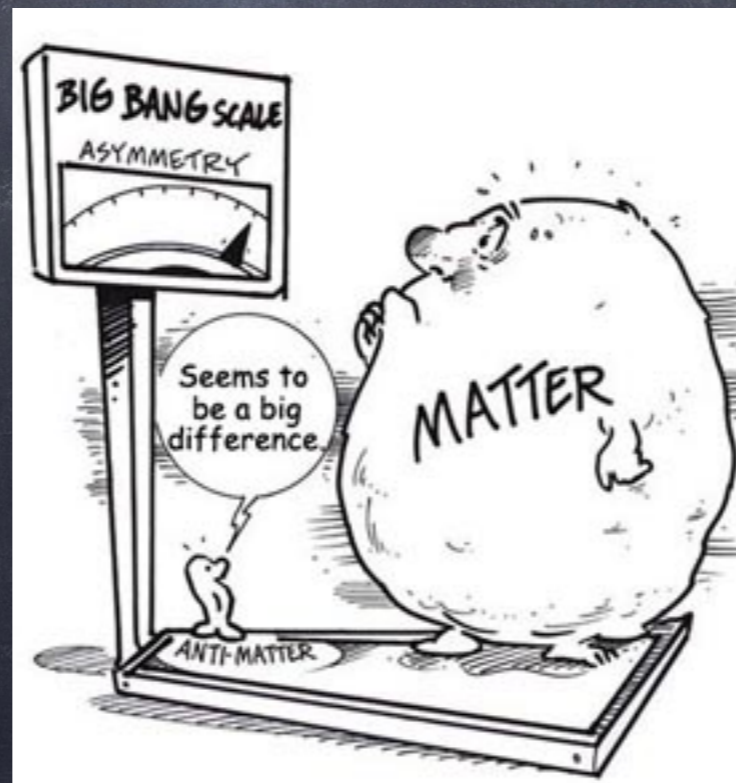


Lectures on Particle Cosmology- III+IV

Pre-SUSY 2014, Manchester

Anupam Mazumdar

Lancaster University



Synthesis of Light Elements (BBN)

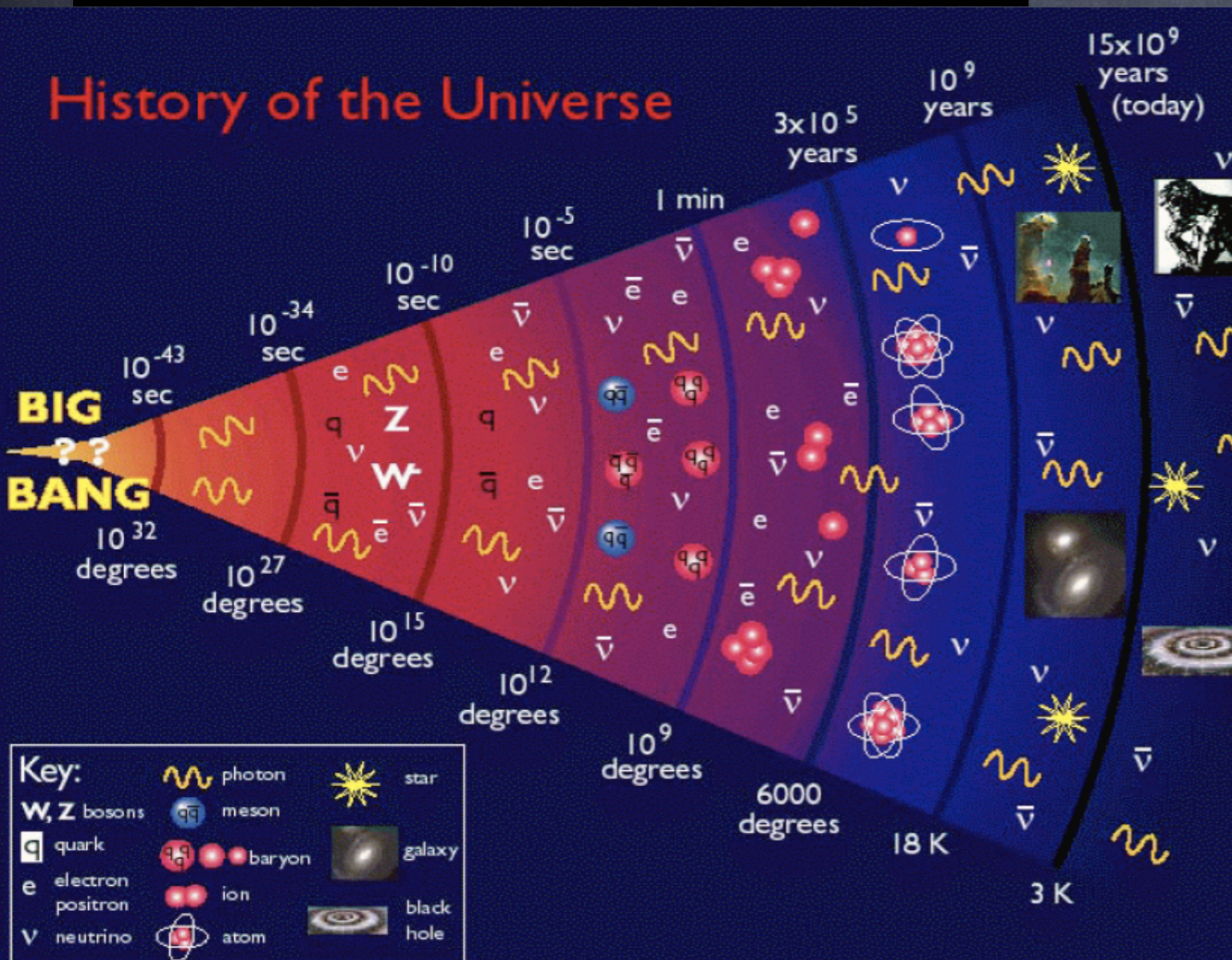
Periodic table - chemist

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra		Rf	Db	Sg	Bh	Hs	Mt	Uun	Uuu	Uub						
		La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	
		Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr	

Periodic table - cosmologist

H																	He
Metals																	

History of the Universe

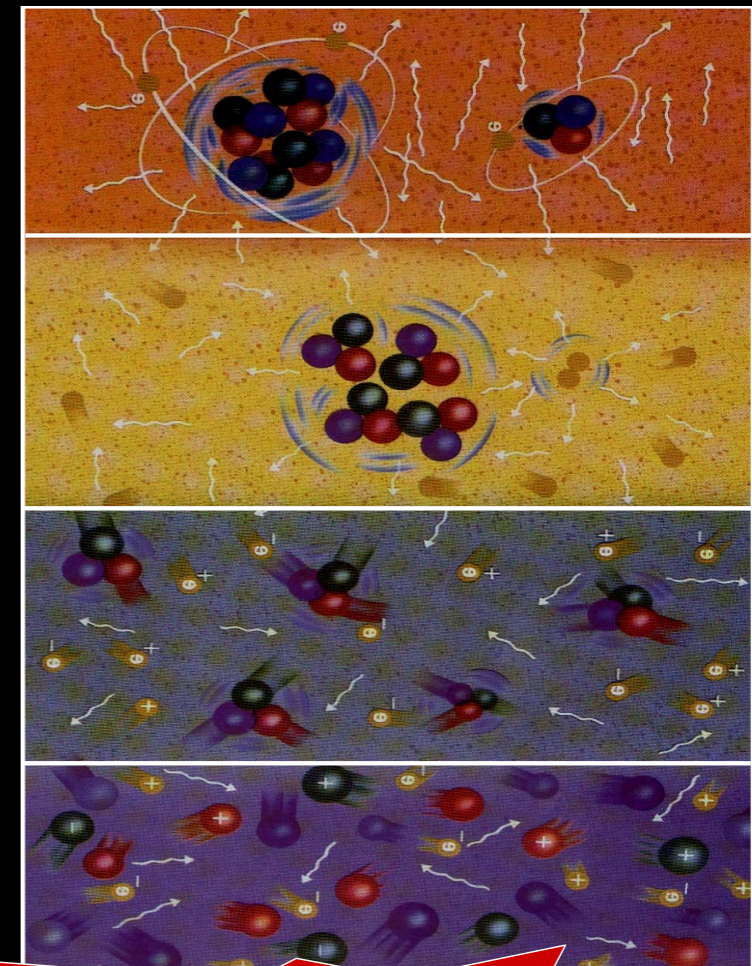


300,000 years

3 minutes

1-microsecond

4-pico seconds



atoms form

nuclei form

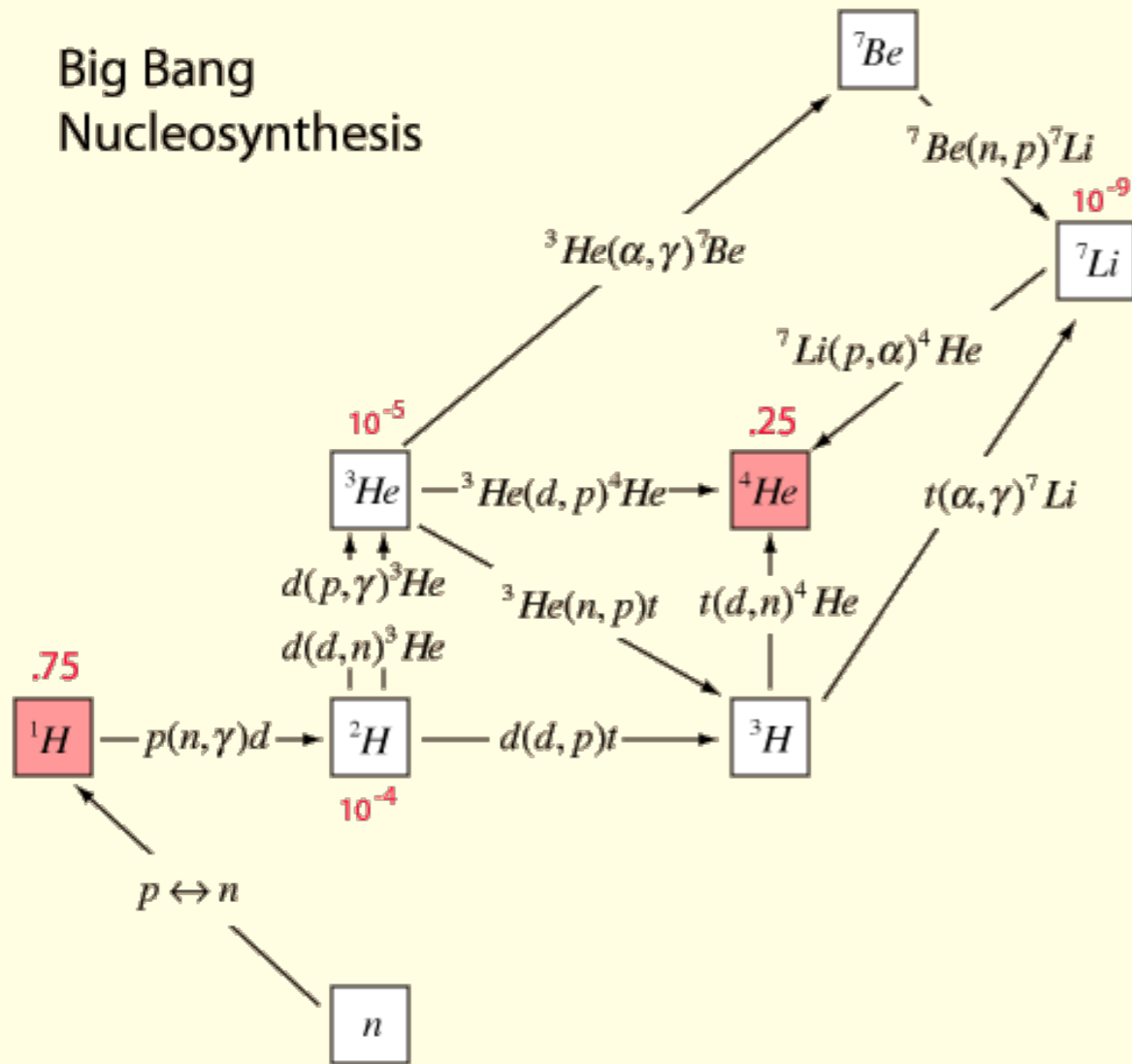
neutrons
protons
form

primordial
soup

BANG!

Big Bang Nucleosynthesis

Big Bang Nucleosynthesis



$$\eta \equiv \frac{n_B}{n_\gamma} = \frac{n_b - n_{\bar{b}}}{n_\gamma} : \text{Baryon Asymmetry}$$

$$X_n \rightarrow X_{n,eq} \equiv \frac{n_n}{n_n + n_p}$$

$$\sim (1/6) ; X_n \sim \frac{1}{6} \exp[-t/\tau_{n \rightarrow pev}] \sim 0.15 \times 0.74 \sim 0.11$$

$$Y_P(^4\text{He}) \approx 2X_n \sim 0.22$$

$$T \gg 1\text{MeV} : n + \nu_e \leftrightarrow p + e^-,$$

$$n_n \simeq n_p$$

$$T = T_F \simeq 1\text{MeV} : \Gamma_{n \leftrightarrow p} \simeq H(T)$$

$$\frac{n_n}{n_p} \simeq e^{(m_n - m_p)/T_F} \simeq \frac{1}{6}$$

$$T = 0.3 - 0.1 \text{ MeV}$$

$$\text{Depending on } \eta = \frac{n_B'}{n_\gamma} \quad \frac{n_n}{n_p} = \frac{1}{7} - \frac{1}{6}$$

$$^4\text{He mass fraction} :$$

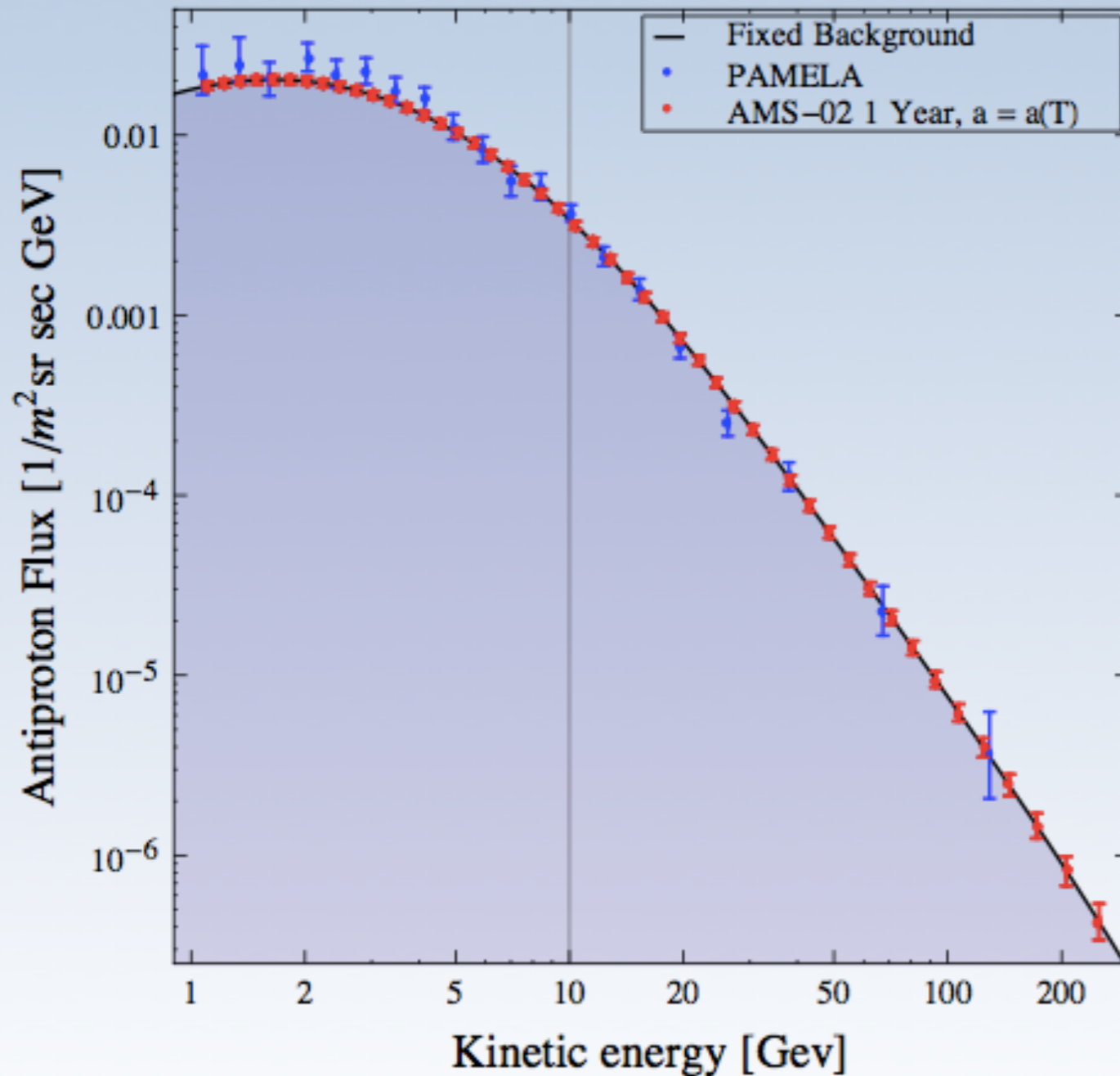
$$Y \equiv \frac{2n_n}{n_n + n_p} \sim 0.22 \Leftrightarrow \frac{n_n}{n_p} \sim \frac{1}{6}$$

$$X_A \propto \eta^{A-1} \quad A = p + n$$

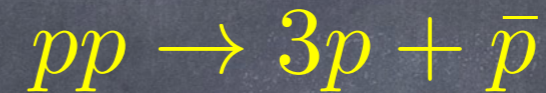
Rest of the elements have been synthesised in stars

Constraints on anti-protons

Pure Background



anti-protons are produced in secondaries




Annihilating/decaying DM into quarks and gauge bosons => hadroniation leads to anti-protons

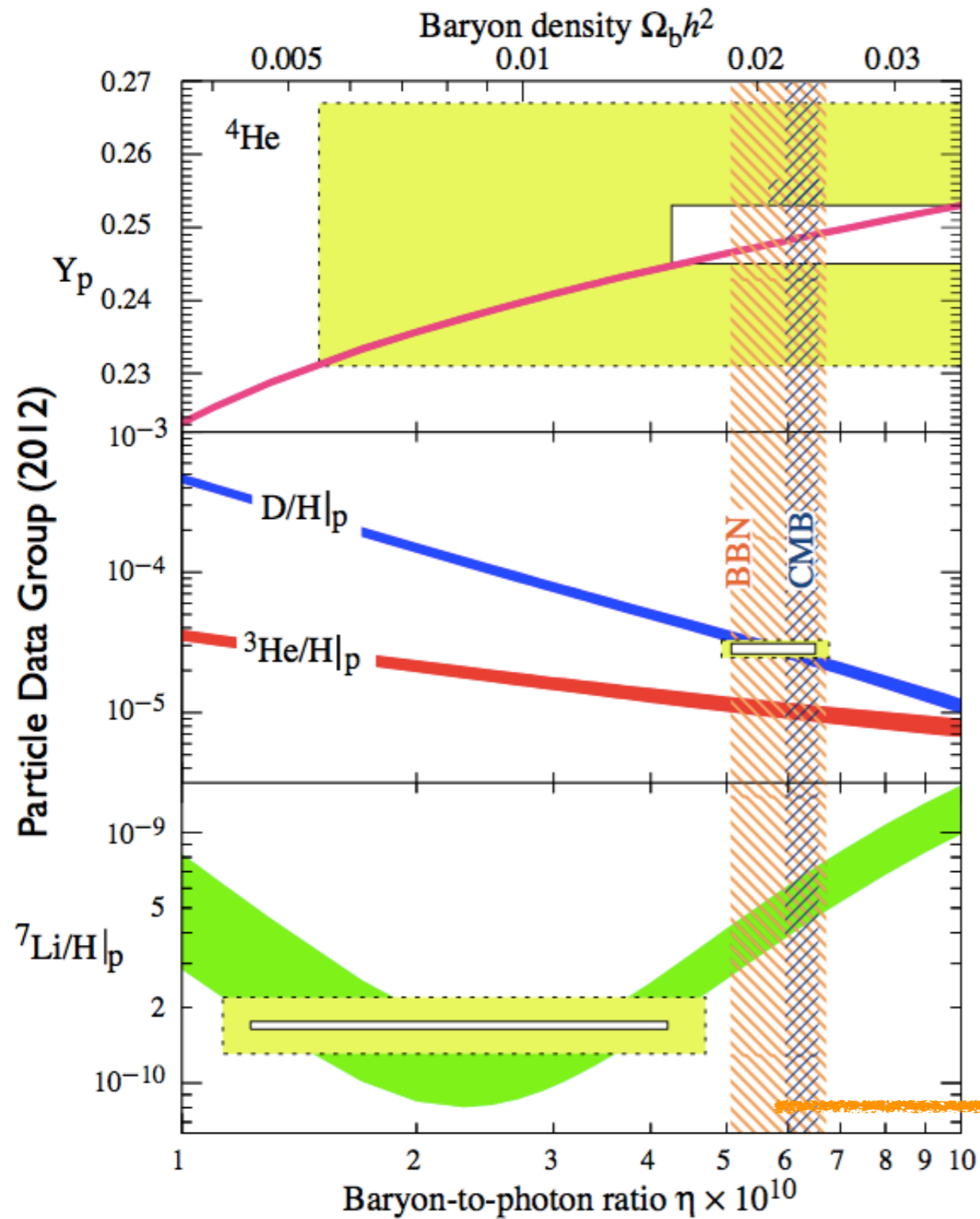
Annihilating/decaying DM into leptons => electroweak corrections yield anti-protons

all observed anti-protons are our cosmic background

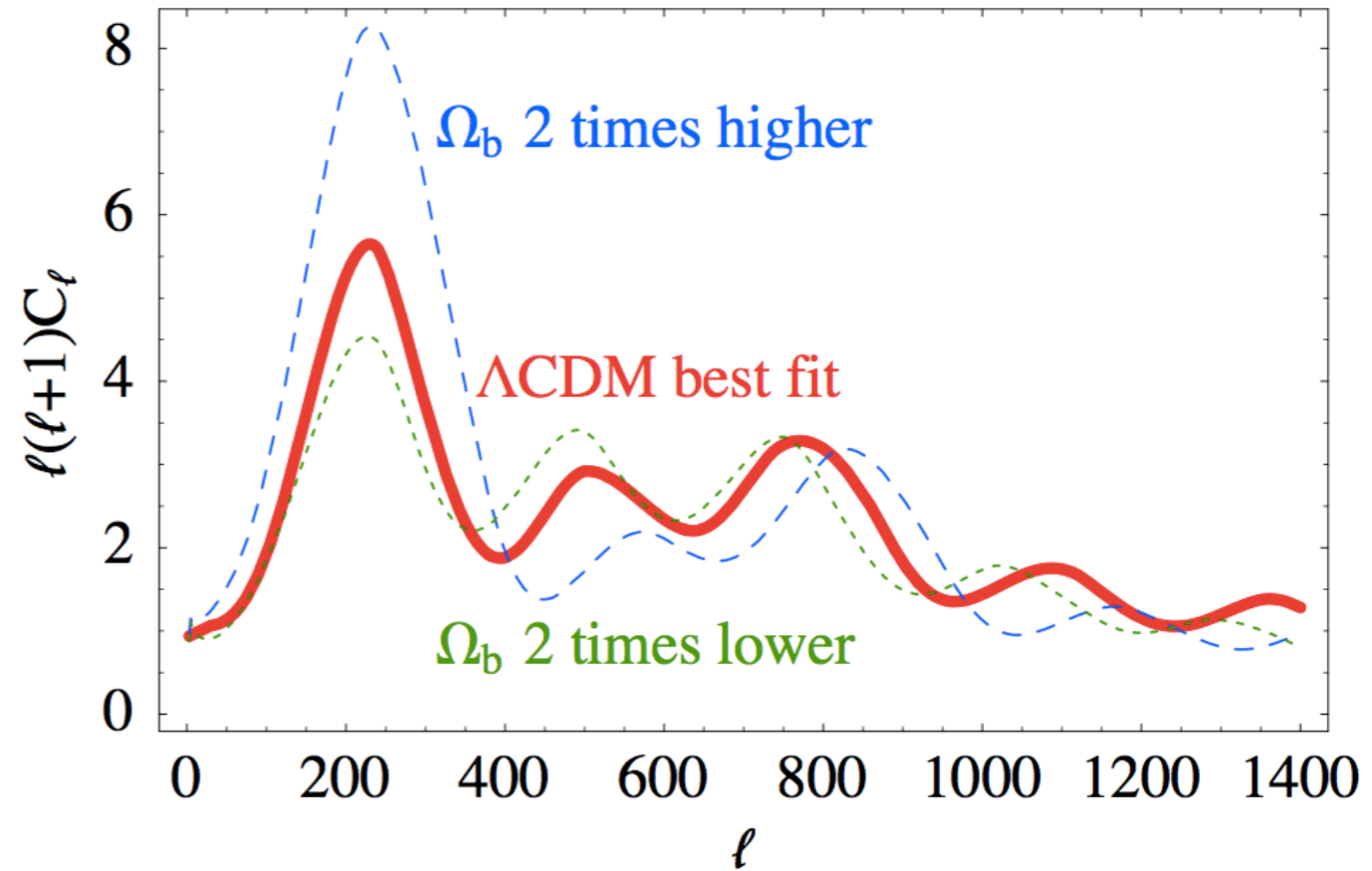
How do we generate Baryon Asymmetry ?


$$\eta \equiv \frac{n_B}{n_\gamma} = \frac{n_b - n_{\bar{b}}}{n_\gamma} : \text{Baryon Asymmetry}$$

CMB & BBN



bands = 95% C.L.
 smaller boxes = $\pm 2\sigma$ statistics
 larger boxes = $\pm 2\sigma$ statistics
 and systematics



$$\eta = (6.04 \pm 0.08) \times 10^{-10} \text{ (Planck)}$$

$$\eta = (5.1 - 6.5) \times 10^{-10}$$

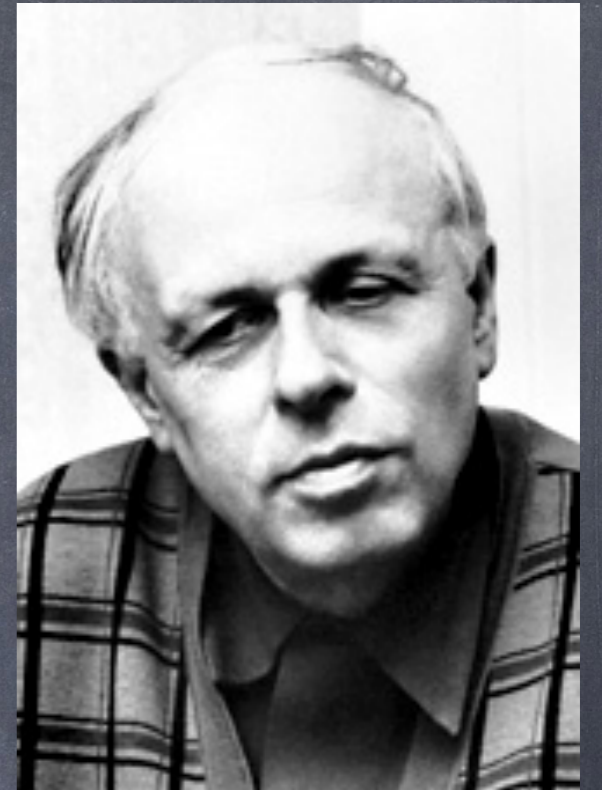
$$\eta \equiv \frac{n_B}{n_\gamma} = \frac{n_b - n_{\bar{b}}}{n_\gamma} : \text{Baryon Asymmetry}$$

How to create baryon asymmetry in the universe?

(1) Baryon number violation (particle physics)

(2) C & CP violation (particle physics)

(3) Departure from thermal equilibrium
(cosmology)



Suppose $\eta = 0$, at $T \leq 1$ GeV :

$$\frac{n_b}{n_\gamma} \approx \frac{n_{\bar{b}}}{n_\gamma} \approx \left(\frac{m_p}{T}\right)^{3/2} e^{-m_p/T} \sim 10^{-18} \quad (\text{for } T \sim 20\text{MeV})$$

$$\Gamma_{ann} \approx n_b \langle \sigma v \rangle \geq H(T) \sim 1.66 g_*^{1/2} (T^2 / M_p)$$

C & CP violation

Charge conjugation symmetry, and the product of charge conjugation and parity are not exact symmetries of nature

Exact C symmetry: $i \rightarrow f \implies \bar{i} \rightarrow \bar{f}$ ($|B_f| = |B_{\bar{f}}|$)

particle \leftrightarrow anti - particle

Exact CP symmetry:

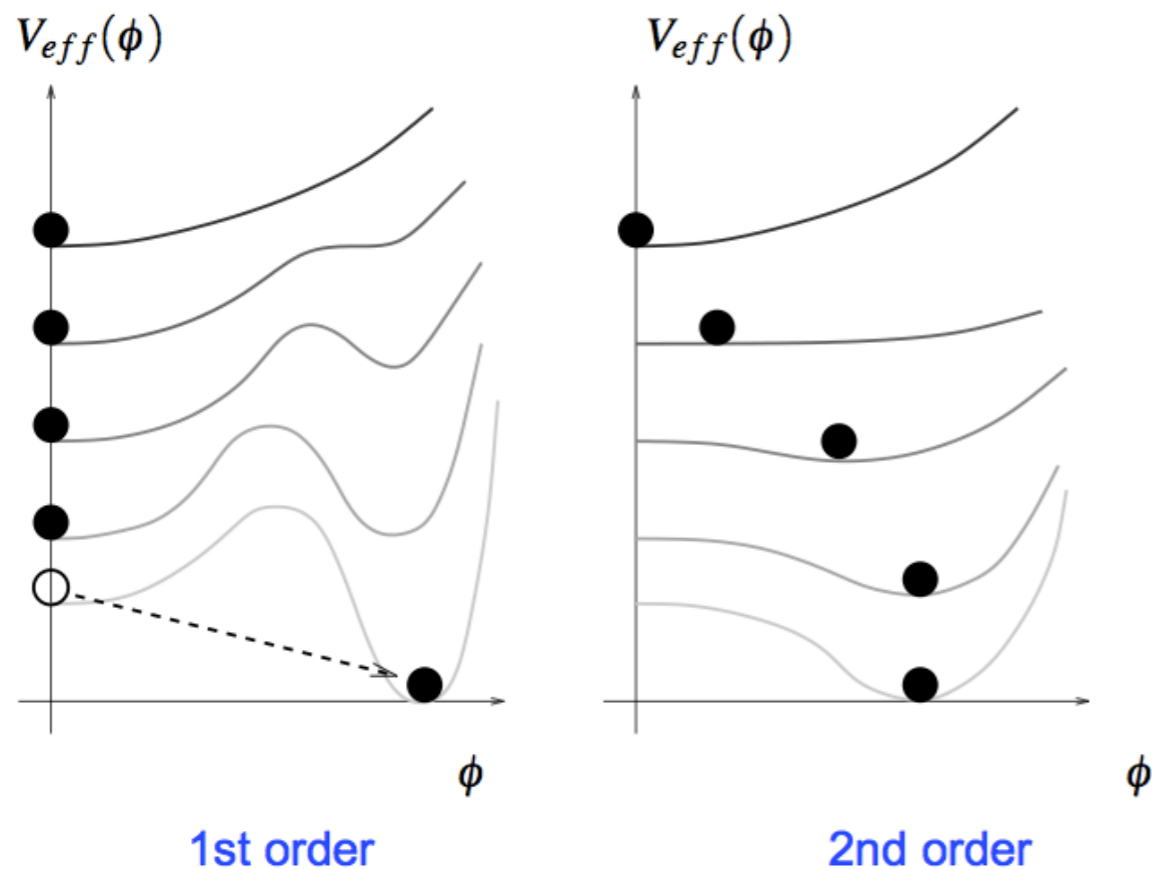
CP invariance means time invariance due to CPT – theorem

$$i(r_i, p_i, s_i) \rightarrow f(r_j, p_j, s_j) = f(r_j, -p_j, -s_j) \rightarrow i(r_i, -p_i, -s_i)$$

**Weak interactions break C and CP both, e.g. neutrino sector,
kaon sector**

Out of Equilibrium Condition

- (1) **Expansion of the Universe** $\Gamma_{process} < H(T) \sim 1.66g_*^{1/2}(T^2/M_p)$
- (2) **First order Phase Transition**
- (3) **Decay of any particle: Inflaton Reheating/Preheating/Moduli late Decay, etc.**



During reheating
or preheating one can
excite heavy states
(out of equilibrium):

$$m_X \gg m_\phi, T_{rh}$$

Production of baryon asymmetry

$$r = \frac{\Gamma(X \rightarrow a)}{\Gamma_X} \quad (\text{Baryon number } B_a), \quad 1 - r = \frac{\Gamma(X \rightarrow b)}{\Gamma_X} \quad (\text{Baryon number } B_b)$$

$$\bar{r} = \frac{\Gamma(\bar{X} \rightarrow \bar{a})}{\Gamma_X} \quad (\text{Baryon number } -B_a), \quad 1 - \bar{r} = \frac{\Gamma(\bar{X} \rightarrow \bar{b})}{\Gamma_X} \quad (\text{Baryon number } -B_b)$$

$$\Delta B = (r - \bar{r})B_a + [(1 - r) - (1 - \bar{r})]B_b = (r - \bar{r})(B_a - B_b)$$

$$\Delta B = \frac{1}{\Gamma_X} \sum_n B_n [\Gamma(X \rightarrow f_n) - \Gamma(\bar{X} \rightarrow \bar{f}_n)] \quad B \equiv \frac{n_B}{s} \approx \frac{\Delta B n_X}{n_\gamma}, \Rightarrow B \equiv \frac{n_B}{s} \approx \frac{\Delta B n_\gamma}{g_* n_\gamma} \approx \frac{\Delta B}{g_*}$$

Out of equilibrium decay:

$$\rho_X \simeq M_X n_X \quad \rho_X \approx \rho_r = \frac{\pi^2}{30} g_* T_{rh}^4 \quad s = \frac{2\pi^2}{45} g_* T^3$$

$$B \equiv \frac{n_B}{s} \sim \frac{n_X}{s} \simeq \frac{3}{4} \frac{T_{rh}}{M_X} \Delta B$$

$$B \simeq \left(\frac{g_*^{-1/2} \alpha_X M_p}{M_X} \right)^{1/2} \Delta B$$

$$\Gamma_X \sim H(T_d) \sim \frac{8\pi\rho_X}{3M_p^2}, \quad \Gamma_\phi = \alpha_\phi M_\phi$$

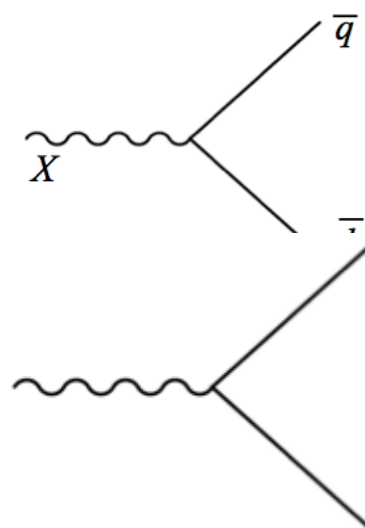
Unified Gauge Theories and the Baryon Number of the Universe

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Department of Physics, Tohoku University, Sendai 980, Japan

(Received 27 April 1978)

I suggest that the dominance of matter over antimatter in the present universe is a consequence of baryon-number-nonconserving reactions in the very early fireball. Unified gauge theories of weak, electromagnetic, and strong interactions provide a basis for such a conjecture and a computation in specific SU(5) models gives a small ratio of baryon- to photon-number density in rough agreement with observation.



SU(5): Baryons and leptons are in same generation

C and CP are violated at one loop

Baryon numbers, B_a, B_b

Unfavored: Requires heavy gauge bosons :

$$T_{rh} \sim 10^{15} \sqrt{\alpha_\phi} \text{ GeV}$$

process	branching ratio	B
$X \rightarrow q q$	r	$2/3$
$X \rightarrow \bar{q} \bar{l}$	$1 - r$	$-1/3$
$\bar{X} \rightarrow \bar{q} \bar{q}$	\bar{r}	$-2/3$
$\bar{X} \rightarrow q l$	$1 - \bar{r}$	$1/3$

Sphalerons

In the Standard Model, baryon and lepton number conservation are accidental symmetries. It was discovered by 't Hooft that non-perturbative effects can violate B and L: via instantons.

Baryon and lepton number are defined as: $B = \int d^3x J_0^B(x), \quad L = \int d^3x J_0^L(x)$

Four current associated to B & L are

$$J_\mu^B = \frac{1}{3} \sum_i \left(\bar{q}_{L_i} \gamma_\mu q_{L_i} - \bar{u}_{L_i}^c \gamma_\mu u_{L_i}^c - \bar{d}_{L_i}^c \gamma_\mu d_{L_i}^c \right)$$

$$J_\mu^L = \sum_i \left(\bar{\ell}_{L_i} \gamma_\mu \ell_{L_i} - \bar{e}_{L_i}^c \gamma_\mu e_{L_i}^c \right) .$$

At the classical level, B and L are conserved:

$$\partial^\mu J_\mu^B = 0, \quad \partial^\mu J_\mu^L = 0$$

For these two currents, the Adler-Bell-Jackiw triangular anomalies do not cancel : **B and L are anomalous at the quantum level**

$$\partial_\mu J_B^\mu = \partial_\mu J_L^\mu = \frac{N_f}{32\pi^2} \left[g_2^2 F_{\mu\nu} \tilde{F}^{\mu\nu} - g_1^2 B_{\mu\nu} \tilde{B}^{\mu\nu} \right]$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$$

N_f : Number of fermion generation

Sphalerons

$$\Delta(B + L) \neq 0 \quad \Delta(B - L) = 0$$

$$\partial_\mu j_{B+L}^\mu = \frac{N_f}{16\pi^2} [g_2^2 \text{Tr}(F_{\mu\nu} \tilde{F}^{\mu\nu}) - g_1^2 B_{\mu\nu} \tilde{B}^{\mu\nu}]$$

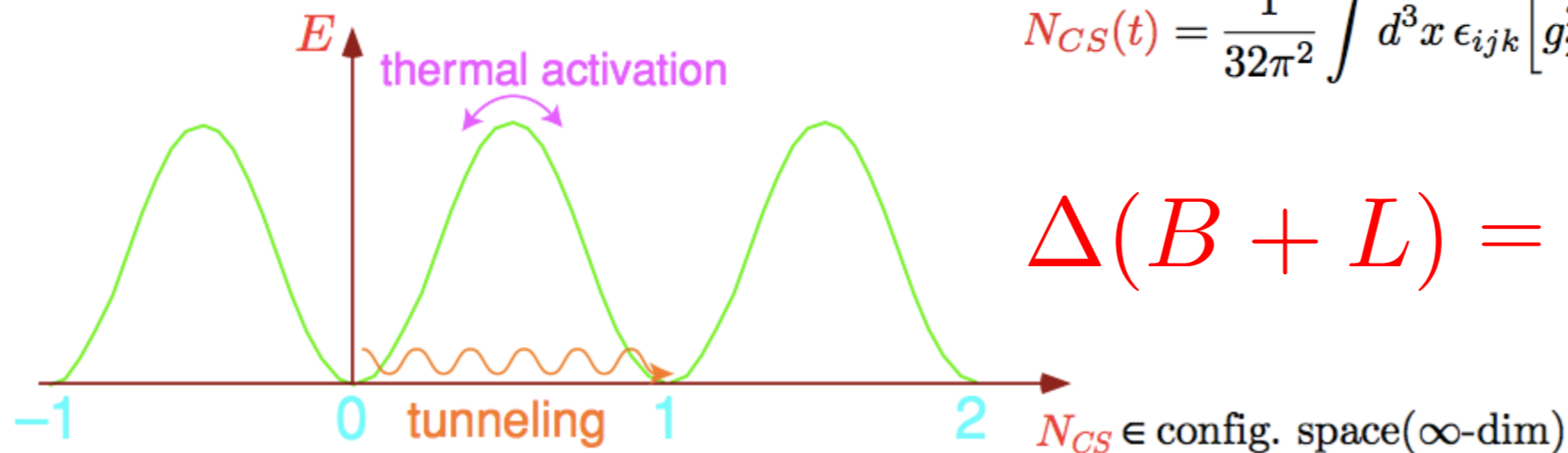
$$\partial_\mu j_{B-L}^\mu = 0$$

Chiral $U(1)_{B+L}$ Anomaly

Change in B and L are related to change in Topological charge: Chern Simons number

$$\begin{aligned} B(t_f) - B(t_i) &= \frac{N_f}{32\pi^2} \int_{t_i}^{t_f} d^4x \left[g_2^2 \text{Tr}(F_{\mu\nu} \tilde{F}^{\mu\nu}) - g_1^2 B_{\mu\nu} \tilde{B}^{\mu\nu} \right] \\ &= N_f [N_{CS}(t_f) - N_{CS}(t_i)] \end{aligned}$$

$$N_{CS}(t) = \frac{1}{32\pi^2} \int d^3x \epsilon_{ijk} \left[g_2^2 \text{Tr} \left(F_{ij} A_k - \frac{2}{3} g A_i A_j A_k \right) - g_1^2 B_{ij} B_k \right]_t$$



$$\Delta(B + L) = 2N_f N_{CS} = 6$$

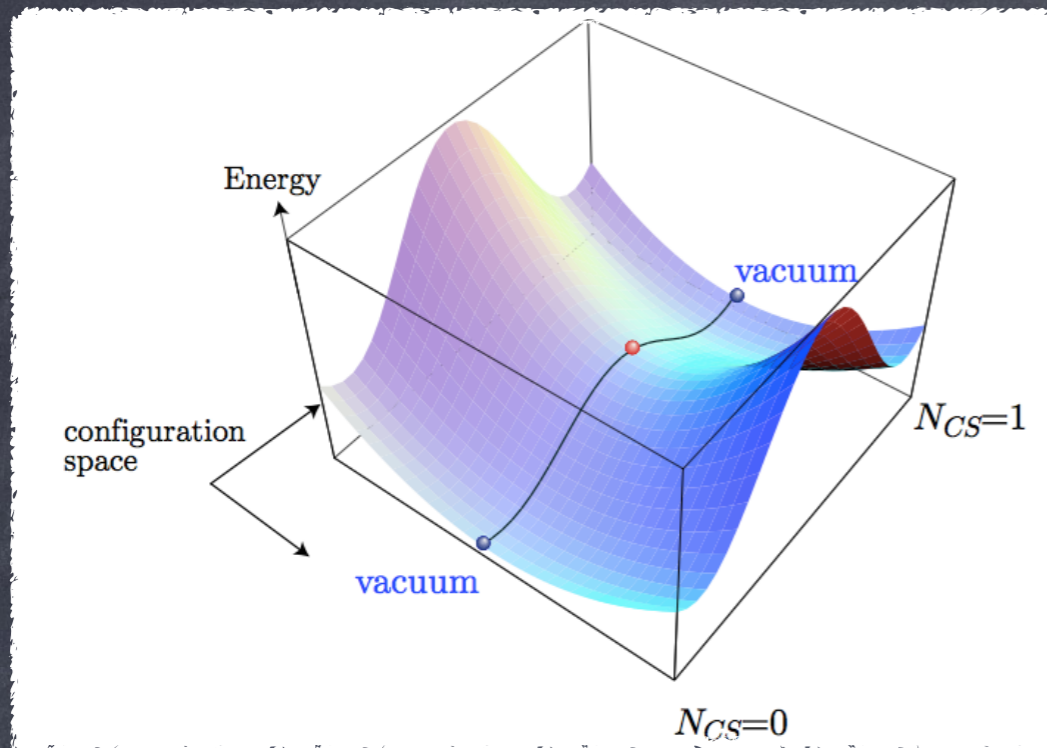
$$\Delta(B + L) \neq 0 \text{ process } \begin{cases} \triangleright \text{Quantum Tunneling} & \text{low-}T \\ \triangleright \text{Thermal Activation} & \text{high-}T \end{cases}$$

$$\text{tunnel. prob.} \sim e^{-2S_{\text{instanton}}} = e^{-8\pi^2/g_2^2} \simeq e^{-164} \ll 1$$

\therefore no proton-decay problem

$$(\Delta(B + L) = 2)$$

Sphaleron: High temperature effects



$$T < T_c \implies \Gamma \sim E e^{-E_{sph}/T}$$

$$T > T_c \implies \Gamma \sim \kappa (\alpha_W T)^4$$

$$10^{-4} \leq \kappa \leq 10^{-1}$$

$$\frac{\Gamma_{sph}}{T^3} \geq H \implies T \leq \alpha_W^4 \frac{M_p}{g_*^{1/2}} \sim 10^{12} \text{ GeV}$$

Sphaleron transitions are active:

$$T_c \sim 100 \text{ GeV} < T < 10^{12} \text{ GeV}$$

ON ANOMALOUS ELECTROWEAK BARYON-NUMBER NON-CONSERVATION IN THE EARLY UNIVERSE

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and

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International Centre for Theoretical Physics, Trieste, Italy

Received 8 February 1985

this means that if the primordial baryon asymmetry is generated by the $(B-L)$ conserving processes (which is the case in the minimal SU(5) model [22]), it is completely washed out by the moment of the electro-weak phase transition.

We estimate the rate of the anomalous electroweak baryon-number non-conserving processes in the cosmic plasma and find that it exceeds the expansion rate of the universe at $T > (\text{a few}) \times 10^2 \text{ GeV}$. We study whether these processes wash out the

Sphalerons

$$B = \frac{B - L}{2} + \frac{B + L}{2}$$

$$B \propto (B - L)_{\text{primordial}} \neq 0 \quad T \leq T_c$$

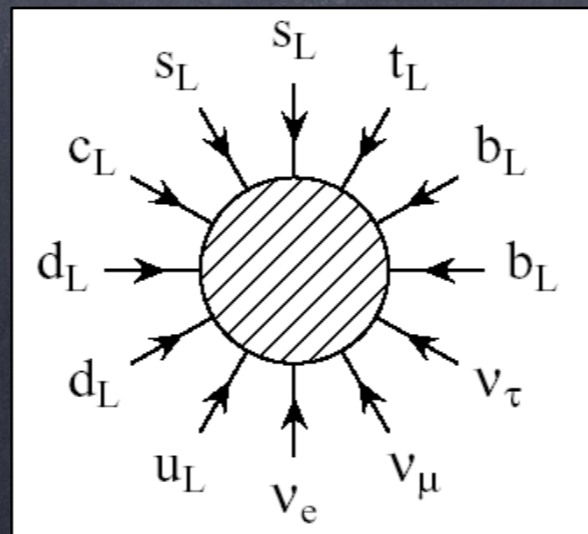
$(B + L) \neq 0$ at EW Transition

Left handed quark asymmetry
into Baryon asymmetry

Quark number density

$$n_{qL} < 0$$

$$n_{qR} > 0$$



$$n_{qL} < 0$$

$$n_{qR} > 0$$

$$n_B > 0$$

Operator involving 12 fermions

Sphalerons: conversion of B-L to B asymmetry

(1) Thermal equilibrium, weak plasma, Chemical potential:

$$n_B - n_{\bar{B}} = \frac{1}{6} g T^2 \sum_{i=1}^{N_f} (2\mu_{Q_i} + \mu_{u_i} + \mu_{d_i})$$
$$n_L - n_{\bar{L}} = \frac{1}{6} g T^2 \sum_{i=1}^{N_f} (2\mu_{\ell_i} + \mu_{e_i})$$

(2) 12 fermion interactions induced by sphalerons:

$$\sum_i (3\mu_{q_i} + \mu_{\ell_i}) = 0$$

(3) SU(3) instantons lead to interactions between LH and RH quarks:

$$\sum_i (2\mu_{q_i} - \mu_{u_i} - \mu_{d_i}) = 0$$

(4) Total hypercharge must vanish in the plasma:

$$\sum_i (\mu_{q_i} + 2\mu_{u_i} - \mu_{d_i} - \mu_{\ell_i} - \mu_{e_i} + \frac{2}{N_f} \mu_H) = 0$$

(5) Yukawa interactions are in thermal equilibrium:

$$\mu_{q_i} - \mu_H - \mu_{d_j} = 0$$

$$\mu_{q_i} + \mu_H - \mu_{u_j} = 0$$

$$\mu_{\ell_i} - \mu_H - \mu_{e_j} = 0$$

Sphalerons: conversion of B-L to B asymmetry

All chemical potentials can be expressed in terms of μ_l

$$\mu_e = \frac{2N_f + 3}{6N_f + 3}\mu_l, \quad \mu_d = -\frac{6N_f + 1}{6N_f + 3}\mu_l, \quad \mu_u = \frac{2N_f - 1}{6N_f + 3}\mu_l$$

$$\mu_q = -\frac{1}{3}\mu_l, \quad \mu_H = \frac{4N_f}{6N_f + 3}\mu_l$$

$$B = -\frac{4}{3}N_f\mu_l, \quad L = \frac{14N_f^2 + 9N_f}{6N_f + 3}\mu_l$$

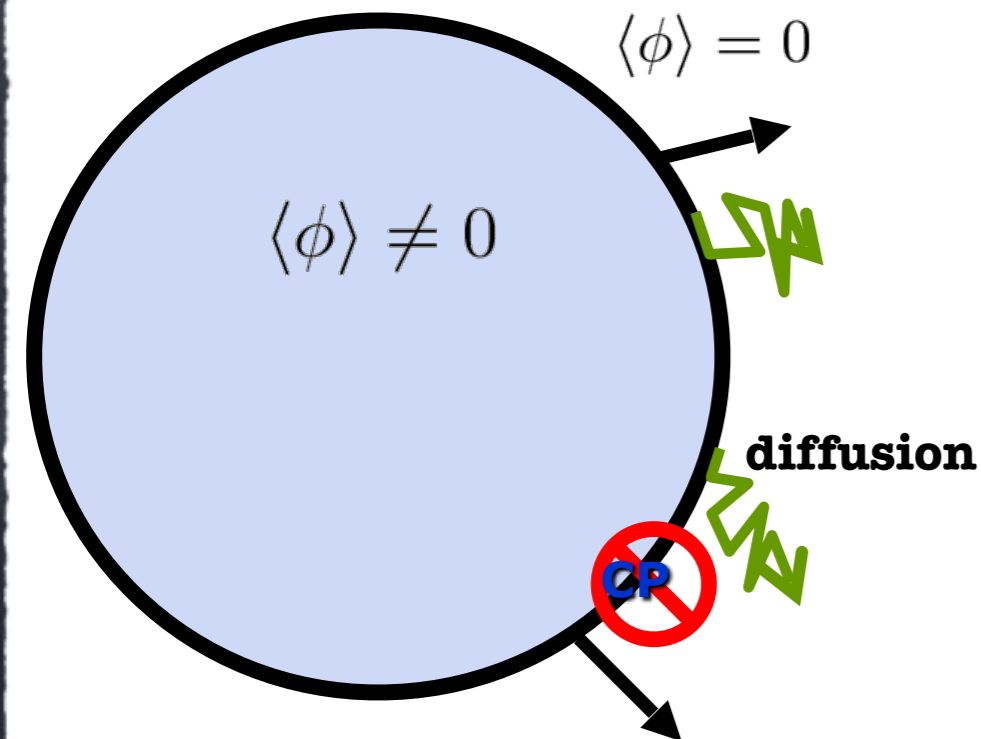
$$B = c(B - L)$$

$$c = \frac{8N_f + 4N_H}{22N_f + 13N_H}$$

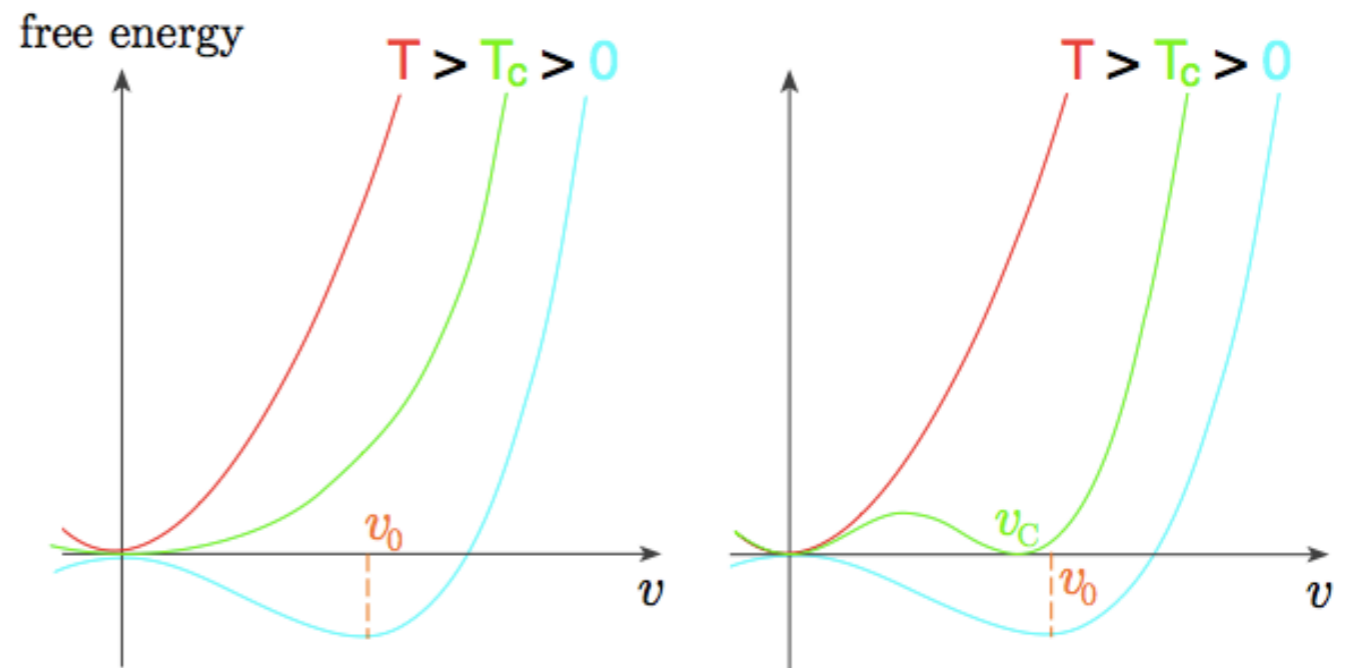
$$L = (c - 1)(B - L)$$

$c = 28/79$ in Standard Model with 3 generations

First order phase transition at the EW scale within Standard Model



moving bubble wall

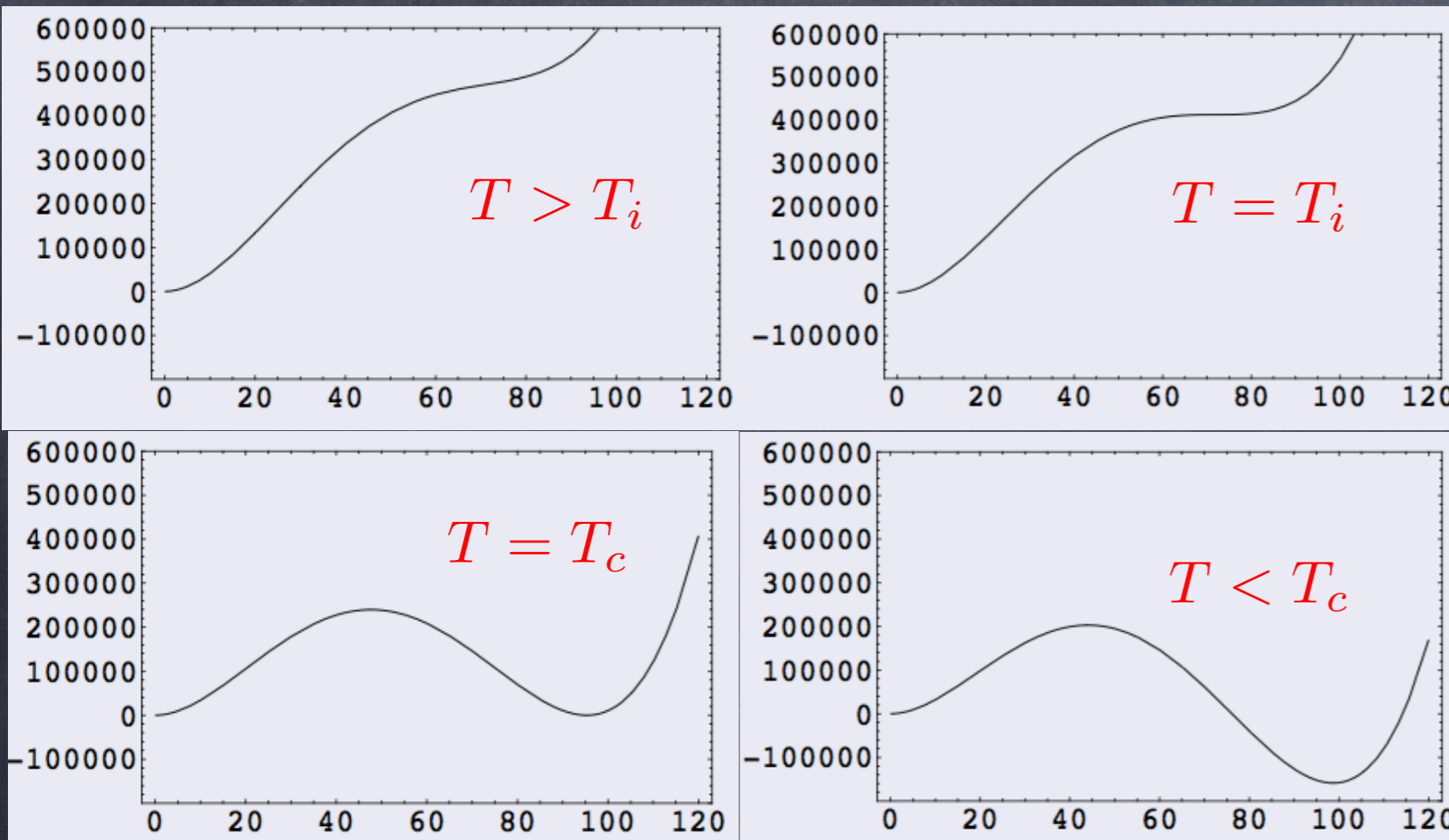


- * Sufficient CP violation
- * Strong 1st order phase transition

$$V_{\text{eff}}(\varphi; T) \simeq D(T^2 - T_0^2)\varphi^2 - ET\varphi^3 + \frac{\lambda_T}{4}\varphi^4$$

At T_C , \exists degenerate minima: $\varphi_C = \frac{2ET_C}{\lambda_{T_C}}$

First order phase transition at the EW scale



$$T_i^2 = \frac{8\lambda_T(T_i)DT_0^2}{8\lambda_T(T_i)D - 9E^2}$$

$$\langle \phi(T_i) \rangle = \frac{3ET_i}{2\lambda_T(T_i)}$$

$$T_c^2 = \frac{\lambda_T(T_c)DT_0^2}{\lambda(T_c)D - E^2}$$

$$\phi_{max, min}(T) = \frac{3ET}{2\lambda_T(T)} \pm \frac{1}{2\lambda_T(T)} \sqrt{9E^2T^2 - 8\lambda_T(T)D(T - T_0^2)}$$

$$\phi_{max}(T_c) = \frac{ET_c}{\lambda_T(T_c)}$$

$$\phi_{min}(T_c) = \frac{2ET_c}{\lambda_T(T_c)}$$

@ $T = T_0$ the barrier disappears

$$\phi_{min}(T_0) = \frac{3ET_0}{\lambda_T(T_0)}$$

Strong 1st order phase transition : $\frac{ET_c}{\lambda_T(T_c)} > 1$

$$\Phi = \begin{pmatrix} \chi_1 + i\chi_2 \\ \frac{\phi_c + h + i\chi_3}{\sqrt{2}} \end{pmatrix}$$

$$V_0(\phi_c) = -\frac{m^2}{2}\phi_c^2 + \frac{\lambda}{4}\phi_c^4 \quad v^2 = \frac{m^2}{\lambda}$$

$$D = \frac{2m_W^2 + m_Z^2 + 2m_t^2}{8v^2}$$

$$m_h^2(\phi_c) = 3\lambda\phi_c^2 - m^2$$

$$m_\chi^2(\phi_c) = \lambda\phi_c^2 - m^2$$

$$m_h^2(v) = 2\lambda v^2 = 2m^2, \quad m_\chi^2(v) = 0$$

$$T_0 = \frac{2m_h^2 - 8Bv^2}{4D}$$

$$m_W^2(\phi_c) = \frac{g^2}{4}\phi_c^2$$

$$E = \frac{2m_W^3 + m_Z^3}{4\pi v^3}$$

$$m_Z^2(\phi_c) = \frac{g^2 + g'^2}{4}\phi_c^2$$

$$B = \frac{3}{64\pi^2 v^4} (2m_W^4 + m_Z^4 - 4m_t^4)$$

$$m_t^2(\phi_c) = \frac{h_t^2}{2}\phi_c^2$$

$$\lambda_T(T) = \lambda - \frac{3}{64\pi^2 v^4} \left(2m_W^4 \log \frac{m_W^2}{A_B T^2} + m_Z^4 \log \frac{m_Z^2}{A_B T^2} - 4m_t^4 \log \frac{m_t^2}{A_F T^2} \right)$$

$$\log A_B = \log a_b - (3/2), \quad \log A_F = \log a_f - (3/2)$$

$$\log a_b = 5.4076, \quad \log a_f = 2.6351$$

Current Status

SM

$$\Gamma_{\text{sph}}^{(\text{br})} < H(T_C) \iff \frac{\varphi_C}{T_C} \gtrsim 1$$

MSSM

$$\frac{2ET_c}{\lambda_T(T_c)} \simeq \frac{4Ev^2}{m_h^2} \geq 1$$

$$m_H = \sqrt{2}\lambda v_0 \leq 46 \text{ GeV}$$

$m_h > 73\text{GeV} \Rightarrow$ PT disappears (crossover)

CP asymmetry is too small
(CKM)

NMSSM ?

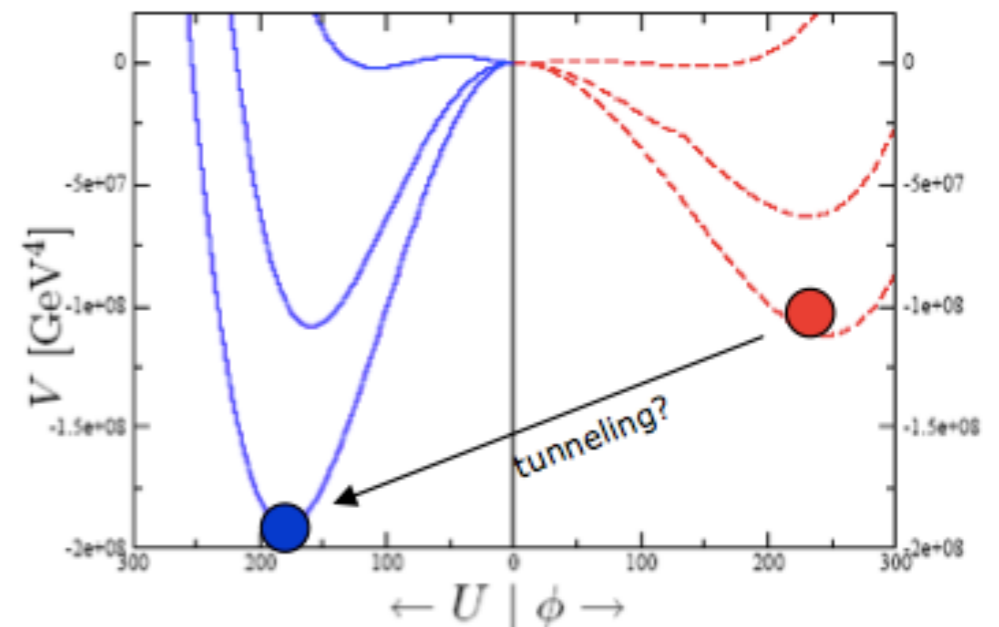
Some of the conditions can be relaxed, specially 1st order transition is relatively easy

Many Bosons, especially Stops
Large cubic coefficient, Strong 1st order phase transition, many sources of CP violations

BUT

RH stop < 125 GeV, LH stop > 6.5 TeV (to avoid color-breaking phase transition) in MSSM

Carena, Nardini, Quiros, Wagner, 2008



ELECTROWEAK BARYON NUMBER NON-CONSERVATION IN THE EARLY UNIVERSE AND IN HIGH ENERGY COLLISIONS

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Abstract

We review recent progress in the study of the anomalous baryon number non-conservation at high temperatures and in high energy collisions. Recent results on high temperature phase transitions are described, and applications to electroweak baryogenesis are considered. The current status of the problem of electroweak instanton-like processes at high energies is outlined. This paper is written on the occasion of Sakharov's 75th anniversary and will memorial volume of Uspekhi (Usp. Fiz. Nauk, volume 166, No 5, May 1996).

MSSM ELECTROWEAK <http://arxiv.org/abs/1207.6330v2> LHC DATA

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ABSTRACT

Electroweak baryogenesis is an attractive scenario for the generation of the baryon asymmetry of the universe as its realization depends on the presence at the weak scale of new particles which may be searched for at high energy colliders. In the MSSM it may only be realized in the presence of light stops, and with moderate or small mixing between the left- and right-handed components. Consistency with the observed Higgs mass around 125 GeV demands the heavier stop mass to be much larger than the weak scale. Moreover the lighter stop leads to an increase of the gluon-gluon fusion Higgs production cross section which seems to be in contradiction with indications from current LHC data. We show that this tension may be considerably relaxed in the presence of a light neutralino with a mass lower than about 60 GeV, satisfying all present experimental constraints. In such a case the Higgs may have a significant invisible decay width and the stop decays through a three or four body decay channel, including a bottom quark and the lightest neutralino in the final state. All these properties make this scenario testable at a high luminosity LHC.

Reviews &
recent activities,
and references therein

arXiv:1207.6330v2 [hep-ph] 30 Jan 2013

arXiv:hep-ph/9603208v2 10 Apr 1996

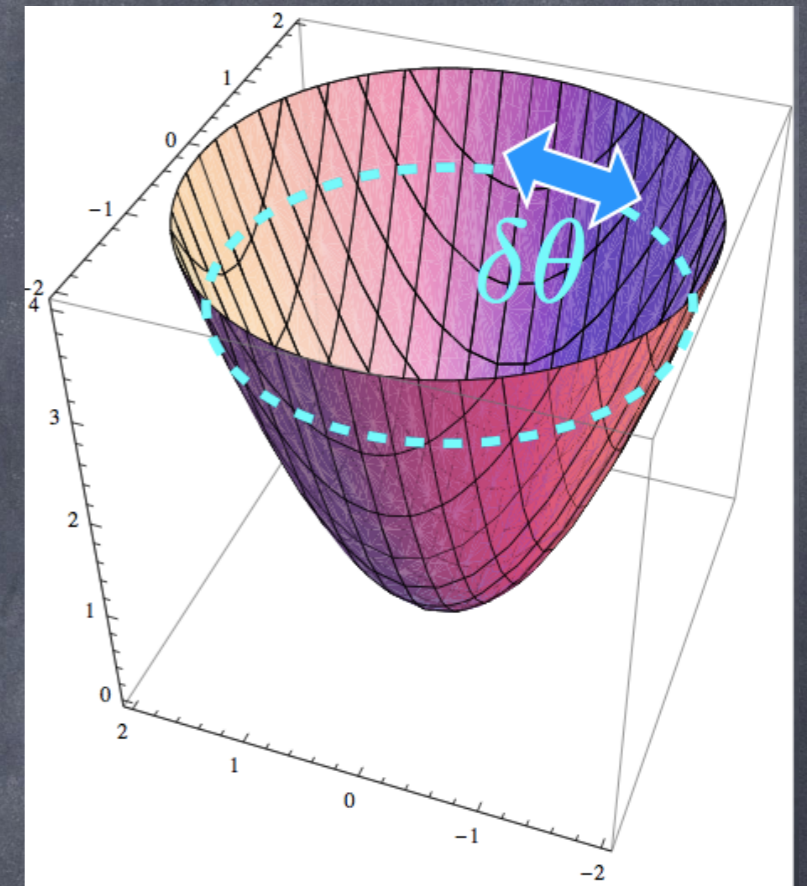
Dynamical generation of baryon number

$$V(\phi) = m^2 |\phi|^2 + \lambda(\phi^4 + \phi^{*4}) + \frac{|\phi|^6}{M^2} + \dots$$

CP is invariant: $\phi \leftrightarrow \phi^*$

Initial condition can break CP

$$\phi = i\phi_0, \quad \dot{\phi} = 0$$



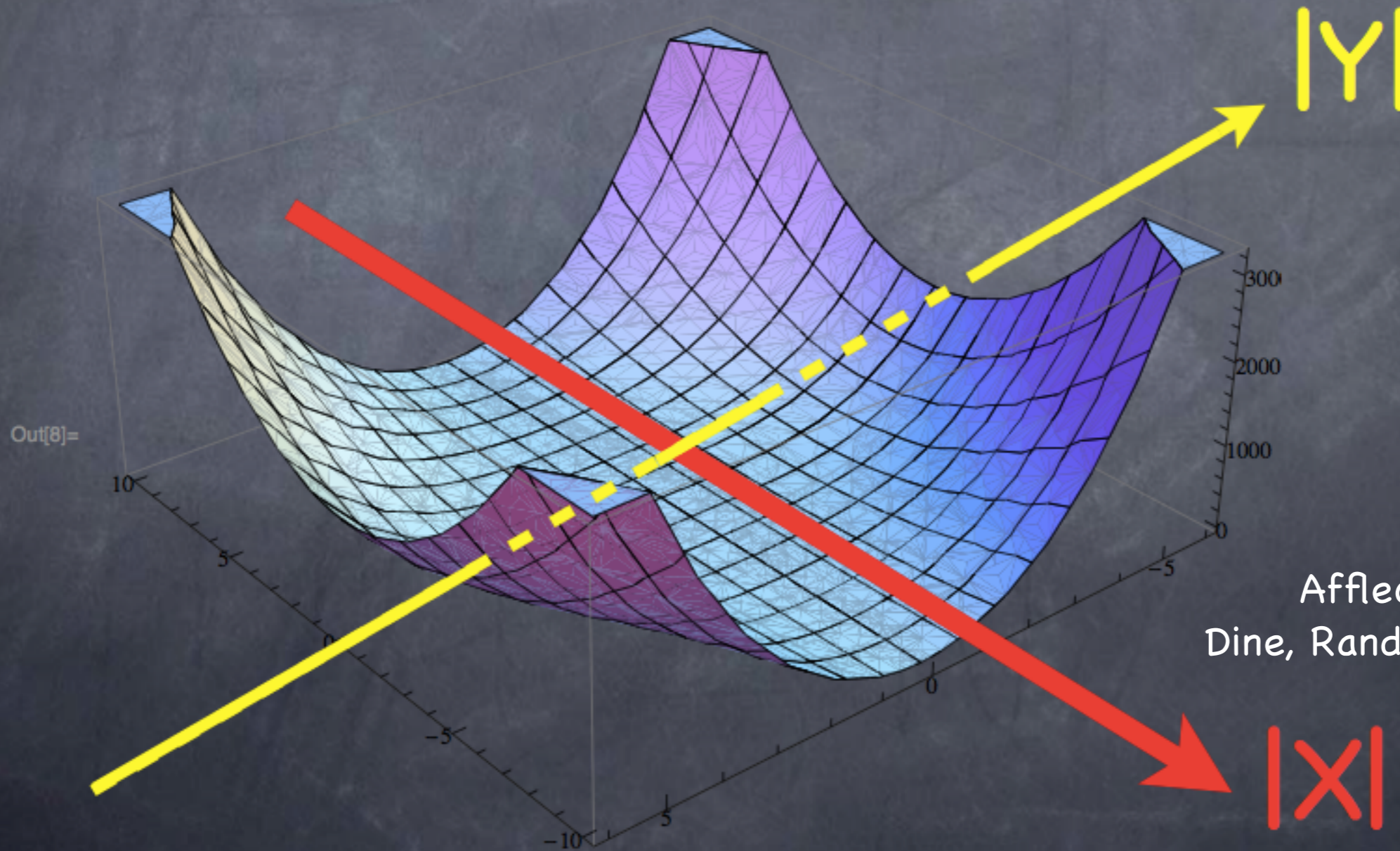
$$\phi_k = \frac{A_k}{mt} \sin(mt + \delta_k). \quad k = I, R$$

$$n_B = 2(\phi_I \dot{\phi}_R - \phi_R \dot{\phi}_I) = \frac{2A_I A_R}{mt^2} \sin(\delta_I - \delta_R)$$

Affleck-Dine Baryogenesis

$$W=XY^2 \longrightarrow V = |Y|^4 + 4|X|^2 |Y|^2$$

The scalar potential vanishes along $|Y|=0$.



Affleck + Dine (84)
Dine, Randall, Thomas (95,96)

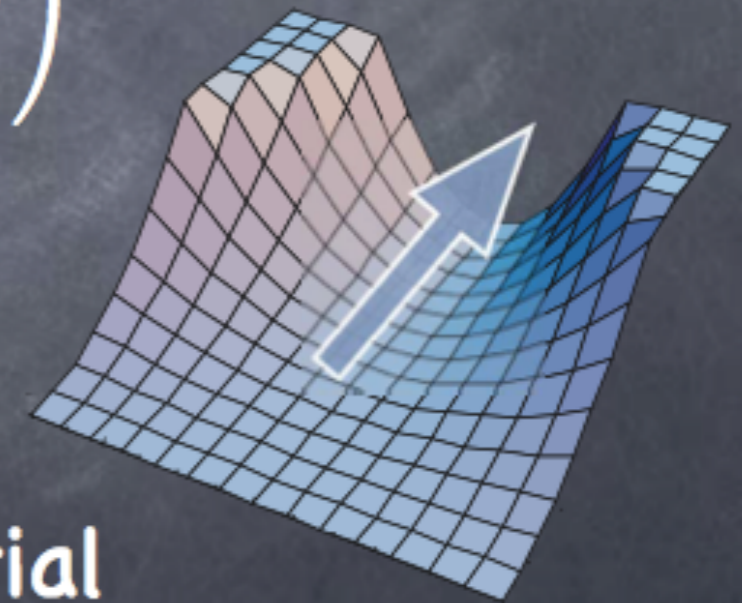
Quantum fluctuations can take large VEVs
along flat direction : it does not cost in energy

Affleck-Dine Baryogenesis/Leptogenesis

In the SSM, there are many flat directions composed of **squarks** and/or **sleptons**. (e.g. udd, eLL)

$$V(\phi) = \sum_i \left| \frac{\partial W}{\partial \phi_i} \right|^2 + \frac{1}{2} \sum_A \left(\sum_{ij} \phi_i^* (t_A)_{ij} \phi_j \right)^2$$

(F-term) (D-term)



Along a flat directions the scalar potential vanishes in the global SUSY limit at the level of renormalizable operators.

Affleck-Dine Baryogenesis

$$W_{\text{NR}} = \frac{\Phi^n}{M^{n-3}} \quad (n = 4 - 9)$$

e.g.) $W = (LH_u)^2, (udd)^2, (eLL)^2$

U(1)-preserving terms

U(1)-breaking terms

$$V(\Phi) = \left(m_{\Phi}^2 - cH^2 \right) |\Phi|^2 + \frac{|\Phi|^{2n-2}}{M^{2n-6}} + \left(a \frac{m_{3/2}}{nM^{n-3}} \Phi^n + \text{h.c.} \right)$$

soft mass

due to
inflaton

non-ren.
operator

A-term:
NR operator
and ~~U(1)~~R

Stabilises the potential

Affleck-Dine Baryogenesis

$$V(\Phi) = (m_{\Phi}^2 - cH^2) |\Phi|^2 + \frac{|\Phi|^{2n-2}}{M^{2n-6}} + \left(a \frac{m_{3/2}}{nM^{n-3}} \Phi^n + \text{h.c.} \right)$$

soft mass

due to inflaton

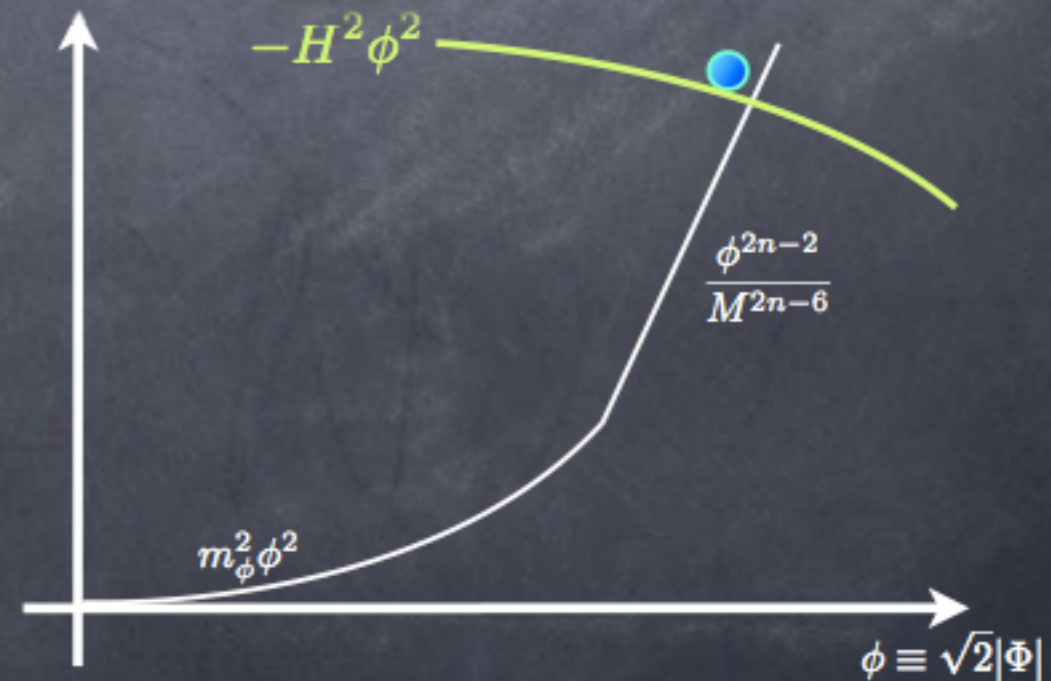
non-ren. operator

A-term:
NR operator
and ~~U(1)R~~

$$\phi \sim (H_I M^{n-3})^{1/(n-2)}$$

e.g.) $\phi \sim 10^{15}$ GeV for

$n = 4$, $H_I = 10^{12}$ GeV, $M = M_P$



$$V(\Phi) = (m_\Phi^2 - cH^2) |\Phi|^2 + \frac{|\Phi|^{2n-2}}{M^{2n-6}} + \left(a \frac{m_{3/2}}{nM^{n-3}} \Phi^n + \text{h.c.} \right)$$

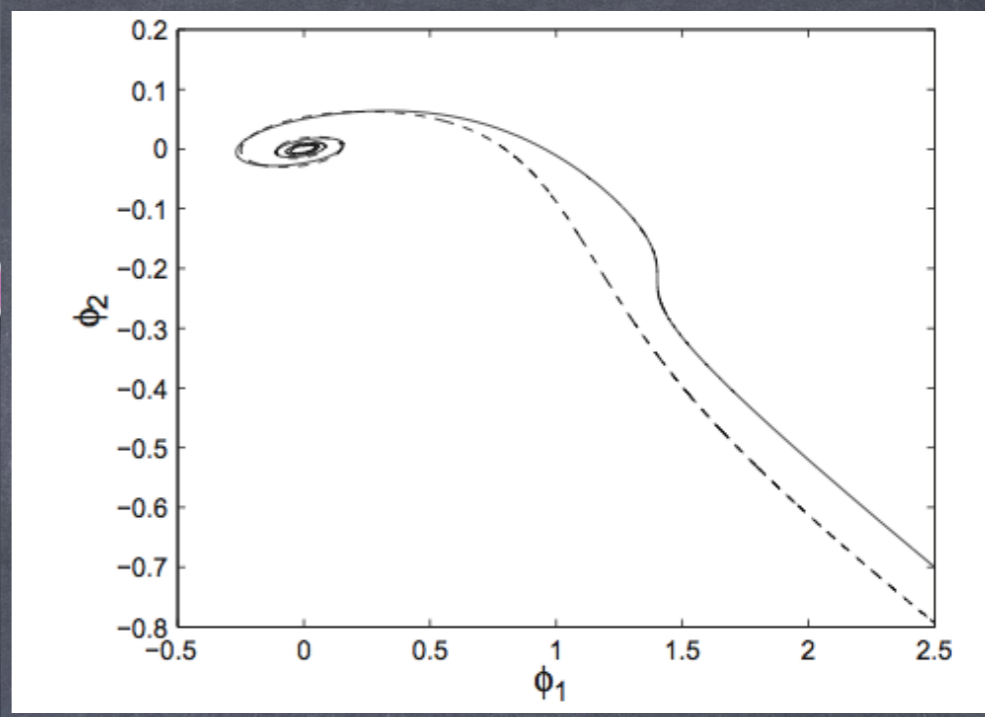
soft mass

due to inflaton

non-ren. operator

A-term: NR operator and $U(1)_R$

The AD field starts to oscillate. Kicked into the phase direction due to the B-number violating term.



$$n_{B,L} = \beta i (\dot{\phi}^* \phi - \phi^* \dot{\phi}) \quad \dot{n}_{B,L} + 3H n_{B,L} = 2\beta \text{Im} \left[\frac{\partial V(\phi)}{\partial \phi} \phi \right] = 2\beta \frac{1}{M_P^{n-3}} \text{Im} [(a_H H + A) \phi^n]$$

$$\frac{n_{B,L}}{s} = \frac{1}{4} \frac{T_R}{M_P^2 H(t_{\text{osc}})^2} n_{B,L}(t_{\text{osc}}) \approx \beta \frac{n-2}{6(n-3)} \frac{T_R}{M_P^2 m_\phi} (m_\phi M_P^{n-3})^{2/(n-2)}$$

$$\frac{n_{B,L}}{s} \approx 10^{-10} \times \beta \left(\frac{1 \text{ TeV}}{m_\phi} \right) \left(\frac{T_R}{10^9 \text{ GeV}} \right)$$

$$\frac{n_{B,L}}{s} \approx 10^{-10} \times \beta \left(\frac{1 \text{ TeV}}{m_\phi} \right)^{1/2} \left(\frac{T_R}{100 \text{ GeV}} \right)$$

A mini review on Affleck–Dine baryogenesis

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Abstract. The Affleck–Dine mechanism is an attractive scenario for generating the observed baryon asymmetry of the universe utilizing flat directions in the scalar potential of supersymmetric theories. In this mini review, we describe this mechanism in its original version, its explicit realization within the minimal supersymmetric standard model and its variants. We discuss the formation of a condensate along the flat directions in the inflationary era, its post-inflationary evolution leading to baryogenesis and its fate. In some cases the condensate may fragment into non-topological solitons, known as Q -balls, during its evolution. In models of gravity-mediated supersymmetry breaking, the Q -balls can be long-lived, in which case their decay will be the source of all baryons and dark matter in the form of the lightest supersymmetric particle. In models of gauge-mediated supersymmetry breaking, the Q -balls can be absolutely stable and form dark matter that can be searched for directly.

Origin of the matter-antimatter asymmetry

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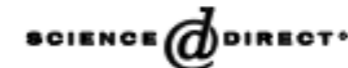
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(Published 16 December 2003)

Although the origin of matter-antimatter asymmetry remains unknown, continuing advances in theory and improved experimental limits have ruled out some scenarios for baryogenesis, for example, sphaleron baryogenesis at the electroweak phase transition in the Standard Model. At the same time, the success of cosmological inflation and the prospects for discovering supersymmetry at the Large Hadron Collider have put some other models in sharper focus. We review the current state of our understanding of baryogenesis with emphasis on those scenarios that we consider most plausible.



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Physics Reports 380 (2003) 99–234

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Cosmological consequences of MSSM flat directions

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Abstract

We review the cosmological implications of the flat directions of the minimally supersymmetric standard model (MSSM). We describe how field condensates are created along the flat directions because of inflationary fluctuations. The post-inflationary dynamical evolution of the field condensate can charge up the condensate with B or L in a process known as Affleck–Dine baryogenesis. Condensate fluctuations can give rise to both adiabatic and isocurvature density perturbations and could be observable in future cosmic microwave experiments. In many cases the condensate is however not the state of lowest energy but fragments, with many interesting cosmological consequences. Fragmentation is triggered by inflation-induced perturbations and the condensate lumps will eventually form non-topological solitons, known as Q -balls. Their properties depend on how supersymmetry breaking is transmitted to the MSSM; if by gravity, then the Q -balls are semi-stable but long-lived and can be the source of all the baryons and LSP dark matter; if by gauge interactions, the

Reviews &
recent activities,
and references therein

Thermal Leptogenesis

“Baryogenesis Without Grand Unification”, Phys.Lett.B174:45,1986,
by Fukugita and Yanagida.

BARYOGENESIS WITHOUT GRAND UNIFICATION

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Received 1 March 1986

A mechanism is presented to generate cosmological baryon number excess without resorting to grand unified theories. The baryon number excess originating from Majorana mass terms may transform into the baryon number excess through the unquenched baryon number violation of electroweak processes at high temperatures.

The current view attributes the origin of cosmological baryon excess to the macroscopic baryon number violation process in the early stage of the Universe [1,2]. The grand unified theory (GUT) of particle interactions is regarded as the standard candidate to account for the baryon number violation. The theory can give the correct order of magnitude for baryon-to-entropy ratio, if the Universe undergoes the inflation epoch after the baryogenesis, however, generated baryon numbers are diluted by a huge factor. The reheating after the inflation is unlikely to raise the temperature above the GUT energy scale. A more serious problem is that no evidence is given so far experimentally for the baryon number violation, which might give some death on the GUT side.

Some time ago, Bilench suggested that the instanton-like effect violates baryon number in the Weinberg-Salam theory through the anomaly term, although the effect is suppressed by a large factor [3]. It has been pointed out, however, that this effect is not important and can be efficient at high temperatures above the Weinberg-Salam energy scale [4]. This baryon number violating process conserves $B - L$, but it cannot explain the baryon asymmetry which would have been generated at the early Universe with $B - L$

violating baryon number violation processes in the standard SU(3) GUT. (Baryon number would remain, if the baryon production takes place at low temperatures $T \ll O(100 \text{ GeV})$, e.g., after reheating [7,8].) The process itself can not produce the baryon asymmetry, since it is unlikely to appear a particular mechanism leading to departure from equilibrium [9].

In this letter, we point out that the electroweak baryon number violation process, if it is supplemented by a lepton number generation at an earlier epoch, can generate the cosmological baryon asymmetry without resorting to the GUT scenario. The lepton number excess in the earlier stage can effectively be transformed into the baryon number excess, if a rather easy to find an agent leading to the lepton number generation. A candidate is the decay process involving Majorana mass terms.

Let us present a specific model which gives lepton number generation. We assume the presence of a right-handed Majorana neutrino N_R^i ($i = 1, \dots, n$) in addition to the conventional leptons. We take the Lagrangian to be

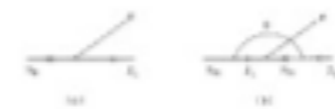


Fig. 1. The explicit diagram corresponding to a net lepton number production. The cross denotes the Majorana mass insertion.

$$\mathcal{L} = \bar{L}_i \gamma_\mu D_\mu L_i + \bar{N}_i \gamma_\mu D_\mu N_i + h.c. + \frac{1}{2} \bar{N}_i M_{ij} N_j + \dots \quad (1)$$

where L_{ij} is the standard Weinberg-Salam lepton, and N_i the standard Majorana doublet. For simplicity we assume three generations of fermions and the mass hierarchy $M_1 \ll M_2 \ll M_3$ in the decay of N_3 .

$$N_3 \rightarrow \nu_e + e, \quad (2a)$$

$$N_3 \rightarrow \bar{\nu}_e + \bar{e}, \quad (2b)$$

there appears a difference between the branching ratios for (2a) and (2b), if CP is violated, through the one-loop radiative correction by a Higgs particle. The net lepton number production due to the decay of a lightest right-handed neutrino N_R^i arises from the interference of the two diagrams in fig. 1, and its magnitude is calculated as [7]

$$\epsilon = (2/\pi) \text{Im}(\bar{h}_{31} h_{11}^2 h_{21}^2 / M_1 M_2 M_3) \quad (3)$$

with

$$h_{ij} = \bar{L}_i \gamma_\mu N_j / (M_j M_i) \quad (4)$$

If we assume h_{ij} to be the largest entry of the Yukawa coupling matrix and $M_3 \gg M_2$, (3) reduces to

$$\epsilon = (2/\pi) \text{Im}(h_{21}^2 / M_1 M_2 M_3) \quad (5)$$

with δ the phase causing CP violation.

We apply the delayed decay mechanism [9] to generate the baryon asymmetry in the Universe. The out-of-equilibrium condition is satisfied, if the temperature T is smaller than the mass M_3 , so that the inverse decay is blocked at the time when the decay rate $\Gamma = (M_3^2/4\pi) \text{Im}(h_{21}^2)$ is equal to the expansion rate of the Universe $H = 1.7 \times 10^4 T^2 / (m_{\text{pl}} \text{ eV})$ = number of degrees of freedom, i.e.,

$$(2/\pi) \text{Im}(h_{21}^2) / T \leq M_3 \quad (6)$$

To obtain numerical factors for this condition, one has to solve the Boltzmann equations. Let us however the results of ref. [9] to obtain a rough number. The lepton number-to-entropy ratio is given as

$$\epsilon(\Delta L)_i / s = 10^{-2} K^{-1/2} \quad (7)$$

with $K = \int \Gamma(t) dt$ for $K > 1$. The parameter in (6) and in the expression of Γ are not directly constrained by low-energy experiments. One may have an idea, however, on the mass scale M_3 as follows. With the parameter in a reasonable range, one may obtain a $\leq 10^{-8}$. Thus to obtain our required number for $\epsilon(\Delta L)_i / s = 10^{-10/2}$ (see below), $K \leq 10$ is necessary, which gives $M_3 \geq 2.4 \times 10^{10} \text{ GeV}$ (see ref. [10]). If we assume $(h_{21})^2 \sim (h_{11})^2 \sim (h_{31})^2$ and take $(M_3)_{\text{pl}} = (M_{\text{pl}})^2 \sim (10^{16})^2$, then we are led to $M_3 \geq 2 \times 10^9 \text{ GeV}$. This constraint can also be expressed in terms of the left-handed Majorana neutrino mass m^* as $m^*_{\text{pl}} = m^*/(4\pi^2) M_3 \leq 0.1 \text{ eV}$. If the lightest left-handed neutrino has a Majorana mass smaller than this value, the required asymmetry can be generated.

Now let us discuss the generation of the baryon asymmetry. In the presence of an instanton-like electroweak effect the baryon asymmetry changes as [4]

$$\Delta(B-L) = \frac{1}{2} \Delta(B-L) + \frac{1}{2} \Delta(B-L) \exp(-5). \quad (8)$$

with $\gamma = T$. At the time of the Weinberg-Salam epoch the expansion is $m_{\text{pl}} T^2 \sqrt{g} = 10^{16}$ and the second term practically vanishes. Therefore we obtain

$$\Delta(B-L) = -5 \Delta L / 2, \quad (9)$$

which survives up to the present epoch, and should give $\Delta(B-L) = 10^{-10/2}$.

¹¹ If we present the dimension of the diagonal matrix elements. More generally speaking, the matrix element is considered by an anomaly differentiation that which appears in the chiral anomaly term. The left-handed neutrino mass matrix is given by $(M_{L_i})_{ij} = \frac{1}{2} \bar{L}_i \gamma_\mu N_j / M_j$ [11]. The doublet fermion eigenstates possess the matrix element $(M_{L_i})_{ij} = \bar{L}_i \gamma_\mu (N_j + \nu_j) / M_j$, while ν_j is either $(\nu_j)^T + \nu_j + \nu_j \gamma_5 / 2 M_j$ or $\nu_j \gamma_5 / 2 M_j$ and ν_j is a fermion. When to take the form where the chiral lepton mass term is Majorana. Therefore, the doublet fermion eigenstates do not conserve lepton number as eq. (1). The reason why they represent anomalies is the appearance of the mass matrix $(M_{L_i})_{ij}$ in (11).

A potential lepton number excess created before the epoch of the right-handed neutrino mass scale should have been washed out by the equilibrium of process (2) and an inverse process, if the Yukawa coupling $(M_3^2/4\pi) \text{Im}(h_{21}^2)$ is large enough. The equilibrium condition $\Gamma_{\text{eq}} \approx \Gamma_{\text{inv}} \approx 1.7 \times 10^4 T^2 / (m_{\text{pl}} \text{ eV}) = 2$ or 10 leads to a constant number $\epsilon(\Delta L)_i / s = 2$ or 10 both to a constant number $\epsilon(\Delta L)_i / s$ with the inequality reversed. The net baryon number destruction factor behaves as $\sim \text{Im}(h_{21}^2) \sim 10^{10} / M_3$. For $K \geq 10^{-10}$, the equilibrium practically erases the whole pre-existing lepton number excess. This condition is expressed as $(M_3)_{\text{pl}} \geq 0.1 \text{ eV}$ for the largest entry of the Yukawa mass matrix.

In the presence of unquenched anomalous electroweak effects, the lepton number equilibrium implies that the baryon excess which existed at the epoch should also be washed out, even if it was produced in the process with $B - L \neq 0$. Namely, if there are interactions with the Majorana mass matrix $\sim 0.1 \text{ eV}$ both baryon and lepton numbers which existed before the epoch are washed out completely of their $B - L$ properties.

In summary, we have the following possible scenarios for the cosmological baryon number excess: (i) At a temperature above the mass scale M (scale of right-handed Majorana neutrino), we started with $\Delta(B-L) \neq 0$. (The asymmetry scenario would give the usual conditions.) Thus the lepton number is generated through the Majorana mass term, and is transformed into the baryon number due to the unquenched instanton-like electroweak effect.

(ii) At the scale $\sim M$, baryon and lepton numbers are generated by the grand unification, or alternatively we start with $\Delta(B-L) \neq 0$. (The equilibrium of N_R^i , ν_j , $\nu_j + \nu_j \gamma_5$ together with the electroweak process washes out both baryon and lepton numbers. Thus the baryon number is newly generated by the out-of-equilibrium scenario, and it remains into the baryon number.)

(iii) The baryon number with $B - L \neq 0$ is generated by the grand unification (i.e., the SU(5) model [12]). If the scale M is too large to establish the equilibrium of N_R^i and $\nu_j + \nu_j \gamma_5$, then the initial $\Delta(B-L) \neq 0$ will not be erased. The electroweak process does not affect $B - L$, and hence the usual baryon

number remains. This case is the original GUT baryon number generation scenario. To achieve this, however, all neutrino mass matrix elements (Majorana mass) should be smaller than $\sim 0.1 \text{ eV}$. If the doublet fermion eigenstates would possess a Majorana mass greater than this value, the scenario fails.

In conclusion we have suggested a mechanism of cosmological baryon number generation without resorting to grand unification. In our scenario the cosmological baryon number can be generated, even if particle decay does not happen at all.

One of us (M.F.) would like to thank V.A. Rubakov for discussions on baryon number nonconservation in electroweak processes.

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Connecting Neutrino masses and Lepton asymmetry

Dirac vs Majorana

$$\bar{\psi}\psi \quad \text{vs.} \quad \psi^T C^{-1} \psi$$

$\psi \rightarrow e^{i\alpha}\psi$: $U(1)$ symmetry : $U(1)_{em}$

e, μ, q, \dots are Dirac,
because $Q_e \neq 0$

Dirac ν : $\nu \neq \bar{\nu}$

(Exact lepton number symmetry)

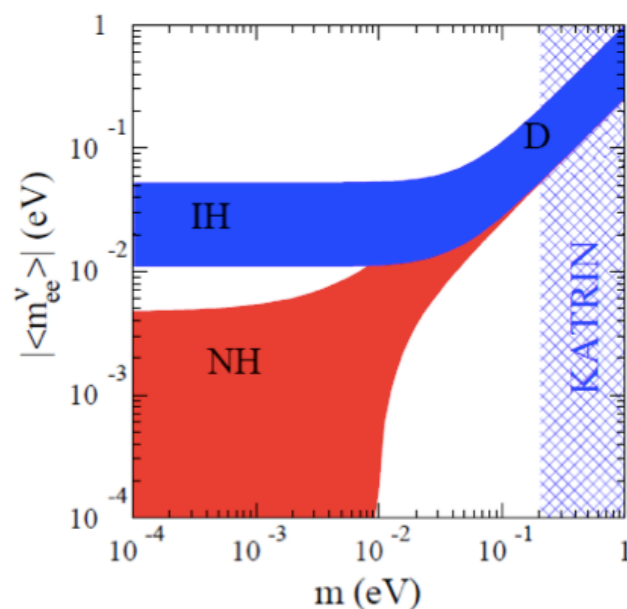
$Q(\nu) = 0$, $U(1)_{em}$ does not
impose ν to be Dirac

Majorana ν : $\nu = \bar{\nu}$

(Lepton number violated)

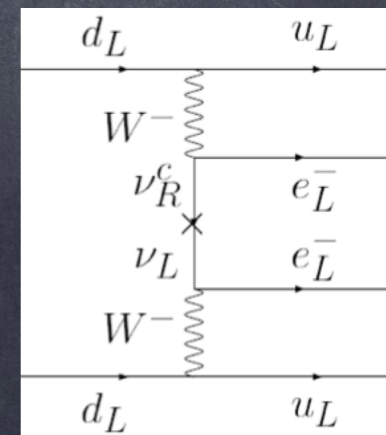
Neutrinoless double beta decay : Majorana

Neutrino: $(A, Z) \rightarrow (A, Z + 2) + e^- + e^-$ (allowed)



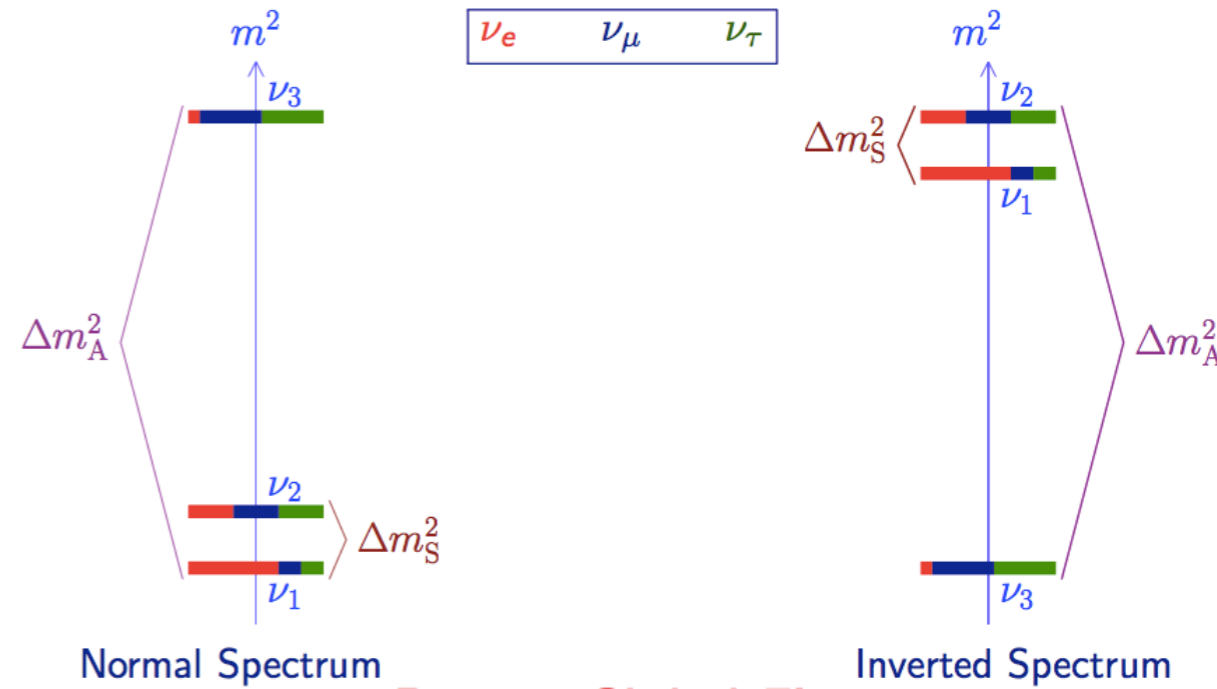
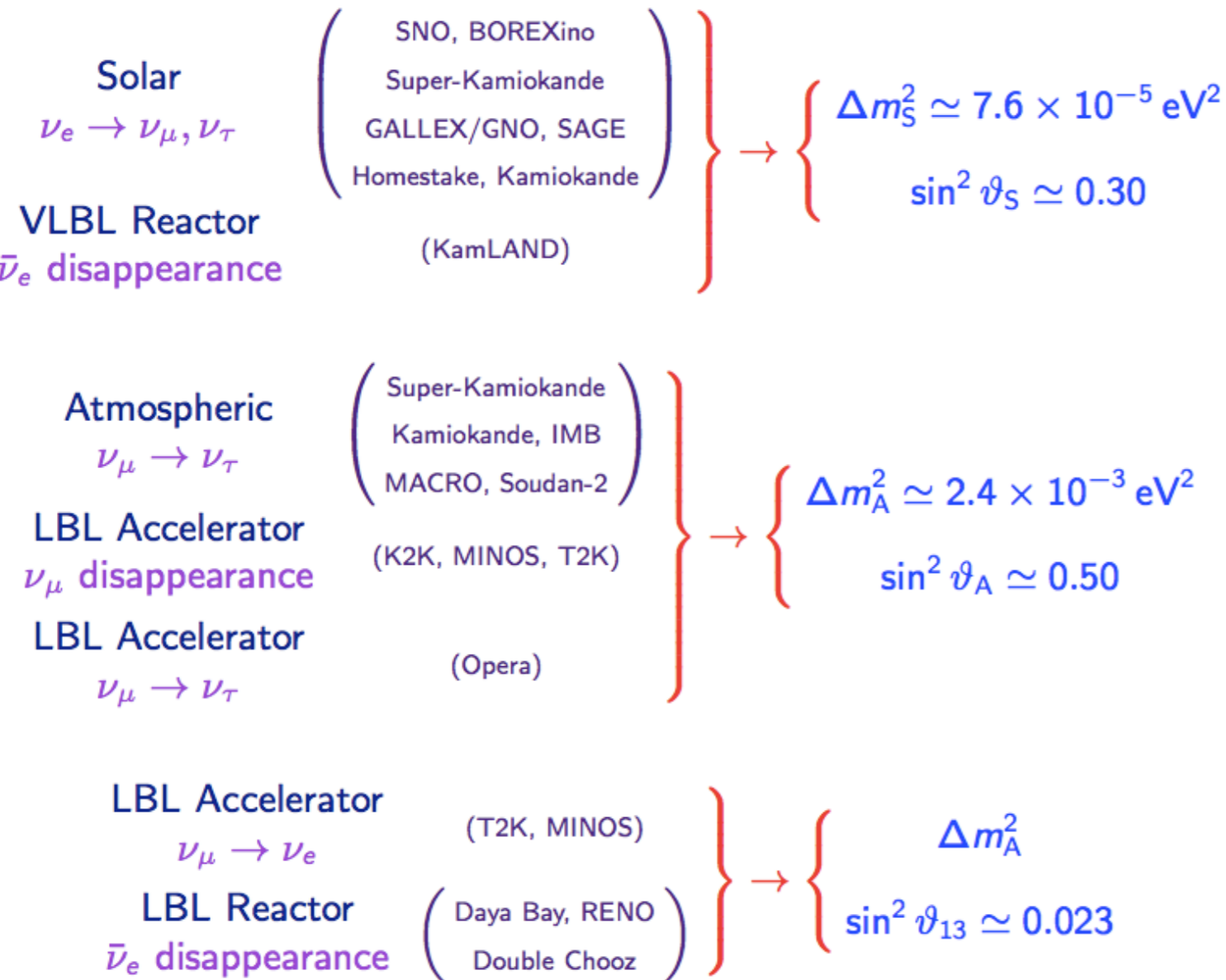
Bahcall, Murayama
Peña-Garay

The rate of $0\nu 2\beta$ depends crucially on the spectrum. If neutrinos are degenerate or inverse hierarchical, $0\nu 2\beta$ could be observed in the next generation of experiments (CUORE, GERDA...)



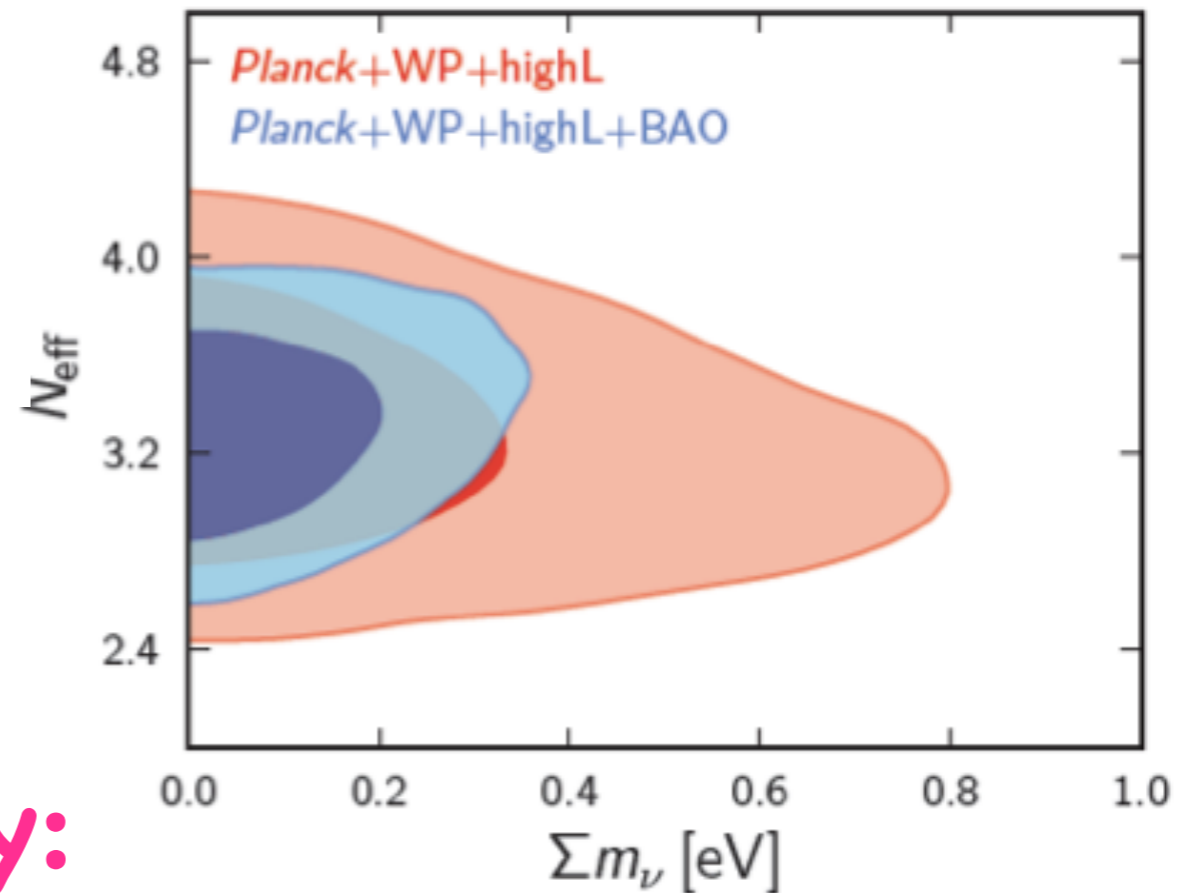
$$\tau_d \sim 10^{24} - 10^{25} \text{ Years}$$

Neutrino mass constraints



Tritium beta decay : $m_{\nu_e} \leq 2 \text{ eV}$ (95%C.L.)

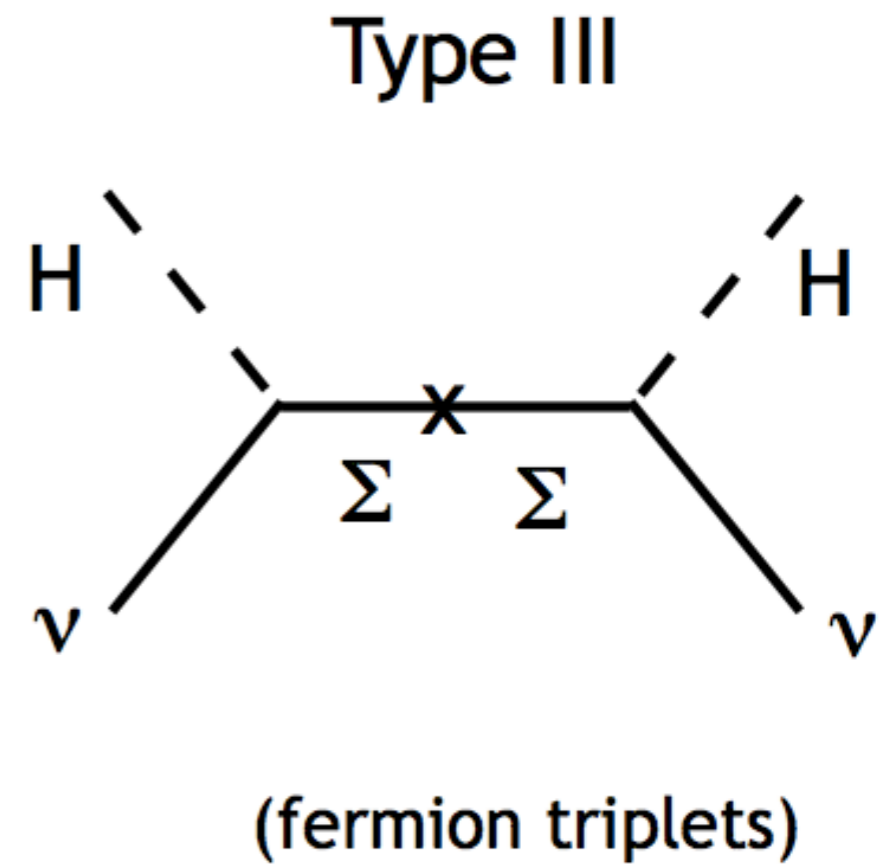
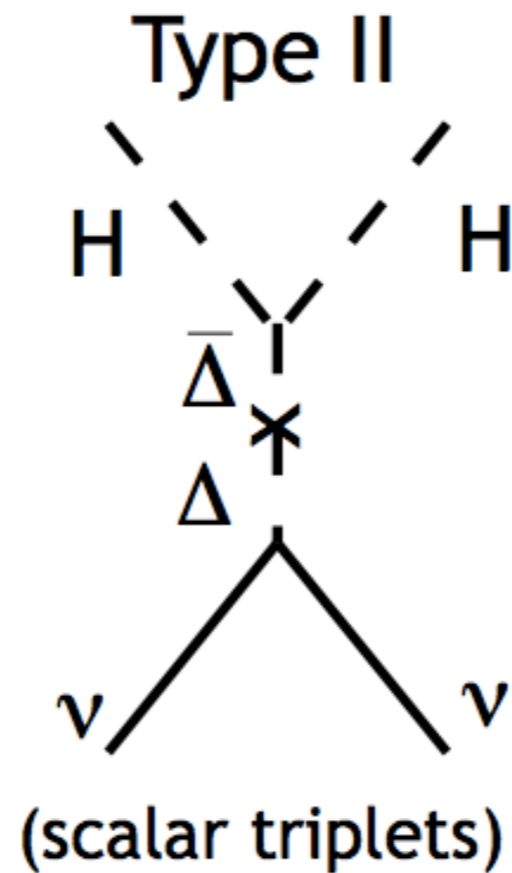
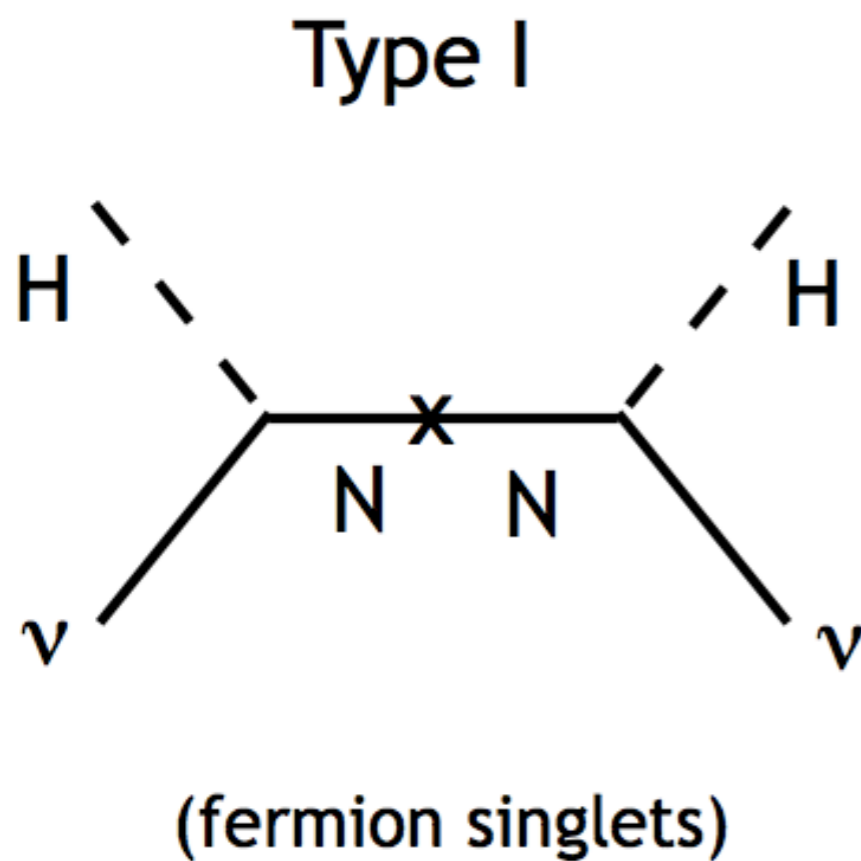
$(0\nu\beta\beta)$ experiments : $m_{\nu_e} \leq 0.34 - 0.78$ (95%C.L.)



Cosmology:

Origin of Neutrino masses

See-Saw mechanism



Type-1 See-Saw mechanism

Gell-Mann, Ramond, Slansky; Yanagida; Glashow; Mohapatra, Senjanović

$$\nu_e, \nu_\mu, \nu_\tau, \nu_{s,1}, \nu_{s,2}, \dots, \nu_{s,N}$$

$$\mathcal{L} = \mathcal{L}_{SM} + \bar{\nu}_{s,a} (i\partial_\mu \gamma^\mu) \nu_{s,a} - y_{\alpha a} H \bar{L}_\alpha \nu_{s,a} - \frac{M_{ab}}{2} \bar{\nu}_{s,a} \nu_{s,b} + h.c.$$

$\alpha = e, \mu, \tau$

$$M = \begin{pmatrix} 0 & D_{3 \times N} \\ D_{N \times 3}^T & M_{N \times 3} \end{pmatrix} \quad D_{ij} = y_{ij} \langle H \rangle \quad (\text{in the SM})$$

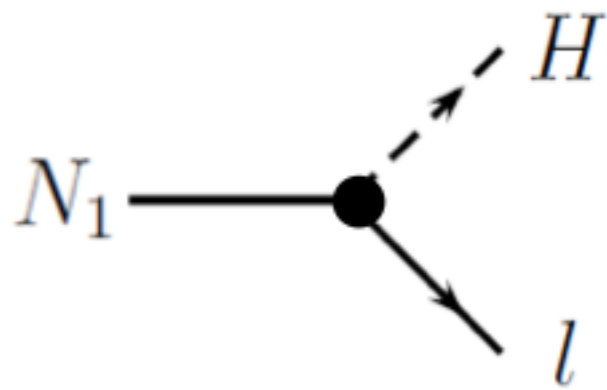
Small neutrino mass may not always imply small Yukawa



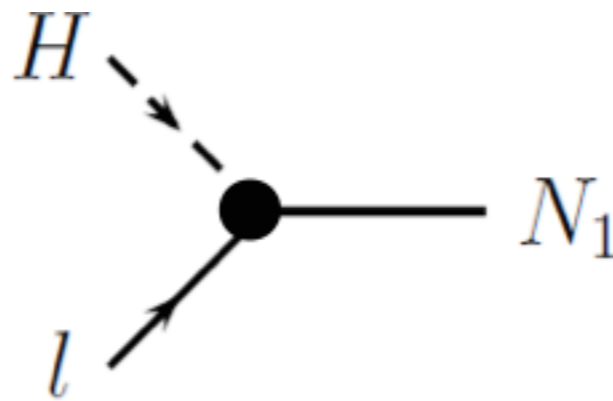
Thermal Leptogenesis

$$\mathcal{L}_N = YNHL + MNN$$

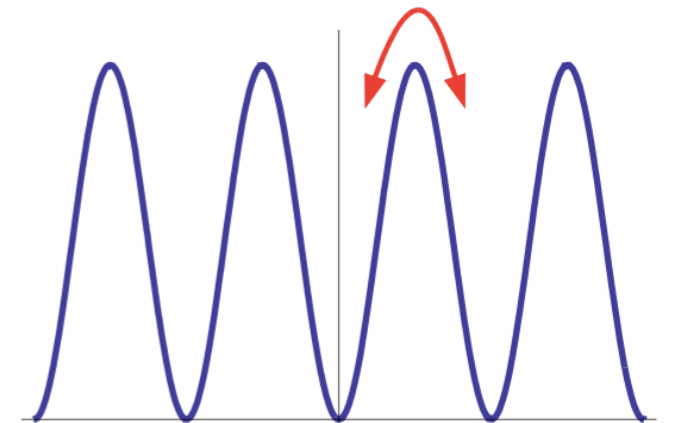
Decay



Wash out



Sphalerons

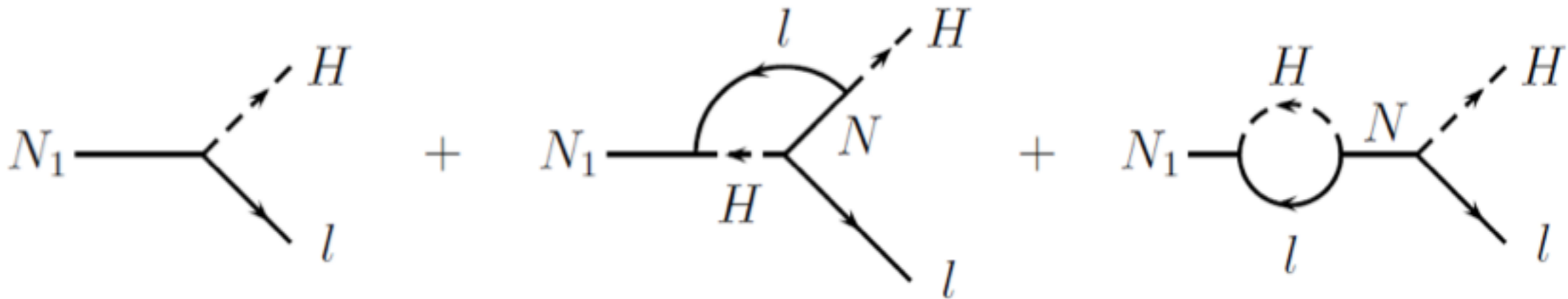


$$\Gamma_{\text{tot}} = \Gamma(N_1 \rightarrow lH) + \Gamma(N_1 \rightarrow l^c H^c) = \frac{1}{8\pi} (h_\nu h_\nu^\dagger)_{11} M_1$$

$$\epsilon_1 = \frac{\Gamma(N_1 \rightarrow lH) - \Gamma(N_1 \rightarrow l^c H^c)}{\Gamma(N_1 \rightarrow lH) + \Gamma(N_1 \rightarrow l^c H^c)} = 0$$

No CP asymmetry

Thermal Leptogenesis



$$\epsilon_1 = \frac{\Gamma(N_1 \rightarrow lH) - \Gamma(N_1 \rightarrow l^c H^c)}{\Gamma(N_1 \rightarrow lH) + \Gamma(N_1 \rightarrow l^c H^c)}$$

$$\approx \frac{1}{8\pi} \frac{1}{(h_\nu h_\nu^\dagger)_{11}} \sum_{i=2,3} \text{Im} \left[(h_\nu h_\nu^\dagger)_{1i}^2 \right] \left[f\left(\frac{M_i^2}{M_1^2}\right) + g\left(\frac{M_i^2}{M_1^2}\right) \right]$$

Yukawa has to be complex

Vertex correction :

$$f(x) = \sqrt{x} \left[1 - (1+x) \ln \left(\frac{1+x}{x} \right) \right]$$

Wavefunction renormalisation :
calculable only when

$$g(x) = \frac{\sqrt{x}}{1-x}$$

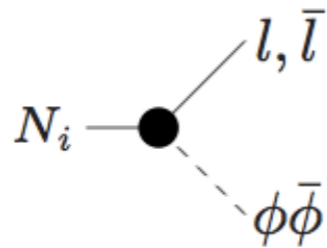
$$|M_i - M_1| \gg |\Gamma_i - \Gamma_1|$$

Resonant enhancement if the masses are degenerate !

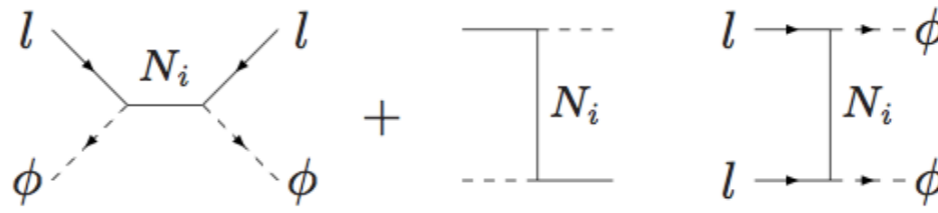
Departure from thermal equilibrium

decays (D), inverse decays (ID)

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



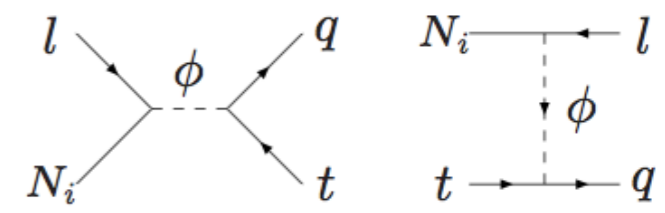
$\Delta L = 2$ processes (N_i virtual)



$$l \bar{\phi} \leftrightarrow \bar{l} \phi \quad (N)$$

$$\begin{aligned} ll &\leftrightarrow \phi \phi \\ \bar{l}\bar{l} &\leftrightarrow \bar{\phi} \bar{\phi} \end{aligned} \quad (N, t)$$

$\Delta L = 1$ processes (N_i real)



$$\begin{aligned} N_i l &\leftrightarrow \bar{t} q \\ &(\phi, s) \end{aligned}$$

$$\begin{aligned} N_i t &\leftrightarrow \bar{l} q \\ &(\phi, t) \end{aligned}$$

Evolve the number density in a co-moving volume

$$\frac{dN_1}{dz} = -(D + S)(N_{N_1} - N_{N_1}^{eq})$$

$$z = \frac{M_1}{T}, \quad D = \frac{\Gamma_D}{Hz} \quad (\text{Decay rate}), \quad S = \frac{\Gamma_S}{Hz} \quad (\text{Scattering rate})$$

$$\frac{dN_{B-L}}{dz} = -\epsilon_1 D(N_{N_1} - N_{N_1}^{eq}) - W N_{B-L}$$

Competition between decay, inverse decay, scattering and washout effects

$$W = \frac{\Gamma_W}{Hz} \quad (\text{Washout rate})$$

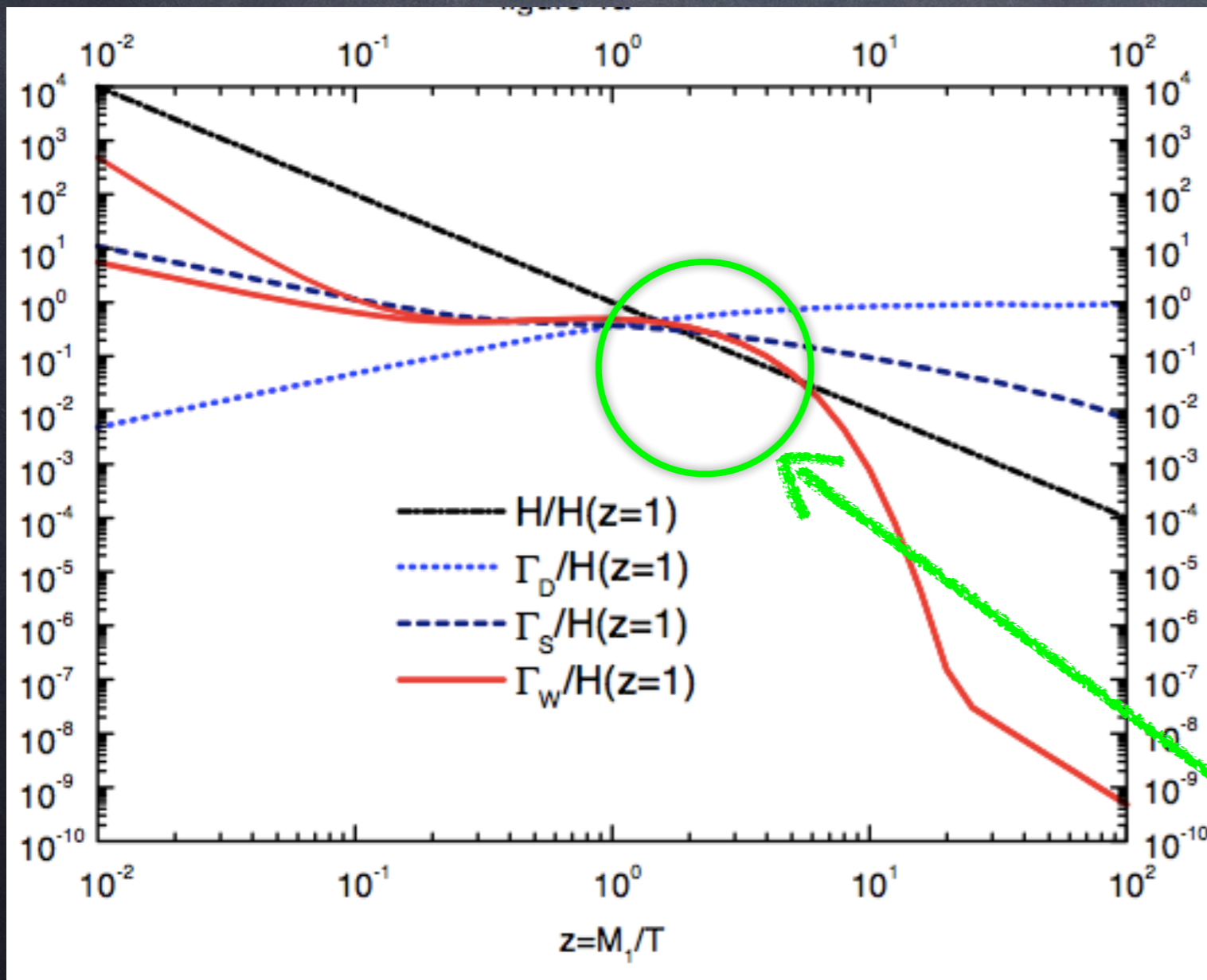
Decay parameter

$$K = \frac{\Gamma_{D_1}|_{T=0}}{H|_{T=M_1}} = \frac{\frac{1}{8\pi}(hh^\dagger)_{11}M_1}{1.66g_*^{1/2}\frac{M_1^2}{M_P}} = \frac{(hh^\dagger)_{11}\frac{v^2}{M_1}}{8\pi 1.66g_*^{1/2}\frac{v^2}{M_P}} = \frac{\tilde{m}_1}{m_*}$$

Effective
neutrino mass

Equilibrium
neutrino mass

Reaction rates of various parameters



$$m_* \simeq 10^{-3} \text{ eV}$$

$$H(T) = 1.66g_*^{1/2} \frac{T^2}{M_p}$$

$$M_1 = 10^{10} \text{ GeV}, \quad \tilde{m}_1 = 10^{-3} \text{ eV},$$

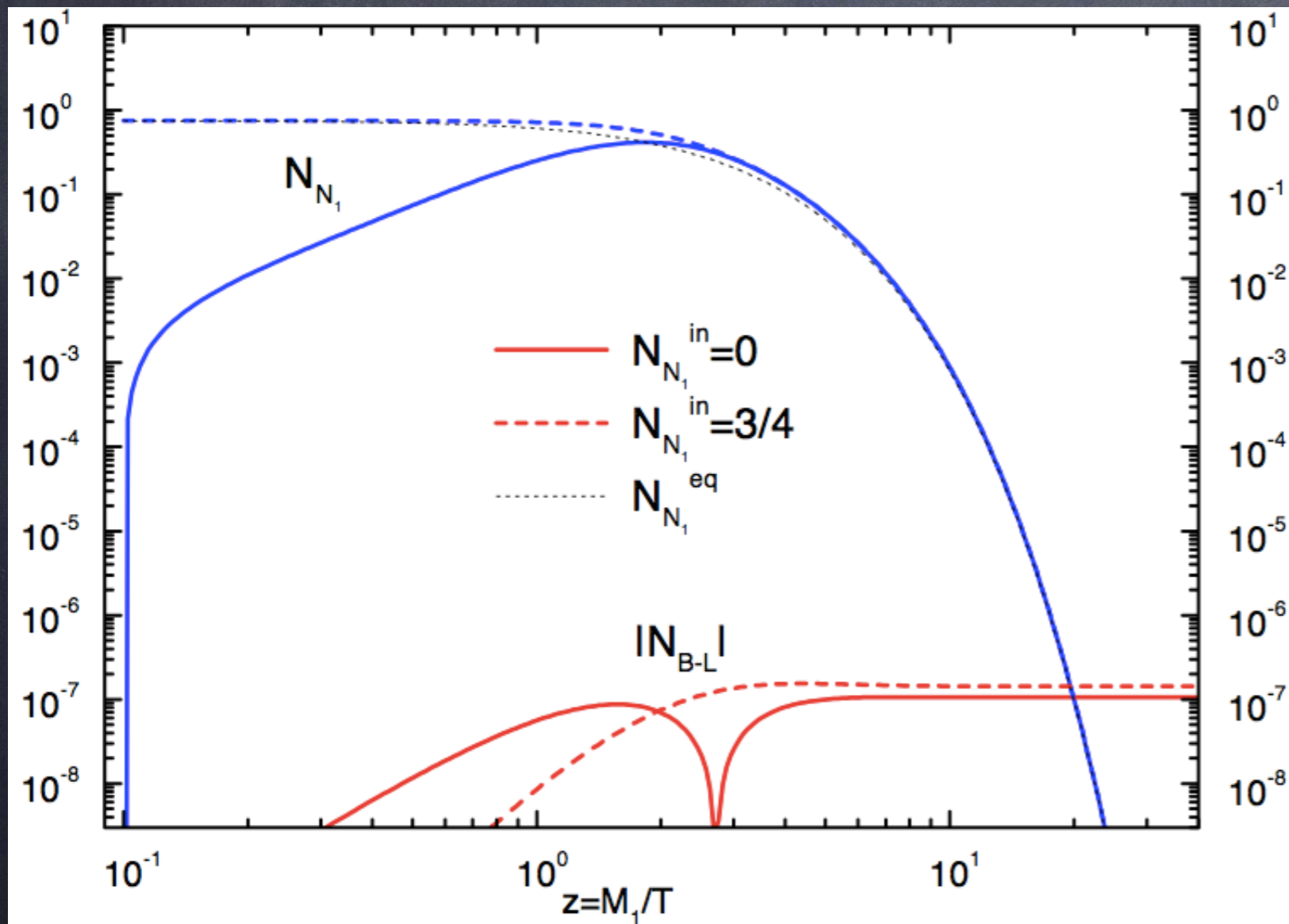
$$\bar{m} = \sqrt{m_{\nu 1}^2 + m_{\nu 2}^2 + m_{\nu 3}^2} = 0.05 \text{ eV}$$

Out of Equilibrium :

$$T \simeq M_1, \quad \tilde{m}_1 \simeq m_*$$

Evolution of B-L

For different initial conditions : zero initial abundance, and thermal abundance



Yukawa interactions are strong enough to bring the heavy neutrinos in thermal equilibrium

$$M_1 = 10^{10} \text{ GeV}, \quad \tilde{m}_1 = 10^{-3} \text{ eV},$$

$$\bar{m} = \sqrt{m_{\nu 1}^2 + m_{\nu 2}^2 + m_{\nu 3}^2} = 0.05 \text{ eV}$$

$$|\epsilon_1| = 10^{-6}$$

Observed asymmetry: $\eta_B \simeq 10^{-3} \times N_{B-L} \sim 10^{-10}$

Key conditions

(1) Initial abundance of right handed neutrinos:

$$N_{N_1}^{in} = 0, \quad \text{or} \quad N_{N_1}^{in} = 3/4$$

(2) Decay parameter: $K = \frac{\Gamma_D(z = \infty)}{H(z = 1)} = \frac{\tilde{m}}{m_*}$ (3) CP asymmetry: ϵ

$$K \ll 1$$

Far out of equilibrium, $z \gg 1$

Weak washout regime : initial B-L asymmetry is not washed out

$$K \gg 1$$

Strong washout regime: final B-L asymmetry is independent of the initial condition

Beyond Vanilla Thermal

Leptogenesis

Flavour effects in heavy RH neutrino sector, and in lepton sector

Resonant Enhancements of CP phase:
One can realize leptogenesis close to TeV scale

Non-thermal leptogenesis
Dirac leptogenesis

S. Davidson, E. Nardi and Y. Nir, *Phys. Rept.* 466, 105 (2008) [arXiv: 0802.2962 [hep-ph]]

A. Pilaftsis and T.E.J. Underwood, *Electroweak-scale resonant leptogenesis*, *Phys. Rev. D* 72, 113001 (2005) [hep-ph/0506107].

W. Buchmüller, P. Di Bari and M. Plumacher, *Leptogenesis for pedestrians*, *Annals Phys.* 315, 305 (2005) [hep-ph/0401240].

Thermal Leptogenesis

Davidson+Ibarra (02), Buchmuller, et.al (03), Hambye, et.al. (03)

CP Asymmetry

For $M_{2,3} \gg M_1$: Upper bound on ϵ

$$\epsilon = \frac{3}{16} \frac{M_1 m_{\nu 3}}{\langle H \rangle^2} f(m_{\nu i}, \tilde{m}_1)$$

Hierarchical:

$$m_{\nu 1} \rightarrow 0 \implies \epsilon = \frac{3}{16\pi} \frac{M_1 m_{\nu 3}}{\langle H \rangle^2}$$

Degenerate:

$$m_{\nu 3} = m_{\nu 1} \implies \epsilon = 0$$

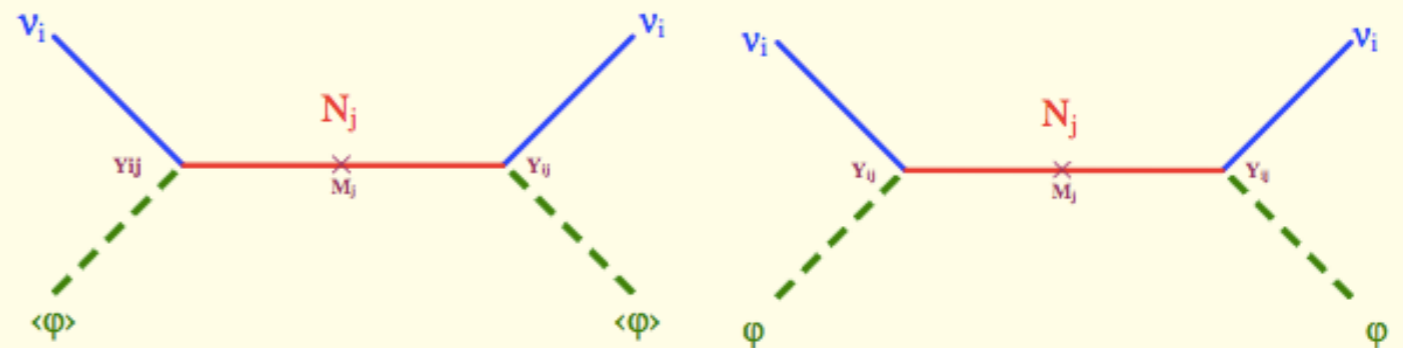
Efficiency parameter

$$\eta = \frac{\Gamma_{N1}}{H(T=M_1)} \leq 1$$

$$\eta \sim \frac{10^{-3} eV}{\tilde{m}_1}$$

$$\tilde{m}_1 \equiv \frac{(Y^\dagger Y)_{11} \langle H \rangle^2}{M_1} \leq 10^{-3} eV$$

$$M_1 \gtrsim 10^9 \text{ GeV} (\implies T_{RH} \gtrsim 10^9 \text{ GeV})$$



Light Neutrino Masses

$$m_i \propto \sum_j Y_{ij}^2 / M_j$$

L -changing $2 \rightarrow 2$ Scattering

$$\sigma \propto \sum_i |\sum_j Y_{ij}^2 / M_j|^2$$

- Require that $\Delta L = 2$ washout effects are not too strong:

$$m_1^2 + m_2^2 + m_3^2 \lesssim (0.15 eV)^2$$

Neutrino decoupling

$$e^+ + e^- \leftrightarrow \nu_e + \bar{\nu}_e, \quad e^\pm + \nu_e \rightarrow^\pm + \nu_e, \quad e^\pm + \bar{\nu}_e \rightarrow e^\pm + \bar{\nu}_e$$

$$\sigma_{e\nu} \approx \mathcal{O}(1) \frac{\alpha_w^2}{M_{W,Z}^4} T^2 \quad \text{Neutrinos decouple : } \Gamma_{e\nu} \sim (\sigma_{e\nu} n_e) \sim H(T)$$

ν_μ , & ν_τ decouple earlier

$$T_{\nu_e} \sim \mathcal{O}(1) \alpha_w^{-2/3} M_W^{4/3} \sim 1.5 \text{ MeV}$$

$$\text{Note : } T \sim m_e \sim 0.5 \text{ MeV}$$

$$\left(\frac{T_\gamma}{T_\nu} \right)^3 \left(\frac{g_\gamma + g_{e^\pm}}{g_\nu} \right) = \text{const.} = \frac{11}{4}$$

$$T_\nu \sim (2.73 \text{ K}/1.4) \sim 1.95 \text{ K}$$

photons: $g_\gamma = 2$ (2 spin states);

neutrinos: $g_\nu = 6$ (6 flavors);

electrons: $g_{e^-} = 2$ (2 spin states);

positrons: $g_{e^+} = 2$ (2 spin states);

$$\rho = g_\star \frac{\pi^2}{30} T^4 \equiv \frac{\pi^2}{30} T^4 \left[\sum_{i=\text{bosons}} g_i + \frac{7}{8} \sum_{i=\text{fermions}} g_i \right]$$

$$g_\star = 2 + \frac{7}{8}(6 + 2 + 2) = 2 + \frac{70}{8} = 2 + 8.75 = 10.75.$$

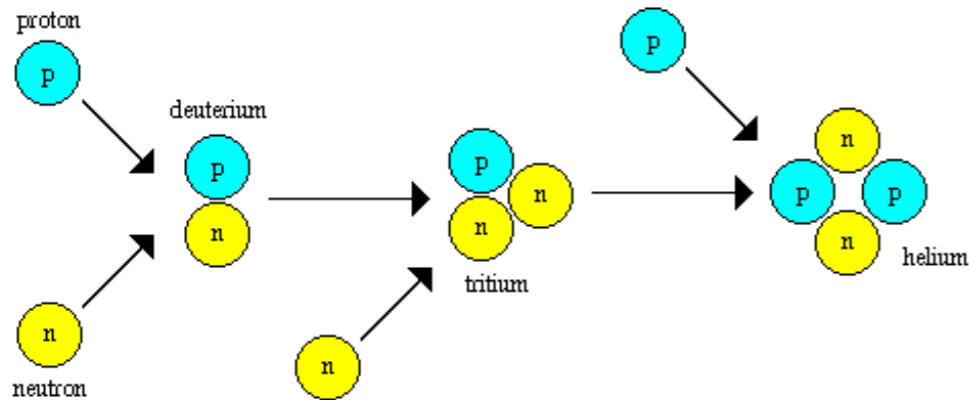
$$\rho = \tilde{g}_\star \frac{\pi^2}{30} T^4 \equiv \frac{\pi^2}{30} \left[T_\gamma^4 \sum_{i=\text{bosons}} g_i + T_\nu^4 \frac{7}{8} \sum_{i=\text{fermions}} g_i \right] = \frac{\pi^2}{30} T_\gamma^4 \left[2 + \left(\frac{4}{11} \right)^{4/3} \frac{21}{4} \right] = \frac{\pi^2}{30} T_\gamma^4 [3.36]$$

Big Bang Nucleosynthesis

Weak interactions & nuclear reactions in an expanding universe

Nucleosynthesis

as the Universe cools, protons and neutrons can fuse to form heavier atomic nuclei



$$\frac{n_p^{(0)}}{n_n^{(0)}} = \frac{g_p \left(\frac{m_p T}{2\pi}\right)^{3/2} e^{-m_p/T}}{g_n \left(\frac{m_n T}{2\pi}\right)^{3/2} e^{-m_n/T}} = \left(\frac{m_p}{m_n}\right)^{3/2} e^{(m_n - m_p)/T} \approx e^{Q/T}$$

$$p + e^- \leftrightarrow n + \nu_e$$

$$p + \bar{\nu}_e \leftrightarrow n + e^+$$

$$n \leftrightarrow p + e^- + \bar{\nu}_e$$

$$\Gamma \sim \langle \sigma |v| \rangle n_A(\eta, T)$$

$$\eta \equiv \frac{n_B}{n_\gamma} = \frac{n_b - n_{\bar{b}}}{n_\gamma} : \text{Baryon Asymmetry}$$

$$\eta = 2.68 \times 10^{-5} (\Omega_B h^2)$$

$$\Gamma_{pe \rightarrow \nu n} = \begin{cases} \Gamma_{n \rightarrow pe\nu} (T/m_e)^3 \exp(-Q/T) & \text{if } T \leq Q, m_e; \\ G_F^2 T^5 & \text{if } T \geq Q, m_e. \end{cases} \quad \Gamma_F/H(T) \sim (T/0.8 \text{ MeV})^3$$

$$\tau_{n \rightarrow pe\nu} \sim 886.7 \text{ s}$$

$$Q \sim 1.293 \text{ MeV}$$

$$X_n \rightarrow X_{n,EQ} \equiv \frac{n_n^{(0)}}{n_n^{(0)} + n_p^{(0)}} = \frac{1}{1 + (n_p^{(0)}/n_n^{(0)})} \sim (1/6); \quad X_n \sim \frac{1}{6} \exp[-t/\tau_{n \rightarrow pe\nu}] \sim 0.15 \times 0.74 \sim 0.11$$

$$Y_P(^4\text{He}) \approx 2X_n \sim 0.22$$

$$X_A \propto \eta^{A-1}$$

Sources of Baryogenesis

$$B = \frac{B - L}{2} + \frac{B + L}{2}$$

Asymmetry in
baryonic sector

Asymmetry in
leptonic sector
(Leptogenesis)

Asymmetry
in both

Conversion into
baryonic
asymmetry

~~EW Accidental
Symmetry~~

Observed baryonic abundance

10^{12} GeV

100 GeV

1 MeV

Thermal history of the universe

Thermodynamics of ultra-relativistic plasma:

Number density: $n = \frac{\xi(3)}{\pi^2} g'(T) T^3$

Energy density: $\rho = 3p = \frac{\pi^2}{30} g(T) T^4$

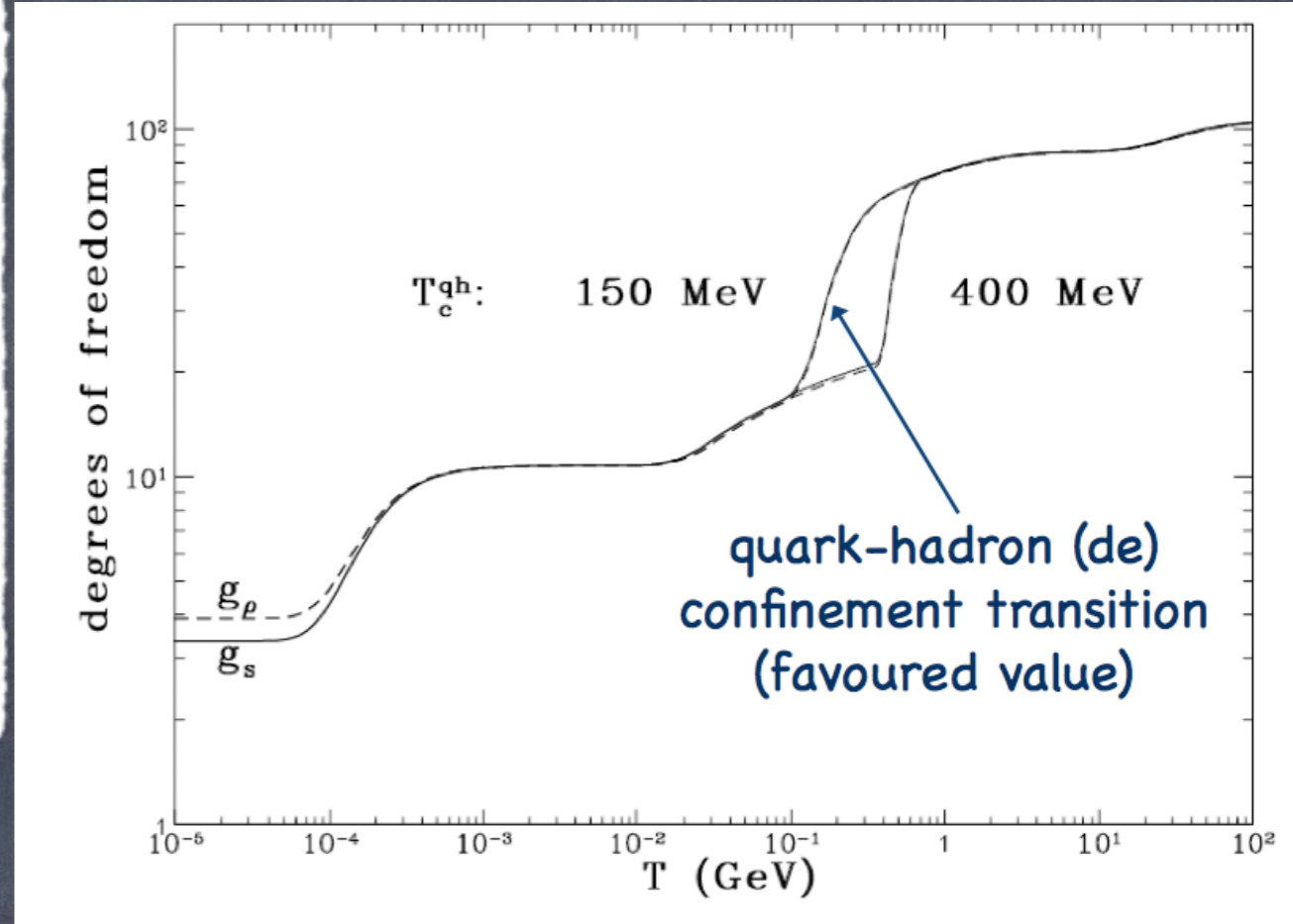
Entropy density: $s \equiv \frac{p+\rho}{T} = \frac{2\pi^2}{45} g(T) T^3$

$$g'(T) = g_b(T) + \frac{3}{4} g_f(T)$$

$$g(T) = g_b(T) + \frac{7}{8} g_f(T)$$

$$H = \left(\frac{\dot{a}}{a} \right) = \sqrt{\frac{\rho}{3M_p^2}} = 1.66 \times g^{1/2} \frac{T^2}{M_p}$$

Entropy Conservation : $\frac{d}{dt}(sa^3) = 0, \Rightarrow s \propto a^{-3}, a(T) \propto \frac{1}{T}$

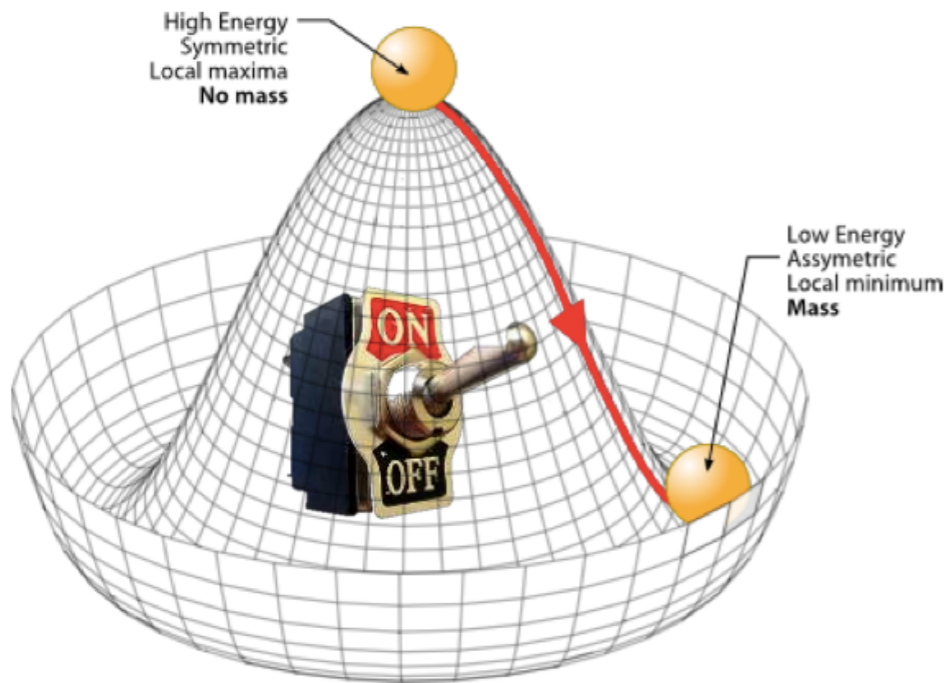
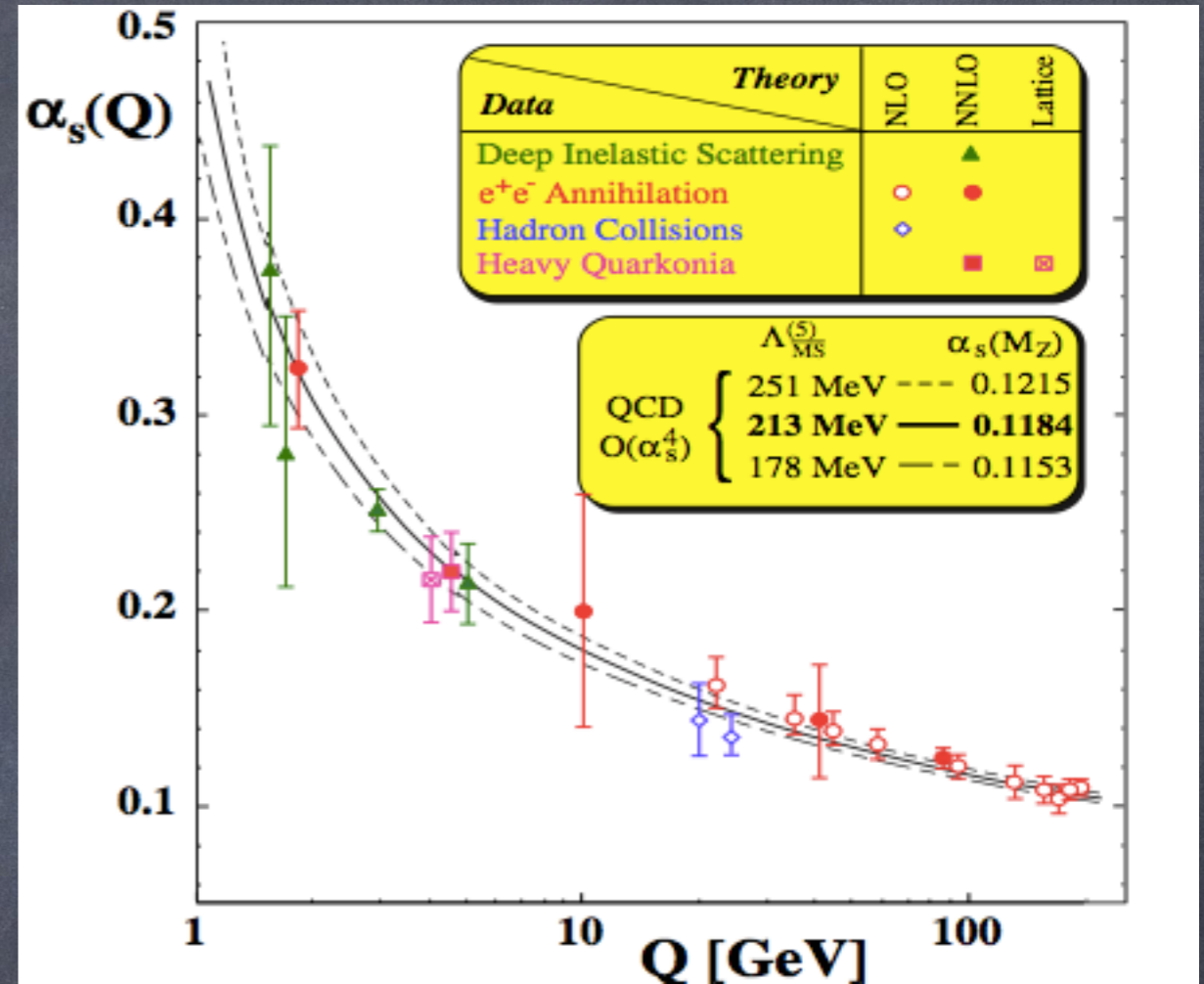
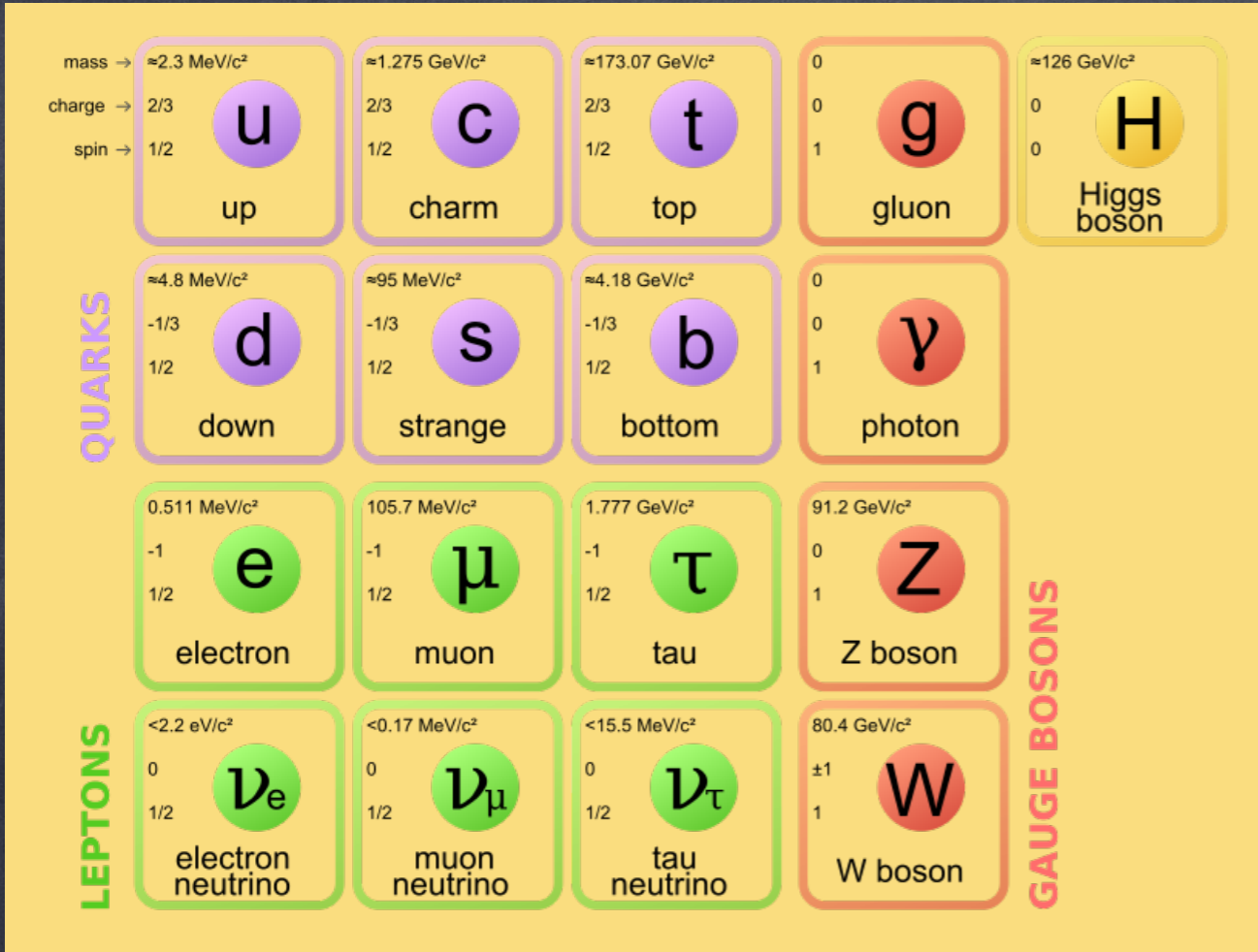


Temperature	Event	Degrees of Freedom	Notes
$T \sim 200$ GeV	all present	106.75	
$T \sim 100$ GeV	EW transition	(no effect)	
$T < 170$ GeV	top-annihilation	96.25	
$T < 80$ GeV	W^\pm, Z^0, H^0	86.25	
$T < 4$ GeV	bottom	75.75	
$T < 1$ GeV	charm, τ^-	61.75	
$T \sim 150$ MeV	QCD transition	17.25	(u,d,g \rightarrow $\pi^{\pm,0}$, 37 \rightarrow 3)
$T < 100$ MeV	π^\pm, π^0, μ^-	10.75	$e^\pm, \nu, \bar{\nu}, \gamma$ left
$T < 500$ keV	e^- annihilation	(7.25)	$2 + 5.25(4/11)^{4/3} = 3.36$

History of $g(T)$

$$\frac{t}{1s} \approx 2.42 \times g^{-1/2} \left(\frac{1 \text{ MeV}}{T} \right)^2$$

Standard Model



$$\mu^2 \frac{\partial \alpha_s(\mu)}{\partial \mu^2} = \beta(\alpha_s(\mu))$$

$$\alpha_s(\mu^2) = \frac{\alpha_s(\mu_0^2)}{1 + \alpha_s(\mu_0^2) \beta_0 \ln \frac{\mu^2}{\mu_0^2}}$$

If $\beta_0 > 0$ we have $\alpha_s(\mu^2) \rightarrow 0$ for $\mu^2 \rightarrow \infty \Leftrightarrow$ Asymptotic Freedom