現代宇宙論

No. 9

What is Baryogenesis?

- One of unsolved physics problems
  - We are sure that we live in matter Universe (not antimatter Universe)
  - Why is there more matter than antimatter in observable Universe?
- Baryogenesis = Baryon + Genesis

Anti particle

Dirac equation for free electron: $(i\gamma^\mu \partial_\mu - m)\psi = 0$

Two solutions
- electron
- almost identical to electron with opposite electric charge

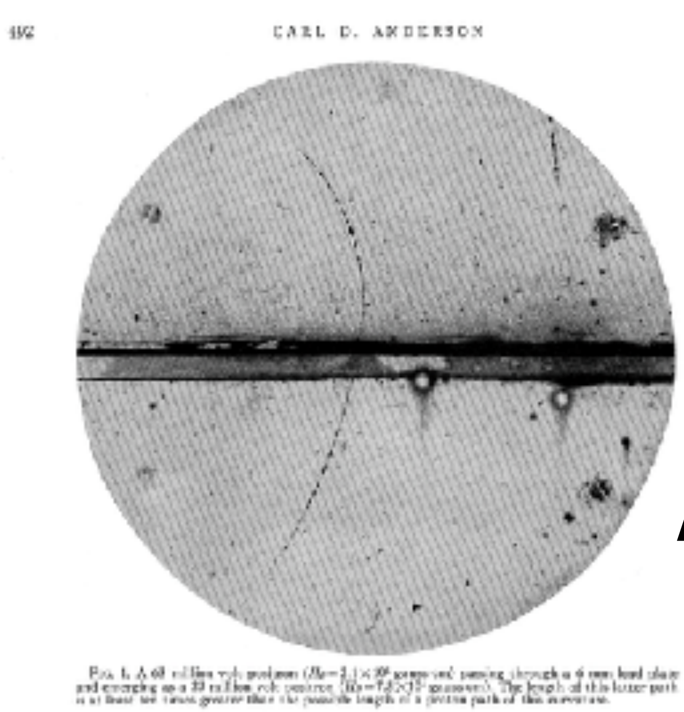
Existence of antiparticle is theoretically predicted (1928)

↓

Discovery of positron (1932)

=

anti-electron



All particles have antiparticles

Same mass, same spin, opposite charge

Definition of anti-particles

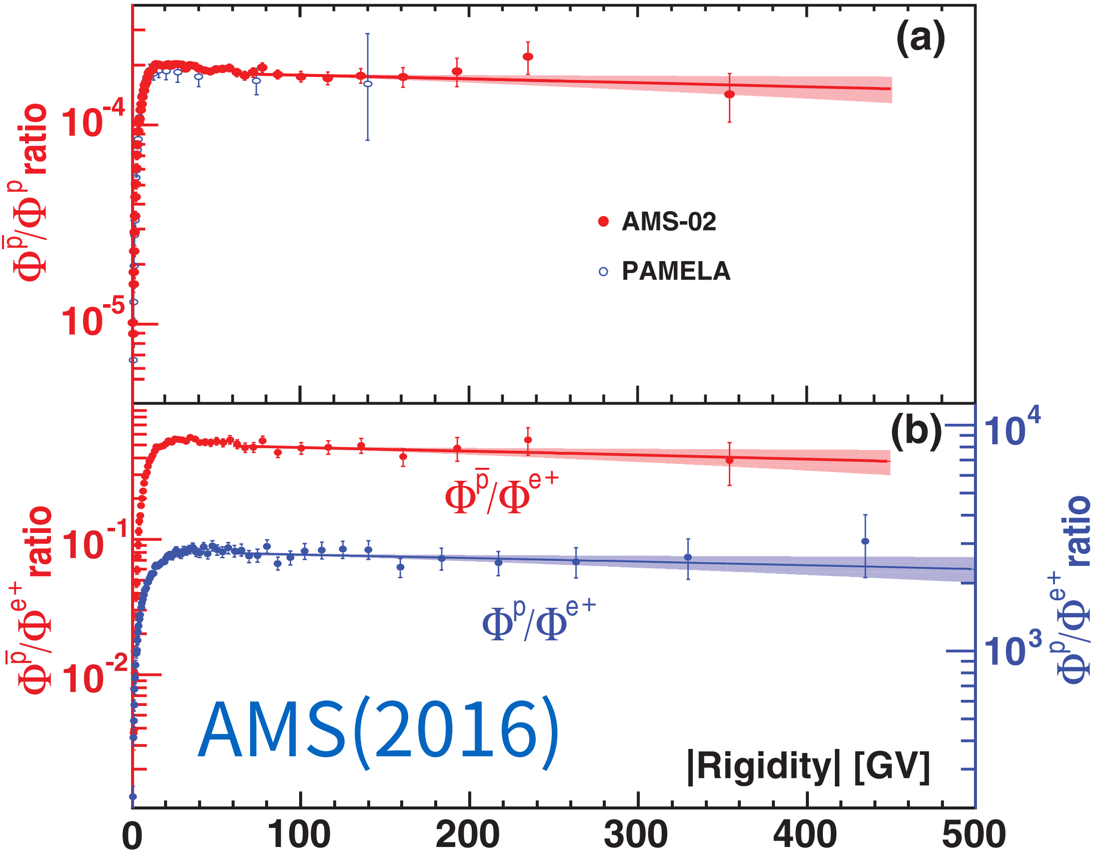
- Quantum ElectroDynamics
  - Symmetric under **C**harge conjugation
- Weak gauge theory (SM)
  - Charge conjugation symmetry is hardly broken
  - **CP** symmetry is an approximate symmetry
    (It is broken by KM phase)

In the weak theory, it is natural to define antiparticle not by C conjugation but by CP conjugation

Observations

We mainly observe matter (not antimatter)

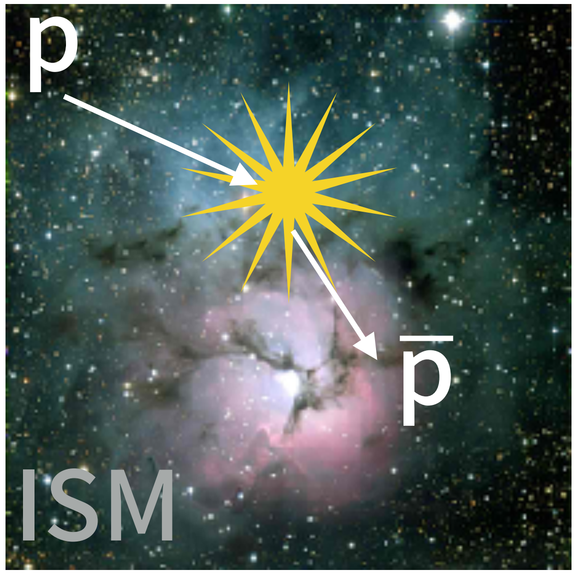
- Earth, Sun, Solar system, …
- Cosmic ray from our galaxy



$$\frac{\text{Anti-proton}}{\text{Proton}} \sim 10^{-4}$$

Consistent with secondary production

$$p + p \to p + p + p + \bar{p}$$



Baryon Asymmetry

There are several ways to describe BAU

- Baryon to photon ratio $\eta = \dfrac{n_b - n_{\bar{b}}}{n_\gamma}$
- Baryon to entropy ratio $Y_B = \dfrac{n_b - n_{\bar{b}}}{s}$ ← Conserved during the expansion of Universe
- Baryonic fraction $\Omega_B = \rho_B / \rho_{\rm crit}$

$$n_\gamma = \frac{2\zeta(3)}{\pi^2} T^3 \simeq 0.2436 T^3$$

$$s = \frac{2\pi^2}{45} g_* T^3 \quad g_* = \frac{43}{11}\text{(at the present age)}$$

$$\longrightarrow \eta = \frac{Y_B}{7.04}$$

Baryonic fraction is related to η as $\eta = 2.74 \times 10^{-8} \Omega_B h^2$

Baryon asymmetry

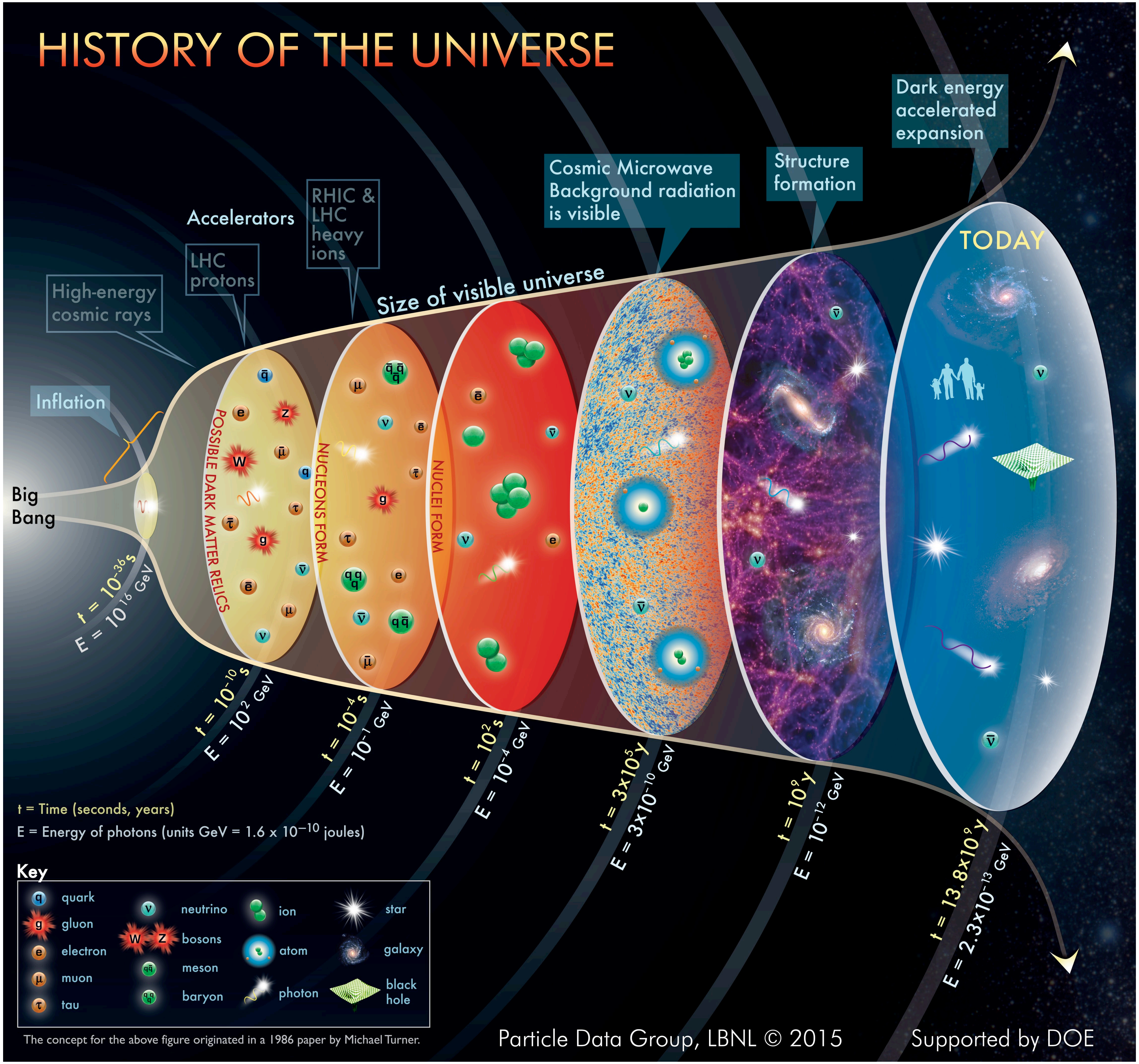
$$Y_B = \frac{n_b - n_{\bar{b}}}{s} = (0.92 \pm 0.05) \times 10^{-10}$$

or

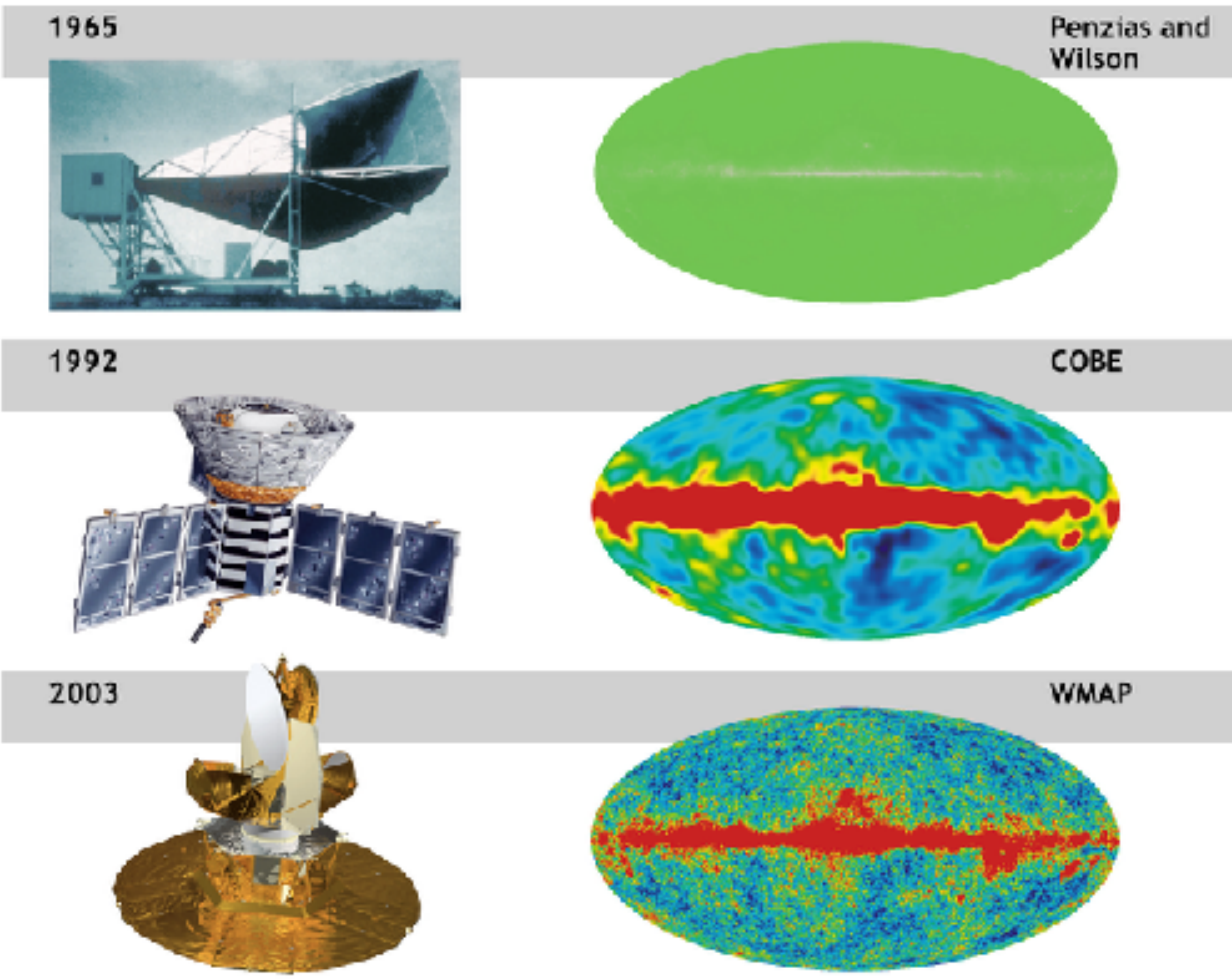
$$\eta = \frac{n_b - n_{\bar{b}}}{n_\gamma} = (6.5 \pm 0.3) \times 10^{-10}$$

How can it be determined by observations?

- Cosmic Microwave Background
- Abundance of light elements


HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Structure formation
Cosmic Microwave Background radiation is visible
RHIC & LHC heavy ions
Accelerators
LHC protons
High-energy cosmic rays
Size of visible universe
TODAY
Inflation
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^-36 s
E = 10^16 GeV
t = 10^-10 s
E = 10^2 GeV
t = 10^-4 s
E = 10^-1 GeV
t = 10^2 s
E = 10^-4 GeV
t = 3x10^5 y
E = 3x10^-10 GeV
t = 10^9 y
E = 10^-12 GeV
t = 13.8x10^9 y
E = 2.3x10^-13 GeV
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6 x 10^-10 joules)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
The concept for the above figure originated in a 1986 paper by Michael Turner.
Particle Data Group, LBNL © 2015
Supported by DOE

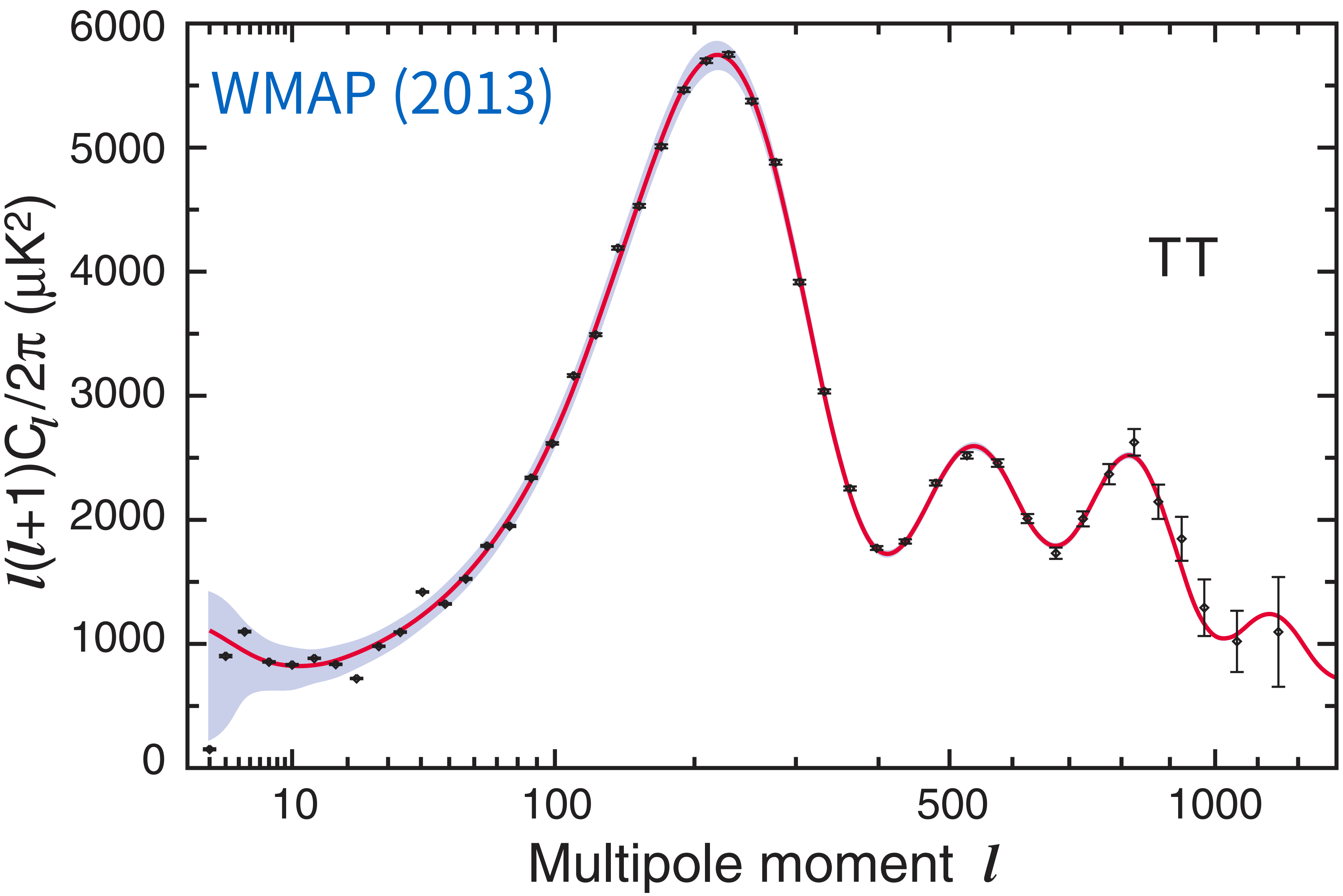
Cosmic Microwave Background



Discovery of 3K microwave background is the first evidence of the Big Bang.

Fluctuations of CMB provides us rich information of our Universe

Power spectrum of CMB



Temperature fluctuations

↓

correlation

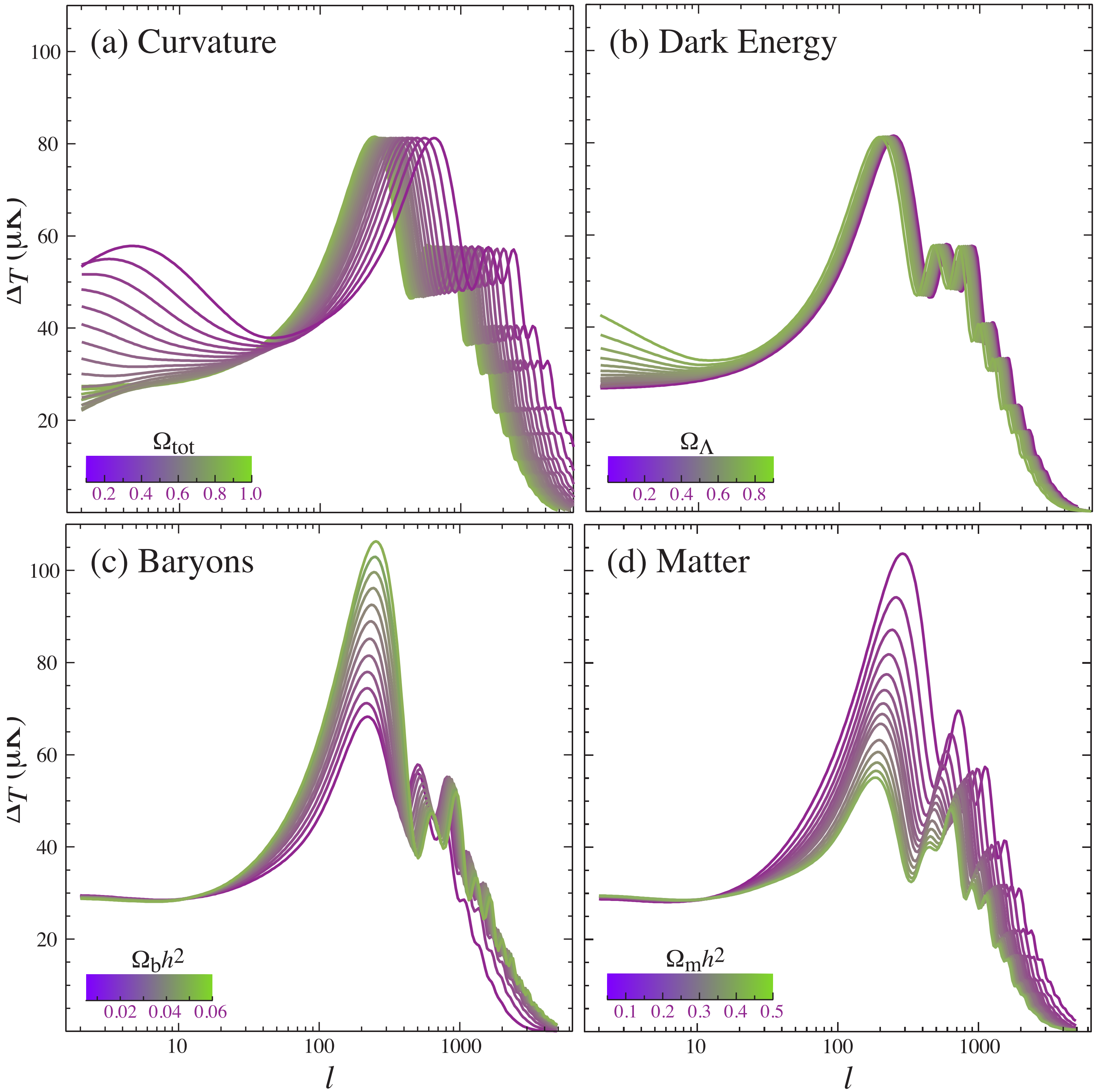
$$\left\langle \frac{\delta T(x)}{T} \frac{\delta T(y)}{T} \right\rangle$$

↓ **Fourier trf**

$$C_\ell$$

ℓ **vs** $\dfrac{\ell(\ell+1)C_\ell}{2\pi}$

Dependence on parameters

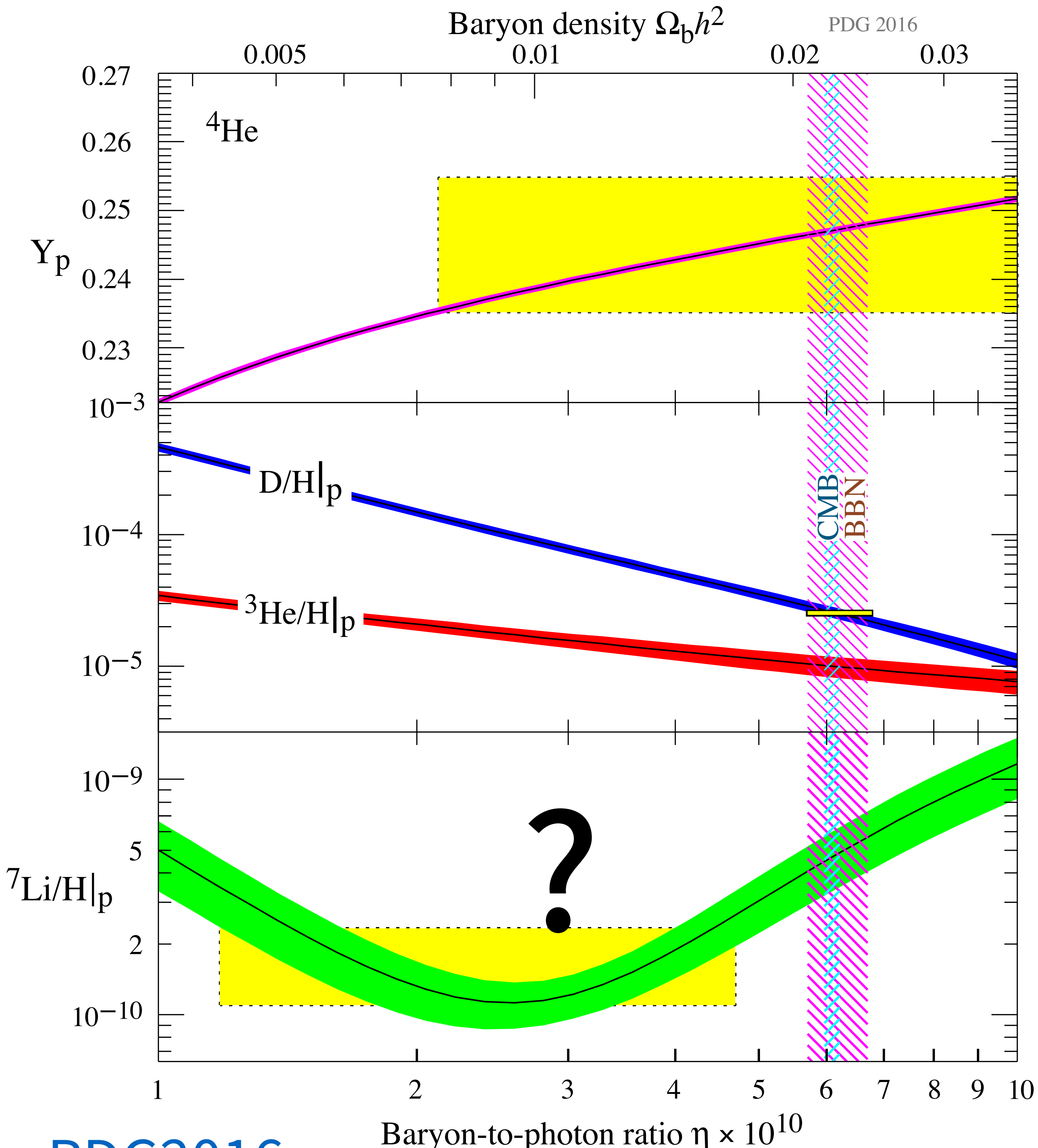


W. Hu and S. Dodelson, astro-ph/0110414

You can play a game at

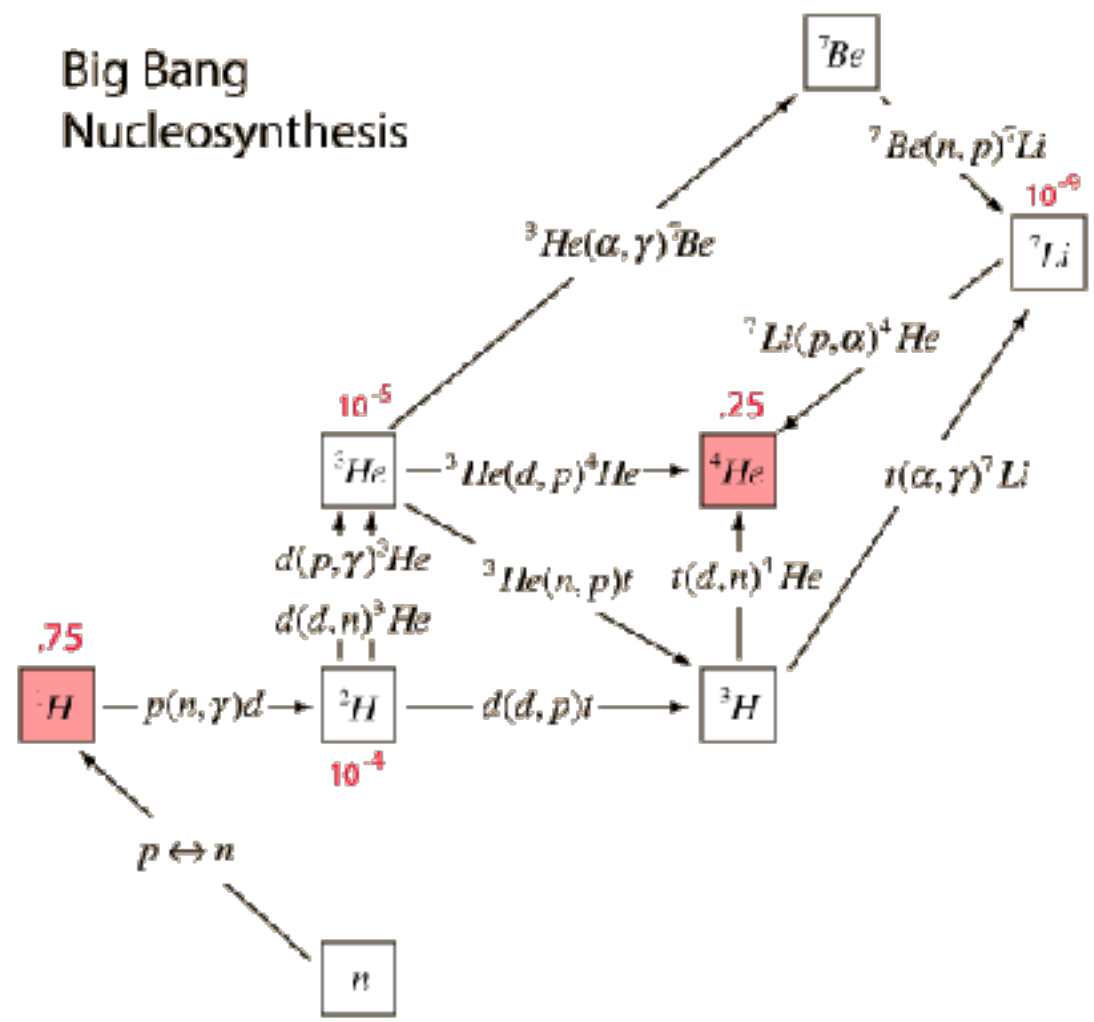
https://map.gsfc.nasa.gov/resources/camb_tool/

Big Bang Nucleosynthesis



PDG2016

One of a great success of the Big Bang cosmology is BBN



It is controlled by BAU

Baryogenesis

$$\frac{n_B}{s} = \frac{n_b - n_{\bar{b}}}{s} = (0.92 \pm 0.05) \times 10^{-10}$$

The observations (CMB, BBN) strongly suggest baryon asymmetric Universe

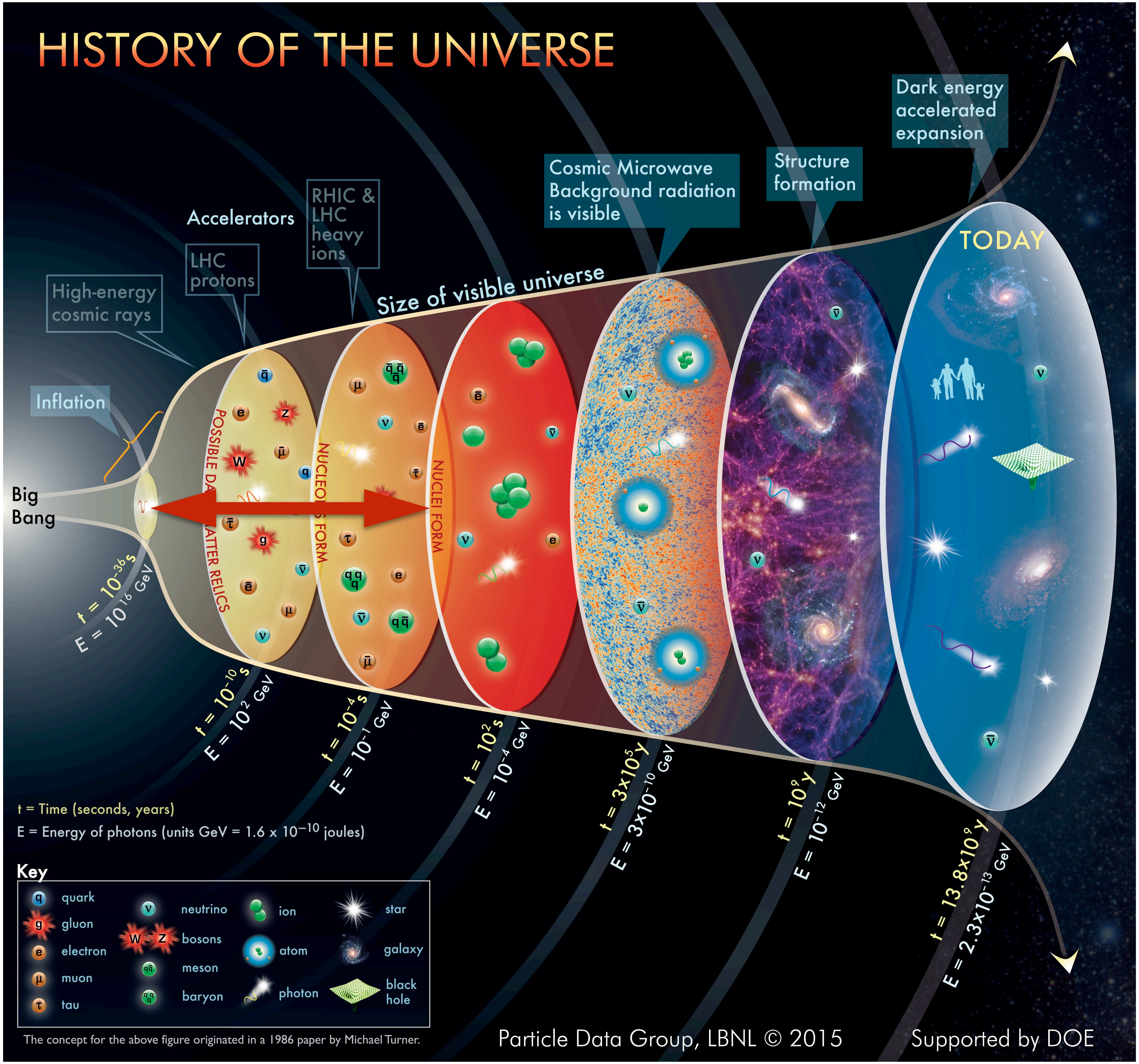
Baryogenesis

How can we produce the appropriate amount of asymmetry in baryon symmetric Universe?

One comment:

In inflation scenario, primordial baryon number is diluted by reheating of Universe

Baryogenesis should occur after inflation!



After inflation, before BBN ($T=O(\mathrm{MeV})$)

Sakharov's conditions

In order to produce BAU, the following three conditions should be satisfied.

- ☆ Baryon number is violated
- ☆ Both C and CP are violated
- ☆ There is an interaction outside of thermal equilibrium

Baryon number violation

#B conservation $\longrightarrow$ no BAU is obtained

$$\cancel{X \to Y + B} \qquad X \to Y + B + \bar{B}$$ (no asymmetry)

In the SM Lagrangian,
there is an accidental global $U(1)_B$ symmetry

$U(1)_{B+L}$ is broken by anomaly (explained later)

In BSM, baryon number violating interaction can be introduced

- GUT: X boson (leptoquarks)
- MSSM: R-parity violating terms

Proton decay search constrains such interactions

C and CP violation

In C symmetric Universe,

$$\Gamma(X \to Y + B) = \Gamma(\bar{X} \to \bar{Y} + \bar{B})$$

B and anti-B are produced with the same rate!

In CP symmetric Universe, let's consider the process

$$\Gamma(X \to q_L q_L) \neq \Gamma(\bar{X} \to \bar{q}_L \bar{q}_L)$$

$$\Gamma(X \to q_L q_L) = \Gamma(\bar{X} \to \bar{q}_R \bar{q}_R) \qquad \Gamma(\bar{X} \to \bar{q}_L \bar{q}_L) = \Gamma(X \to q_R q_R)$$

$$\Gamma(X \to q_L q_L) + \Gamma(X \to q_R q_R) = \Gamma(\bar{X} \to \bar{q}_R \bar{q}_R) + \Gamma(\bar{X} \to \bar{q}_L \bar{q}_L)$$

Then the B and anti-B are produced with the same rate!

C and CP violation

More precisely,

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

Observable: $\langle\mathcal{O}\rangle(t) = \mathrm{tr}[\rho(t)\mathcal{O}]$

Time evolution of the density operator is described by Liouville equation

$$i\frac{\partial\rho(t)}{\partial t} + [\rho(t), H] = 0$$

Initial condition: Baryon symmetric Universe

$$\langle n_B\rangle_0 = \mathrm{tr}\left[\rho_0 n_B\right] = 0$$

C and CP violation

Universe is C or CP symmetric $\longrightarrow [H, C] = 0$ or $[H, CP] = 0$

$\downarrow$

$[\rho, C] = 0$ or $[\rho, CP] = 0$

Baryon number is odd under C and CP

$$C n_B C^{-1} = -n_B \qquad (CP) n_B (CP)^{-1} = -n_B$$

Therefore,

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

or

$$\langle n_B \rangle = \mathrm{tr}[\rho n_B] = \mathrm{tr}[\rho C P n_B (CP)^{-1}] = -\mathrm{tr}[\rho n_B] = 0$$

Both C and CP should be broken !

Out of equilibrium

In thermal equilibrium, $t = \frac{1}{\Gamma} \ll t_H = \frac{1}{H(T)}$

$$\Gamma(X \to Y + B) = \Gamma(Y + B \to X)$$

The produced Baryon number is washed out by the inverse process!

↓

Any baryogenesis must happen under conditions outside of thermal equilibrium

e.g. Heavy particle decay in expanding Universe

$$\Gamma_D(X \to qq) \simeq H(T = m_X) \qquad H(T) \simeq 1.66\sqrt{g_*}\frac{T^2}{m_{\rm PL}}$$

(radiation dominant era)

The process becomes out of equilibrium

Boltzmann equation

How to treat out-of-equilibrium processes?

The out-of-equilibrium is caused by Hubble expansion, and the process is homogenous

↓

We can use Boltzmann equation

Current anomaly in SM

B,L currents are anomalous in the SM

$$\partial_\mu j^\mu_B = \partial_\mu j^\mu_L = \frac{N_f}{32\pi^2}\left[g^2 \mathrm{tr}(W^a_{\mu\nu}\tilde{W}^{a\mu\nu}) - g'^2 B_{\mu\nu}\tilde{B}^{\mu\nu}\right]$$

↓

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

B+L is violated due to the vacuum structure

$$\partial_\mu j^\mu_{B+L} = 2N_f \partial_\mu K^\mu$$

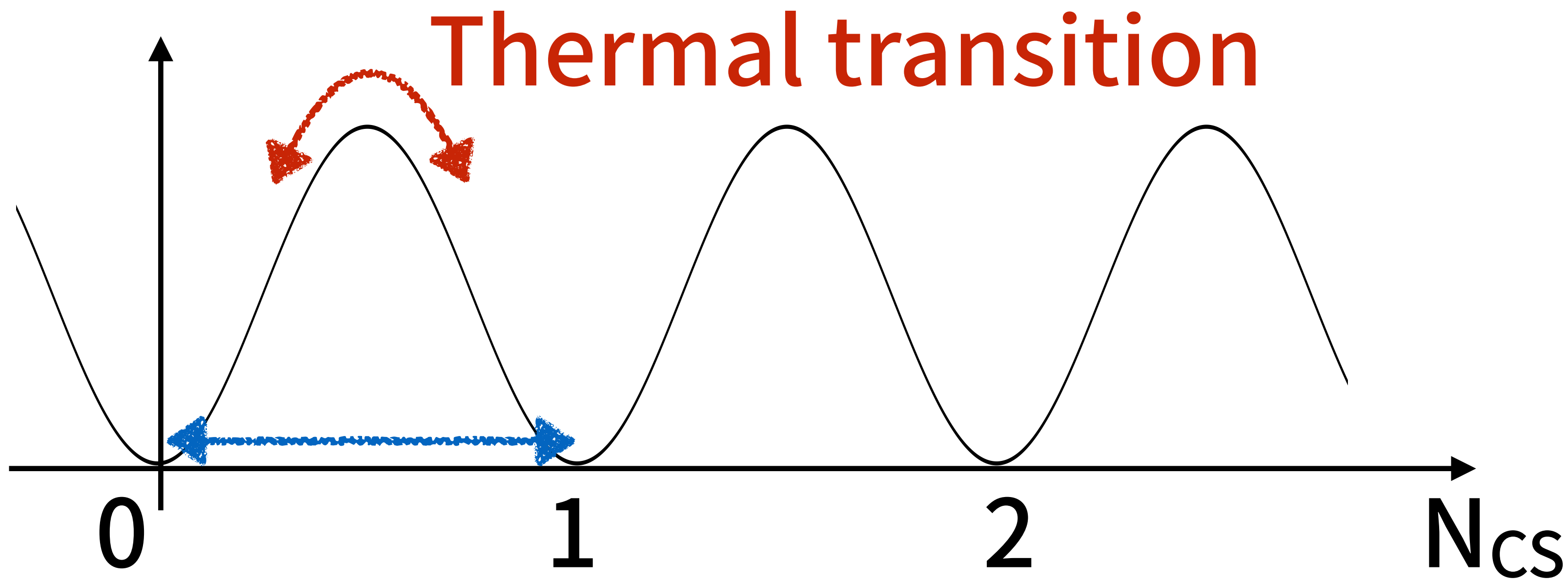
$$B(t_f) - B(t_i) = \int_{t_i}^{t_f} dt \int d^3x \partial^\mu j_{B\mu} = N_f \left[N_{cs}(t_f) - N_{cs}(t_i)\right]$$

$$N_{cs}(t) = \frac{g^3}{96\pi^2}\int d^3x \epsilon_{ijk}\epsilon^{IJK} W^{Ii} W^{Jj} W^{Kk}$$

Chern-Simons number $\Delta N_{cs} = \pm 1, \pm 2, \cdots$

Vacuum structure

Classical vacuum of the SU(2) gauge system



$$W_\mu = iU^{-1}\partial_\mu U$$

$$U \in \mathrm{SU}(2) \simeq S^3$$

$$\pi_3(S^3) = Z$$

The vacuum is characterised by N_{CS}

Tunnelling rate $\sim e^{-2S_{\text{instanton}}} = e^{-8\pi^2/g^2} \simeq e^{-164} \ll 1$

Thermal transition rate
- symmetric phase $\Gamma \simeq T^4 e^{-E_{\text{sph}}/T}$
- broken phase $\Gamma \simeq \kappa(\alpha_W T)^4$

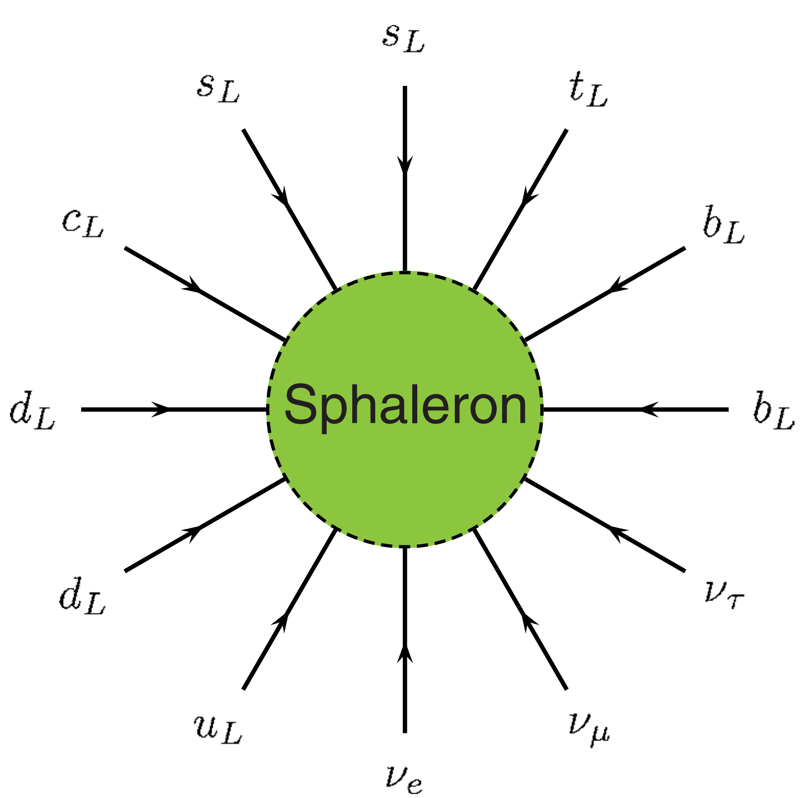
It is significant at finite temperature

Sphaleron

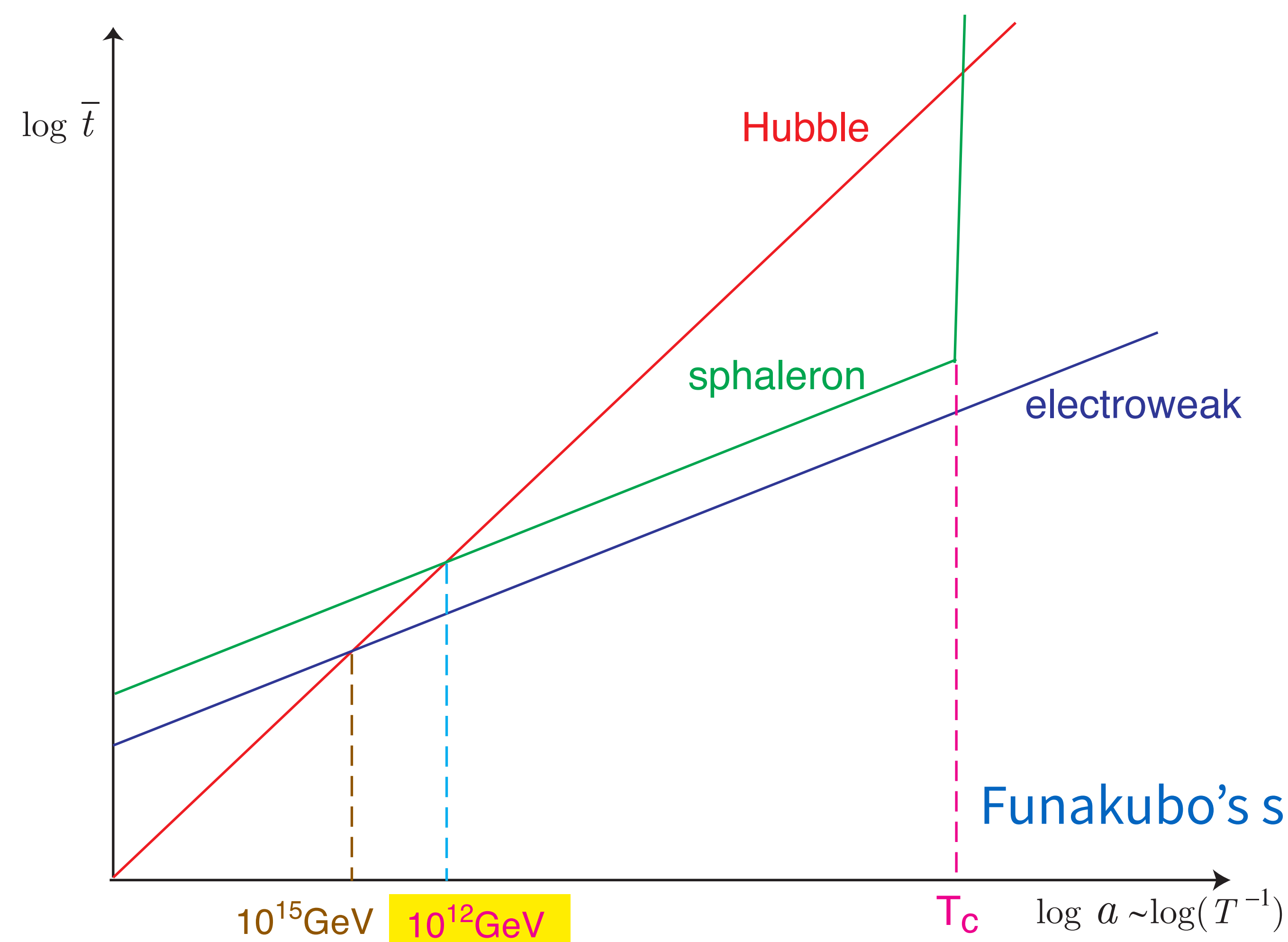
“Sphaleron process” leads to the effective operator

$$O_{B+L} = \Pi_i (q_{Li} q_{Li} q_{Li} \ell_{Li})$$

All left handed!



Taken from hep-ph/0406014



The process is in the thermal bath at

$$100 \text{ Gev} \leq T \leq 10^{12} \text{ GeV}$$

Sphaleron

- B+L is violated (only in the left-hand fermions)
- B-L is conserved
- The process is relevant when T=100GeV-10^{12}GeV

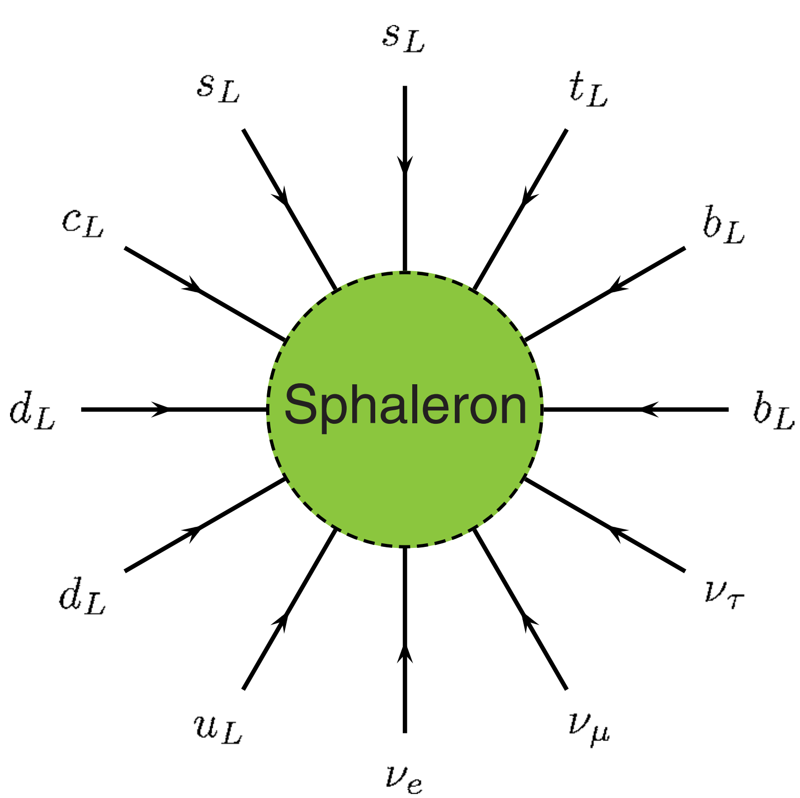
Because of the sphaleron, all the baryogenesis scenarios are classified into two cases

- B-L is produced before the sphaleron decoupling era.
- B is produced by the 1st order electroweak phase transition just before the sphaleron decoupling.

Sphaleron

"Sphaleron process" leads to the effective operator

$$O_{B+L} = \Pi_i(q_{Li}q_{Li}q_{Li}\ell_{Li})$$ **All left handed!**



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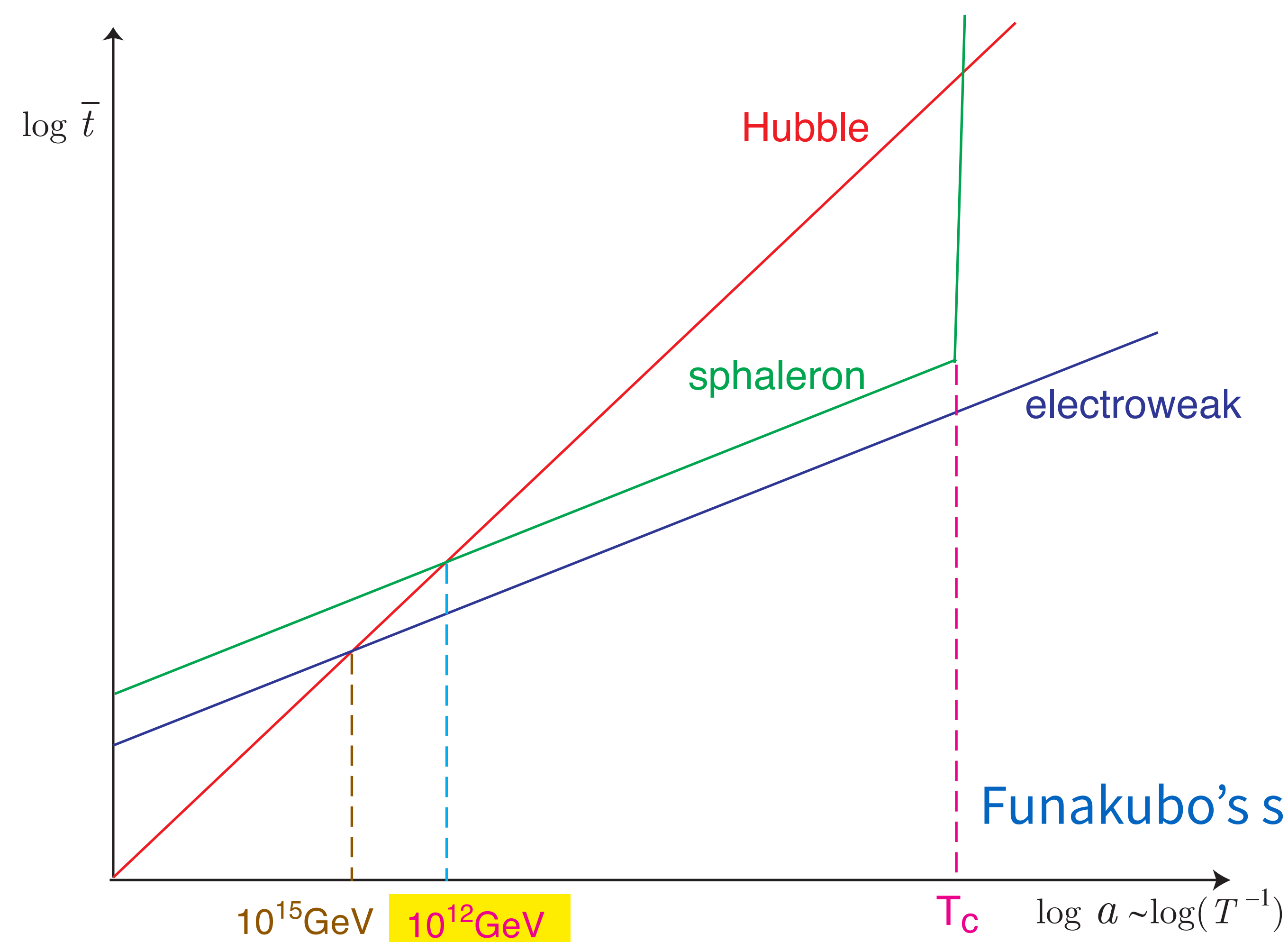


Funakubo's slide

The process is in the thermal bath at

$$100 \text{ Gev} \leq T \leq 10^{12} \text{ GeV}$$

Scenarios of Baryogenesis

Very many scenarios are considered in literatures

Shaposhnikov, J.Phys.Conf.Ser.171:012005,2009.

1. GUT baryogenesis. 2. GUT baryogenesis after preheating. 3. Baryogenesis from primordial black holes. 4. String scale baryogenesis. 5. Affleck-Dine (AD) baryogenesis. 6. Hybridized AD baryogenesis. 7. No-scale AD baryogenesis. 8. Single field baryogenesis. 9. Electroweak (EW) baryogenesis. 10. Local EW baryogenesis. 11. Non-local EW baryogenesis. 12. EW baryogenesis at preheating. 13. SUSY EW baryogenesis. 14. String mediated EW baryogenesis. 15. Baryogenesis via leptogenesis. 16. Inflationary baryogenesis. 17. Resonant leptogenesis. 18. Spontaneous baryogenesis. 19. Coherent baryogenesis. 20. Gravitational baryogenesis. 21. Defect mediated baryogenesis. 22. Baryogenesis from long cosmic strings. 23. Baryogenesis from short cosmic strings. 24. Baryogenesis from collapsing loops. 25. Baryogenesis through collapse of vortons. 26. Baryogenesis through axion domain walls. 27. Baryogenesis through QCD domain walls. 28. Baryogenesis through unstable domain walls. 29. Baryogenesis from classical force. 30. Baryogenesis from electrogenesis. 31. B-ball baryogenesis. 32. Baryogenesis from CPT breaking. 33. Baryogenesis through quantum gravity. 34. Baryogenesis via neutrino oscillations. 35. Monopole baryogenesis. 36. Axino induced baryogenesis. 37. Gravitino induced baryogenesis. 38. Radion induced baryogenesis. 39. Baryogenesis in large extra dimensions. 40. Baryogenesis by brane collision. 41. Baryogenesis via density fluctuations. 42. Baryogenesis from hadronic jets. 43. Thermal leptogenesis. 44. Nonthermal leptogenesis.

Now even more…

Baryogenesis

There are two possible cases of Baryogenesis

1. B-L is produced before the sphaleron decoupling era.

2. B is produced by the 1st order electroweak phase transition just before the sphaleron decoupling.

Let us first consider the case 1

Conversion to #B

Number densities in terms of chemical potential (μ)

q_L	u_R	d_R	ℓ_L	e_R	h
μ_q	μ_u	μ_d	μ_ℓ	μ_e	μ_h

6 parameters

Here, flavour effect is neglect for simplicity

Gauge+Yukawa+Sphaleron are in thermal equilibrium

Sphaleron: $O_{B+L} = \Pi_i(q_{Li}q_{Li}q_{Li}\ell_{Li}) \longrightarrow N_f(3\mu_q + \mu_\ell) = 0$

Yukawa: $\mu_h = \mu_u - \mu_q = \mu_q - \mu_d = \mu_\ell - \mu_e$

Hyper charge conservation:

$$N_f\left(\frac{1}{6}\times 3\times 2\times \mu_q + \frac{2}{3}\times 3\times \mu_u - \frac{1}{3}\times 3\times \mu_d - \frac{1}{2}\times 2\times \mu_\ell - \mu_e\right) + \frac{1}{2}\times 2\times 2\times \mu_h = 0$$

5 equations

Conversion to #B

With $B = N_f(2\mu_q + \mu_u + \mu_R)$
$L = N_f(2\mu_\ell + \mu_e)$ (in the unit of $T^2/6$)

$\downarrow$

$$B = \frac{8N_f + 4}{22N_f + 13}(B - L)$$

#(B-L) is converted to #B

If #L is produced, it is converted to #B $\longrightarrow$ Leptogenesis

Thermal Leptogenesis

M. Fukugida&T. Yanagida, PLB174,45;
W. Buchmüller, P. Di Bari, and M. Plümacher, Annals. Phys. 315,305;
G. F. Giudice et al, NPB685,89 ....

Basic idea:

- Introducing Right-handed neutrinos to the SM
  - By seesaw mechanism, light neutrino masses are generated
- Right-handed neutrino decay produces lepton number
- The lepton number is converted to the Baryon number by sphaleron process

Seesaw model

Introducing Right-hand neutrinos (RNs) to the SM

☆ RNs are singlet under SM gauge group

☆ RNs have Majorana mass terms

$$-\mathcal{L} = Y_E \bar{e}_R \ell_L \cdot \bar{\phi} + Y_N \bar{N} \ell_L \cdot \phi + \frac{1}{2} M_N \bar{N} N^c$$

↓ RNs are integrated out

$$-\mathcal{L} = Y_E \bar{e}_R \ell_L \cdot \bar{\phi} - \frac{1}{2} \kappa (\ell_L \cdot \phi)^2 \qquad \kappa = Y_N^T M_N^{-1} Y_N$$

PMNS matrix

$$m_\nu = U^* \mathrm{diag}(m_1, m_2, m_3) U^\dagger = \langle \phi \rangle^2 \kappa$$

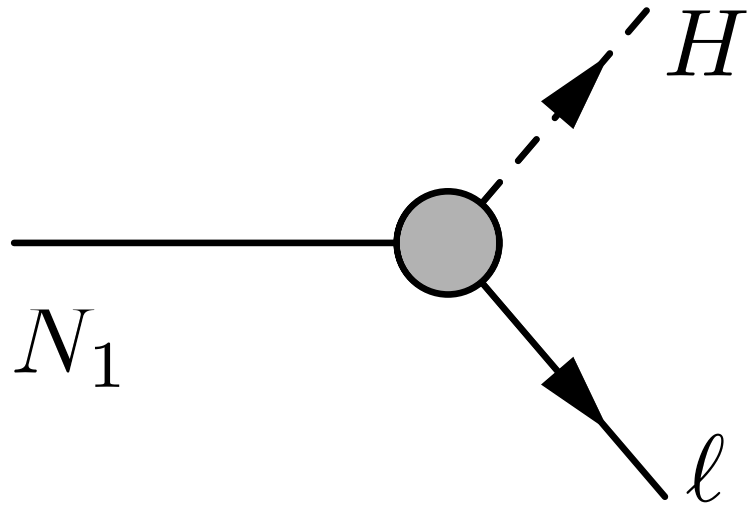
Tiny neutrino mass is naturally generated

e.g. $m_\nu \sim 0.1 \text{ eV} \quad Y_N \sim y_\tau \longrightarrow M_N \sim 10^{11} \text{GeV}$

Sakharov's conditions

☆ Baryon number is violated	Sphaleron
☆ Both C and CP are violated	RH decay
☆ There is an interaction outside of thermal equilibrium	RH decay

CP violating RN decay



$$\varepsilon_1 = \frac{\Gamma(N_1 \to \ell H) - \Gamma(N_1 \to \ell^c H^*)}{\Gamma(N_1 \to \ell H) + \Gamma(N_1 \to \ell^c H^*)}$$

Primordial B-L is washout by inverse decay of N_1

In general, CPV comes from the interference of tree and one-loop amplitude

$$N_1 \to \ell H \qquad \mathcal{M} = c_0 \mathcal{A}_0 + c_1 \mathcal{A}_1$$

$$N_1 \to \ell^c H^* \qquad \bar{\mathcal{M}} = c_0^* \bar{\mathcal{A}}_0 + c_1^* \bar{\mathcal{A}}_1$$

CP violating RN decay

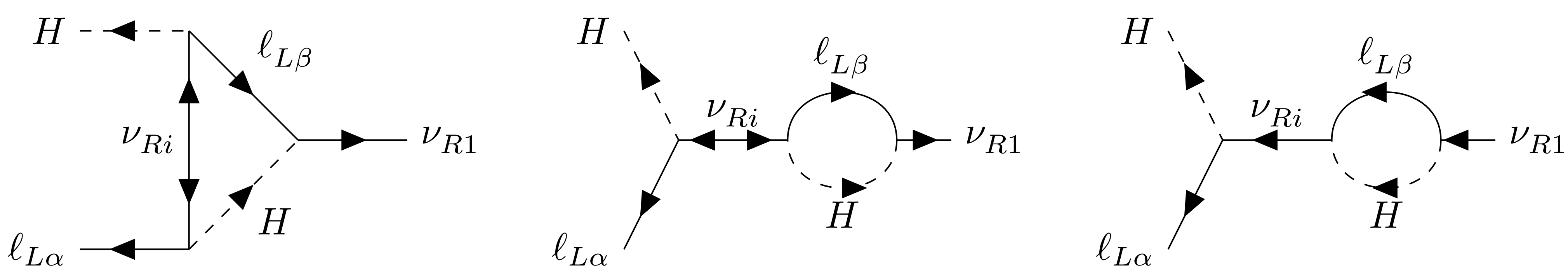
$$|\mathcal{A}_i|^2 = |\bar{\mathcal{A}}_i|^2 \ , \ \mathcal{A}_0 \mathcal{A}_1^* = \bar{\mathcal{A}}_0 \bar{\mathcal{A}}_1^*$$

$$\varepsilon_1 = \frac{\int |c_0 \mathcal{A} + c_1 \mathcal{A}_1|^2 dQ - \int |c_0 \mathcal{A} + c_1 \mathcal{A}_1|^2 dQ}{2 \int |c_0 \mathcal{A}|^2 dQ}$$

$$= -2 \frac{\mathrm{Im}(c_0^* c_1)}{|c_0|^2} \frac{\int \mathrm{Im}(\mathcal{A}_0^* \mathcal{A}_1) dQ}{\int |\mathcal{A}_0|^2 dQ}$$

In the seesaw model,

tree +



CP violating RN decay

$$x_j = M_j^2/M_1^2$$

$$\varepsilon_1 = \frac{1}{8\pi}\sum \frac{\mathrm{Im}((Y_N Y_N^\dagger)^2_{1j})}{(Y_N Y_N^\dagger)_{11}} \sqrt{x_j}\left(1-(1+x_j)\log\frac{1+x_j}{x_j}\right)$$

$$+\frac{1}{8\pi}\sum \frac{M_1}{M_j - M_1} \frac{\mathrm{Im}\left\{\left[M_j (Y_N Y_N^\dagger)_{j1} + M_j (Y_N Y_N^\dagger)_{1j}\right](Y_N Y_N^\dagger)_{1j}\right\}}{(Y_N Y_N^\dagger)_{11}}$$

If $M_1 \ll M_{2,3}$

$$\varepsilon_1 \simeq \frac{3M_1}{16\pi}\sum \frac{\mathrm{Im}\left((Y_N Y_N^\dagger)_{1j} M_j^{-1} (Y_N Y_N^\dagger)_{1j}\right)}{(Y_N Y_N^\dagger)_{11}} + \mathcal{O}(M_j^2/M_1^2)$$

Davidson-Ibarra bound

We can parameterise Y_N as

$$Y_N = i\sqrt{\hat{M}_N} R \sqrt{\hat{\kappa}} U^\dagger \qquad R^T R = R R^T = 1$$

matrix of eigenvalues

$$\varepsilon_1 = \frac{3M_1}{8\pi v^2} \frac{\mathrm{Im}(m_i^2 R_{1i}^2)}{\sum m_i |R_{1i}^2|}$$

Then, $$|\varepsilon_1| \leq \frac{3M_1}{8\pi v^2} \frac{|m_3^2 - m_1^2|}{m_1 + m_3} \propto M_1$$

Davidson-Ibarra bound

Boltzmann equations

- Out-of-equilibrium decay is described by Boltzmann equations

- Coupled equations for $Y_N = \dfrac{n_N}{s}$ and $Y_\Delta = \dfrac{n_{B-L}}{s}$

$$\frac{Y_N}{dz} = -\frac{z}{sH(M_1)}\left(\frac{Y_N}{Y_N^{\rm eq}} - 1\right)\gamma_D + \text{scattering}$$

$$\frac{Y_{B-L}}{dz} = \frac{z}{sH(M_1)}\left\{-\varepsilon_1\left(\frac{Y_N}{Y_N^{\rm eq}} - 1\right)\gamma_D - \frac{1}{2}\frac{\tilde{m}}{m_*}\gamma_D\frac{Y_{B-L}}{Y_{B-L}^{\rm eq}}\right\} + \text{scattering}$$

Source Washout

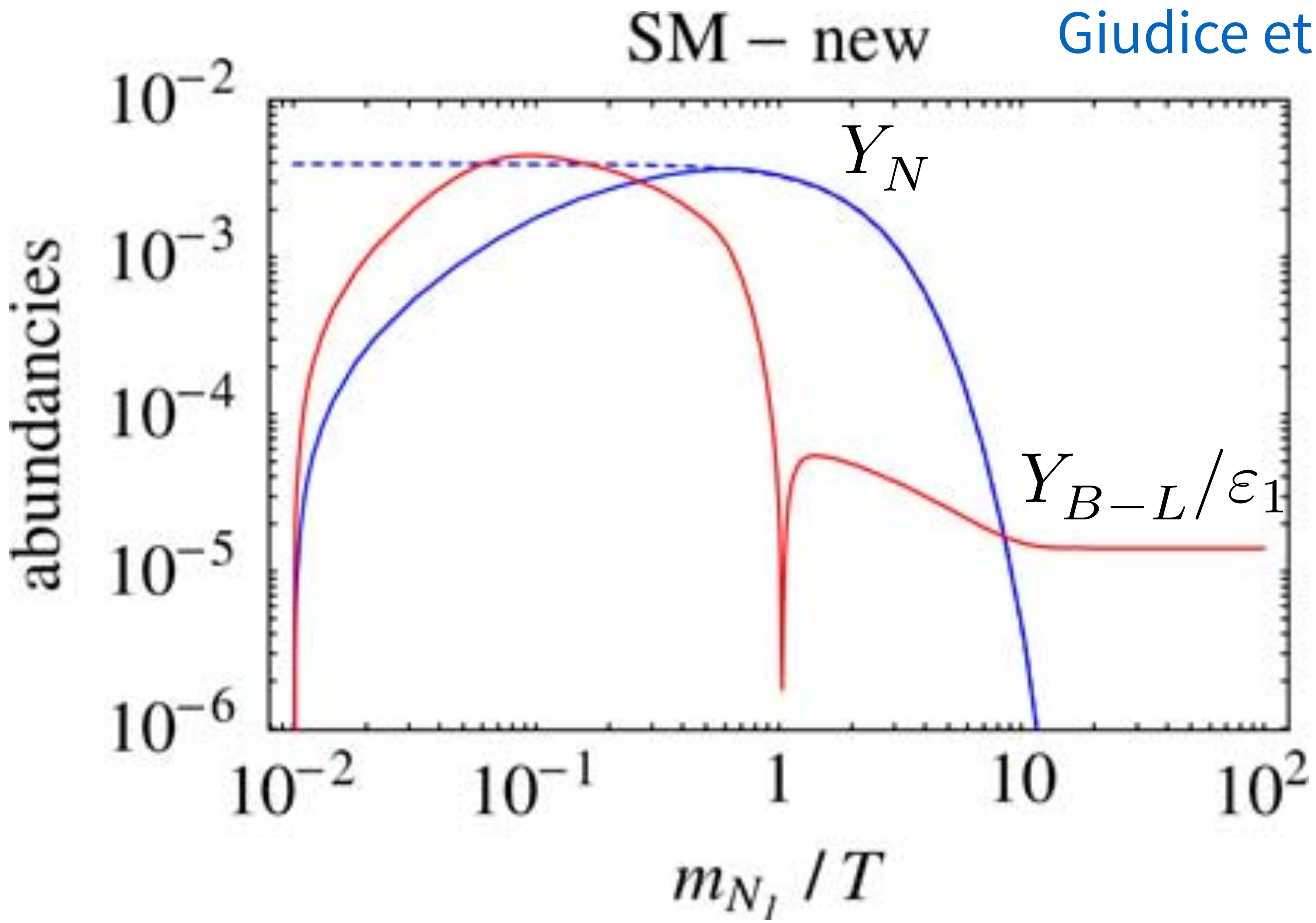
$$\tilde{m}_1 = \frac{(Y_N Y_N^\dagger)_{11} v^2}{M_1} \qquad m_* = \frac{H(M_1)\tilde{m}_1}{\Gamma_D} = \sqrt{\frac{8\pi^3 g_*^P{\rm eff}}{90}}\frac{8\pi v^2}{M_{\rm Pl}} \simeq 1.07 \text{ meV}$$

Boltzmann equations

For more realistic analysis,

thermal mass corrections etc are taken into account

Giudice et al., NPB685, 89(2004)



B-L is frozen out

$\tilde{m}_1 = 0.06$ eV $\quad M_{N_1} = 10^{10}$ GeV

Thermal leptogenesis

$$\eta_B = -0.02\varepsilon_1\eta(\tilde{m})$$ ← efficiency

sphaleron → -0.02

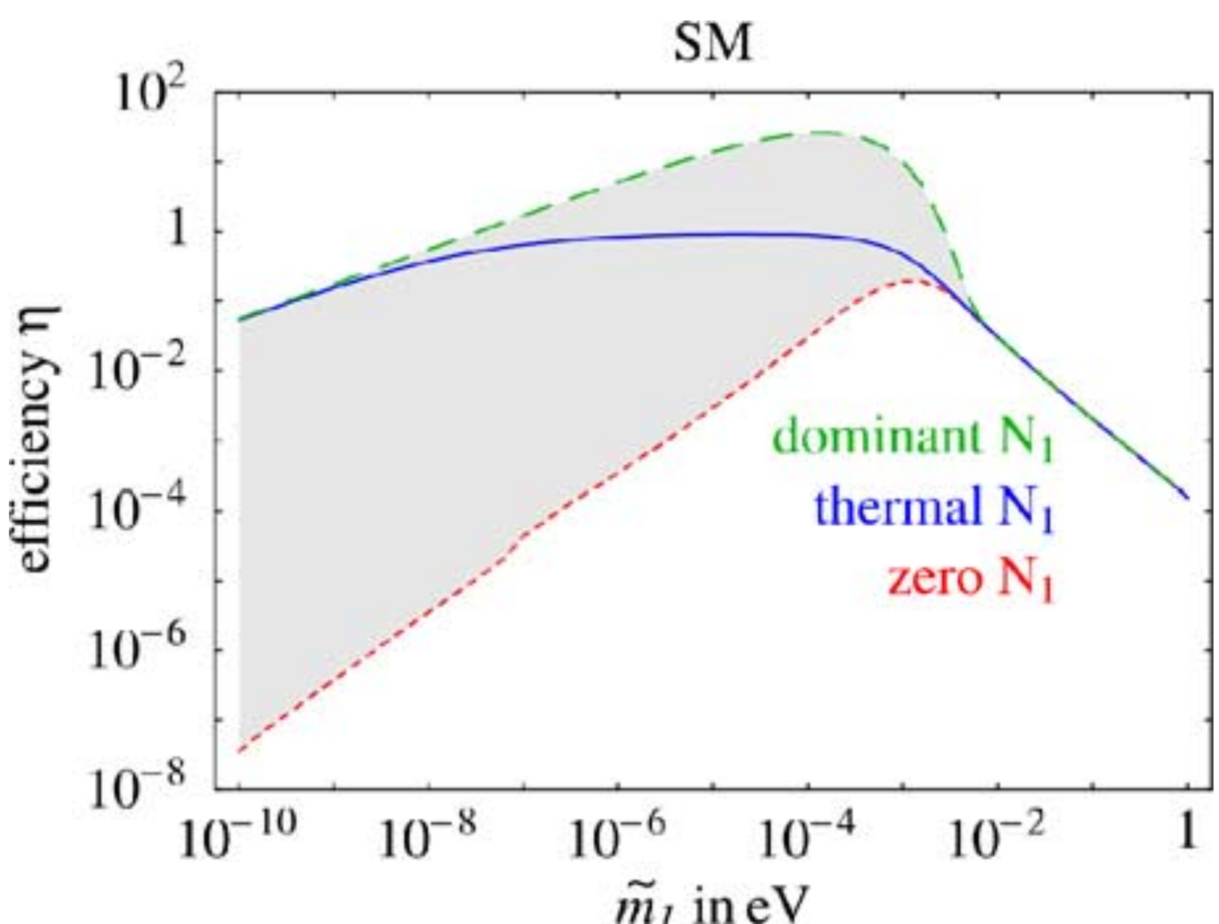
CPV → ε_1

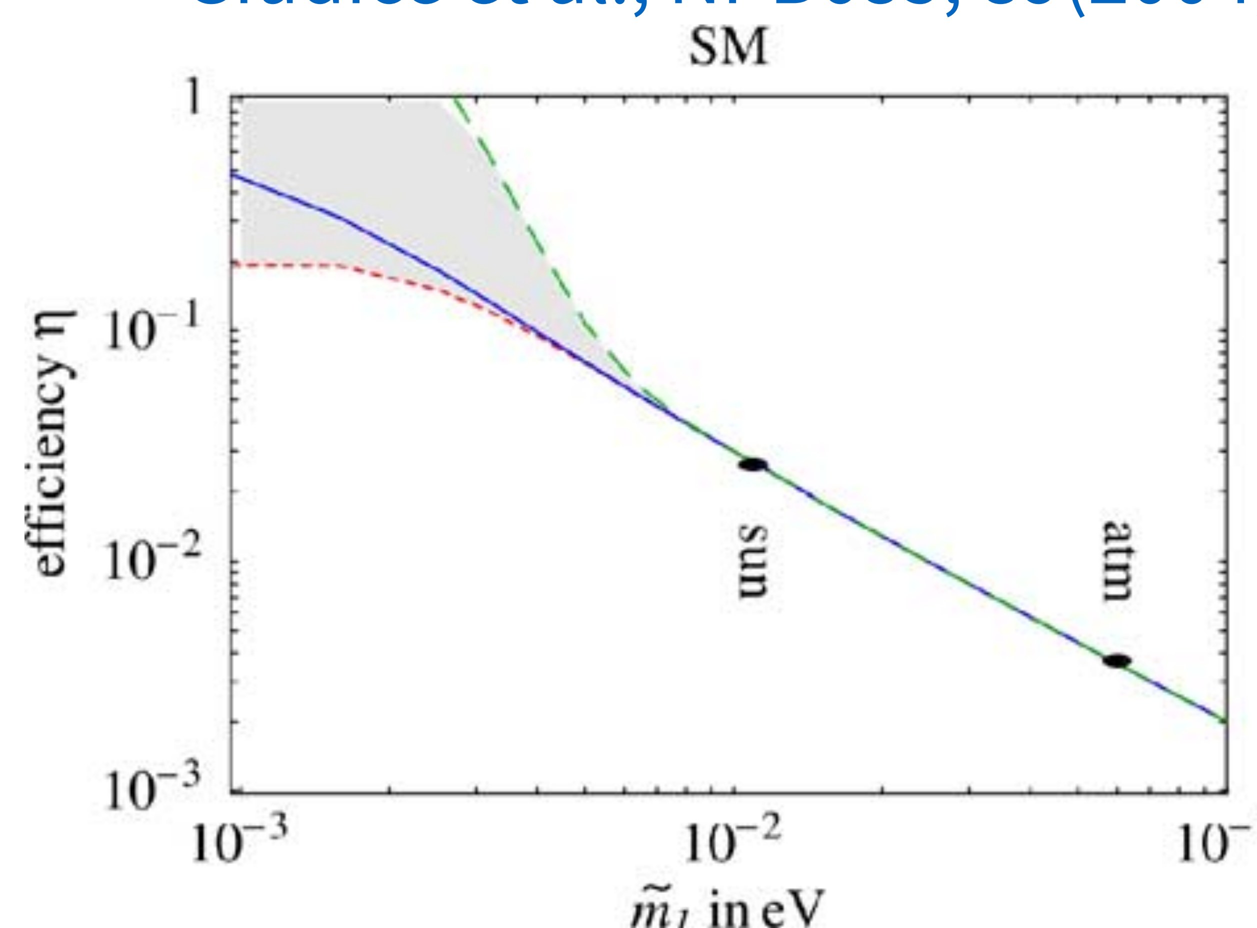
For zero N_1, $\eta < 0.2$

↓

$\varepsilon_1 > 10^{-6}$

Giudice et al., NPB685, 89(2004)





Bound on M_1

$$|\varepsilon_1| \leq \frac{3M_1}{8\pi v^2}\frac{|m_3^2 - m_1^2|}{m_1 + m_3}$$ **and** $$\varepsilon_1 > 10^{-6}$$

$$M_1 \gtrsim 10^9 \text{ GeV}$$

Thermal leptogenesis can works
in the inflation scenario with T_R>10^9GeV

Variations

- Flavour effects
- Resonant leptogenesis
- Leptogenesis with charged singlet scalar
- Leptogenesis from N oscillation

} RN ~TeV is possible

Electroweak Baryogenesis

The second one is electroweak baryogenesis

1. B-L is produced before the sphaleron decoupling era.
2. B is produced by the 1st order electroweak phase transition just before the sphaleron decoupling.

Electroweak Baryogenesis

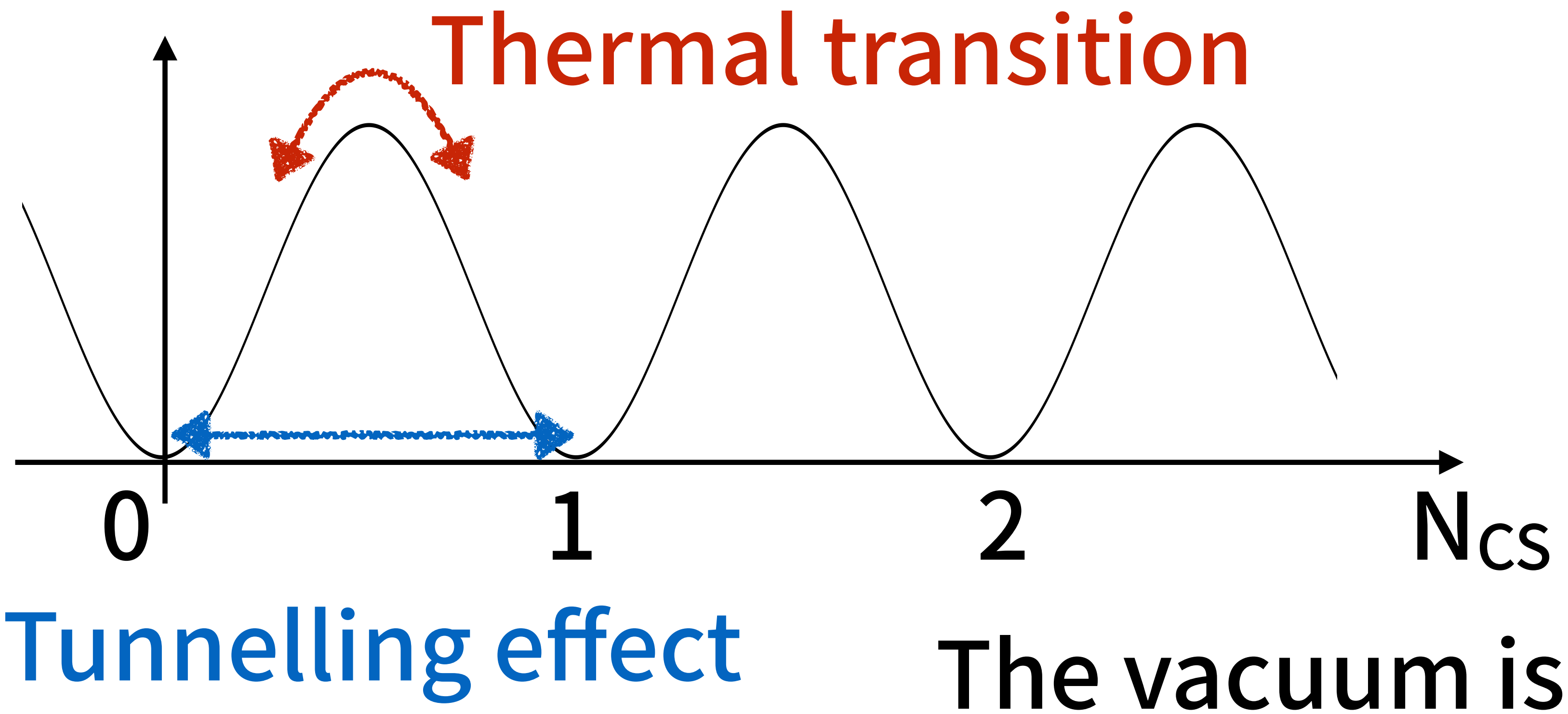
Kuzmin, Rubakov, Shaposhnikov, PLB155,36

How to satisfy the Sakharov's conditions?

- ☆ Baryon number is violated — Sphaleron
- ☆ Both C and CP are violated — Chiral gauge int. / Complex phases
- ☆ There is an interaction outside of thermal equilibrium — 1st order EWPT with expanding bubble wall

Vacuum structure

Classical vacuum of the SU(2) gauge system



$$W_\mu = iU^{-1}\partial_\mu U$$

$$U \in \mathrm{SU}(2) \simeq S^3$$

$$\pi_3(S^3) = Z$$

The vacuum is characterised by N_{CS}

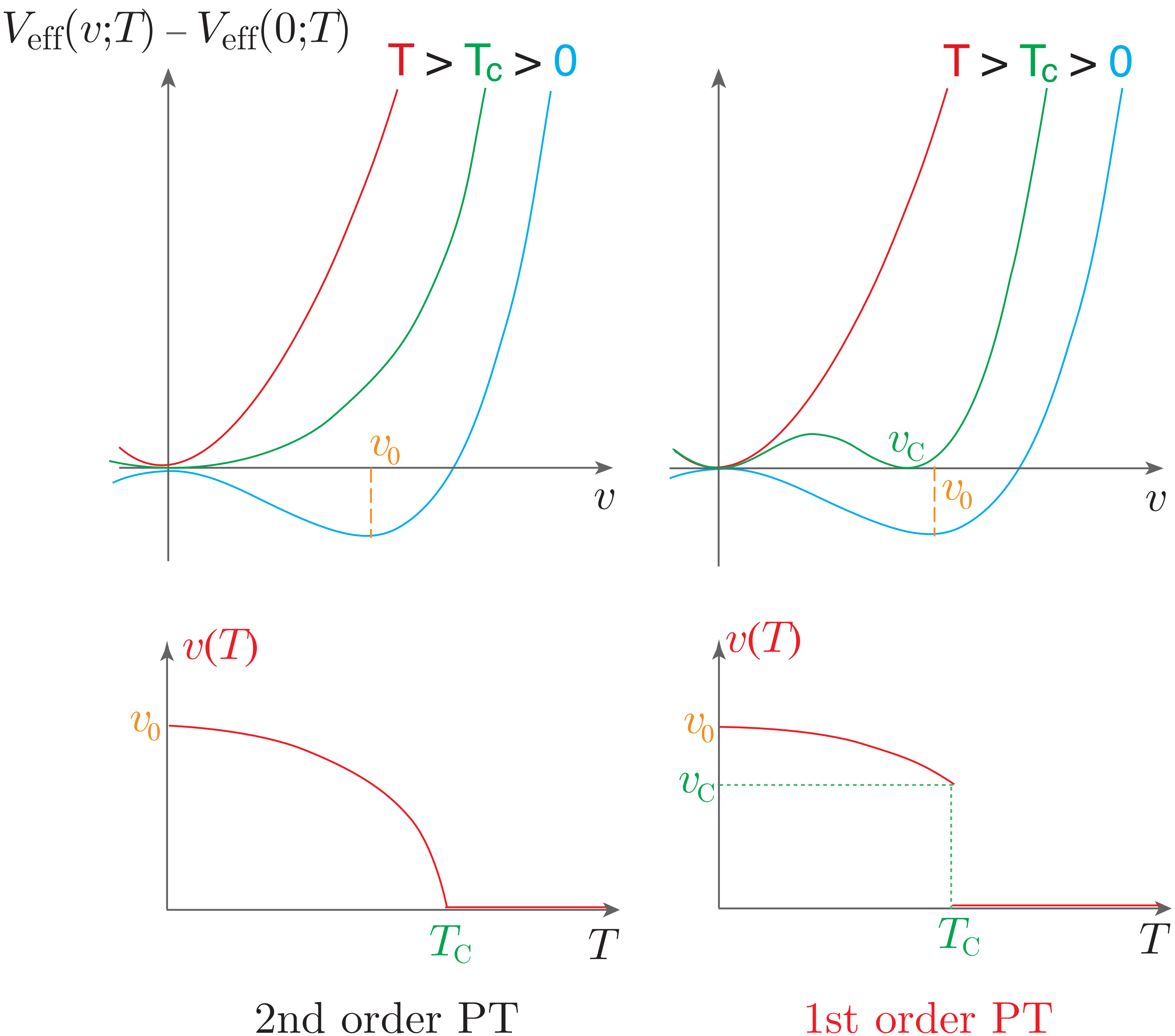
Tunnelling rate $\sim e^{-2S_{\rm instanton}} = e^{-8\pi^2/g^2} \simeq e^{-164} \ll 1$

Thermal transition rate

- broken phase $\Gamma \simeq T^4 e^{-E_{\rm sph}/T}$
- symmetric phase $\Gamma \simeq \kappa(\alpha_W T)^4$

It is significant at finite temperature

1st order or 2nd order?



order parameter

=

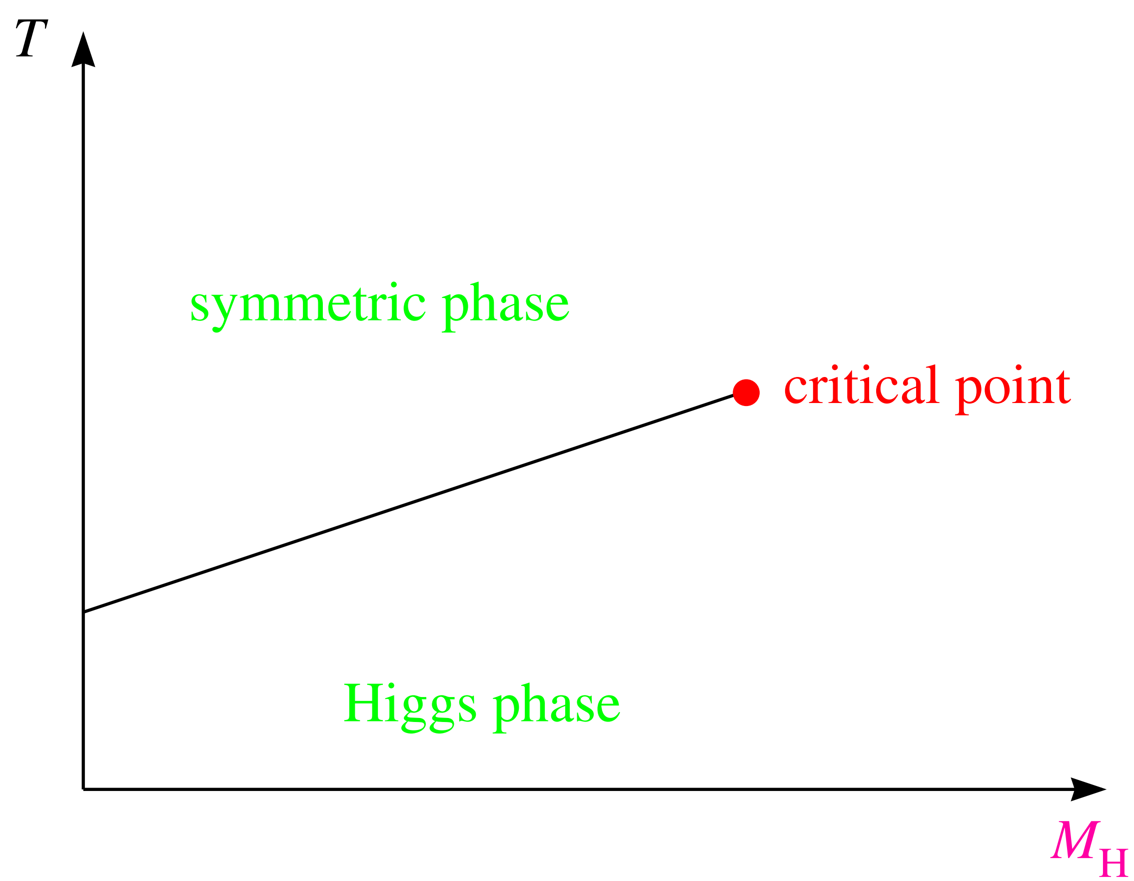
Higgs vev

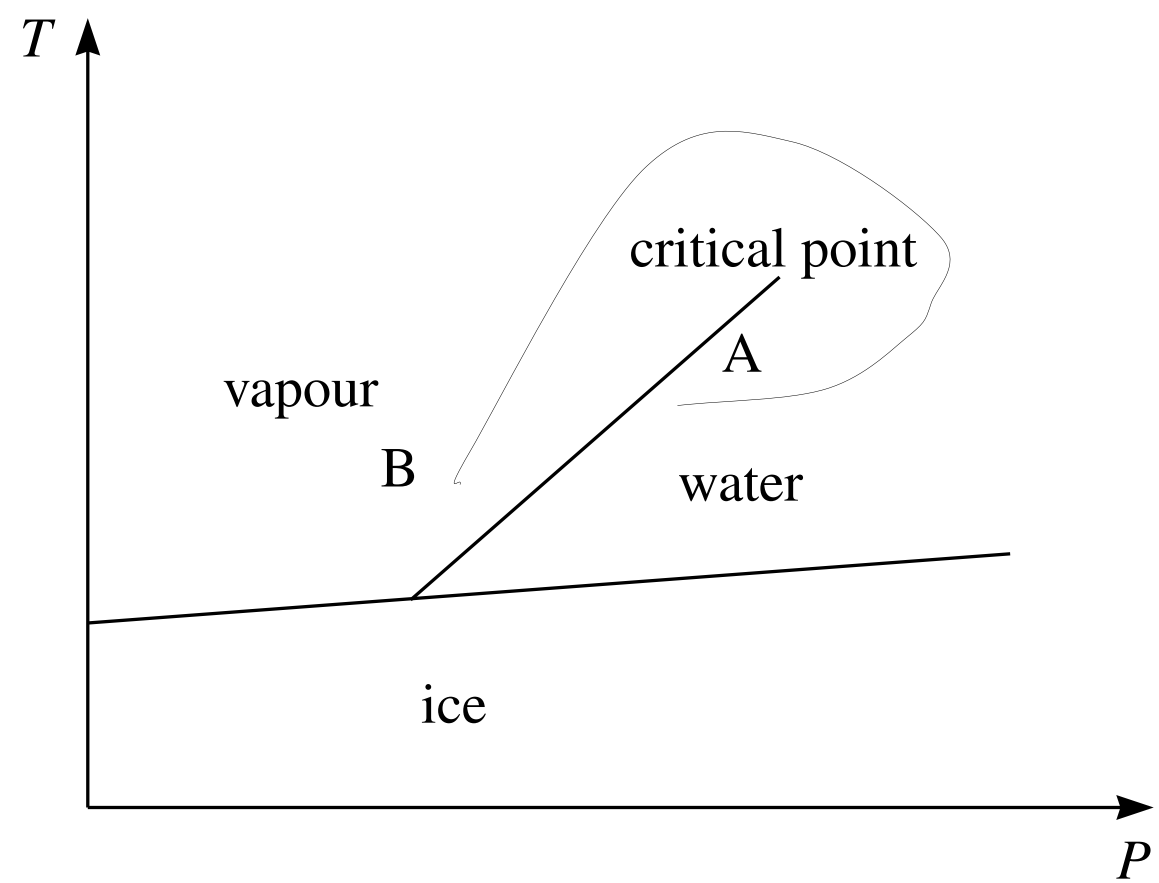
In EWBG, 1st order EWPT is necessary

Funakubo's slide

Phase diagram in the SM

M. Shaposhnikov, Phil.Trans.Roy.Soc.Lond. A373, 20140038

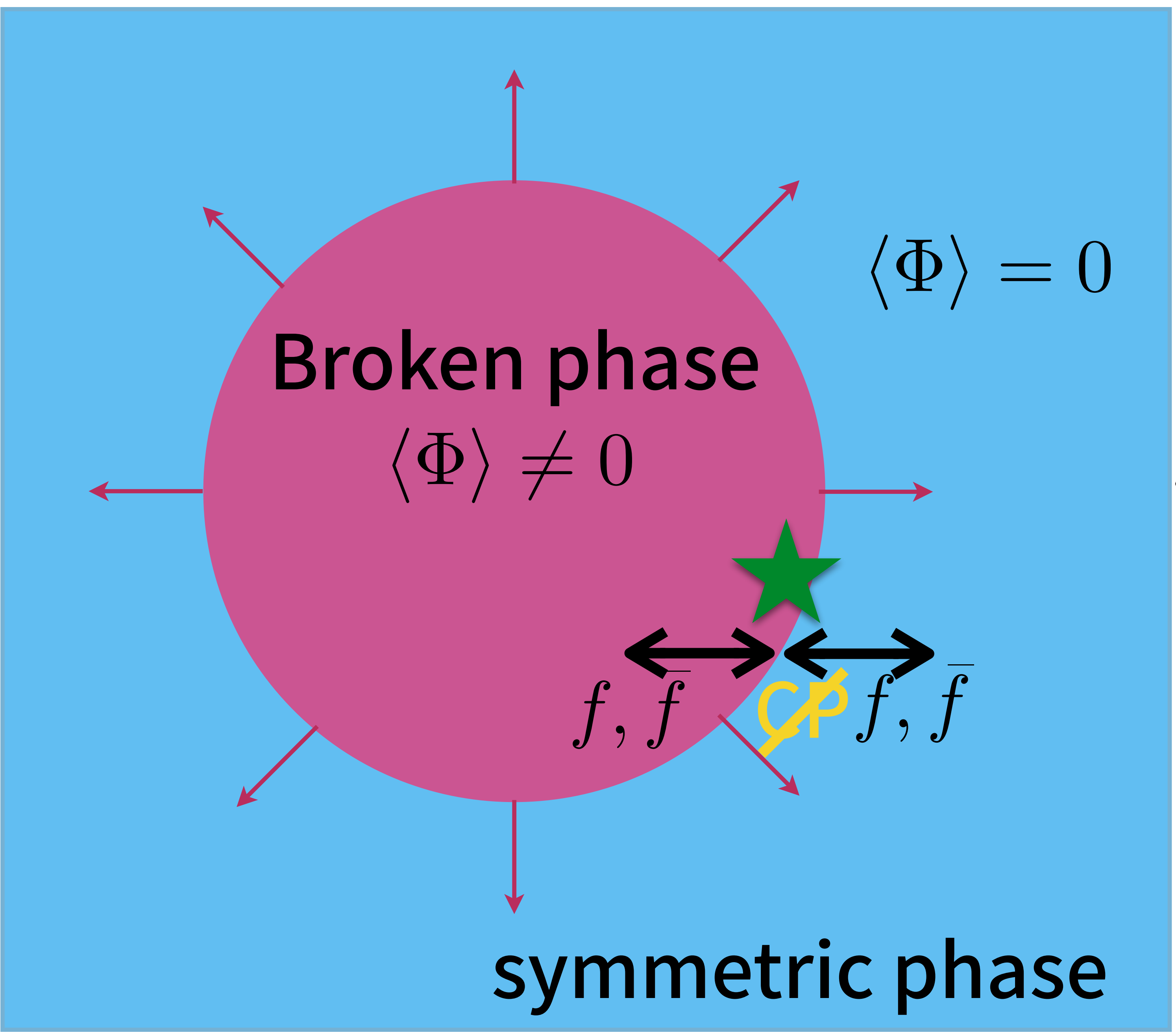


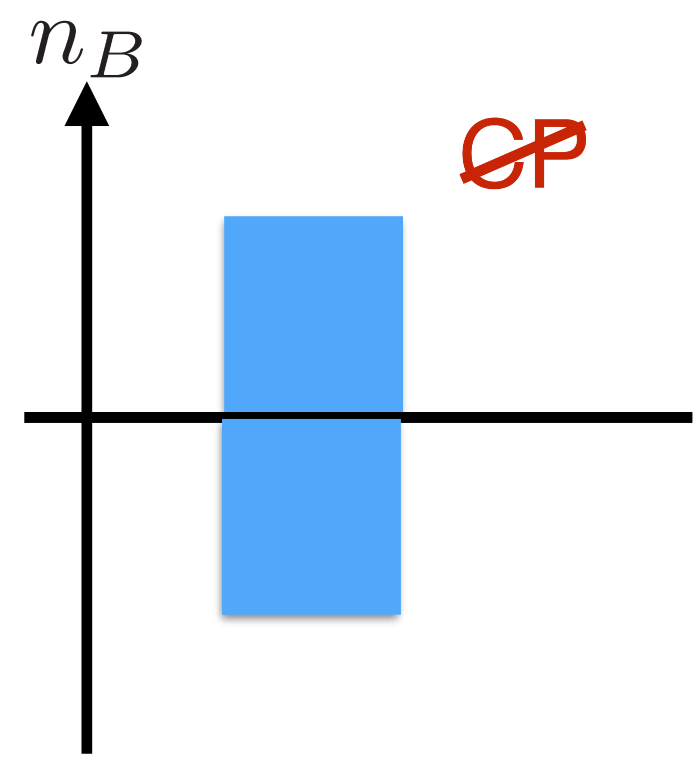


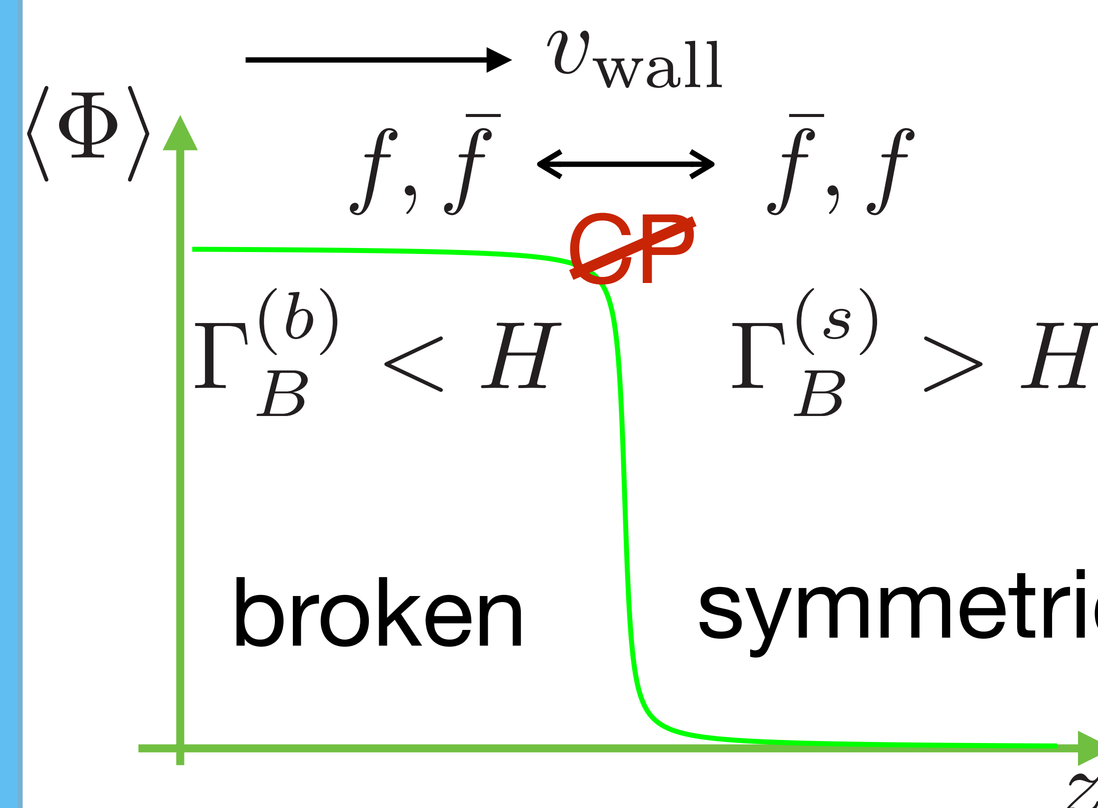
Mechanism of EWBG

1. Asymmetry is produced by CPV but no #B

$$n_B = \left(n_b^L - n_{\bar{b}}^L\right) + \left(n_b^R - n_{\bar{b}}^R\right) = 0$$





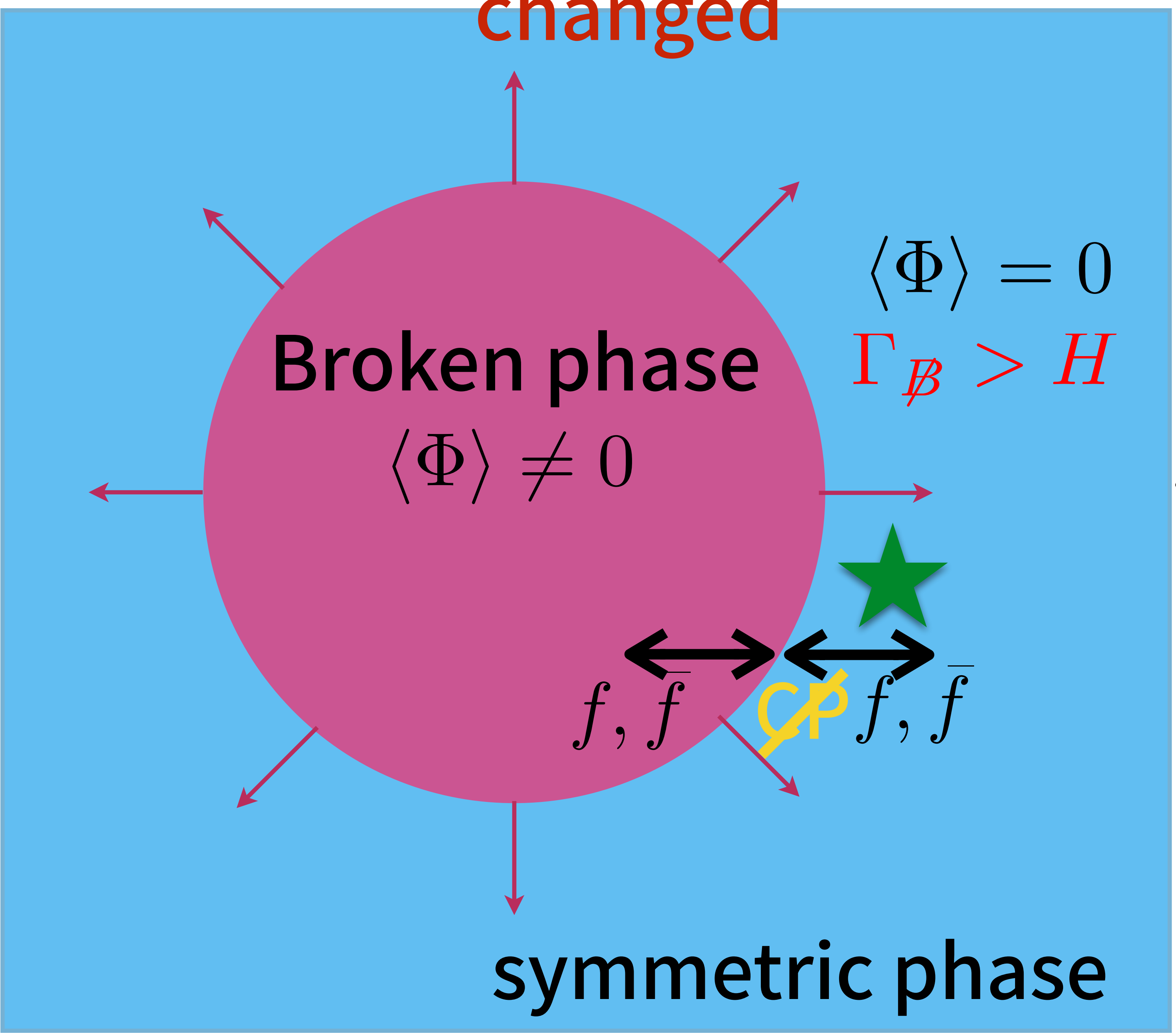


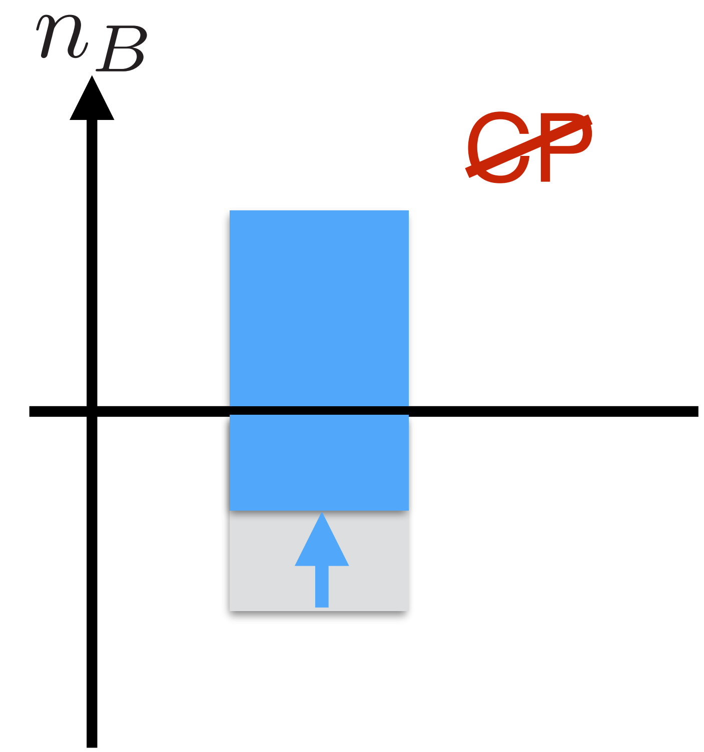
Mechanism of EWBG

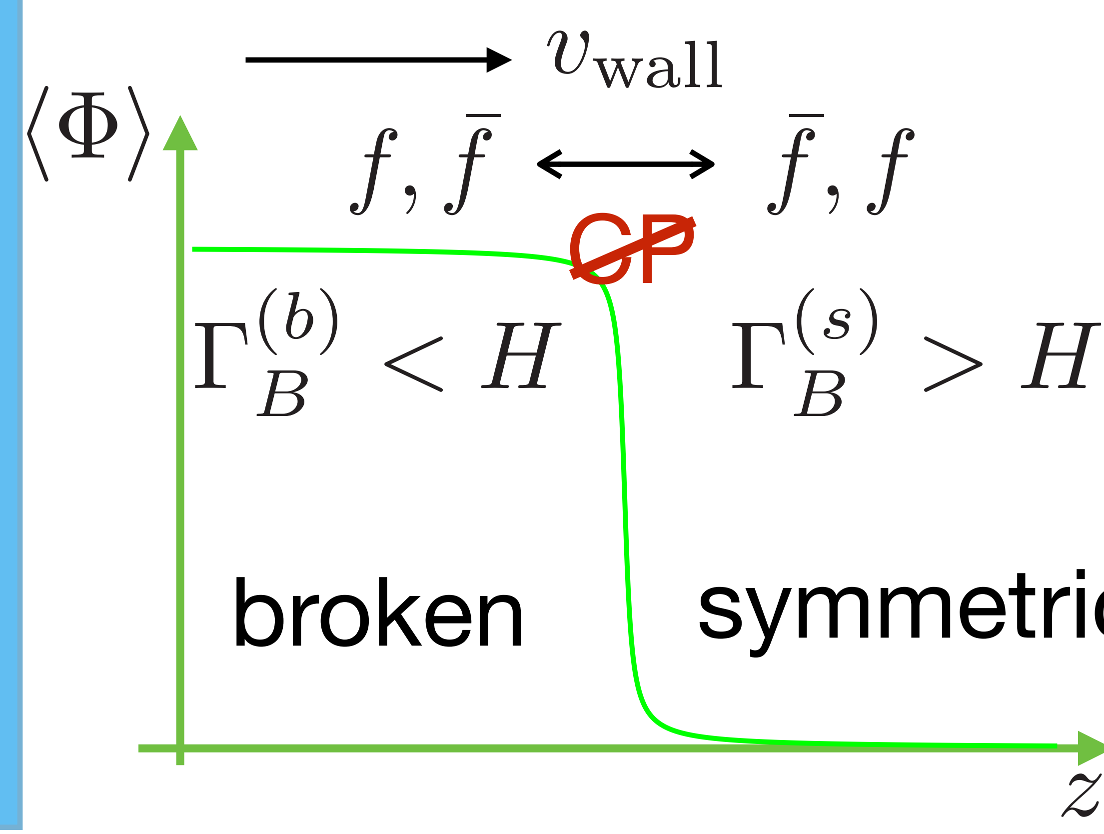
2. Sphaleron affect LH fermions ⟶ BAU

$$n_B = n_b^L - n_{\bar{b}}^L + n_b^R - n_{\bar{b}}^R = 0$$

changed



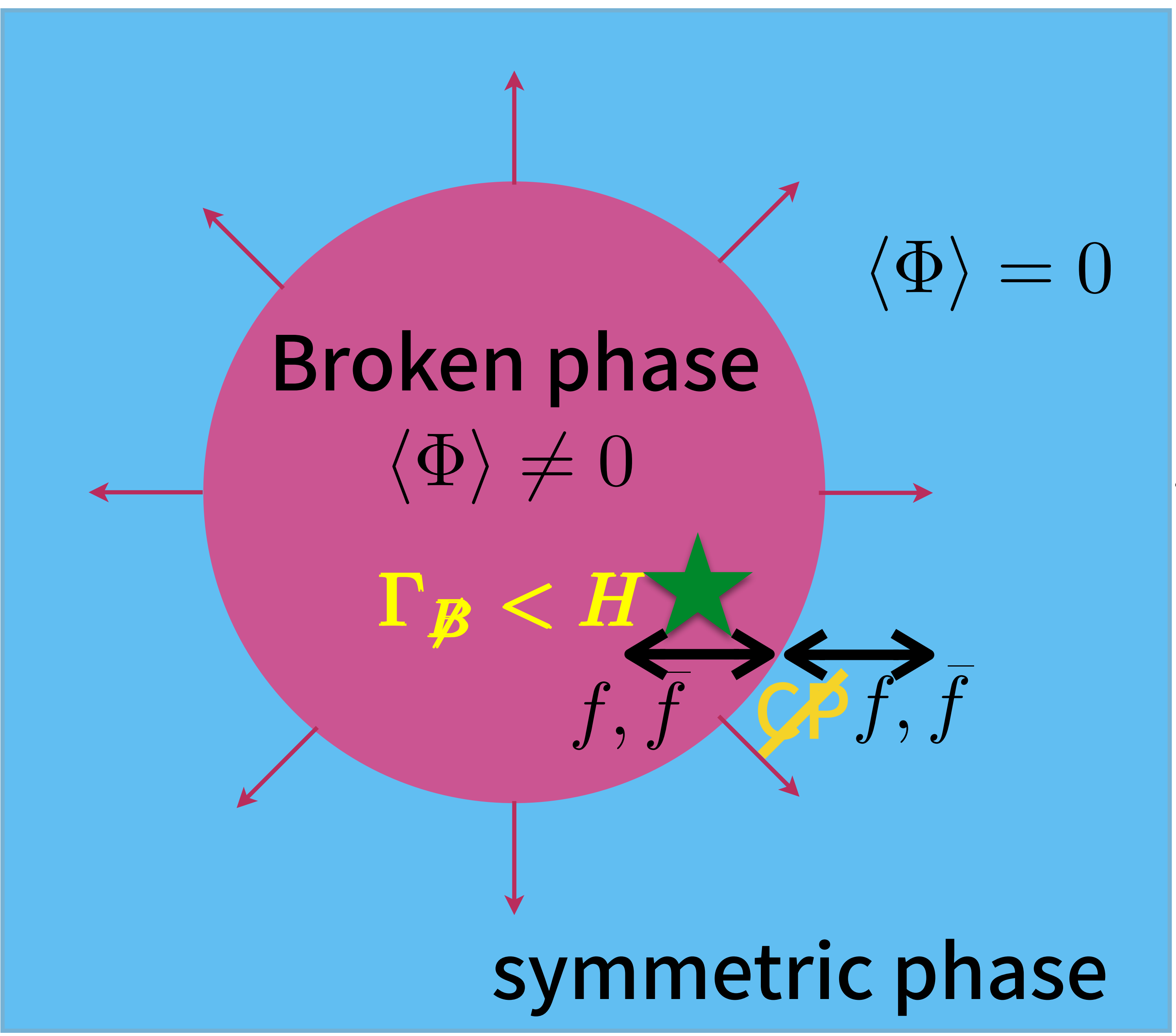


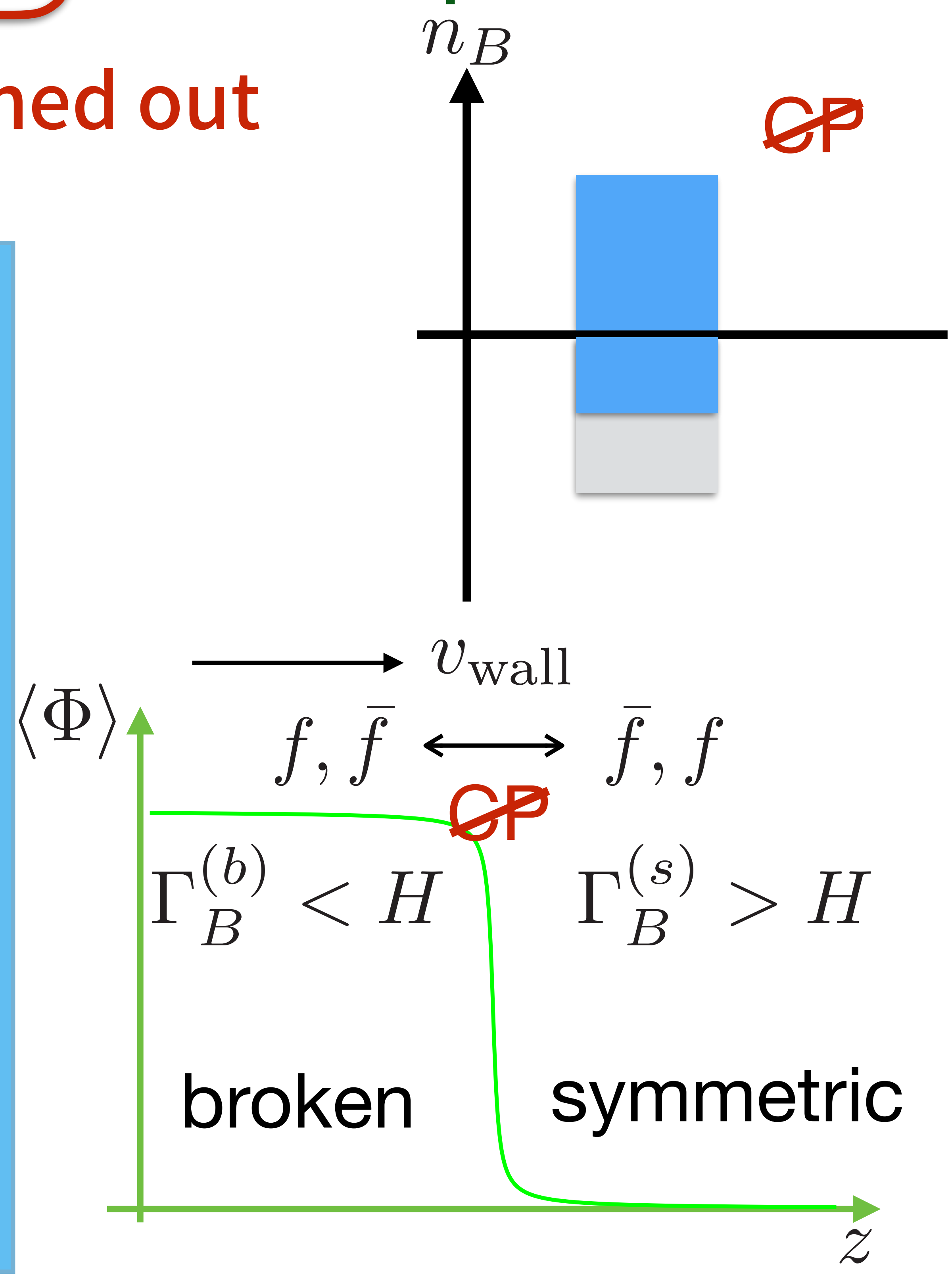


Mechanism of EWBG

3. The #B can survive if $\Gamma_{\not B} < H$ in broken phase

If sphaleron is fast, #B is washed out

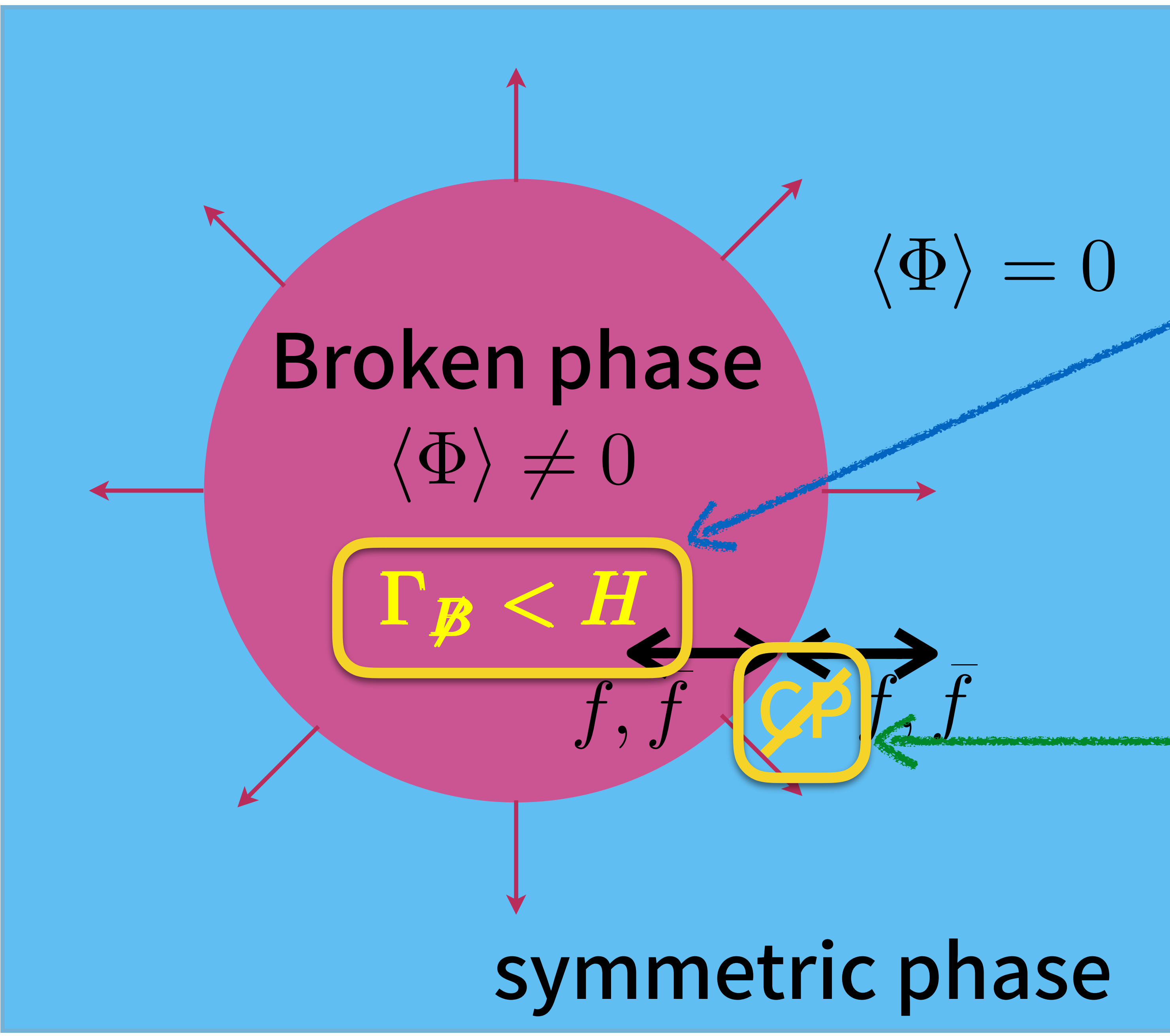




Test of the scenario

We cannot repeat the EWBG in laboratory

But we can test the necessary conditions



Probe by Higgs physics at zero temperature

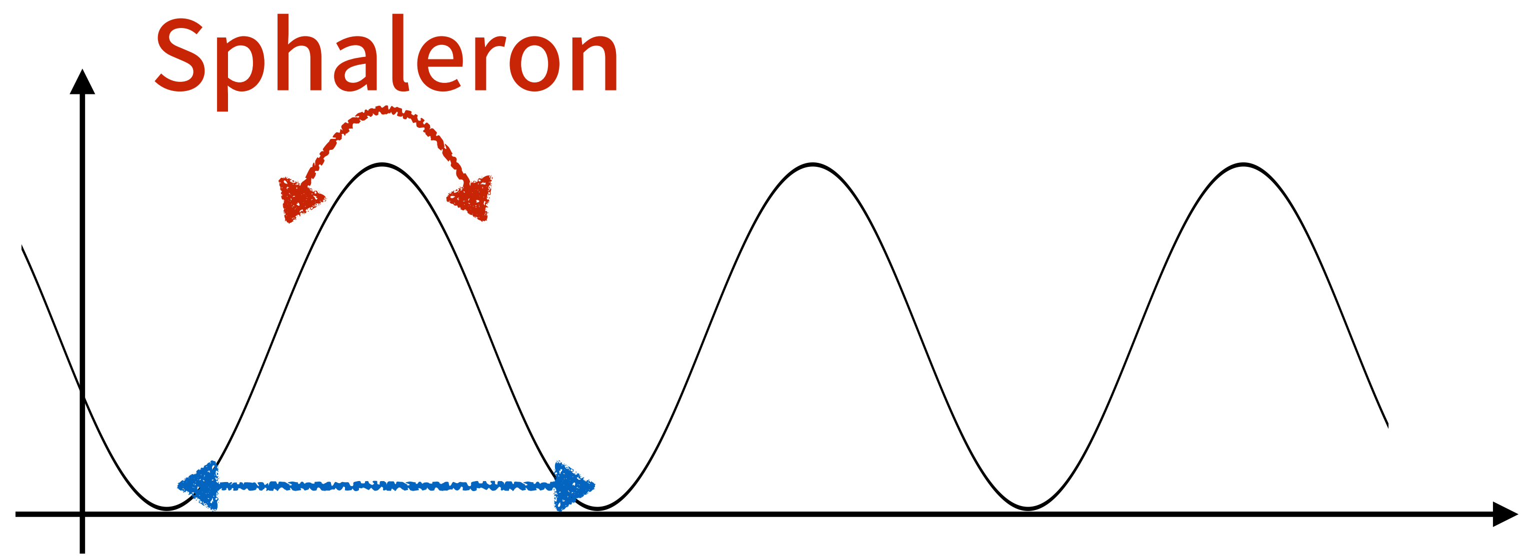
Collider experiments

Probe by CP violating phenomena

electric dipole moment

Strong 1st order EWPT

$\Gamma_{\not{B}} < H$



In broken phase

$$\Gamma_{\not{B}} \simeq (\text{prefactor}) e^{-E_{\rm sph}/T}$$

E_{sph} is proportional to the Higgs vev $E_{\rm sph} \propto v$

<u>Then, large Higgs vev</u>

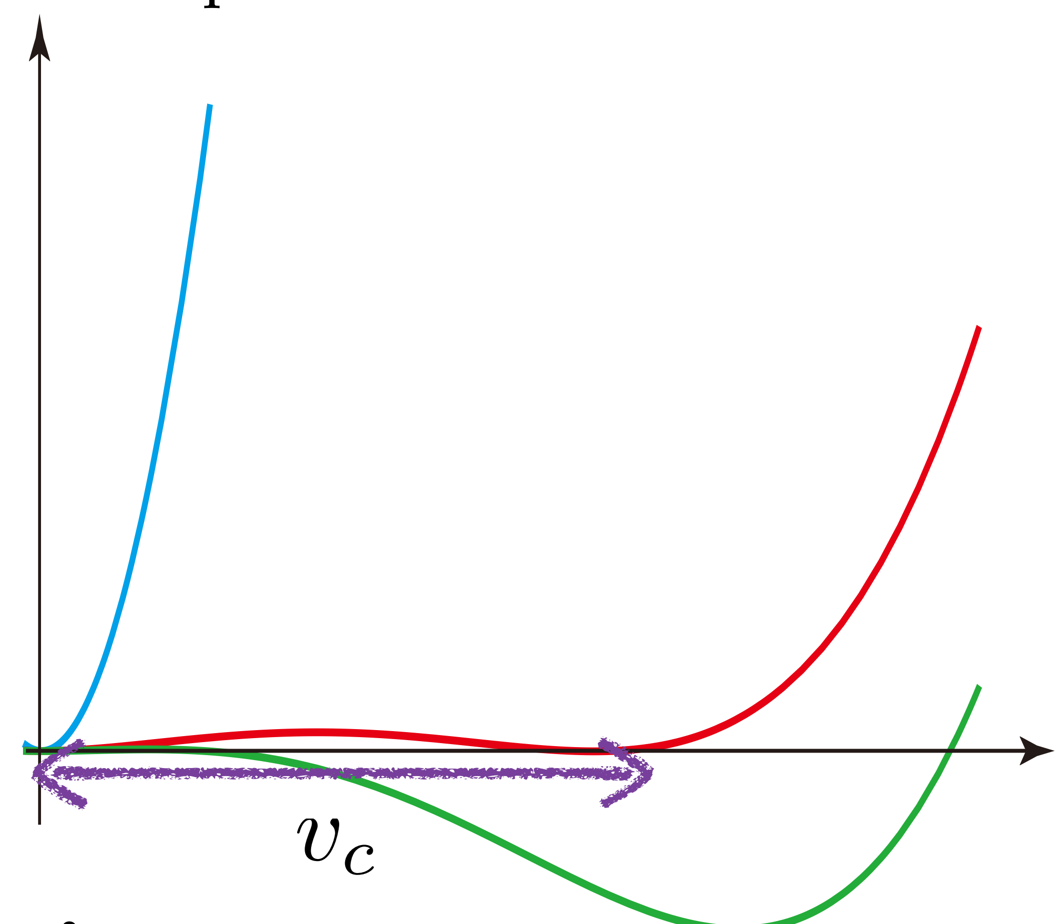
<u>after EWPT is required</u>

↓

EWPT should be strong 1st order

$$\Gamma_{\not{B}}(T_c) < H(T_c) \rightarrow \frac{v_c}{T_c} > \zeta_{\rm sph}(T_c)$$

$$\zeta_{\rm sph} \sim 1$$



In the SM, $\zeta_{\rm sph} \simeq 1.16$ **for 125 GeV Higgs**

EWPT in the SM

In the high temperature approximation,

$$V(\varphi, T) \simeq D(T^2 - T_0^2)\varphi^2 - ET\varphi^3 + \frac{\lambda_T}{4}\varphi^4 + \cdots$$

$$\varphi_c/T_c = 2E/\lambda_{T_c}$$

1st order PT is possible due to the cubic term

$$E = \frac{1}{12\pi v^3}(6m_W^3 + 3m_Z^3)$$

$$\lambda_T = \frac{m_h^2}{2v^2} + \log\text{ corrections}$$

$$\varphi_c/T_c \propto 1/m_h^2$$

Light Higgs is required !!

In SM, Higgs should be lighter than 50GeV

m_h=125GeV

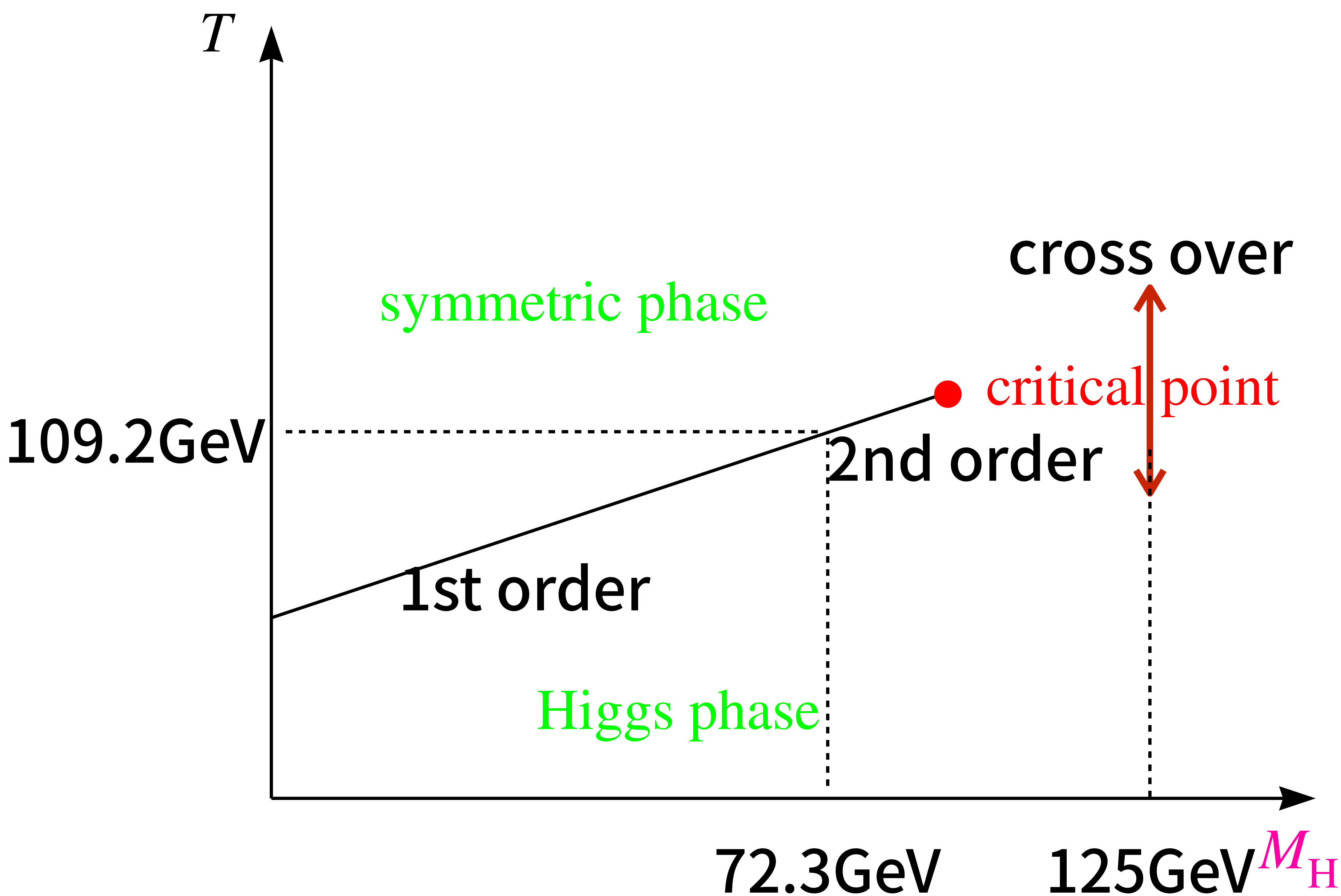
NEW CP phases are also necessary for successful baryogenesis

Extension of the SM at TeV scale is necessary

It can be tested by experiments

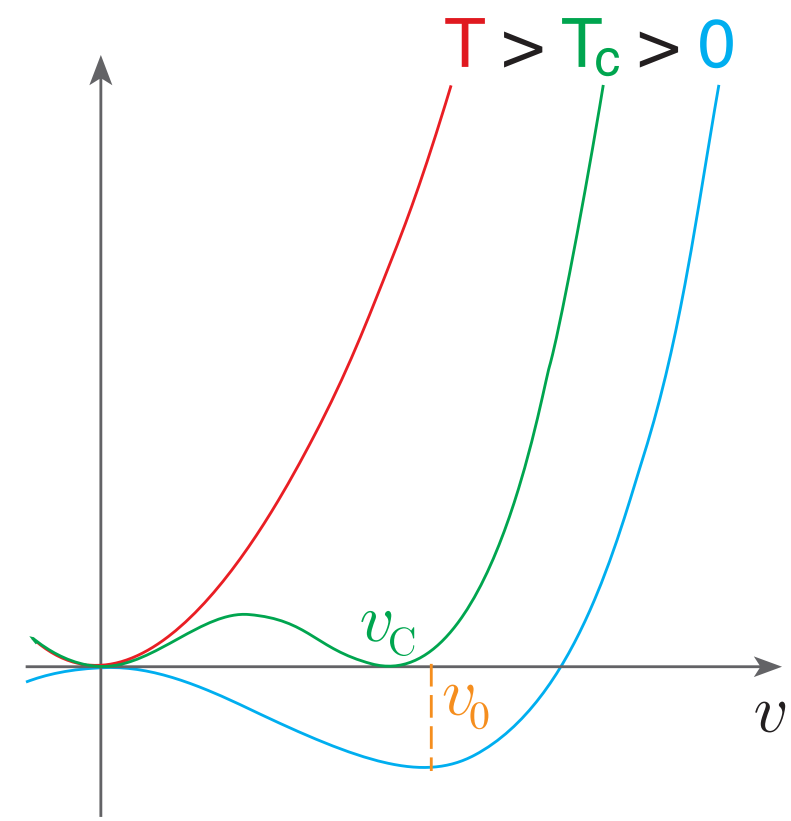
- New bosonic loop contribution
- Higher dim. term in the potential
- …

Phase diagram of SM



How to enhance EWPT?

$$V(\varphi, T) \simeq D(T^2 - T_0^2)\varphi^2 - ET\varphi^3 + \frac{\lambda_T}{4}\varphi^4 + \cdots$$



Negative contribution is necessary

- Bosonic loop
- Higher dimensional terms
- …

In many cases,

Higgs potential (at zero temperature) is modified

It may be tested by collider experiments

Bosonic loop

Scalar does not always enhance it

The scalar mass consists of two parts

$$m^2 = M^2 + \lambda_{HS}\varphi^2$$

- Vev dominant $M^2 \ll \lambda_{HS}\varphi^2$

$$V_{\rm eff} \ni -\lambda_{HS}^{3/2} T \varphi^3 \left(1 + \frac{M^2}{\lambda_{HS}\varphi^2}\right)^{3/2}$$

contribution!

- Mass param. dominant $M^2 \gtrsim \lambda_{HS}\varphi^2$

$$V_{\rm eff} \ni -|M^3| T \left(1 + \frac{\lambda_{HS}\varphi^2}{M^2}\right)^{3/2}$$

no cubic term

Large coupling and small M2 are required

An example, 2HDM

Strong 1st order EWPT requires extension of the SM

Extra boson loop can enhance ϕ_c/T_c

↓

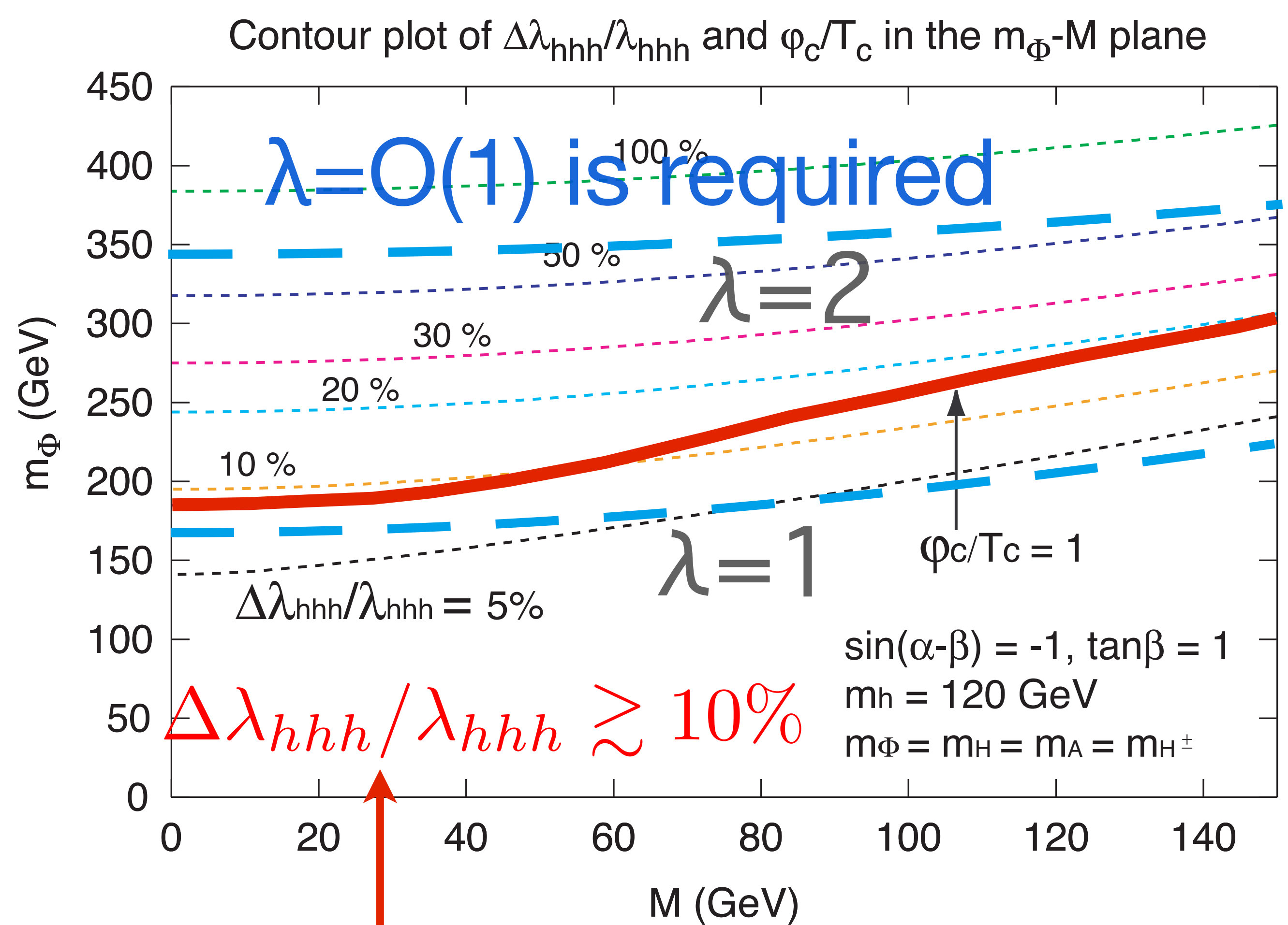
Extended Higgs sector!

e.g. 2HDM

$$\mathcal{L} = \frac{\lambda_i}{2} h^2 |\Phi_i|^2$$

$$m^2_\Phi(\varphi) = M^2 + \lambda_i \varphi^2$$

Extra Higgs bosons as H,A H±



Kanemura, Okada, Senaha, PLB606,361

Testable@Collider exp.

{ The boson mass should be dominated by Higgs VEV
Heavy mass (strong coupling with Higgs) is preferable

EWPT in the MSSM

Carena et al.,PLB380,81;···

Lighter stop loop can contribute

large top Yukawa coupling

enhance

$$\varphi_c/T_c = 2E/\lambda_{T_c} > 1$$

$$E \simeq \frac{1}{12\pi v^3}(6m_W^3 + 3m_Z^3) + \frac{m_t^3}{2\pi v^3}\left(1 - \frac{|A_t + \mu \cot\beta|^2}{M_{\tilde{q}}^2}\right)^{3/2}$$

where the maximal contribution case is considered;

$$m_{\tilde{t}_1}^2(\varphi, \beta) = M_{T_R}^2 + \frac{y_t^2 s_\beta^2}{2}\left(1 - \frac{|A_t + \mu \cot\beta|^2}{M_{\tilde{q}^2}}\right)\varphi^2$$

$M_{T_R}^2 \sim 0$

For larger M_{TR}, the effect is smaller

Light stop is necessary ⟷ { No new coloured particles at LHC; m_h=125GeV }

Even with such a maximal case, it's not easy to get $\phi_c/T_c>1$

Carena et al.,NPB812,243; Funakubo,Senaha,PRD79,115024

MSSM should be also modified at TeV scale for EWBG

What are possible models?

EWBG in the SM has been excluded!

- ☆ SUSY
  - ☆ MSSM, NMSSM, U(1)'-MSSM, …

    EWPT is O.K. and CPV is O.K.
- ☆ Extended Higgs sector

	1st order EWPT	CPV
real singlet	OK	NG
complex singlet	OK	OK
MHDM (M≥2)	OK	OK
real triplet	OK	NG
complex triplet	OK	NG

Summary

- Baryogenesis is a big problem in the SM
- In many scenarios, sphaleron in the SM is used
- Two typical scenarios are introduced
  - Thermal leptogenesis
  - Electroweak baryogenesis
- Baryogenesis may be a key to BSM physics

References

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授業全体のまとめ

- 素粒子の知識を使って宇宙創生＆進化を理解する
  - いくつかの謎：暗黒物質，バリオン数生成，etc
- 宇宙は天然の実験場