8) Baryogenesis and CP violation

What do we know?

We see no anti-nucleus in the cosmic ray.

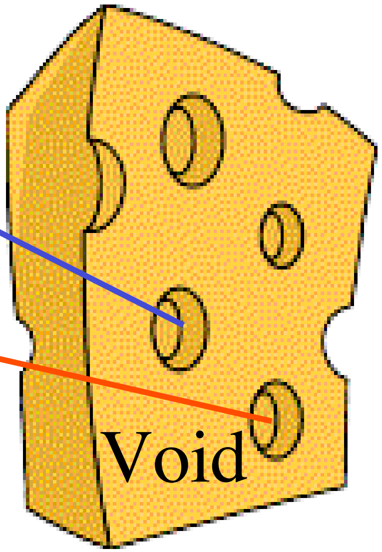
We se no γ rays from $p\bar{p}$ annihilation in space.

Conclusion

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

(~20 Mps ≈10^8 light-years)

Can our universe be “inverse” Emmental Cheese?



Difficult!!

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

(~3000 Mps ≈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 $\approx$ 0 but $\neq$ 0

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

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

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

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
ℓ: lepton B=0

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

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

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

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

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

+ 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.

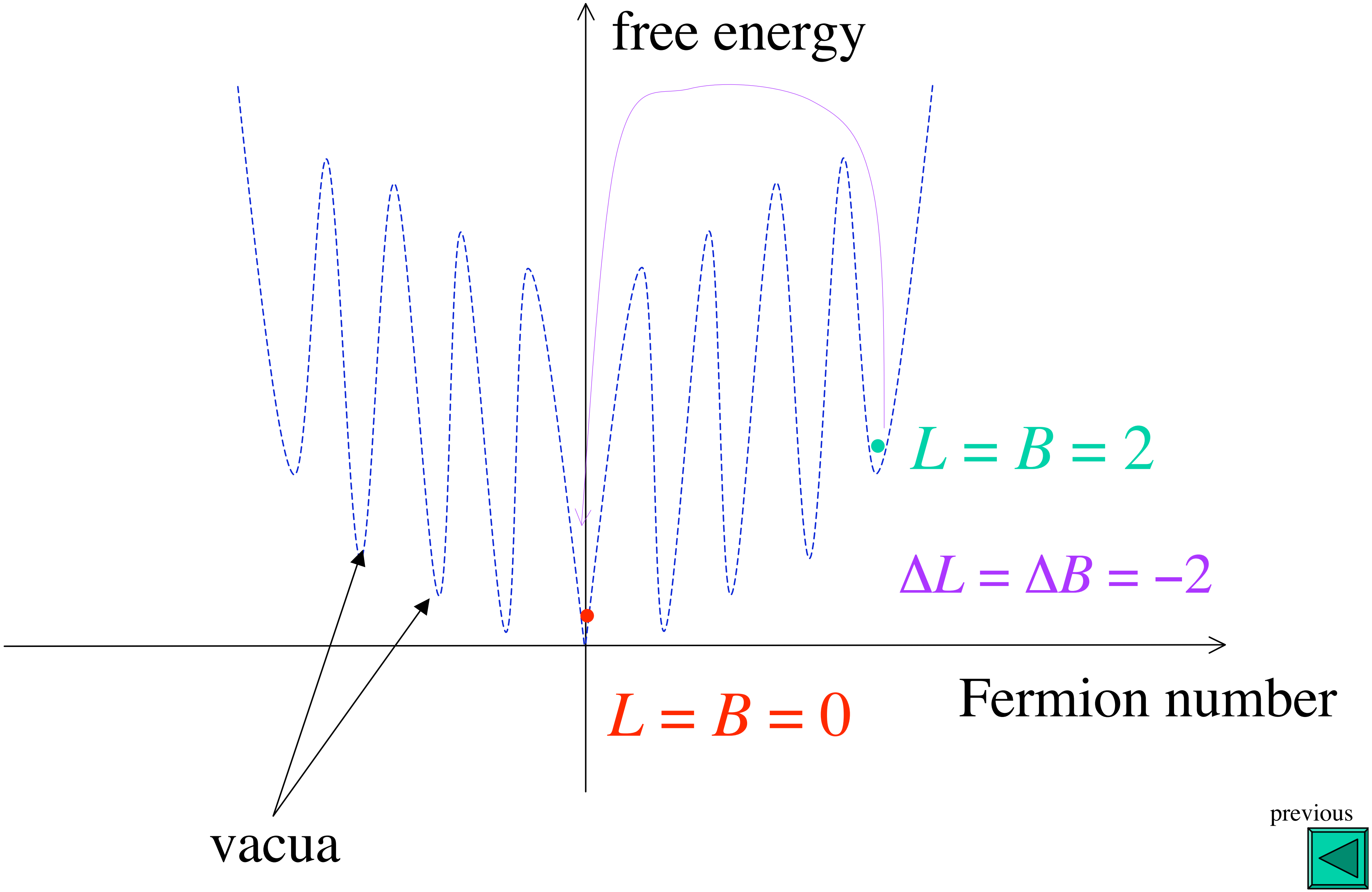
In the Standard Model

- 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

🟩

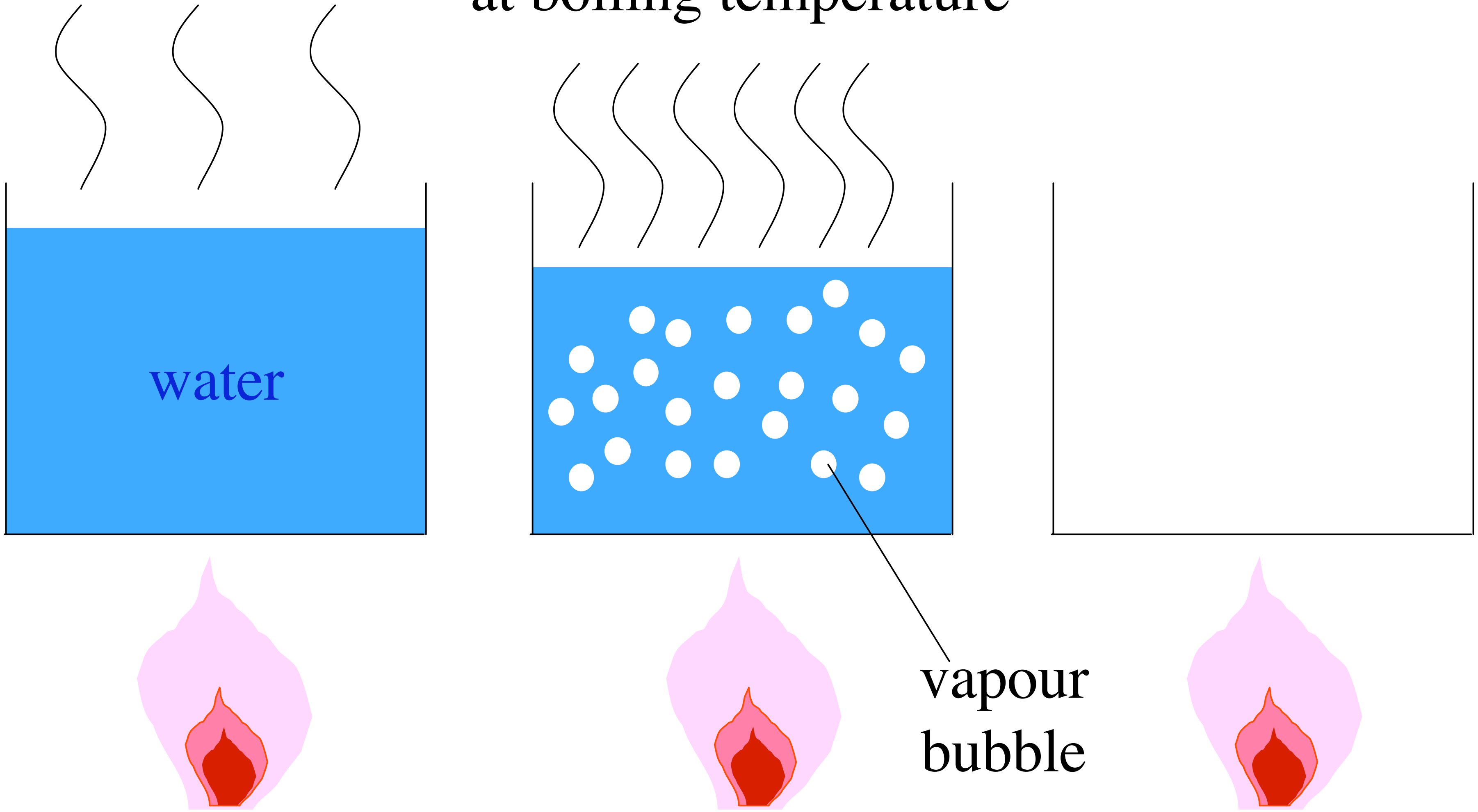


previous

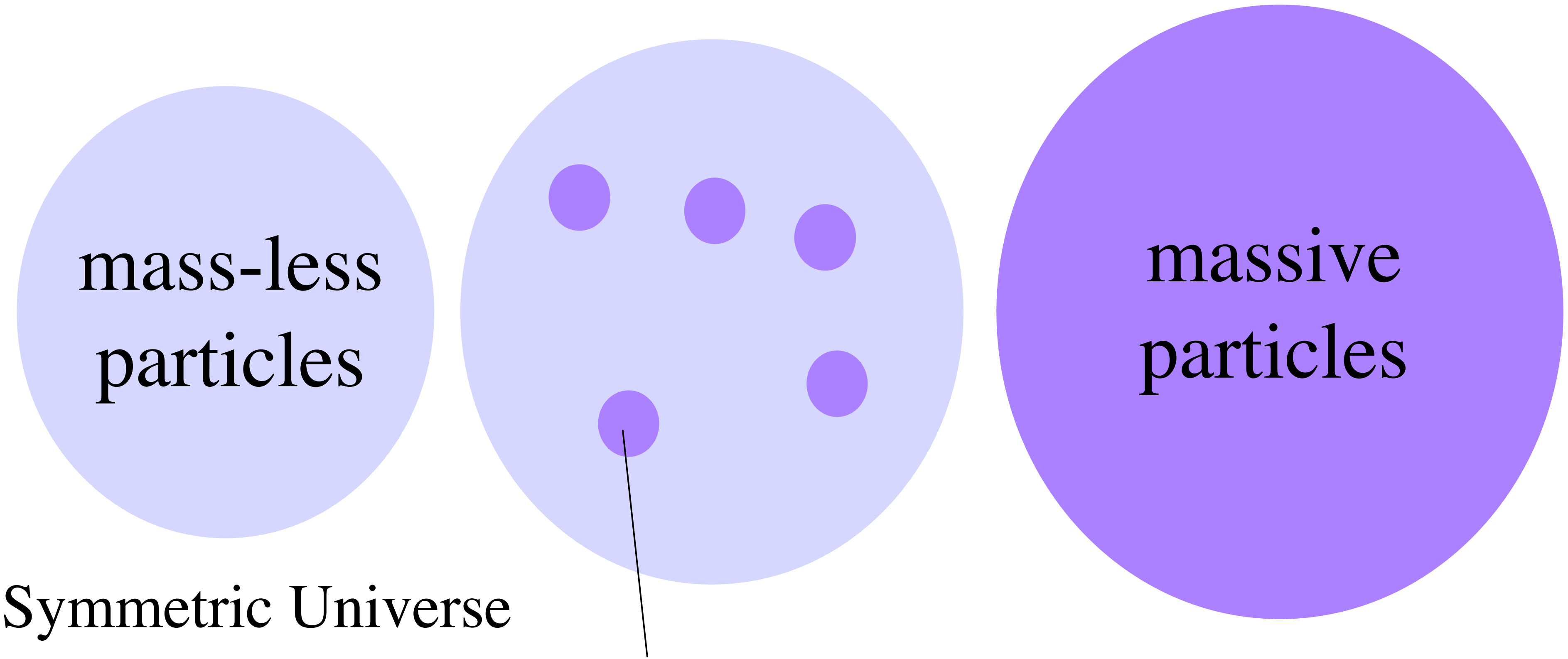
back

Boiling Water

phase transition
at boiling temperature



Electroweak phase transition

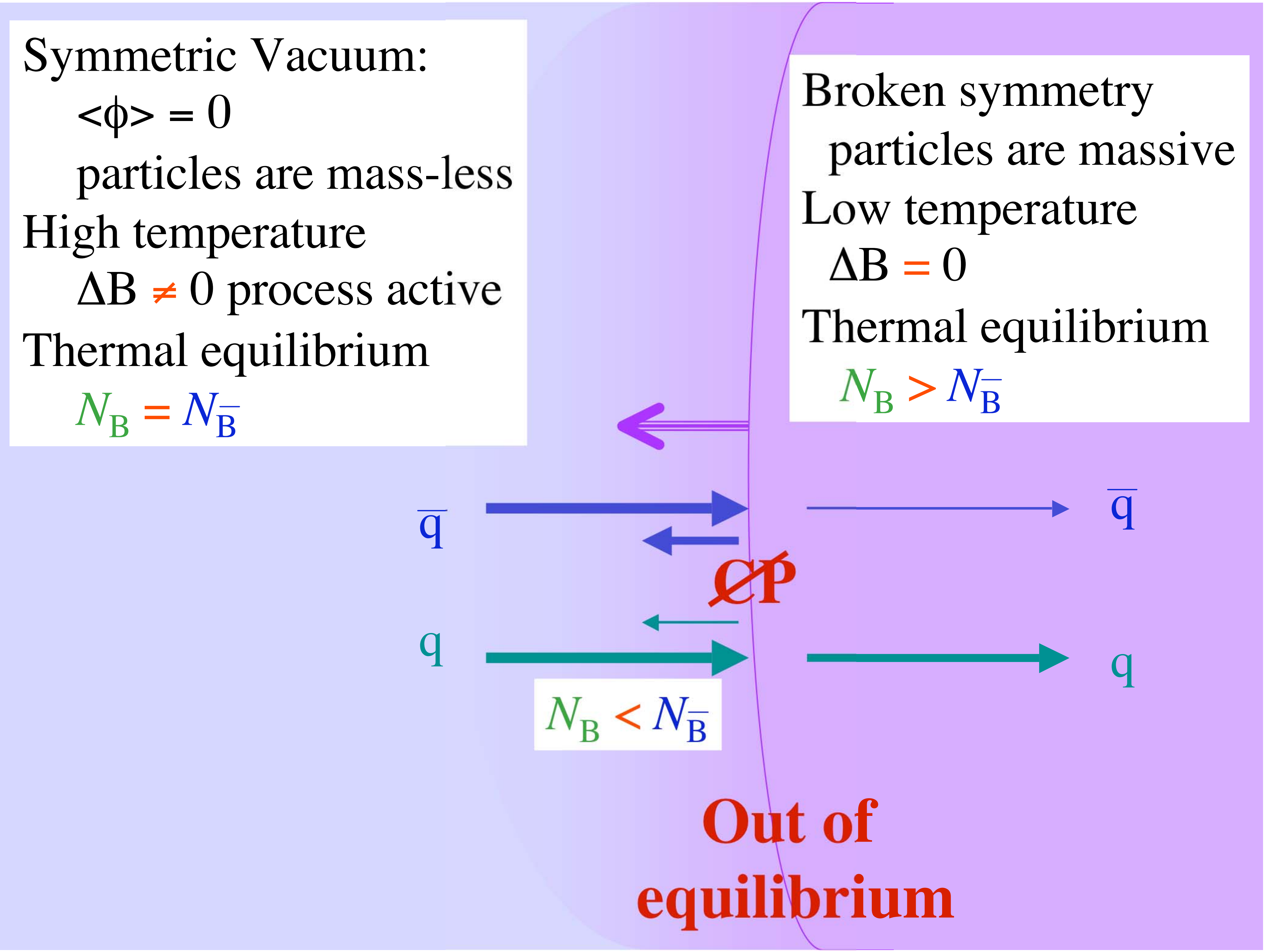


mass-less particles

massive particles

Symmetric Universe

Symmetry broken spontaneously (massive particles)



Symmetric Vacuum:

$<\phi> = 0$

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

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

Out of equilibrium

Two problems with the minimal Standard Model:

1) Too heavy Higgs mass

In order to have the first-order phase transition:

▶

$$m_{\mathrm{H}} \lesssim 70\ \mathrm{GeV}/c^2$$

LEP results:

$$m_{\mathrm{H}} \gtrsim 100\ \mathrm{GeV}/c^2$$

2) **Too small CP violation**

With KM phase:

$$\frac{N_{\mathrm{B}} - N_{\bar{\mathrm{B}}}}{N_{\mathrm{B}} + N_{\bar{\mathrm{B}}}} < \frac{J_{\mathrm{CKM}}}{T_{\mathrm{c}}^{12}} \approx 10^{-20}$$

$\sim 4\times10^{10}$

$$\begin{aligned} J_{\mathrm{CKM}} &\approx (m_{\mathrm{t}}^2-m_{\mathrm{c}}^2)(m_{\mathrm{t}}^2-m_{\mathrm{u}}^2)(m_{\mathrm{c}}^2-m_{\mathrm{u}}^2) \\ &\times(m_{\mathrm{b}}^2-m_{\mathrm{s}}^2)(m_{\mathrm{b}}^2-m_{\mathrm{d}}^2)(m_{\mathrm{s}}^2-m_{\mathrm{d}}^2) \\ &\times \mathrm{s}_1\mathrm{s}_2\mathrm{s}_3 \sin\delta \end{aligned}$$

$\sim 10^{-5}$

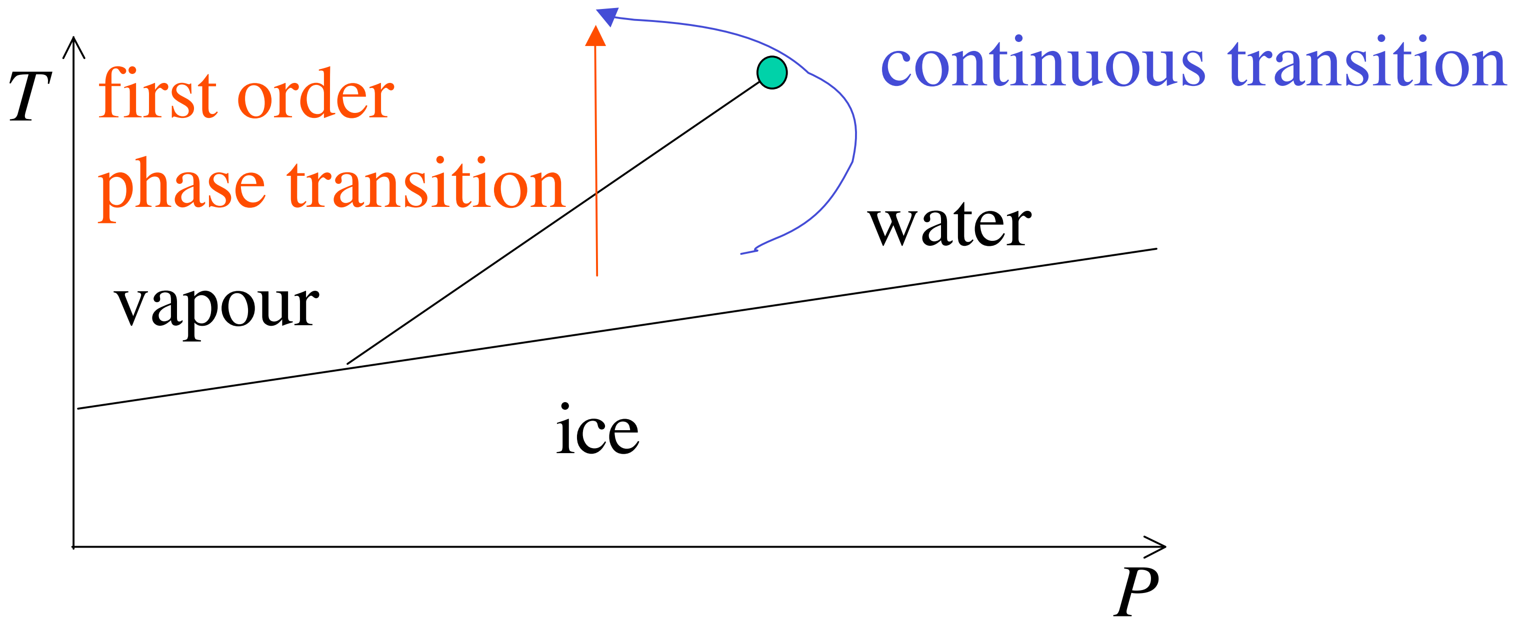
$$T_{\mathrm{c}} \approx 100\ \mathrm{GeV}$$

Required from $N(\mathrm{B})/N(\gamma)$

$$\approx 10^{-10}$$

skip

■



T

first order

phase transition

continuous transition

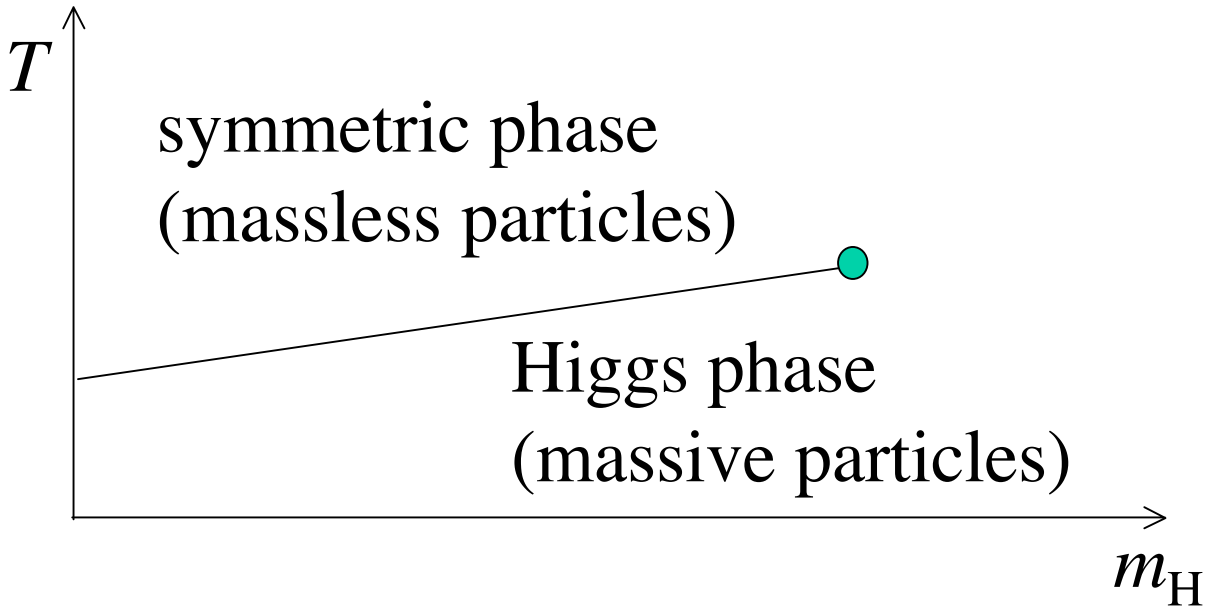
water

vapour

ice

P

● critical point



T

symmetric phase

(massless particles)

Higgs phase

(massive particles)

m_{H}

They can be 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.

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

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

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

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

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

The Standard Model “SU(2) anomaly” process:

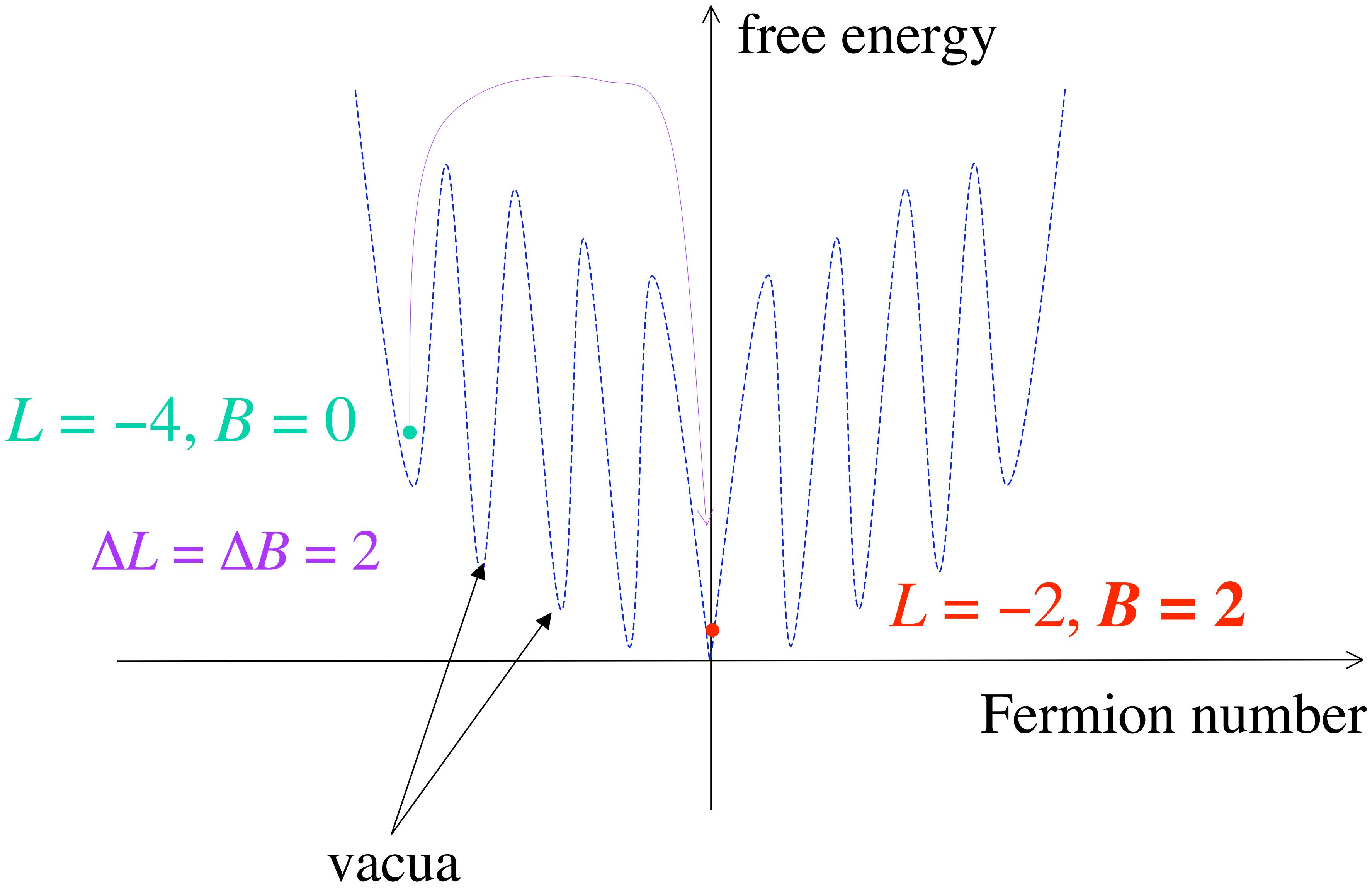
$L+B \rightarrow 0$: i.e. $\Delta L > 0$

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.


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

9)Search for new physics via CP violation

(Biased?) Conclusion:

A good chance that there exists new sources of $\cancel{C}P$.

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

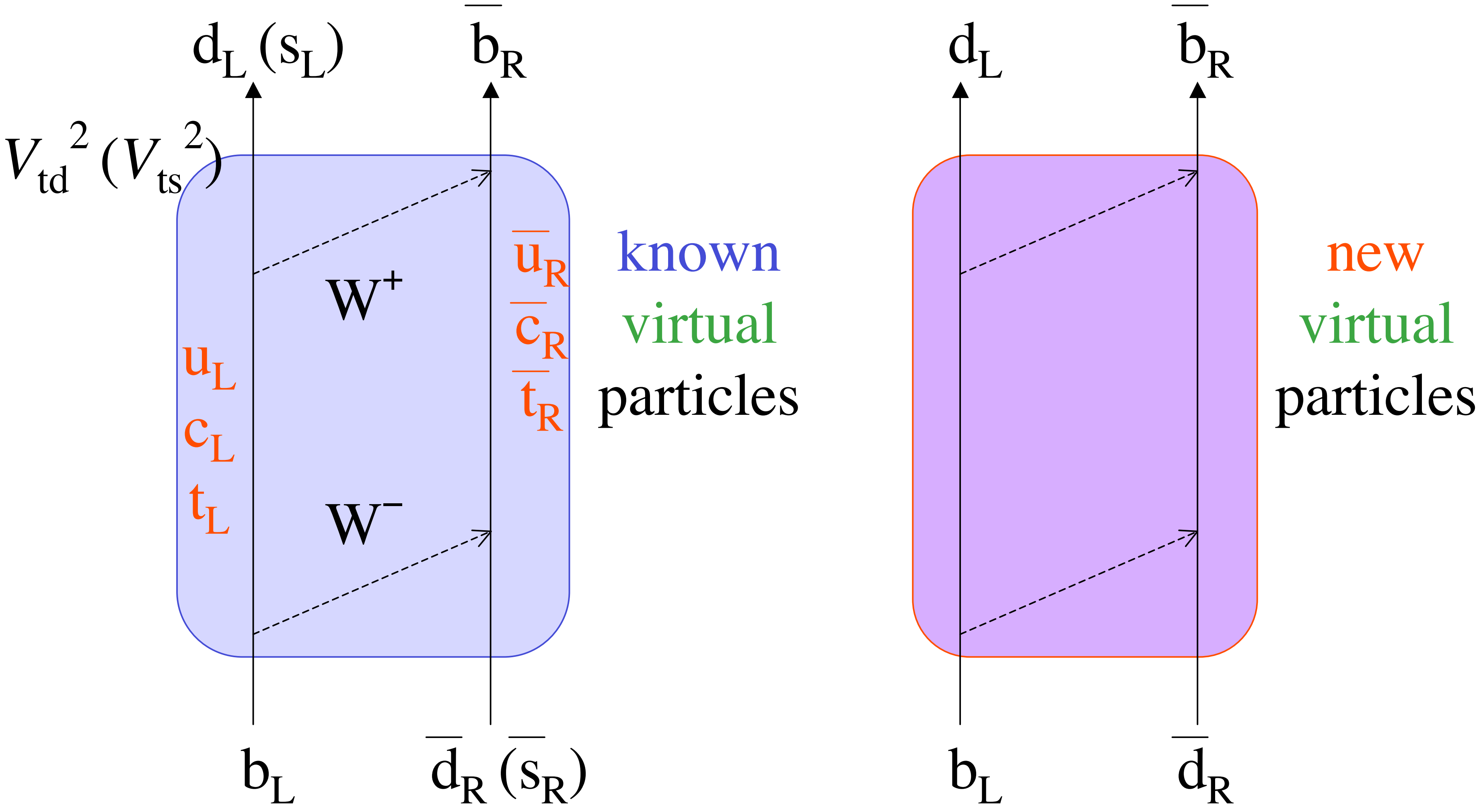
2) The Standard Model predictions are precise.

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

Many decay modes in the B meson system

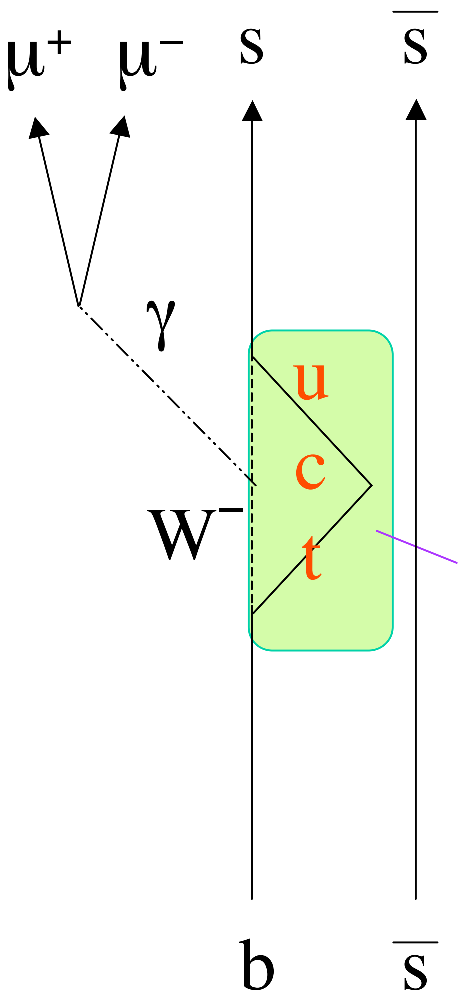
V_{td} and V_{ts} measurements

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

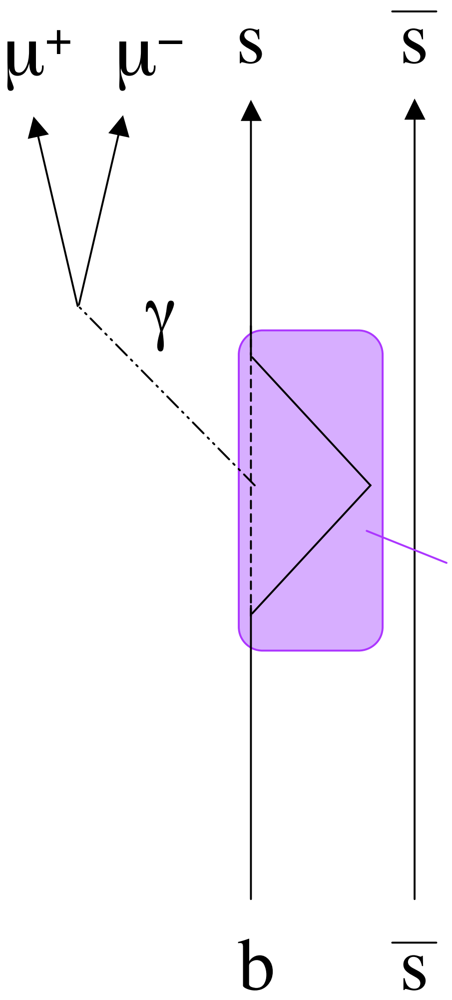


Also in the decays

$\overline{B}_s^0 \rightarrow \phi\mu^+\mu^-$ decays



known virtual particles



new virtual particles

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%

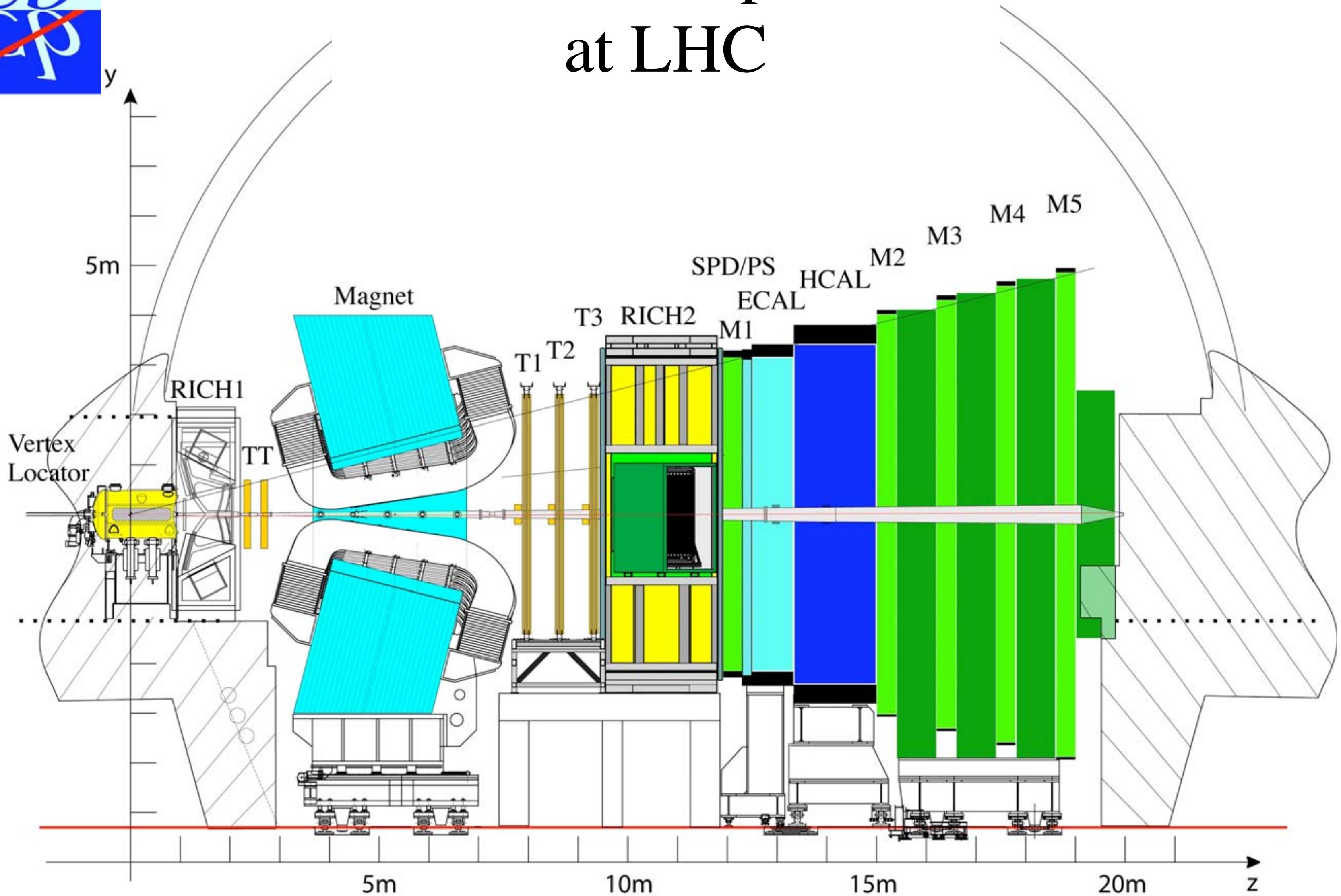
cf. 20% at e^+e^- machines

many tracks in one event (30 to 50)

cf. only b decay tracks at e^+e^- machines

→ **a specialised experiment needed!**

The ***LHCb*** Experiment at LHC



Good mass and eigentime resolution: VELO + tracking system
Hadron identification: RICH system
L0 Lepton and Hadron p_{T} trigger: Calorimeter and muon system

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

- $\cancel{CP}$ and $\cancel{C}$ are clearly seen in the neutral K and B systems.
- $\cancel{CP}$ and $\cancel{C}$ are seen in both oscillations and decays,
  compatible with the Standard Model expectation
- Baryogenesis indicates that there must be $\cancel{CP}$ and $\cancel{C}$
  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)!!!