HPNP 2019 @ Osaka
2019 Feb 21 (18 -22)

Hierarchy problem

- from bottom-up and/or top-down -

Satoshi Iso (KEK & Sokendai)

"and" = a hope to connect these two approaches
"or" = they are not yet connected.

Hierarchy "problems" are ubiquitous in nature.

Particle physics, Cosmology
Condensed matter physics,
Fluid dynamics, Astrophysics, ...

Hierarchy of scales in fluid: "effective theory" approach

徳島県立脇町高校科学同好会
http://wakimachi-hs.tokushima-ec.ed.jp/joapls1un-282/

Karman vortices in various scales

Behind Cheju island

済州島 （ひまわり）

Jupiter (NASA Voyager2)

Navier-Stokes eq. is described by a single dimensionless parameter = R.

$$\frac{D\mathbf{u}}{Dt} = -\frac{1}{\rho}\nabla p + \nu \Delta \mathbf{u} \quad \Rightarrow \quad \frac{D\tilde{\mathbf{u}}}{D\tilde{t}} = -\tilde{\nabla}\tilde{p} + \frac{1}{R}\tilde{\Delta}\tilde{\mathbf{u}}$$

$$R = LU/\nu$$

Reynolds number

But Cheju Karman vortices cannot be explained if we use the molecular viscosity ν .

$$\nu(\mathrm{Cheju}) \sim 10^8 \ \nu(\mathrm{micro})$$

Eddy viscosity   molecular viscosity

Viscosity is scale-dependent.

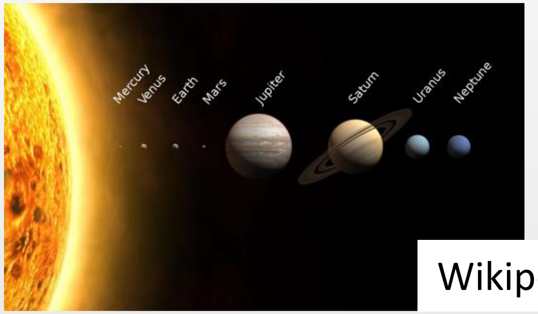
The framework of LEET can be determined by the IR physics, e.g
symmetry (Navier-Stokes eq., Chiral Lagrangian)
renormalizability (Standard Model)

But, the parameters in the EFT are obtained by integrating out UV physics.

This is nothing but the idea of Renormalization Group.

→ **UV determines IR parameters through RG.**

Hierarchy of scales in orbital motions: "geometric" approach



Wikipedia

Radius of orbital motions

Earth r=10000000 km

Pluto r=5000000000 km

ISS r=6400+400 km

Suppose that we were always faced to the sun.

How could we understand

why the distance is fixed at r=10^7 km? why it is different from r on Pluto?

why the sun is not falling down to the earth ?

In this setup, a classical solution (configuration) is first determined by the initial condition first, and then we can calculate its effective potential on each planet.

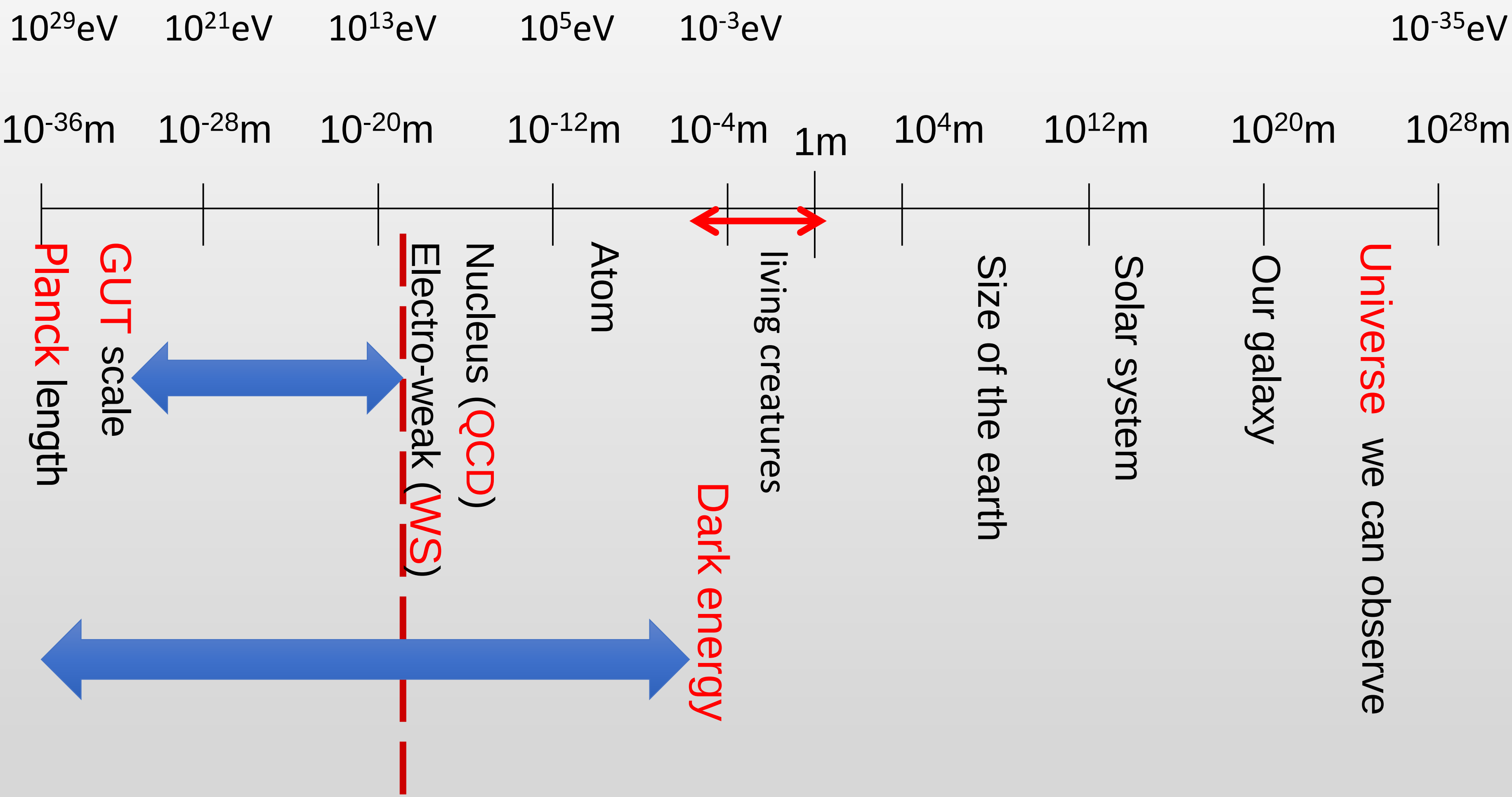
→ Thus, effective potentials are different on Earth and on Pluto.

Phenomena on planets, e.g., Coriolis force, is solution-dependent.

Solution comes first, Effective potential next!

"IR" geometry determines effective potential in a top-down way.

Hierarchy of scales in the universe



Naturalness problem = Hierarchy of various scales in nature

In this talk, I will focus on

the hierarchy of M_{EW} against M_{Planck}

from bottom-up (part 1) and from top-down (part 2)

Especially I will pay particular attention to

the vev of Higgs <H> itself

NOT a parameter in the Higgs potential

Note that <H> is a solution to the EOM of Higgs field.

Part 1
Bottom-up approach
to the Higgs hierarchy problem

- LHC and Classical conformal models –

N.Okada, Y.Orikasa, SI *PLB(2009) & PRD(2009)*
Y.Orikasa, SI *PTEP(2012)*
M.Hashimoto , Y.Orikasa, SI *PRD(2013) & PRD(2014)*

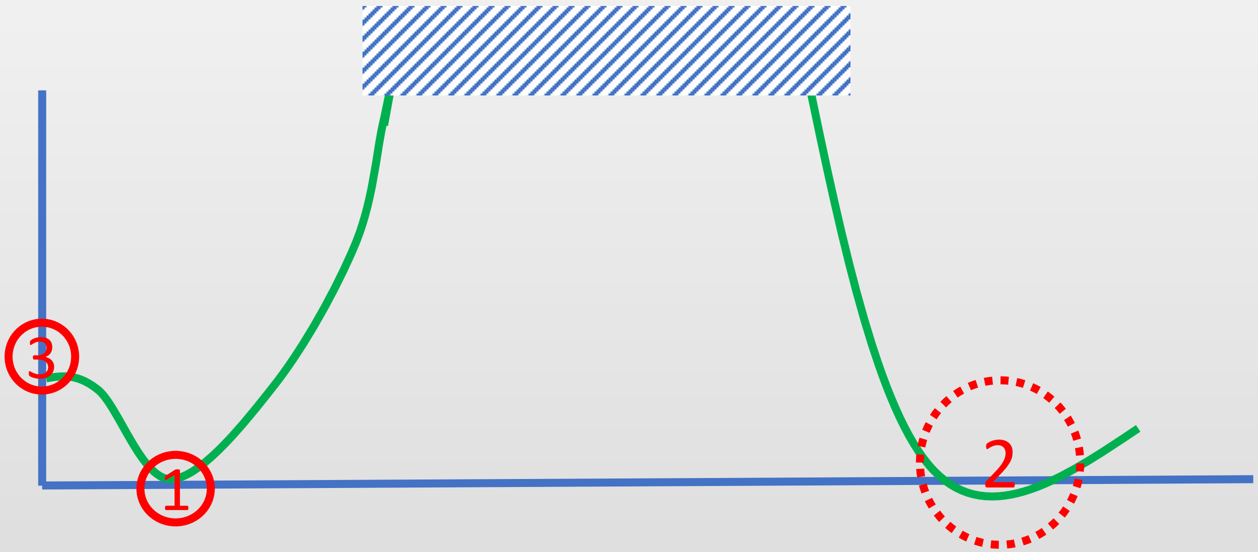
- QCD induced EW phase transition -

K. Kohri & K. Shimada , SI *PRD(2015) & PRD (2016)*
P. Serpico, K. Shimada, SI PRL (2017)

We have now many experimental data about the Higgs sector

including Higgs mass, Higgs VEV, quartic coupling, Yukawa couplings

→ Rough picture of the Higgs potential: (at least) 3 important points



1 Higgs VEV v= 246 GeV → SM (present universe)

2 UV scale $M_{UV} > 10^{10}$ GeV or M_{Planck}

→ gravity, string theory & origin of Higgs

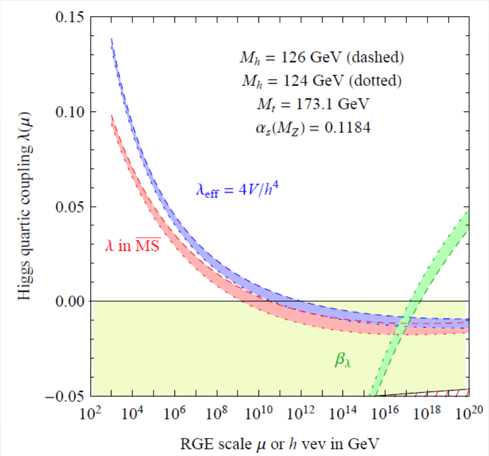
3 h=0 (origin) → history of the early universe

The behaviors around 2 and 3 control the early universe,
but they are only indirectly accessible by using RG and theoretical biases.

2 important lessons from LHC for the Higgs potential

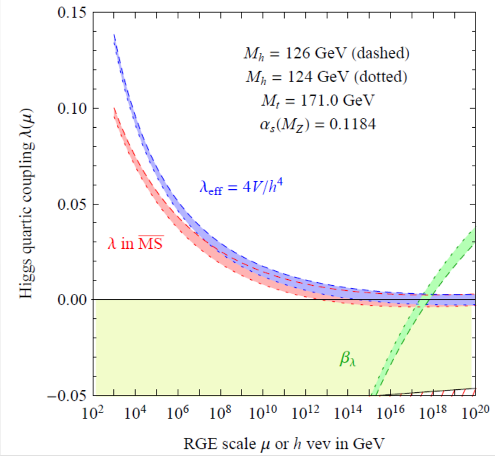
(1) mass = 125 GeV

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



still controversial ...

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



"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

If μ=0 at UV scale, it will be never radiatively generated in the IR
if there are no intermediate scales strongly coupled to the SM.

Wetterich (94)
Bardeen (95)

→ Classically conformal models (scalar potential is radiatively generated.)

flat potential V(H)=0 at M_{Pl}

Scalar fields often appear as **moduli**
with flat potential in string theory.

From UV to IR: Naturalness problem = how can we interpolate ?

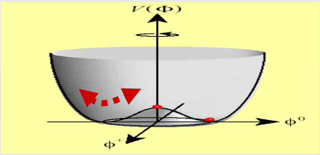
"UV physics" either Quantum scale invariance in QG
or String theory (flat moduli in non-susy vacua)

Start from a flat potential V(H)=0 at M_{Pl} , or M_{string}

No intermediate scales between UV and IR

Coleman-Weinberg mechanism

Radiatively generate



"IR Physics": SM + (inevitably) an additional sector

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

because CW mechanism requires that
the beta-function of the quartic scalar coupling must be positive $\beta_\phi > 0$
(Within the SM, β_{Higgs} <0 and CW mechanism does not work.)

Several possibilities of extensions: Classically conformality to solve naturalness

(1) SM + scalars Foot, Kobakhidze, Volkas (07), Meissner,Nicolai (07) ....
(2) SM + gauge sector B-L: SI, Okada, Orikasa (09)
L-R symmetric: Holthausen, Lindner, Schmidt (10)
$SU(2)_X$: Hambye Strumia (13) , ...
(3) SM + strongly couple sector Hur, P. Ko (11), Holthausen, Kubo, Kim, Kindner (13) ....

In the following, we focus on a specific model

Okada, Orikasa, SI (09)

"classically conformal (B-L)-extension of SM"

IR physics

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

No intermediate scales

UV physics

Planck scale
V(h)=0

(1) Free from naturalness problem (no intermediate scales)

B-L breaking at 10 TeV by CW mechanism → triggers EWSB at 100 GeV

Everything occurs radiatively.

(2) Minimal extension of SM & Phenomenologically viable

ν oscillation, (resonant) leptogenesis,

DM candidate (e.g. right-handed ν with Z_2)

IR physics

Standard Model +

B-L sector

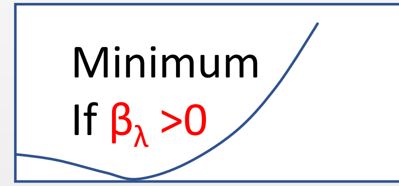
$U(1)_{B-L}$ gauge	Z'	necessary for $\beta_\phi > 0$
SM singlet scalar	ϕ	CW mechanism
Right-handed ν	ν_R^i i=1~3	necessary for anomaly cancellation

Scalar potential:

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

EWSB

(B-L) scalar



CW-mechanism

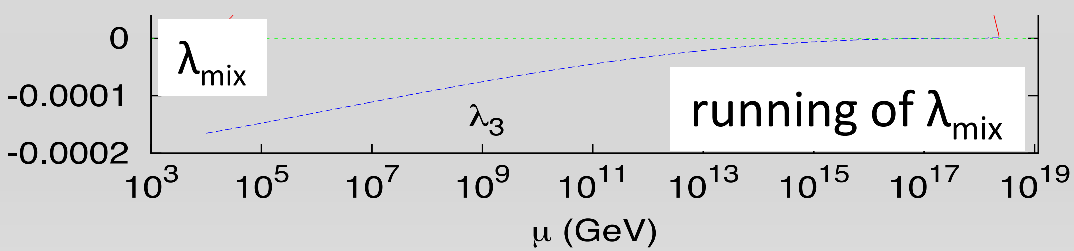
$$\langle H \rangle = \sqrt{\frac{-\lambda_{mix}}{\lambda_H}} M_{B-L}$$

$\lambda_{\rm mix} < 0$

Some properties of the potential

① Negative small value of the scalar mixing λ_{mix} can be radiatively induced from the flat potential $\lambda_{mix} = 0$ @ M_{Pl} .

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



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

Orikasa, SI ('12)

② The condition $\beta_\phi > 0$ for CW mechanism in B-L sector

D ~ 41

$$B \approx \frac{c_0^4}{8\pi^2}\left(3(2g)^4 - 2\mathrm{Tr}\left(\frac{Y}{\sqrt{2}}\right)^4 - D\,\lambda_{\mathrm{mix}}^2\right) \Rightarrow m_{Z'}^4 > \frac{2\mathrm{Tr}\,m_N^4}{3} + \frac{D\,m_h^4}{3}$$

B= 2λ c_0 ~1

$$m_{Z'} = 2gM \qquad m_{N_i} = Y_i M/\sqrt{2} \qquad m_h \approx \sqrt{|\lambda_{\mathrm{mix}}|}\,M$$

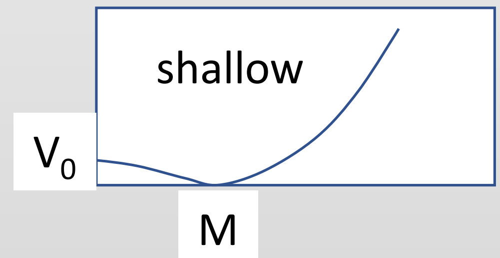
Right-handed neutrinos are lighter than $M_{Z'}$, typically TeV or lighter.

③ B-L scalar (pNG boson) is very light.

$$m_\phi < 470\ \mathbf{GeV} \qquad m_\phi = \sqrt{B}M$$

④ Vacuum energy at the origin is given by Z' mass

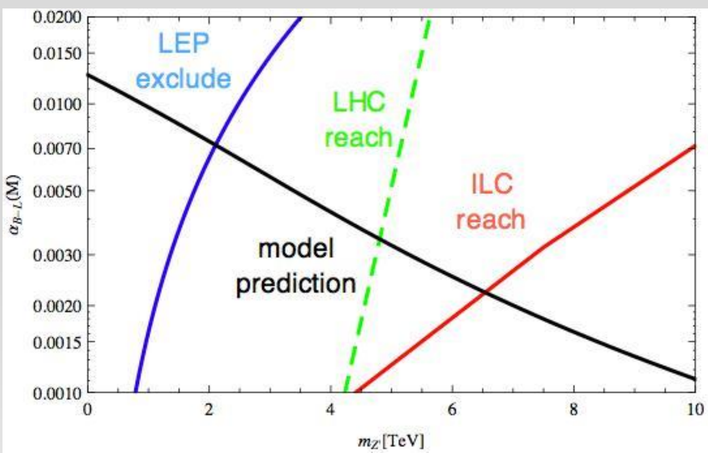
V_0 = B M^4 /16 < $(3/128\,\pi^2)\, m_{Z'}^{\ 4}$ << M^4



V_0 becomes smaller if m_ϕ becomes lighter.

⑤ $M_{Z'}$ is typically 5-10 TeV.

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



$$m_{Z'} = 2gM$$

"Classically conformal B-L extension of SM"
is a minimal & phenomenologically viable model

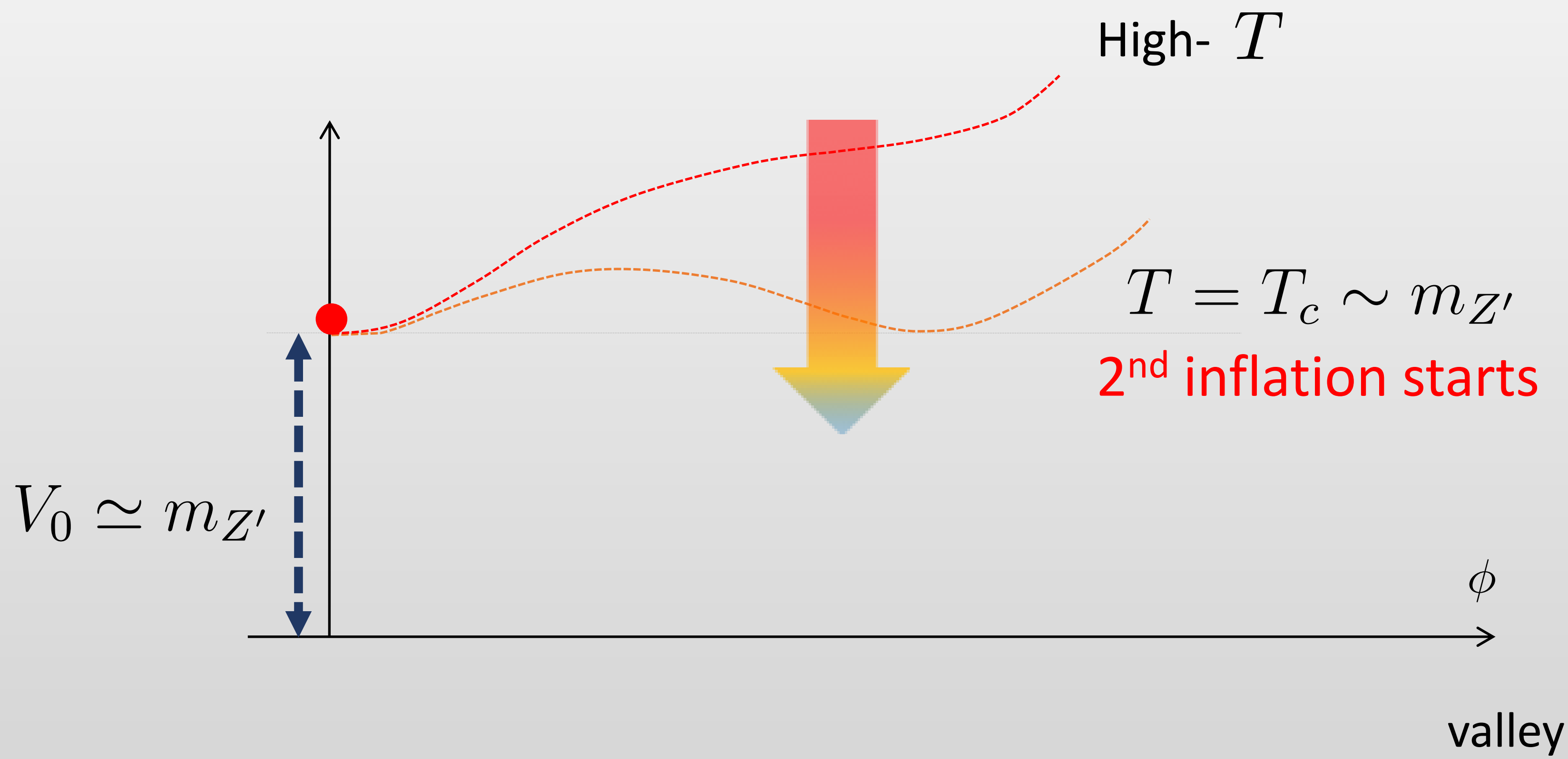
In order to verify (or falsify) the model
Look for Z' : 5-10 TeV but $\alpha_{B\text{-}L}$ is relatively small
ϕ : difficult to find, too light and weakly coupled
ν_R : TeV scale (resonant) leptogenesis
But it is difficult to distinguish this kind of models from others.

Is there any clearer evidence for the classical conformality?

Yes
Super-cooling of the B-L and EW symmetry breaking
in the early universe

Witten (80)
Serpico, Shimada, SI (17)
see also, Konstandin, Servant (11)

After primordial inflation, universe is preheated up to high T>> T_C .



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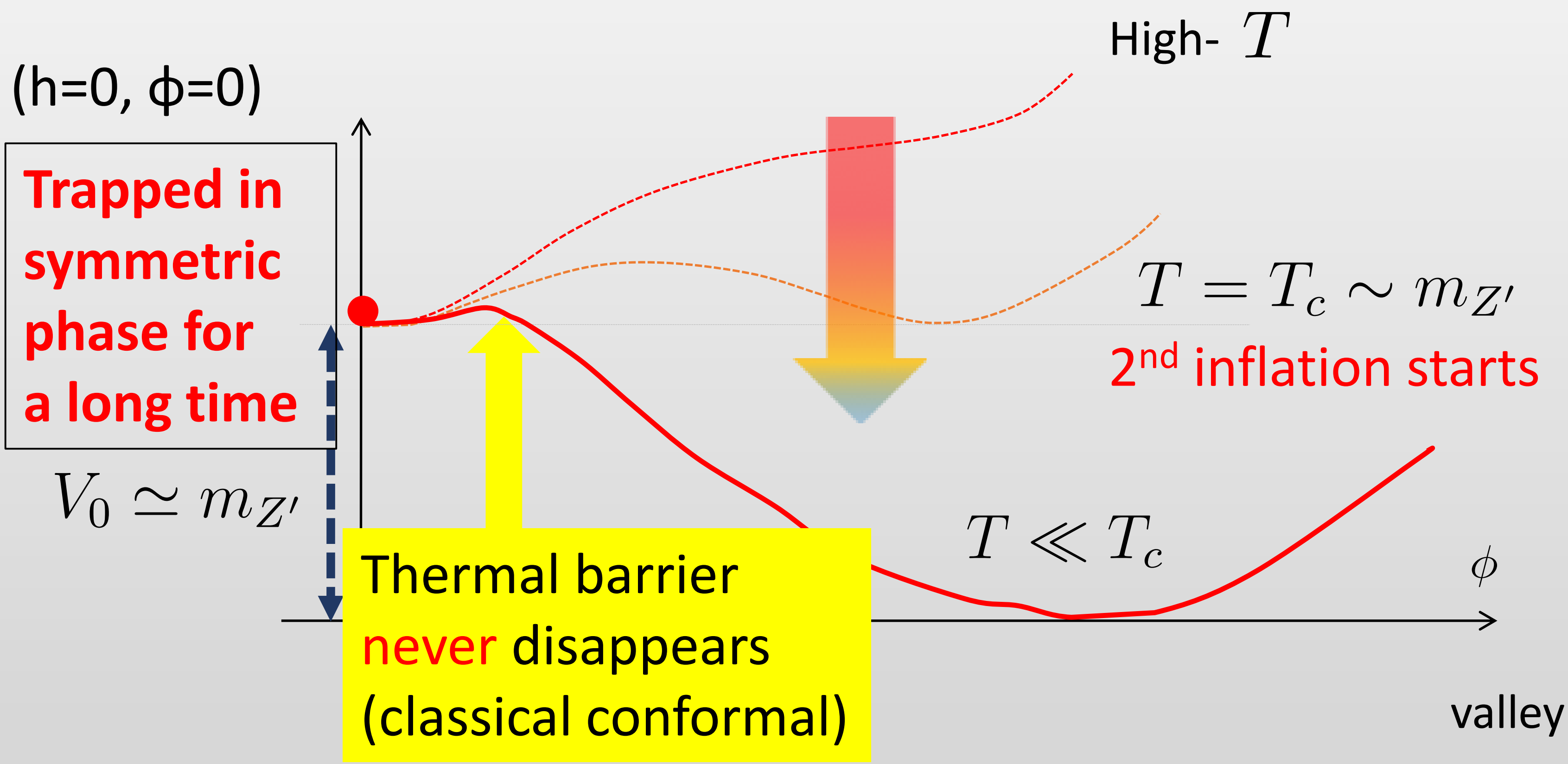
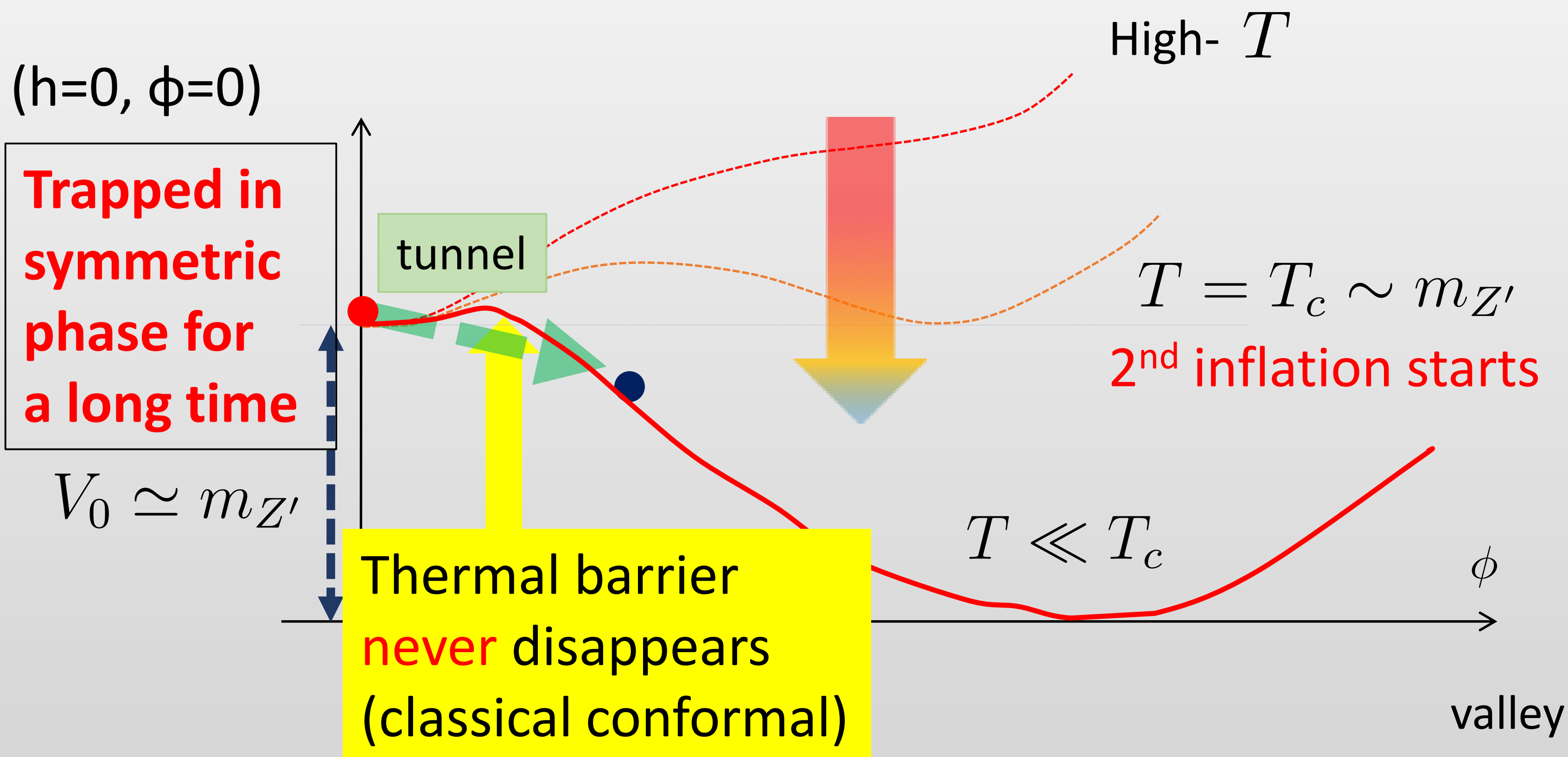


Supercooling of (B-L)+EW → PT much below T_C

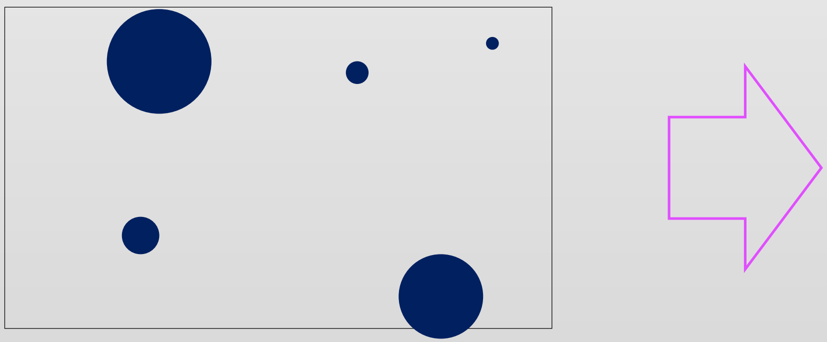


Bubble of true vacuum is created by tunneling.

Percolation of true vacuum

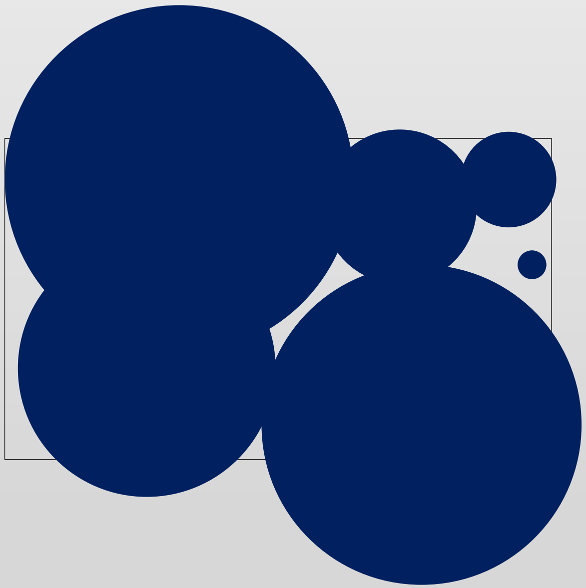
Guth Weinberg (82)

Bubbles of true vacuum are created by tunneling



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

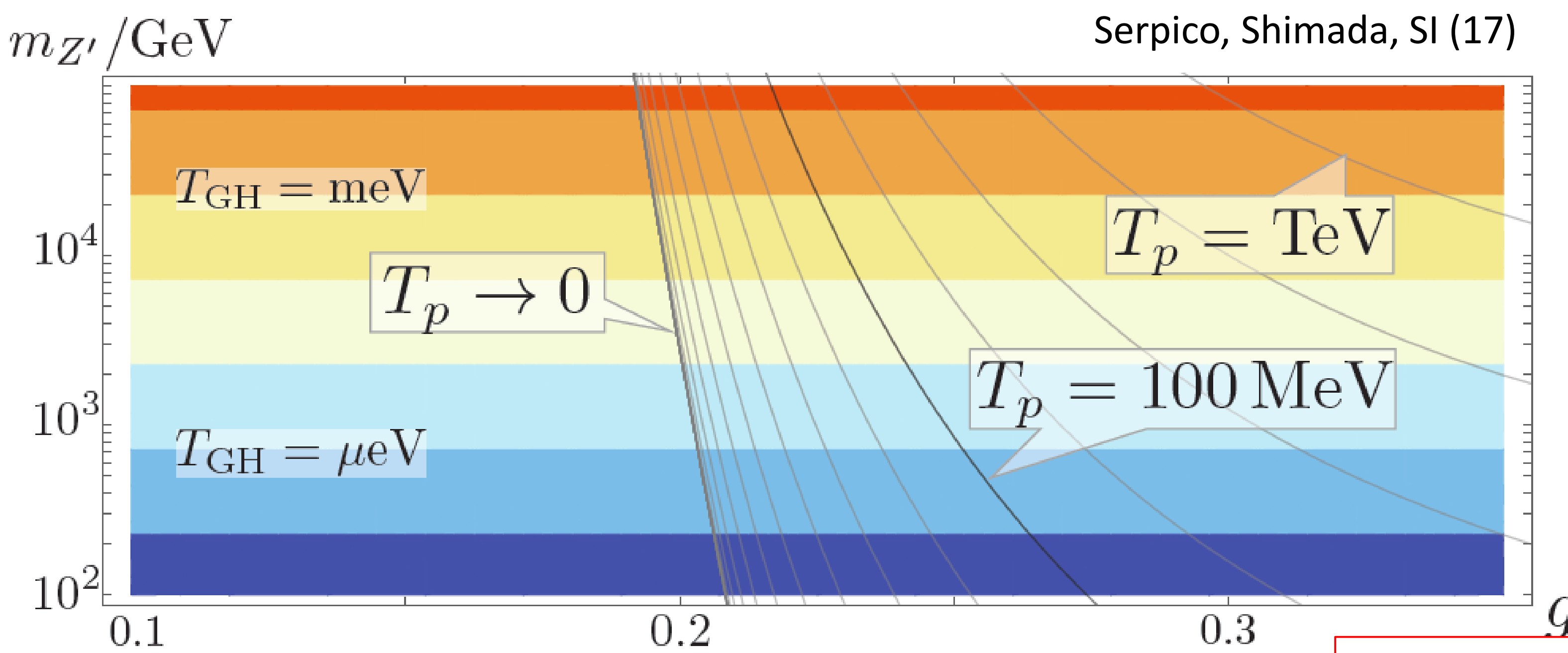
T_p : percolation temperature



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.

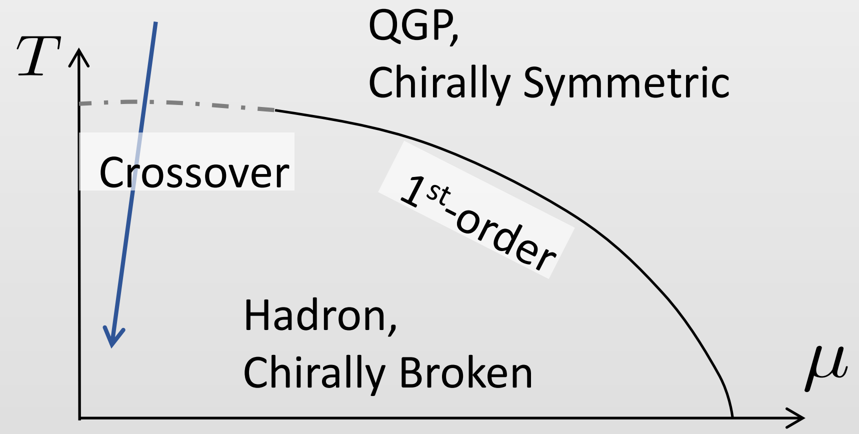
Note that de Sitter fluctuation $\sim T_{\mathrm{GH}} = \mathcal{H}/2\pi$ is negligible at 100 MeV.

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

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)

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

Electroweak symmetry is broken (EWSB)

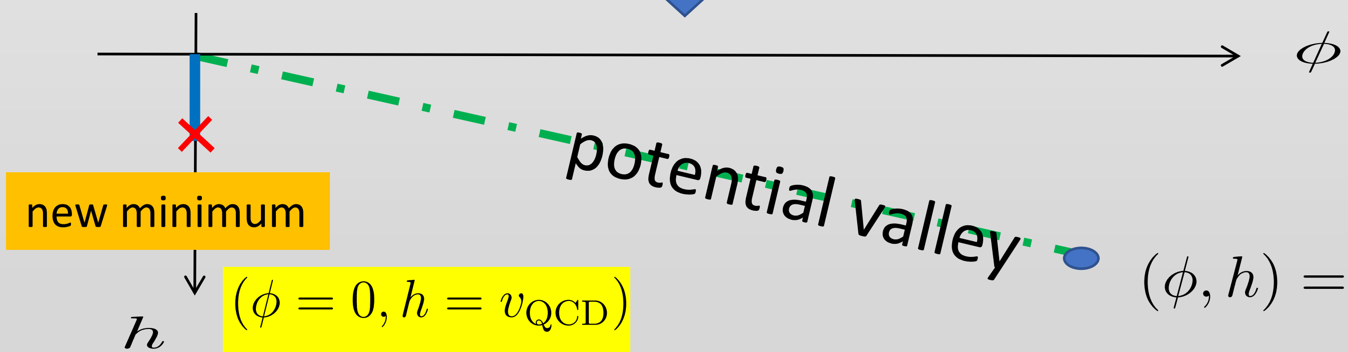
Quigg Shrock (09)

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

Higgs linear term is generated via Yukawa interaction

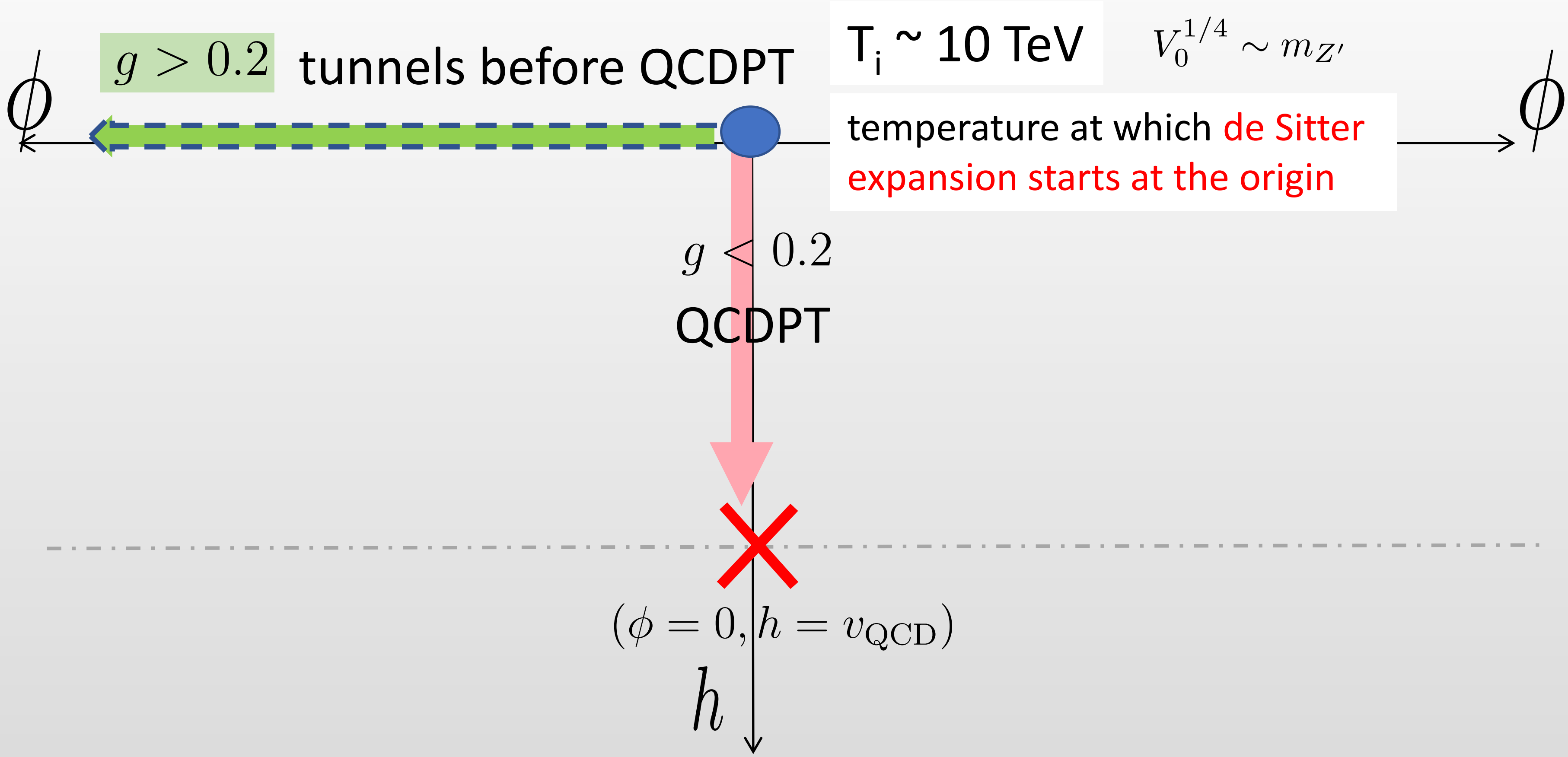
$$y_i h \langle \bar{q}_i q_i \rangle \sim (y_i \Lambda^3_{\rm QCD}) h$$

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



$$(\phi, h) = (M, 246\mathrm{GeV})$$

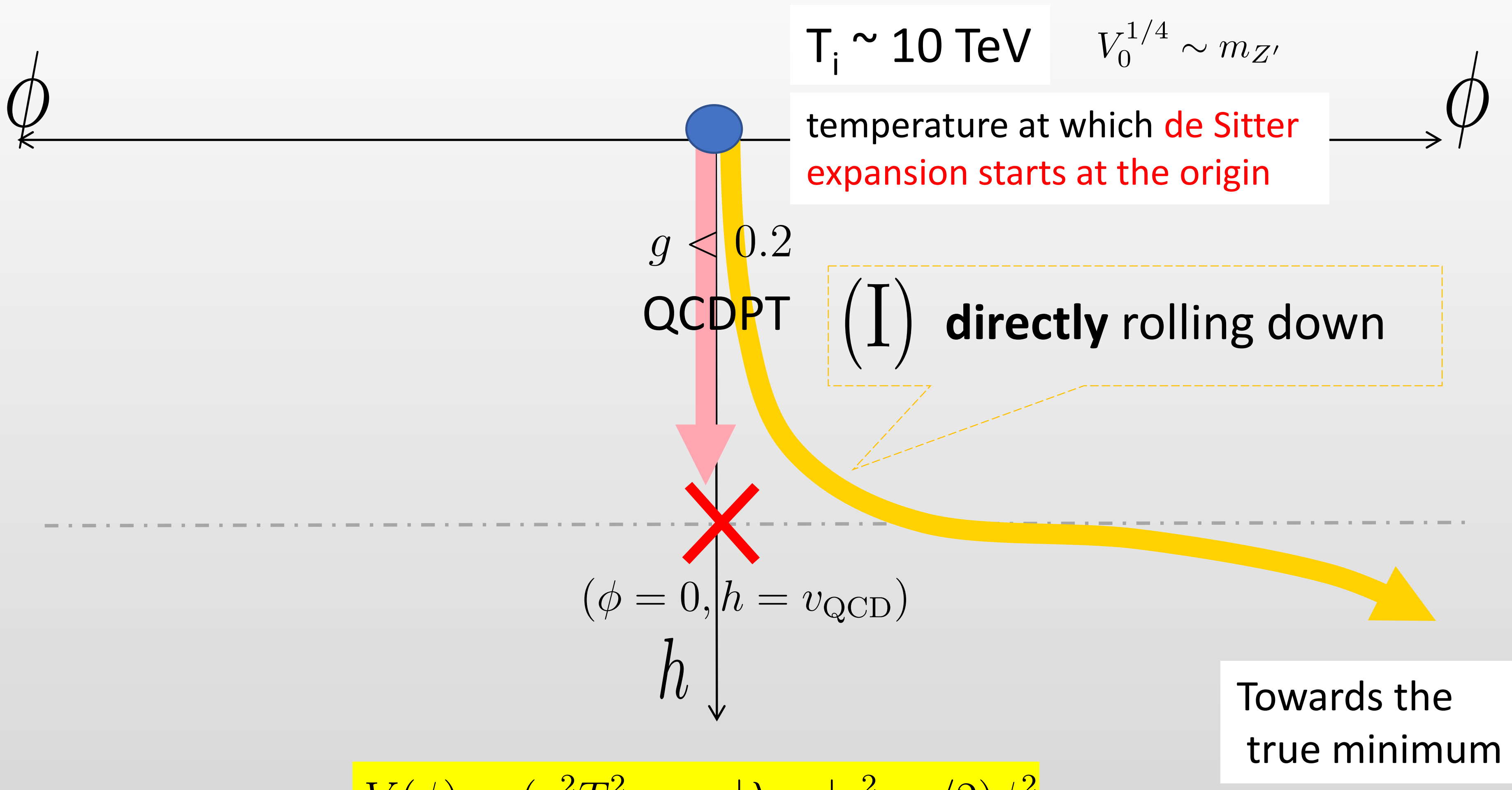
$$v_{\rm QCD} = \left(\frac{y_t \langle \bar{t} t \rangle}{\sqrt{2} \lambda_h} \right)^{1/3} \sim \Lambda_{\rm QCD}$$



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

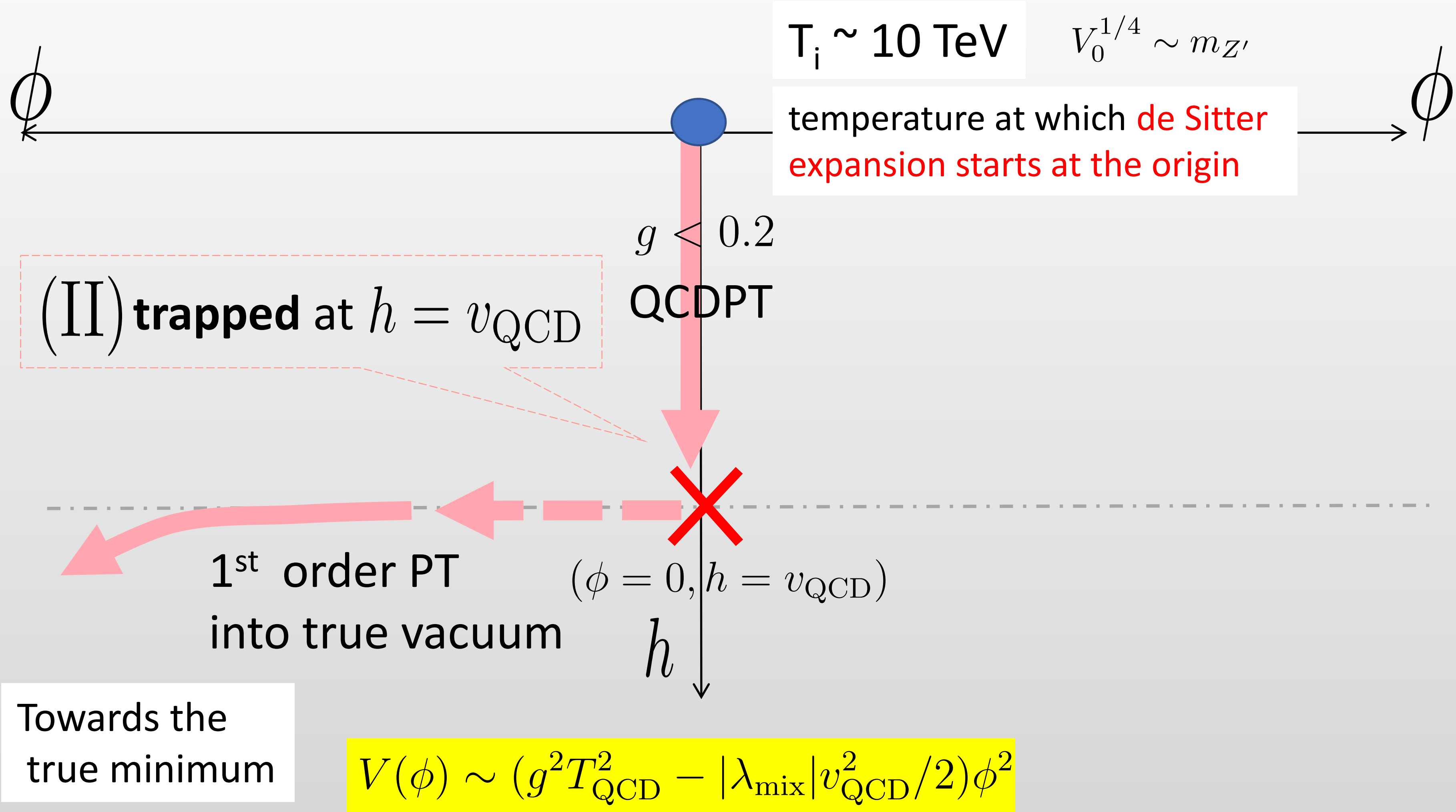
Interplay of [QCD χSB, confinement, B-L, EW]:

similar to the 2-step EWSB
by M.J. Ramsey-Musolf



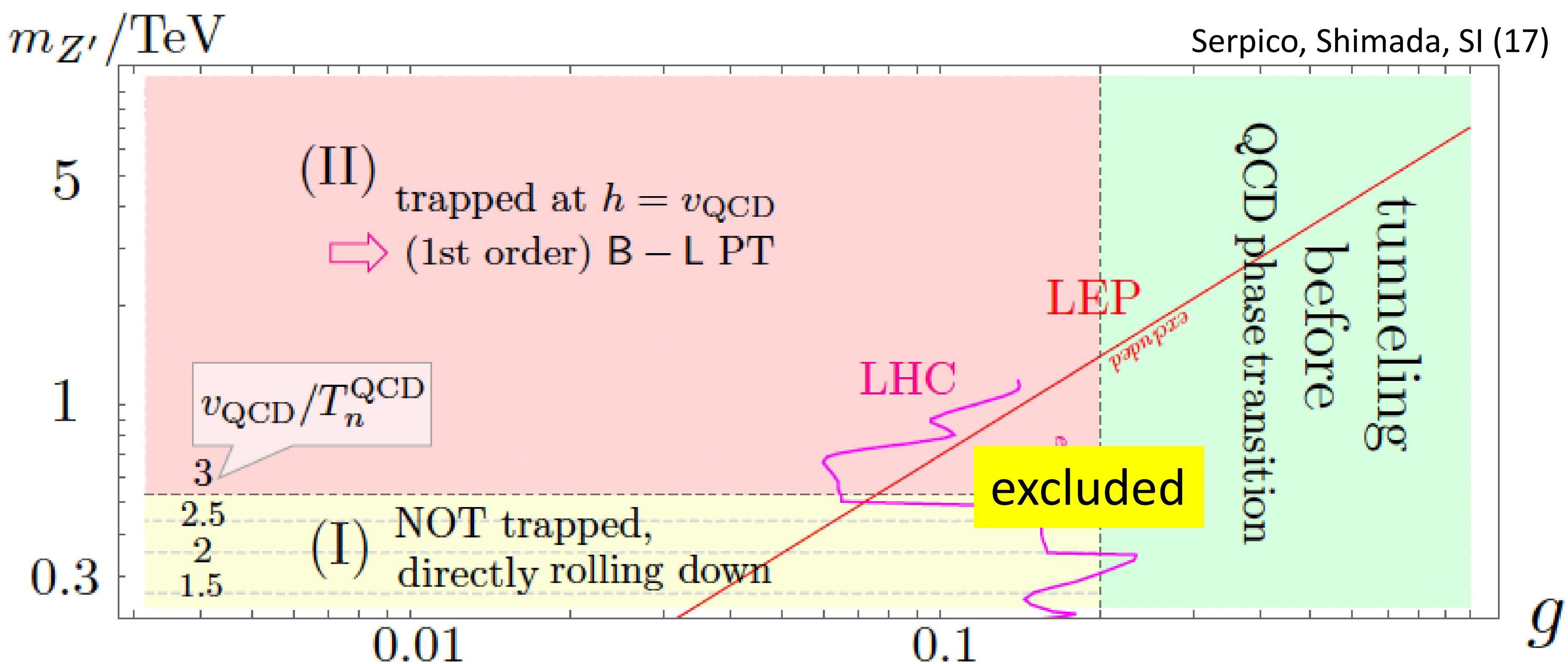
$$V(\phi) \sim (g^2 T_{\rm QCD}^2 - |\lambda_{\rm mix}| v_{\rm QCD}^2/2)\phi^2$$

Interplay of [QCD χSB, confinement, B-L, EW]:



Interplay of [QCD χSB, confinement, B-L, EW]:

Classification of histories of the early universe



Super-cooling generates the second inflation with N ~10

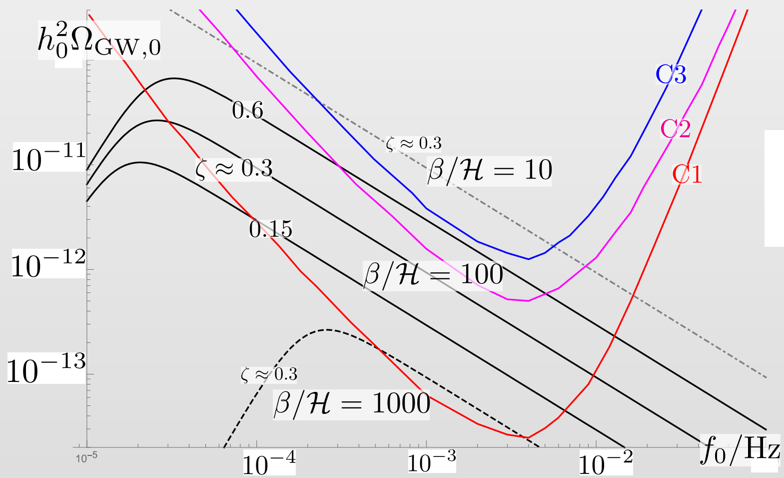
$$N = \ln \frac{T_i}{T_N^{\mathrm{QCD}}} \sim \ln \frac{m_{Z'}}{T_N^{\mathrm{QCD}}}$$

N ~ 10 in region (I)(II) for $m_{Z'}$ =10 TeV
N < 10 for g>0.2

Cosmological consequences

In scenario (I) [QCD + (B-L) + EW] strong 1st order phase transition expected

Bubble collsions → Sizable Stochastic Gravitational Waves from 1st order PT



eLISA sensitivities
from C.Caprini et al. (2016)

Serpico, Shimada, SI ('17)
Jinno, Takimoto ('17)
Hashino et.al. ('18) ......

Many other implications : talk by T. Konstandin

- dilution factor 10^6 dilutes relics from high energy (high temperature)
  WIMP DM, baryon asymmetry → supercool DM Hambye Strumia Teresi(18)
- low reheat temperature after 2nd mini-inflation ($T_R < 100$ GeV)
  Baryon asymmetry at low T: e.g. Cold EWBG Konstandin, Servant (11) ....
- Enhanced scalar fluctuations
- PBH by 1st order QCD PT or Ultra-compact mini halo Jedamzik (97), Ricotti et(09)

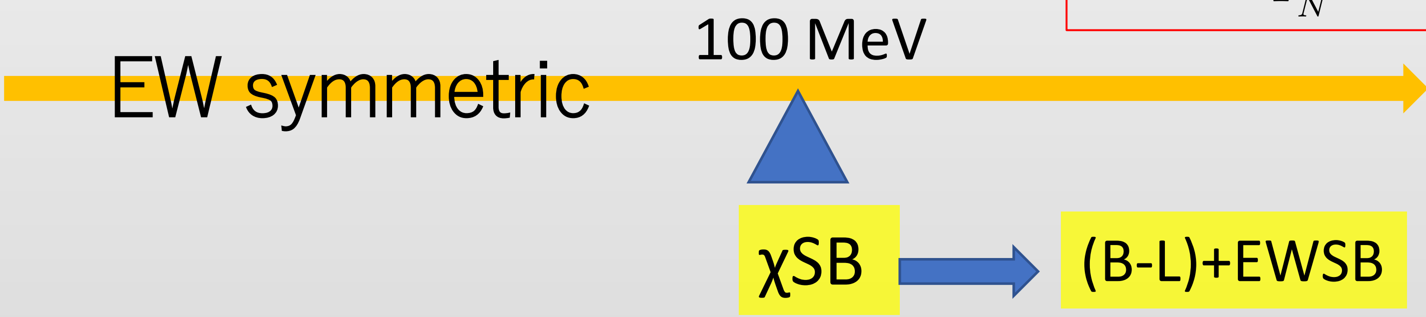
Summary of part 1

Serpico, Shimada, SI (17)

In classically conformal models motivated by naturalness,
the early universe is drastically different

extreme SUPERCOOLING and the second inflation with N~10

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



Interesting cosmological consequences

Stochastic GW, PBH, Cold EWBH, axion abundance , supercool DM

Supercooling is also expected in other models,
e.g. Randall-Sundrum models, Harling, Servant (18)

Part 2
Top-down approach
to the Higgs hierarchy problem

- Revolving D-branes –

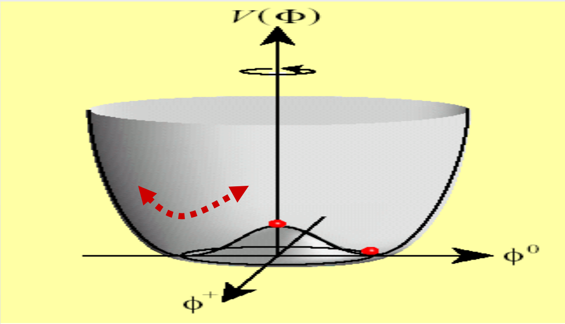
N. Kitazawa, SI *PTEP (15)*
H. Ohta, T. Suyama, SI *arXiv:1812.11505*
N. Kitazawa, SI *arXiv:1812.08912*

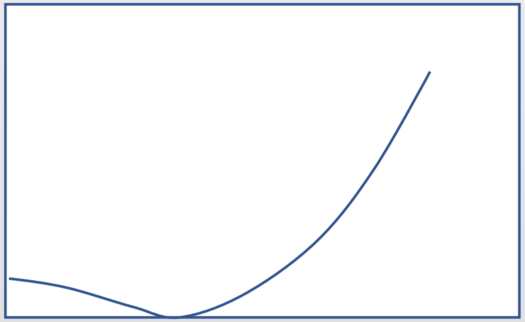
In a field theoretic approach,

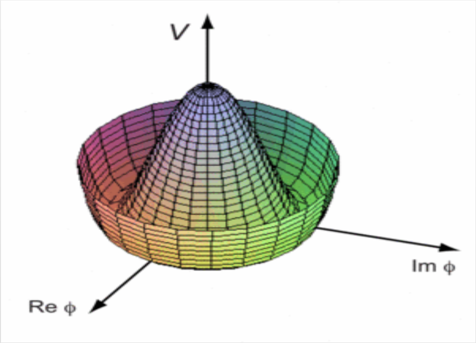
there are many different proposals to solve the hierarchy problem.

But there is one common basic assumption:

"Calculate the Higgs potential first !"



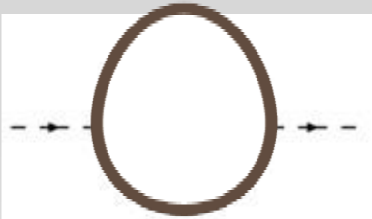




And then obtain a solution = minimum of the potential.

one solution to one Higgs potential

→ Then we are often faced with the naturalness problem

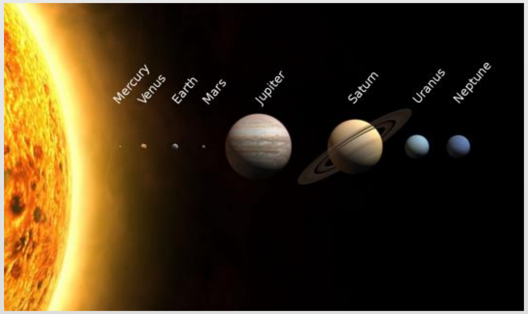


$$= \frac{3y_t^2}{8\pi^2}\Lambda^2$$

Question:

Can we first obtain a solution of <H> in a geometric way and then calculate low-energy EFT in the SM.

Analogy with



Any radius of orbits is a solution to the effective potential.
Initial condition (angular momentum) gives a different orbit.

Higgs potential itself may be a function of <H>.

The mechanism looks as if any value of <H> is a minimum of V(H; <H>).

Stringy view of our "universe" and "Higgs" sector:

Geometry in string theory = Dynamics in QFT

[1] (3+1)-dimensional space-time is embedded in d=9+1.

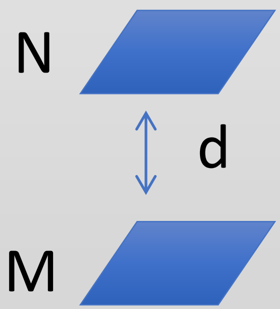
Either compactification or brane-world scenario

[2] Higgs (scalar) field is a geometrical "moduli" field

e.g. distance between D-branes

volume / shape of extra-dimension etc.

[3] VEVs of moduli fields are proportional to the geometrical size.



D-branes

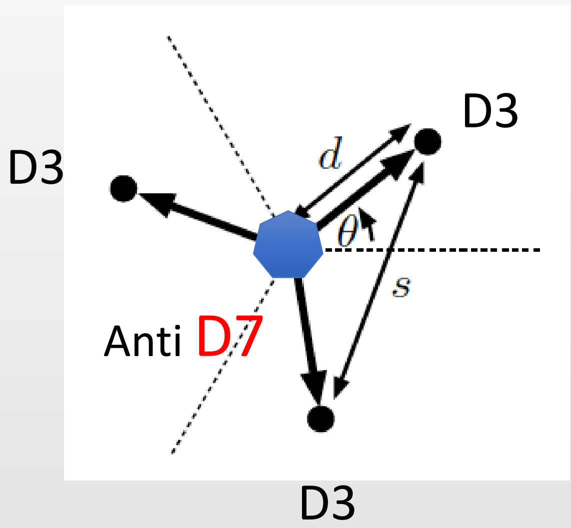
U(N+M) → U(N) × U(M)

$$d = \frac{M}{M_s^2}$$

The natural scale of M should be the string scale, not the EW scale.

Hierarchy problem in string theory

An example of D-brane configurations for SM



Attractive force between D3s and anti-D7
due to open string 1-loop amplitudes

$$\mu^2 \sum_a |Z_3^{(a)}|^2$$

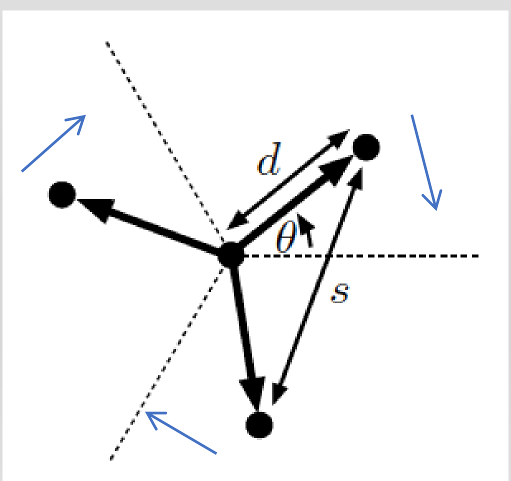
$$\mu^2 = \frac{1}{C^2}\frac{g^2}{16\pi^2}M_s^2$$

1-loop suppressed

Repulsive centrifugal force
by revolution of D3s

Solution:
Hierarchy of EW scale

$$M \ll M_s$$



N.Kitazawa SI
PTEP,2015

High angular frequency $\omega = \mu \sim \frac{g}{4\pi}M_s$

Low velocity $v = \omega d \sim \frac{v_0}{M_s} \ll 1$

It is possible to make a classically stable state with a short distance;

$$d \ll l_{string} \,.$$

Such short distance region is described by low energy modes of open strings (D-brane EFT) instead of closed strings (supergravity).

→ Hierarchy problem can be avoided by using the geometrical approach in string theory

But the large angular frequency causes two serious problems

$$\omega = \mu \sim \frac{g}{4\pi} M_s$$

- Lorentz symmetry is violated in the dispersion relation of Higgs field (Coriolis force) .
- closed string emission → unstable

To avoid large angular frequency, we need weaker attractive force

→ BPS configuration of D-branes

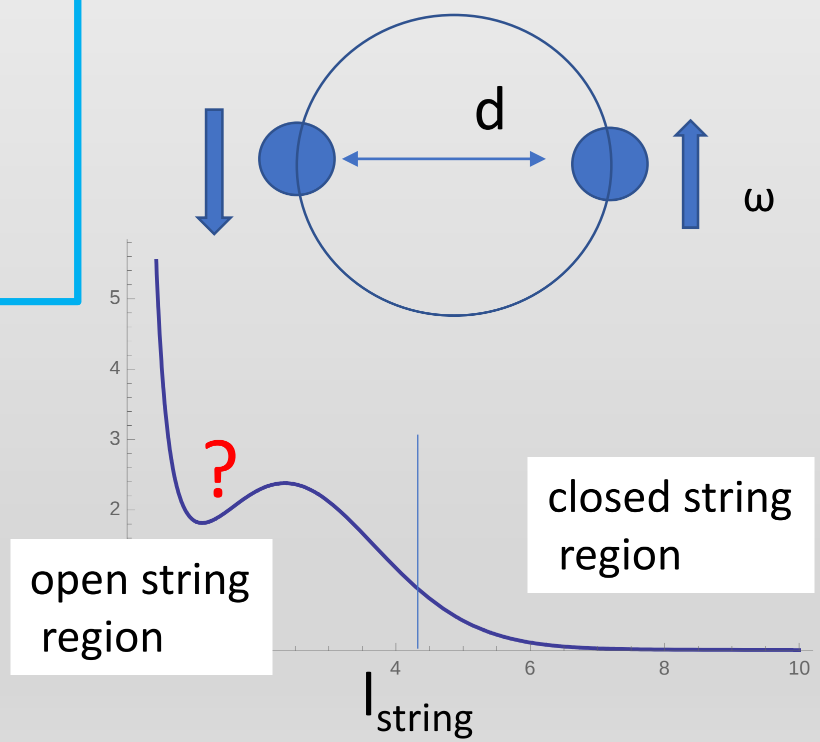
no-force (flat potential) at rest,

but attract each other when they are moving.

Is it possible to make
a "sufficiently stable resonant state"
of D-branes
with $d \ll l_{string}$ and $\omega \ll m_{string}$?

The first step is to calculate
potential between revolving branes.

H. Ohta, T. Suyama SI (18)



Next step: supersymmetry breaking.

Experimental test of the geometric scenario

Lorentz violation in the Higgs sector
(Coriolis force for Higgs field since it is geometrical.)

$$\omega^2 = M^2 + (1 + \frac{4\omega_0^2}{M^2})p^2 + 16\frac{\omega_0^4}{M^6}p^4 + \cdots$$

N. Kitazawa, SI ('18)

$\omega_0 < 0.1$ GeV

Message in Part 2 (top-down approach)

In string theory, Higgs has a geometrical meaning.
And if it is stabilized by stationary motion,
it will be tested (or falsified) by looking at
a tiny violation of Lorentz invariance in the Higgs sector.

Summary

QCD-induced EW PT

Higgs physics
@ LHC + ILC + ...

early universe

String theory
space-time physics

Lorentz violation in Higgs

naturalness
stability
Yukawa couplings

Dark matter
Baryogenesis
Inflation, PBH, ...

moduli = geometry
SUSY breaking
Dark energy

- From the bottom-up
  classically conformal = no dimensionful paraemter in Lagrangian
  → CW mechanism → <H> given radiatively
  intriguing phenomenology & cosmology (supercooling)

- From the top-down
  Flat moduli = no dimensionful paraemter in Lagrangian
  → revolution of D3 breaks SUSY → <H> given geometrically
  Lorentz violation in Higgs sector

Hierarchy problem

- from bottom-up and/or top-down -

・ In both approaches,
No dimensionful parameters in Lagrangian
but its dimensionful value <H> is govey by
"dimensional transmutation".

First determine Higgs vev <H>, then calculate the Higgs potential.

I hope to connect bottom-up and top-down in near future.

Higgs is a probe for new physics = HPNP