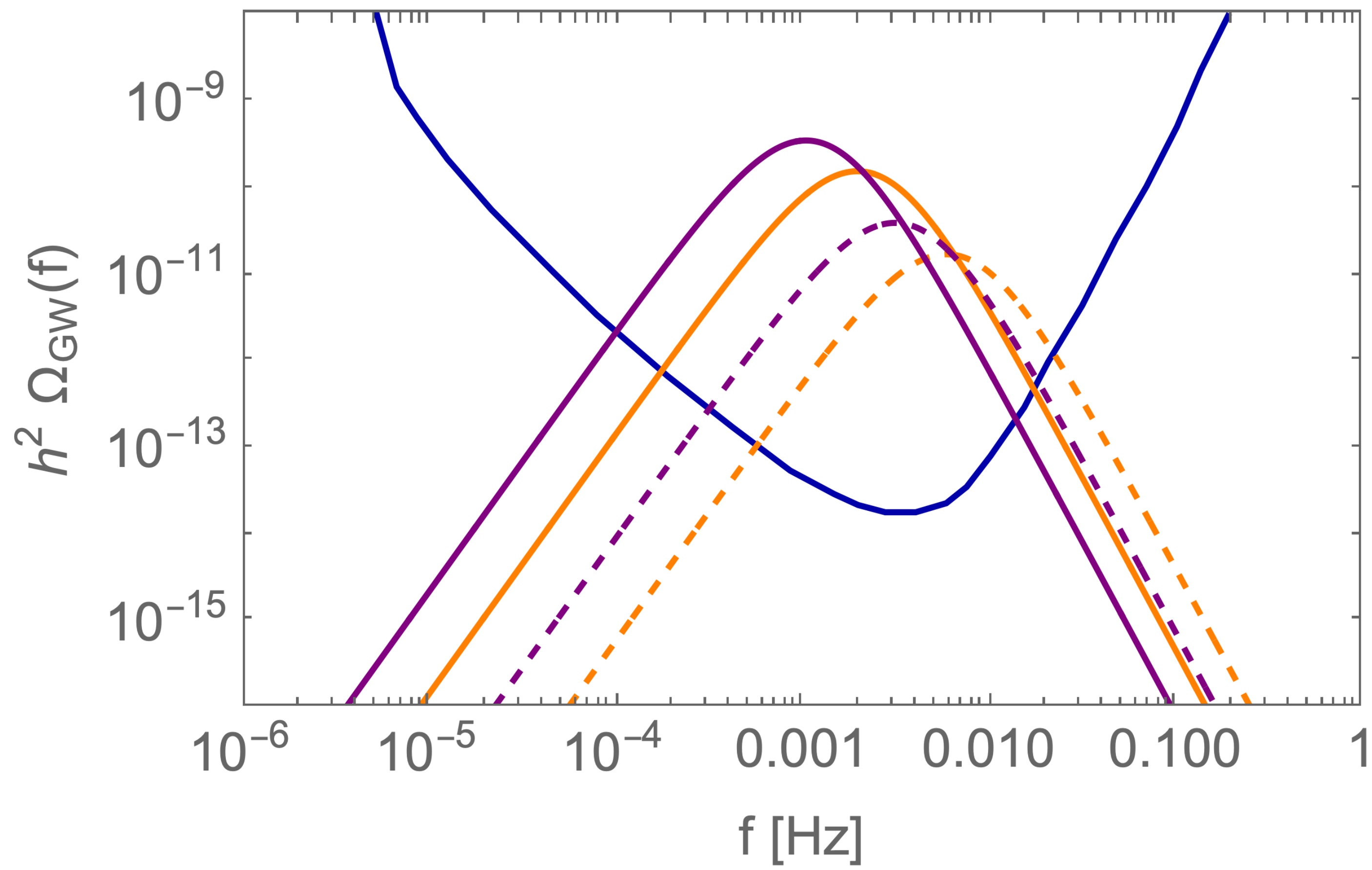
Example 2: Light composite Higgs boson

[Bruggisser, von Harling, Matsedonskyi, Servant '18,..,'22]



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**!





Left: viable region for dilaton mass given present electron EDM bound of ACME; heavy mass spectrum ~ 5 TeV; strong constraints from Higgs couplings

Right: predited GW spectrum for different dilaton masses

Leptogenesis

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

SM with right-handed neutrinos

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

After electroweak symmetry breaking charged lepton and Dirac neutrino masses, $m_D = h^\nu\langle\phi\rangle \equiv h^\nu v_{\text{EW}}$, 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:

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

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!):

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

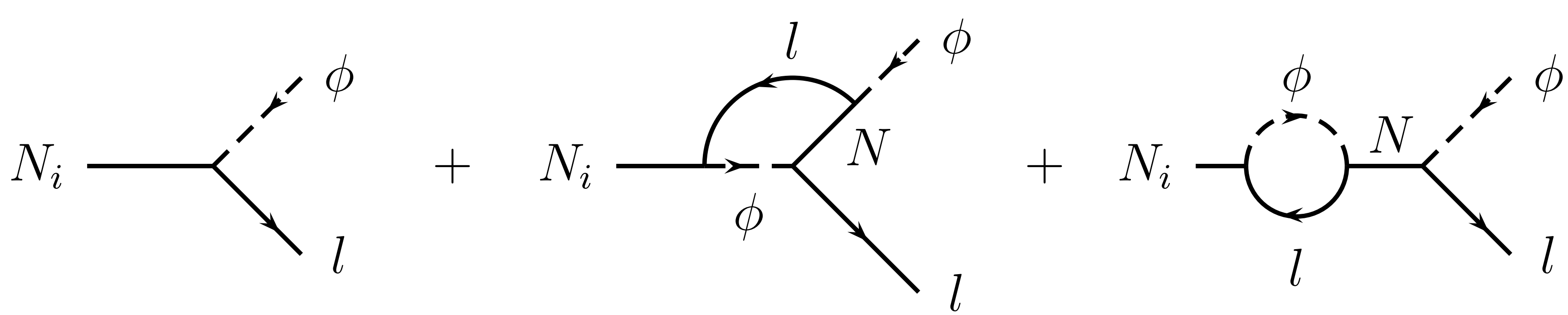
hierarchical heavy Majorana neutrinos N_i:

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

Covi, Roulet, Vissani ’96

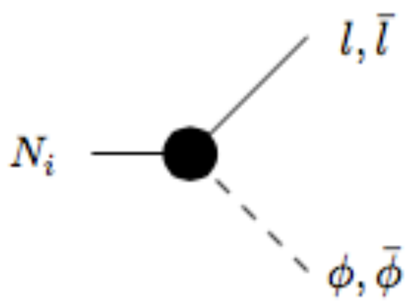
quasi-degenerate heavy Majorana neutrinos N_i:

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

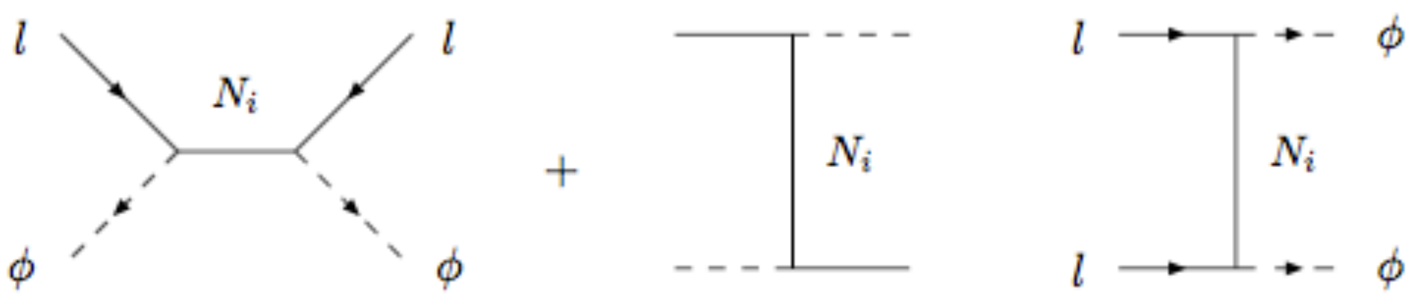


Decays (D) and inverse decays (ID)

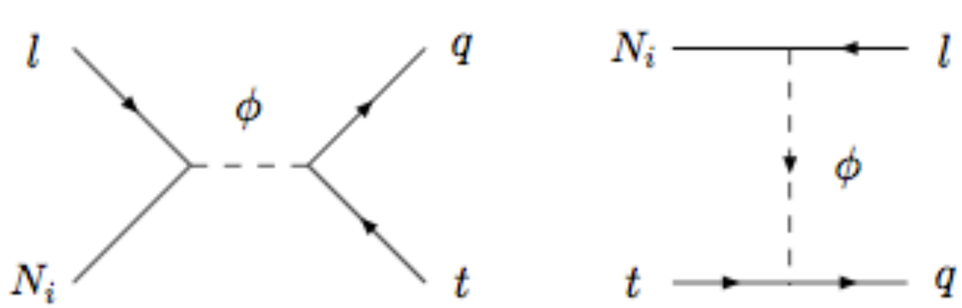
$N_i \leftrightarrow l\,\phi\,,\ \bar{l}\,\bar{\phi}$



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



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



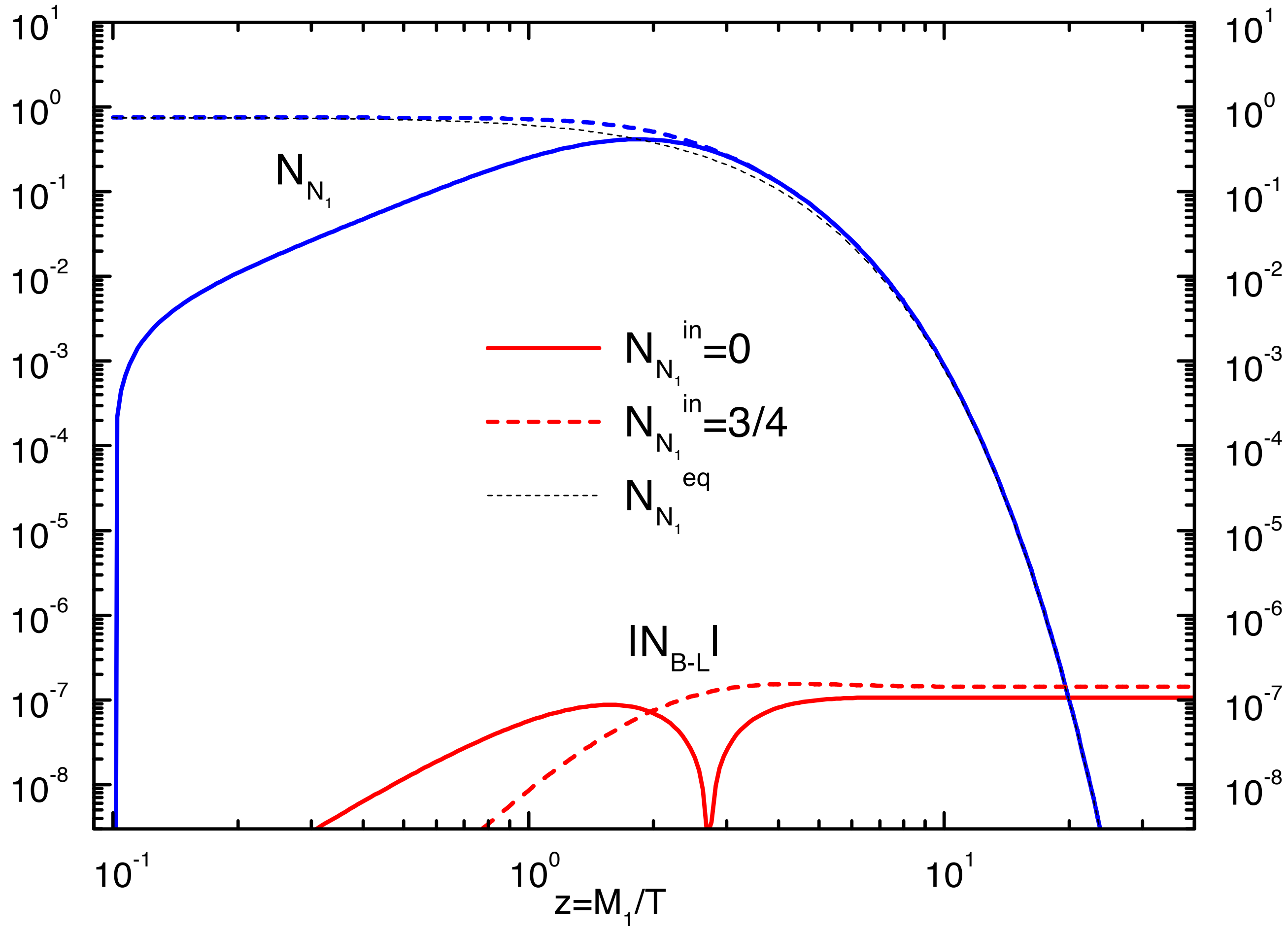
Luty '92, Plumacher '96, …

basic decay and scattering processes of heavy neutrinos in plasma, generation of asymmetry and washout (or "wash-in")

further important: interactions with gauge bosons!

Quantitative description via Boltzmann equations (decays “D”, scatterings “S”, washout “W”; simple for sum over lepton flavours, $z = M_{N_1}/T$):

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

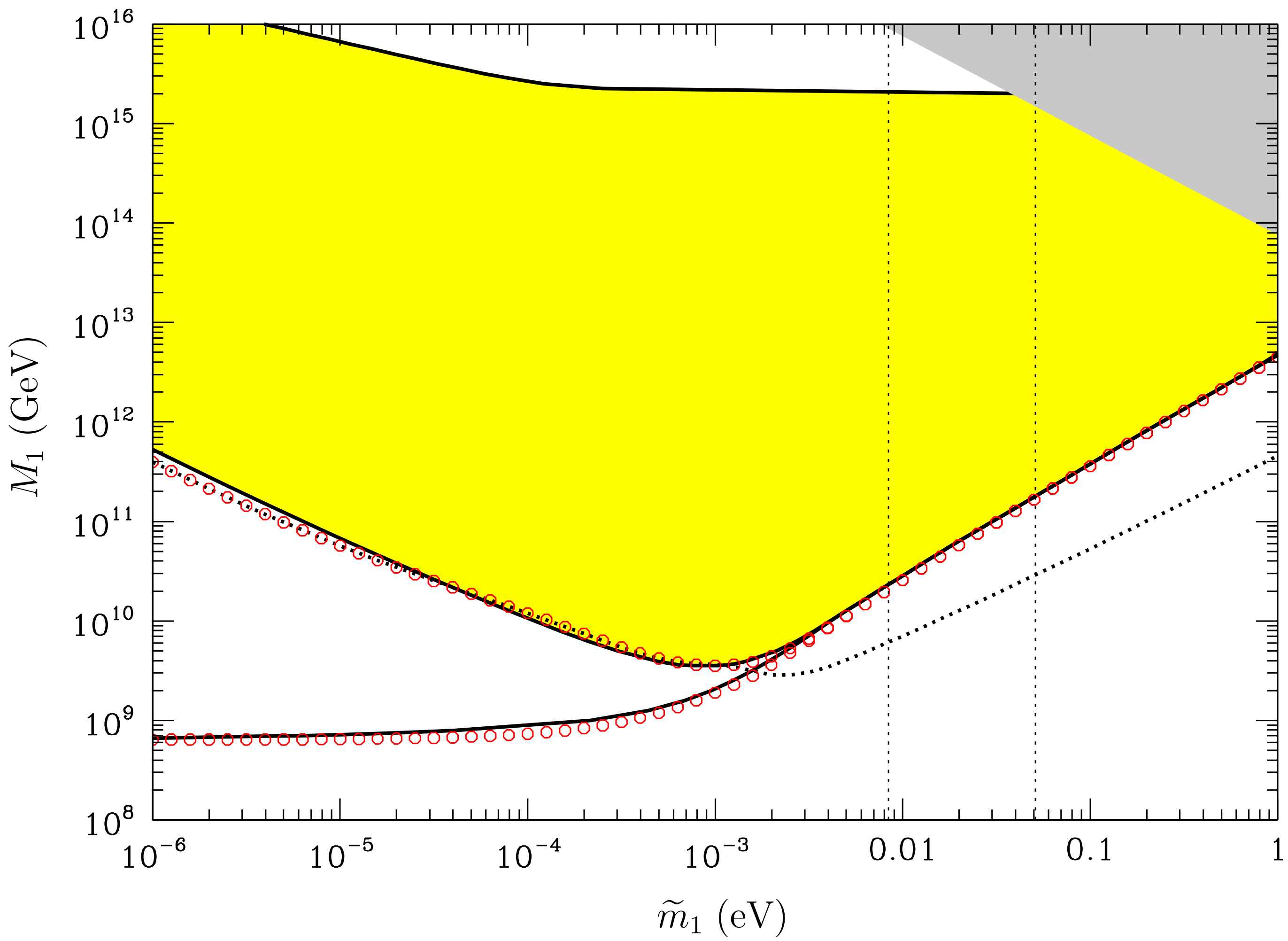


heavy neutrino densities & baryon asymmetry; leptogenesis process close to equilibrium; in “strong washout regime,”

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

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

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



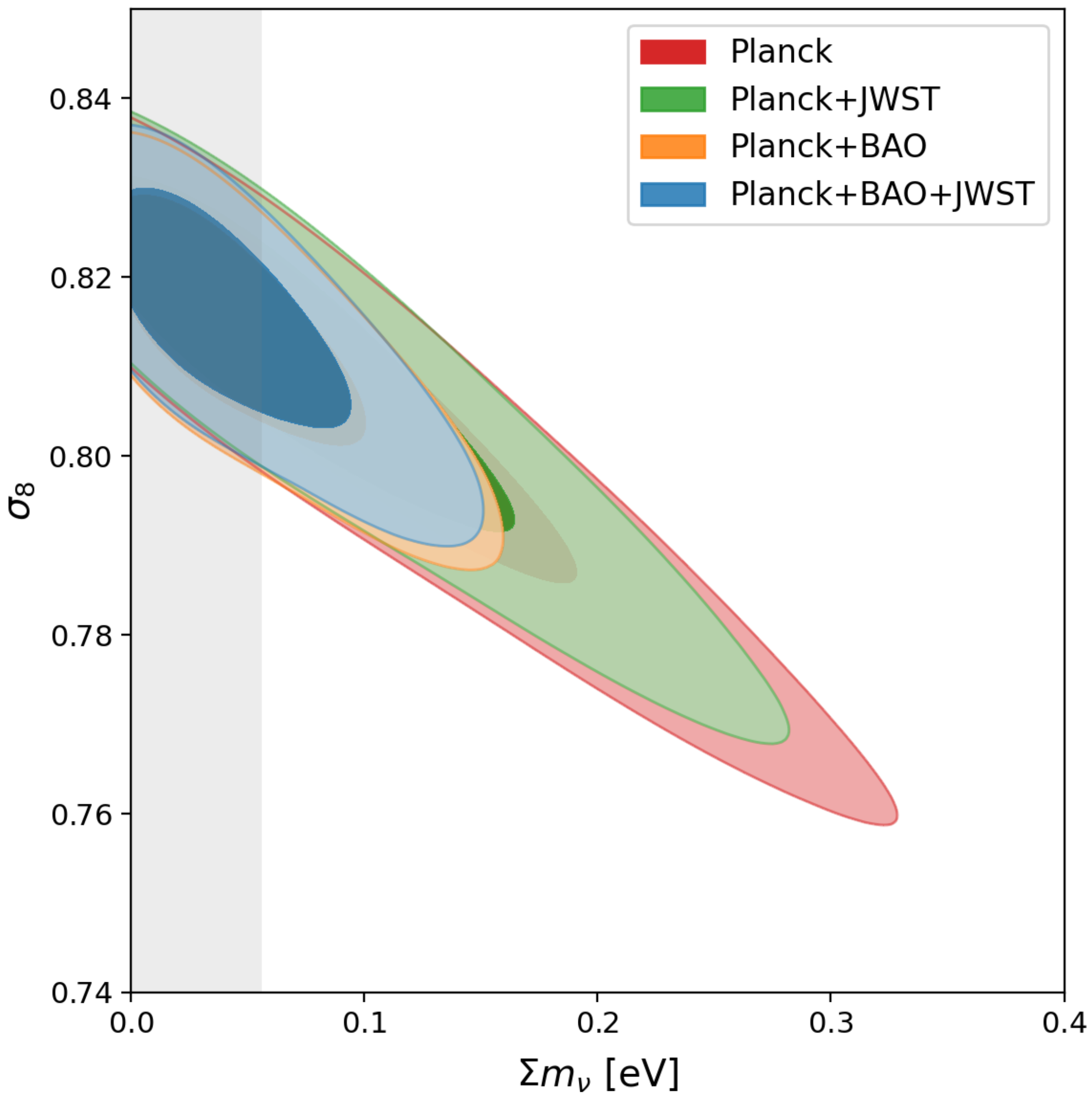
Upper bound on CP asymmetry [Davidson, Ibarra '02] and detailed study of Boltzmann equations [WB, Di Bari, Plumacher '02-'04] leads to bounds on light and heavy neutrino masses (and reheating temperature); in simplest approximation (sum over lepton flavours):

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

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]); lower bound on heavy neutrino masses ("leptogenesis scale") can be lowered by at least two orders of nagnitude (fine tuning), upper bound on light neutrino masses not affected [Mofat, Pascoli, Petcov,…'18]; NO bound for type-II seesaw!



Cosmological upper bound on light neutrino masses

from CMB, BAO and recent data from JWST

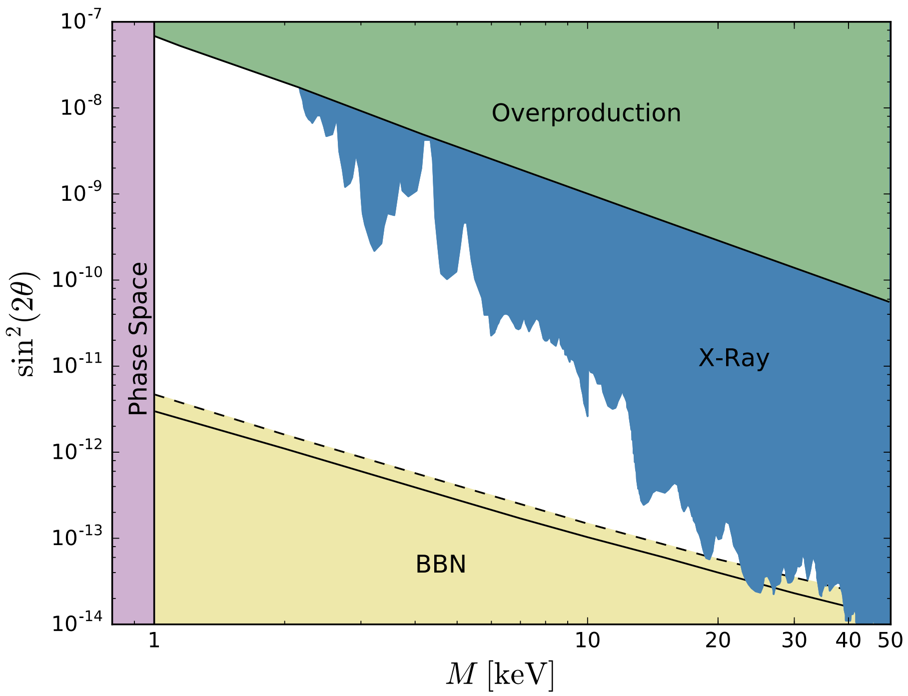
[Liu, Huang, Su '23]

Historical remark: considered neutrino masses in early studies $m_\nu \sim \mathrm{keV}$ [Luty '92] or $m_{\nu_\tau} \sim 5\ \mathrm{eV}$ [WB, Plumacher '96] (already disfavored); since then cosmological mass bounds more and more stringent; today:

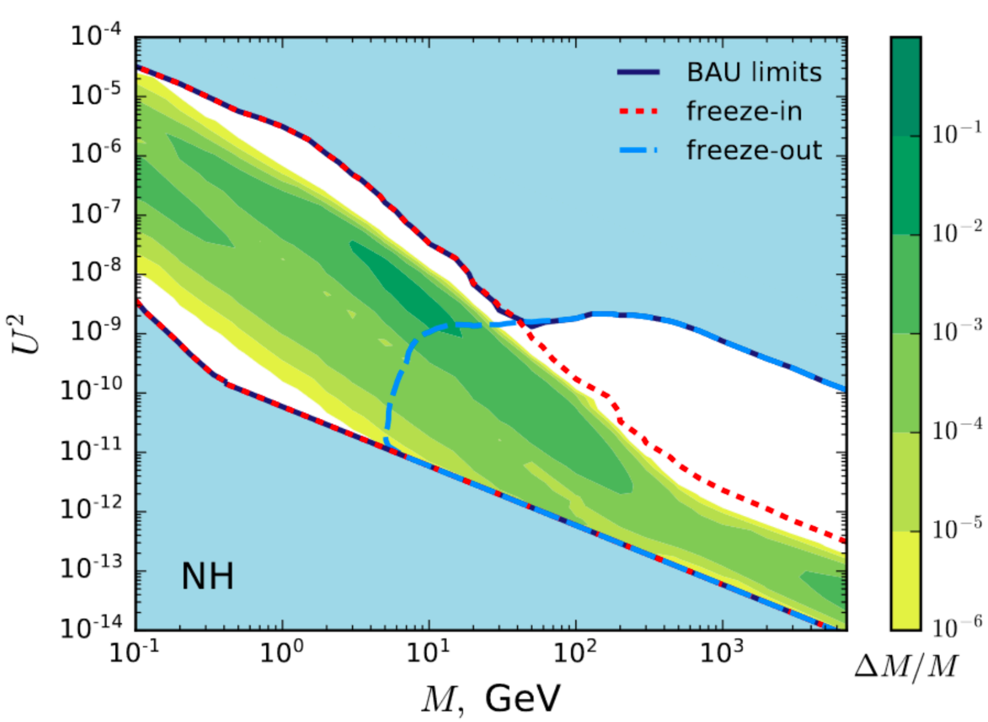
$$\sum m_\nu < 0.114\ \mathrm{eV} \quad (95\%\ \mathrm{c.l.})$$

successful "prediction" of high-scale leptogenesis! ($\sum m_\nu \sim 0.06\ \mathrm{eV}$?!)

Sterile-neutrino oscillations



[Bodeker, Klaus '20]



[Klaric, Shaposhnikov, Timiryasov '21]

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:

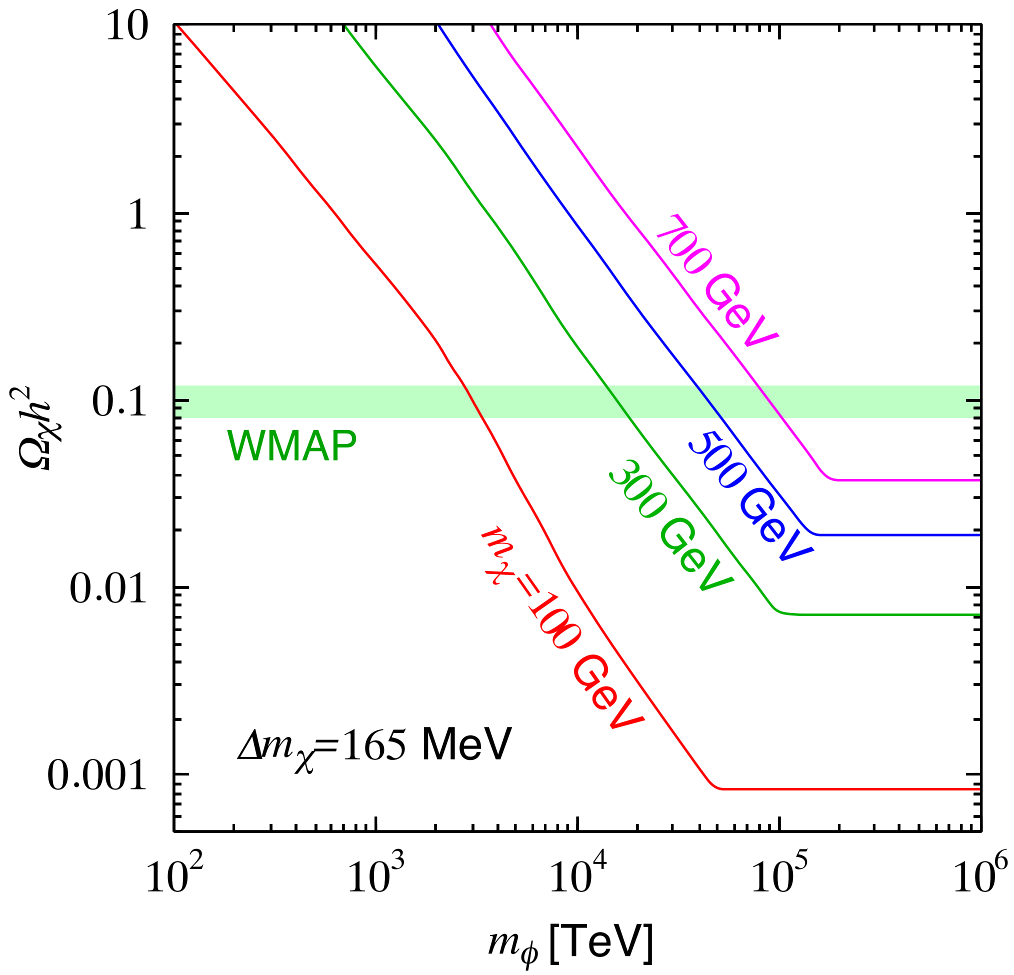
$$\delta = \frac{|M_2 - M_3|}{|M_2 + M_3|} \sim 10^{-13}$$

3.5 keV γ-ray line from DM decay?

3 N oscillations: $M_i > 100$ MeV possible, HNLs interesting for DUNE, BELLE II, NA62, LHC, …

Heavy modulus decay

[Kitano, Murayama, Ratz '07]



Connection between matter and dark matter? Common origin in complex modulus decay (string theory) to up/down quarks:

$$W \supset \frac{1}{M_\mathrm{p}} \Phi(UDD) \ ,$$

$$U = (\tilde{u}^c, u^c, F_u), \ D = (\tilde{d}^c, d^c, F_d)$$

Baryon charge stored in time-dependent complex condensate Φ; in anomaly mediation with wino LSP, $m_\chi/m_{3/2} \sim g_2^2/(16\pi^2)$,

$$\frac{\Omega_\chi}{\Omega_b} \ \sim \ |\kappa|^{-1} \times 10^{-2} \times \frac{m_\chi}{m_\mathrm{nucleon}}$$

For wino mass $m_\chi = \mathcal{O}(100 \text{ GeV})$ observed ratio $\Omega_\mathrm{CDM}/\Omega_b \simeq 5$ natural value; no sphalerons, very low reheating temperature

Leptogenesis & grand unification

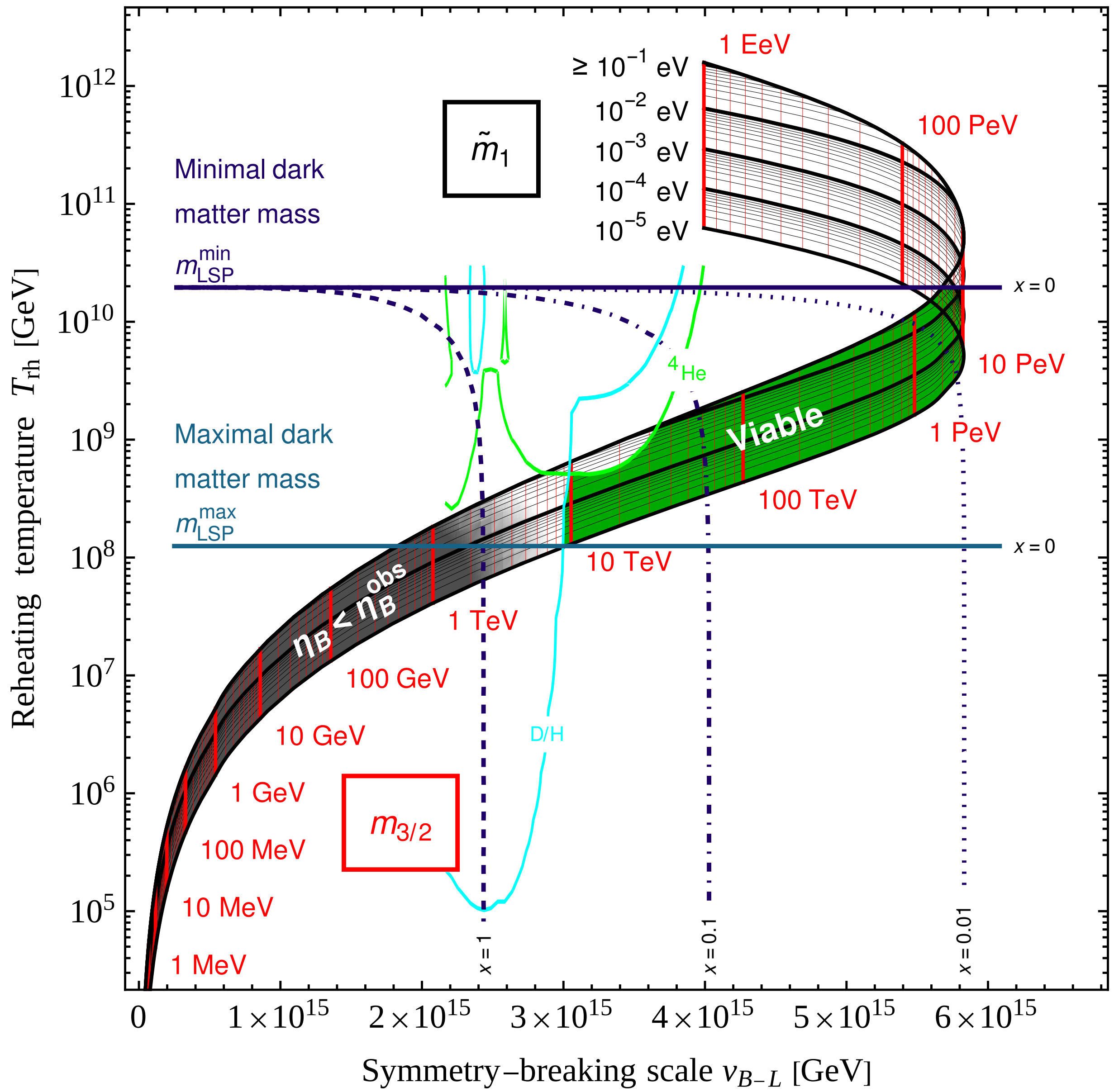
Can GUT-scale leptogenesis be tested? RH neutrinos very heavy! Compare with grand unification:

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! For hierarchical heavy neutrinos:

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

Connection with inflation and dark matter; example: cosmological $\mathrm{U}(1)_{\mathrm{B-L}}$ breaking after SUSY hybrid inflation



GUT scale: $\sim 10^{15}$ GeV

SUSY scale: 10 TeV $\ldots 10$ PeV

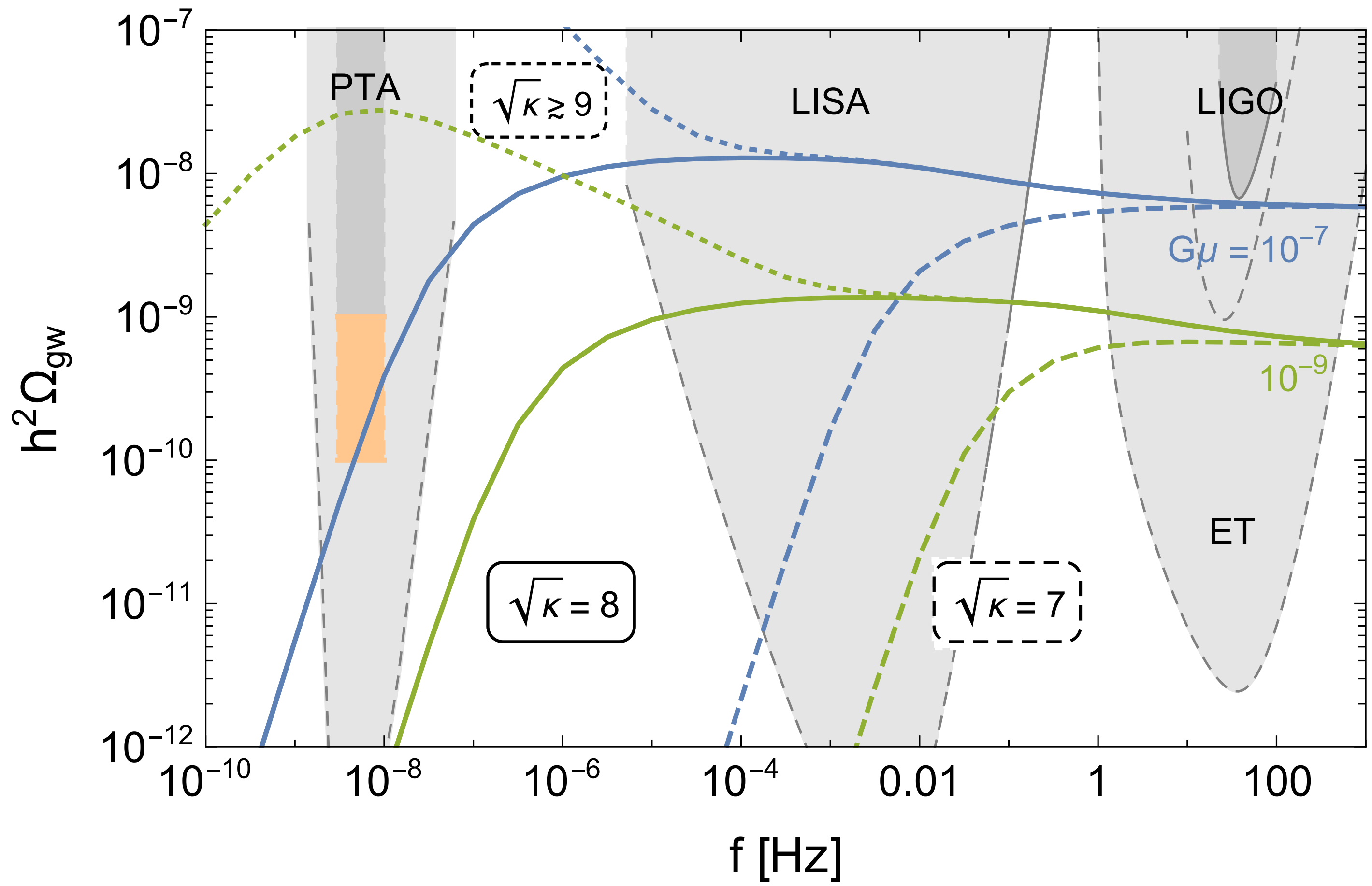
reheating temp: $\sim 10^{10}$ GeV

higgsino dark matter
(gravitino decays)

[WB, Domcke, Murayama, Schmitz '19]

problem: production of strings after inflation with $G\mu \sim 10^{-6}, \ \mu \sim v_{B-L}^2$
until 2020 upper bound from PTAs [pulsar timing arrays]: $G\mu < 10^{-11}$

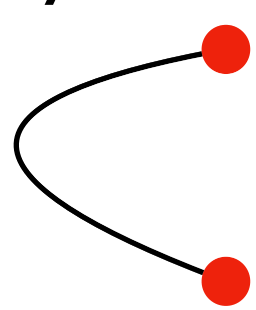
Solution: metastable cosmic strings (MSCS)



spectrum falls off at small frequencies due to decay of cosmic string network; consistent with recent PTA results for $\sqrt{\kappa} \sim 8$

[WB, Domcke, Murayama, Schmitz '19, WB, Domcke, Schmitz '20-'23]

decay rate per string unit length [Vilenkin '82, Preskill and Vilenkin '92'; …]



$$\Gamma_d = \frac{\mu}{2\pi} \exp\left(-\pi\kappa\right) \ , \quad \kappa = \frac{m_M^2}{\mu}$$

Strings and monopoles in Pati-Salam and SO(10) symmetry breaking:

$$S \subset (\mathbf{4}, 1, \mathbf{2}) \subset \overline{\mathbf{16}} \sim \Phi^c \ , \quad S_c \subset (\bar{\mathbf{4}}, 1, \mathbf{2}) \subset \mathbf{16} \sim \Phi$$

large right-handed Majorana neutrino masses $L_i^c = (n_i^c, e_i^c)^T$ from nonrenormalizable operator

$$\mathcal{L}_n = \frac{1}{M_*} h_{ij} \, S^T L_i^c S^T L_j^c \subset \frac{1}{M_*} h_{ij} \, \Phi^c \psi_i \Phi^c \psi_j$$

large vev $\langle S \rangle = \langle \Phi^c \rangle$ implies $\mathrm{U(1)_{B\text{-}L}}$ seesaw mechanism:

$$\mathrm{SO(10)} \to \mathrm{G}_{PS} \to \mathrm{SU(3)}_c {\times} \mathrm{U(1)}_{B-L} \times \mathrm{SU(2)}_L \times \mathrm{U(1)}_R \ ,$$
$$\mathrm{U(1)}_{B-L} \times \mathrm{U(1)}_R \to \mathrm{U(1)}_Y$$

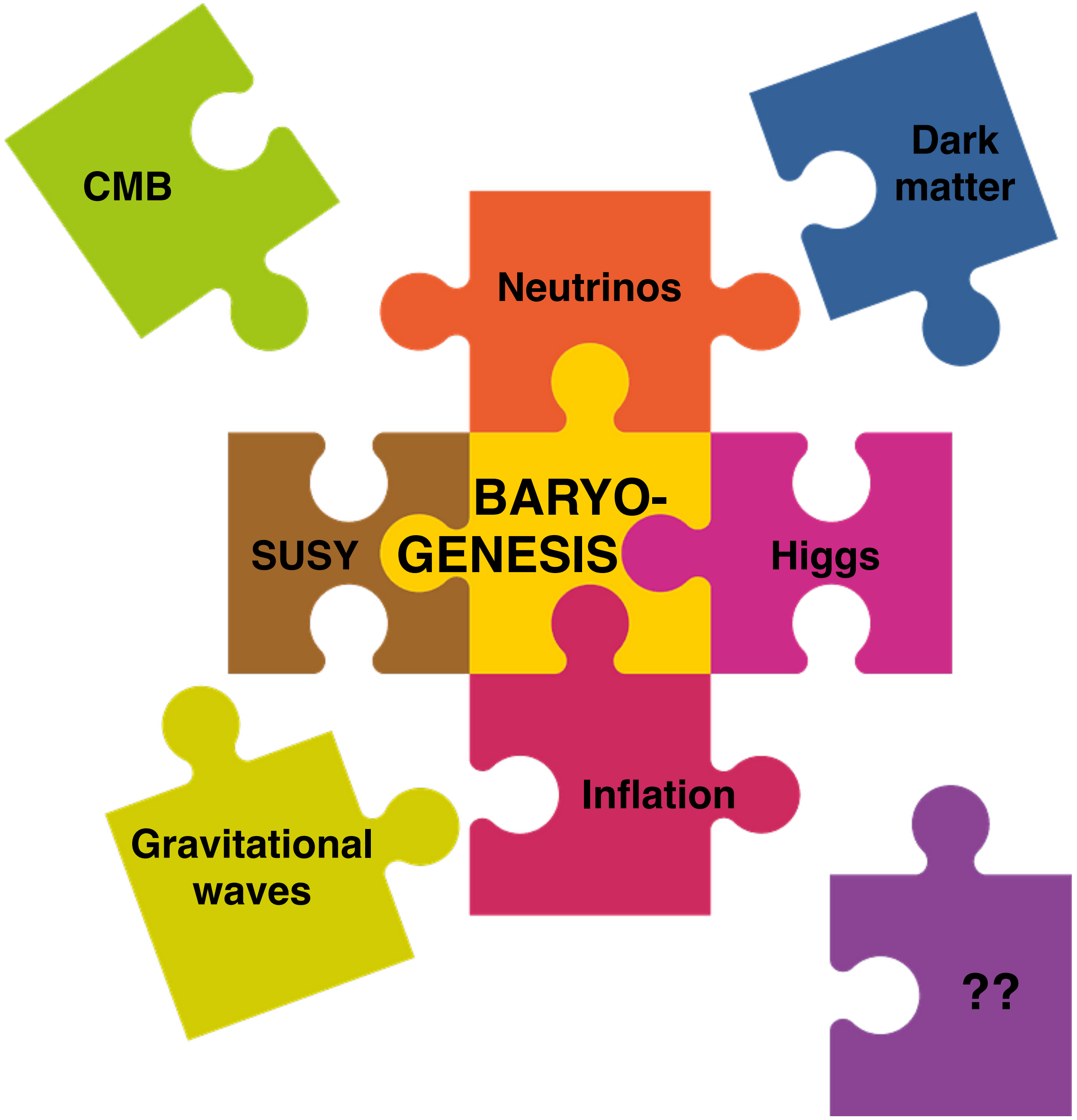
relevant monopoles from SU(4) and SU(2)_R breaking; interesting hybrid structures; after recent PTA results large theoretical activity [Lazarides, Shafi et al, King, Pascoli et al, Antusch et al, Ellis et al, …, WB, Domcke, Schmitz, Afzal et al, … '23], all models with leptogenesis; GW have become part of the puzzle

Other models

- Affleck-Dine mechanism: generic possibility (particularly attractive for flat directions in MSSM)
- Spontaneous baryogenesis
- Cold baryogenesis
- Baryogenesis from strong CP violation and the QCD axion
- Baryogenesis from B-meson oscillations
- “Wash-in” leptogenesis
- ………

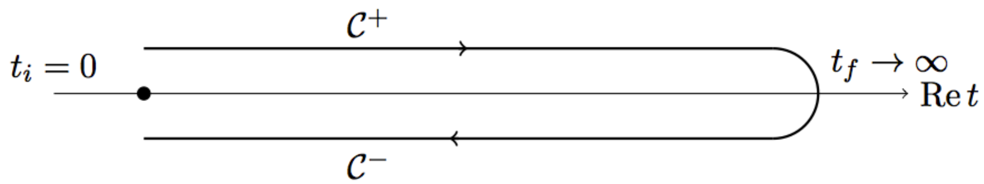
Summary

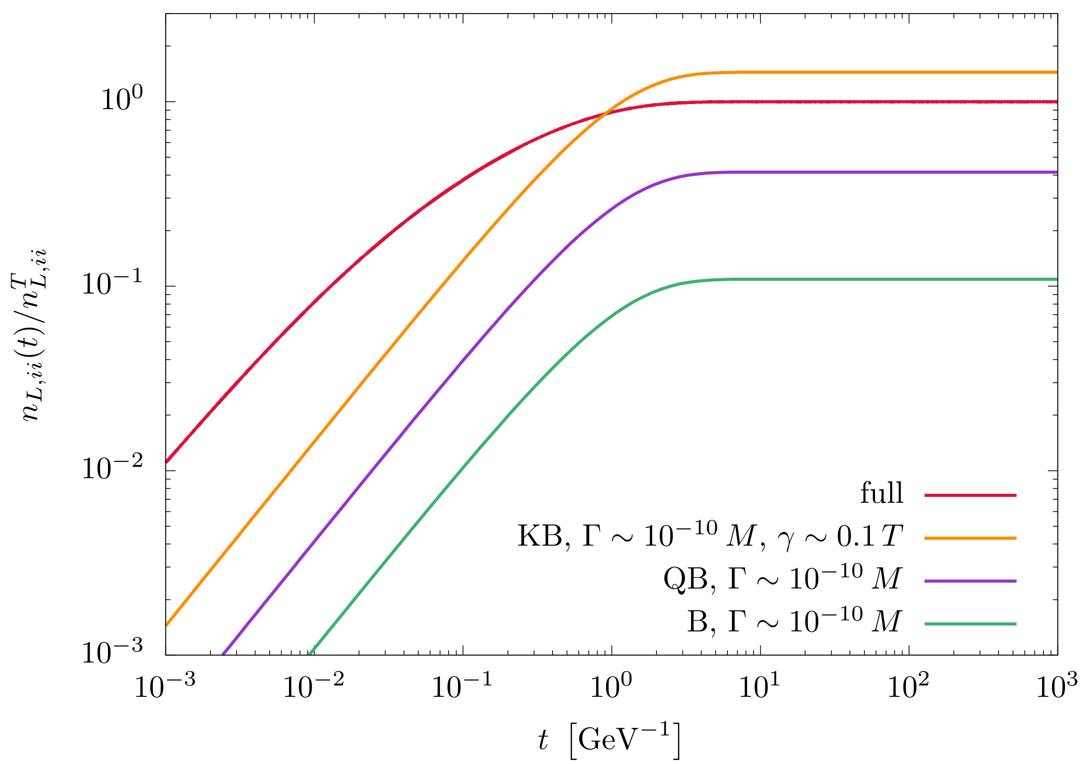
Baryonasymmetry has to be dynamically explained; closely related to other aspects of particle physics and cosmology, Higgs/LHC, neutrino masses and mixings, inflation, dark matter and SUSY, axions, gravitational waves …
… some discovery will come!



BACKUP SLIDES

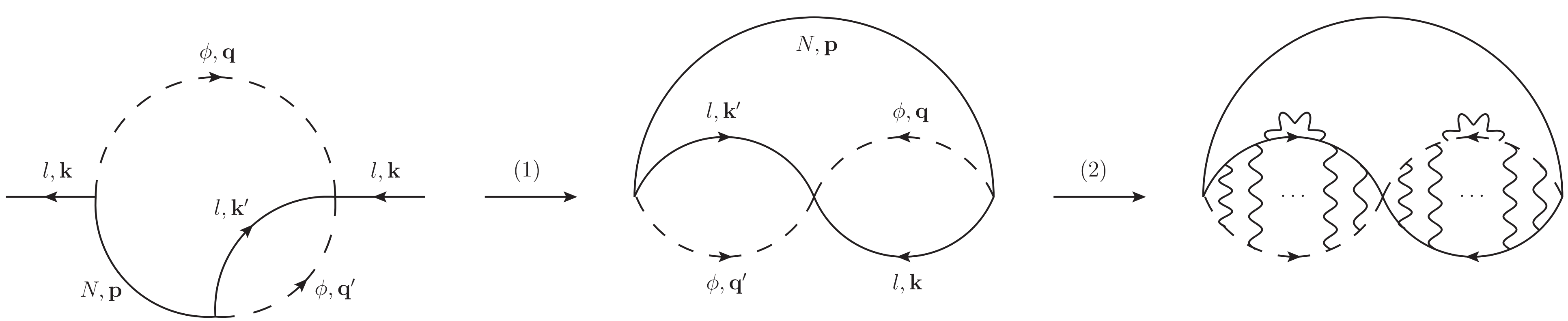
Toward a theory leptogenesis





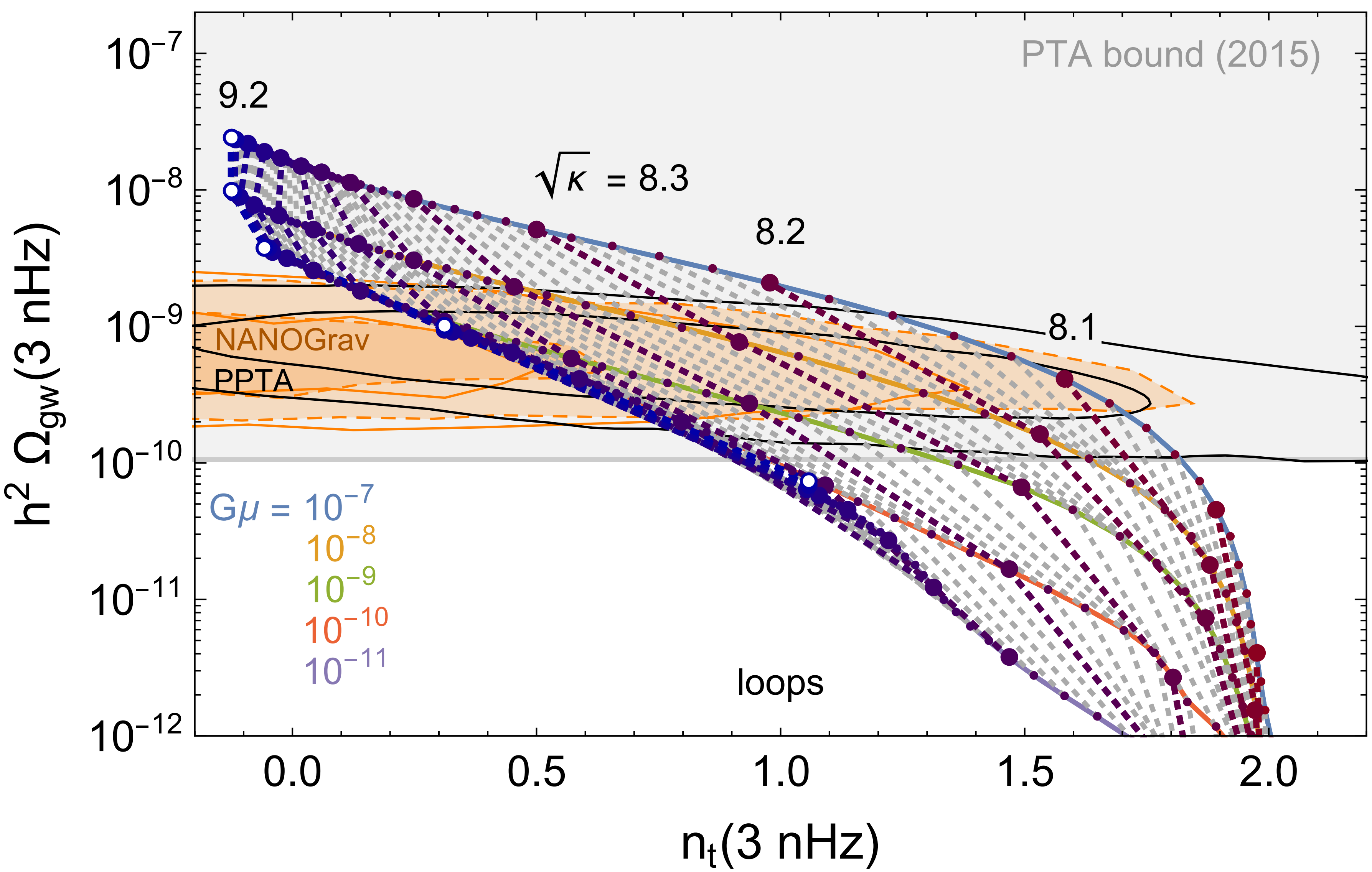
[Depta, Halsch, Hutig, Mendizabal, Philipsen '20]

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 $\mathcal{O}(1)$



Detailed analysis of NANOgraph and PPTA data

data yield ellipse in amplitude-slope plane (NANOGraph & PPTA, 1σ & 2σ); observations larger than previous upper bound!

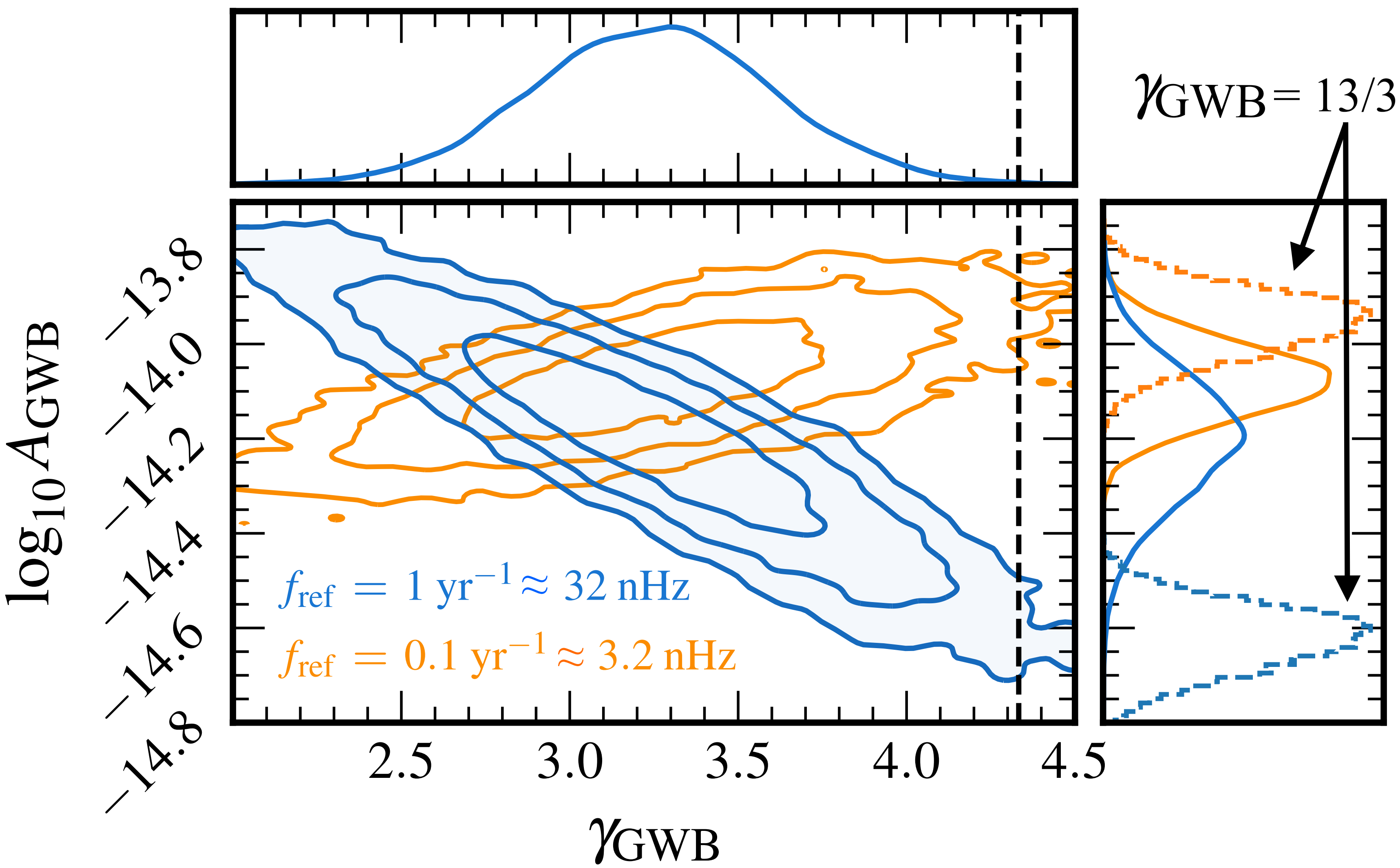


NANOGraph & PPTA ellipses, 1σ & 2σ; lines of constant Gμ and κ

[WB, Domcke, Schmitz '21]

successful MSCS prediction for $2 \times 10^{-11} < G\mu < 2 \times 10^{-7},\ \sqrt{\kappa} \sim 8$

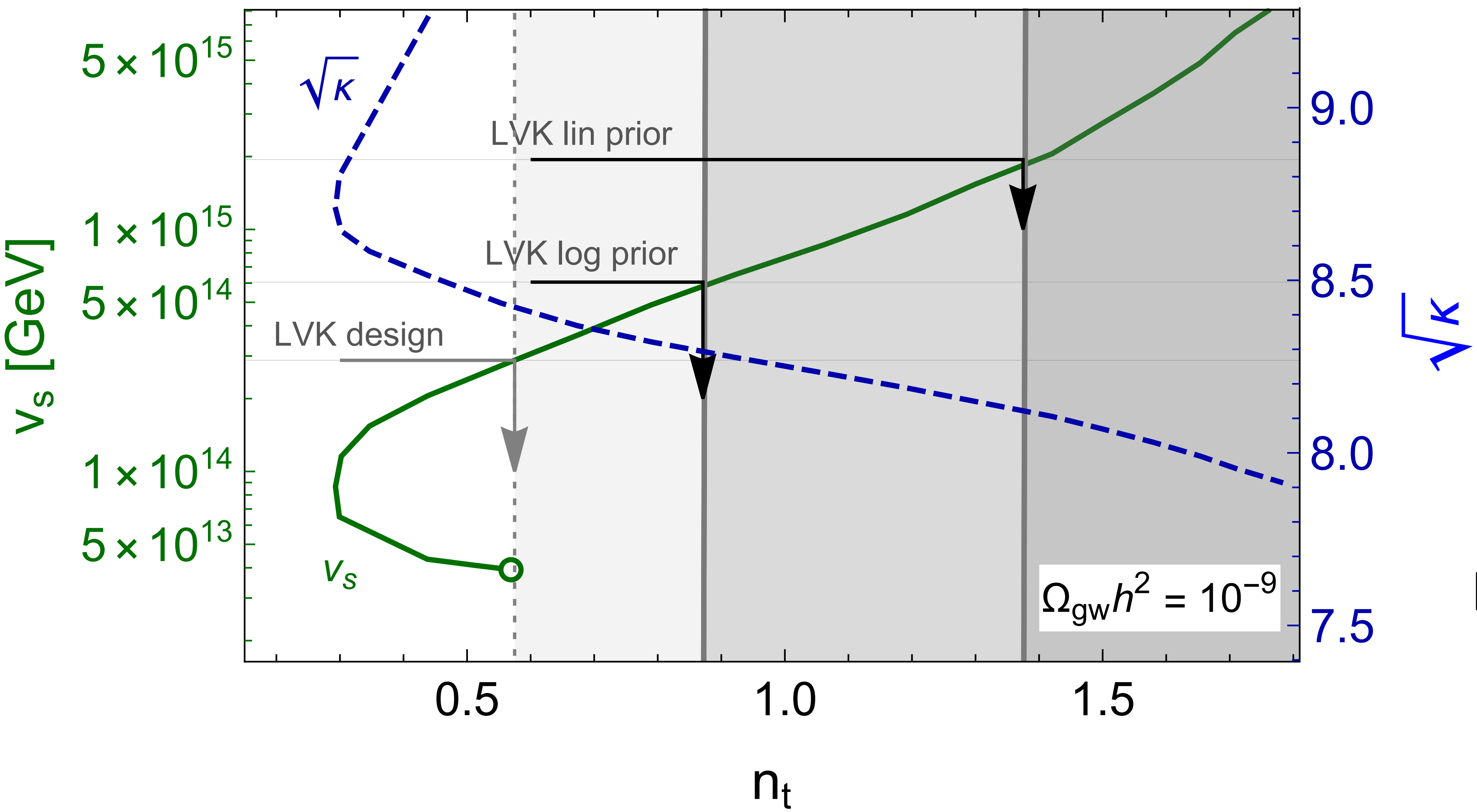
June 2023: evidence for **Hellings-Downs** spatial correlations (~4σ) and therefore gravitational wave signal, NANOGraph, PPTA, EPTA, CPTA, more precise determination of amplitude and slope, $\gamma = 5 - n_t$



NANOGraph
1σ, 2σ & 3σ

What is it? SMBHB (γ = 13/3, slightly disfavoured?), MSCS, stable strings (sightly disfavoured?), superstrings, global strings, inflation, domain walls, PBHs … ? Time (more data) will tell

Current and future information on string scale (MSCS)



[WB, Domcke, Schmitz '23]

recent PTA data: $10^{-10} \lesssim \Omega_{\rm gw}^{\rm PTA} h^2 \lesssim 10^{-9},\ 0 \lesssim n_t \lesssim 3\ (n_t \simeq 1)$;
for fixed $\Omega_{\rm gw}^{\rm PTA}$ MSCS predict dependence $v_s(n_t)$; **upper bound** from LIGO-Virgo-KAGRA (LVK); sweet spot

$$v_s = \text{few} \times 10^{14}\text{GeV},\ n_t \simeq 1$$

Hope: discovery of SGWB at LVK!

MSCS and SO(10) grand unification

Formation of topological defects generic feature of cosmological GUT phase transitions[Kibble '76]: strings, monopoles etc. Hot topic after new PTA data in June [Lazarides, Shafi et al, King, Pascoli et al, Antusch et al, Ellis et al, …, WB, Domcke, Schmitz]. PTA data disfavour stable strings but favor superstrings and metastable strings [NANOGraph, Afzal et al '23]: