2017/8/3@NCTS20th anniversary

Congratulations for 20th Anniversary !!

A possibility of QCD-induced EWSB in the early universe

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Based on collaborations with

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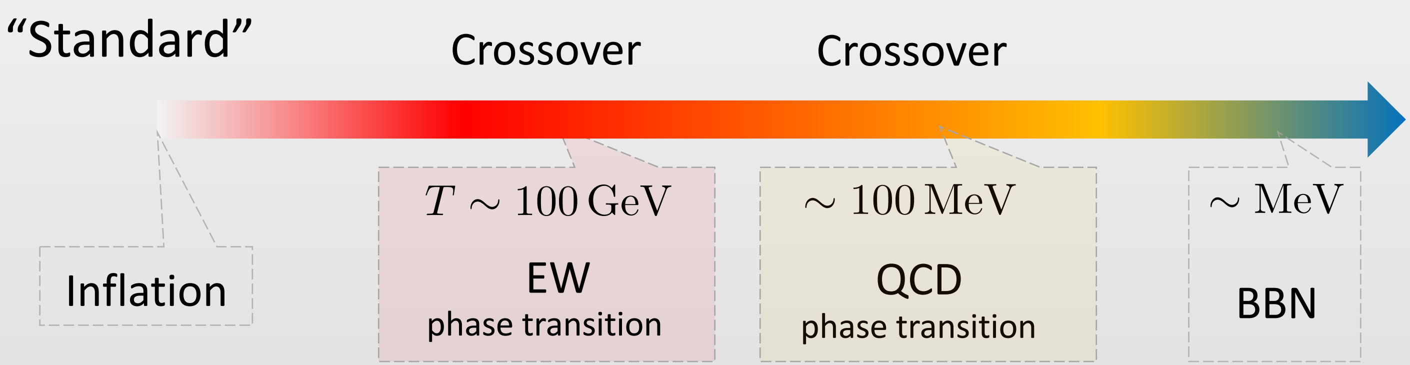
(LAPTh, Annecy)

Today's main message

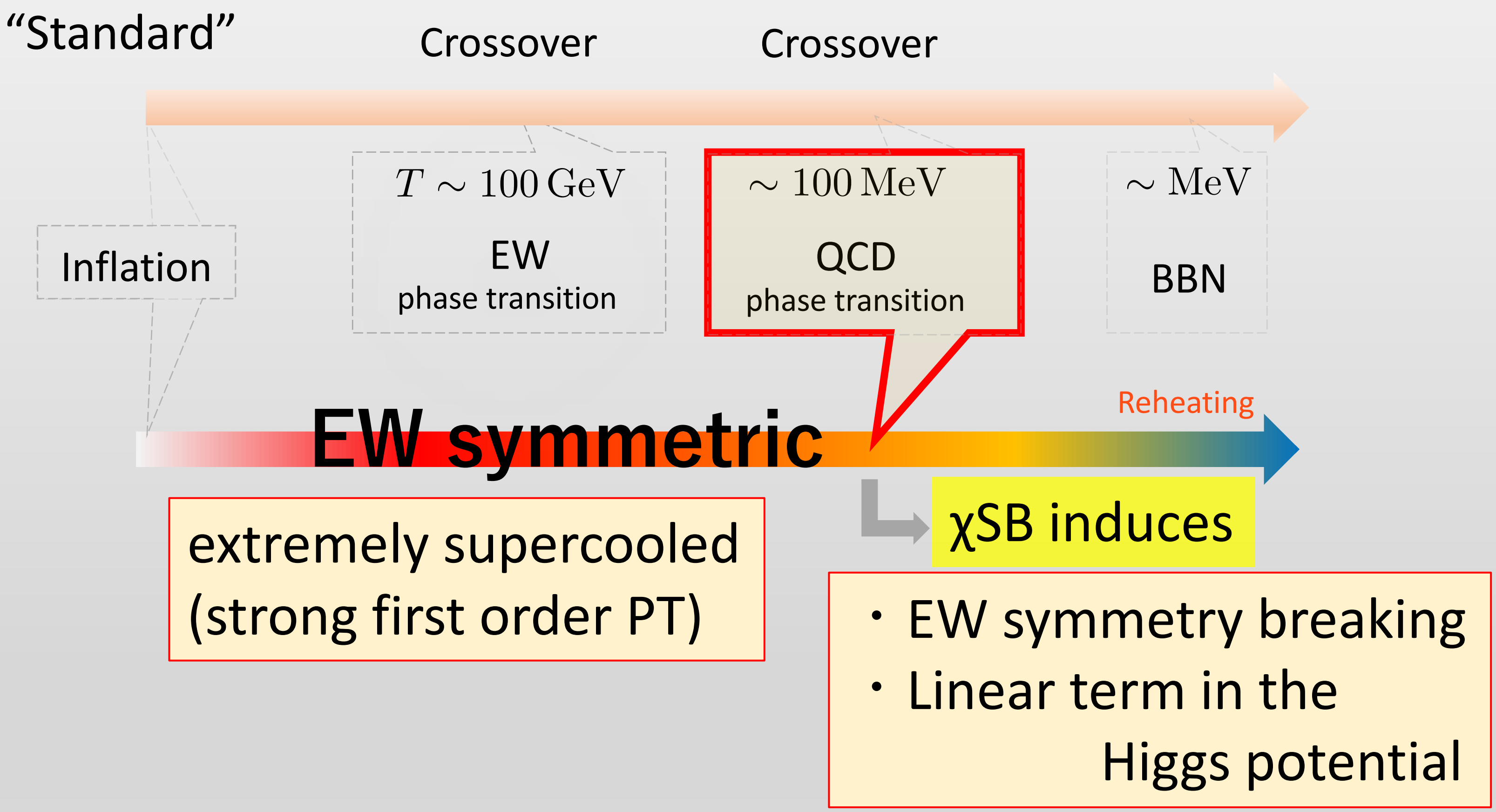
Standard thermal history of the universe



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

Today's main message

Thermal history of the universe



→ different cosmological consequences

"classically conformal models"

- no dimensionful parameters in scalar potential
  quadratic term is assumed to be absent

$$\boxed{V(\phi) = \lambda(|\phi|^2)^2}$$

- motivated by LHC experiments
  naturalness & m_H = 125 GeV

- Symmetry breaking must occur radiatively
  via Coleman-Weinberg mechanism

$$V(\phi) = \frac{\lambda}{4}\phi^4(\ln\frac{\phi^2}{M^2} - \frac{1}{2})$$

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

- $U(1)_{B\text{-}L}$ 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

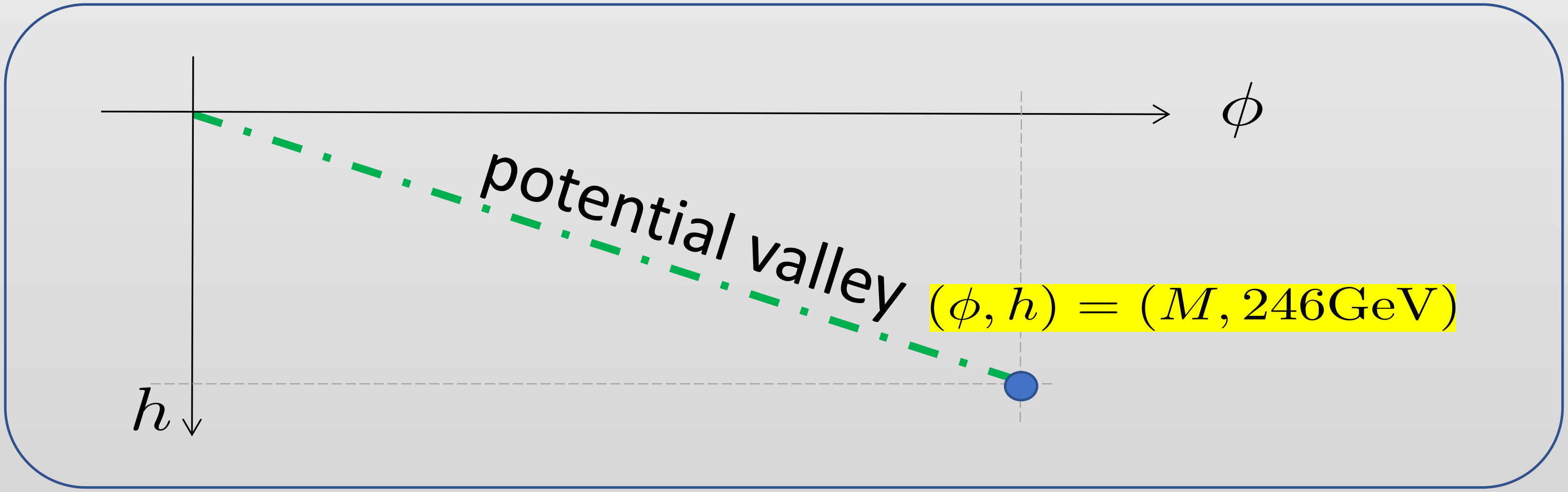
No quadratic terms in classically conformal models

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

Higgs

$\lambda_{\rm mix} < 0$

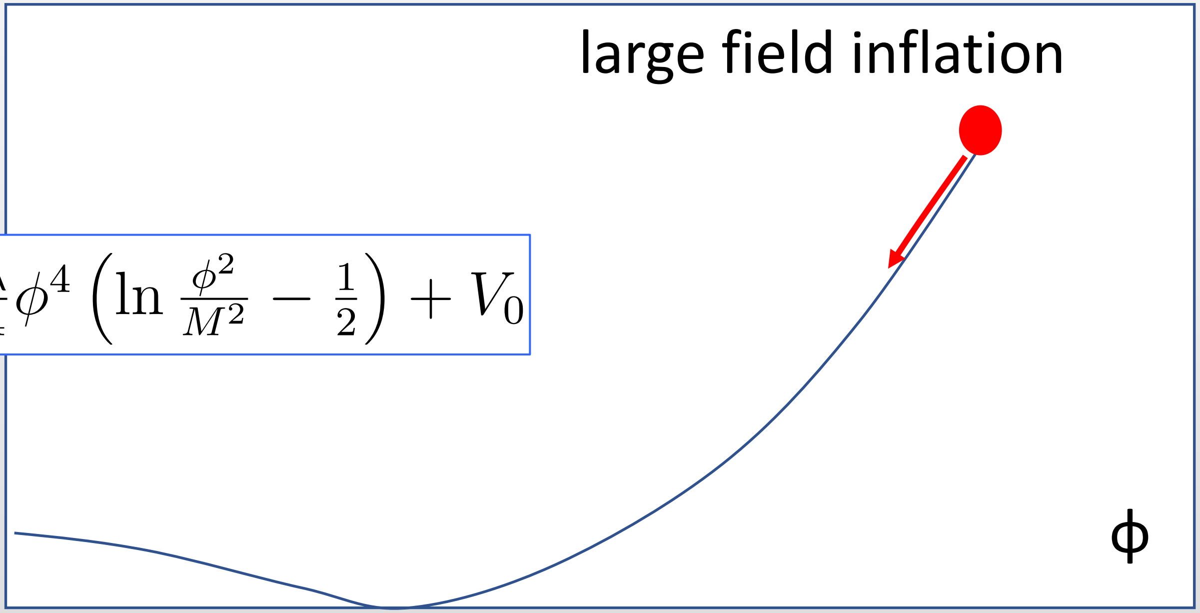
(B-L) scalar



The early universe of classically conformal models

K.Shimada, P.Serpico, SI
1704.04955

Inflationary universe in classically conformal model



$$V(\phi) \sim \frac{\lambda}{4}\phi^4 \left(\ln \frac{\phi^2}{M^2} - \frac{1}{2}\right) + V_0$$

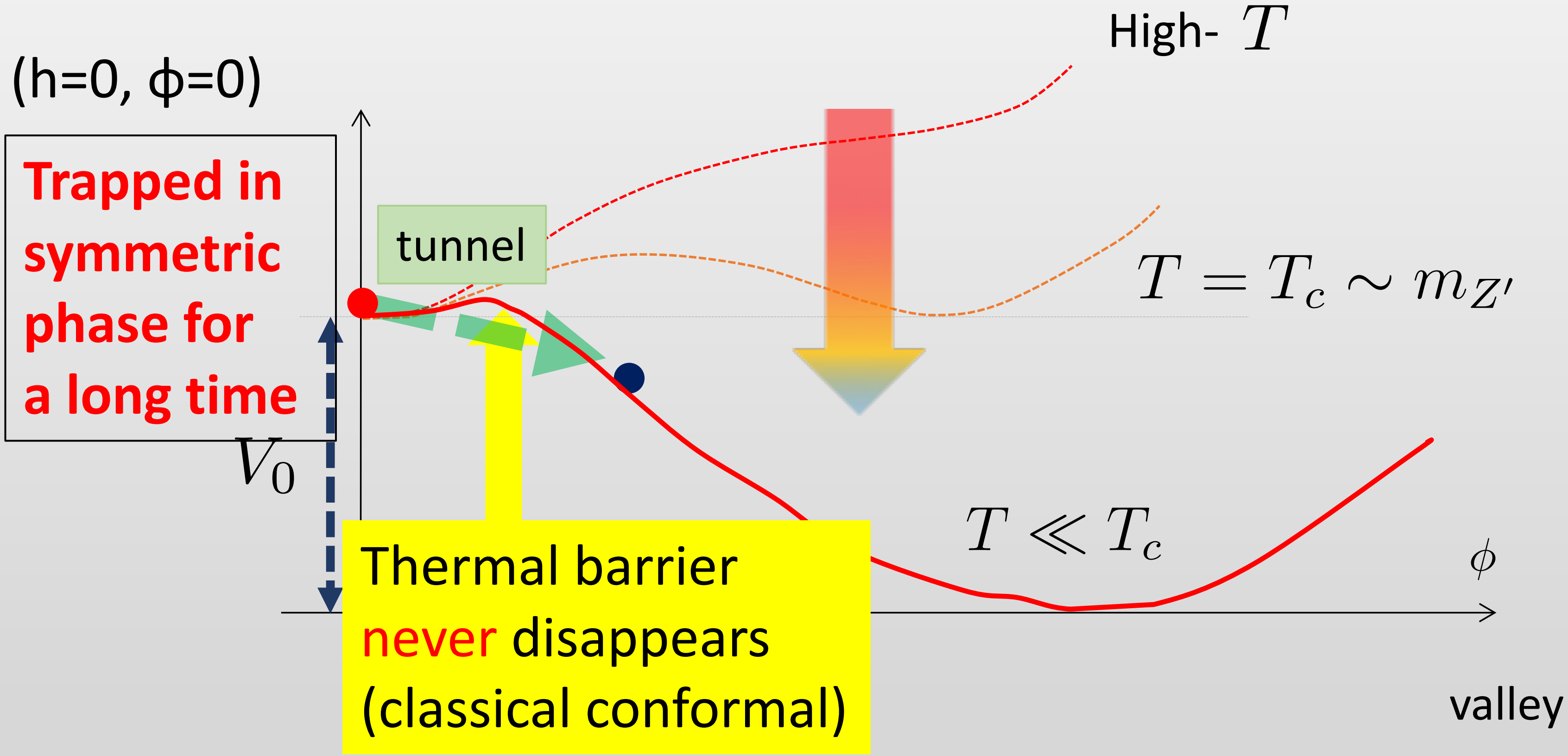
1 Large Field Inflation

2 Z' creation by Preheating → generates large potential

3 Trap the field around $\phi = 0$ → thermalize

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

Hypercooling of (B-L)+EW SB much below T_c



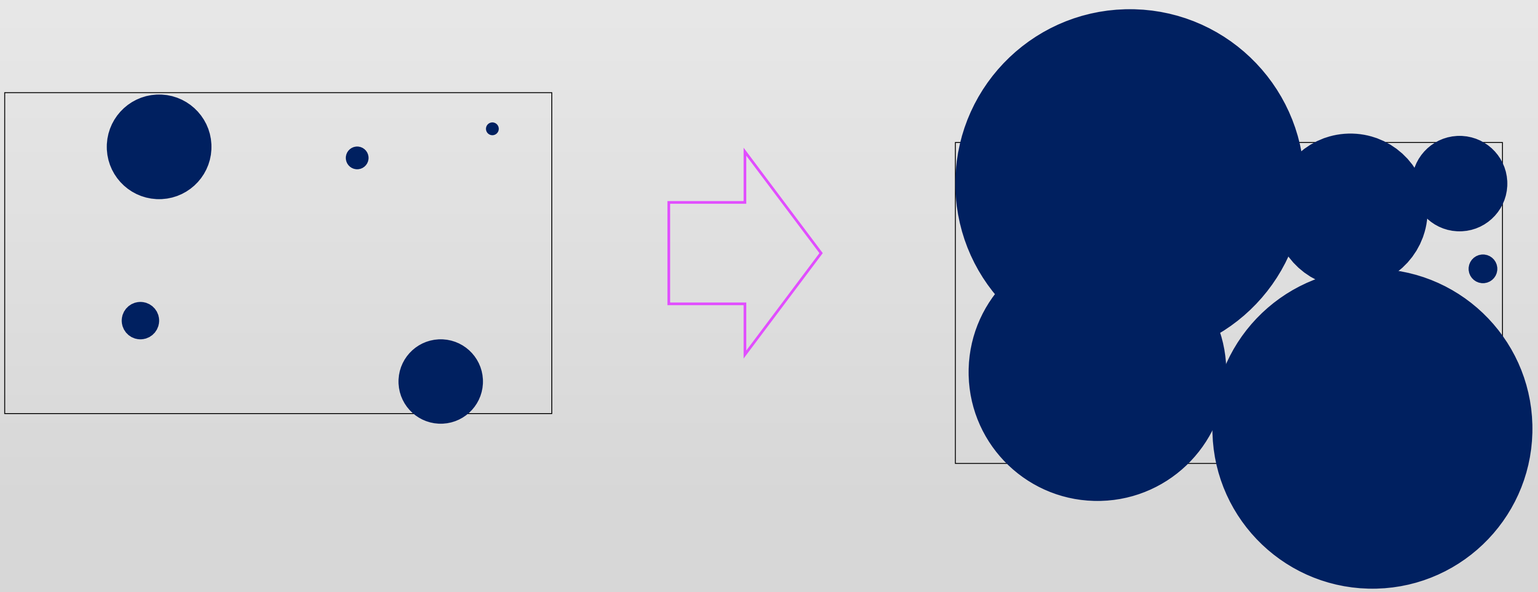
Bubble of true vacuum is created by tunneling.

Percolation of true vacuum

Guth Weinberg (82)

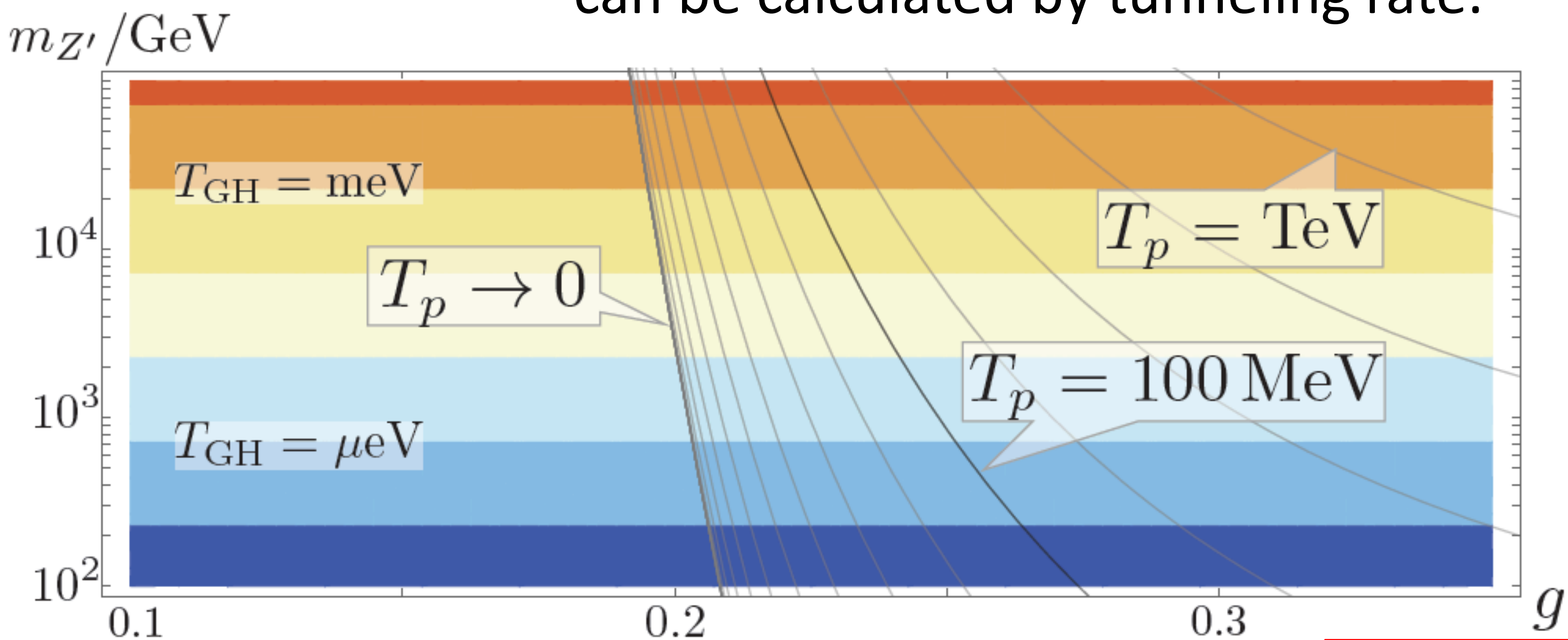
Bubbles of true vacuum
are created by tunneling

T_p : percolation temperature



Universe is occupied with
true vacuum bubbles

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.

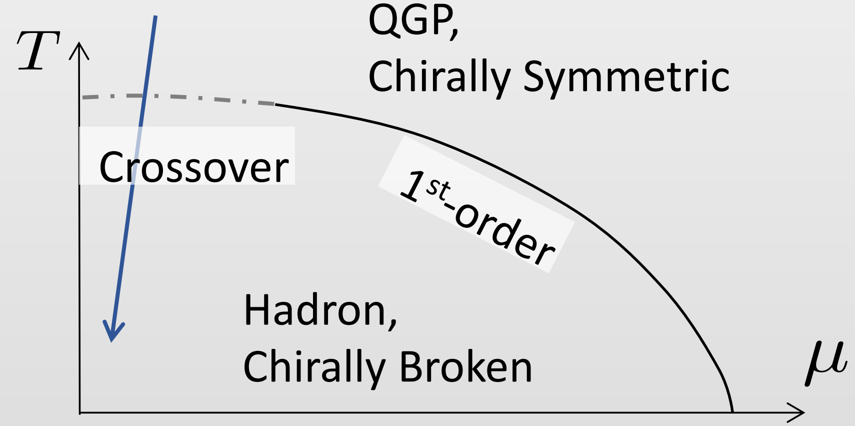
Note that de Sitter fluctuation $\sim T_{\mathrm{GH}} = \mathcal{H}/2\pi$ is negligible at 100 MeV.

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

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)

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

Electroweak symmetry is broken (EWSB)

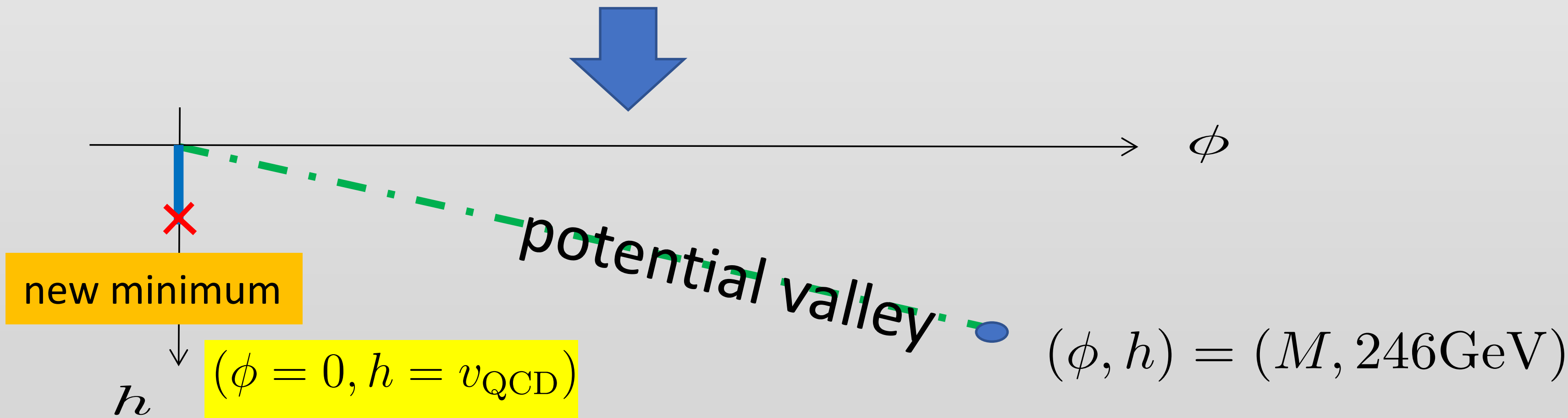
Quigg Shrock (09)

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

Higgs linear term is generated via Yukawa interaction

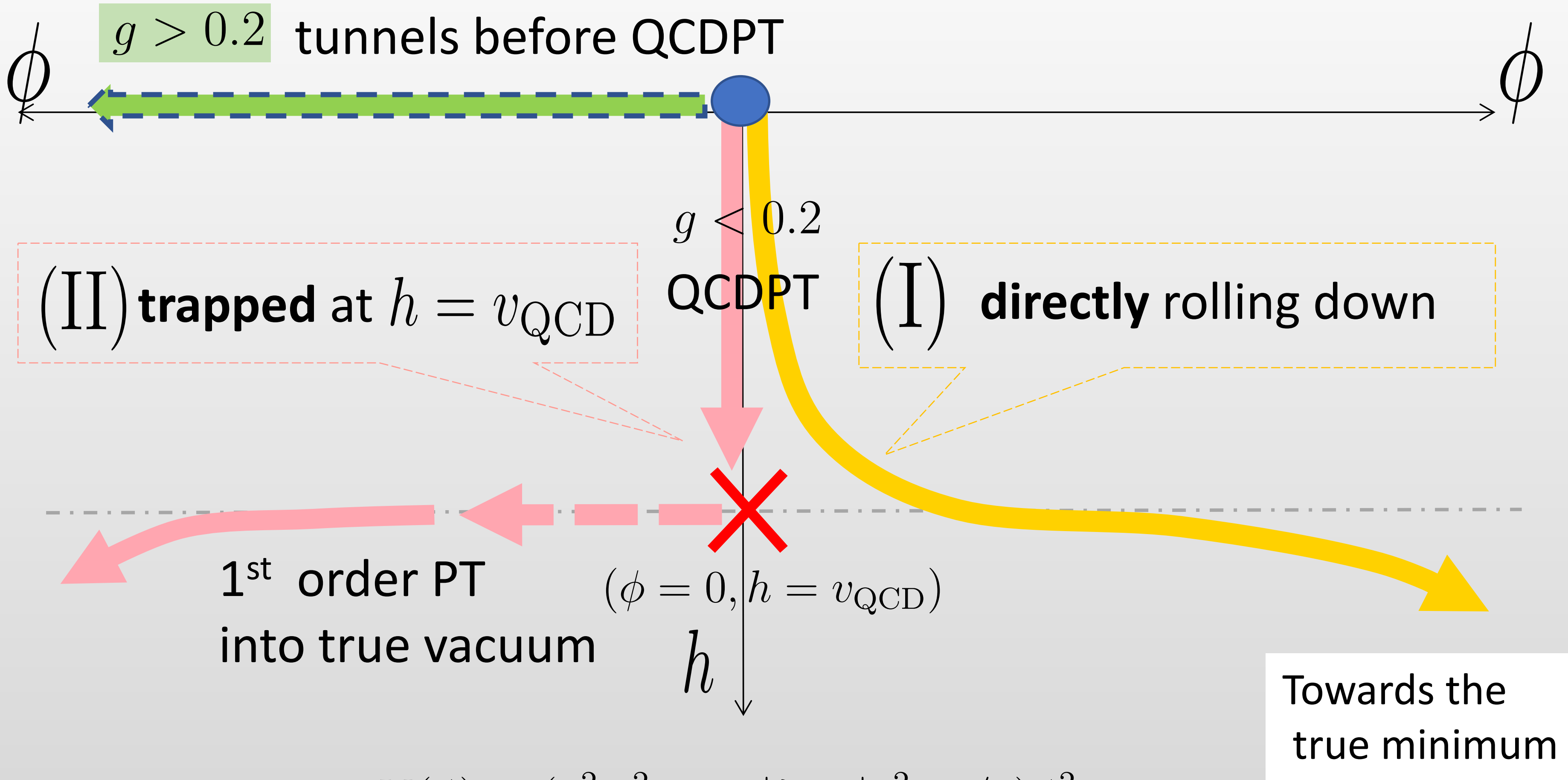
$$y_i h \langle \bar{q}_i q_i \rangle \sim (y_i \Lambda_{\rm QCD}^3) h$$

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



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

Classification of the histories of the early universe

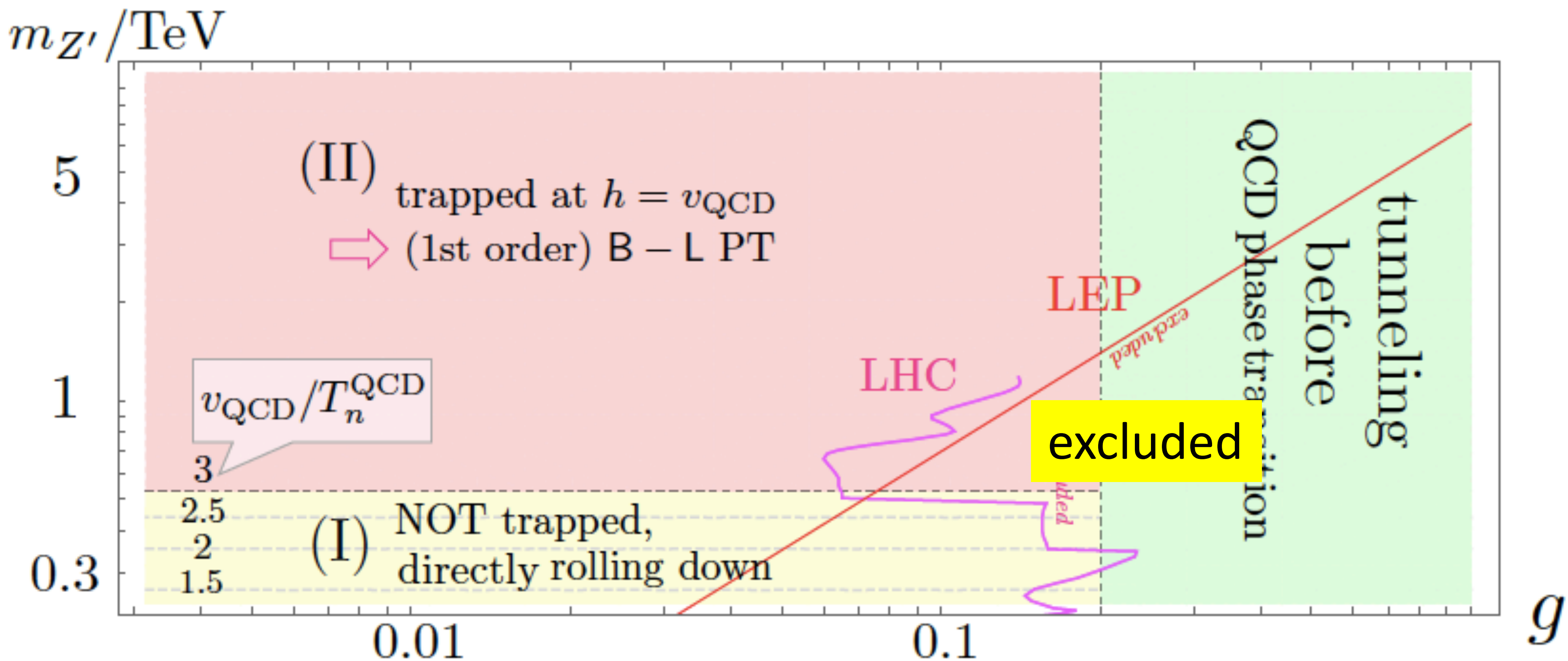


$$V(\phi) \sim (g^2 T_{\mathrm{QCD}}^2 - |\lambda_{\mathrm{mix}}| v_{\mathrm{QCD}}^2/2)\phi^2$$

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



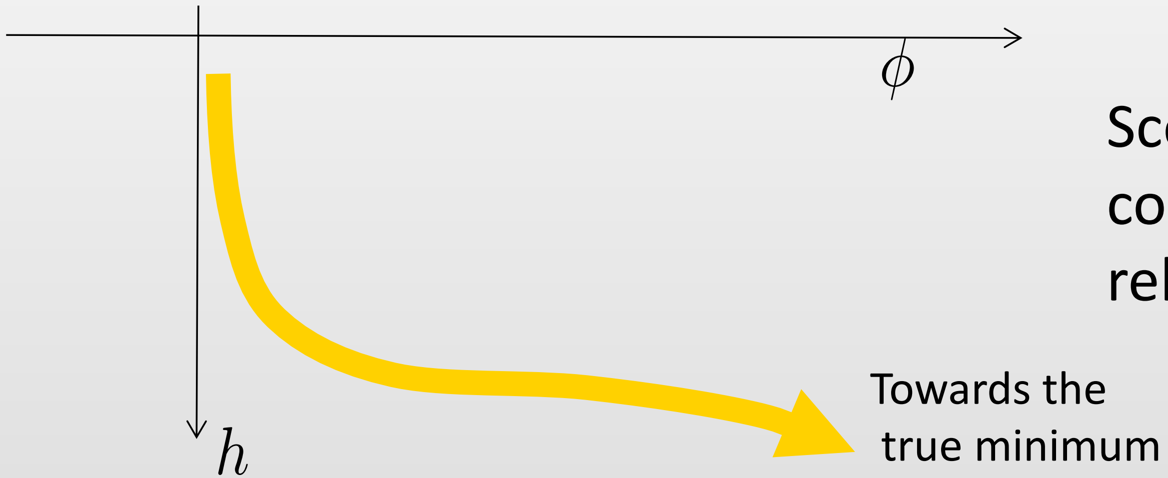
In this parameter region, slow roll inflation does not occur.

$m_{Z'} \sim$ a few hundred GeV

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).

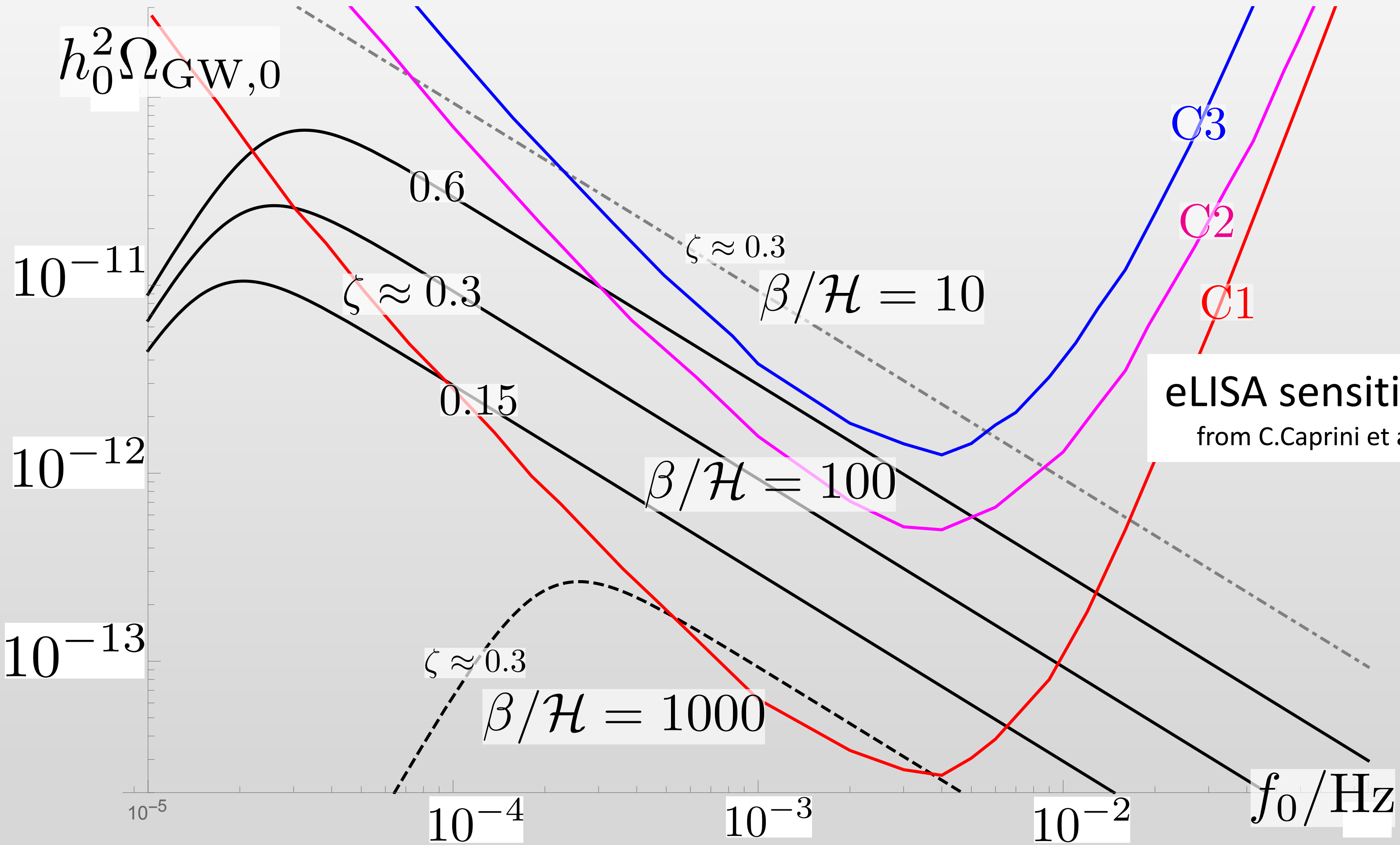
Release of the vacuum energy V_0 reheats the universe up to < 10 GeV.
→ Chiral symmetry restored → crossover QCD PT.

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.

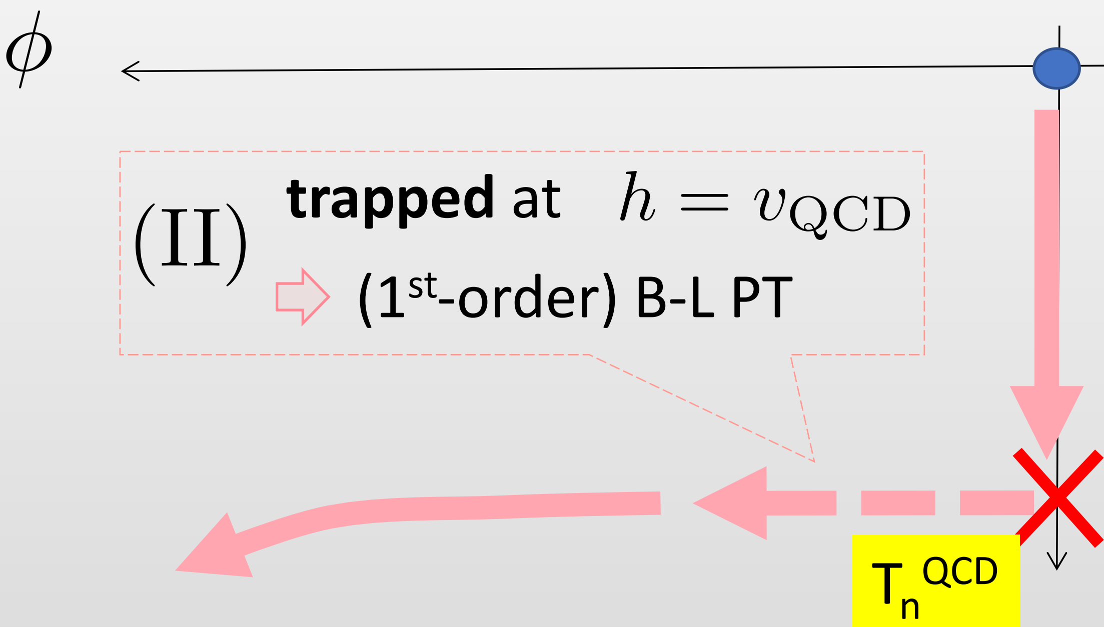
Background Gravitational Waves from 1st order PT in scenario (I)



1/β : duration of PT $\zeta \sim T_{\mathrm{rh}}/V_0^{1/4}$ 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_i ~ a few 10 GeV $V_0^{1/4} \sim m_{Z'}$

temperature at which de Sitter expansion starts at the origin

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

e-folding is small.

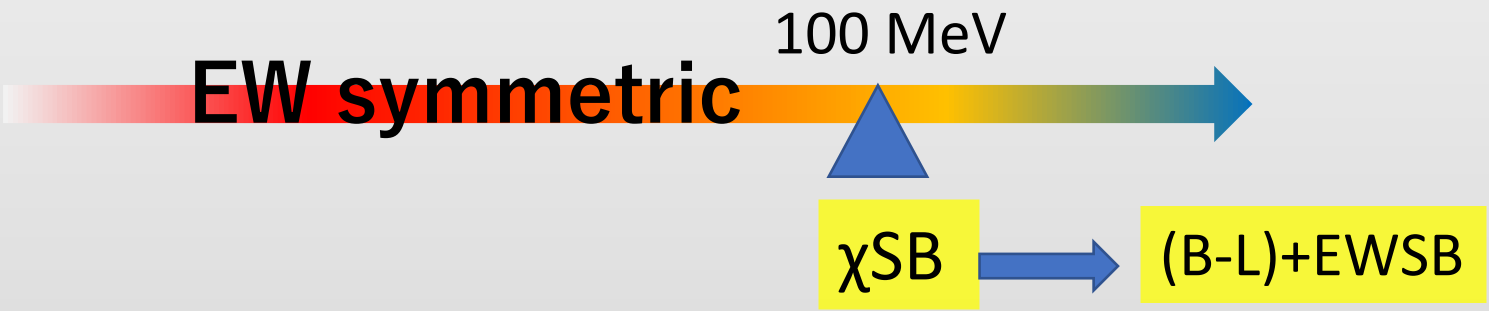
An interesting possibility is
generation of large scalar fluctuations
& formation of PBHs with QCD-Hubble mass = $1 M_{\odot}$

Jedmzek (97)

Summary

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

hypercooling (if the gauge coupling is not large, e.g. $g<0.2$)



Classifications of early universe histories

Scenario (I) → GW

Scenario (II) → thermal inflation, PBH?

Other interesting possibilities: cold EWBG, dark matter

Thank you very much

and

Congratulations for 20th Anniversary !!

NCTS

Theory Center KEK

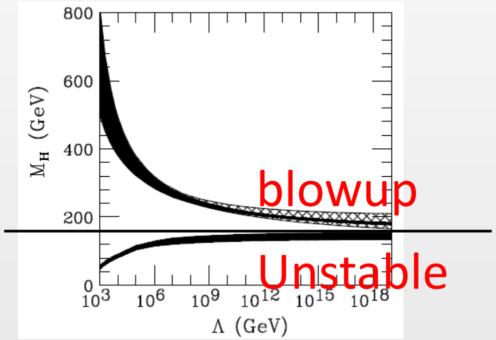
Collaborations, Partnership and Friendship back up

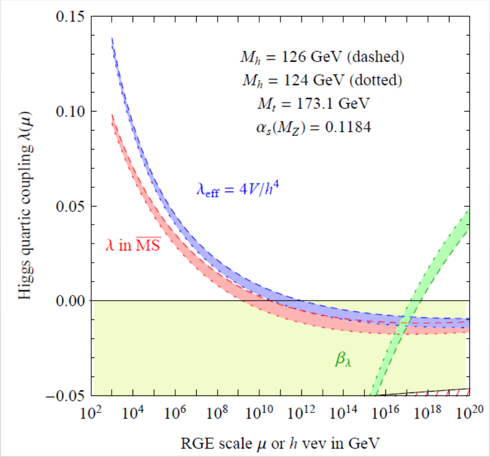
Philosophy behind
"classically conformal models"

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

(1) mass = 125 GeV

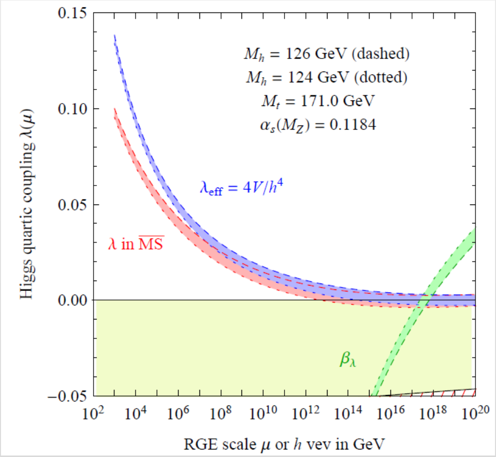
$$V = -\mu^2|H|^2 + \boxed{\lambda(|H|^2)^2}$$





vs

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

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

Quadratic divergence is related to "physical intermediate scale. "
To save naturalness, let's 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

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

→ Classically conformal models

(scalar potential is radiatively generated.)

Classification of histories

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