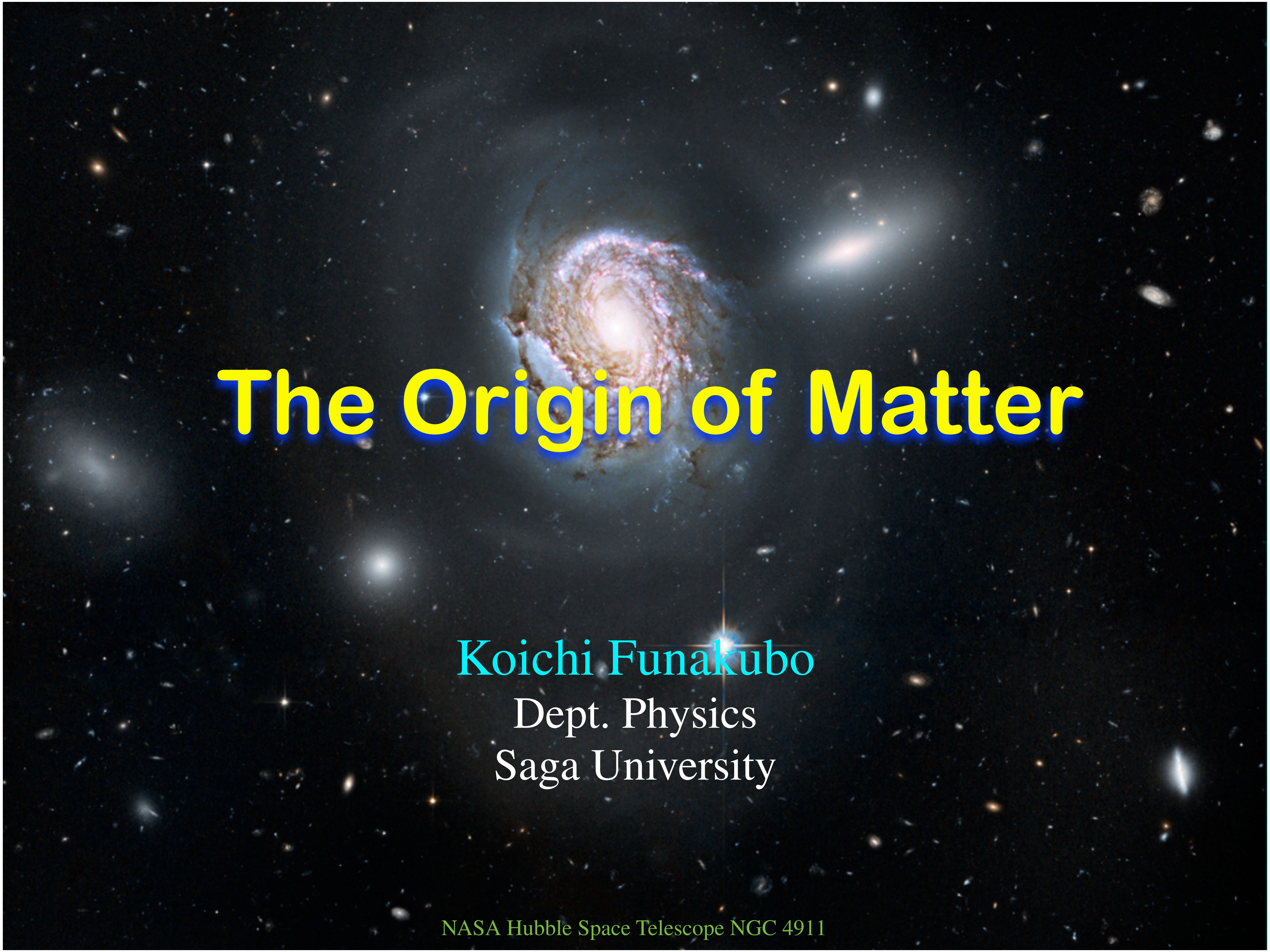

The Origin of Matter

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fundamental theory of elementary particles

Local Quantum Field Theory

causality relativistic quantum theory

CPT Theorem

↓

For each particle species, there is an antiparticle with the same mass and the opposite charge.

The Standard Model

particle	electron e	quark u	W^- W
antiparticle	positron e^+	antiquark $\bar{u}$	W^+ W^+

particle = antiparticle

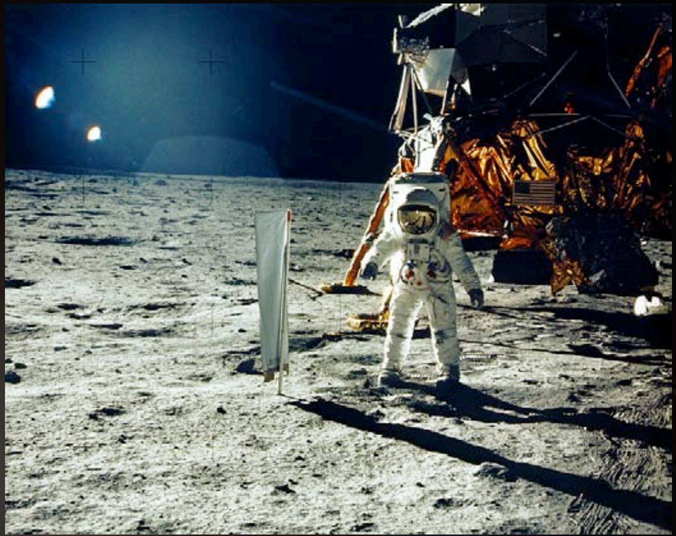
photon, gluon, Z, h

The theory is ***almost* symmetric**
under exchange of
the particle and its antiparticle.

However, the Nature is ...

We find only the particles in the Universe.

We refer to them as ***particles***.



★The Moon, solar system

★Our Galaxy (the Milky Way)

cosmic ray from the Milky Way

$$\frac{\text{antiproton}}{\text{proton}} = 10^{-4}$$ secondary particles

★Galaxies, clusters of galaxies

10^{12} times of the solar mass

If the Universe were matter-antimatter-symmetric, it would be impossible to separate the matters from the antimatters at some epoch in eary universe.

content of my talk

- The **B**aryon **A**symmetry of the **U**niverse
- Requirements for the generation of the asymmetry
- Scenarios of baryogenesis
- Can the Standard Model explain the BAU ?

Baryon Asymmetry of the Universe

$$\frac{n_B}{s} = \frac{n_b - n_{\bar{b}}}{s} = (0.67 - 0.92) \times 10^{-10}$$ (95%CL)

entropy density

$$s = \frac{2\pi^2}{45} g_{*S} T^3 = \frac{2\pi^2}{45} \left(\sum_B g_B(T) + \frac{7}{8} \sum_F g_F(T) \right) T^3$$

invariant during adiabatic expansion of the Universe

$s = 7.04 n_\gamma$ at present

$$\eta \equiv \frac{n_B}{n_\gamma} = \frac{n_b - n_{\bar{b}}}{n_\gamma} = (4.7 - 6.5) \times 10^{-10}$$

The value of BAU is determined by cosmological observations.

Light-element abundances

H, D, T, ^{3}He, ^{4}He, ^{7}Li,...

Big Bang Nucleosynthesis

Fluctuation in the CMB temperature

Cosmic Microwave Background $T = 2.726K$

remnants of the equilibrium plasma

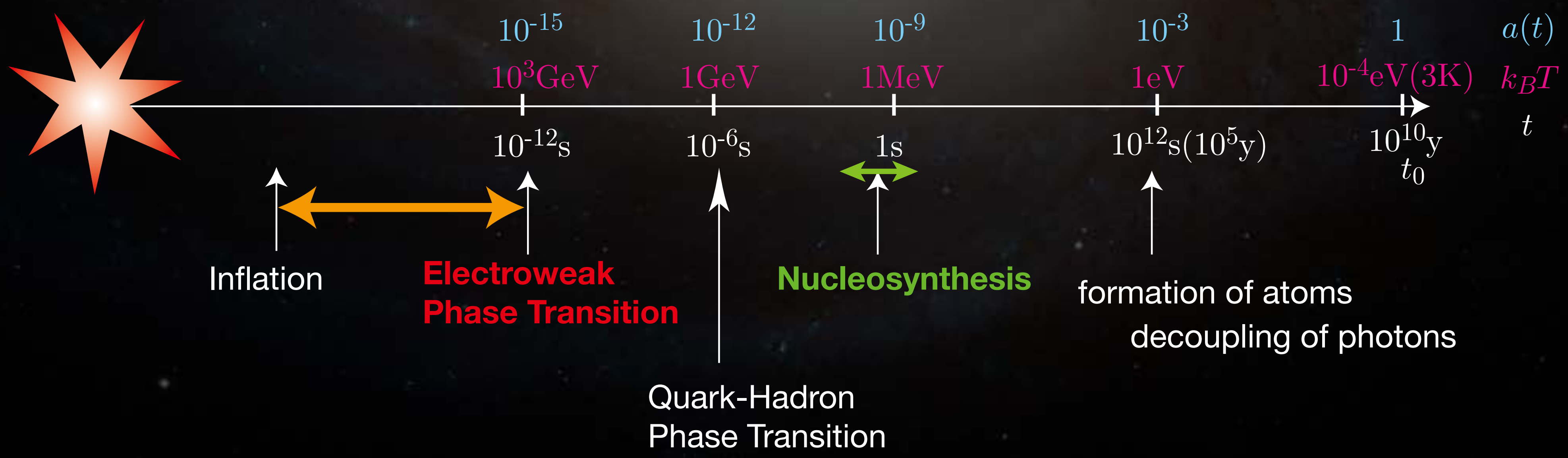
The small fluctuation is related to the cosmological paramters.

$$\frac{\delta T}{T} \sim 10^{-5}$$

Big Bang Nucleosynthesis

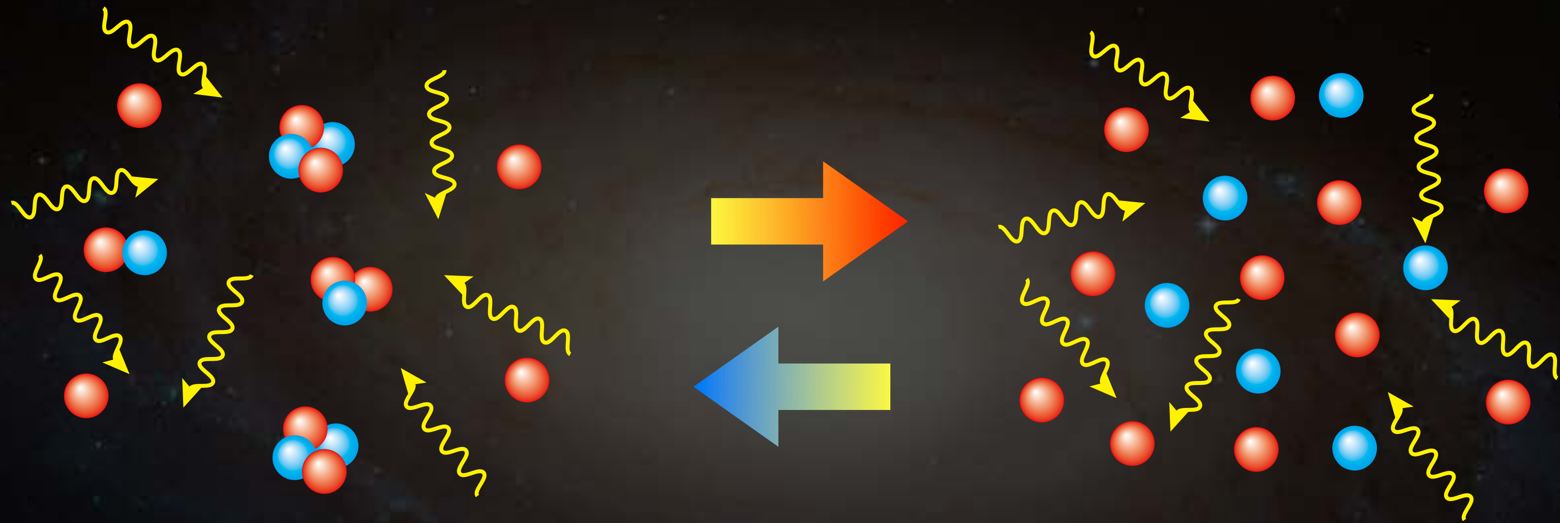
The Big Bang cosmology naturally explains

- expansion of the Universe
- existence of the CMB
- light element abundances



When T>1MeV

energy of photons > binding energy of nuclei



As the Universe cools down,
nucleons bind with each other.

BBN predicts the abundances of
the light elements *quantitatively*.

$T \gg 1\mathrm{MeV}$ $(k_B = 1)$

$n + \nu_e \rightleftharpoons p + e^-$ $n + e^+ \rightleftharpoons p + \bar{\nu}_e$ in chemical equil.

#(neutrons)／#(protons) $\dfrac{n_n}{n_p} \simeq e^{-Q/T} \simeq 1$

$Q \equiv m_n - m_p = 1.29\mathrm{MeV}$

$T \simeq 1\mathrm{MeV}$

$\Gamma_{n\leftrightarrow p} \simeq H(T)$ expansion rate

the reaction is frozen: $\left(\dfrac{n_n}{n_p}\right)_{\mathrm{freeze-out}} \simeq 0.167$

Then the number of neutrons decreases by

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

$T \simeq 0.1\mathrm{MeV}$ the light elements are synthesized

$$\begin{aligned} p + n &\rightarrow \mathrm{D} + \gamma \\ \mathrm{D} + \mathrm{D} &\rightarrow {}^3\mathrm{He} + n, \ {}^3\mathrm{H} + p \\ {}^3\mathrm{H} + \mathrm{D} &\rightarrow {}^4\mathrm{He} + n \\ {}^3\mathrm{H} + p &\rightarrow {}^4\mathrm{He} + \gamma \\ {}^3\mathrm{He} + \mathrm{D} &\rightarrow {}^4\mathrm{He} + p \end{aligned}$$

binding energies

	E_B (MeV)	E_B/A (MeV)
D	2.22	1.11
^{3}H	6.92	2.31
^{3}He	7.72	2.57
^{4}He	28.3	7.08

$^4\mathrm{He} + {}^3\mathrm{He} \rightarrow {}^7\mathrm{Li} + \gamma$ etc. elements up to ^{7}Li are produced

Almost all the neutrons are caught within ^{4}He.

Abundance of ^{4}He is determined by that of the neutrons at BBN.

$\eta = \frac{n_B}{n_\gamma}$ is larger → BBN starts with more neutrons

In detail, we solve the Boltzmann equations.

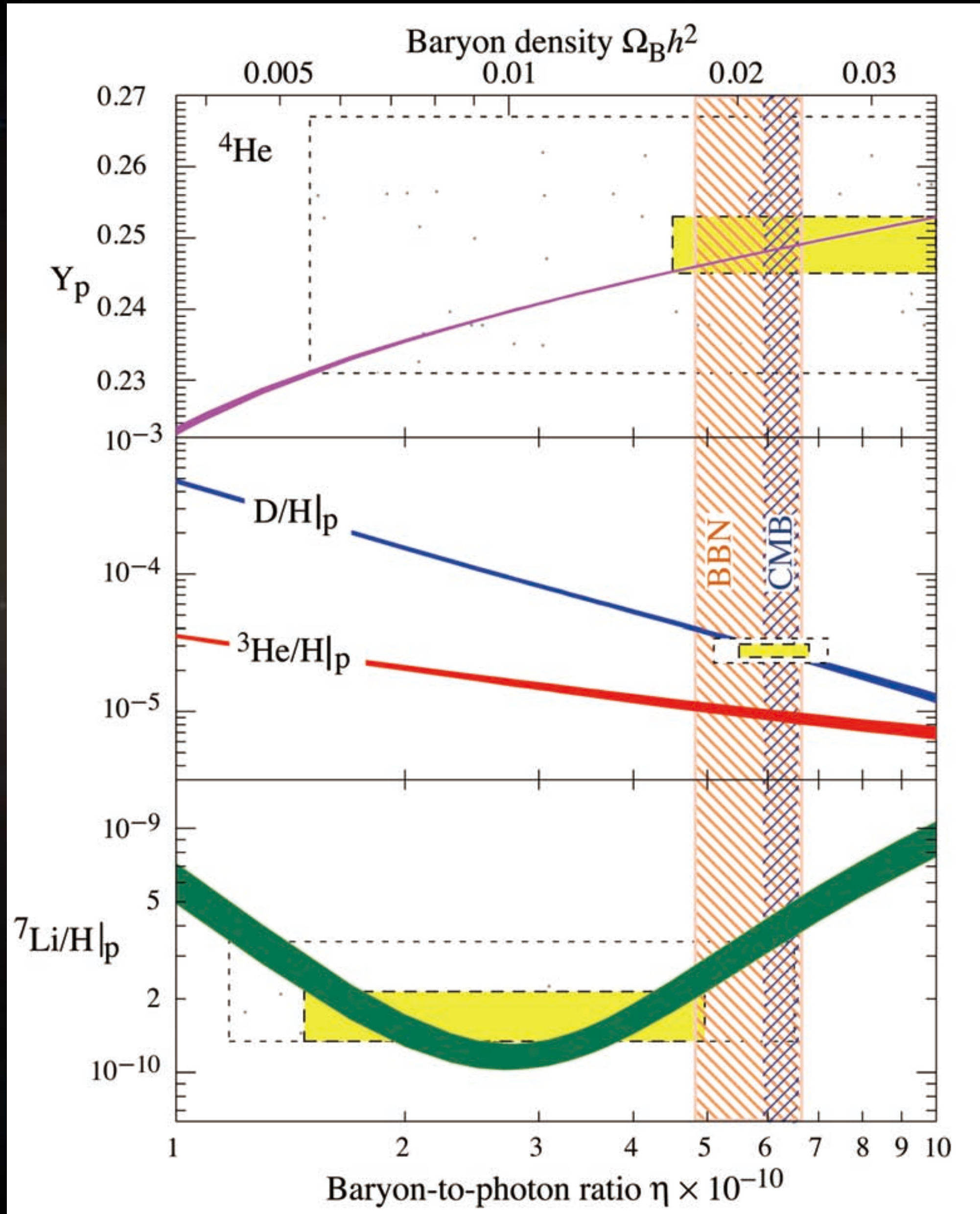
η vs light element abundances

mass fraction of ^{4}He

$$Y = \frac{(2m_p + 2m_n)n_n/2}{m_p n_p + m_n n_n}$$

$$= \frac{2n_n/n_p}{1 + n_n/n_p}$$

$$n_n/n_p = 0.13 \Rightarrow Y = 0.23$$



↕ observation (95%CL)

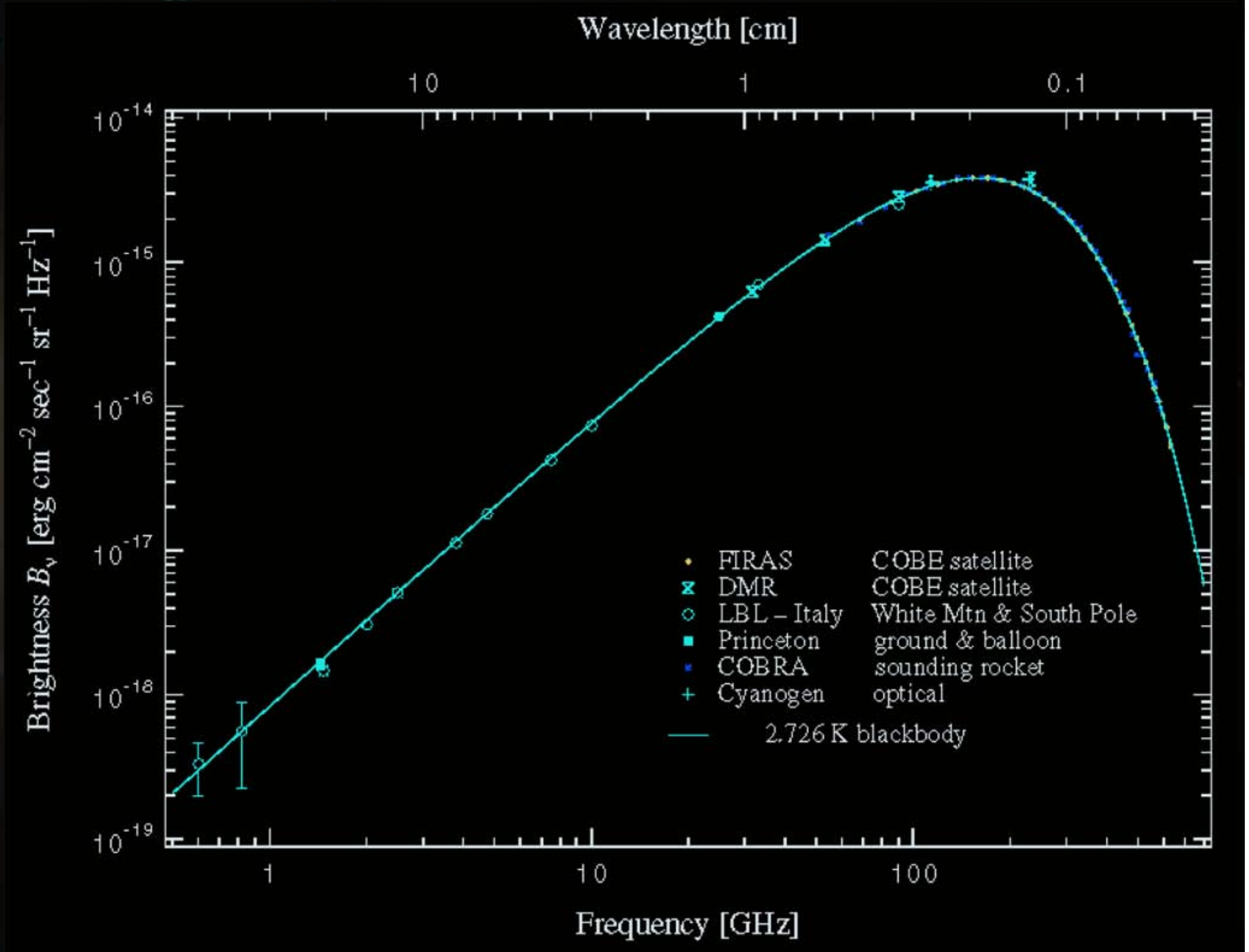
CMB anisotropy

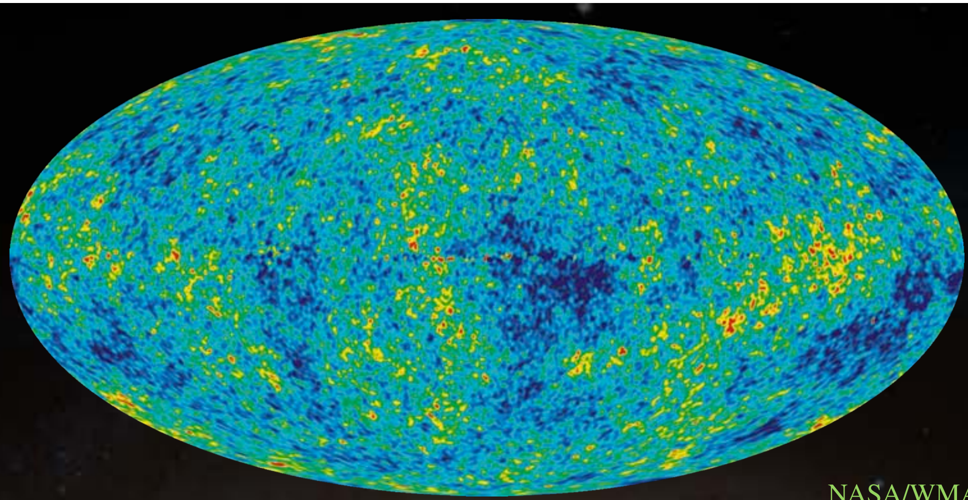
agreement with
the Planckian
at T=2.725K

$$\frac{\delta T}{T} \sim 10^{-5}$$

↑

dynamics of the
plasma and photon
at the decoupling





NASA/WMAP project

evolution of $\delta T(\boldsymbol{x})$

$h, \Omega_m h^2, \Omega_B h^2, \Omega_\Lambda, \ldots$

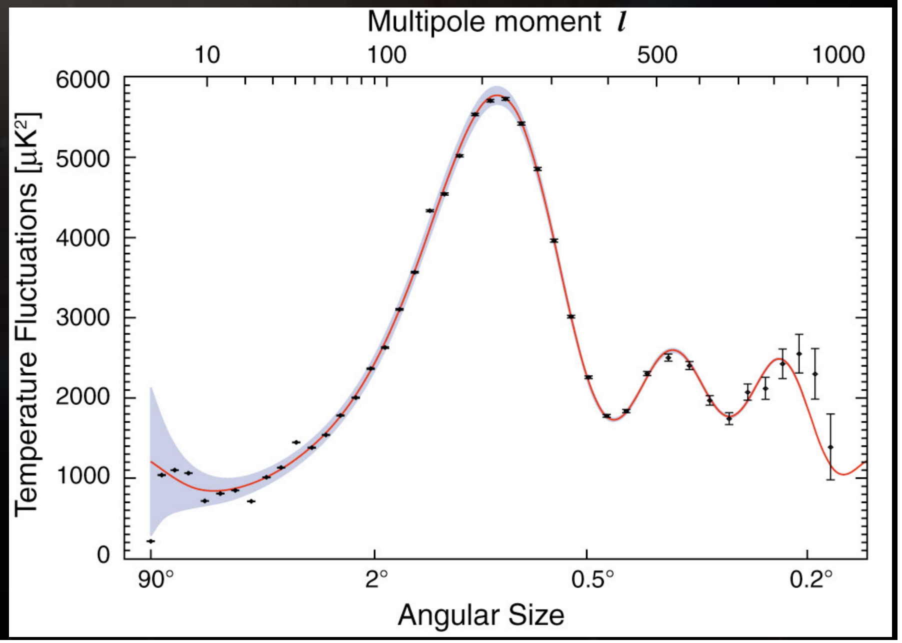
as parameters

$H_0 = 100\, h \,\mathrm{km/s\, Mpc^{-1}}$

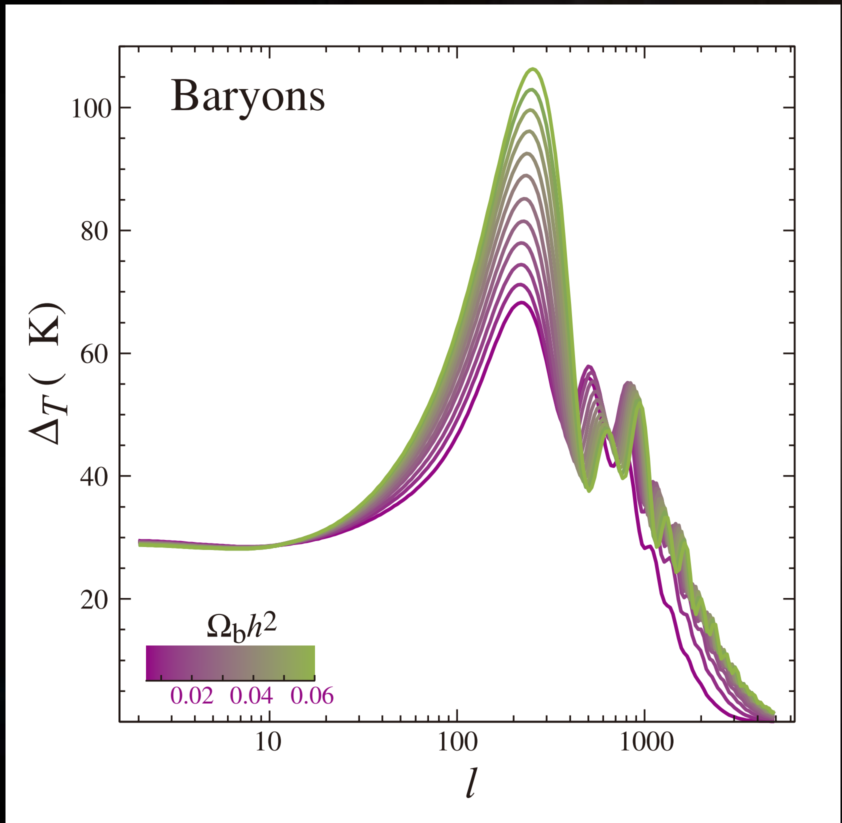
$$\left\langle \frac{\delta T(\boldsymbol{x})}{T} \frac{\delta T(\boldsymbol{y})}{T} \right\rangle$$

Fourier trf.

$$C_l \rightarrow l \text{ vs } \sqrt{\frac{l(l+1)C_l}{2\pi}}$$



Fitting the fluctuation spectrum data, we find the values of the cosmological parameters.



$$\Omega_B h^2 = 0.0227 \pm 0.0006 \quad (68\%\mathrm{CL})$$

$$h = 0.72 \pm 0.03$$

$$\Omega_B = \frac{\rho_B}{\rho_C} = \frac{m_p n_B}{\frac{3H_0^2}{8\pi G}}$$

Before the nucleosysthesis (T=1MeV), we need

$$\frac{n_B}{s} = \frac{n_b - n_{\bar{b}}}{s} = (0.67 - 0.92) \times 10^{-10}$$

What is the origin of this asymmetry ?

★Initial condition of the Universe anthropic principle

Huge entropy generated by **Inflation** dilutes the asymmetry.

★**Baryogenesis**

The Universe begins with B-symmetry and the BAU was generated before the nucleosysthesis.

↓

The BAU should be quantitatively explained by particle physics.

Requirements for Baryogenesis

[Sakharov, JETP Lett. 5 (1967) 24]

(1) Baryon number nonconservation

(2) C and CP violation

(3) out of equilibrium

The condition (1) is obvious.

Without the condition (3), generated BAU is washout by the inverse process.

C and CP symmetries

represented by unitary transformations in QFT

P transformation (space inversion)

$$\phi(t,\boldsymbol{x}) \mapsto \pm\phi(t,-\boldsymbol{x})$$
$$A_\mu(t,\boldsymbol{x}) \mapsto (A_0(t,-\boldsymbol{x}),-\boldsymbol{A})(t,-\boldsymbol{x}))$$
$$\psi(t,\boldsymbol{x}) \mapsto \gamma_0\psi(t,-\boldsymbol{x})$$

$$\psi_L(x) \leftrightharpoons \psi_R(x)$$

C transformation (charge conjugation)

$$\phi(x) \mapsto \phi^*(x)$$
$$A_\mu(x) \mapsto A_\mu^T(x)$$
$$\psi(x) \mapsto C\bar{\psi}^T(x) = i\gamma^2\gamma^0\bar{\psi}^T(x)$$

$$\begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix} \mapsto \begin{pmatrix} i\sigma_2\psi_R^* \\ -i\sigma_2\psi_L^* \end{pmatrix}$$

$$\psi_L \overset{CP}{\mapsto} \psi_L^* \qquad \psi_R \overset{CP}{\mapsto} \psi_R^*$$

Withoug the condition (2),

any BAU cannot be generated starting from B-sym. Universe.

density operator representing
the state of the Universe

$$\rho(t) = \sum_n p_n |\psi_n(t)\rangle\langle\psi_n(t)|$$

expectation value

$$\langle\mathcal{O}\rangle(t) = \mathrm{Tr}\left[\rho(t)\mathcal{O}\right]$$

time evolution Liouville eq. : $$i\hbar\frac{\partial\rho(t)}{\partial t} + [\rho(t), H] = 0$$

initial cond. ρ_0 : B-sym. Universe $\langle n_B\rangle_0 = \mathrm{Tr}[\rho_0 n_B] = 0$

The solution can be expressed in terms of
ρ_0 and H

- H has C or CP sym. $\quad [\rho(t), \mathcal{C}] = 0$ or $[\rho(t), \mathcal{CP}] = 0$

- Baryon number is odd under C and CP

$$\mathcal{C} B \mathcal{C}^{-1} = -B, \quad \mathcal{CP} B \mathcal{CP}^{-1} = -B$$

Starting from a B-symmetric ρ_0,

if H is symmetric under C or CP,

$$\langle n_B \rangle = \mathrm{Tr}[\rho\, n_B] = \mathrm{Tr}[\rho\, \mathcal{C} n_B \mathcal{C}^{-1}] = -\mathrm{Tr}[\rho\, n_B] = 0$$

$$\langle n_B \rangle = \mathrm{Tr}[\rho\, n_B] = \mathrm{Tr}[\rho\, \mathcal{CP} n_B \mathcal{CP}^{-1}] = -\mathrm{Tr}[\rho\, n_B] = 0$$

In order to have $\langle n_B \rangle \neq 0$,

both C and CP must be violated.

The first example of baryogenesis

[Yoshimura, Phys. Rev. Lett. 41(1978)]

Grand Unified Theories

SM gauge group $SU(3)_c \times SU(2)_L \times U(1)_Y \subset G_{\rm GUT}$

quarks and leptons within a single multiplet $\not{B},\ \not{L},$

process	Branch. Ratio	ΔB
$X \longrightarrow qq$	r	$2/3$
$X \longrightarrow \bar{q}\bar{l}$	$1-r$	$-1/3$
$\bar{X} \longrightarrow \bar{q}\bar{q}$	$\bar{r}$	$-2/3$
$\bar{X} \longrightarrow ql$	$1-\bar{r}$	$1/3$

by decay of $X\bar{X}$ pair thermally populated

$$\langle \Delta B \rangle = \frac{2}{3}r - \frac{1}{3}(1-r) - \frac{2}{3}\bar{r} + \frac{1}{3}(1-\bar{r}) = r - \bar{r}$$

C or CP is converved $\longrightarrow$ $r = \bar{r}$ $\qquad \langle \Delta B \rangle = 0$

X decays at temperature $T \simeq m_X \simeq 10^{16}\mathrm{GeV}$

decay rate ⟷ expansion rate

$$\Gamma_D \simeq \alpha m_X \quad (\alpha \sim 1/40)$$

$$H(T \simeq m_X)$$

$$H(T) \simeq 1.66\sqrt{g_*}\frac{T^2}{m_{\mathrm{P}}}$$

Then the pair production and pair annihilation of $X\bar{X}$ are suppressed.
The X and $\bar{X}$ decay into qq and ql.

The theory explicitly violates the baryon number cons.

proton decay $p \rightarrow e^+\pi^0,\ \nu_e\pi^+,\ \cdots$

$\tau_p > 10^{31-33}\mathrm{y}$ Kamiokande nucleon decay exper. / neutrino detection exper.

Scenarios of Baryogenesis

How to satisfy the 3 requirements.

(1) Baryon number nonconservation

never observed so far

Standard Model $\mathcal{L}_{\rm SM}$ is symmetric under $U(1)_B \times U(1)_L$

$U(1)_{B+L}$ is violated *nonperturbatively*

effective at finite tepmeratures, free from proton decay

GUTs

Supersymmetric models

$\langle \tilde{q} \rangle \neq 0, \ \left\langle \tilde{l} \right\rangle \neq 0$ at some time in the early universe

(2) C and CP violation

C violation — chiral gauge interactions

$$\bar{u}_L\gamma^\mu d_L W_\mu^+ + \bar{d}_L\gamma^\mu u_L W_\mu^- \qquad \left(\frac{1}{6}\bar{u}_L\gamma^\mu u_L + \frac{2}{3}\bar{u}_R\gamma^\mu u_R\right) B_\mu$$

CP violation

renormalizable (mass dim. ≦ 4) operators:

chiral gauge interactions and Yukawa interactions ($N_f \geq 3$),
scalar trilinear and quartic interactions
Majorana mass term, θ-term

hermitian conjugate

$$\mathcal{L}_{CC} = \frac{g_2}{\sqrt{2}}\left[\bar{u}_{AL}\gamma^\mu V_{AB} d_{BL} W_\mu^+ + \bar{d}_{AL}\gamma^\mu V_{AB}^\dagger u_{BL} W_\mu^-\right]$$

$$\bar{u}_{AL}\gamma^\mu d_{BL} W_\mu^+ \overset{CP}{\rightleftarrows} \bar{d}_{BL}\gamma^\mu u_{AL} W_\mu^-$$

(3) Out of equilibrium

B-changing rate

$$\Gamma_{\Delta B \neq 0} < \begin{cases} H(t) = \dfrac{\dot{a}(t)}{a(t)} & : \text{ expnasion rate of the Universe} \\ (\text{time scale of variation of some background field})^{-1} \\ \quad \vdots \end{cases}$$

GUTs baryogenesis

$$\Gamma_D(X \to qq, ql) \simeq H(T) \quad \text{at } T \simeq M_{\rm GUT}$$

Scenarios of Baryogenesis

scenarios	$\Delta B \neq 0 (\Delta L \neq 0)$	CP violation	out of equil.
GUTs	decay of leptoquarks	decay vertex	$\Gamma_D < H(T)$
Electroweak	$(B+L)$-anomaly	Yukawa, gauge,...	1st order PT
Leptogenesis	decay of the heavy-ν	decay vertex	$\Gamma_D < H(T)$
Affleck-Dine[(1)]	$\langle \tilde{q} \rangle , \langle \tilde{l} \rangle \neq 0$	scalar potential	moving scalar field
string, DW[(2)]	anomaly	Yukawa, gauge	moving defects
inflationary[(3)]	$\langle \tilde{q} \rangle , \langle \tilde{l} \rangle \neq 0$	scalar potential	(p)reheating

(1) Affleck and Dine, Nucl. Phys. B249 ('85)
Dine, Randall and Thomas, Nucl. Phys. B458 ('96)
(2) Brandenberger and Davis, Phys. Lett. B308 ('93)
Brandenberger, Davis and Trodden, Phys. Lett. B349 ('94)
(3) KF, Kakuto, Otsuki and Toyoda, Prog. Theor. Phys. 105 ('01)
Rangarajan and Nanopoulos, Phys. Rev. D64 ('01)

After the discovery of the **sphaleron solution** in the Standard Model, we come to notice that baryon number can be generated from lepton number.

sphaleron process

(B+L)-changing process through the ***chiral anomaly*** at high temperatures

suppressed by $e^{-8\pi^2/g_2^2} \simeq e^{-164}$ at $T = 0$

free from the proton decay

What is the sphaleron ?
What is its role in baryon number violation?

Baryon number violation in electroweak theories

$U(1)_B$ and $U(1)_L$ invariance of $\mathcal{L}$

Both *B* and *L* are conserved classically.

The $U(1)_{B+L}$ is broken by the **chiral anomaly**.

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

$SU(2)_L$ $\qquad$ $U(1)_Y$

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

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu - g[A_\mu, A_\nu]$$

$$\tilde{F}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\rho\sigma}F_{\mu\nu}$$

$$N_f = \#(\text{generations})$$

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

$$= N_f\left[N_{CS}(t_f) - N_{CS}(t_i)\right]$$

Chern-Simon number $A_0 = 0$

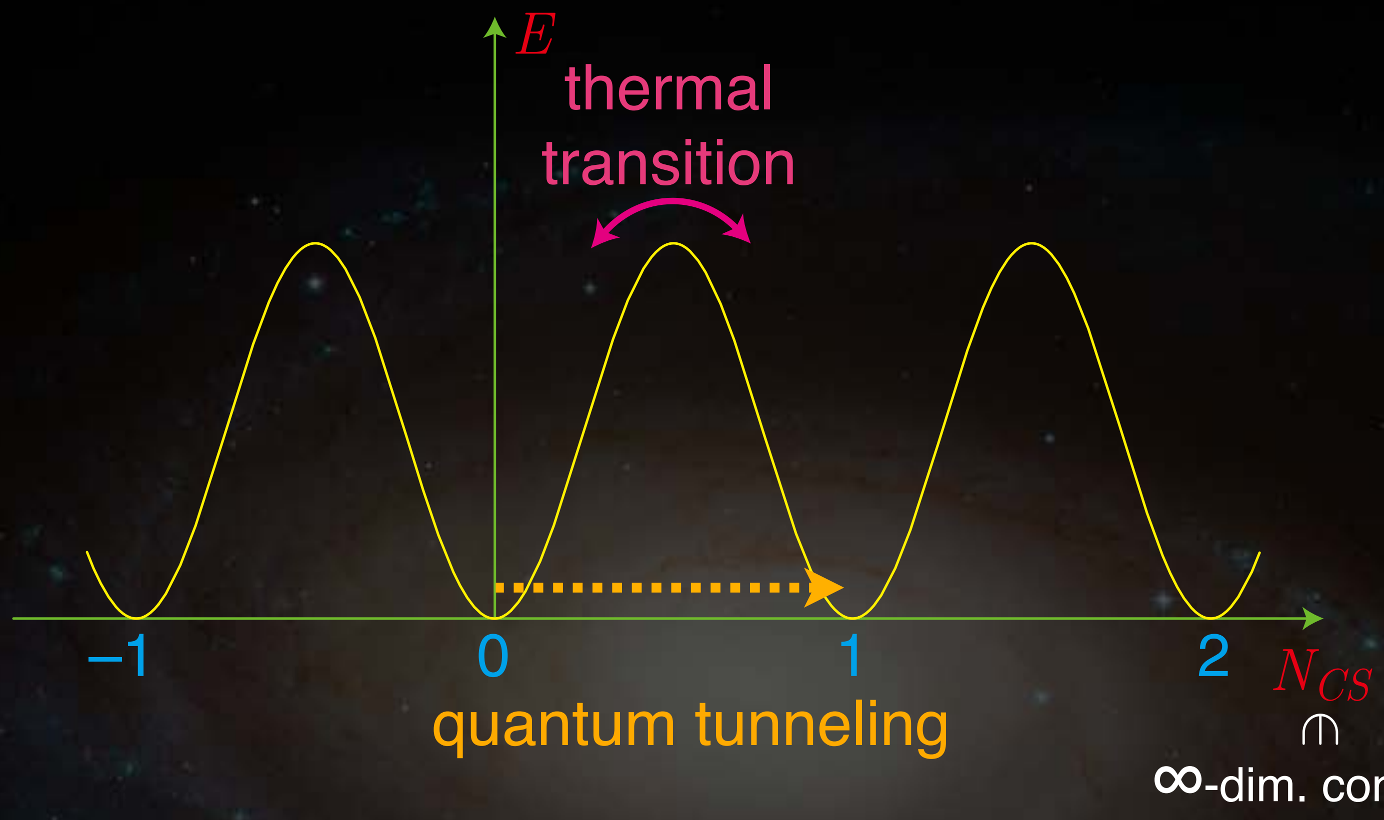
$$N_{CS}(t) = \frac{1}{32\pi^2}\int d^3\boldsymbol{x}\,\epsilon_{ijk}\left[g_2^2 \mathrm{Tr}\left(F_{ij}A_k - \frac{2}{3}g_2 A_i A_j A_k\right) - g_1^2 B_{ij} B_k\right]$$

Classical vacua of the gauge fields $\mathcal{E} = \frac{1}{2}(\boldsymbol{E}^2 + \boldsymbol{B}^2) = 0$

$$F_{ij} = B_{ij} = 0 \longleftrightarrow A_i = iU^{-1}(\boldsymbol{x})\partial_i U(\boldsymbol{x}), \quad B_i = \partial_i v(\boldsymbol{x})$$

$$U(\boldsymbol{x}) : S^3 \to SU(2) \simeq S^3$$

$\pi_3(S^3) \simeq \mathbf{Z} \longrightarrow U(\boldsymbol{x})$ is classified by the integer N_{CS}



(B+L)-changing rate

$T = 0$ tunneling prob. $\sim e^{-2S_{\rm instanton}} = e^{-8\pi^2/g_2^2} \simeq e^{-164} \simeq 0$

$T \neq 0$ thermal trans. $\sim e^{-F(T)/T}$ $\quad F(T) \propto v(T)$

expectation value
of the Higgs field

The thermal transition rate is determined by the top-of-barrier configuration.

‖

sphaleron

$\sigma\varphi\alpha\lambda\epsilon\rho o\varsigma$ = ready to fall

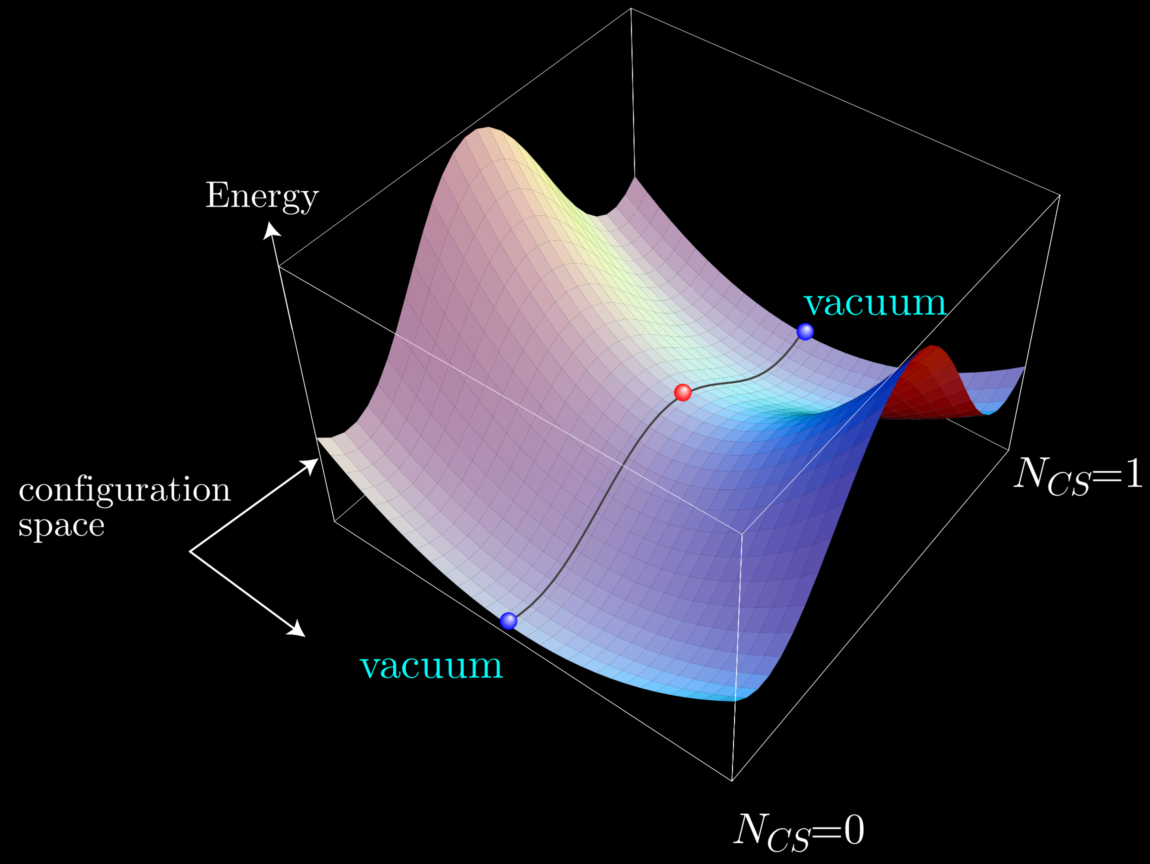
Klinkhamer & Manton, Phys. Rev. D30 ('84)

cf. a·sphalt

- classical static solution to the field theory
- unstable — one negative mode in the fluctuation spectrum

4-dim. SU(2) gauge + 1-doublet Higgs	Klinkhamer & Manton, Phys. Rev. D30 ('84)
2-dim. U(1) gauge-Higgs model	Bocharev & Shaposhnikov, Mod. Phys. Lett. A2 ('87)
2-dim. O(3) nonlinear sigma model	Mottola & Wipf, Phys. Rev. D39 ('89)
2-Higgs-Doublet Model	Kastening, Peccei and Zhang, Phys. Lett. B266 ('91)
Next-to-MSSM	KF, Kakuto, Tao and Toyoda, Prog. Theor. Phys. 114 ('05)

saddle point = the max. energy config. along the least energy path



the least-E path/(large) gauge trf. = noncontractible loop

↕

spherically symmetric config.

Manton, Phys. Rev. D28 (1983) 2019

$(B+L)$-changing rate (1/volume/time)

4-dim. SU(2) 1 Higgs doublet [Arnold & McLerran, Phys. Rev. D36 ('87)]

★ **broken phase**

$$\Gamma_{\rm sph}^{(b)}(T) \simeq k \mathcal{N}_{\rm tr} \mathcal{N}_{\rm rot} \frac{\omega_-}{2\pi} \left(\frac{\alpha_W(T)T}{4\pi} \right)^3 e^{-E_{\rm sph}/T}$$

fluxtuation zero modes: $\mathcal{N}_{\rm tr} = 26,\ \mathcal{N}_{\rm rot} = 5.3 \times 10^3$ for $\lambda = g^2$

negative mode: $\omega_-^2 \simeq (1.8 \sim 6.6) m_W^2$ for $10^{-2} \leq \lambda/g^2 \leq 10$

$k = O(1)$

★ **symmetric phase** SU(2) pure gauge system

$$\Gamma_{\rm sph}^{(s)}(T) \simeq \kappa(\alpha_W T)^4$$

$\kappa = 1.09 \pm 0.04$ [Ambjorn & Krasnitz, Phys. Lett. B362 ('95)]

MC simulation $\langle N_{CS}(t) N_{CS}(0) \rangle \sim \langle N_{CS} \rangle^2 + A e^{-\Gamma V t}$

fermion number nonconservation

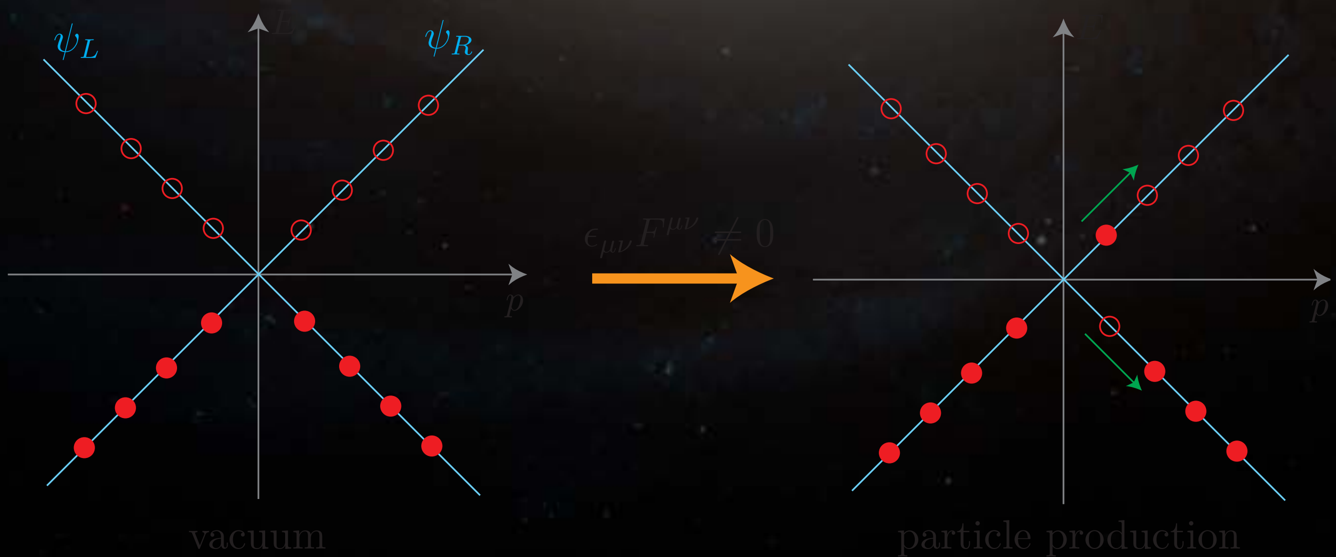
by change of the background bosonic fieds

Atiyah-Singer index theorem

$$n_R - n_L = \nu = \frac{g_2^2}{16\pi^2}\int d^4x\, \mathrm{Tr} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Pontrjagin index = instanton number

spectral flow (level crossing)



Sphaleron process in equilibrium

Irrespective of the existence of the solution,
we call the anomalous process as sphaleron process.

$\Gamma_{\rm sph}(T) > H(T)$ ⟶ B+L washout $B_{\rm final} \propto (B-L)_{\rm primordial}$

Nonvanishing Lepton number before the sphaleron decoupling leads to nonzero Baryon number.

New possibilities of Baryogenesis

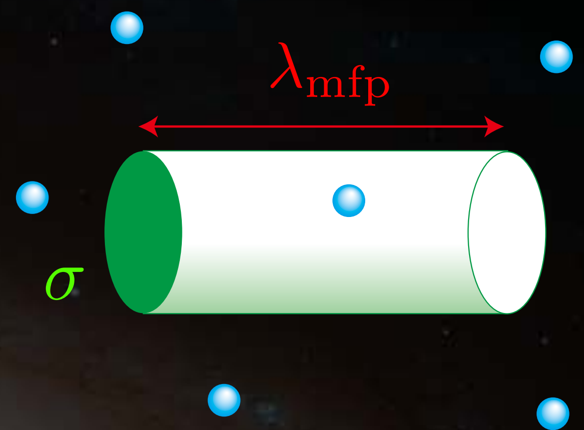
e.g. Leptogenesis

Time scales of various processes at high temperatures

for a relativistic particle $\bar{t} = \lambda_{\rm mfp}$

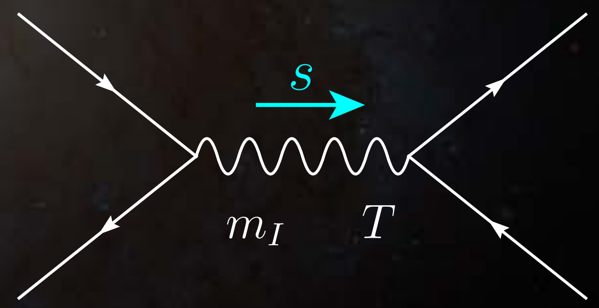
total cross section σ

number density $n(T) \simeq g_{*n} \dfrac{\zeta(3)}{\pi^2} T^3$



$$\sigma \cdot \lambda_{\rm mfp} \cdot n(T) = 1$$

$$m_I \ll T \rightarrow \sigma \simeq \frac{\alpha^2}{s} \simeq \frac{\alpha^2}{T^2}$$



$$\bar{t} = \lambda \simeq \frac{10}{g_* T^3} \left(\frac{\alpha^2}{T^2} \right)^{-1} = \frac{10}{g_* \alpha^2 T}$$

T=100GeV

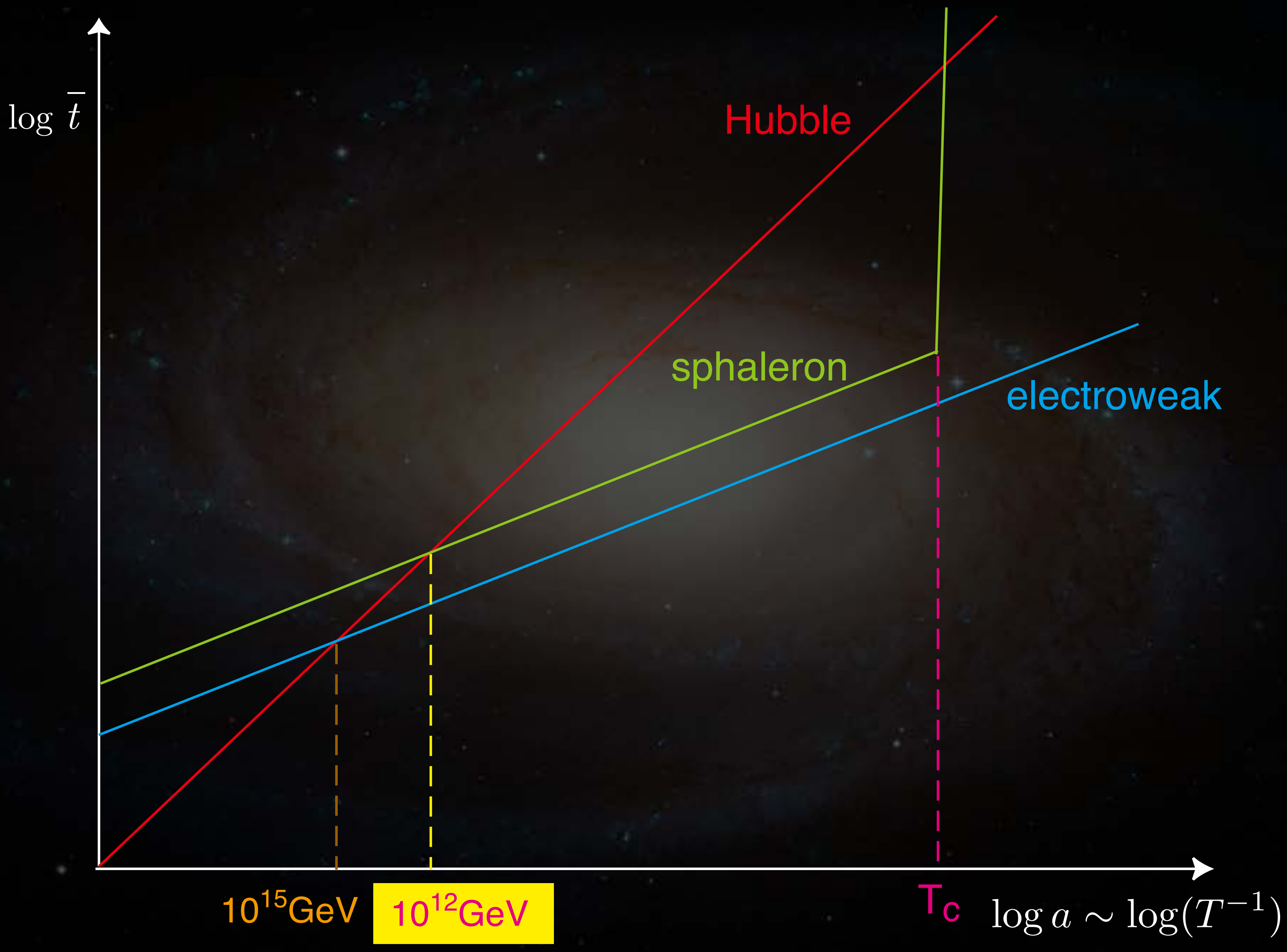
expansion	$H(T)^{-1} \simeq \frac{m_{\rm Pl}}{1.66\sqrt{g_*}T^2}$	$10^{14}\mathrm{GeV}^{-1}$
particle interaction	$\bar{t} \simeq \lambda_{\rm mfp} = \frac{1}{\sigma n(T)} \simeq \frac{1}{\alpha^2 T}$	$1 - 10\mathrm{GeV}^{-1}$
sphaleron process	$\bar{t}_{\rm sph}^{\rm (sym)} \simeq \frac{1}{\alpha_W^4 T}$	$10^3\mathrm{GeV}^{-1}$
	$\bar{t}_{\rm sph}^{\rm (br)} \simeq \frac{1}{\alpha_W^4 T} e^{E_{\rm sph}/T}$	

EW symmetric phase

$SU(2)\times U(1)$ restored

$$\bar{t}_{\rm QCD} < \bar{t}_{\rm EW} < \bar{t}_{\rm sph}^{\rm (sym)} << H(T)^{-1}$$

All the gauge interactions and sphaleron process are in chemical equilibrium.



$\log \bar{t}$
Hubble
sphaleron
electroweak
10^{15}GeV
10^{12}GeV
Tc
$\log a \sim \log(T^{-1})$

In order to have nonzero BAU at present, either of the followings had to occur.

(i) $B-L \neq 0$ exists before the sphaleron process decoupled.

(ii) $B+L$ was generated at the electroweak phase transition and the sphaleron process decoupled just after it.

(i) → Leptogenesis, (B–L)-violating GUTs, Affleck-Dine, ...

(ii) → Electroweak Baryogenesis

Can the SM make it possible ?

Electroweak Baryogenesis

based on the SM and its extension

testable
more constrained

(1) Baryon number violation sphaleron process

must decouple just after the PT

(2) CP violation KM phase is insufficient (see below)

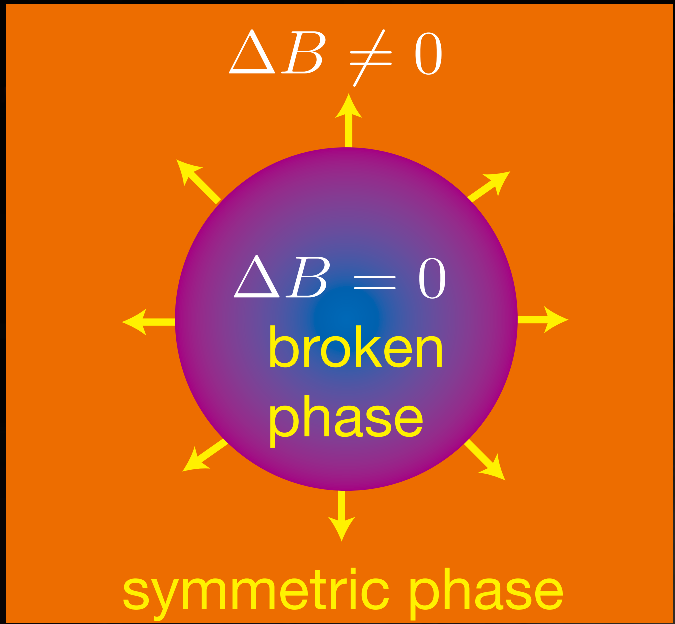
extension of the SM SUSY-SM, extra Higgs, ...

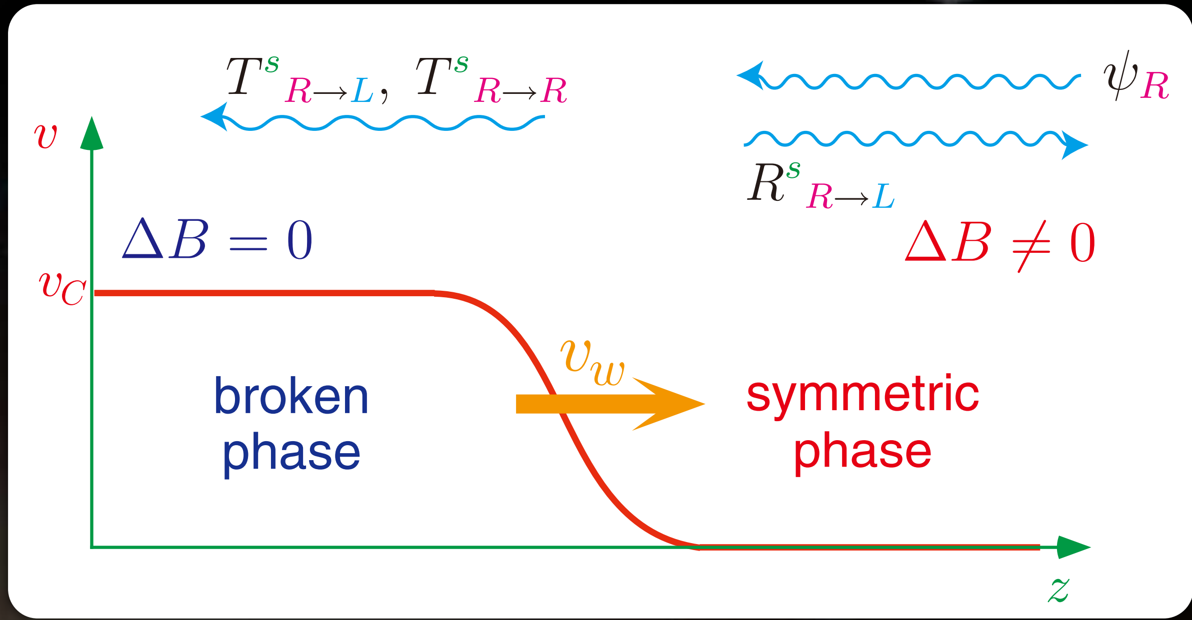
(3) Out of equilibrium At T=100GeV, one can ignore the expansion.

$$\bar{t}_{\rm EW} = 10{\rm GeV}^{-1} < \bar{t}^{\rm (sym)}_{\rm sph} = 10^3{\rm GeV}^{-1} \ll H(T)^{-1} = 10^{14}{\rm GeV}^{-1}$$

EW phase transition must be of first order accompanying nucleation and growth of the phase boundaries.

This also requires some extension of the SM.





particles interact with the bubble wall with CP violation

$q,\ l$ Higgs profile B-conserving

↓

difference in reflection rate of chiral fermions + bubble wall motion

↓

chiral charge flows into the symmetric phase region

$(Q_L - Q_R)(R^s_{R\to L} - R^s_{L\to R})$

conserved in the sym. phase $Q_Y,\ I_3$

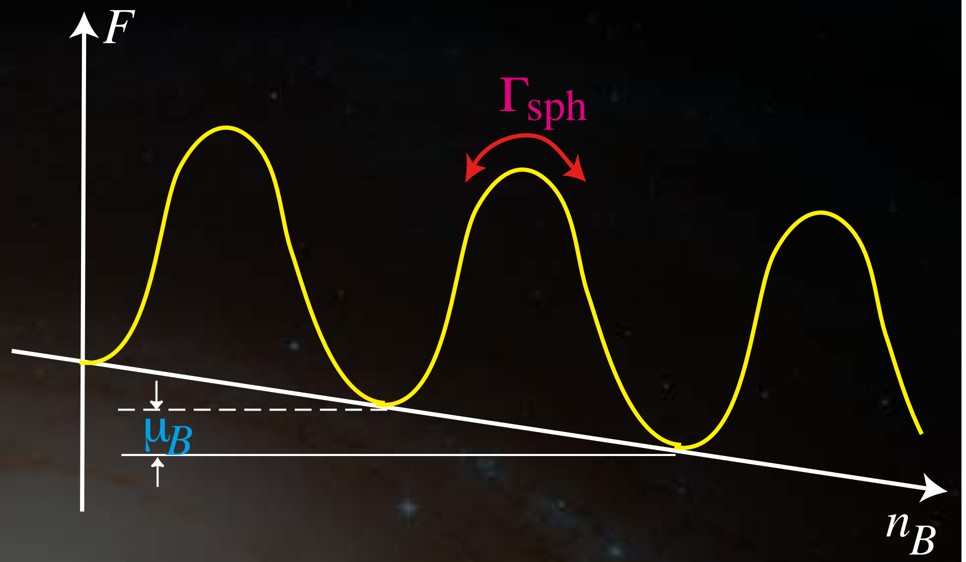
↓

bias on the sphaleron process in the sym. phase $\mu_B \neq 0$

↓

baryon number generation

$$\dot{n}_B = -\frac{\mu_B}{T}\Gamma_{\rm sph}^{\rm (sym)}(T)$$



↓

after the PT, frozen in the broken phase $\frac{v(T_C)}{T_C} > 1$

for detail, see KF, Prog. Theor. Phys. 96 ('96)

and other reviews

Rubakov and Shaposhnikov, Phys. Usp. 39 ('96) 461
Riotto and Trodden, Ann. Rev. Nucl. Part. Sci. 49 ('99) 35
Bernreuther, Lect. Notes Phys. 591 ('02) 237

Electroweak Phase Transition

Spontaneously broken SU(2)xU(1) restores at high temperatures

Standard Model

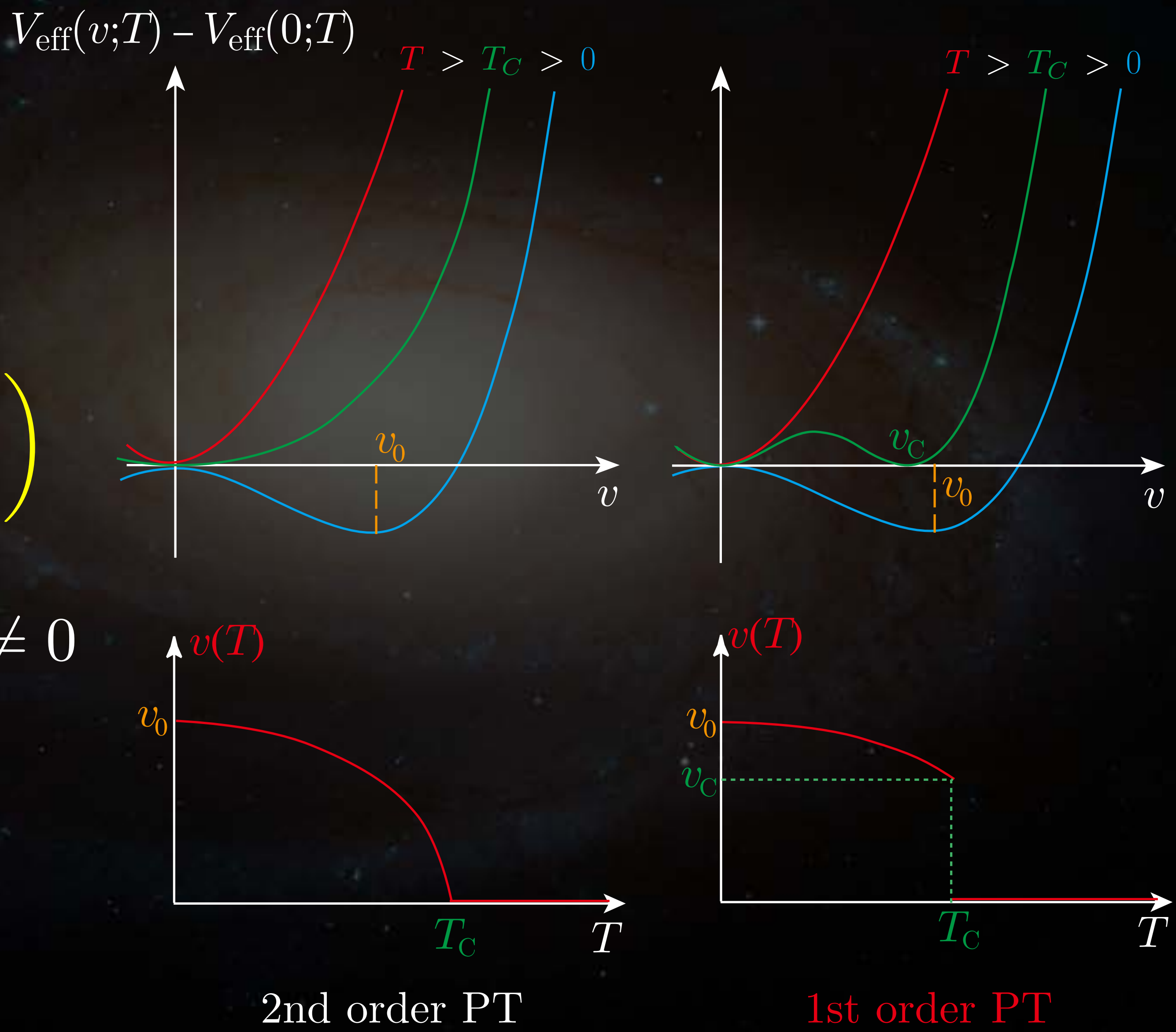
order parameter

$$\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v(T) \end{pmatrix}$$

$$v_C \equiv \lim_{T \uparrow T_C} v(T) \neq 0$$

⇕

first order



study by the effective potential (=free energy density)

Standard Model

$$V_{\text{eff}}(v;T) = -\frac{1}{2}\mu^2 v^2 + \frac{\lambda}{4}v^4 + 2Bv_0^2 v^2 + Bv^4\left[\log\left(\frac{v^2}{v_0^2}\right) - \frac{3}{2}\right] + \bar{V}(v;T)$$

$$B = \frac{3}{64\pi^2 v_0^4}(2m_W^4 + m_Z^4 - 4m_t^4)$$

$$\bar{V}(v;T) = \frac{T^4}{2\pi^2}\left[6I_B(a_W) + 3I_B(a_Z) - 6I_F(a_t)\right], \quad \left(a_A = \frac{m_A(v)}{T}\right)$$

$$I_{B,F}(a) \equiv \int_0^\infty dx\, x^2 \log\left(1 \mp e^{-\sqrt{x^2+a^2}}\right)$$

infrared unanalyticity

high-T expansion $[\, a = m/T \ll 1]$

$$I_B(a) = -\frac{\pi^4}{45} + \frac{\pi^2}{12}a^2 - \frac{\pi}{6}(a^2)^{3/2} - \frac{a^4}{16}\log\frac{\sqrt{a^2}}{4\pi} - \frac{a^4}{16}\left(\gamma_E - \frac{3}{4}\right) + O(a^6)$$

$$I_F(a) = \frac{7\pi^4}{360} - \frac{\pi^2}{24}a^2 - \frac{a^4}{16}\log\frac{\sqrt{a^2}}{\pi} - \frac{a^4}{16}\left(\gamma_E - \frac{3}{4}\right) + O(a^6)$$

Assuming $T > m_W, m_Z, m_t$

$$V_{\rm eff}(v;T) \simeq D(T^2 - T_0^2)v^2 - ETv^3 + \frac{\lambda_T}{4}v^4$$

$$D = \frac{1}{8v_0^2}(2m_W^2 + m_Z^2 + 2m_t^2), \qquad E = \frac{1}{4\pi v_0^3}(2m_W^3 + m_Z^3) \sim 10^{-2}$$

$$\lambda_T = \lambda - \frac{3}{16\pi^2 v_0^4}\left[2m_W^4 \log\frac{m_W^2}{\alpha_B T^2} + m_Z^4 \log\frac{m_Z^2}{\alpha_B T^2} - 4m_t^4 \log\frac{m_t^2}{\alpha_F T^2}\right.$$

$$T_0^2 = \frac{1}{2D}(\mu^2 - 4Bv_0^2), \qquad \log \alpha_{F(B)} = 2\log(4)\pi - 2\gamma_E$$

At T_C $v = 0$ degenerates with v_C $\qquad v_C = \frac{2ET_C}{\lambda_{T_C}}$

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

sphaleron decoupling condition

→ upper bound on λ $\xrightarrow{m_h = \sqrt{2}\,\lambda v_0}$ $m_h < 46\,\mathrm{GeV}$

Lattice MC calculation

scalar fields $\Phi(x)$ → sites

gauge fields $U_\mu(x) = e^{igA_\mu(x)}$ → links

$$Z(T) = \mathrm{Tr}\left(e^{-H/T}\right) = \int_{\phi(1/T)=\phi(0)} [d\Phi\, dU_\mu]\exp(-S_E[\Phi, U])$$

Standard Model

3-dim. system high-T limit [Laine & Rummukainen, hep-lat/9809045]

4-dim. 1st order PT at $m_h < 66.5 \pm 1.4\mathrm{GeV}$ [Csikor, hep-lat/9910354]

both find the end point of PT at

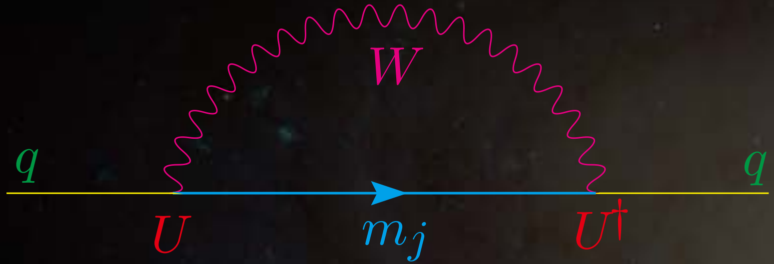
$m_h = 72.3 \pm 0.7\mathrm{GeV}$

$m_h = 72.1 \pm 1.4\mathrm{GeV}$

Can the SM generate the BAU ?

★ $m_h > 114\text{GeV}$ → no phase boundary   out ~~of~~ equil.

★ viable CP violation is the KM phase



$m_i \neq m_j$

→ O(α_W) CP viol. in the dispersion

[Farrar and Shaposhnikov, Phys. Rev. D50 ('94)]

It is too small, since it is a one-loop effect.

decoherence by QCD correction and multiple scattering with the wall

[Gavela, et al., Nucl. Phys. B430 ('94)]   [Huet and Sather, Phys. Rev. D51 ('95)]

$$\rightarrow \quad \left|\frac{n_B}{s}\right| < 10^{-26}$$

Extensions of the SM are needed for

1st order EWPT and CP violation

for 1st order EWPT

- from bosonic loops $V_{\text{eff}}(v;T) \sim -T\left(m(v)^2\right)^{3/2}$

  bosons interacting with the Higgs $m(v)^2 \sim g^2 v^2$ (for $v \sim 0$)

  extra Higgs in the 2HDM, sferminos in SUSY-SM

$$m(v)^2 = m_0^2 + g^2 v^2 \quad (m_0^2 \ll g^2 v_0^2)$$

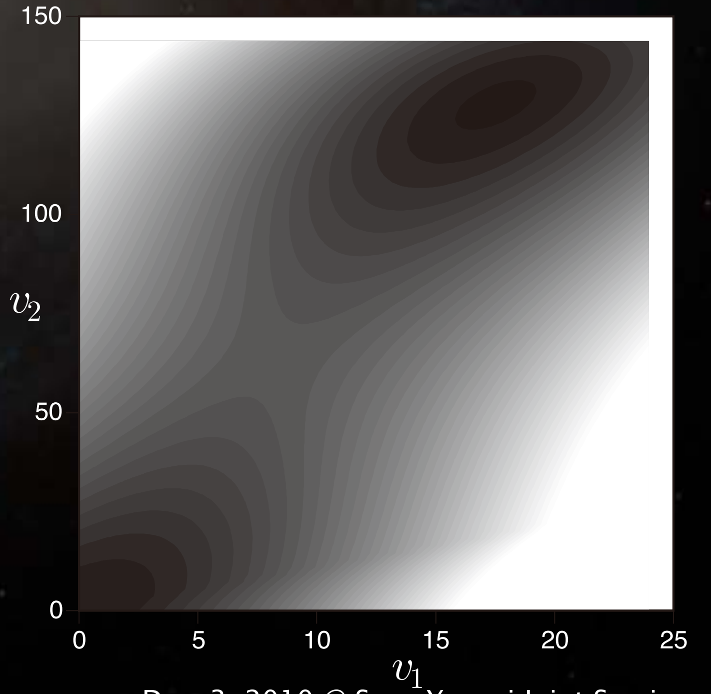
e.g. MSSM $m_{H^\pm} > 200\text{GeV}$ ⟶ SM-like EWPT

light Higgs, light stop

$m_h < 105\text{GeV},\ m_{\tilde{t}_1} < m_t$

⟶ $v_C/T_C > 1$

$V_{\text{eff}}(v_1, v_2, v_3 = 0; T_C)$



- new type of PTs in a mode with a singlet scalar

  NMSSM [KF, Tao and Toyoda, PTP 114 ('05)]

complex parameters for CP violation

- ★ **scalar self-interaction**

  $\lambda_{6,7}$ in 2HDM; μB, A in the MSSM

- ★ **complex Majorana mass**

  gaugino mass, μ in the MSSM

- ★ **expectation values of complex scalar fields**

  relative phase of the expectation values
  in the neighborhood of the bubble wall

some combinations of these phase are physical

$\mathrm{Im}(\mu M_2)$, $\mathrm{Im}(\mu A_t)$, $\cdots$

constrained by experiments: EDM, decay asym., etc.

With these extensions, successful models can be constructed.

MSSM a light stop is necessary

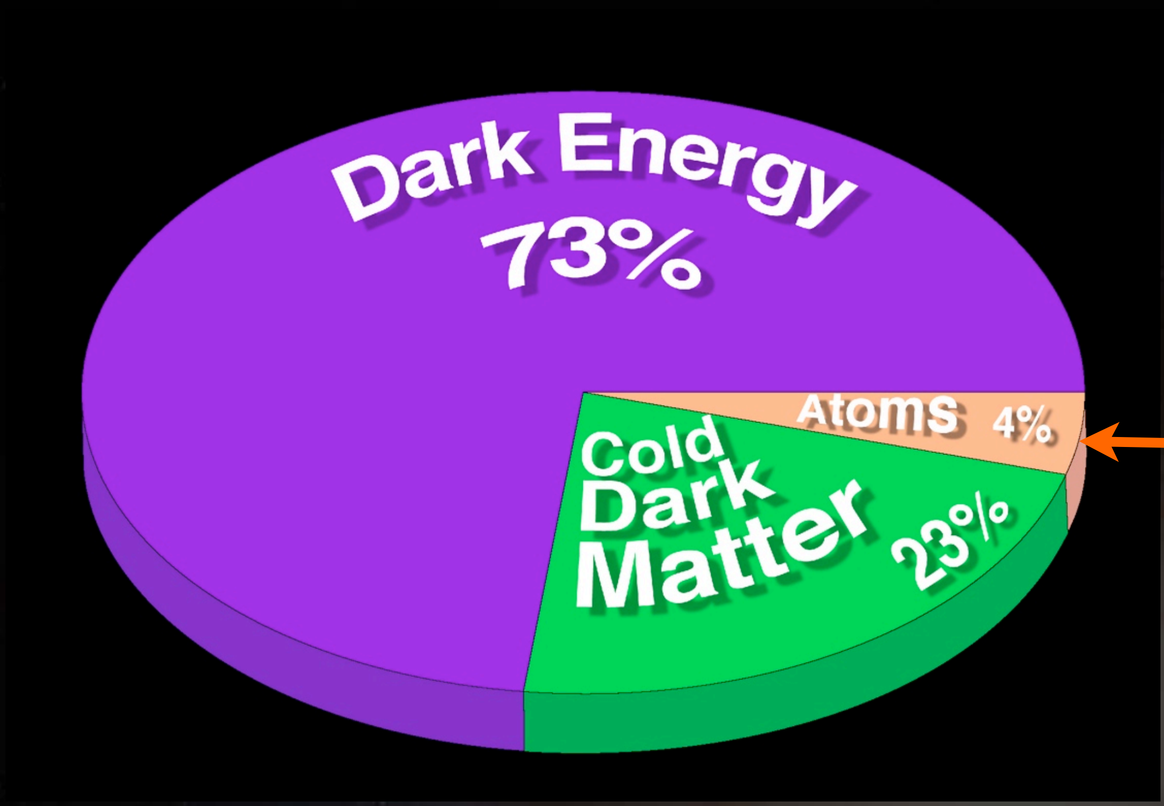
non-SM like EWPT requires light Higgs bosons

decoupling limit → SM-like EWPT

2HDM
NMSSM still broad parameter space is available
etc.

Concluding remarks

- ★ The existence of the BAU is obvious and its value is definite.
- ★ The Standard Model cannot explain the origin of the BAU.
- ★ Some extensions of the SM could generate the BAU at the EW scale.
- ★ Leptogenesis, Affleck-Dine mechanism and GUTs baryogenesis are still candidates for the origin, but it’s difficult to check whether one of them did generate the BAU.



We've discussed this tiny portion.

A discovery of CP violation beyond the KM phase is an essential key to the origin of matter in the Universe.