2017/9/21@Bologna
Post-inflationary string cosmology (Sep 18 – 21)

A possibility of QCD-induced EWSB in the early universe

Satoshi Iso (KEK, Sokendai)

Based on a collaboration with

1704.04955
to appear in PRL

Kengo Shimada (LAPTh →Lausanne) and Pasquale Serpico (LAPTh)

related works

Naturalness (Wilsonian RG) *H.Aoki (Saga), SI* *Phys.Rev.D86(2012)013001*

Phenomenological models based on this idea

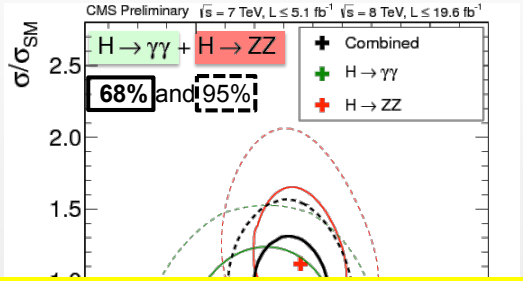
N.Okada (Alabama), Y.Orikasa (Osaka), SI *PLB(2009) & PRD(2009)*

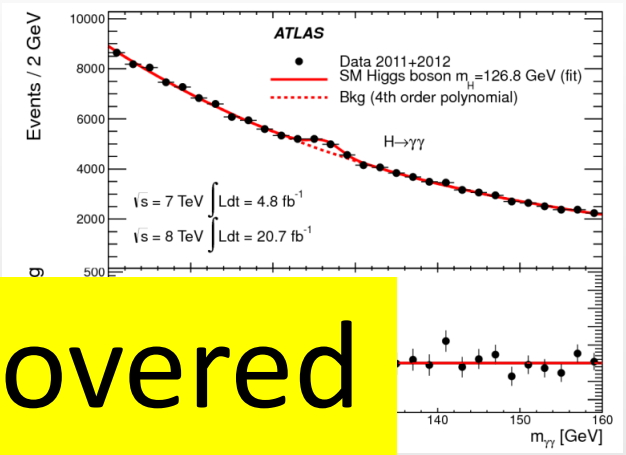
Y.Orikasa (Osaka), SI *PTEP(2013)*

M.Hashimoto (Chubu), Y.Orikasa (Osaka), SI *PRD(2013) & PRD(2014)*

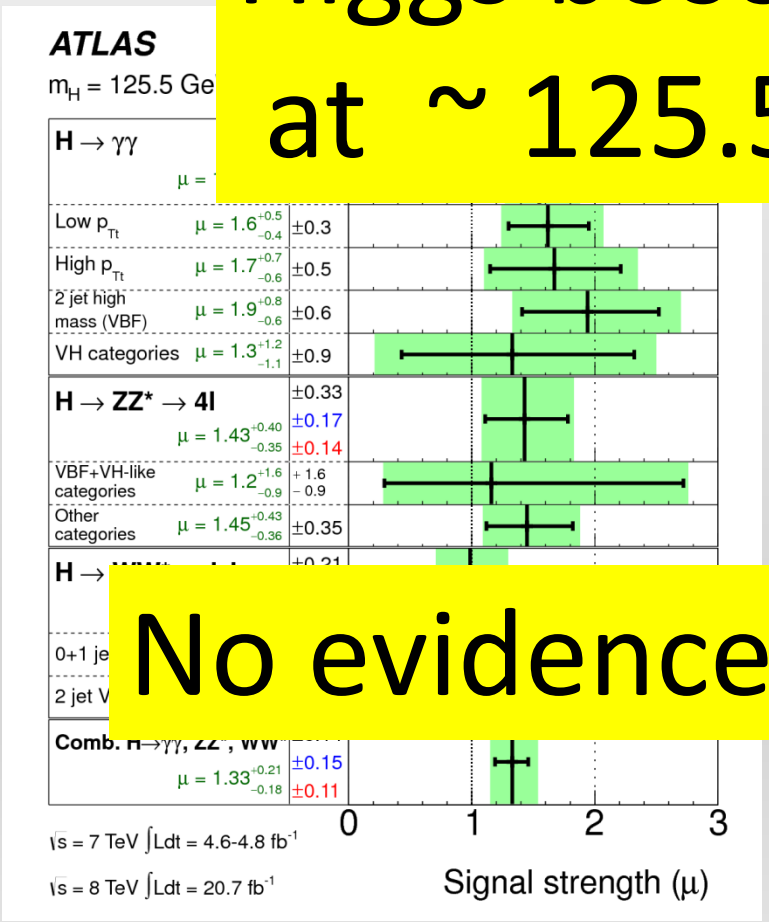
Cosmology of the model

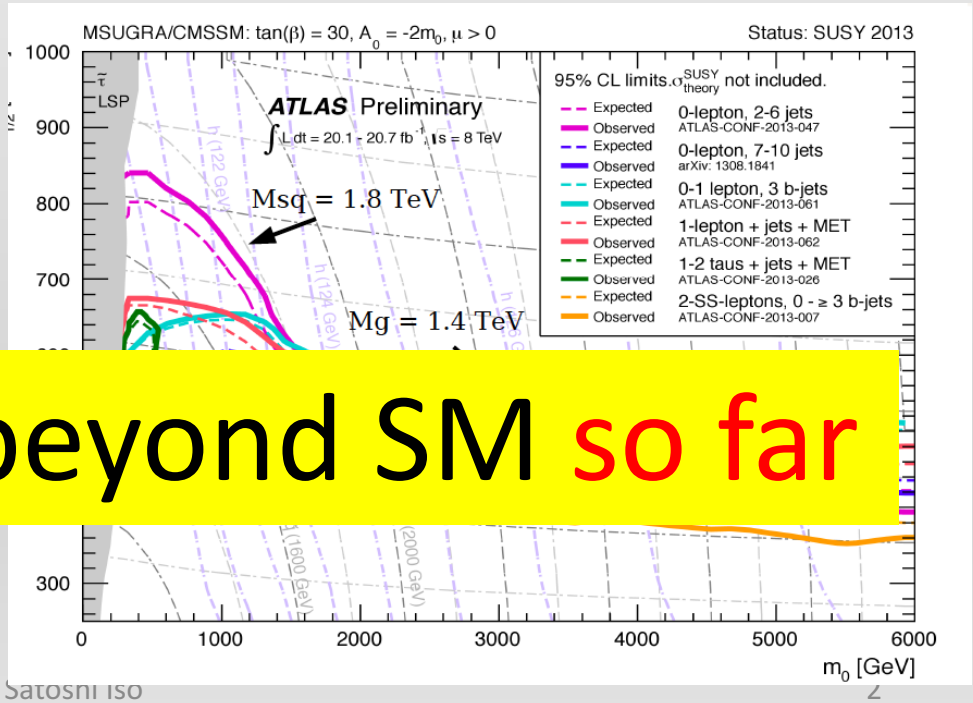
K. Kohri (KEK) & K. Shimada (LAPTh) , SI *PRD91(2015) & PRD93 (2016)*





Higgs boson is discovered at ~ 125.5 GeV



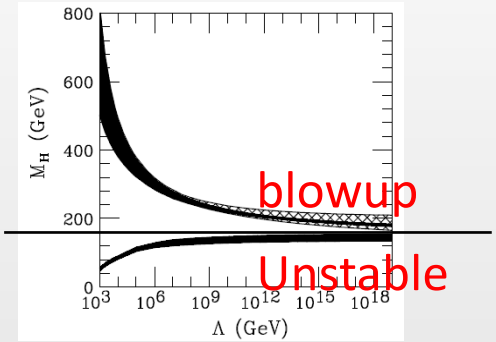


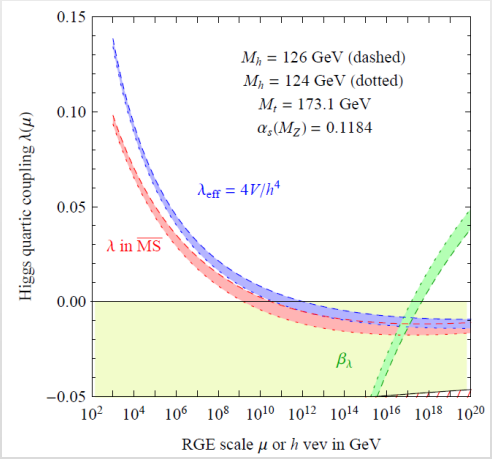
No evidence beyond SM so far

What can we learn from LHC ? ... (my personal view)

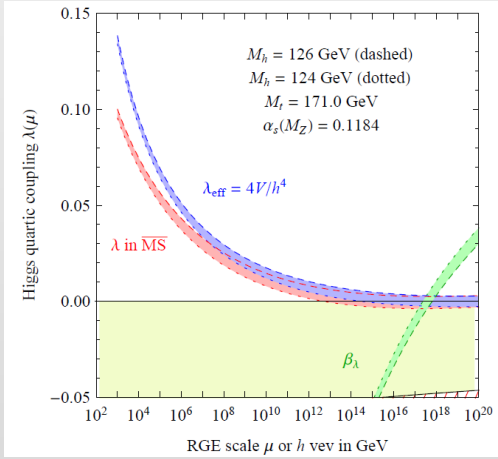
(1) mass = 125 GeV

$$V = -\mu^2|H|^2 + \lambda(|H|^2)^2$$





Strumia et.al.(12)
Elias-Miro et.al.(12)
Alkhin, Djouadi, Moch (12)



still controversial ...

"EW" physics may be directly related to Planck scale physics
without intermediate scales in between.

Froggatt Nielsen (96)
M.Shaposhnikov (07)

(2) No deviations from SM / no TeV SUSY? → Naturalness

$$V = -\mu^2|H|^2 + \lambda(|H|^2)^2$$

Naturalness is often discussed in relation to quadratic divergences.
But physically, it is the log-divergence with a large coefficient.
To assure naturalness, we assume the following 2 conditions.

(a) No intermediate scale strongly coupled to SM

e.g. No "M_{GUT}^2" terms

(b) Correct boundary condition at UV: No "M^2_{pl} term"

Just an assumption now for we do not know much about gravity

asymptotic safety (e.g. Strumia et.al.)

If μ=0 at UV scale, it will be never radiatively generated in the IR.

→ Classically conformal models

(scalar potential is radiatively generated.) WRG

Indication to the Higgs potential

$$V = -\mu^2|H|^2 + \lambda(|H|^2)^2$$

flat potential

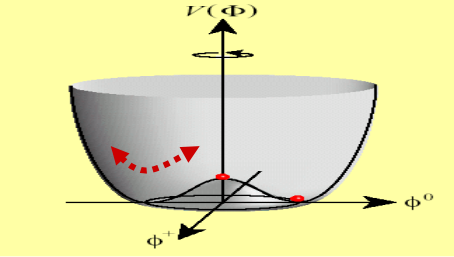
H

flat potential V(H)=0 at Planck.

M_{PL}

Radiatively generate

Coleman-Weinberg mechanism



EWSB @ M_{EW}

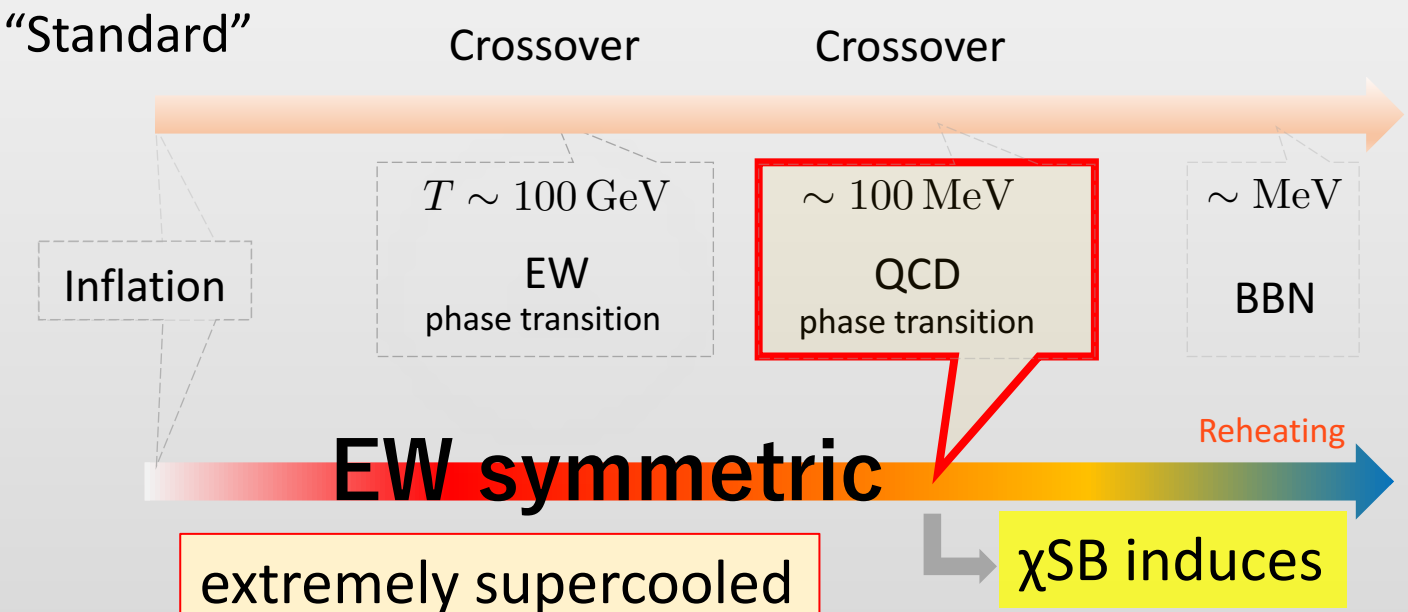
Today's main message

If EWSB is described by a classically conformal model,
the history of the early universe will be drastically different.

See also
Konstandin, Servant 2011
(motivated by RS model)

Today's main message

Thermal history of the universe



extremely supercooled
(strong first order PT)

χSB induces

- EW symmetry breaking
- Linear term in the Higgs potential

→ different cosmological consequences: GW, DM, PBH ...

Coleman-Weinberg mechanism does not work in SM.

the **large top Yukawa** coupling **invalidates the CW** mechanism

↓

Extension of SM is necessary !

Meissner Nicolai (07)
Foot et al (07)

(B-L) extension of SM with flat Higgs potential at Planck

SM + B-L sector
- $U(1)_{B-L}$ gauge
- SM singlet scalar ϕ
- Right-handed ν

Okada, Orikasa, SI
0902.4050
0909.0128
1210.2848

"Occam's razor" scenario

that can explain

- B-L breaking triggers EWSB (126 GeV Higgs)
- Naturalness problem
- ν oscillation, baryon asymmetry

Scalar potential of (h, ϕ) at zero temperature

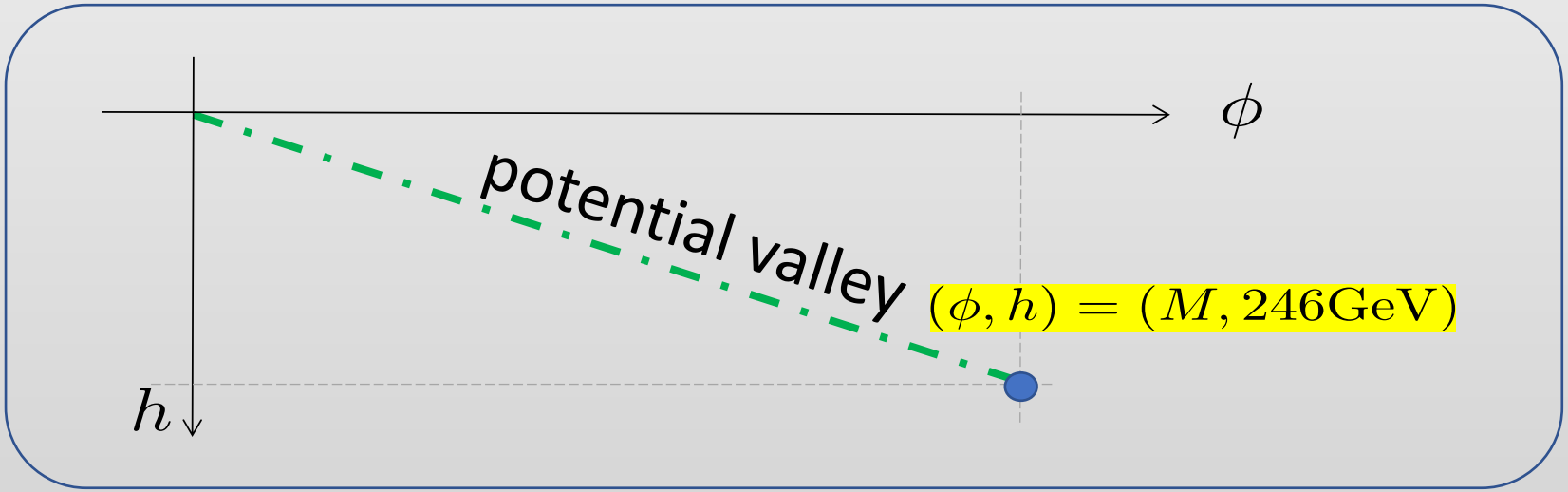
No quadratic terms in classically conformal models

$$V(\phi,h) = \frac{\lambda_h}{4}h^4 + \frac{\lambda_{\rm mix}}{4}\phi^2h^2 + \frac{\lambda_\phi^{\rm eff}(\phi)}{4}\phi^4$$

Higgs

$\lambda_{\rm mix} < 0$

(B-L) scalar

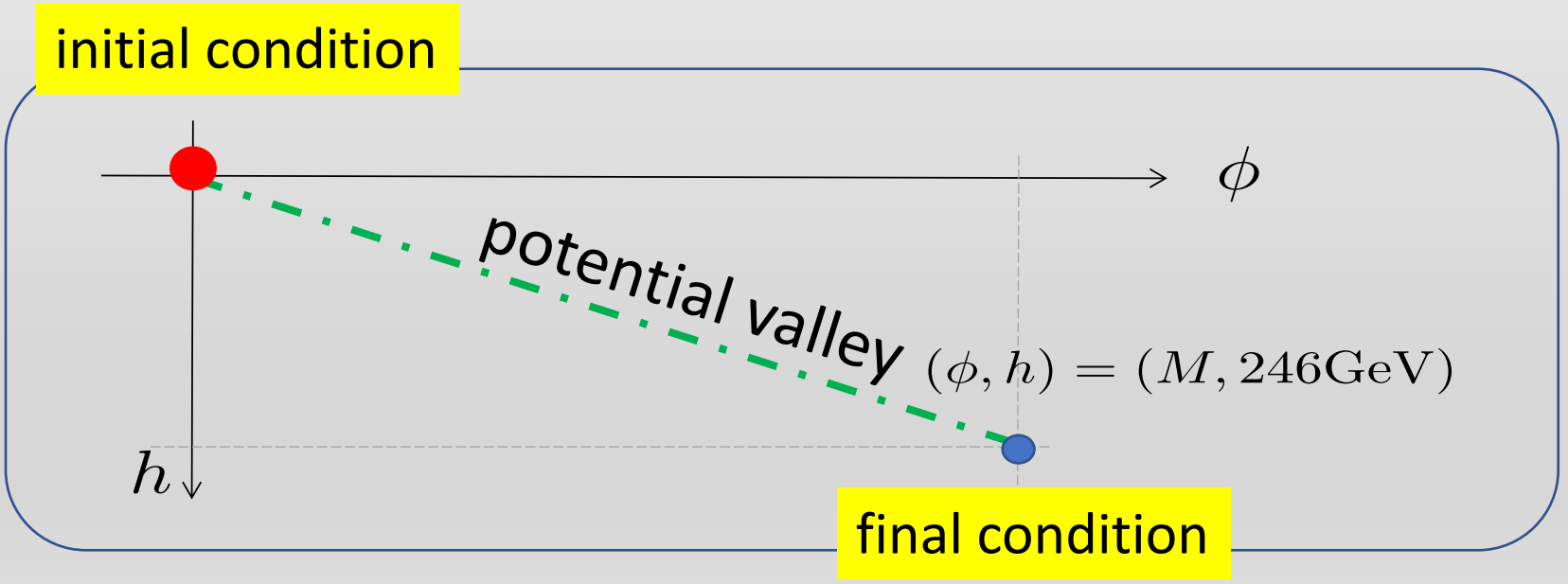


Radiative B-L breaking triggers EWSB.

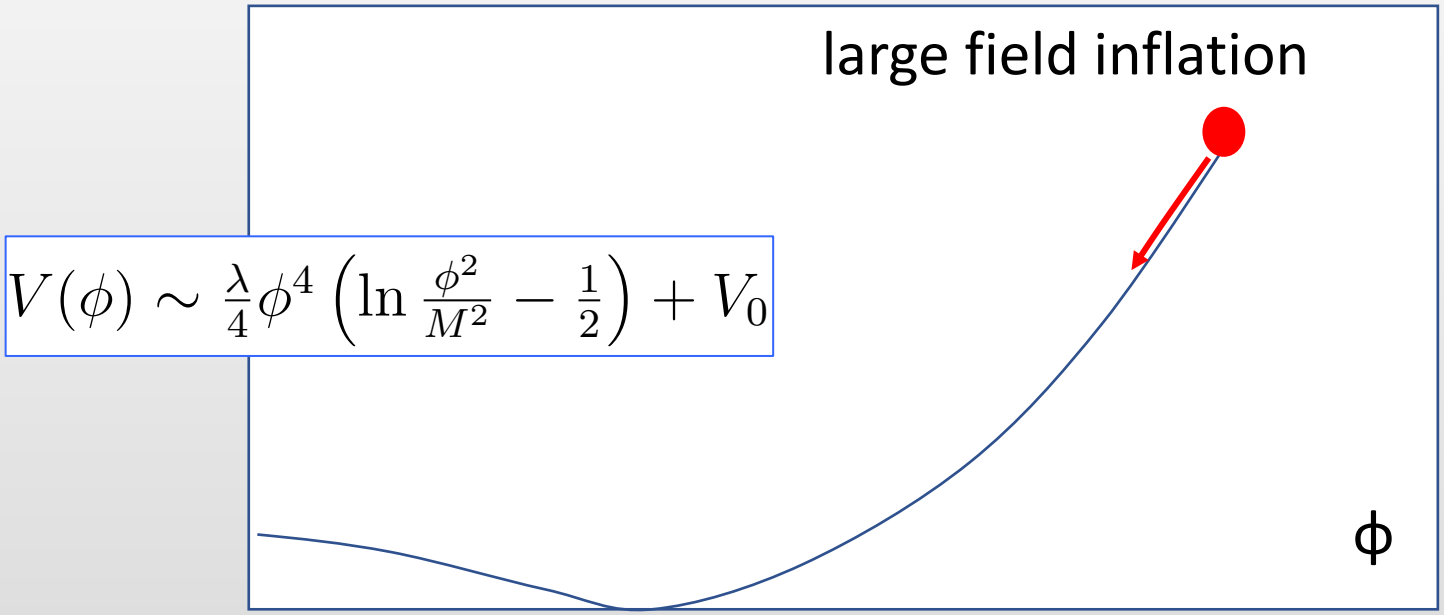
λmix

K.Shimada, P.Serpico, SI
1704.04955 (PRL)

The early universe of classically conformal models



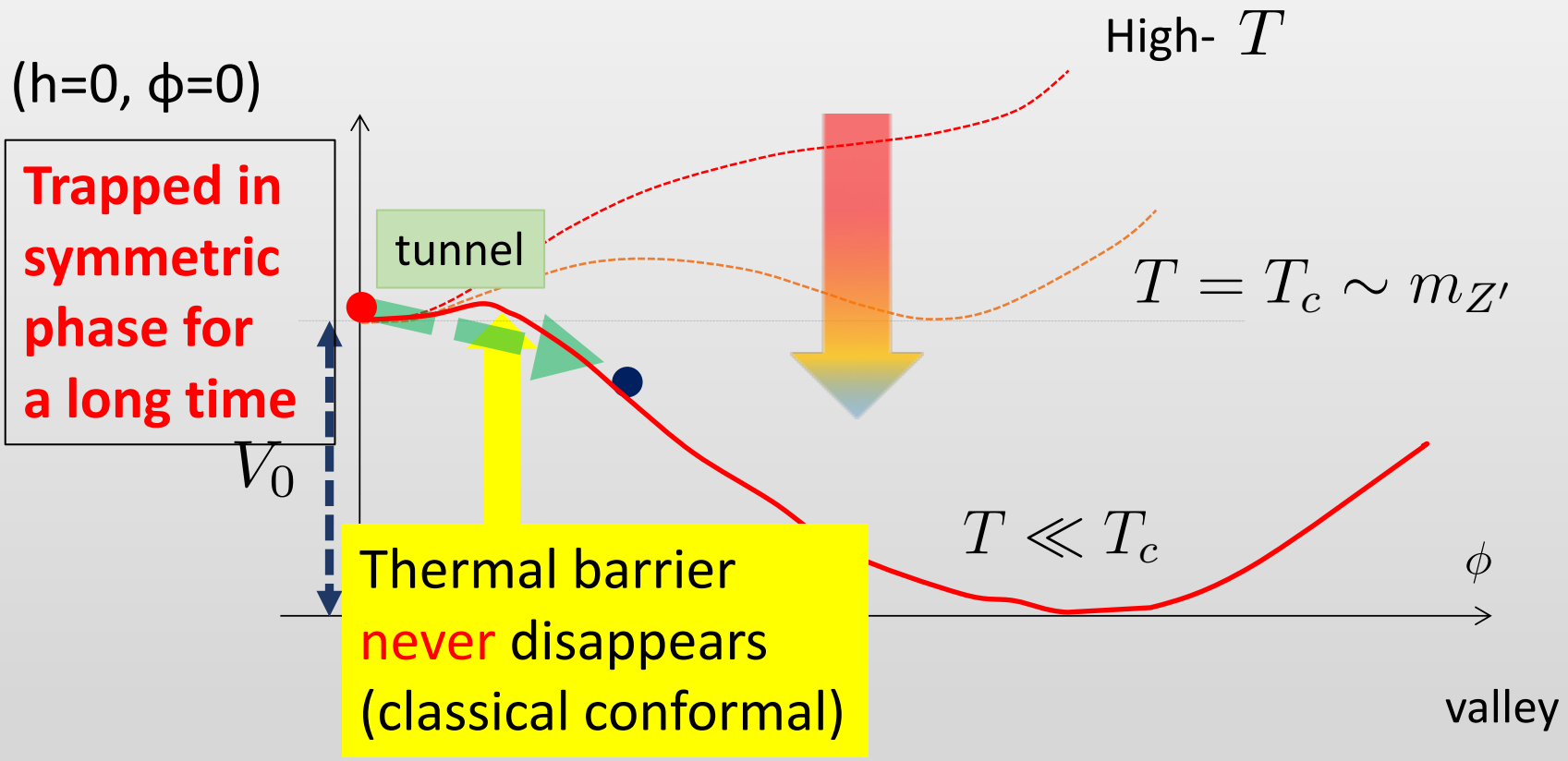
Setting the initial condition



1 Large Field Inflation
2 Z' creation by Preheating → generates large potential
3 Trap the field around ϕ =0 → thermalize

Linde (82), Kofman et.al.(96)
Shimada, Kohri, SI (06)

Hypercooling of (B-L)+EW → PT much below T_C



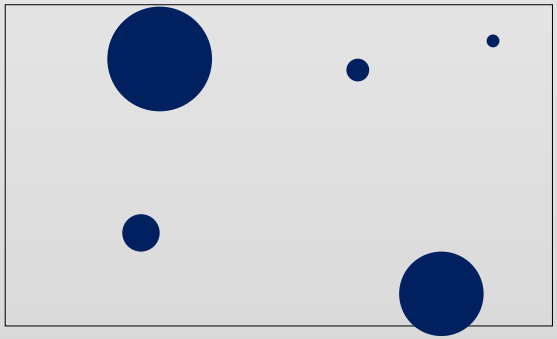
Bubble of true vacuum is created by tunneling.

Percolation of true vacuum

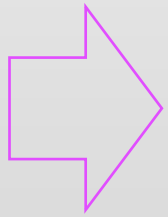
Guth Weinberg (82)

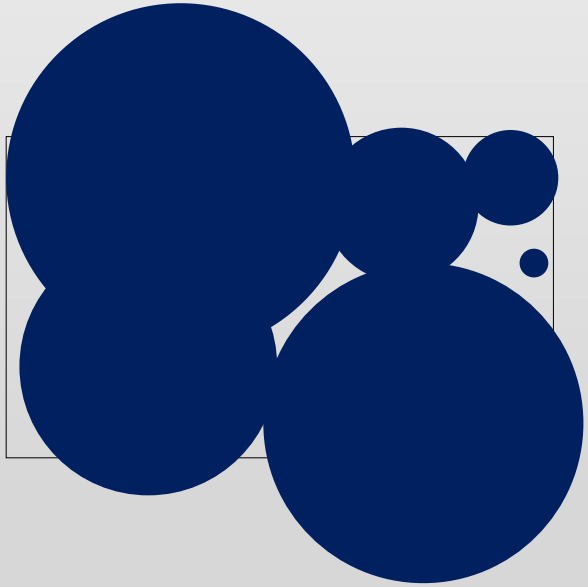
Bubbles of true vacuum
are created by tunneling

T_p : percolation temperature



$$\Gamma \approx T^4 e^{-S_3/T}$$

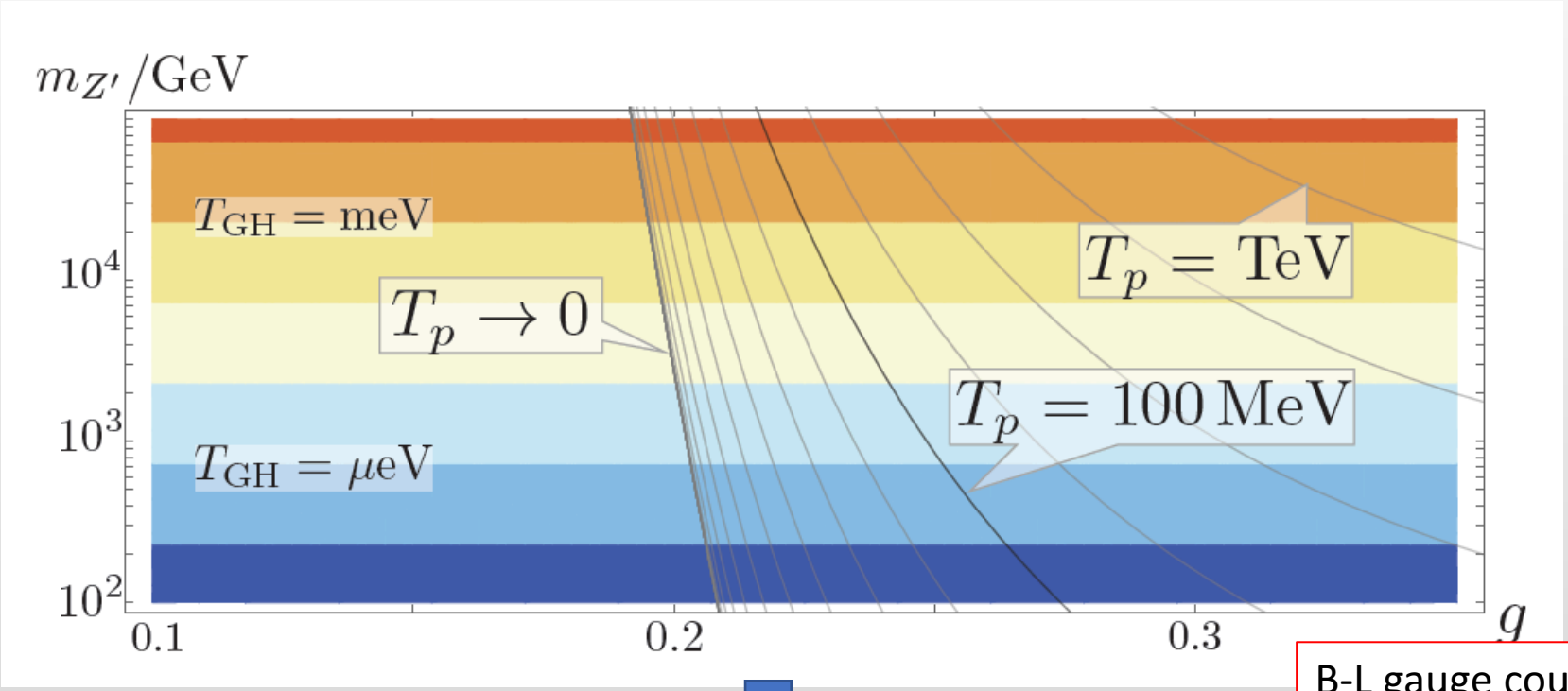




Universe is occupied with
true vacuum bubbles

critical bubble action
$S/T \sim 1/g^3$

T_P = percolation temperature
can be calculated by tunneling rate.



B-L gauge coupling

If g < 0.2, universe is never occupied with true vacuum until T decreases down to 100 MeV or less.

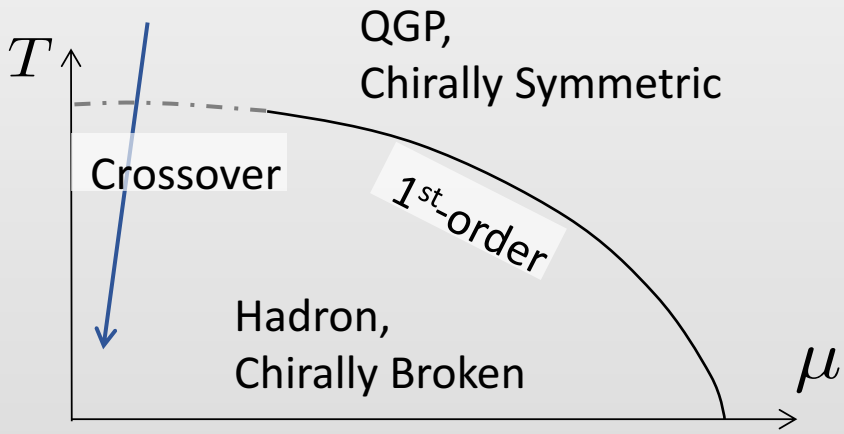
Note that de Sitter fluctuation $\sim T_{\rm GH} = \mathcal{H}/2\pi$ is negligible at 100 MeV.

$$V_0^{1/4} \sim m_{Z'}$$

When temperature decreases down to 100 MeV at (ϕ=0, h=0)

$$\langle \bar{q}_i q_i \rangle \sim \Lambda_{\rm QCD}^3$$

In the standard scenario
with N_f =(2+1)
→ crossover



In the present case, since h=0
all N_f =6 quarks are massless !
→ 1st order phase transition for $N_f \geq 3$

Pisarski Wilczek (1983)

$\langle \bar{q}_i q_i \rangle \sim \Lambda^3_{\rm QCD}$ SU(2)$_L$ doublet with U(1)$_Y$ charge

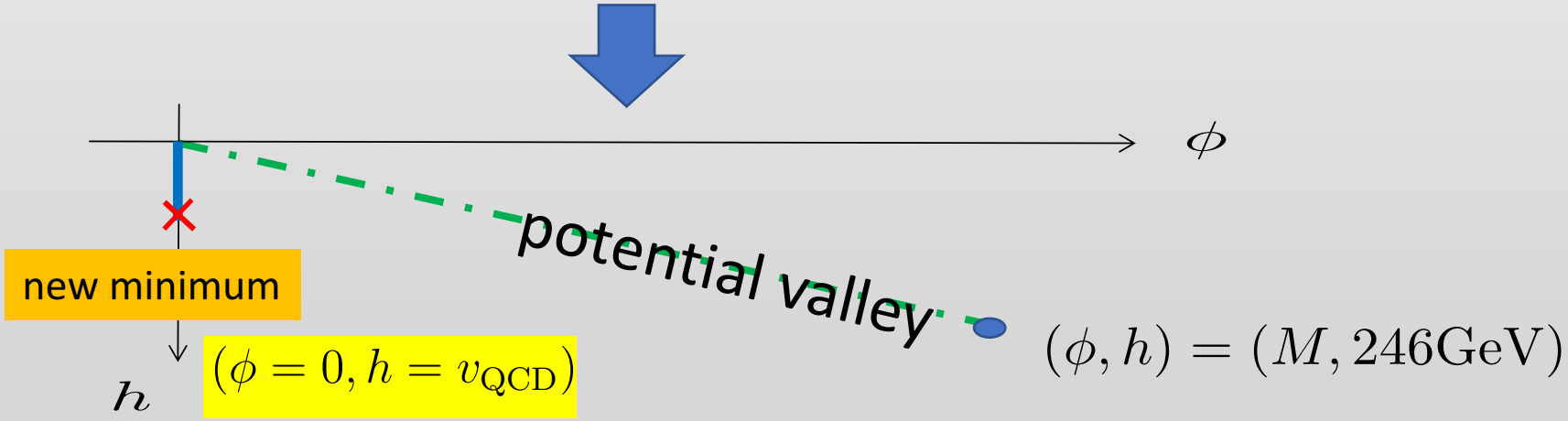
Electroweak symmetry is broken (EWSB) Quigg Shrock (09)

$$SU(2)_L \times U(1)_Y \to U(1)$$

Higgs linear term is generated via Yukawa interaction

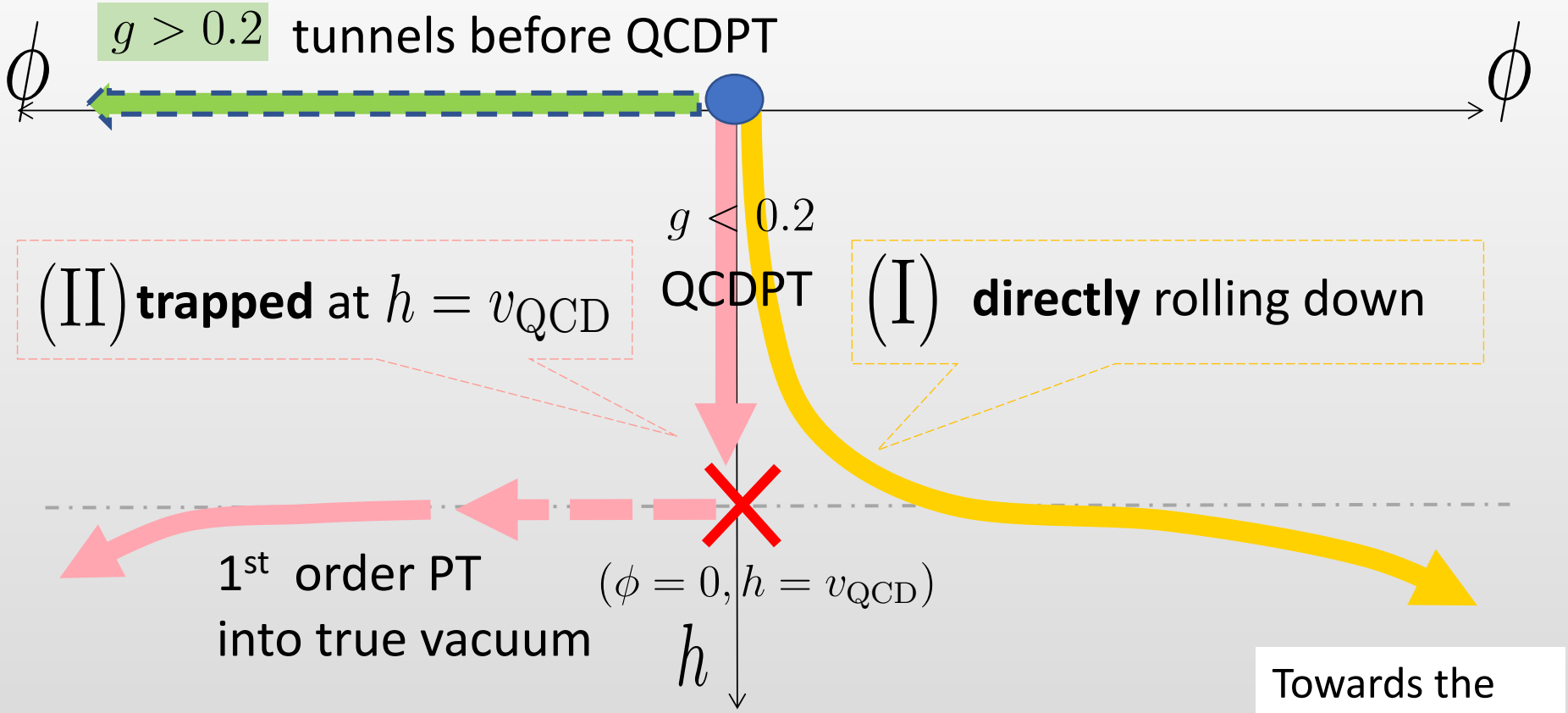
$$y_i h \langle \bar{q}_i q_i \rangle \sim (y_i \Lambda^3_{\rm QCD}) h$$

Witten (81)
Buchmuller et al (90)
Kuzmin et.al.(92)



$$v_{\rm QCD} = \left(\frac{y_t \langle \bar{t} t \rangle}{\sqrt{2} \lambda_h} \right)^{1/3} \sim \Lambda_{\rm QCD}$$

Classification of the histories of the early universe

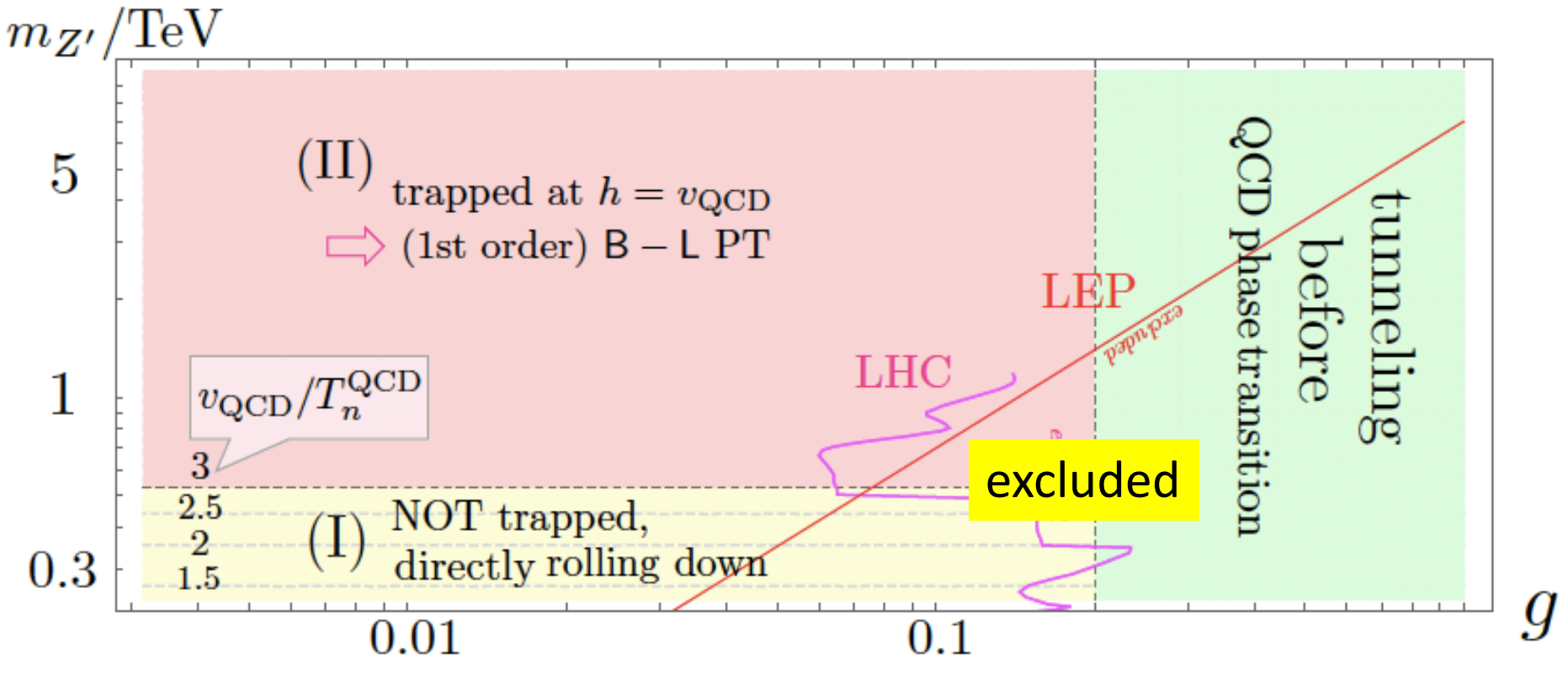


$$V(\phi) \sim (g^2 T_{\mathrm{QCD}}^2 - |\lambda_{\mathrm{mix}}| v_{\mathrm{QCD}}^2/2)\phi^2$$

On top of it, slow roll inflation occurs if $g \lesssim 10^{-2}\,(m_{Z'}/\mathrm{PeV})^3$

$$|\eta| = m_{\mathrm{pl}}^2 |V''|/V_0 < 1$$

Classification of histories of the early universe



In this parameter region, slow roll inflation does not occur.

Some cosmological consequences

Scenario (I)

[QCD + (B-L) + EW]

strong 1st order phase transition is expected

Scenario (I) gives ideal condition to observe relics of PT (e.g. GW).

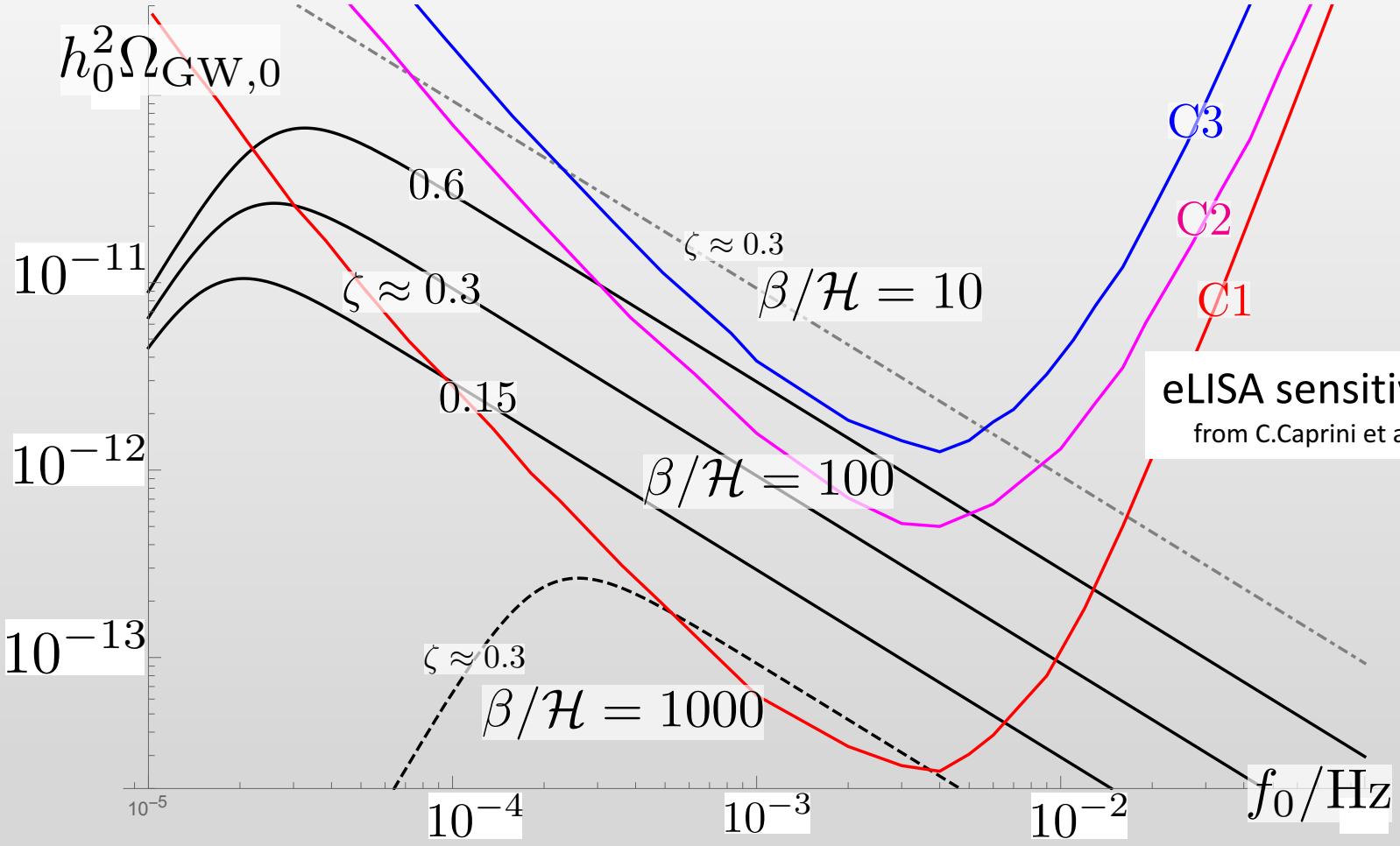
Release of the vacuum energy V_0 reheats the universe up to < 20 GeV.
→ Chiral symmetry restored → crossover QCD PT.

Also this parameter region is phenomenologically interesting since very light new particles are predicted

$$m_{RH\nu}, m_\phi \ll m_{Z'} \sim \text{several hundred GeV}$$

probed by SHiP exp.

Stochastic Gravitational Waves from 1st order PT in scenario (I)

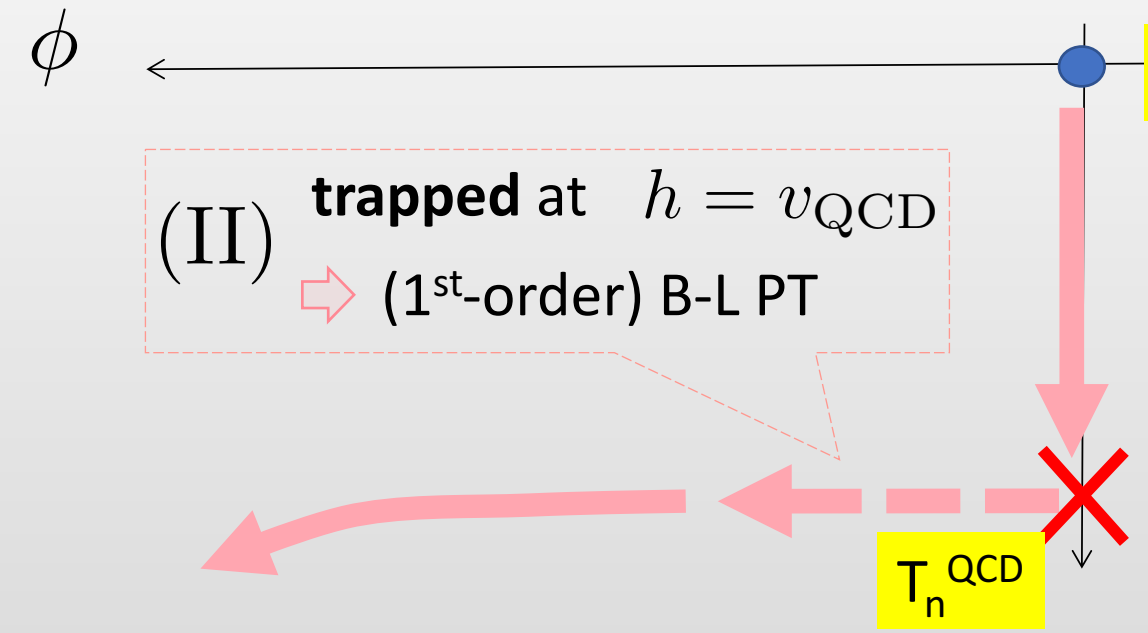


1/β : duration of PT $\quad \zeta \sim T_{\mathrm{rh}}/V_0^{1/4}$ efficiency of reheating

(for stronger coupling, e.g. Jinno Takimoto (17))

Scenario (II)

[QCD] and [(B-L) + EW] 1st order phase transitions are separated by thermal inflation at h = v_{QCD}



T_{rh} may be higher than M_{EW}

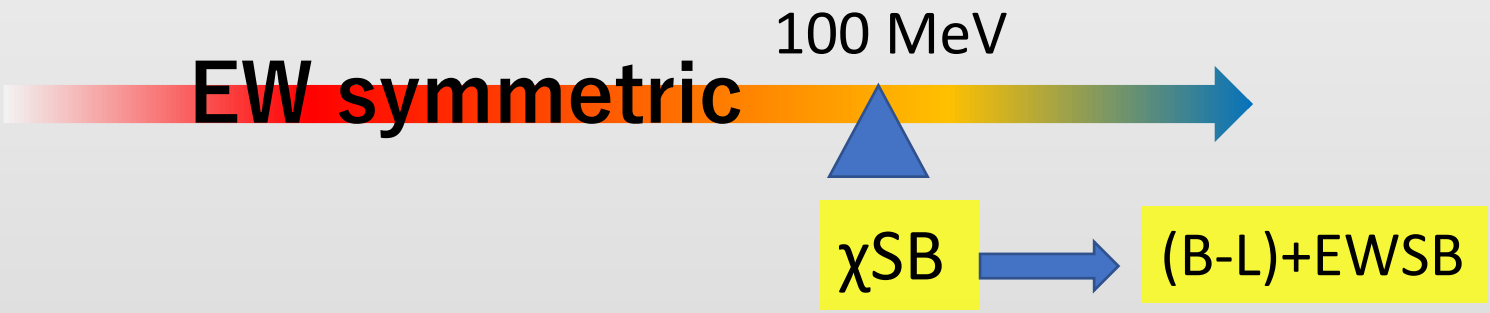
$$N = \ln \frac{T_i}{T_N^{\rm QCD}} \sim \ln \frac{m_{Z'}}{T_N^{\rm QCD}}$$

e-folding is small (typically N ~ 10)

Summary

In classically conformal models motivated by LHC experiments, completely different history of the early universe is realized!

extreme supercooling occurs (for $g<0.2$)



Classifications of early universe histories

Scenario (I) → GW

Scenario (II) → thermal inflation

Future works: other interesting possibilities

(II) DM, PBH

(I) Cold EWBG J. Smit, Tranerg (2002), Konstandin, Servant (2011)

Thank you
Grazie

Many thanks to the organizers for the wonderful workshop !

Cicoli, Michele (Bologna U. & ICTP)
Ciupke, David (Bologna U.)
Parameswaran, Susha (Liverpool U.)
Pedro, Francisco (IFT, Madrid)
Shukla, Pramod (ICTP)

back up

Philosophy behind "classically conformal models"

Question: Is quadratic divergence really the issue of the hierarchy problem?

- It can be always subtracted with no effects on physics.
  (additive renormalization)

  It is different from logarithmic divergences (multiplicative renorm.)

- No quadratic divergences in dimensional regularization.
  (minimal subtraction)

See e.g.
Bardeen (1995)
Hill (2005)
Fujikawa (2011)
Aoki Iso (2012)

Bardeen (1995 @ Ontake summer institute)

Standard model is classically scale invariant if Higgs mass term is absent.

$$T^{\mu}_{\mu} = 0$$

Quantum anomaly breaks the invariance (if not conformal)

$$T^{\mu}_{\mu} = \beta(\lambda_i)\mathcal{O}_i$$

The common wisdom is that the breaking is not soft and we have

$$T^{\mu}_{\mu} = \beta(\lambda_i)\mathcal{O}_i + const.\ \Lambda^2 \bar{h} h$$

Bardeen argued that it should be

$$T^{\mu}_{\mu} = \beta(\lambda_i)O_i + \delta m^2 \bar{h} h$$

$$\delta m^2 = const. \times m^2 \neq const. \times \Lambda^2$$

if no intermediate scales exist.

Support for Bardeen by Wilsonian RG

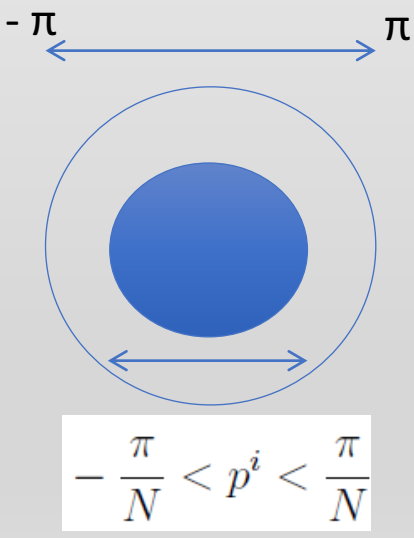
H. Aoki, SI (2012)

Scalar field in d-dim

$$S = \int_{\Lambda^d} \frac{d^d p}{(2\pi)^d} \frac{1}{2}(p^2 + m^2)\phi(p)\phi(-p) + \frac{1}{4!}\lambda \int_{\Lambda^d} \prod_{a=1}^{4} \frac{d^d p_a}{(2\pi)^d} (2\pi)^d \delta^{(d)}\left(\sum_{a=1}^{4} p_a\right) \phi(p_1)\phi(p_2)\phi(p_3)\phi(p_4)$$

$$\Lambda^d = \{p | -\pi < p^i < \pi, \ \forall i = 1, 2, \cdots, d\}$$ Lattice cutoff

All quantities (mass, field) are dimensionless.
Measured in units of the lattice cut-off.



2 steps of RG transformation

Step 1: Integration over higher momentum modes $|p^i| \geq \frac{\pi}{N}$

Remaining modes $-\frac{\pi}{N} < p^i < \frac{\pi}{N}$

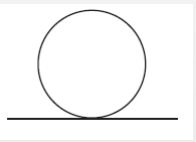
Step 2: Rescaling $p' = Np$ $\phi'(p') = N^{-\theta}\phi(p)$

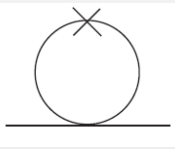
θ is chosen so that the kinetic term becomes canonical.

RG transformations

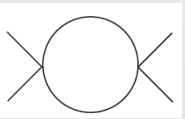
$$\frac{m^2}{\Lambda^2} \ll 1$$

$$m^{2\,\prime} = N^{2\theta-d}(m^2 + c_1\lambda - c_2 m^2 \lambda)$$





$$\lambda' = N^{4\theta-3d}(\lambda - 3c_2\lambda^2)$$



$$c_1 = \frac{1}{2}\int_{\Lambda^d_{\rm out}} \frac{d^dq}{(2\pi)^d}\frac{1}{q^2} \longrightarrow \Lambda^2$$

$$c_2 = \frac{1}{2}\int_{\Lambda^d_{\rm out}} \frac{d^dq}{(2\pi)^d}\left(\frac{1}{q^2}\right)^2 \longrightarrow \Lambda^0 \ln N$$

$$\theta = (d+2)/2$$

Solution

$d \neq 4$

$$\frac{1}{\lambda'} - \frac{1}{\lambda^*} = N^{-(4\theta-3d)}\left(\frac{1}{\lambda} - \frac{1}{\lambda^*}\right) + \mathcal{O}(\lambda)$$

$$\lambda^* = \frac{N^{4\theta-3d}-1}{3c_2}$$

$d = 4$

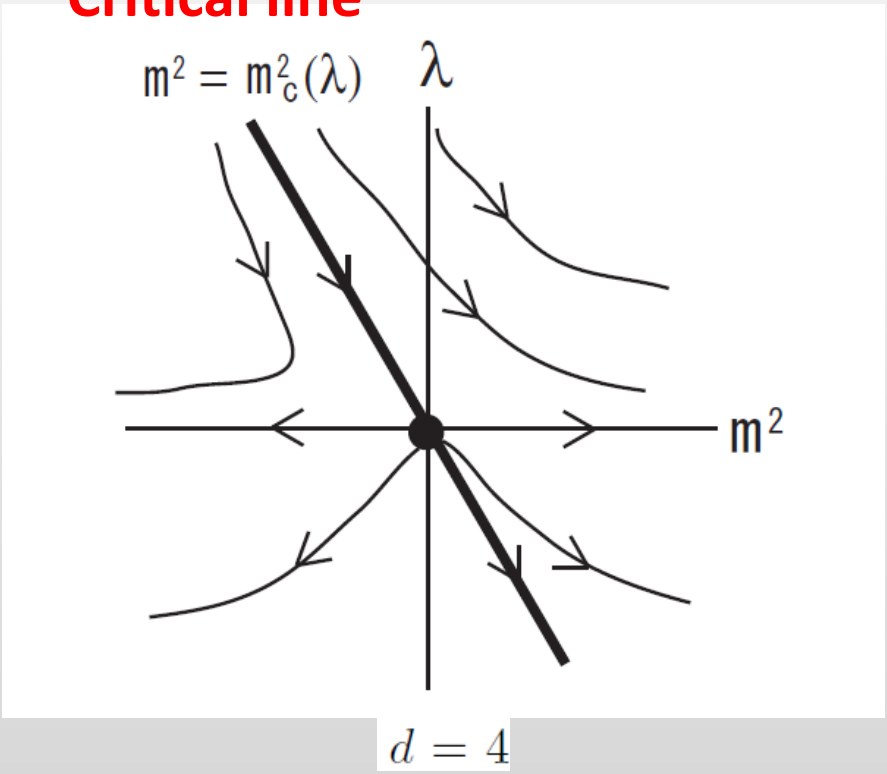
$$\frac{1}{\lambda_n} = \frac{1}{\lambda_0} + 3c_2 n$$

$$m^{2\,\prime} - m_c^2(\lambda') = N^{2\theta-d}(1 - c_2\lambda)(m^2 - m_c^2(\lambda))$$

$$m_c^2(\lambda) = -\frac{c_1}{1 - N^{2(\theta-d)}}\lambda$$

Quadratic divergence from Wilsonian Renormalization Group

Critical line



critical line Quadratic divergence

$$m_c^2(\lambda) = -\frac{c_1}{1 - N^{2(\theta-d)}}\lambda$$

Quadratic divergence determines the position of critical line.

Scaling behavior of RG flow is determined only by Logarithmic div.

Such property does hold at all orders of perturbations.

Continuum Limit

$$m_0^2 - m_c^2(\lambda_0) = N^{-2} e^{c_2 \sum \lambda_i} (m_R^2 - m_c^2(\lambda_R))$$

In terms of the **dimensionless** parameter m,
we need to fine-tune the bare mass close to the critical line.

In terms of **dimensionful** parameter,

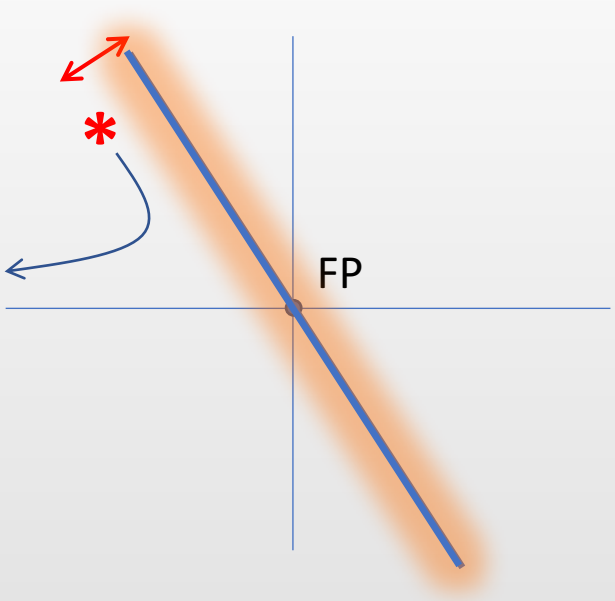
$$\tilde{\Lambda}_0 = N^n \tilde{\Lambda}_n = N^n M$$

$$\tilde{m}_k^2 = \left(\frac{\tilde{\Lambda}_k}{\Lambda} \right)^2 m^2$$

$$\tilde{m}_0^2 - \tilde{m}_c^2(\lambda_0) = e^{c_2 \sum \lambda_i} (\tilde{m}_R^2 - \tilde{m}_c^2(\lambda_R))$$

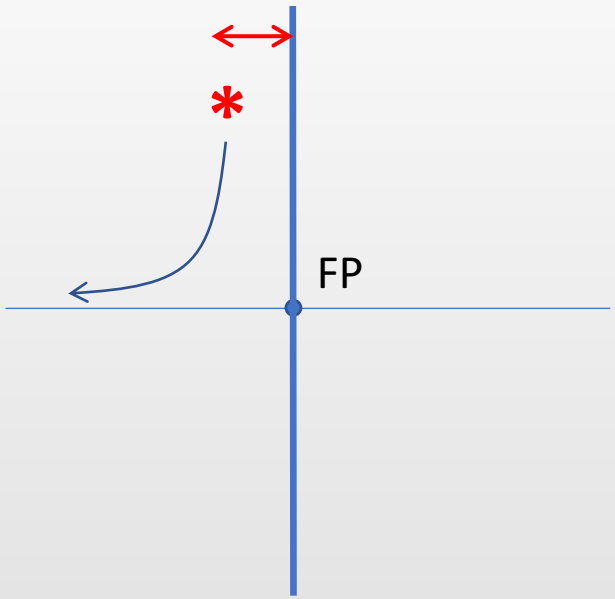
Log scaling of mass term

This type of tuning has nothing to do with quadratic divergences.



With quadratic div.

$\Lambda^2 \neq 0$



No quadratic div.

$\Lambda^2 = 0$

Fine - tuning of the **distance from the critical line** = **Low energy mass scale**

This fine-tuning always occurs for both non-susy and susy.
i.e. It has nothing to do with quadratic divergences.
Most natural possibility is to put the theory on the critical line.

back

What is the real issue of the Hierarchy problem?

1. Initial boundary condition at UV
   the same for both susy and non-susy

2. Mixing of multiple relevant operators
   TeV susy can avoid this problem.

back

Mixing of multiple relevant operators by Logarithmic div.

$$S = \int_{\Lambda^d} \left[\sum_{\alpha=1}^{S} \left(\frac{1}{2}(p^2 + m_\alpha^2)\phi_\alpha^2 + \frac{1}{4!}\lambda_{\alpha\alpha}\phi_\alpha^4 \right) + \sum_{\alpha\neq\beta} \frac{1}{8}\lambda_{\alpha\beta}\phi_\alpha^2\phi_\beta^2 \right]$$

Solution → $$\tilde{m}^2_{\alpha(0)} - \tilde{m}^2_{c\alpha}(\lambda_{(0)}) = \sum_\beta \left(M^{-1}\right)_{\alpha\beta} \left(\tilde{m}^2_{\beta(n)} - \tilde{m}^2_{c\beta}(\lambda_{(n)})\right)$$

Critical line $$m^2_{c\alpha}(\lambda) = -\frac{c_1}{1 - N^{2(\theta-d)}} \sum_\beta \lambda_{\alpha\beta} + \mathcal{O}(\lambda^2)$$

Example:

$$\begin{aligned} \tilde{m}^2_{1(n)} - \tilde{m}^2_{c1}(\lambda_{(n)}) &= m^2_{\mathrm{W}} \\ \tilde{m}^2_{2(n)} - \tilde{m}^2_{c2}(\lambda_{(n)}) &= m^2_{\mathrm{GUT}} \end{aligned}$$

Mixing of weak scale with Gut scale

$$m^2_{\mathrm{W}} \simeq \frac{1}{(M^{-1})_{11}}(\tilde{m}^2_{1,0} - \tilde{m}^2_{c1}(\lambda_0)) - \frac{(M^{-1})_{12}}{(M^{-1})_{11}}\, m^2_{\mathrm{GUT}}$$

Classification of divergences

1. Power divergences Λ^2

It can be simply subtracted at UV scale = boundary condition at UV

Once subtracted, no longer appears in IR.

---

2. Logarithmic divergences $m^2 \log(\Lambda/m)$

$$\frac{dm^2}{dt} = \frac{m^2}{16\pi^2}\left(12\lambda + 6Y_t^2 - \frac{9}{2}g^2 - \frac{3}{2}g_1^2\right)$$

scalar mass within SM

3. Large Logarithmic divergences: $M^2 \log(\Lambda/M)$

$$\frac{dm^2}{dt} = \frac{m^2}{16\pi^2}\left(12\lambda + 6Y_t^2 - \frac{9}{2}g^2 - \frac{3}{2}g_1^2\right) + \frac{M^2}{8\pi^2}\lambda_{mix}$$

$$\delta m^2 = \frac{\lambda_{mix} M^2}{16\pi^2}\log(\Lambda^2/M^2)$$

Heavy particles beyond SM

m	<<	M
Low energy physics		High energy physics

back

B-L symmetry is radiatively broken via CW mechanism.
How does the EWSB occur ?

Flat potential is suggested by LHC

$$V(H) = 0 \quad @M_{PL}$$

$$\cancel{m_H^2 H^2} + \cancel{\lambda_H H^4} + \cancel{\lambda_{H\Phi} H^2 \Phi^2}$$

classically conformal

126 GeV

key to relate EW and B-L @TeV

The coefficient must be small and negative.

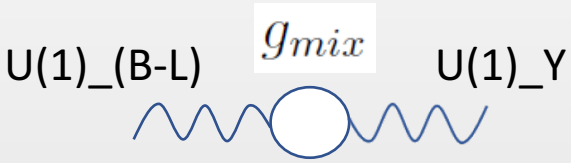
$$\langle H \rangle = \sqrt{\frac{-\lambda_{H\Phi}}{\lambda_H}} M_{B-L}$$

Can the small scalar mixing appear naturally?

→ Yes (Orikasa, SI 2012) : 1210.2848(PTEP)

Scalar mixing can be generated via gauge mixing of $U(1)_Y$ and $U(1)_{B-L}$

★ U(1) mixing is radiatively generated



★ Then a small negative scalar mixing is radiatively generated

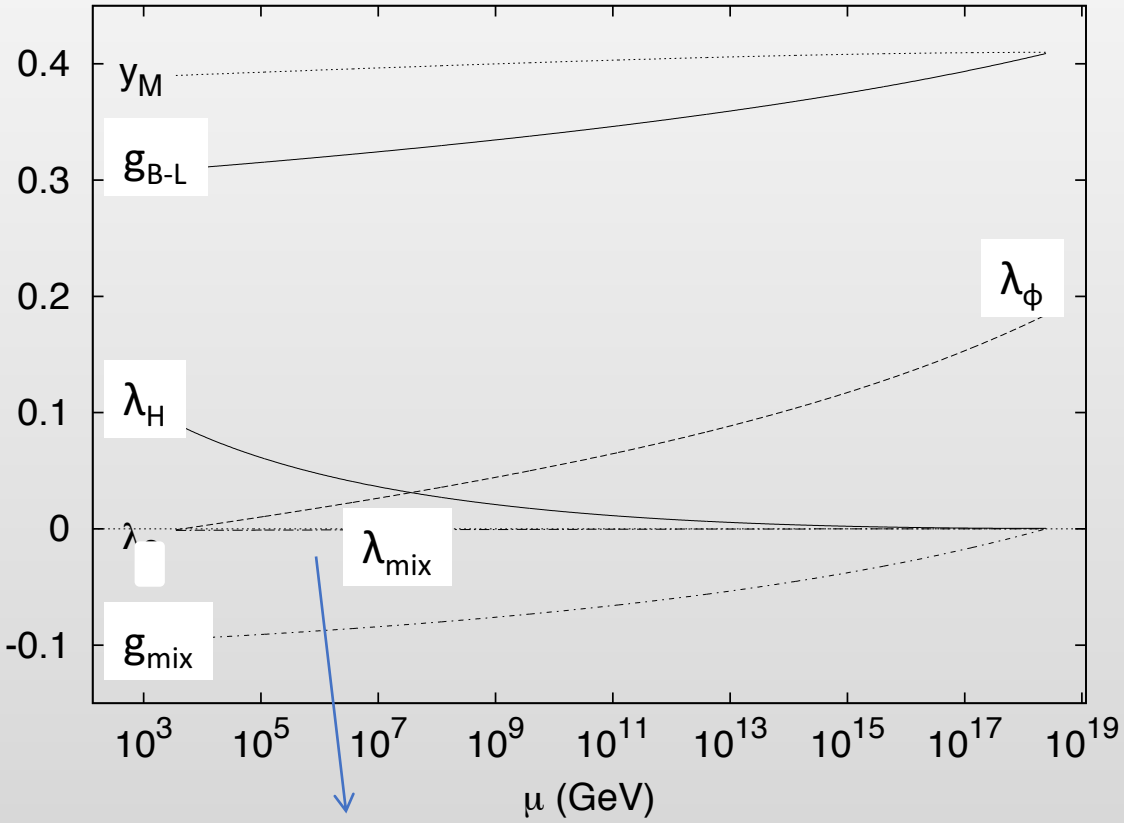
$$\frac{d\lambda_{H\Phi}}{dt} = \frac{1}{16\pi^2}\left(6g_{B-L}^2 g_{mix}^2 + \lambda_{H\Phi} \times (\cdots)\right) \longrightarrow \lambda_{H\Phi} \sim -g_{B-L}^2 g_{mix}^2$$

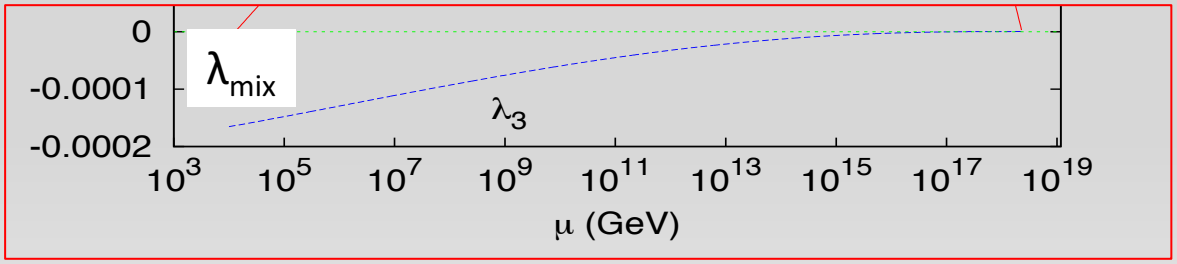
The scalar mixing triggers EWSB.

The scalar mixing is very small and negative.
This triggers the EWSB.
→ small hierarchy between B-L scale and EW scale.

$$\langle H \rangle = \sqrt{\frac{-\lambda_{mix}}{\lambda_H}} M_{B-L} \sim c\frac{\alpha_{B-L}\alpha_Y}{\sqrt{\lambda_H}} M_{B-L}$$

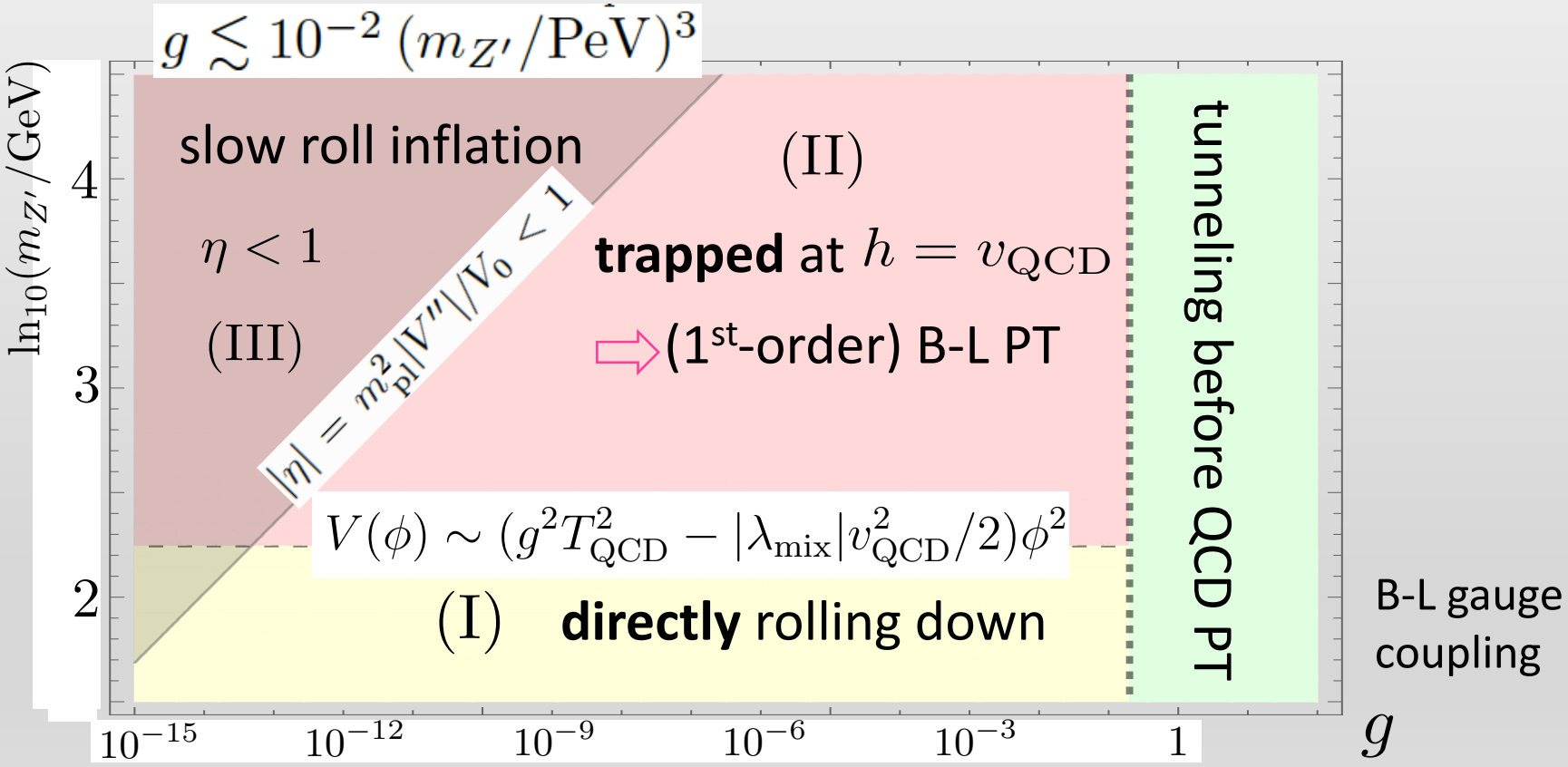
A typical behavior of RGE





M_{B-L} = 3.55 TeV,
m_ϕ = 200 GeV,
m_N= 2.8 TeV

M_{EWSB} = 246 GeV,
m_H = 126 GeV

A small negative scalar mixing is generated !!

Classification of histories
For heavier Z' mass $m_{Z'} \gg m_N$