

電弱階層性問題が示唆する過冷却宇宙 とその現象論的帰結

磯 曜 (KEK & Sokendai)

Based on the following papers

Serpico, Shimada SI (2017, PRL):

QCD-Electroweak First-Order Phase Transition in a Supercooled Universe

N Kitazawa, SI (2018, MPL): A Possibility of Lorentz Violation in the Higgs Sector

Ohta, Suyama, SI (2018, JHEP) : Effective Potential for Revolving D-branes

N Kitazawa, Ohta, Suyama, SI (2018, JHEP):

Dynamics of Revolving D-Branes at Short Distances

N Kitazawa, Ohta, Suyama, SI (2020, JHEP) :

More on Effective Potentials for Revolving D-Branes

Kawana, Shimada, SI (2020): QCD Axions and CMB Anisotropy

ヒッグス物理の根幹 Hierarchy problem

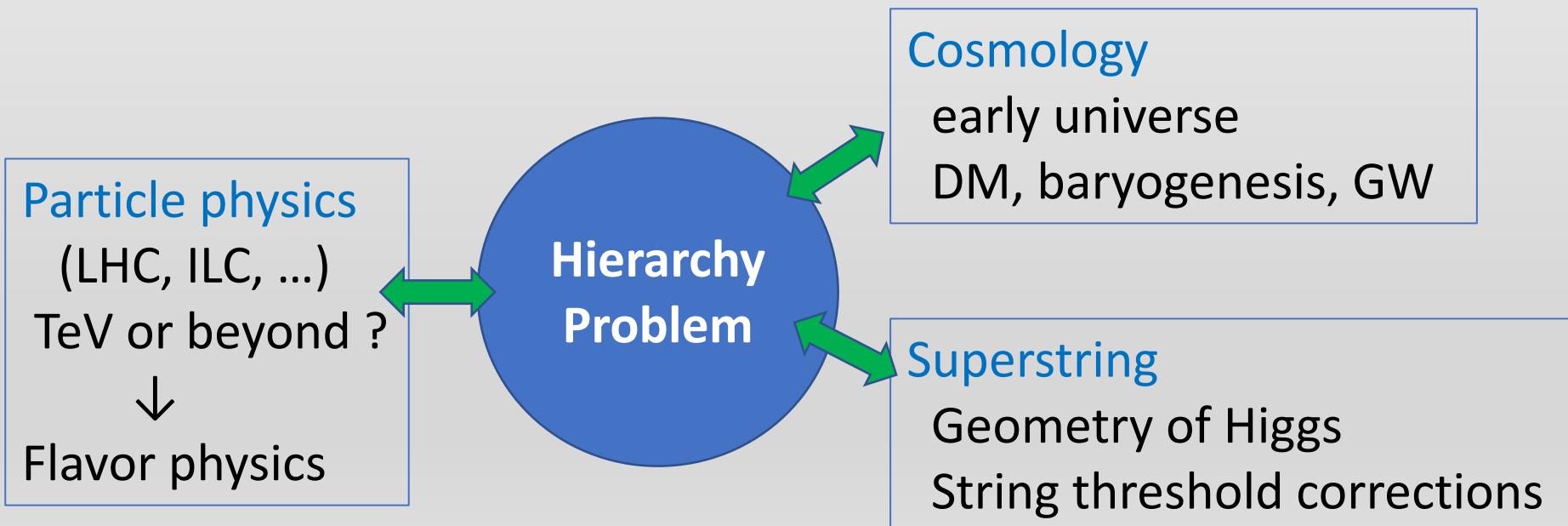
= Dynamics of EWSB and its Stability

How EWSB occurs dynamically ?

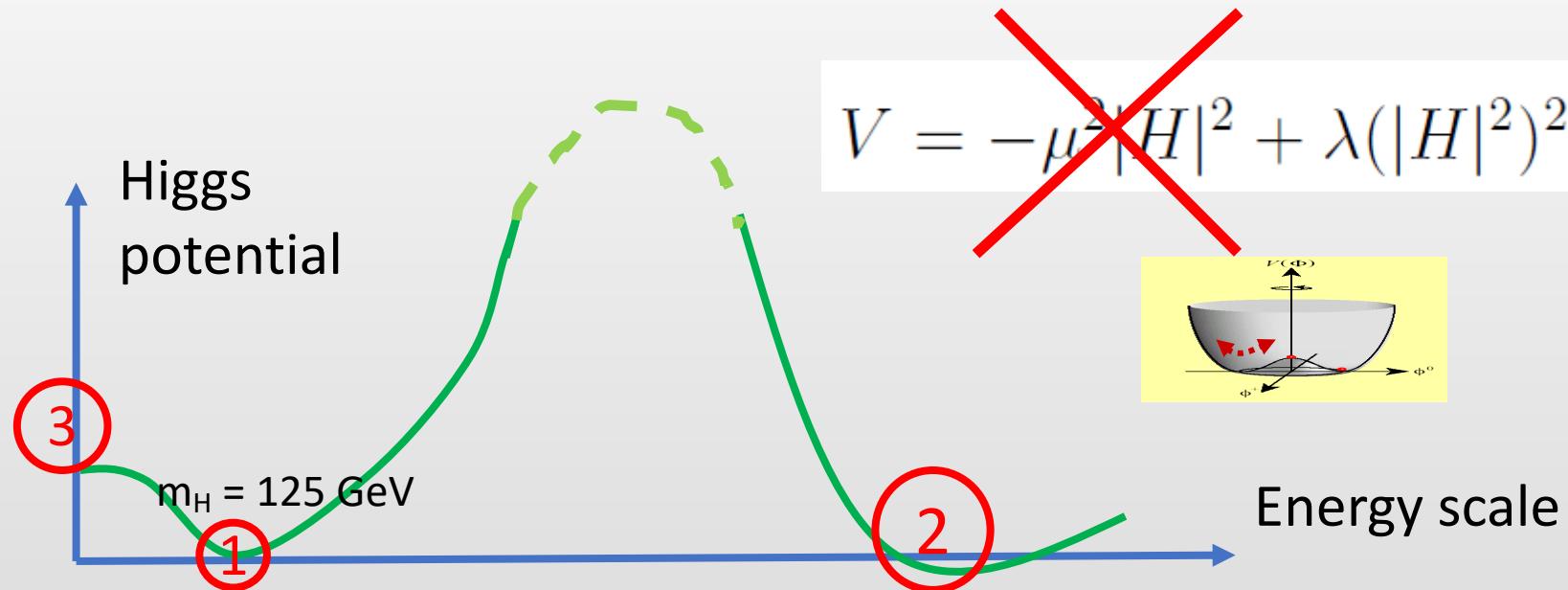
Who ordered the Higgs potential ?

Why Higgs VEV $\langle H \rangle = 256 \text{ GeV}$, Higgs mass $m_H = 125 \text{ GeV}$?

Why are they **stable against (possible) high energy scales?**



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



- 1 Higgs VEV $v = 246 \text{ GeV} \rightarrow \text{Particle physics 現在の宇宙}$
- 2 UV scale $\text{真空の安定性 or プランクスケールの物理} \rightarrow \text{Quantum Gravity, String}$
- 3 $h=0$ (origin) $\rightarrow \text{Cosmology (初期宇宙) 過冷却の可能性}$

All regions (1, 2, 3) are related by RG and theoretical biases.

階層性問題を“理解”する一つの方法：輻射補正によるEWSB
Coleman Weinberg 機構

An additional sector to the SM is inevitably needed.

Within SM, CW mechanism predicted Higgs mass lighter than 10 GeV.

A phenomenologically viable minimal extension will be
(B-L)-extension of SM

Okada, Orikasa, SI (09)
also Lindner et.al. (10)

IR physics B-L sector @ TeV

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

No intermediate scales

UV physics

Planck scale
 $V(h)=0$

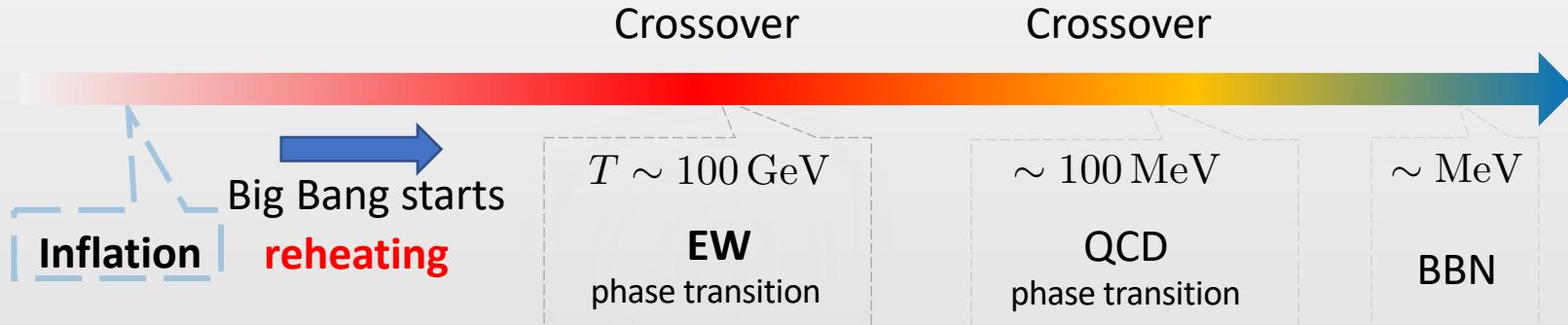
特徴 (1) B-L breaking by CW mechanism → triggers EWSB at 100 GeV
Everything occurs radiatively.

(2) Minimal extension of SM & Phenomenologically viable → collider物理

問題 (1) $|H|^2$ を禁止する正当性 → 弦理論？ (回転するブレーン模型？)
(2) 他の模型との違い → 初期宇宙の振る舞いが大きく異なる

通常の初期宇宙シナリオ

Standard thermal history of the universe

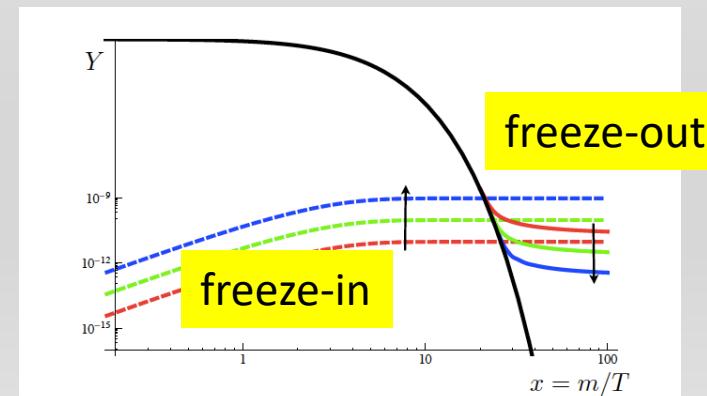


現在の宇宙（素粒子物理）の性質は、初期宇宙シナリオで決まる

例：暗黒物質残存量計算

freeze-out: DM (thermalized) \rightarrow decoupled at T_{FO}
WIMP miracle = abundance is determined
by annihilation cross-section @ pb = TeV scale
 ρ/s is indep of its mass.

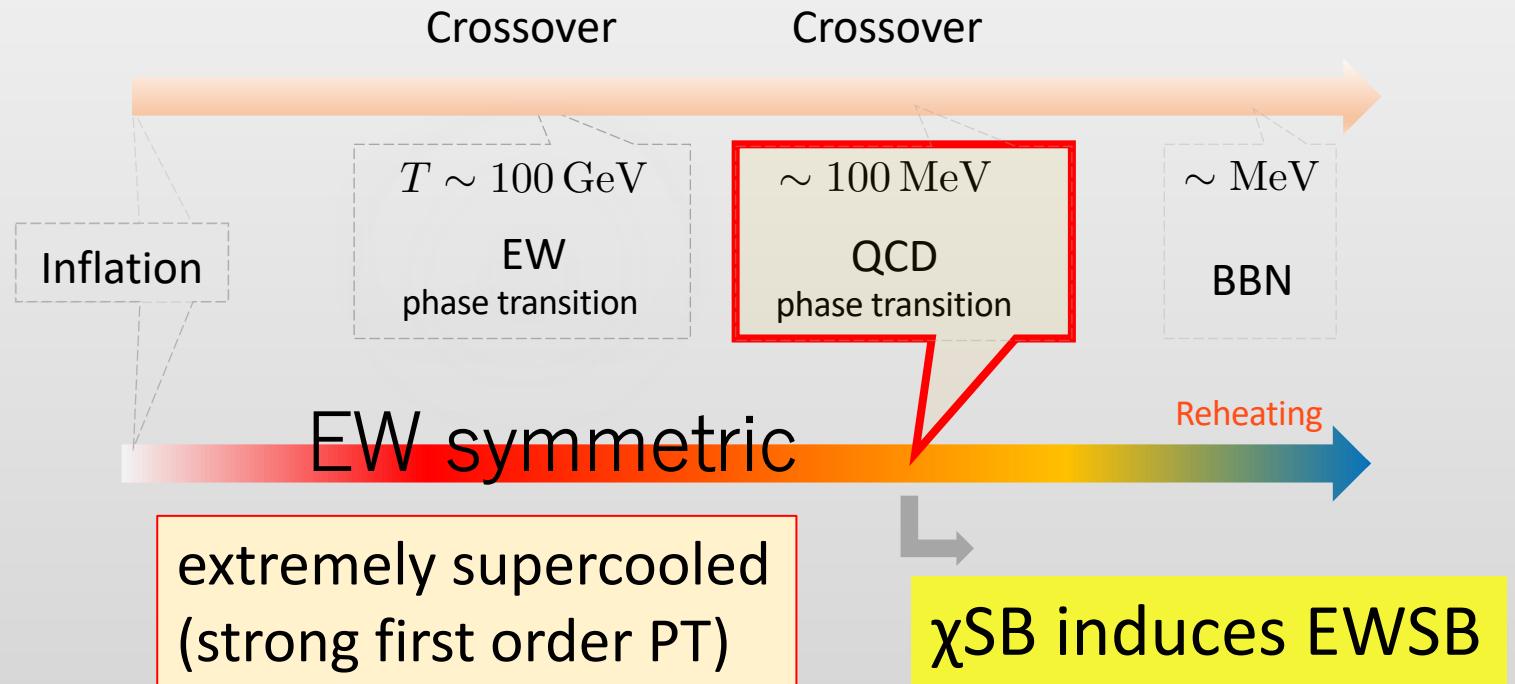
freeze-in: DM = 0 \rightarrow gradually generated at low T
FIMP (very weak interaction)



EWSBが輻射補正で起こった場合の初期宇宙シナリオは全く異なる

Serpico, Shimada, SI (17)

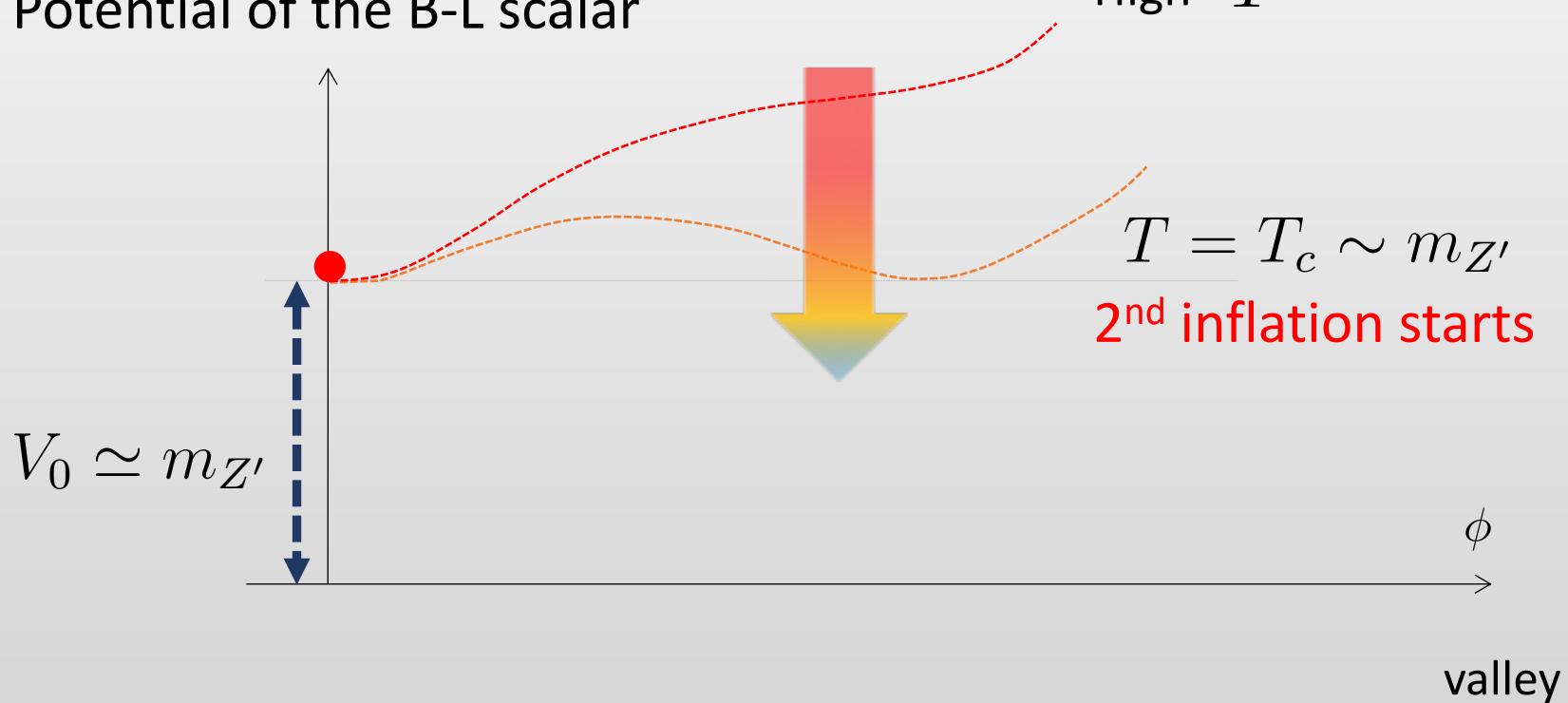
電弱対称性破れが過冷却を起こし、QCD温度まで破れない

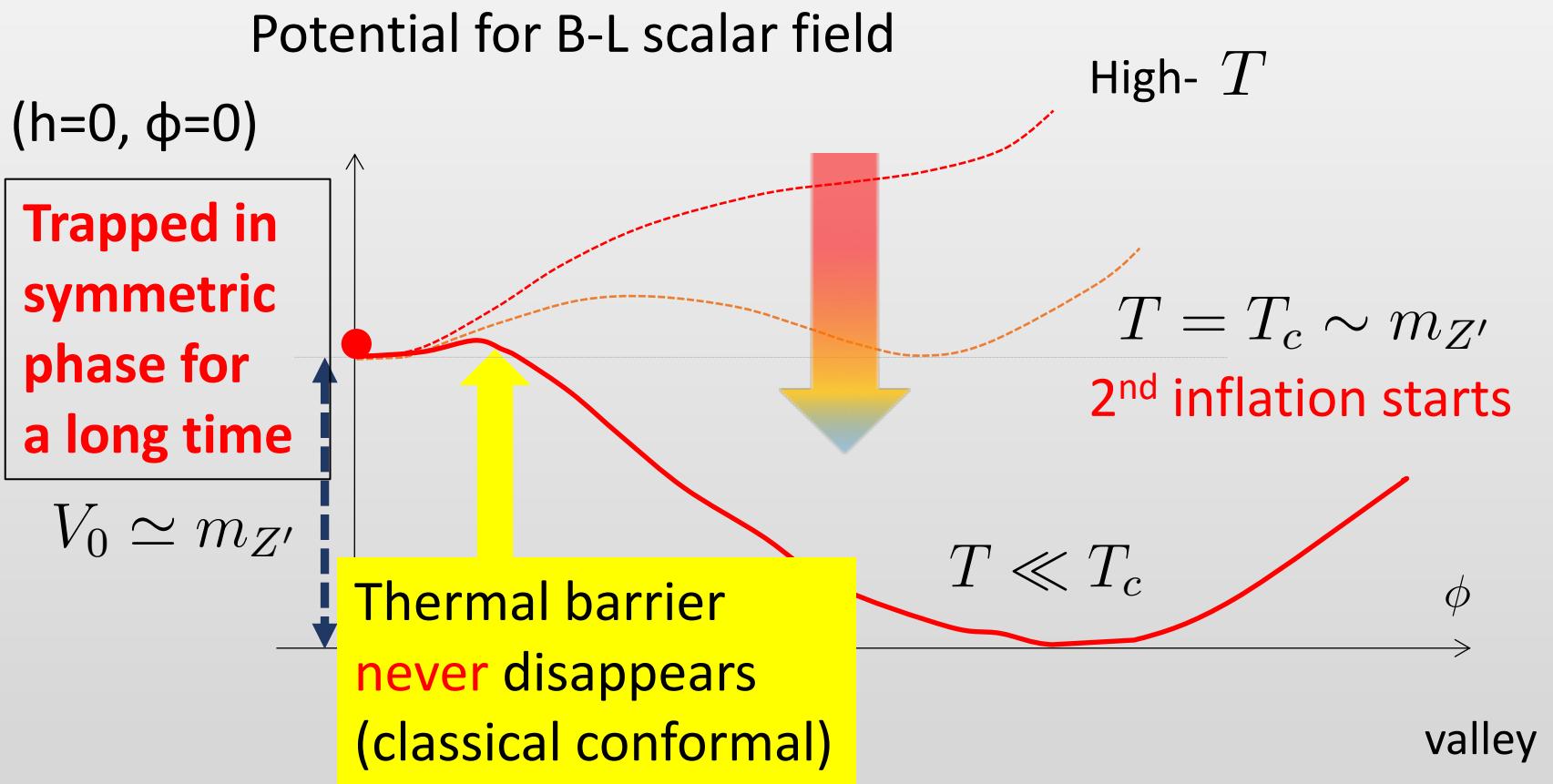


→ cosmological consequences: GW, DM, CMB, PBH ...

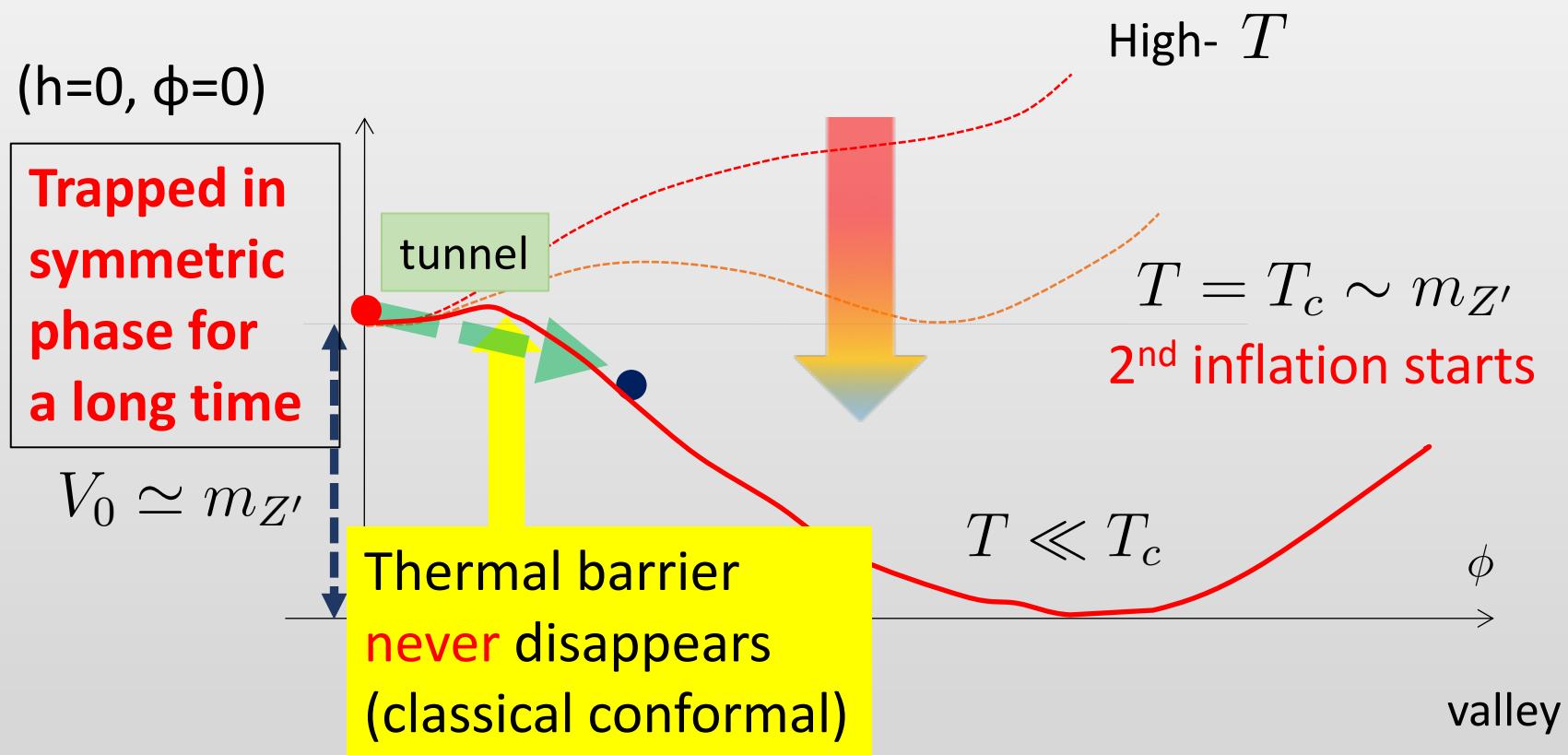
After primordial inflation, hot universe starts at $T \gg T_c$.

Potential of the B-L scalar





Supercooling of (B-L)+EW \rightarrow PT much below T_c

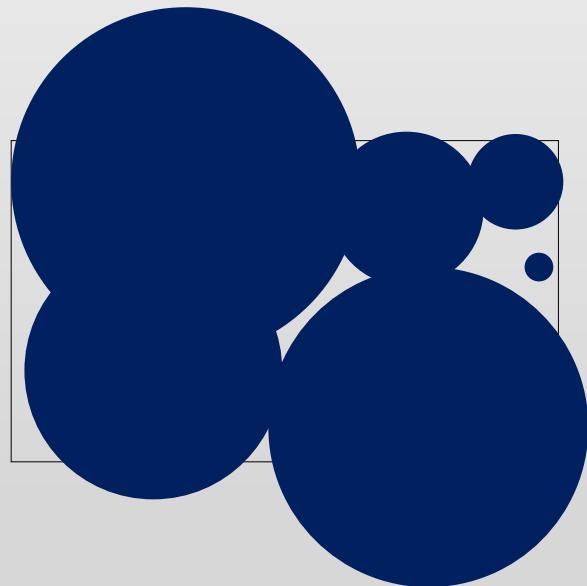
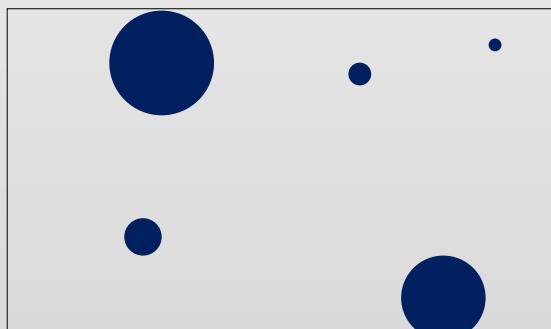


Percolation of true vacuum

Guth Weinberg (82)

Bubbles of true vacuum
are created by tunneling

T_p : percolation temperature

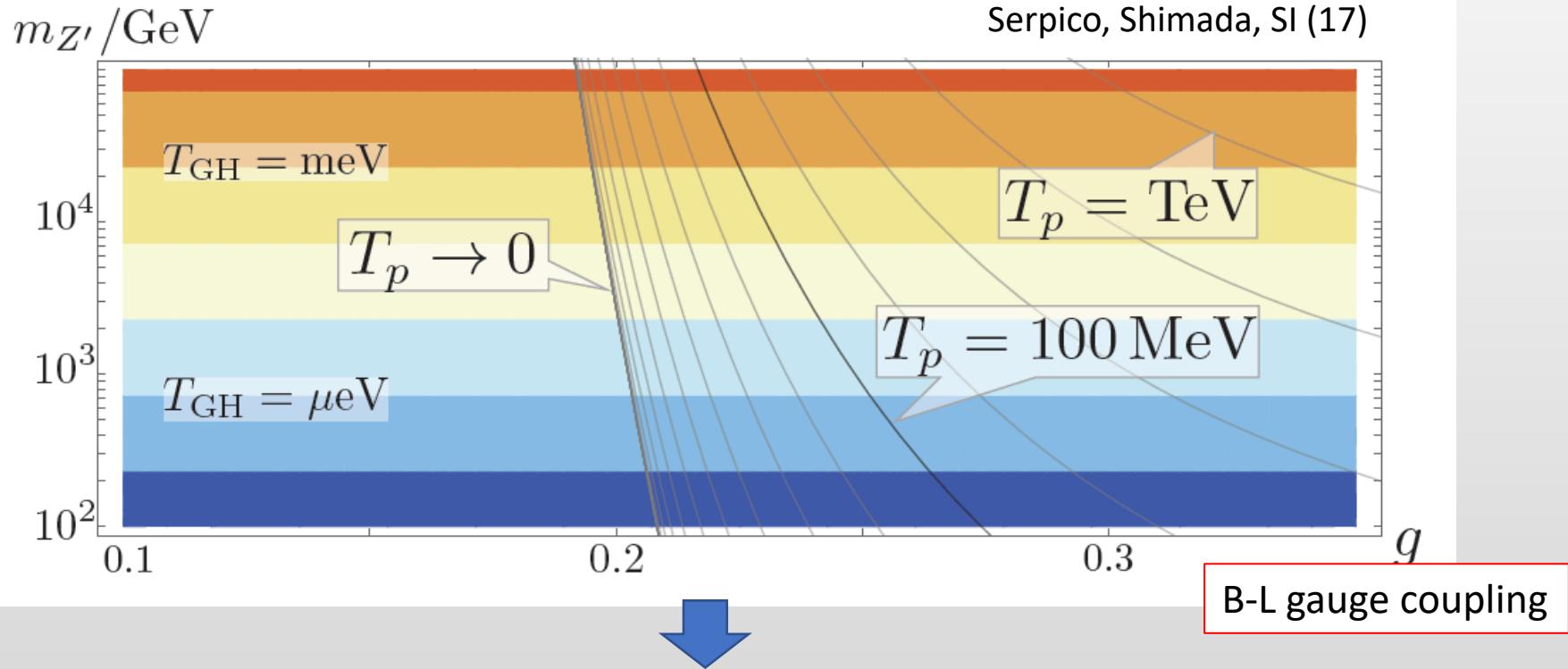


$$\Gamma \approx T^4 e^{-S_3/T}$$

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.



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

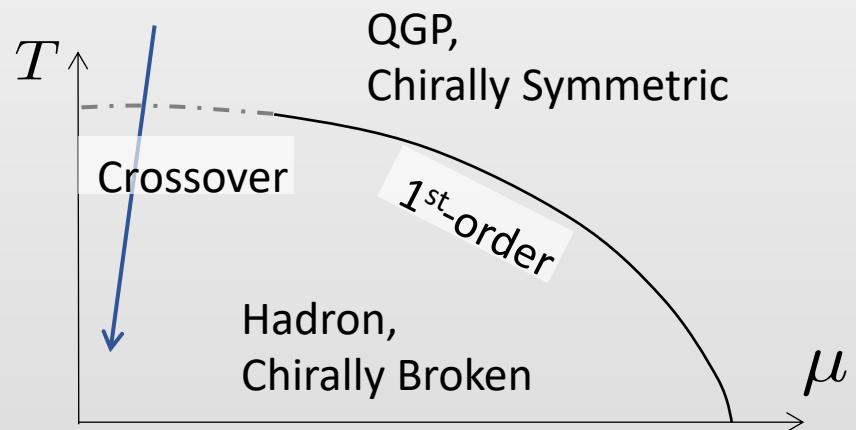
Note that de Sitter fluctuation $\sim T_{\text{GH}} = \mathcal{H}/2\pi$ is negligible at 100 MeV.

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

But when temperature decreases to 100 MeV at ($\phi=0$, $h=0$)

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

In the ordinary scenario,
 χ SB with $N_f = (2+1)$
is crossover



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

Pisarski Wilczek (1983)

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

Electroweak symmetry is broken (**EWSB**)

Quigg Shrock (09)

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

Higgs linear term is generated via Yukawa interaction

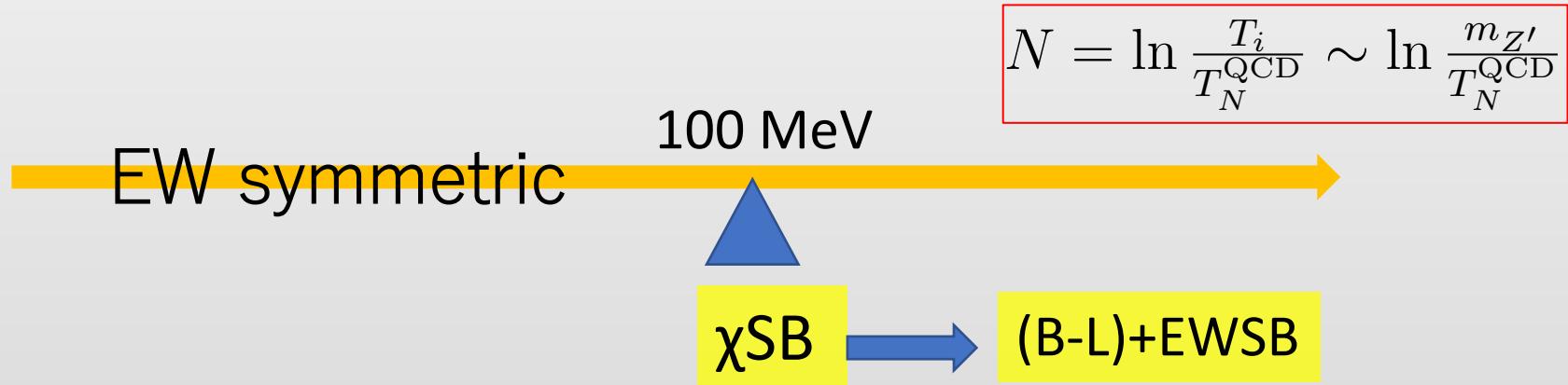
$$y_i h \langle \bar{q}_i q_i \rangle \sim (y_i \Lambda_{\text{QCD}}^3) h$$

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



QCD χ SB triggers B-L and EWSB

- (1) 電弱対称性破れの過冷却
- (2) Thermal inflation: e-folding $N = 10$



Interesting cosmological consequences

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

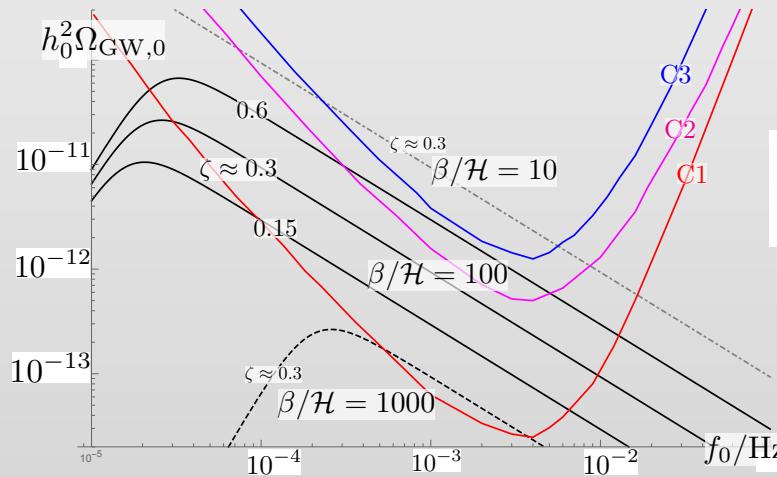
Supercooling is also expected in other models,
e.g. Randall-Sundrum models, Harling, Servant (18)

宇宙論的帰結

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

(1) 重力波

Bubble collisions → Sizable Stochastic **Gravitational Waves** from 1st order PT



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

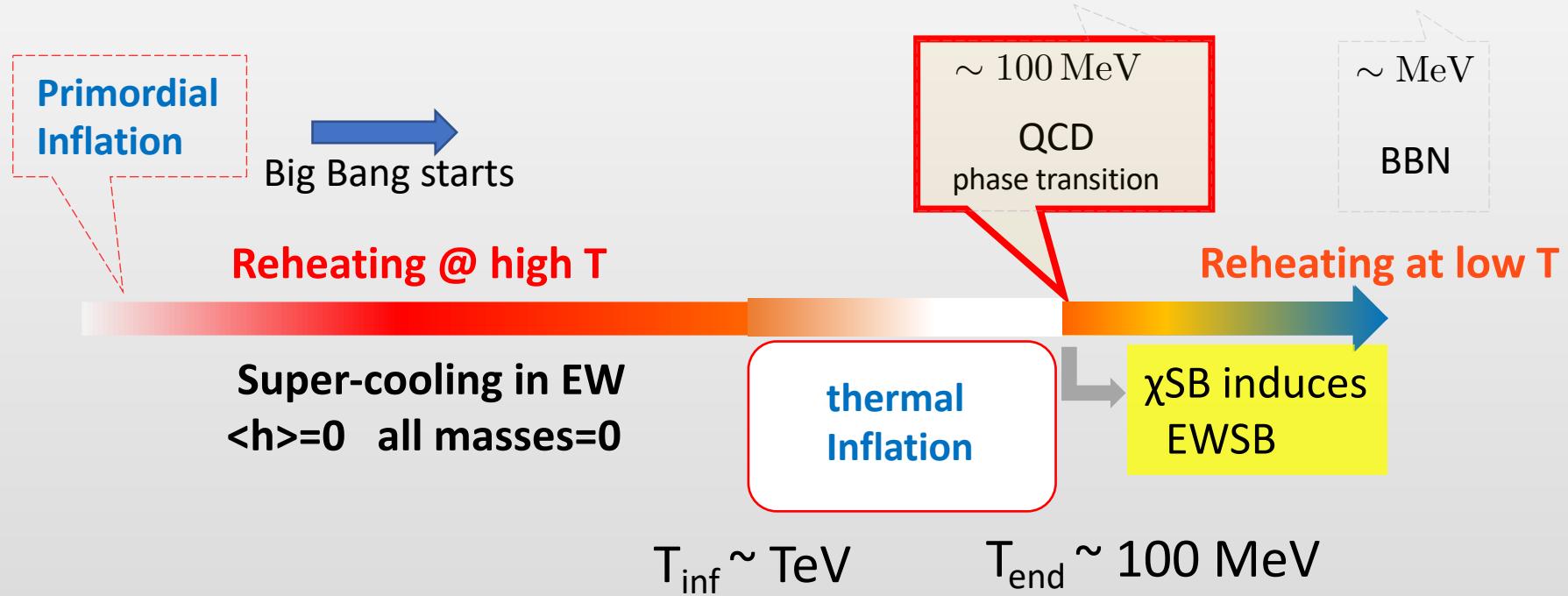
Serpico, Shimada, SI ('17)
Jinno, Takimoto ('17)
Hashino et.al. ('18)
→ cf 兼村さん

より正確に予言をするためには、EW相転移とQCD相転移の競合の考慮が必要
under investigation ...

(2) 暗黒物質 Supercool DM

Hambye Strumia Teresi(18)

thermal inflation w/ **dilution** factor 10^6 dilutes relics at high temperature



DM produced → dilute → "super-cool DM"
 (an appropriate number of e-folding)
 in addition frozen-in DM
 "sub-thermal" DM

$$Y_{\text{DM}} \approx Y_{\text{DM}}|_{\text{super-cool}} + Y_{\text{DM}}|_{\text{sub-thermal}}.$$

CMB温度揺らぎ (Planck 2018)

$$A_s := \mathcal{P}_{\mathcal{R}\mathcal{R}}(k_*) = 2.1 \times 10^{-9}$$

原始 inflation中の inflaton量子揺らぎ

$$\mathcal{P}_{\mathcal{R}\mathcal{R}}(k) = \frac{V}{24\pi^2 m_{pl}^2 \epsilon} \Big|_{k=a\bar{H}}$$

もし Inflaton 揺らぎの寄与が観測値より小さいならば、

→ curvaton シナリオ (inflaton以外の場の揺らぎが揺らぎを作る)

curvatonは最終的にSMの輻射に崩壊して、それが密度揺らぎ

→ QCD - axion場がCMB揺らぎを作る可能性？

curvatonとの違い：崩壊でなく、axion potential生成時に曲率揺らぎに転化

通常、SMでは不可能だが、

QCDスケールでのthermal inflationがあると可能

Kawana Shimada SI 20

クリアすべき 3 つの問題

(a) 十分な大きさの揺らぎを生成できるか？

(b) 等曲率揺らぎの観測からの制限

(c) 非ガウス性の観測からの制限

結果に関する3つのパラメータ

(1) 揺らぎの大きさ $\langle (\delta A_{\text{ini}}/\bar{A}_{\text{ini}})^2 \rangle \sim \bar{H}_{\text{exit}}^2/(f_A \bar{\theta}_{\text{ini}})^2$ 2.1×10^{-9}

(2) axionポテンシャル生成時 @ T_{QCD} でのaxion量 $R = \Omega_A/\Omega_r$

(3) 現在の axion 量 $r_A = \Omega_A/\Omega_{\text{CDM}}|_{\text{today}}$

(c) 非ガウス性からの制限 $\rightarrow R$ が十分に大きい $R \gtrsim 0.01$

(b) 等曲率揺らぎからの制限
 $\rightarrow r$ が十分に小さい \rightarrow QCDスケールでのinflationが必要 $r_A < 8.2 \times 10^{-3} R$

過冷却宇宙の場合、QCD axion場の揺らぎがCMB揺らぎを説明する可能性がある

(但し、B-L模型の場合、条件(a)が厳しい \rightarrow 模型修正必要)

Conclusion

QCD-induced EW PT

Higgs physics
@ LHC + ILC + ...

naturalness
stability
Yukawa couplings

early universe

Dark matter
Baryogenesis
Inflation, PBH, ...

String theory
space-time physics

moduli = geometry
SUSY breaking
Dark energy

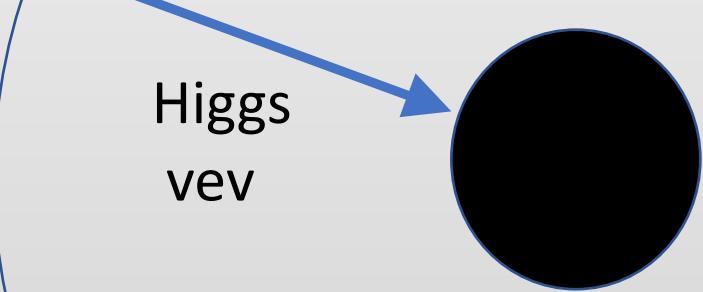
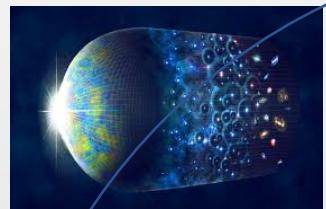
Hierarchy problem is a key idea to go beyond SM
in particle physics, cosmology, string theory

問題(2) 初期宇宙シナリオの違いで他の模型との識別

- ・過冷却宇宙 → GW, supercool DM, CMB揺らぎ
- ・inverse symmetry breaking の可能性
(高温で対称性が回復しない) : scalar混合が大きい時

問題(1) $|H| \ll m_{pl}$ を実現する弦理論模型? → 公転するブレーン宇宙

N Kitazawa, Ohta, Suyama, SI (18,20)



- if 宇宙がDp-brane
静止→力は働かない
引力 ~ 加速度
→ 束縛状態できるか?
弦理論で計算

N Kitazawa, SI (18)

- ローレンツ不変性の
破れは Higgs セクター
に出現 (コリオリ力)

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

$$\omega_0 < 0.1 \text{ GeV}$$

Super-cool Dark Matter

Thomas Hambye^a, Alessandro Strumia^{b,c,d}, Daniele Teresi^a

desired value of DM

$$Y_{\text{DM}} = \frac{n_{\text{DM}}}{s} = \frac{0.40 \text{ eV}}{M_{\text{DM}}} \frac{\Omega_{\text{DM}} h^2}{0.110} \\ = 0.4 \times 10^{-12} \frac{1 \text{ TeV}}{M_{\text{DM}}} \frac{\Omega_{\text{DM}} h^2}{0.11}$$

Super-cool DM

$$Y_{\text{DM}}|_{\text{super-cool}} = Y_{\text{DM}}^{\text{eq}} \frac{T_{\text{RH}}}{T_{\text{infl}}} \left(\frac{T_{\text{end}}}{T_{\text{infl}}} \right)^3, \quad Y_{\text{DM}}^{\text{eq}} = \frac{45 g_{\text{DM}}}{2\pi^4 g_*} \sim 10^{-2}$$

For instantaneous reheating after the second inflation $T_{\text{RH}} = T_{\text{infl}}$

Sub-thermal DM : For larger DM cross section, this component becomes dominant

$$Y_{\text{DM}}|_{\text{sub-thermal}} = \lambda \int_{z_{\text{RH}}}^{\infty} \frac{dz}{z^2} Y_{\text{eq}}^2 = \lambda \frac{2025 g_{\text{DM}}^2}{128 \pi^7 g_{\text{SM}}^2} e^{-2z_{\text{RH}}} (1 + 2z_{\text{RH}})$$

$$\lambda = M_{\text{Pl}} M \langle \sigma_{\text{ann}} v_{\text{rel}} \rangle \sqrt{\pi g_{\text{SM}} / 45}$$