Physics of CP Violation (V)

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8) Baryogenesis and CP violation

What do we know?

We see no anti-nucleus in the cosmic ray.

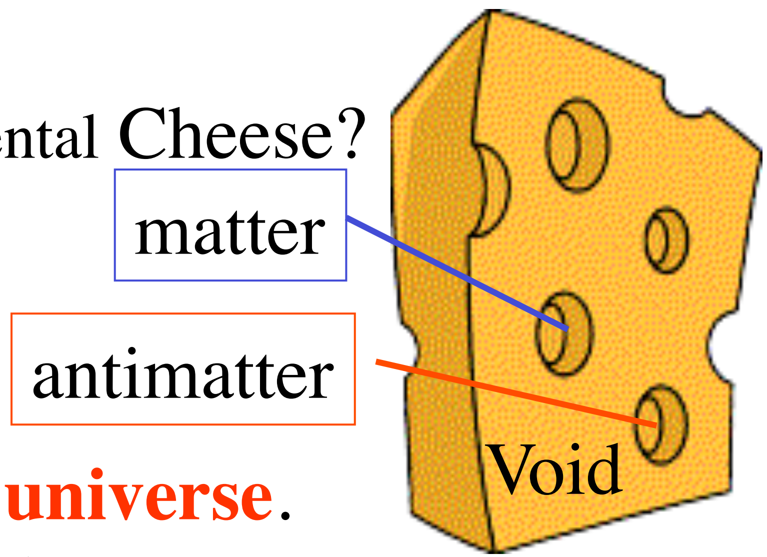
We se no γ rays from $p\bar{p}$ annihilation in space.

Conclusion

No evidence of anti-matter in our domain of universe.

(~20 Mps $\approx 10^8$ light-years)

Can our universe be "inverse" Emmental Cheese?



Unlikely!!

Most likely, **no anti matter in our universe**.

(~3000 Mps $\approx 10^{10}$ light-years)

Two key numbers

stars, gas etc.

$$\frac{\text{Number of baryons } (n_B)}{\text{Number of photons } (n_\gamma)} \approx 5\times10^{-10}$$

cosmic microwave background radiation

Number of baryons now ≈ 0 but $\neq 0$

$n_\gamma \approx (N_B + N_{\bar{B}})/2 \qquad n_B = N_B - N_{\bar{B}}$

$N_{B(\bar{B})}$ initial number of (anti)baryons

$$\Longrightarrow \quad \frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}} \approx 10^{-10}$$

1 baryon out of 10^{10} did not annihilate and survived.

How can we generate

$$\frac{N_{\mathrm{B}} - N_{\bar{\mathrm{B}}}}{N_{\mathrm{B}} + N_{\bar{\mathrm{B}}}} \approx 10^{-10}$$

from $N_{\mathrm{B}} - N_{\bar{\mathrm{B}}} = 0$ (initial condition for Big Bang at $t = 0$)?

Necessary conditions:

1) Baryon number violations:
   initial and final baryon numbers are different.
2) C and CP violation:
   partial decay widths are different.
3) Out of equilibrium:
   no reversing reaction installing the initial state.

(A.Sakharov, 1967)

Baryon genesis at very high energy (~10^{19}GeV): a la GUT

Universe is expanding very rapidly = out of equilibrium

X particles: B non-conserving decays

q: quark B=1/3 $\quad X \to qq: \Gamma_{qq}, \quad X \to \bar{q}\bar{\ell}: \Gamma_{q\ell}$

ℓ: lepton B=0 $\quad \bar{X} \to \bar{q}\bar{q}: \bar{\Gamma}_{qq}, \quad \bar{X} \to q\ell: \bar{\Gamma}_{q\ell}$

CPT: $\Gamma_{qq} + \Gamma_{q\ell} = \bar{\Gamma}_{qq} + \bar{\Gamma}_{q\ell} \equiv \Gamma_{tot}$

~~CP~~ and ~~C~~: $\Gamma_{q\ell} \neq \bar{\Gamma}_{q\ell}$

$$\left.\begin{array}{l} N_B \propto (2\Gamma_{qq} + \bar{\Gamma}_{q\ell})/3 \\ N_{\bar{B}} \propto (2\bar{\Gamma}_{qq} + \Gamma_{q\ell})/3 \end{array}\right\} N_B - N_{\bar{B}} = 2\underbrace{(\Gamma_{tot} - \bar{\Gamma}_{tot})}_{=0}/3 + \underbrace{(\bar{\Gamma}_{q\ell} - \Gamma_{q\ell})}_{\neq 0} \neq 0$$

$$N_L - N_{\bar{L}} = (\bar{\Gamma}_{q\ell} - \Gamma_{q\ell}) = N_B - N_{\bar{B}} \neq 0$$

+ Simple to explain.

− Generated at very early time of universe;

$B = L$ asymmetry would have been diluted in the evolution.

Baryon genesis at "low" energy ($\sim 10^2$GeV):

Physics at electroweak scale:

the Standard Model + possibly SUSY, L-R, TC etc.

+ No asymmetry dilution possible afterwards.
+ Physics is accessible with the accelerators,

− Difficult to explain.

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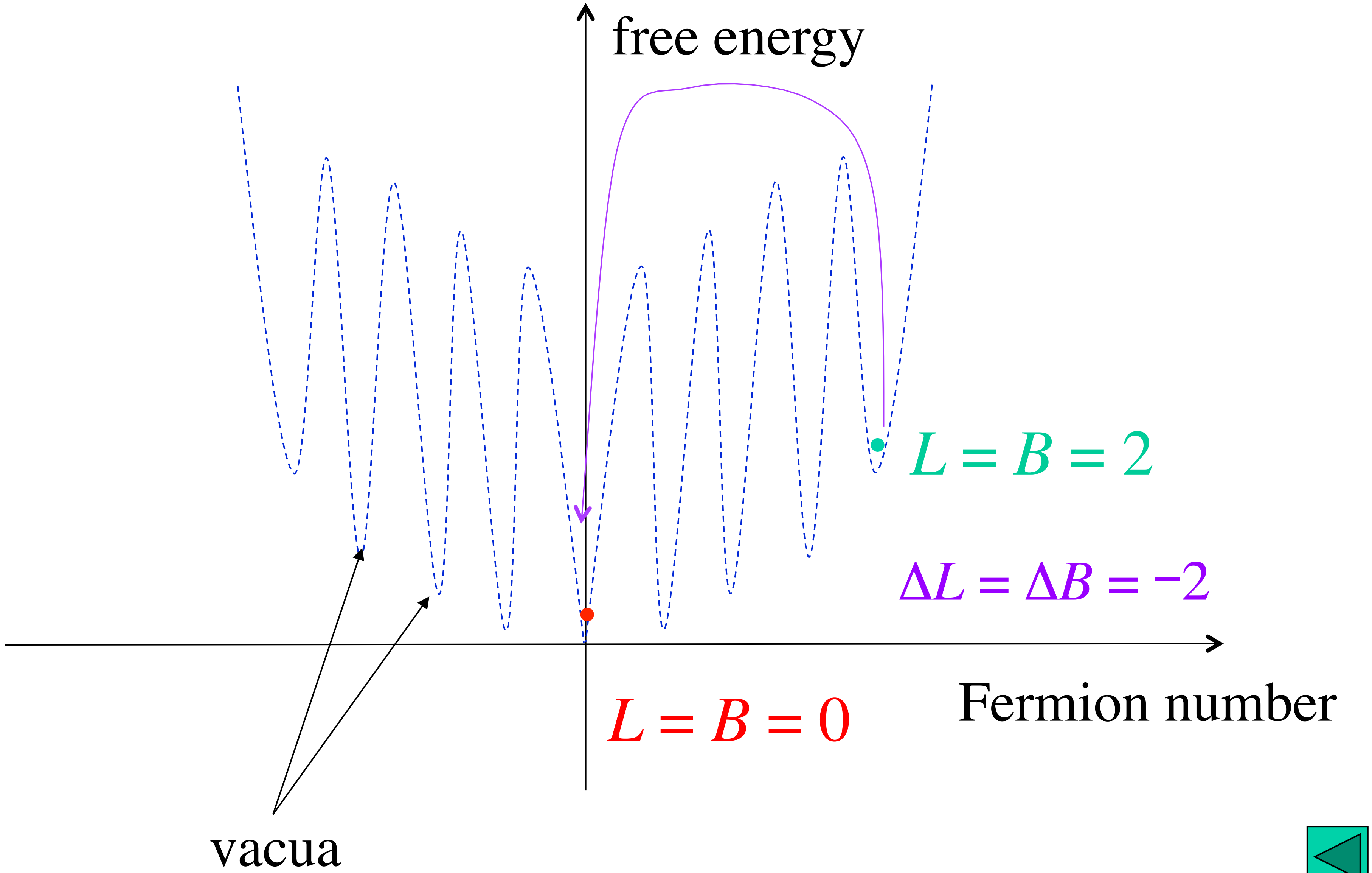
In the Standard Model

- Baryon number violation due to "SU(2) anomaly"

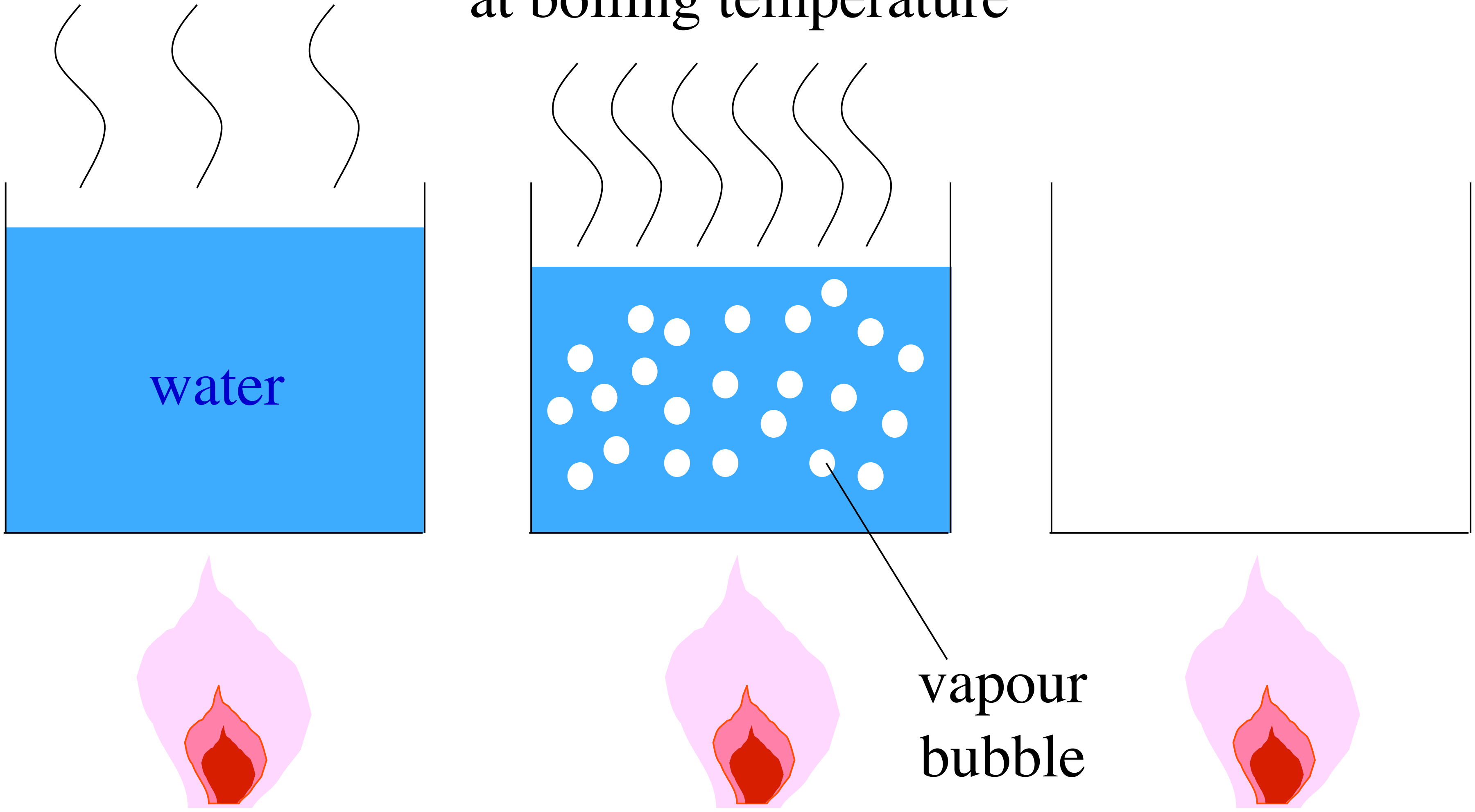
  → transitions to different vacuum states: $\Delta L = \Delta B$

  (change in baryon number = change in lepton number)
- CP violation through the KM phase
- Out of equilibrium through the first-order phase transition

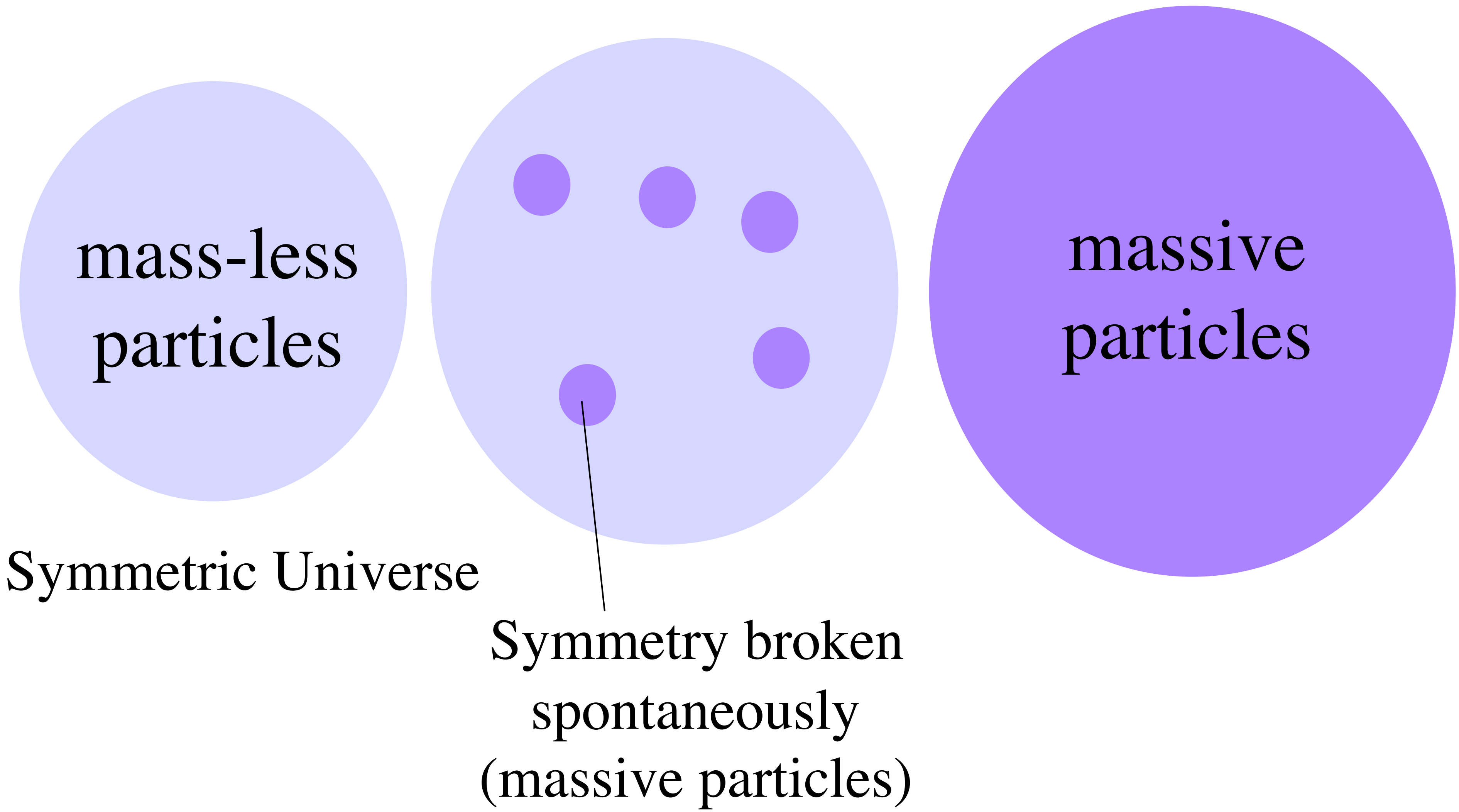

free energy
$L = B = 2$
$\Delta L = \Delta B = -2$
$L = B = 0$
Fermion number
vacua

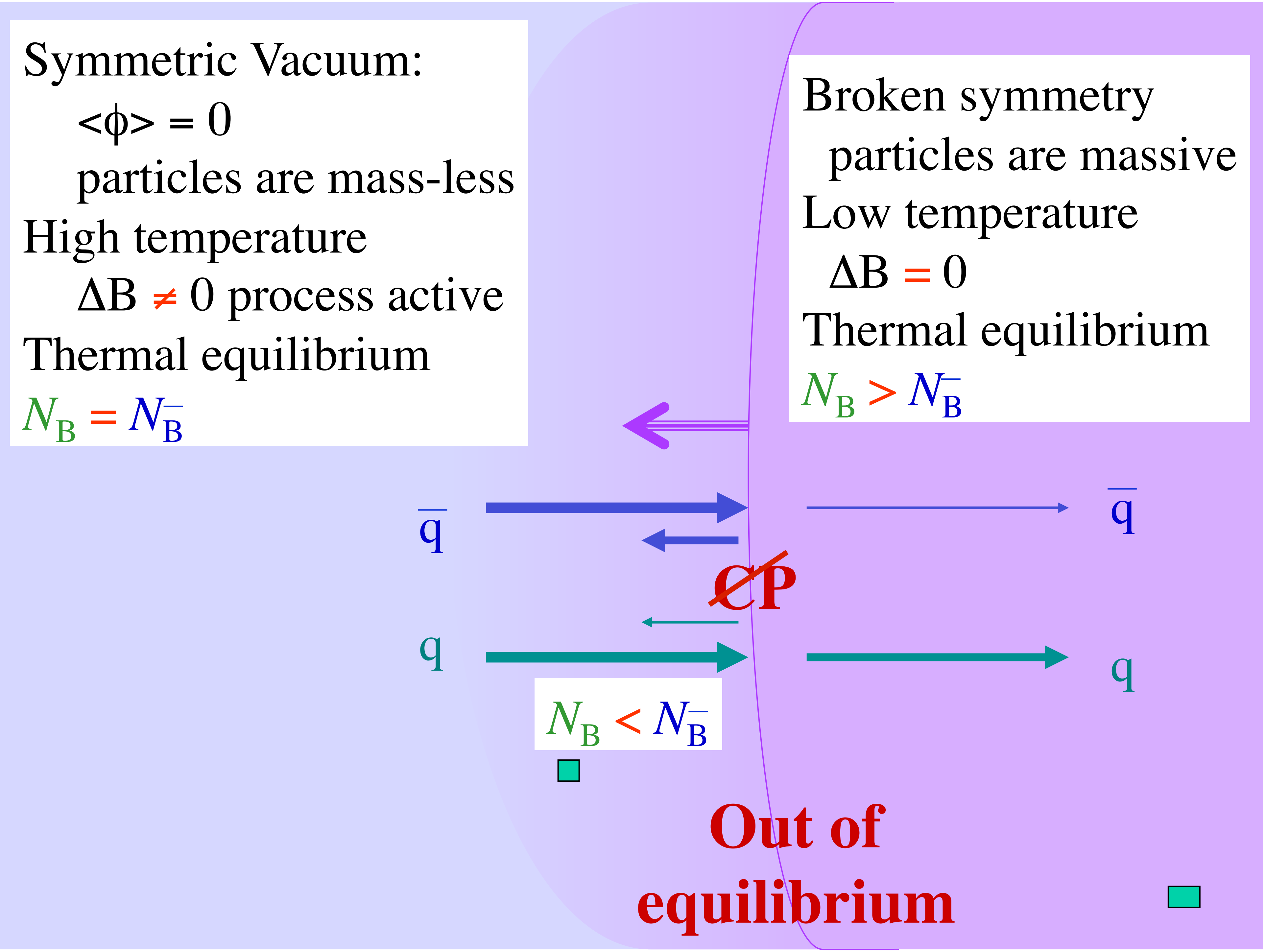
Boiling Water

phase transition
at boiling temperature



Electroweak phase transition





Symmetric Vacuum:
$\langle\phi\rangle = 0$
particles are mass-less
High temperature
$\Delta B \neq 0$ process active
Thermal equilibrium
$N_B = N_{\bar{B}}$
Broken symmetry
particles are massive
Low temperature
$\Delta B = 0$
Thermal equilibrium
$N_B > N_{\bar{B}}$
$\bar{q}$
$\bar{q}$
CP
q
q
$N_B < N_{\bar{B}}$
Out of equilibrium

Two problems with the minimal Standard Model:

1) Too heavy Higgs mass

In order to have the first-order phase transition:

$$m_H \lesssim 70\ \text{GeV}/c^2$$

LEP results:

$$m_H \gtrsim 100\ \text{GeV}/c^2$$

2) Too small CP violation

With KM phase:

$$\frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}} < \frac{J_{CKM}}{T_c^{\ 12}} \approx 10^{-20}$$

$$J_{CKM} \approx (m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2) \times (m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2) \times s_1 s_2 s_3 \sin\delta$$

$(m_t^2 - m_c^2)\cdots(m_s^2 - m_d^2) \sim 4\times10^{10}$

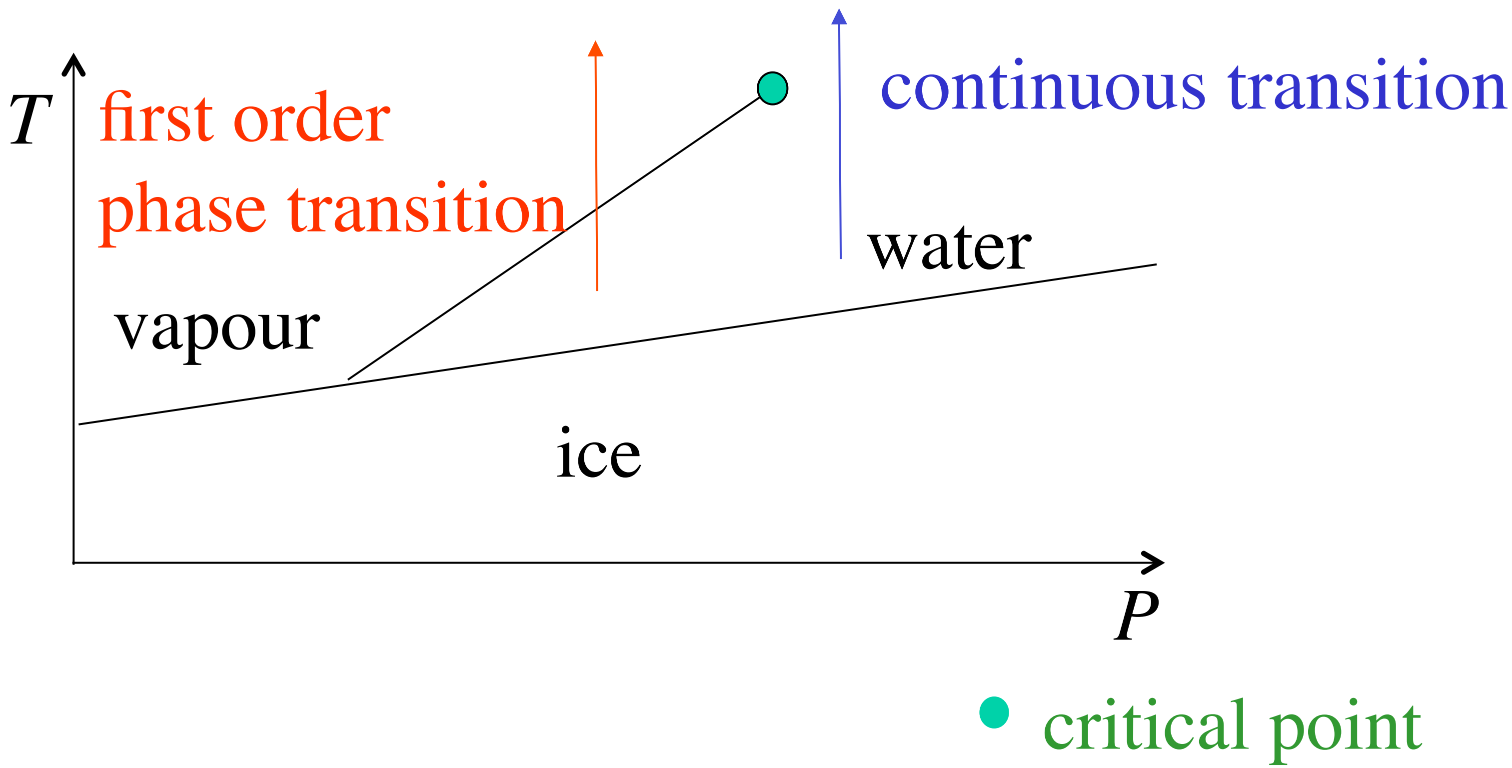
$s_1 s_2 s_3 \sin\delta \sim 10^{-5}$

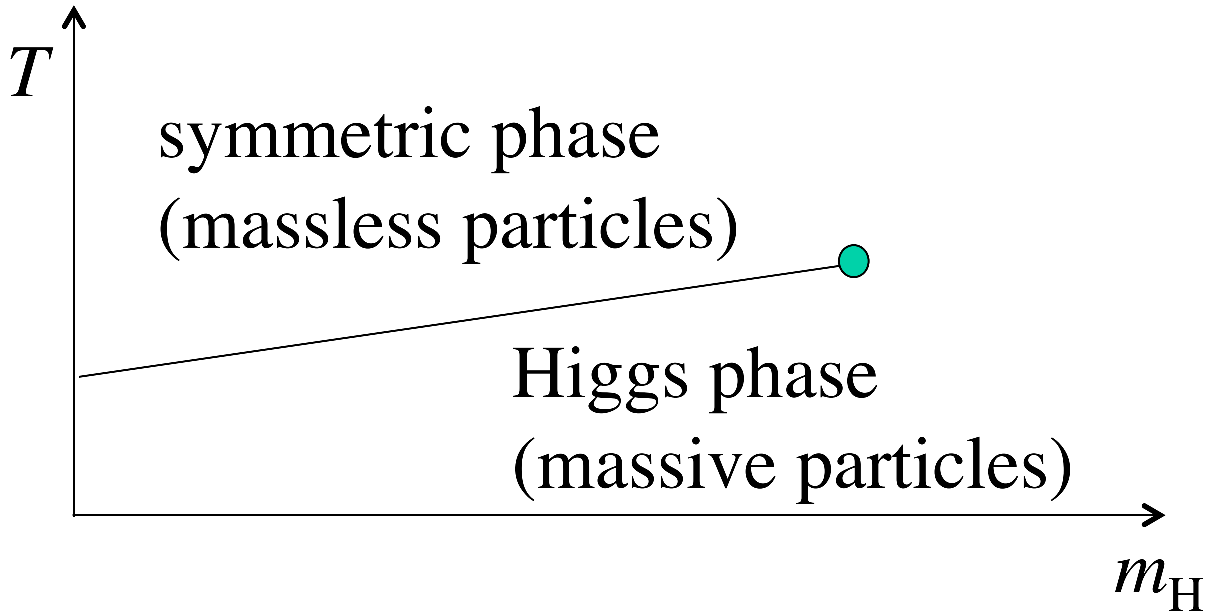
$T_c \approx 100$ GeV

Required from $N(B)/N(\gamma)$

$\approx 10^{-10}$

skip


T
first order
phase transition
continuous transition
water
vapour
ice
P
critical point


T
symmetric phase
(massless particles)
Higgs phase
(massive particles)
m_H

They can be overcome by some
"minor" extension of the Standard Model:

- Super Symmetry
- Multi Higgs doublet
- etc...

which should appear in "electroweak" energy scale.

Search for
new particles,
unexpected effects in CP violation and rare decays.

Baryogenesis through leptogenesis

Recent results indicate;
Neutrinos have masses and mix each other, like quarks.

One of the most favoured pictures:

Neutrinos are Majorana particles

(no experimental evidence)

neutrino = anti-neutrino

There exists very heavy leptons

Heavy right handed Majorana neutrino N_R:

$$m_R \approx 10^{10} - 10^{11}\ \mathrm{GeV}$$

Decays into light leptons are CP violating

$$\Gamma(N_R \rightarrow L) < \Gamma(N_R \rightarrow \bar{L})$$

Once the temperature of the universe becomes $T \lesssim 10^{10}$ GeV,

all the N_R decay away: $N_L < N_{\bar{L}}$

lepton number generated; $L = N_L - N_{\bar{L}} < 0$

The Standard Model "SU(2) anomaly" process:

$L+B \rightarrow 0$: i.e. $\Delta L > 0$

Since $\Delta L = \Delta B$, this generates Baryon number $B > 0$

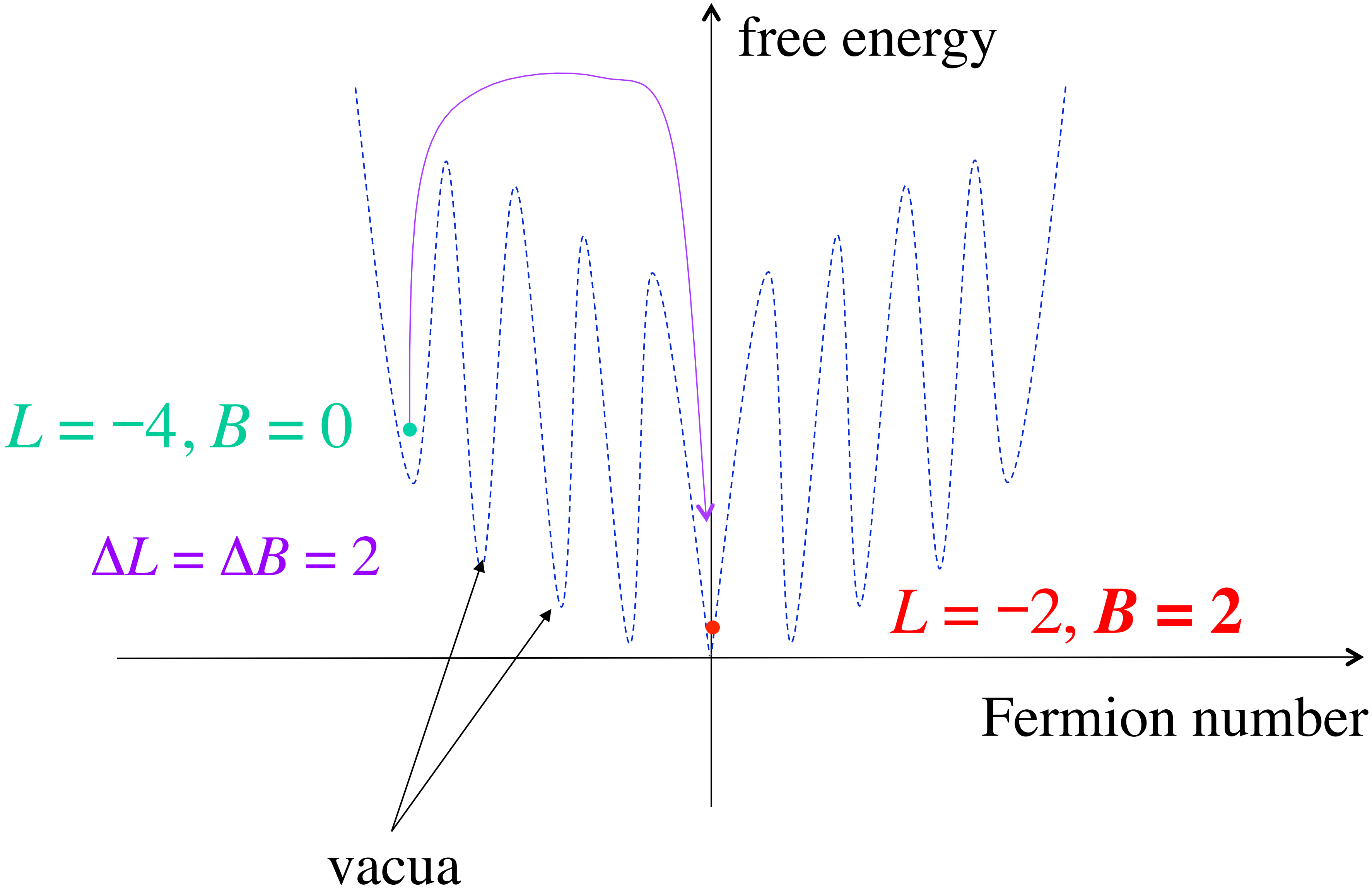
No electroweak phase transition!!!

+ elegant

+ measurable parameters at our energy have no relation to what happens at very high energies.

NB: CP violation in ν oscillations cannot make this effect

$\text{Prob}(\nu_i \rightarrow \nu_j) \neq \text{Prob}(\bar{\nu}_i \rightarrow \bar{\nu}_j)$ but $\sum_i N(\nu_i) = \sum_i N(\bar{\nu}_i)$



free energy
$L = -4, B = 0$
$\Delta L = \Delta B = 2$
$L = -2, \boldsymbol{B = 2}$
Fermion number
vacua

Search for new physics via CP violation

(Biased?) Conclusion:

A good chance that there exists new sources of $\not{C}\!P$.

What do we look for?

Deviation from the Standard Model predictions.

Where do we look for?

1) Deviation could be large.

example: neutron electric dipole moment

2) The Standard Model predictions are precise.

$K^0 \to \pi^0 \nu\bar{\nu}$

Many decay modes in the B meson system

We still need to understand why
we did not have disappeared!