Baryogenesis via Spontaneous Lorentz Violation

Jing Shu
Argonne / University of Chicago

In collaboration with: Sean Carroll

Outline

- Motivation
- General Discussion on Baryogenesis via Spontaneous Lorentz violation
- Experimental Bounds
- Possible Sources for Spontaneous Lorentz violation (Specific models)
- Conclusion

Motivation

- Experiments show that:

$$\eta_B \equiv \frac{n_B}{s} = 9.2^{+0.6}_{-0.4} \times 10^{-11}$$

# of baryons - # anti-baryons (n_B)

Entropy density (s)

- Evidence:
  - Big-Bang Nucleosynthesis.
  - Cosmic Microwave background.
- Inflation will dilute everything after it ends, which sets the inital condition that B=0.

Motivation

Sakharov Conditions:

A. D. Sakharov, Pis'ma Zh. Eksp. Teor. Fiz. 5, 32 (1967)

1. **B Violation:** We must generate baryon number ("B") through B-violating processes.

2. **C and CP Violation:** Essentially, if we don't violate C and CP, the sum of all baryon-violating processes will still result in no net baryon number.

3. **Out of Equilibrium:** If the processes which violate B are in equilibrium, the reverse processes will cancel out the B generated.

Motivation

However, there is another possibility:

first discussed in "spontaneous baryogenesis"

A.G. Cohen, D.B. Kaplan, Phys.Lett. B 199, 251 (1987)

A.G. Cohen, D.B. Kaplan, Nucl.Phys. B 308, 913 (1988)

SOLUTION:

- CPTV
- Baryon number violation in equlibrium

Motivation

CPT theorem: any lorentz invariant, local quantum field theory preserve CPT.

An good possibliltiy is to break the the lorentz symmetry spontaneously.

We break the lorentz symmetry spontaneously because such SLVB is very common in the early universe evolution.

General Discussion

$$\mathcal{S} = \int d^4x\sqrt{-g}(\mathcal{L}_A + \mathcal{L}_{int} + \mathcal{L}_m)$$

metric $(-,+,+,+)$

A_μ could be composite operators: $\partial_\mu\theta$ $\bar{\psi}\gamma_\mu\psi$, etc

$\mathcal{L}_A$ makes the A_μ field condesate.

$\langle A_\mu A^\mu \rangle < 0$ $A_\mu = (a_0, 0, 0, 0)$

no spacial condensate as our universe is isotropic

General Discussion

$$\mathcal{L}_{int} = gA_\mu J^\mu = -ga_0 Q$$

Appling to baryon current, the addtional term becomes

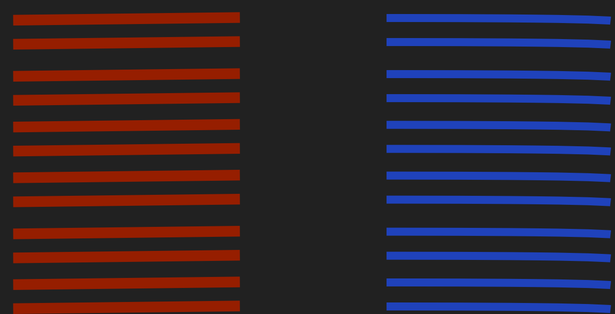
$-ga_0(n_b - n_{\bar{b}})$

As far as the matter field is concerned, the interaction term could be viewed as an additional "chemical potential"

Such a chemical potential term will split the free enrgy of baryon and antibaryon

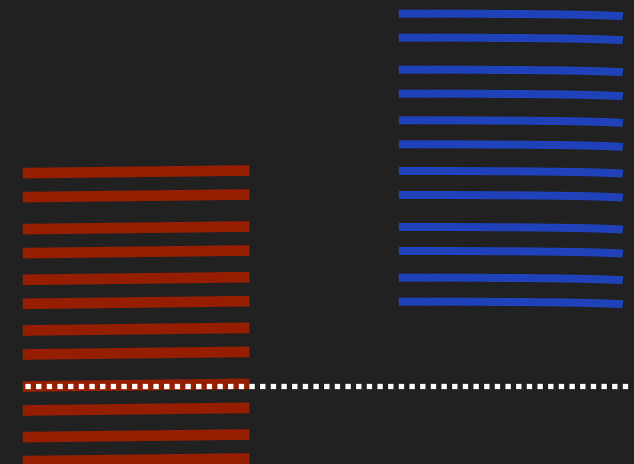
General Discussion

Without SLVB



Baryon Anti-baryon

With SLVB



$\mu_b^0 = g a_0$ $\mu_{\bar{b}}^0 = -g a_0$

$$n_B = n_b - n_{\bar{b}} \approx \frac{g_b T^3}{6\pi^2}\left(\pi^2 \frac{\mu_b^0}{T}\right) \approx \mu_b^0 T^2$$

$$\frac{n_B}{s} \sim \frac{\mu_b^0}{g_{*s} T_F} = \frac{g a_0}{g_{*s} T_F}$$

The sphaleron transition

In the presence of SLVB, the energy disspertion relation is modified to $E_{\pm} = \sqrt{\vec{k}_i^2 + m^2} \pm \mu^0$

The role of sphaleron transitions in thermal equilibrium is adjusting different particle density distributions in a way that preserve B-L to minimize the free energy.

The free energy of given fermion of mass m and chemical potential μ

$$F(m,\mu) = -T \int \frac{d^3K}{(2\pi)^3} [\ln(1 + e^{-(E_+ + \mu)/T}) + \ln(1 + e^{-(E_- - \mu)/T})]$$

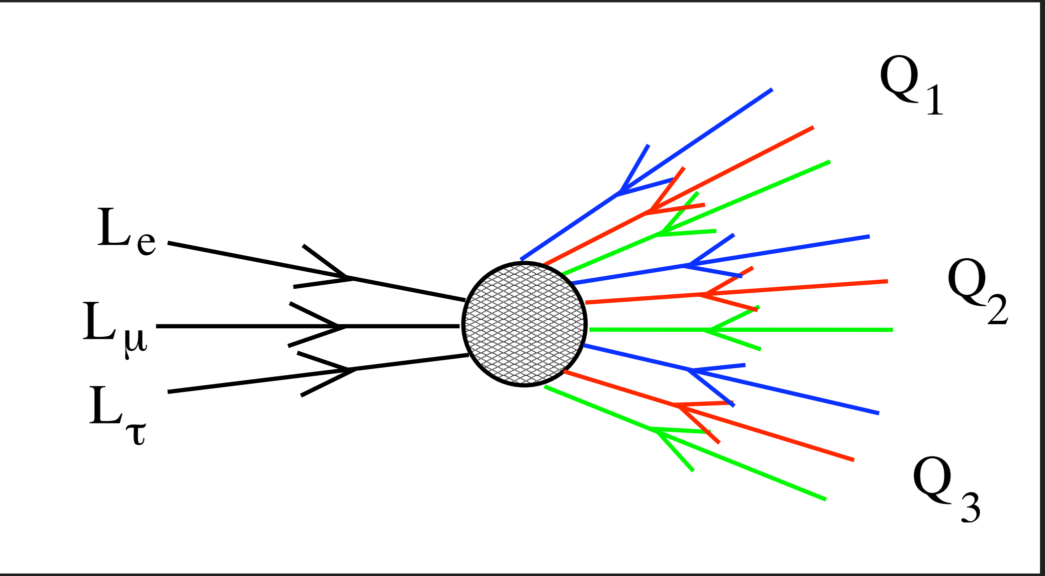
The sphaleron transition

Write the number densities in terms of chemical potential in the high T appoximation (T >>m)

$$B \approx -\frac{1}{3}(\mu + \mu^0)T^2\alpha$$

$$\alpha \equiv 6 - \frac{3}{2\pi^2}\sum_{i=1}^{6}\frac{m_{q_i}^2}{T^2}$$

addtional potential term for quarks from SLVB



$$L_i \approx \frac{1}{2}(\mu_i + \mu_i^0)T^2\beta_i$$

$$\beta_i \equiv 1 - \frac{1}{\pi^2}\frac{m_{l_i}^2}{T^2}$$

additional potential term for ith lepton from SLVB

The sphaleron transitions convert 3N quarks or N lepton into nothing:

$$\mu = -\sum_{i=1}^{N}\frac{\mu_i}{3N}$$

Conserved quantity: No Lepton Flavor Violation

$$\Delta_i \equiv L_i - \frac{1}{N}B \approx \frac{(\mu + \mu_0)T^2}{3N}\alpha - \frac{(\mu_i + \mu_i^0)T^2}{2}\beta_i$$

number of generation

The sphaleron transition

Calculate the corresponding chemical potential from the conserved quantity and write them back to the baryon expression, we can see there is an addtional term coming from SLVB

$$B^{(\mu)} = -\frac{2N}{13}T^2(3\mu^0 + \frac{1}{N}\sum_{i=1}^{N}\mu_i^0) \quad (B-L=0)$$

It reduced to

$$B \propto (\mu_B^0 + \mu_L^0) = 2\mu_{B+L}^0$$

assume leptons have the same chemical potential

As long as SLVB couple to J_{B+L} ,

the sphaleron transtion will not wash out B+L. Instead, it will generate B+L!

The Free-out Temperature

The sphaleron transition is the only source we know that violates B and connects B with L.

In general, the background field could also coupled to the lepton current.

$$\mathcal{L}_{int} = g_B A_\mu J^\mu_B + g_L A_\mu J^\mu_L = g_- A_\mu J^\mu_{B-L} + g_+ A_\mu J^\mu_{B+L}$$

$$\frac{n_{B-L}}{s} = \frac{g_- a_0(T_-)}{g_{*s} T_-},$$

lowerst possible freeze-out temperature for any interactions that violate B-L

$$\frac{n_{B+L}}{s} = \frac{g_+ a_0(T_+)}{g_{*s} T_+}$$

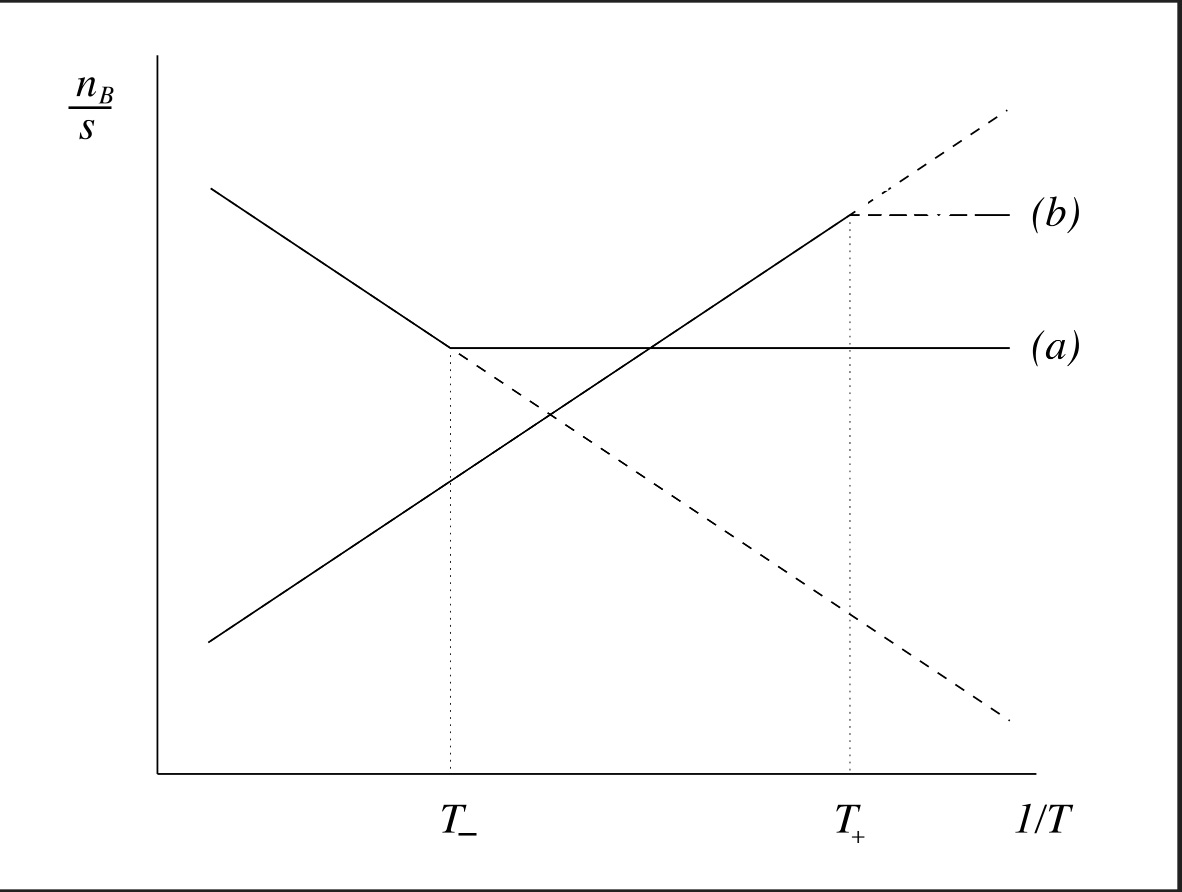
always negected in previous studies!

The final baryon asymmetry depends on which one is bigger

The Free-out Temperature

Assume $g_+ \approx g_-$

and we know $T_+ = 150\text{GeV} \ll \text{T}_-$



(a) :
a_0/T decreases as a function of $1/T$

(b) :
a_0/T increases as a function of $1/T$

The Free-out Temperature

$$\frac{n_B}{s} = \begin{cases} \frac{n_{B+L}}{2s} \sim \frac{g_+ a_0(T_+)}{g_{*s} T_+} & \text{if } \frac{|a_0(T)|}{T} \text{ increase with 1/T} \\ \frac{n_{B-L}}{2s} \sim \frac{g_- a_0(T_-)}{g_{*s} T_-} & \text{if } \frac{|a_0(T)|}{T} \text{ decrease with 1/T} \end{cases}$$

T_- is very model dependent,

In general, $10^{11} \sim 10^{13}\mathrm{GeV}$ for Majarana mass.

In some modified seesaw model, T_- could be as low as TeV

Experimental Constraints

No real constraints as baryogenesis happens in the early universe while all experiments are at least later than CMB.

The experiment bounds are very constrained today, so perhaps the SLVB undergoes a phase transition if it doesn't decay away.

Experimental Constraints

- The constraints for vector current (neutral meson mixing) $J_B, \; J_L$ are the vector currents
  - For a single species, $a_\mu \bar{\psi} \gamma^\mu \psi$ could be eliminated by a field redefinition. $\psi \to \exp(i a_\mu x^\mu) \psi$
  - We can only measure the difference of the coupling for different species.

$$\Delta a_\mu = r_{q_1} a_\mu^{q_1} - r_{q_2} a_\mu^{q_2}$$

some quark blinding and normalization effects

KTeV

  - For neutral K-mesons (d, s quark) $|\Delta a_0| \leq 10^{-20} \; \mathrm{GeV}$
  - For neutral D-mesons (u, c quark) $|\Delta a_0| \leqslant 10^{-15} \mathrm{GeV}$

FOCUS

Experimental Constraints

- Constraints for axial vector current
  - electrons $ga_0 \leqslant 10^{-25}\mathrm{GeV}$
  - nucleons $ga_0 \leqslant 10^{-24}\mathrm{GeV}$
- Constraints for astrophysics.
  - distant radio source (quasars)
  - Future CMB polarization experiment.

$$ga_0 \leqslant 10^{-42}\mathrm{GeV}$$

Vector/Tensor Fields as SLVB

The vector field has a Mexican hat potential

$$V(A_\mu) = \frac{\mu^2}{2} A_\mu A^\mu + \frac{\lambda}{4}(A_\mu A^\mu)^2$$

$$a_0{}^2 = \frac{\mu^2}{\lambda}$$

$\frac{a_0}{T}$ increases with time

we ignore terms like

$(\nabla_\mu A^\mu)^2$ $(\nabla_{(\mu} A_{\nu)})^2$

for simplicity.

$T_F = T_+ = 150\mathrm{GeV}$ → $a_0 = \mu = 1\mathrm{kev}$

We need a phase transition

Higgs

Replace μ^2 into $(\mu'^2 - \alpha|\Phi|^2)$ with $\mu'^2 - \alpha\nu^2 < 0$

High T → $\langle\Phi^2\rangle = 0$ → $\langle A_\mu A^\mu \rangle < 0$

Low T → $\langle\Phi^2\rangle > 0$ → $\langle A_\mu A^\mu \rangle = 0$

Vector/Tensor Fields as SLVB

Symmetry non-restoration:

The finite temperature corrections to the effective potential make the vev zero at high temperature

This is very rare!

Tensor field

$$\mathcal{L}_{int} \supset \frac{g\langle T\rangle}{M^k}\bar{\psi}(\gamma^0)^{k+1}(i\partial_0)^k\psi + h.c.$$

$$\frac{n_B}{s} \sim g\frac{\langle T\rangle T_F^{k-1}}{g_{*s}M^k}$$

$k > 1 \quad T_F = T_-$

O. Bertolami, D. Colladay, V.A. Kesteleckey, and R. Potting
Phys.Lett. B 395, 178 (1997)

Ghost as SLVB

Ghost field: wrong sign of kinetic term

$$\mathcal{L} = P(X) \qquad X = -\partial^\mu \phi \partial_\mu \phi$$

From e.o.m. $\partial_\mu \phi = \text{constant}$

$$\phi = -M^2 t + \pi$$

small fluctuations

Stability against π : $P'(M^4) > 0$

$$P'(M^4) + 2M^4 P''(M^4) > 0$$

In order to generate enough baryons

$$a_0 = gM^2/f = 1\text{kev}$$

→ We need a phase transition

Rolling Fields as SLVB

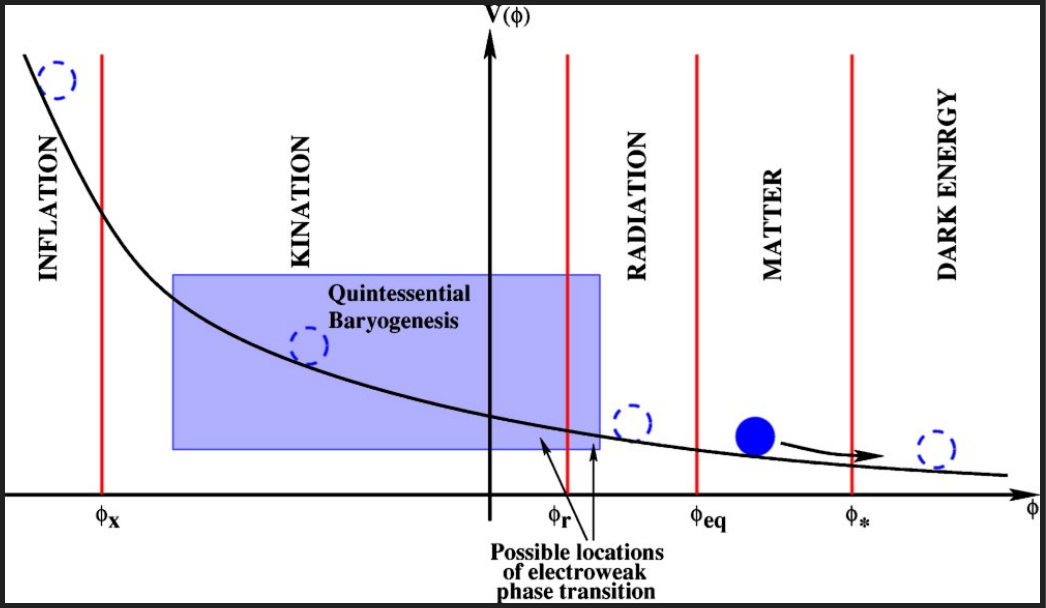
- Quintessential baryogenesis
  - tracking behavior

$$\dot{\phi} \propto \sqrt{V(\phi)} \propto \sqrt{\rho_{\rm back}} = T^2$$

Mingzhe Li, *et. al.* Phys. Rev. D 65, 103511 (2003)

A. Felice, *et. al.* Phys. Rev. D 67, 043509 (2003)

M. Yamaguchin, Phys. Rev. D 68, 063507 (2003)



- Gravitational baryogenesis

$$\frac{1}{M_*^2}\int d^4x\sqrt{-g}(\partial_\mu \mathcal{R})J^\mu$$

H. Davoudiasl *et. al.* Phys. Rev. Lett. 93, 201301 (2004)

$$\dot{\mathcal{R}} \propto \dot{\rho} \propto T^5$$

$T_F = T_-, T_-$ and cut off scale is very model dependent.

$$\frac{\partial_\mu \mathcal{R}}{\mathcal{R}} J^\mu \qquad \frac{\dot{\mathcal{R}}}{\mathcal{R}} \propto T^2$$

Hong Li *et. al.* Phys. Rev. D 70, 047302 (2004)

PNGB as SLVB

If SLVB come from scalar field, it must have a shift symmetry $\theta \sim \theta + c$ so it must be PNGB.

$$\mathcal{L} = \frac{f^2}{2}(\partial\theta)^2 - \Lambda^4[1 - \cos(\theta)] \qquad \phi = f\theta \qquad m = \frac{\Lambda^2}{f}$$

We make the following assumptions:

- The initial value $\phi \sim f$.
- Freeze-out occurs at the end of rolling, but not begin to oscillate $H \sim m$

Combining with e.o.m.

$$3H\dot{\phi} + \frac{dV}{d\phi} = 0$$

$$T_F \sim 10^{-8} M_{pl} \sim 10^{10}\ \text{GeV}$$

$$m \sim \frac{T_F^2}{M_{pl}} \sim 100\ \text{GeV}$$

a weak scale mass!

Conclusion

General conditions:

- We need a vector background vev spontanteously break LI, it can vary with time or undergoes a phase transtion.
- Such background field will couple to baryon/lepton number current.

Not necessary, could be some other charges and then converted into baryon number.

- We need B/L violation in thermal EQ. If a_0/T increases with time, the freeout temperature is $T_+ \approx 150\mathrm{GeV}$. If a_0/T decreases with time, the freeout temperature is T_- which is model dependent.

Conclusion

In the presence of SLVB, the sphaleron transtion will generate B+L in stead of washing it out!

- For a constant vector background, baryon is generated by sphaleron transition and we need phase transition to avoid experiment constraints.
- For a decrasing vector background, baryon is generated by B-L violation process. Experiments may still give a strong constraints to its late time behavior.
- For the PNGB, baryon is generated with a weak-scale PNGB mass. No experiment constraints on LV as the PNGB will decay soon.

Important Results

- Sphaleron transitions will generate B+L in the presence of SLVB
- The freeze-out temperature also depends on how the SLVB evolves with time.
  - This provide a general rule to categorize different models of baryogenesis via SLVB and understand them in a unified picture.
- Propose two interesting models
  - Baryon asymmetry is generated through with spahleron transitions with constant SLVB.
  - SLVB comes from PNGB with weak scale mass, baryon asymmetry is generated through B-L violation at intermediate scale. 10^{10} GeV

My Curiosity

EWPT from the Higgs profile spontaneously break the Lorentz invariance.

$$\langle A_\mu A^\mu \rangle < 0 \quad \Longrightarrow \quad \dot{\theta} \neq 0$$

If θ is the CP violating phase, and it varies with time, then any currents coupled to such CPV phase will have a nonzero charge in thermal equilibrium.

Actually, this is used in non-local electroweak baryogenesis, where a nonzero $\dot{\theta}$ is inside the bubble wall when the bubble is expanding.

In general, you need a space-time dependent CPV phase, such CPV phase is different from inside and outside of bubble wall.

"spontaneous electroweak baryogenesis"

A. G. Cohen, D. B. Kaplan and A. E. Nelson, Phys. Lett. B 263, 86 (1991)

A. E. Nelson, D. B. Kaplan and A. G. Cohen, Nucl. Phys. B. 373, 453 (1992)

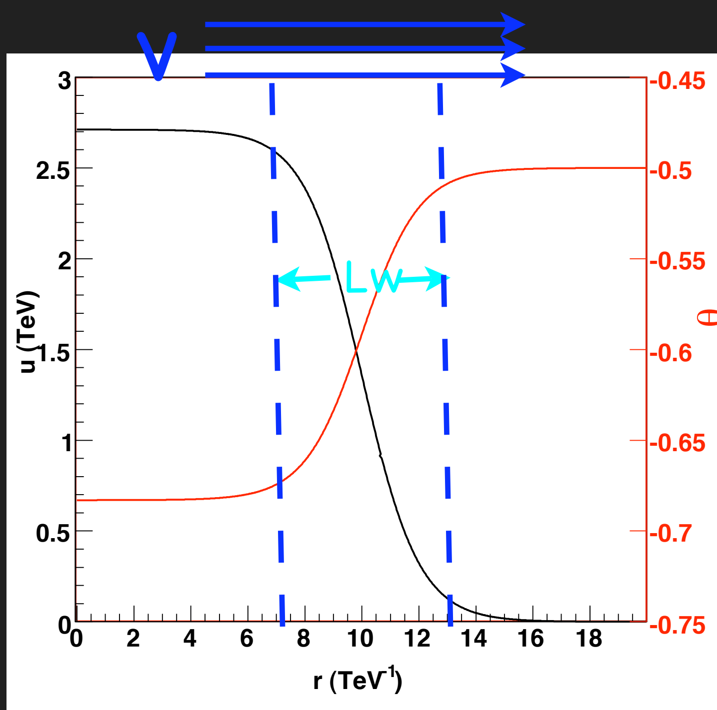
My Curiosity

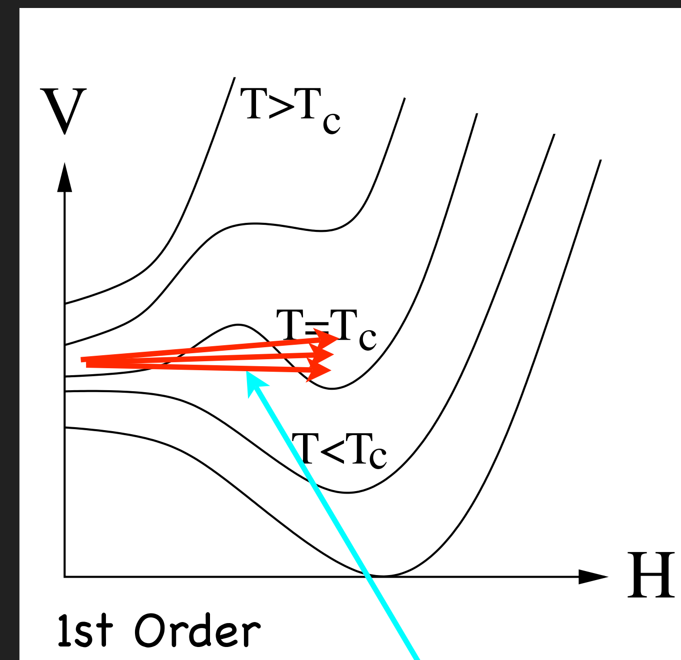
MSSM, CPV in the squark sector.

$$\mathcal{L} = y_t \tilde{t_L} \tilde{t_R^*}(A_t H_u - \mu^* H_d) + \text{h.c.}$$

$$e^{i\theta(x)} \sim A_t H_u(x) - \mu^* H_d(x)$$

$$\dot{\theta} \propto \partial_0 (H_u(x)/H_d(x)) \sim \dot{\beta}$$



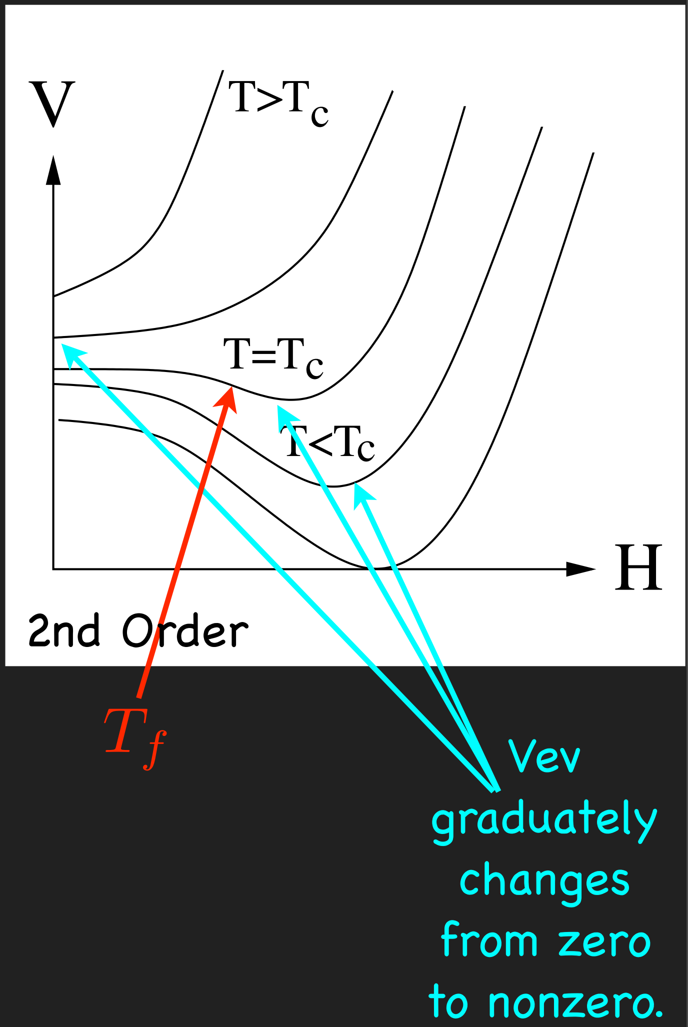


$$\dot{\beta} = \frac{\Delta\beta}{\Delta t} = \frac{v_w \Delta\beta}{L_w}$$

Vev jumps from zero to nonzero as the bubble is expanding.

My Curiosity

What if it is NOT a strongly first order phase transition, or even without phase transition (cross over)? as long as I have a nonzero $\dot{\theta}$?



It really doesn't matter if $\dot{\theta}$ jumps in a 1st order PT or graduately changes

$$\frac{d\theta}{dt} = -HT\frac{d\theta}{dT}\bigg|_{T_f}$$

Notice that T_f is the freeze-out temperature for sphaleron transitions, it is really before the Higgs vev become constant.

My Curiosity

We need a very fast Hubbe expansion at
the electroweak scale.

$H_{ew} \sim E_{ew}$ You can relax it by serveal orders, not too much.

- Modified Gravity! (FRW)
- Extra dimenions
- Kination domianted universe.

As long as we get a nonzero $\dot{\theta}$, it should couple to some currents, eventually the themal interactions will convert the corresponding charges generated to baryon number.

My Curiosity

Such a idea is only realized in some toy model, I was thinking if I could generalize it to MSSM, or other models. I need to find time...............

M. Joyce. Phys. Rev. D. 55, 1875 (1997)

M. Joyce, T. Prokopec. Phys. Rev. D. 57, 6022 (1998)

If it works!

Constraints from higgs physics greatly relaxed! We maybe able to realize baryogenesis in more models beyond SM and still test those theory at LHC.