Some correction

While calculating opacity, we do not normally include contribution from neutral atom scattering.

x-section $\propto \omega^4$

Even though $n_{1s} \gg n_e$, the scattering probability from 1s state is still small.

Baryon asymmetry.

- We have more baryons than anti-baryons
- Where does this come from?

Even if we assume the universe started with an asymmetry, inflation dilutes it.

During inflation $\cancel{\lambda} \to e^{60} \lambda$

densities $\to e^{-180} \times$ original density.

$\Rightarrow$ We must produce this after inflation.

Sakharov's 3 conditions:

① Microscopic theory must have B-violating interactions. ✓

② The microscopic theory must have C and CP violation.

C: charge conjugation   P: parity.

③ the universe must be out of thermal equilibrium.

② C, CP violation:

Suppose some process produces more B than $\bar{B}$.

The its C conjugate process will produce more $\bar{B}$ than B.

Same argument holds for CP.

Formally, suppose that the universe is described by some density matrix ρ.

Initially $C \rho C^{-1} = \rho$

With time ρ evolves as

$$\rho(t) = e^{iHt} \rho \, e^{-iHt} \quad , \quad C H C^{-1} = H$$

$$\Rightarrow \; C \rho(t) C^{-1} = \rho(t)$$

$\rightarrow$ same argument works for CP.

Density matrix we average over ~~a~~ different distr. of matter in space.

ρ is C-invariant.

$$e^{-\beta H}$$

CPT is always a symmetry.

Expanding universe breaks Time reversal invariance.

③ The universe must be out of thermal equilibrium.

Suppose we have some conserved densities $\tilde{n}_{(\ell)} = \sum_{\alpha} C_{\alpha}^{(\ell)} (n_{\alpha} - \bar{n}_{\alpha})$, $\ell = 1, \dots, L$

$\rightarrow$ introduce chemical potential $\tilde{\mu}_{(\ell)}$ for each conserved charge.

$$\mu_{\alpha} = \sum_{\ell=1}^{L} C_{\alpha}^{(\ell)} \tilde{\mu}_{(\ell)}, \quad \bar{\mu}_{\alpha} = -\sum_{\ell=1}^{L} C_{\alpha}^{(\ell)} \tilde{\mu}_{(\ell)}$$

If $\tilde{n}_{(\ell)} = 0$ for $\ell = 1, \cdots, L$. then the soln. for $\tilde{\mu}_{(\ell)}$ is $\tilde{\mu}_{(\ell)} = 0$ for $\ell = 1, \cdots, L$.

$\Leftarrow \left| \frac{d}{dt}(\tilde{n}_{(\ell)} \lambda^3) = 0 \right.$

$\mu_\alpha = 0, \ \bar{\mu}_\alpha = 0$ for every α.

$$n_\alpha = \frac{g_\alpha}{2\pi} \int_0^\infty k^2 dk \ \frac{e^{-\frac{1}{T}(\sqrt{k^2+m_\alpha^2} - \mu_\alpha)}}{1 \mp e^{-\frac{1}{T}(\sqrt{k^2+m_\alpha^2} - \mu_\alpha)}}$$

$$\bar{n}_\alpha = \frac{g_\alpha}{2\pi} \int_0^\infty k^2 dk \ \frac{e^{-\frac{1}{T}(\sqrt{k^2+m_\alpha^2} + \mu_\alpha)}}{1 \mp e^{-\frac{1}{T}(\sqrt{k^2+m_\alpha^2} + \mu_\alpha)}}$$

$\Rightarrow n_\alpha = \bar{n}_\alpha \left| n_B = \sum A_\alpha (n_\alpha - \bar{n}_\alpha) \right|$

Can SM do this?

2. C, CP violation → already present.

1. B-violation:

classical Lagrangian has a symmetry that implies B conservation.

B assignment: quarks : $\frac{1}{3}$

anti-quarks : $-\frac{1}{3}$

everything else : 0

$$\left.\begin{array}{l} q \to e^{i\frac{\theta}{3}} q \\ \bar{q} \to e^{-i\frac{\theta}{3}} \bar{q} \end{array}\right.$$

However this symmetry is anomalous.

$\rightarrow$ fails in quantum theory.

$$\text{Violation} \propto e^{-4\pi^2/g_w^2} \sim 10^{-160}$$

$\rightarrow$ not observable in any experiment.

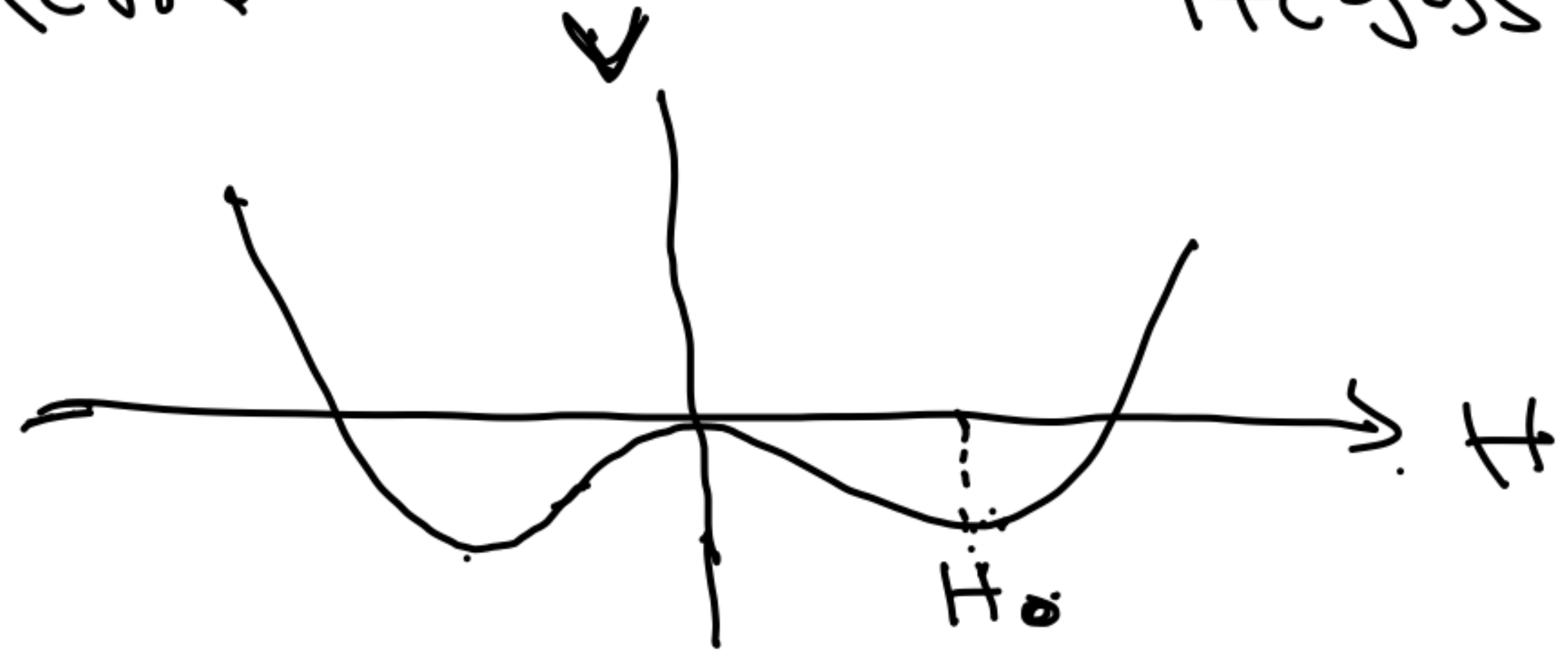
However, at high temperature this suppression disappears.

In principle in SM at high temp.
condition 1 and 2 are satisfied.

What about condition 3?
Was the universe out of equilibrium
at high T?

→ tied to the electroweak phase transition.

Higgs potential



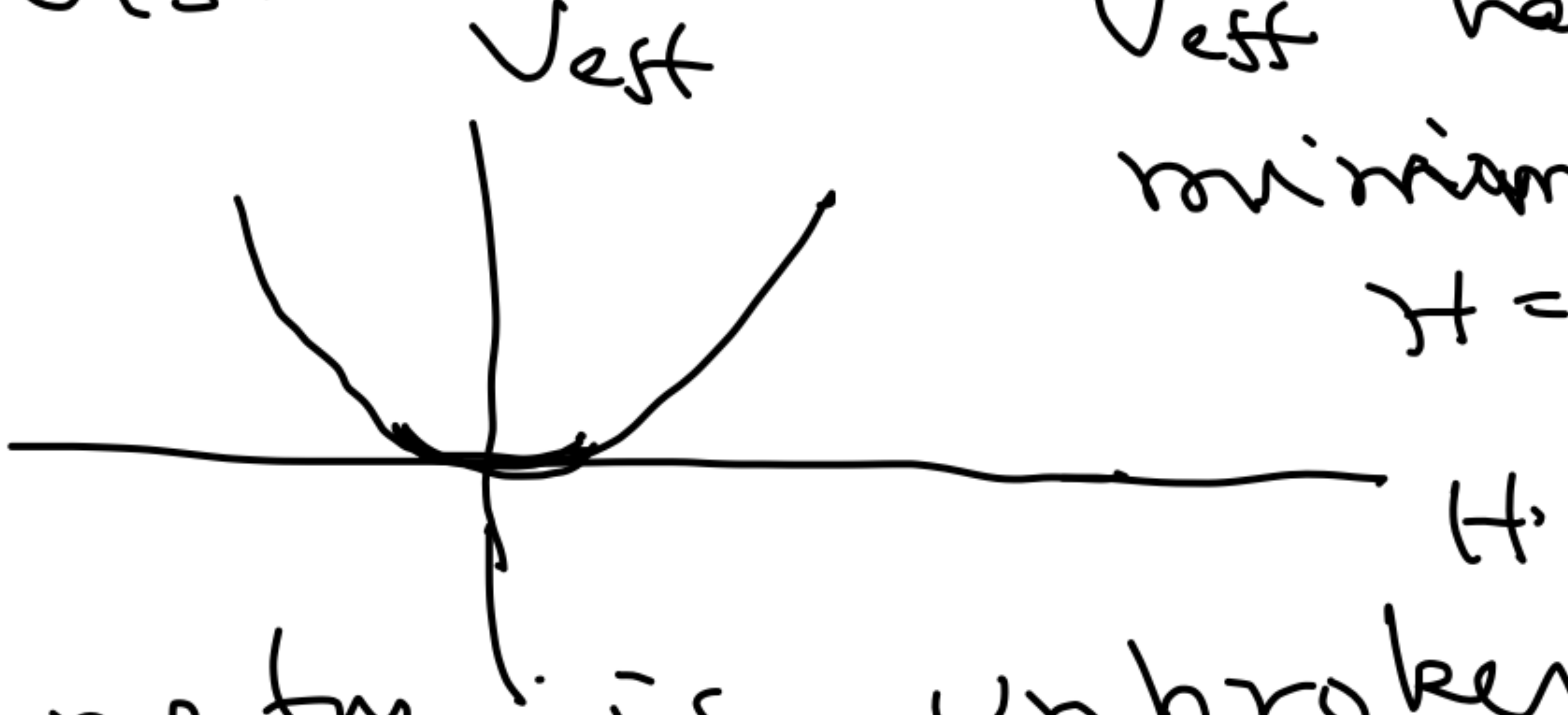
At finite T, one can introduce the notion of an effective potential.

→ Landau - Ginzburg potential.

$$V_{eff}(H,T) = a(T)\,|H|^2 + b(T)\,|H|^4 + c(T)\,|H|^6 + \cdots$$

$a(T)$, $b(T)$, $c(T)$ calculable in terms of SM parameters.

At high T



V_{eff} has minimum at $H = 0$.

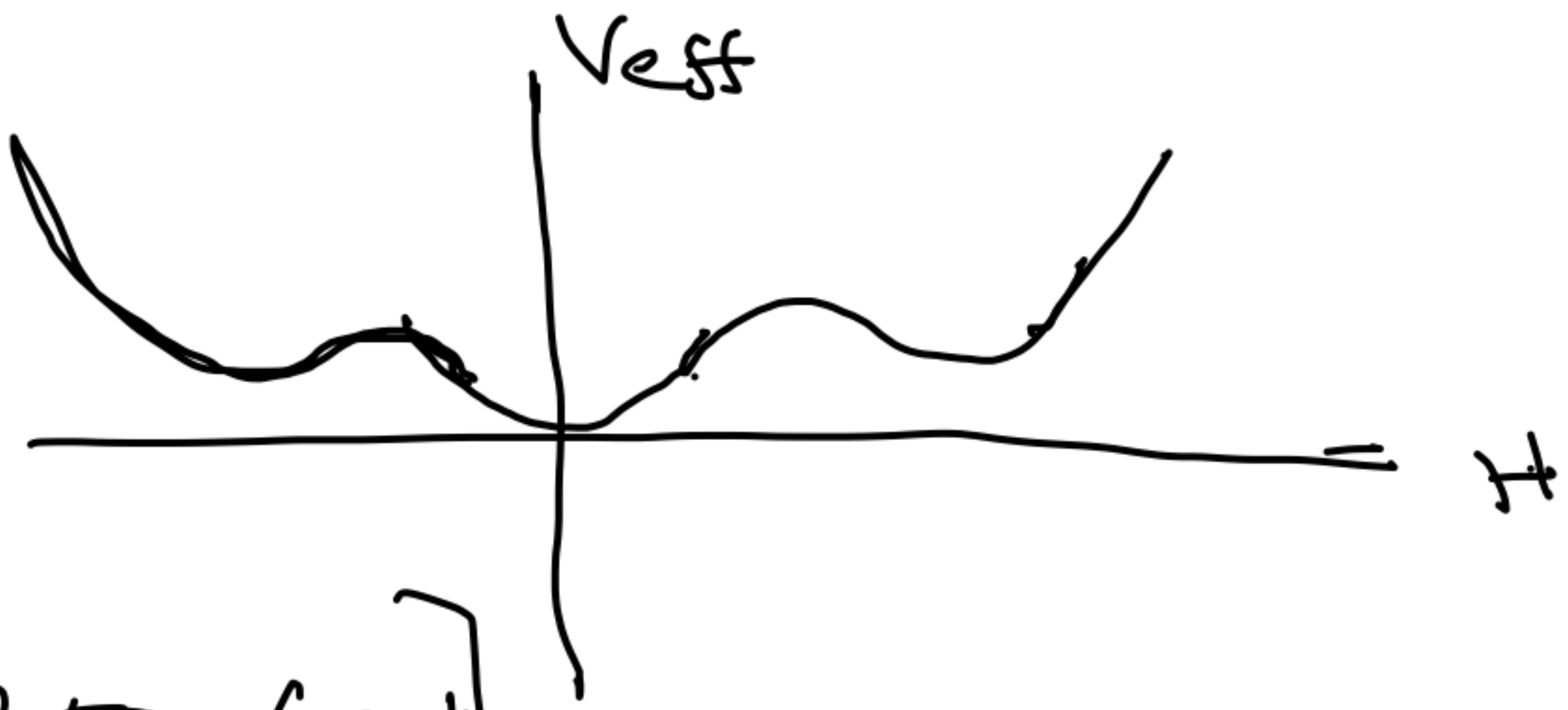
$\langle H \rangle = 0 \Rightarrow$ symmetry is unbroken.

As T reduces at some value T_c,

$a(T_c) = 0$

$$V_{eff} = a(T)\,|H|^2 + b(T)\,|H|^4 + c(T)\,|H|^6 + \cdots$$

(i) As $T \downarrow$, even when $a(T) > 0$, V_{eff} develops other local minima..



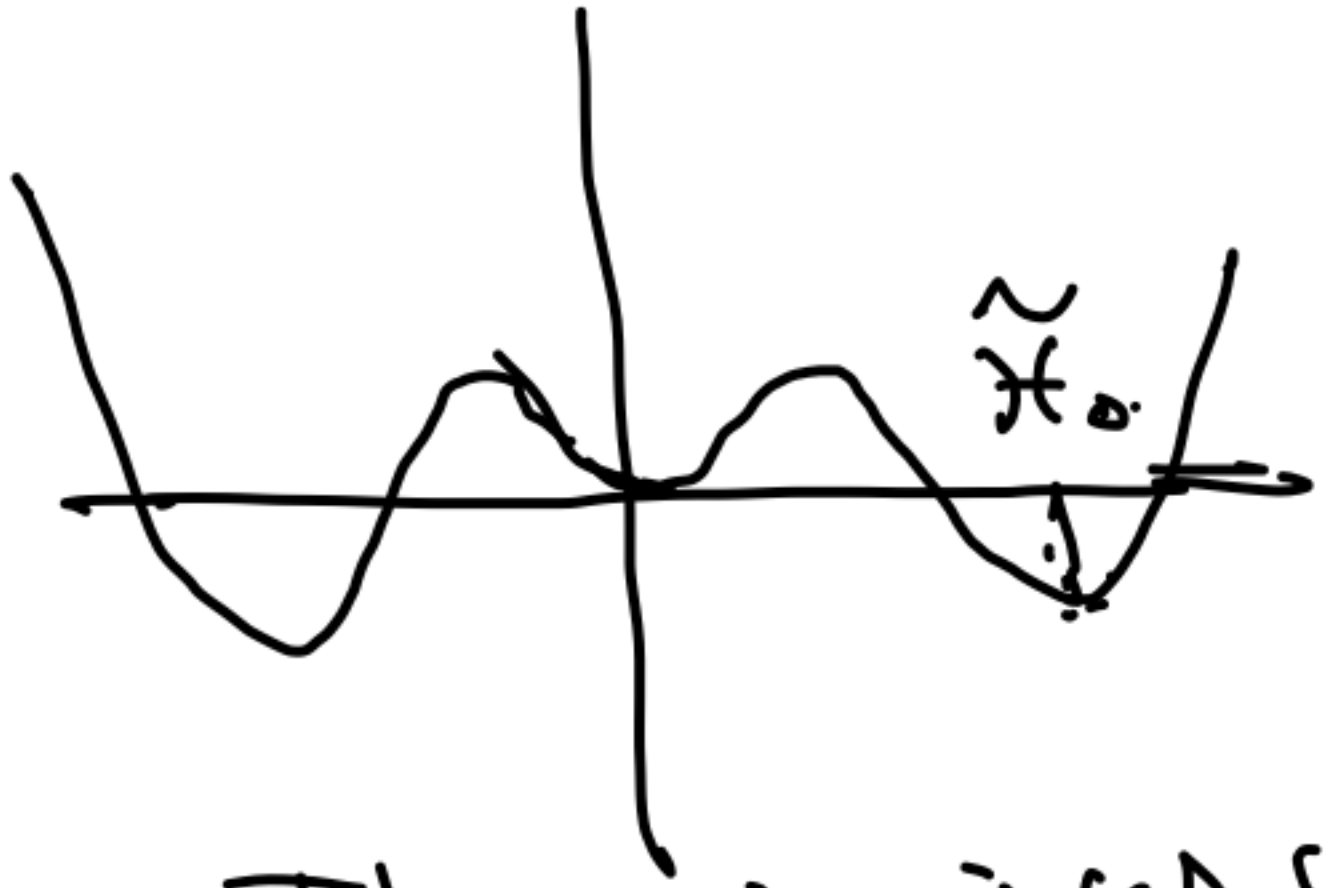
Higg vev jumps from 0 to $\tilde{H}_0$

$T \sim 100-200$ GeV

$T \downarrow 0$

$T \downarrow 0.$

$a(T) > 0.$



$\Rightarrow$ 1st order phase transition $\rightarrow$ The universe goes out of equilibrium

2nd possibility:

Minimum of V_{eff} remains at $H=0$ up to T_c.

$$a(T)\,|H|^2 + b(T)\,|H|^4 + \cdots$$

$a(T) = k(T-T_c)$

$\Rightarrow$ Min. at $|H|^2 = -\dfrac{a}{2b} = k(T_c-T)/(2b)$

As T goes below T_c

$\rightarrow$ 2nd order phase transition

$\rightarrow$ The universe remains in equilibrium.

Q. Which scenario holds for SM?

Given W, Z masses and the g_W

the only unknown in SM is

the coefficient of $|H|^4$ term

$\Longleftrightarrow$ Higgs mass.

a(T), b(T), c(T) calculable in terms of SM parameters

If $m_H < 72$ GeV then the phase transition is first order.

For $m_H > 72$ GeV it is second order.

Today we know that $m_H \simeq 126\,\text{GeV}$.

$\Rightarrow$ Phase transition is 2nd order.

$\Rightarrow$ The universe remains in equilibrium.

We cannot produce baryon no. by SM physics.

Grand unified theories unify the

$SU(3) \times SU(2) \times U(1)$ into a single group.

e.g. $SU(5) \rightarrow 25-1=24$ gauge bosons

spontaneously broken into $\longrightarrow SU(3) \times SU(2) \times U(1)$

$\rightarrow 8+3+1 = 12$

6

Additional massive gauge bosons.

X, Y

6 $\quad$ $\rightarrow 6$

Interactions:

$$d + u \to e^+ + \bar{u}$$

$$uud \to e^+ \underbrace{\bar{u}u}_{\pi^0}$$

$$p \to e^+ + \pi^0$$

Can violate baryon no.

Life-time $> 10^{34}$ Years.

$\Rightarrow \quad M_X \gtrsim 10^{16}$ GeV.

Bad news:

Any baryon no. that might have been generated earlier will be washed out by SM physics.

What we saw is that if $\tilde{n}_{(\ell)} = 0$ for every ℓ, then $n_\alpha - \bar{n}_\alpha = 0$ in thermal equilibrium.