8) Baryogenesis and CP violation

What do we know?

We see no anti-nucleus in the cosmic ray.

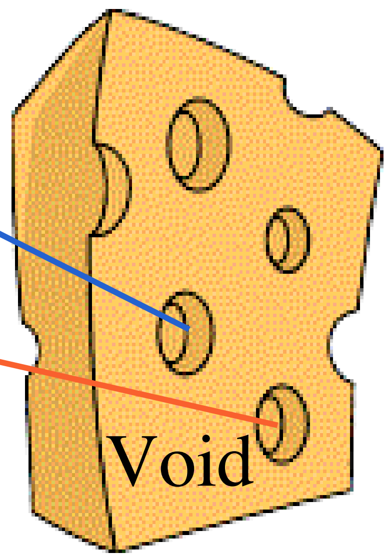
We se no γ rays from $p\bar{p}$ annihilation in space.

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?



Difficult!!

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

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

Two key numbers

stars, gas etc.

$$\frac{\text{Number of baryons } (N_B)}{\text{Number of photons } (N_\gamma)} = 10^{-9} \sim 10^{-10}$$

cosmic microwave background radiation

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

$$\Longrightarrow \quad \frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}} = 10^{-9} \sim 10^{-10}$$

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

How can we generate

$$\frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}} = 10^{-9} \sim 10^{-10}$$

from $N_B - N_{\bar{B}} = 0$ (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 ($\sim 10^{19}$GeV): a la GUT

Universe is expanding very rapidly = out of equilibrium

X particle: B non conserving decays

q: quark B=1/3

ℓ: lepton B=0

$X \to qq: \Gamma_{qq}, \quad X \to \bar{q}\bar{\ell}: \Gamma_{q\ell}$

$\bar{X} \to \bar{q}\bar{q}: \bar{\Gamma}_{qq}, \quad \bar{X} \to q\ell: \bar{\Gamma}_{q\ell}$

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

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

$$N_B \;\mu\; (2\Gamma_{qq} + \bar{\Gamma}_{q\ell})/3$$

$$N_{\bar{B}} \;\mu\; (2\bar{\Gamma}_{qq} + \Gamma_{q\ell})/3$$

$$N_B - N_{\bar{B}} = 2\underbrace{(\Gamma_{tot} - \bar{\Gamma}_{tot})}_{=0}/3 + \underbrace{(\bar{\Gamma}_{q\ell} - \Gamma_{q\ell})}_{\neq 0} \neq 0$$

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

\+ 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 (~10^2GeV):

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.

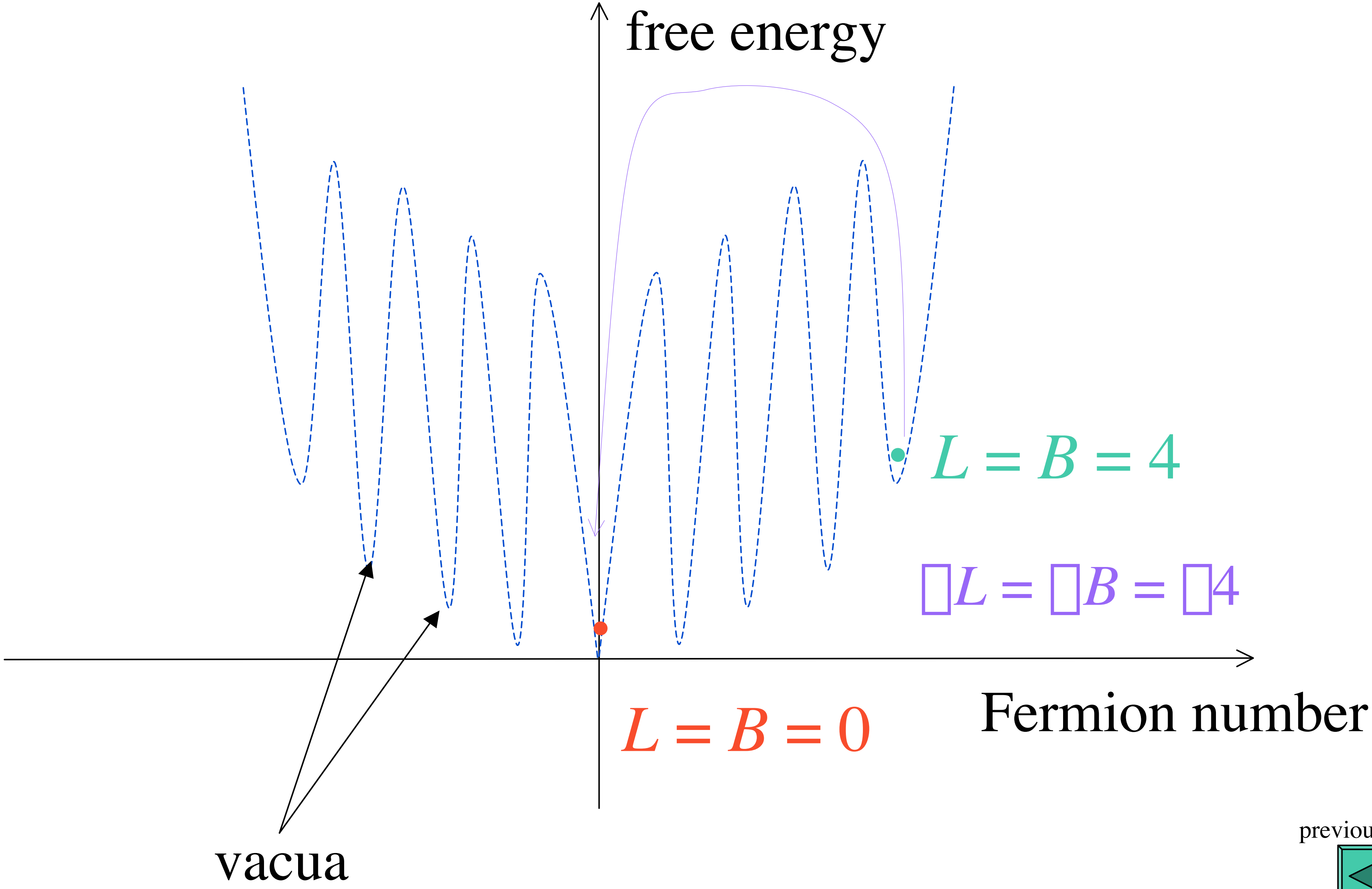
In the Standard Model

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

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

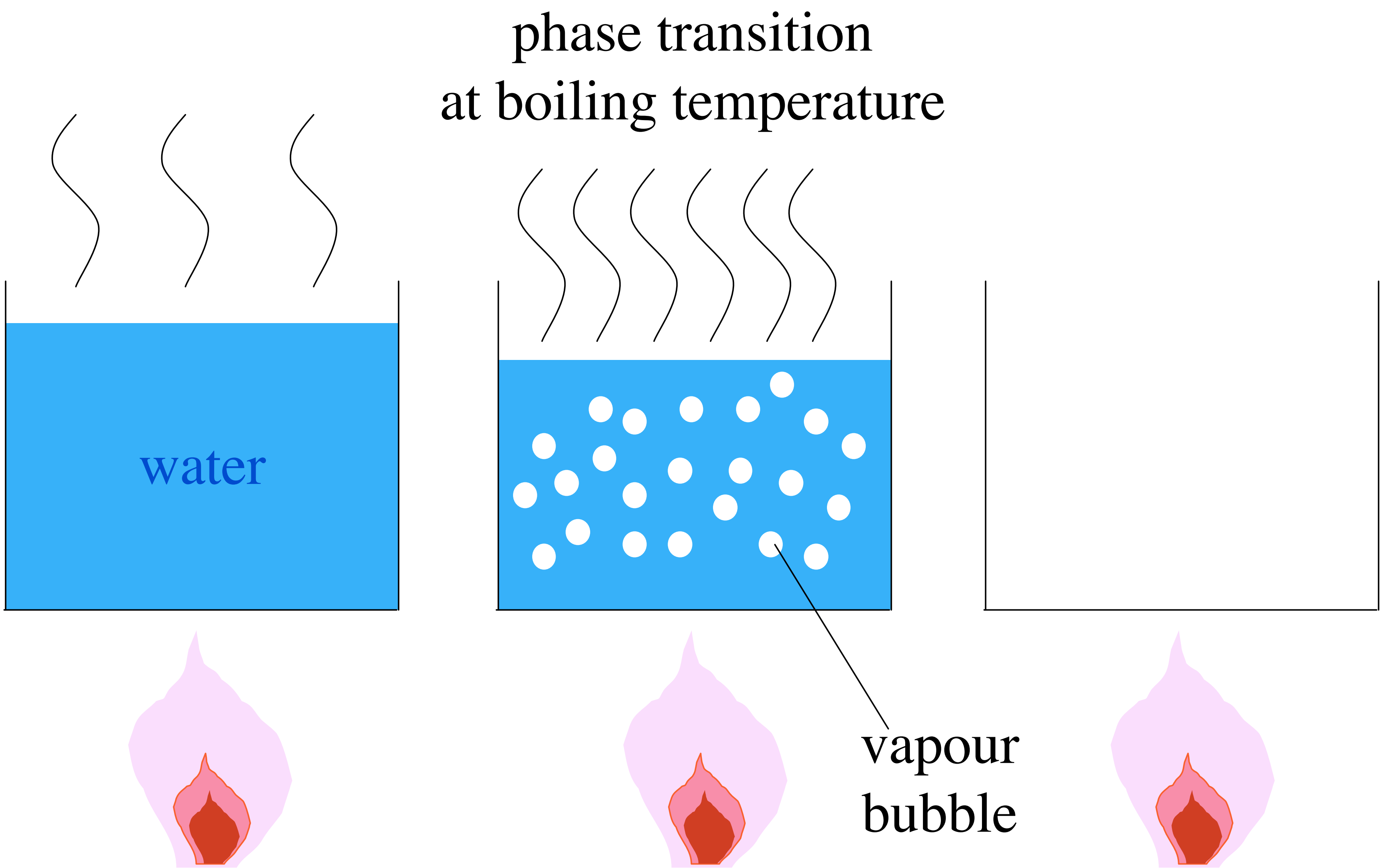
  (change in baryon number = change in lepton number)

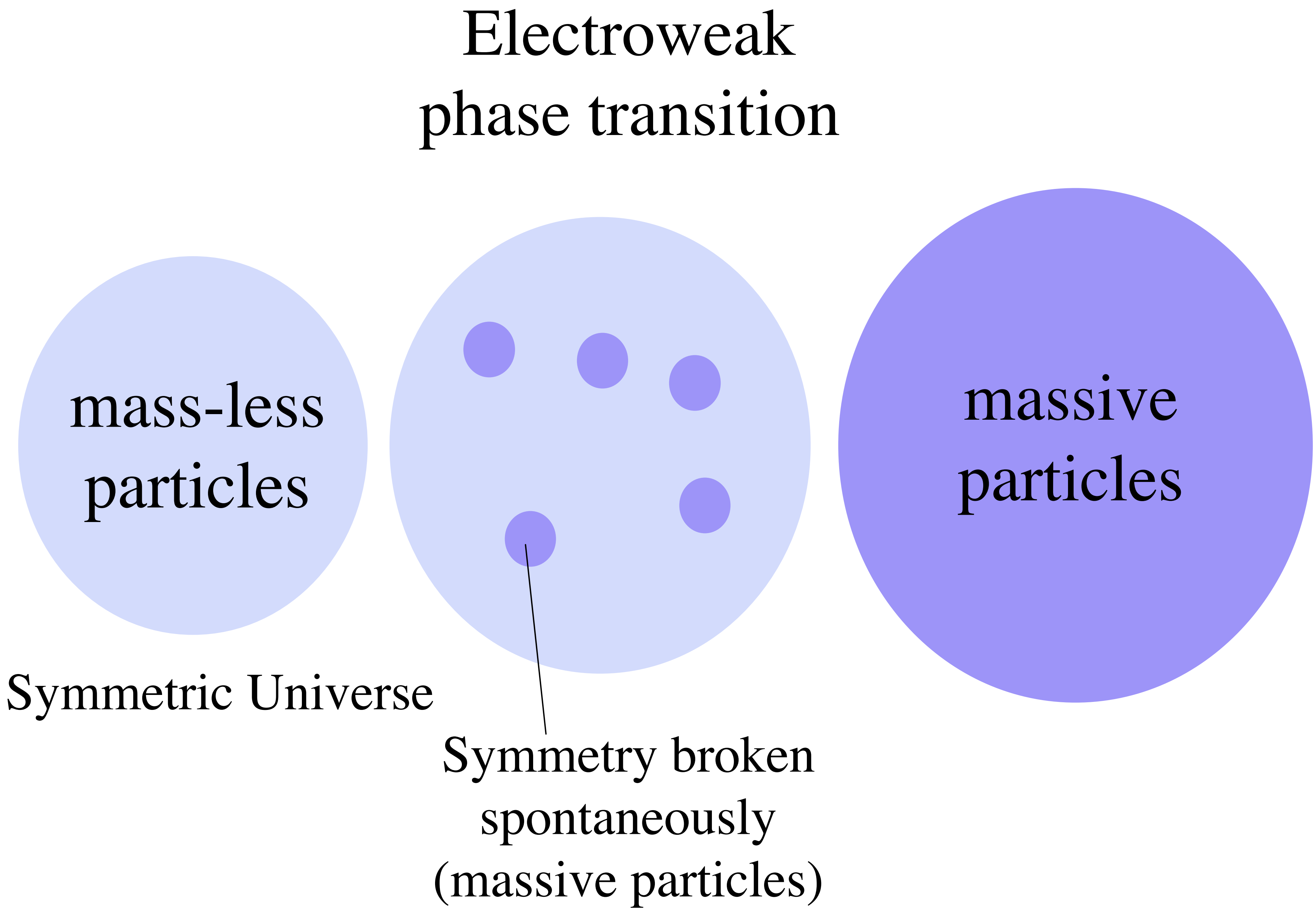
- CP violation through the KM phase
- Out of equilibrium through the first-order phase transition



previous
back

Boiling Water




Electroweak
phase transition
mass-less
particles
Symmetric Universe
Symmetry broken
spontaneously
(massive particles)
massive
particles

Symmetric Vacua:

<□>=0

particles are mass-less

High temperature

□B≠0

Thermal equilibrium

$N_B = N_{\bar{B}}$

Broken symmetry

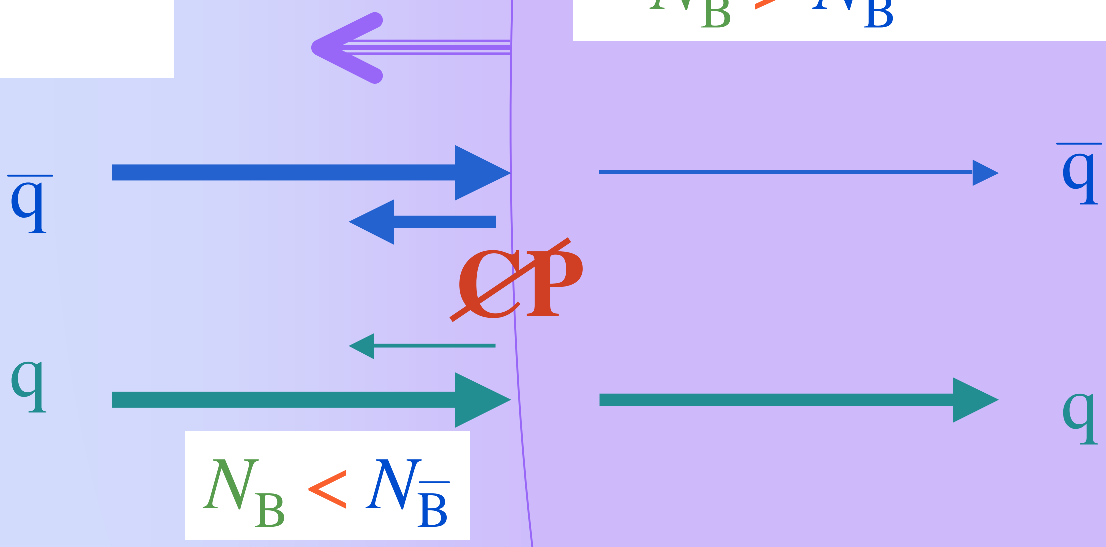
particles are massive

Low temperature

□B=0

Thermal equilibrium

$N_B > N_{\bar{B}}$



Out of equilibrium

Two problems with the minimal Standard Model:

1) Too heavy Higgs mass

In order to have the first-order phase transition:

$$m_H < \sim 70\ \mathrm{GeV}/c^2$$

LEP results:

$$m_H > \sim 100\ \mathrm{GeV}/c^2$$

2) **Too small CP violation**

With KM phase:

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

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

$$= 10^{-9} \sim 10^{-10}$$

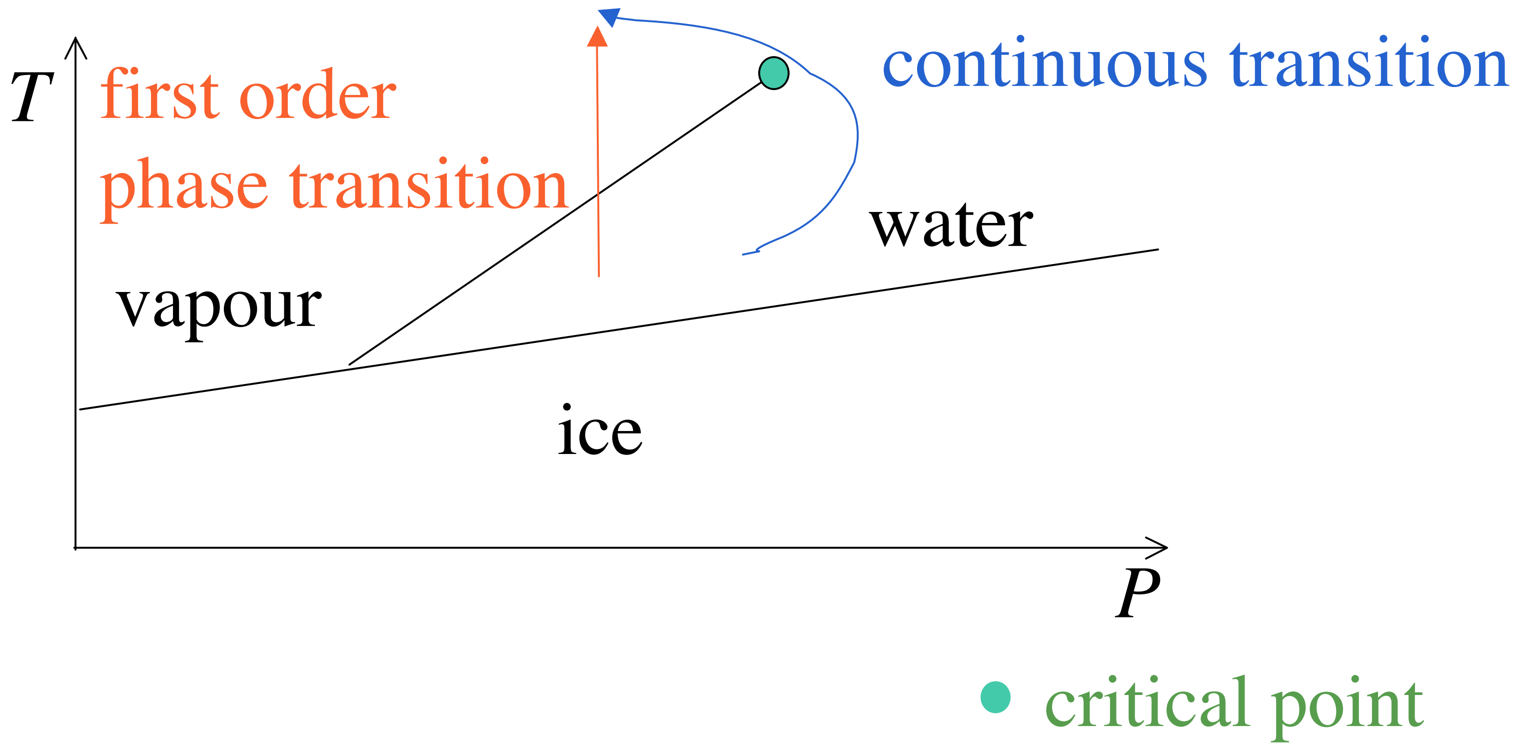
$$J_{CKM} \approx (m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2) \times (m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2) \times s_1 s_2 s_3 \sin\delta$$

$\sim 4 \times 10^{10}$

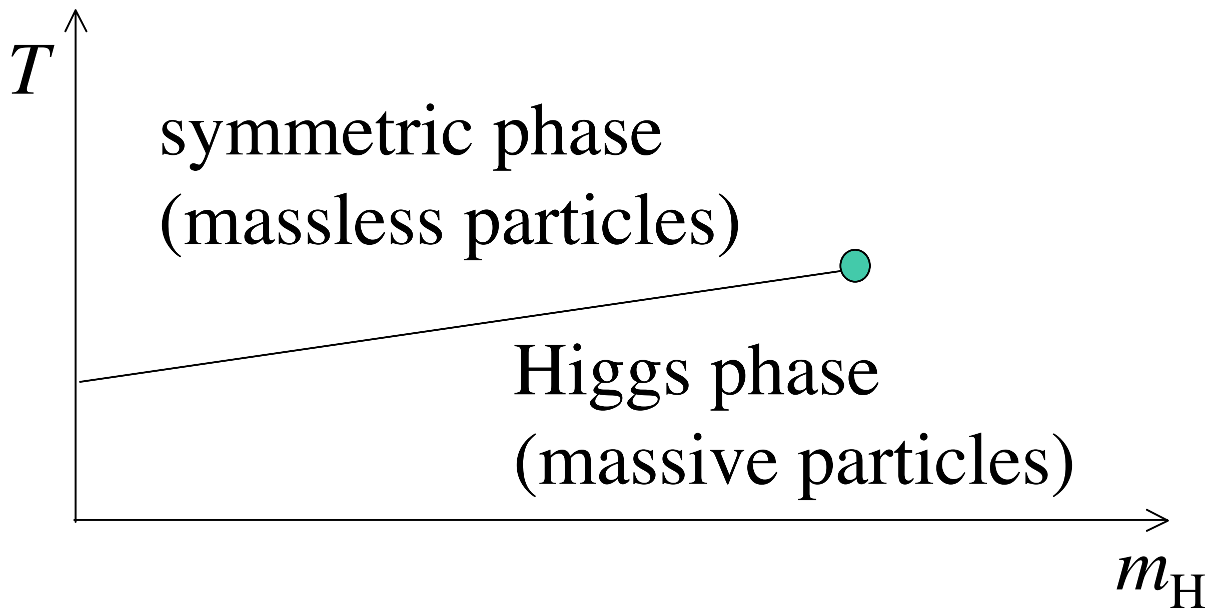
$\sim 10^{-5}$

$$T_c \approx 100\ \mathrm{GeV}$$

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 easily 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.

Baryon genesis through lepton genesis

Recent results indicate;
Neutrinos may 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:

$m_R \simeq 10^{10}$ - 10^{11} GeV

Decays into light leptons are CP violating

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

Once the temperature of the universe becomes T<~10^{10} GeV,

$N_L < N_{\bar{L}}$

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

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

L □ 0: i.e. □$L > 0$

Since □L = □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.

9)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

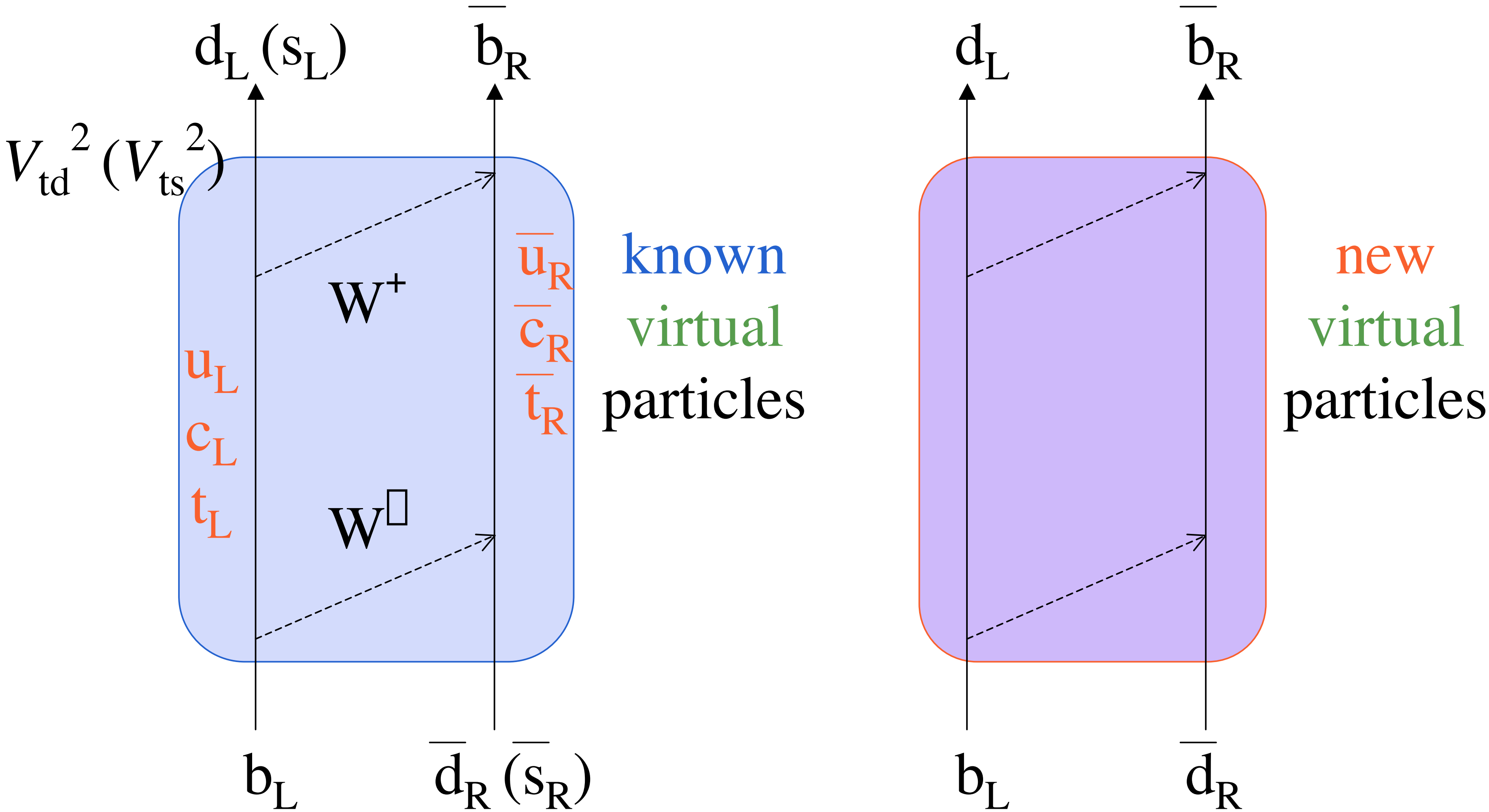
2) The Standard Model predictions are precise.

K^0□ □^{0}□□

Many decay modes in the B meson system

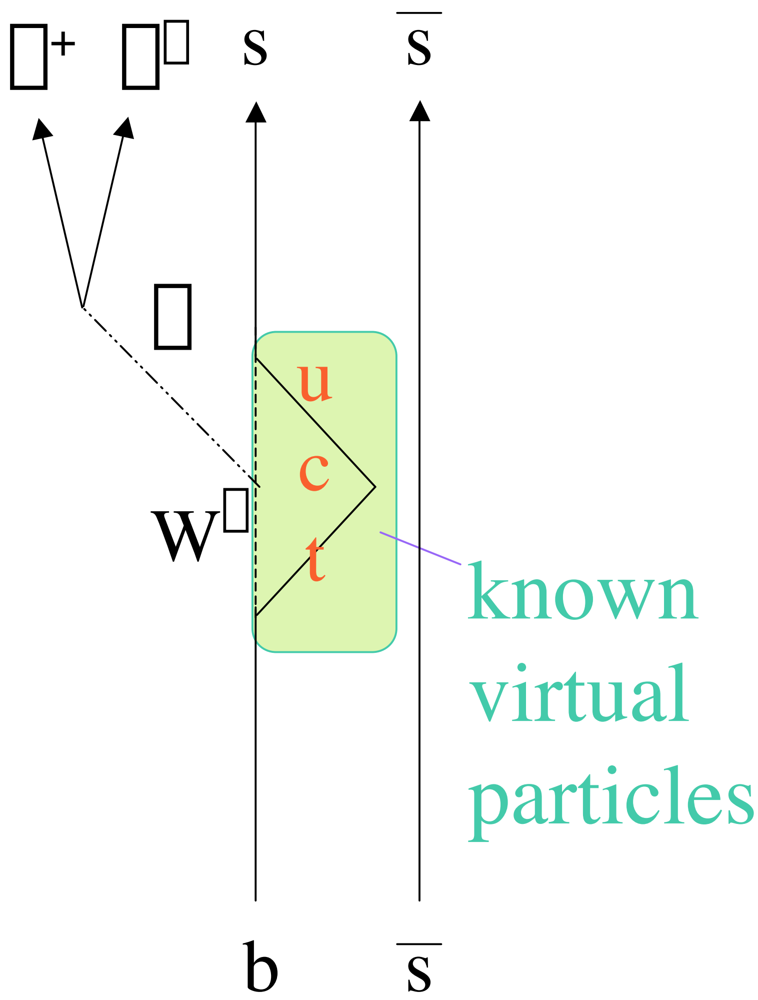
V_{td} and V_{ts} measurements

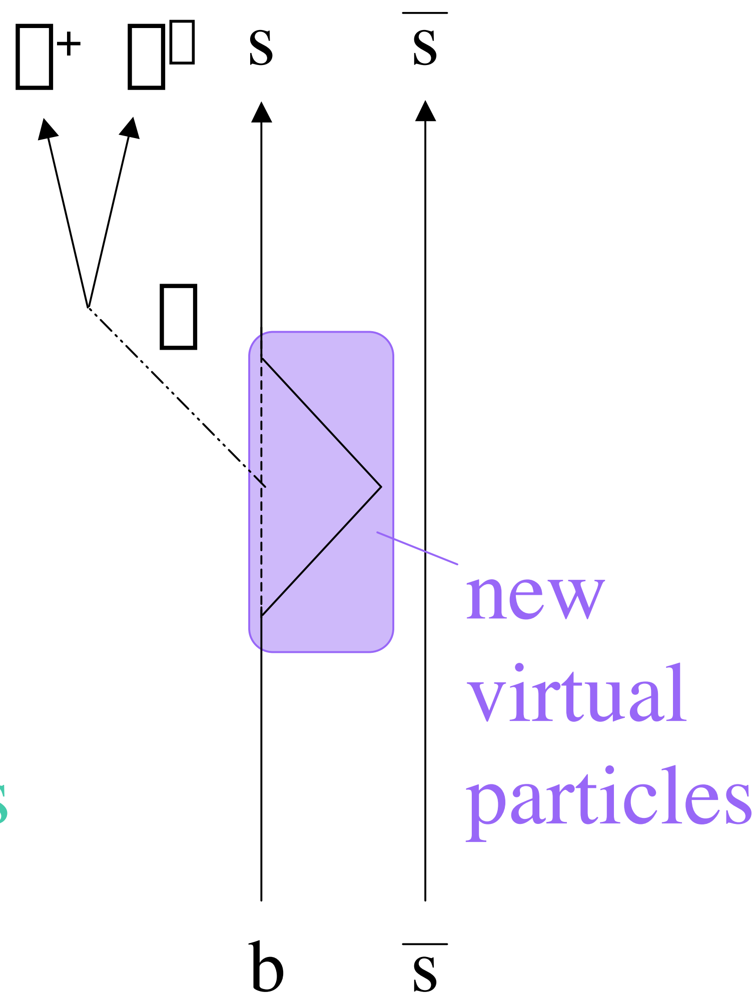
could be **highly affected** by “new physics”.



Also in the decays

$\overline{B}_s^0$□ □□$^+$□$^□$ decays





Precise determination of the phase of the elements from CP violation in the B-meson systems.

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

arg V_{ub} from
CP violation in
B□ $D^{□}$□, B_s□ D_sK
BTeV and LHCb >2006

arg V_{ts} from
CP violation in B_s□ J/□□
ATLAS, CMS, LHCb and BTeV >2006

arg V_{td} from
CP violation in B_d□ J/□K_S *BABAR* and BELLE
to be improved byATLAS, CMS, LHCb and BTeV >2006

At LHC

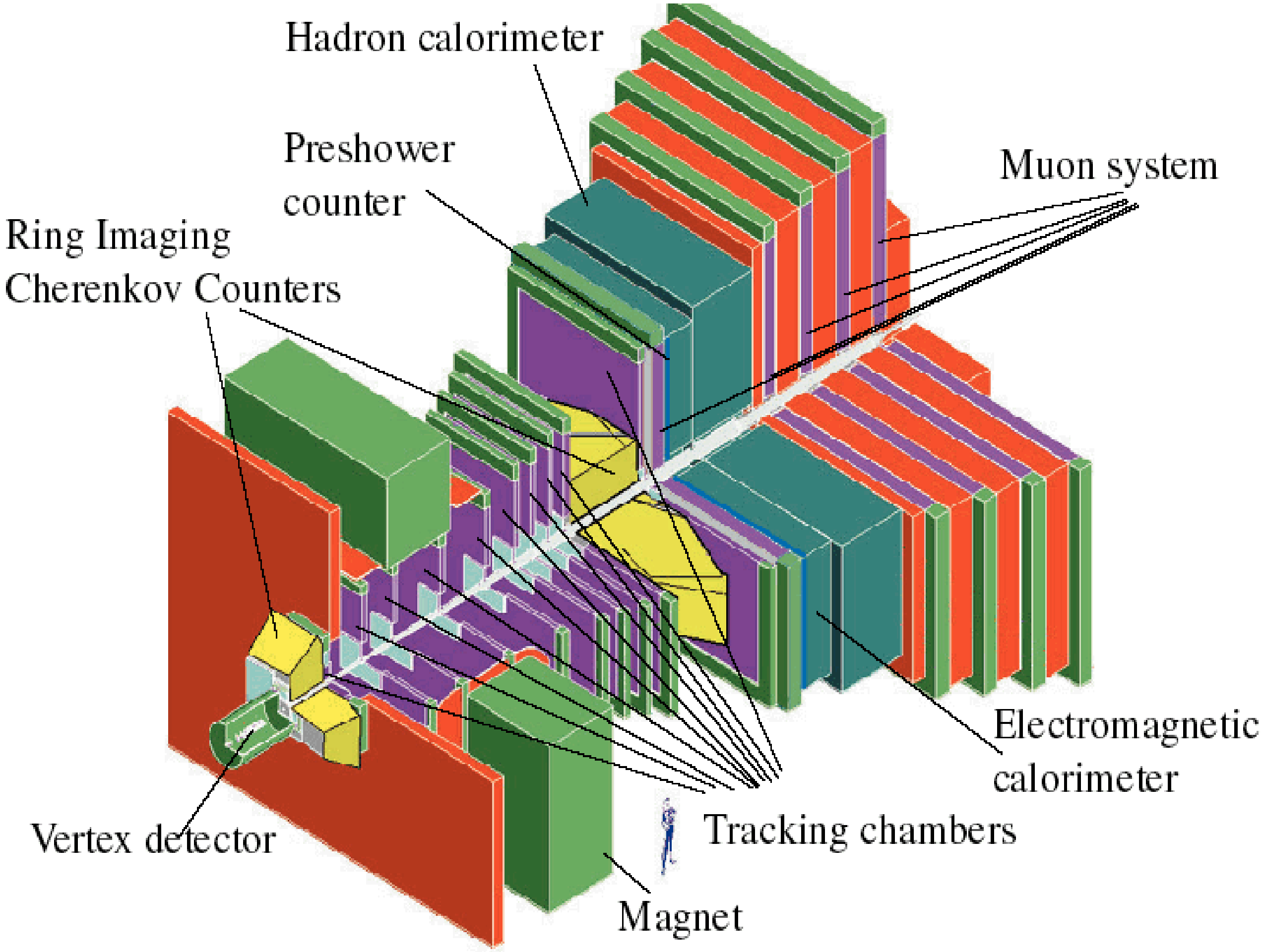
+ many b quarks 10^{11} to 10^{12} / years
  cf. 10^{8} to 10^{9} / year at e^+e^- machines

+ B_u, B_d, B_s, B_c, b-baryons
  cf. B_u and B_d at e^+e^- machines

− large background
  $b\bar{b}$ events are less than 1%
  cf. 20% at e^+e^- machines
  many tracks in one event (30 to 50)
  cf. only b decay tracks at e^+e^- machines

⇒ **a specialised experiment needed!**

The *LHCb* Experiment



Brazil

Finland

France

Germany

Italy

Poland

PRC

Netherlands

Romania

Russia

Ukraine

UK

Switzerland

Spain

At LHC,
physics beyond the Standard Model
will be studied
directly (detection of new particles)
by ATLAS and CMS
and
indirectly (CP violation)
by LHCb.

Summary

- $\not{CP}$ and $\not{C}$ are clearly seen in the neutral K and B systems.
- $\not{CP}$ and $\not{C}$ are seen in both oscillations and decays,
  compatible with the Standard Model expectation
- Baryogenesis indicates that there must be $\not{CP}$ and $\not{C}$
  beyond the Standard Model,
  which could be just around the corner...
- Several experiments are being done:
  and more are in preparation...

We may discover a new source of CP violation soon...
since we have not been annihilated (yet)!!!