Higgs inflation and cosmological electroweak phase transition with N scalars in the post-Higgs era

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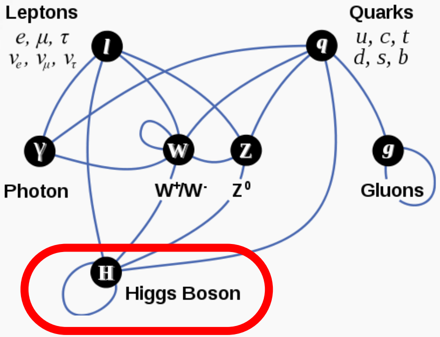
2018.06 Shanghai Jiao Tong University

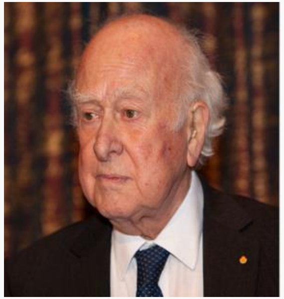
Based on latest work with Ligong-Bian
arXiv:1805.00199

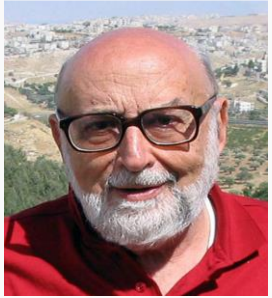
Outline ❯

1.Motivation

The standard model of particle physics (SM)







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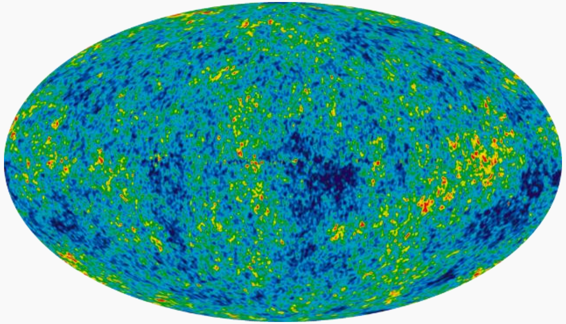
Problems

A. Horizon and flatness

B. Existence of dark matter

C. Baryon asymmetry



CMB

Solving

a) Cosmic inflation

In order to solve the problems of horizon and flatness in the cosmology of thermal big bang, Guth made it clear in the early 1980s that **the universe under went a period of near exponential acceleration before the big bang.** universe's violent expansion is also called inflation. It was the violent expansion of the universe during the period of The process of the inflation that wiped out the inhomogeneity and anisotropy of the early universe.

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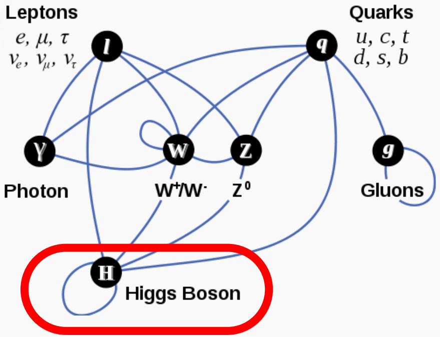

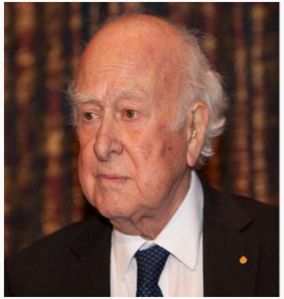

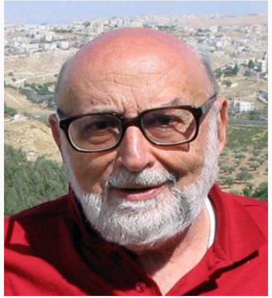

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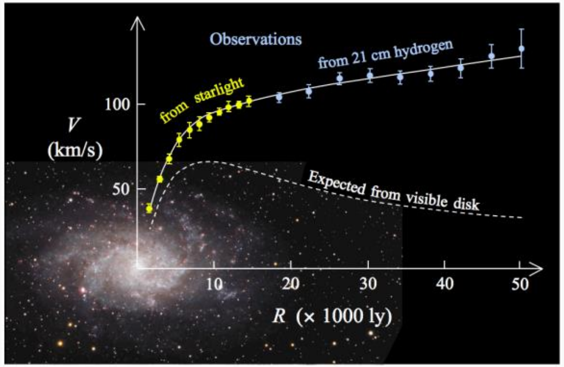
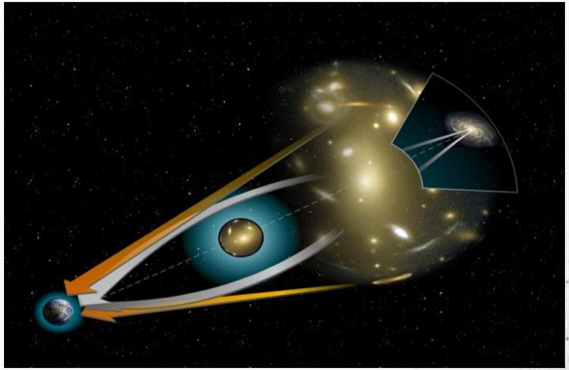


Rotation curve of a disc galaxy

Solving

b) Extend SM



Gravitational lens

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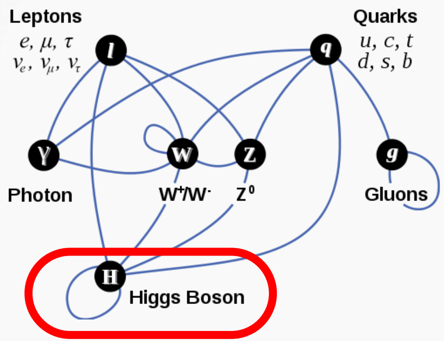

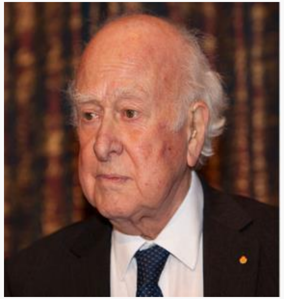

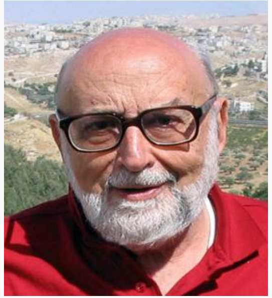

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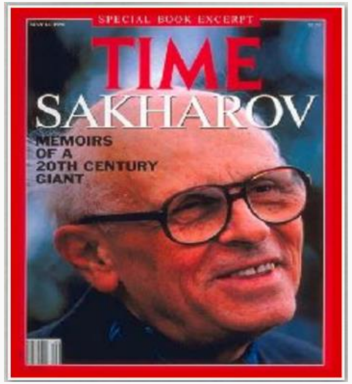

The Sakharov conditions :

★ Baryon number violation

★ C&CP violation

★ Departure from thermal equilibrium

Solving

c) strong first order electroweak phase transitions (SFOEWPT)

The mechanism of Electroweak brayogenesis (EWBG) can solve the puzzle of the BAU with a SFOEWPT occurs at the electroweak scale, followed by the electroweak symmetry breaking.

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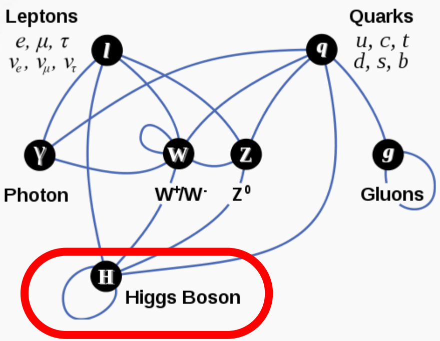

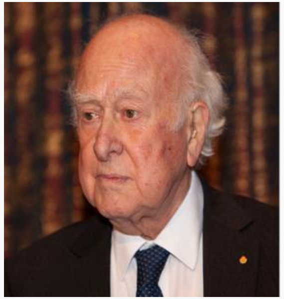

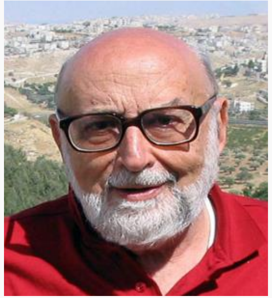

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Combination of those theory simultaneously

		Inflation	**SFOEWPT**	**Abundant**
SM +One singlet scalar		Small λ_{hs}	Large λ_{hs}	Under
SM +N singlet scalars	O(N)			
	O(N→N-1)			

2 Models

The zero temperature tree-level potential

$$V_0(H,S) = -\mu_h^2 H^\dagger H + \lambda_h |H^\dagger H|^2 + \frac{\mu_s^2}{2} S_i S_i + \frac{\lambda_s}{4}(S_i S_i)^2 + \frac{1}{2}\lambda_{hs}|H|^2 S_i S_i \,,$$

with $H^T = (G^+, (v+h+iG^0)/\sqrt{2})$.

01 O(N) scenario

After the spontaneously symmetry breaking of the Electroweak symmetry, the mass term of s_i is given as

$$m_{S_i}^2 = \mu_s^2 + \lambda_{hs} v^2/2$$

02 O(N → N−1) scenario

The N singlet scalar s_i with O(N) being spontaneously broken to O(N −1) symmetry

$$\frac{dV_0(h,s,A)}{dh}\Big|_{h=v} = 0, \quad \frac{dV_0(h,s,A)}{ds}\Big|_{s=v_s} = 0$$

$$\mu_h^2 = \lambda_h v^2 + \lambda_{hs} v_s^2/2, \mu_s^2 = -(\lambda_{hs} v^2/2 + \lambda_s v_s^2).$$

$$\mathcal{M}^2 = \begin{pmatrix} 2v^2\lambda_h & vv_s\lambda_{hs} \\ vv_s\lambda_{hs} & 2v_s^2\lambda_s \end{pmatrix} \quad R = \begin{pmatrix} \cos\theta, & \sin\theta \\ -\sin\theta, & \cos\theta \end{pmatrix}$$

$$m_{h_1,h_2}^2 = \lambda_h v^2 + \lambda_s v_s^2 \mp \frac{\lambda_s v_s^2 - \lambda_h v^2}{\cos 2\theta},$$

$$\lambda_h = \frac{m_{h_2}^2 \sin^2\theta + m_{h_1}^2 \cos^2\theta}{2v^2},$$

$$\lambda_s = \frac{m_{h_2}^2 \cos^2\theta + m_{h_1}^2 \sin^2\theta}{2v_s^2},$$

$$\lambda_{hs} = \frac{(m_{h_2}^2 - m_{h_1}^2)\sin 2\theta}{2vv_s}.$$

2.1Theoretical constraints

I **Perturbativity**

$$|\lambda_h| < 1,\ |\lambda_s| < \sqrt{4\pi},$$

$$|\lambda_{sh}| < \sqrt{4\pi}\ .$$

II **Vacuum stability**

$$\lambda_h > 0,\ \lambda_s > 0,\ \lambda_{sh} > 0$$

$$\text{or } \lambda_{sh} > -2\sqrt{\lambda_h \lambda_s}\ .$$

III **Perturbative unitarity**

$$\frac{1}{32\pi}\left(3\lambda + (N+2)\lambda_s + \sqrt{(3\lambda - (N+2)\lambda_s)^2 + 4N\lambda_{hs}^2}\right) < \frac{1}{2}$$

R G E

$$\beta_{g_s} = \frac{g_s^3}{(4\pi)^2}(-7) + \frac{g_s^3}{(4\pi)^4}\left(\frac{11}{6}g'^2 + \frac{9}{2}g^2 - 26g_s^2 - 2x_h y_t^2\right),$$

$$\beta_g = \frac{g^3}{(4\pi)^2}\left(-\frac{39 - x_h}{12}\right) + \frac{g^3}{(4\pi)^4}\left(\frac{3}{2}g'^2 + \frac{35}{6}g^2 + 12g_s^2 - \frac{3}{2}x_h y_t^2\right),$$

$$\beta_{g'} = \frac{g'^3}{(4\pi)^2}\left(\frac{81 + x_h}{12}\right) + \frac{g'^3}{(4\pi)^4}\left(\frac{199}{18}g'^2 + \frac{9}{2}g^2 + \frac{44}{3}g_s^2 - \frac{17}{6}x_h y_t^2\right),$$

$$\beta_{\lambda_h} = \frac{1}{(4\pi)^2}\left(6(1+3x_h^2)\lambda_h^2 - 6y_t^4 + \frac{3}{8}(2g^4 + (g^2 + g'^2)^2) + \lambda_h \gamma_h + \frac{N x_s^2}{2}\lambda_{sh}^2\right),$$

$$\beta_{\lambda_{sh}} = \frac{\lambda_{sh}}{(4\pi)^2}\left(12x_h^2\lambda_h + 4x_h x_s \lambda_{sh} + 6N x_s^2 \lambda_s + 6y_t^2 - \frac{9}{2}g^2 - \frac{3}{2}g'^2\right),$$

$$\beta_{\lambda_s} = \frac{1}{(4\pi)^2}(18N x_s^2 \lambda_s^2 + 2x_h^2 \lambda_{sh}^2),$$

$$\beta_{y_t} = \frac{y_t}{(4\pi)^2}\left[-\frac{9}{4}g^2 - \frac{17}{12}g'^2 - 8g_s^2 + \frac{23 + 4s}{6}y_t^2\right].$$

with $\gamma_h = (-9g^2 - 3g'^2 + 12y_t^2)$, g, g' and y_t are the standard model $SU(2), U(1)$ and top-quark Yukawa couplings, and

$$x_h = \frac{1 + \xi_h h^2/M_p^2}{1 + \xi_h h^2/M_p^2 + 6\xi_h^2 h^2/M_{pl}^2},\quad x_s = \frac{1 + \xi_s s^2/M_p^2}{1 + \xi_s s^2/M_p^2 + 6\xi_s^2 s^2/M_{pl}^2}.$$

2.2 Higgs precisions

$\mathcal{L} \supset \frac{c_H}{\Lambda^2} O_H + \frac{c_6}{\Lambda^2} O_6$ With $O_H \equiv \frac{1}{2}(\partial |H^\dagger H|)^2$ $O_6 \equiv |H^\dagger H|^3$

Tree-level		Loop-level
$c_H^N = N \frac{\lambda_{hs}^2}{2\lambda_s}$,	$c_6^N = 0$,	$c_H^N = \frac{N\lambda_{hs}}{48\pi^2}$, $c_6^N = -\frac{N\lambda_{hs}^3}{48\pi^2}$,
$c_H^{N\to N-1} = \frac{\lambda_{hs}^2}{2\lambda_s}$,	$c_6^{N\to N-1} = 0$.	$c_H^{N\to N-1} = \frac{\lambda_{hs}}{48\pi^2}$, $c_6^{N\to N-1} = -\frac{\lambda_{hs}^3}{48\pi^2}$.

$$\mathcal{L}_{eff} \supset (1+\delta Z_h)\frac{1}{2}(\partial_\mu h)^2$$

with $\delta Z_h = 2v^2 c_H / m_{S(h_2)}^2$ for $O(N)$ $(O(N \to N-1))$

2.2 Higgs precisions

For O(N) scenario

I **Confine to N and $\lambda_{hs,s}$ from LHC, ILC, CEPC, and FCC-ee.**

Production cross section of $e^+e^- \to hZ$:

$$\delta\sigma_{Zh} = -2\frac{v^2 c_H}{m^2_{S(h_2)}} \quad \text{where} \quad c_H^N v^2/(2m_S^2) \sim N\lambda_{hs}^2 v^2/(2\lambda_s m_S^2)$$

II **Confine from the S and T parameters.**

$$\Delta S = \frac{1}{12} c_H \frac{v^2}{m^2_{S(h_2)}} \log\left(\frac{m^2_{S(h_2)}}{m^2_W}\right)$$

$$\Delta T = -\frac{3}{16\pi c_W^2} c_H \frac{v^2}{m^2_{S(h_2)}} \log\left(\frac{m^2_{S(h_2)}}{m^2_W}\right)$$

Gfitter Group
Eur. Phys. J. C 74, 3046 (2014)
doi:10.1140/epjc/s10052-014-3046-5

$$S = 0.06 \pm 0.09, \ T = 0.10 \pm 0.07$$

2.2 Higgs precisions

For O(N → N−1) scenario

I **Confine from the T parameter.**

$$T = -\left(\frac{3}{16\pi s_W^2}\right)\left\{\cos^2\theta\left[\frac{1}{c_W^2}\left(\frac{m_{h_1}^2}{m_{h_1}^2 - M_Z^2}\right)\ln\frac{m_{h_1}^2}{M_Z^2} - \left(\frac{m_{h_1}^2}{m_{h_1}^2 - M_W^2}\right)\ln\frac{m_{h_1}^2}{M_W^2}\right] + \sin^2\theta\left[\frac{1}{c_W^2}\left(\frac{m_{h_2}^2}{m_{h_2}^2 - M_Z^2}\right)\right.\right.$$
$$\left.\left.\times\ln\frac{m_{h_2}^2}{M_Z^2} - \left(\frac{m_{h_2}^2}{m_{h_2}^2 - M_W^2}\right)\ln\frac{m_{h_2}^2}{M_W^2}\right]\right\},$$

2.2 Higgs precisions

For O(N → N−1) scenario

II Confine from the invisible decay.

$$\mathcal{L} \supset \lambda_{h_i h_j h_j} h_i h_j h_j + \lambda_{h_i s_{N-1} s_{N-1}} h_i s_{N-1} s_{N-1}$$

$$\lambda_{h_2 h_1 h_1} = -\frac{m_{h_1}^2}{2 v v_s} \sin(2\theta)(v_s \cos\theta + v \sin\theta)(1 + m_{h_2}^2/2m_{h_1}^2) ,$$

$$\lambda_{h_2 s_{N-1} s_{N-1}} = m_{h_2}^2 \cos\theta/(2v_s) ,$$

$$\lambda_{h_1 s_{N-1} s_{N-1}} = -m_{h_1}^2 \sin\theta/(2v_s) ,$$

$$\lambda_{h_1 h_2 h_2} = \lambda_{h_1 s_{N-1} s_{N-1}} .$$

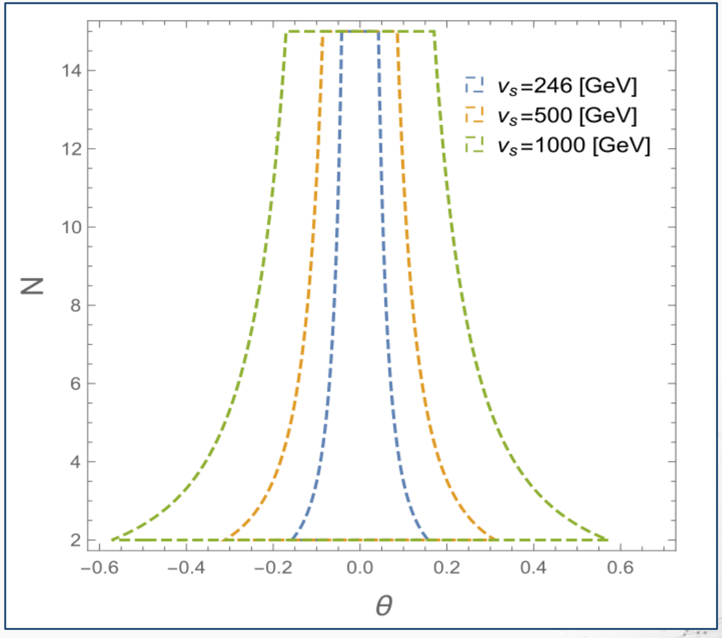
$$\Gamma_{h_2}^{tot} = \Gamma_{h_2}(h_2 \to h_1 h_1) + \sin^2\theta \Gamma_h \Big|_{m_h \to m_{h_2}} + (N-1)\Gamma_{h_2}(h_2 \to s_{N-1} s_{N-1})$$

$$= \Gamma_{h_2}(h_2 \to h_1 h_1) + \sin^2\theta \Gamma_h^{SM} \Big|_{m_h \to m_{h_2}} + (N-1)\frac{\lambda_{h_2 s_{N-1} s_{N-1}}^2}{32\pi m_{h_2}}$$

$$\Gamma_{h_1}^{tot} = \cos^2\theta \Gamma_h^{SM} + (N-1)\Gamma_h(h \to s_{N-1} s_{N-1})$$

$$= \cos^2\theta \Gamma_h^{SM} + (N-1)\frac{\lambda_{h_1 s_{N-1} s_{N-1}}^2}{32\pi m_{h_1}} ,$$

$$\Gamma(h_2 \to h_1 h_1) = \frac{\lambda_{h_2 h_1 h_1}^2}{32\pi m_{h_2}} \sqrt{1 - 4m_{h_1}^2/m_{h_2}^2} . \quad \Gamma(h_1 \to h_2 h_2) = \frac{\lambda_{h_1 h_2 h_2}^2}{32\pi m_{h_1}} \sqrt{1 - 4m_{h_2}^2/m_{h_1}^2} .$$



LHC (ATLAS+CMS) set $B_{BSM} < 0.34$ at 95% CL.

3.1 The Higgs inflation with N singlet scalars

Action

$$\tilde{g}_{\mu\nu} = \Omega^2 g_{\mu\nu}, \quad \Omega^2 \equiv 1 + \frac{\xi_s S^2}{M_P^2} + \frac{\xi_h h^2}{M_P^2}.$$

$$\frac{d\chi_h}{dh} = \sqrt{\frac{\Omega^2 + 6\xi_h^2 h^2/M_P^2}{\Omega^4}}, \quad \frac{d\chi_s}{ds} = \sqrt{\frac{\Omega^2 + 6\xi_s^2 S^2/M_P^2}{\Omega^4}},$$

Conformal Transformation

01 S_J

02 CT

03 S_E

Action in the Jordan frame

$$S_J = \int d^4x\sqrt{-g}\Big[-\frac{M_p^2}{2}R - \xi_h(H^\dagger H)R - \xi_s S^2 R + \partial_\mu H^\dagger \partial^\mu H + (\partial_\mu S)^2 - V(H,S)\Big],$$

Action in the Einstain frame

$$S_E = \int d^4x\sqrt{-\tilde{g}}\Big(-\frac{1}{2}M_P^2 R + \frac{1}{2}\partial_\mu\chi_h\partial^\mu\chi_h + \frac{1}{2}\partial_\mu\chi_S\partial^\mu\chi_S + A(\chi_S,\chi_h)\partial_\mu\chi_h\partial^\mu\chi_S - U(\chi_S,\chi_h)\Big),$$

3.1 The Higgs inflation with N singlet scalars

S_{inf}

h-direction inflation

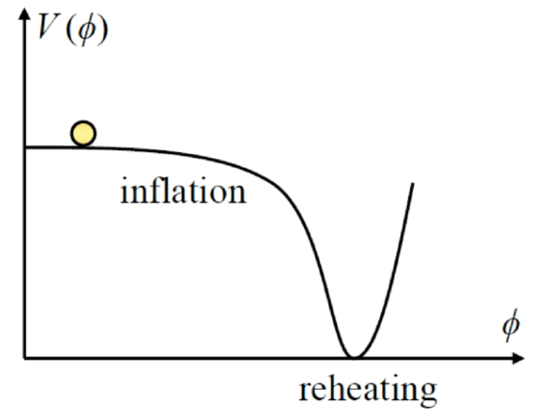
$$S_{\mathrm{inf}} = \int d^4x\sqrt{\tilde{g}}\left[\frac{M_{\mathrm{p}}^2}{2}R + \frac{1}{2}(\partial\chi)^2 - U(\chi)\right],$$

where $$U(\chi) = \frac{\lambda_h (h(\chi))^4}{4\Omega^4},$$

$$\frac{d\chi}{dh} \approx \left((1+\xi_h h^2/M_{\mathrm{p}}^2 + 6\xi_h^2 h^2/M_{\mathrm{p}}^2)/(1+\xi_h h^2/M_{\mathrm{p}}^2)^2\right)^{1/2}$$

3.1 The Higgs inflation with N singlet scalars

Constrains



Slow-roll inflation

1

The slow-roll parameters

$$\varepsilon(\chi) = \frac{M_{\rm p}^2}{2}\left(\frac{dU/d\chi}{U(\chi)}\right)^2,$$

$$\eta(\chi) = M_{\rm p}^2\left(\frac{d^2U/d\chi^2}{U(\chi)}\right).$$

$(\varepsilon << 1 \; and \; |\eta| << 1)$

2

The e-folding numbers

$$N_{\rm e-folds} = \int_{\chi_{\rm end}}^{\chi_{\rm in}} d\chi \frac{1}{M_{\rm p}\sqrt{2\varepsilon}}.$$

$(N_{e-fold} \sim 60)$

3.1 The Higgs inflation with N singlet scalars

Observables

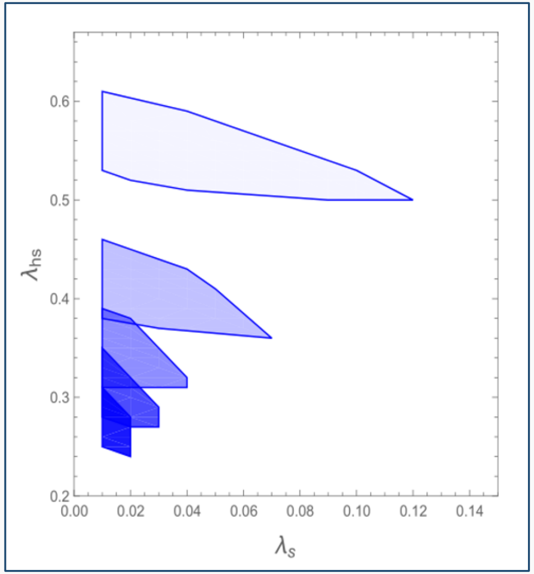
Spectrum index $n_s = 1 + 2\eta - 6\varepsilon \sim 0.97$

Tensor to scalar $r = 16\varepsilon < 0.11$

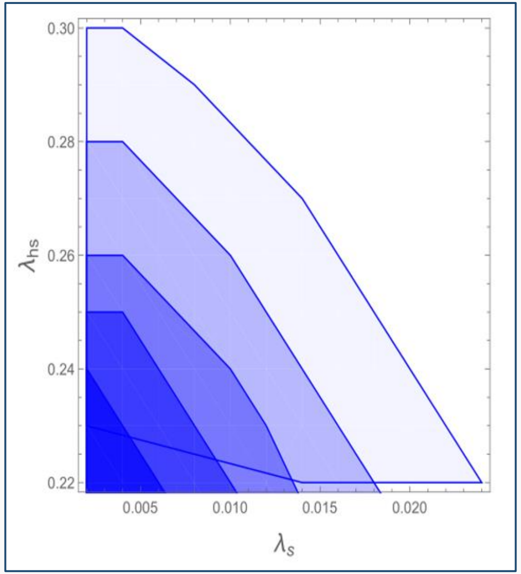
Amplitude of scalar spectrum fluctuations

$$\Delta_{\mathcal{R}}^2 = \frac{1}{24\pi^2 M_p^4} \frac{U(\chi)}{\varepsilon} = 2.2 \times 10^{-9} .$$

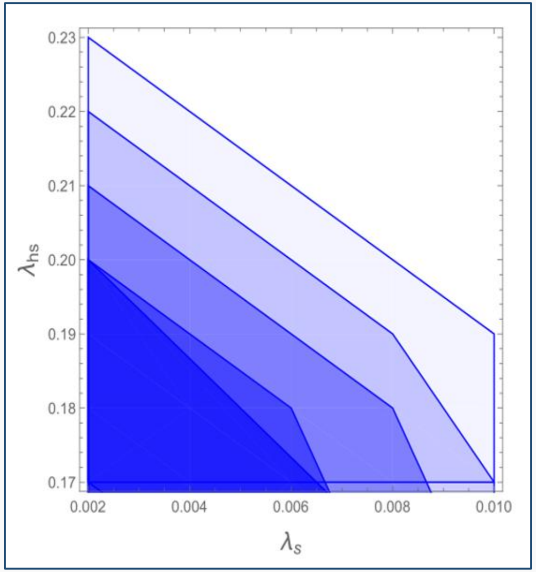
3.1.1 O(N) scenario



N are 1 → 5



N are 6 → 10

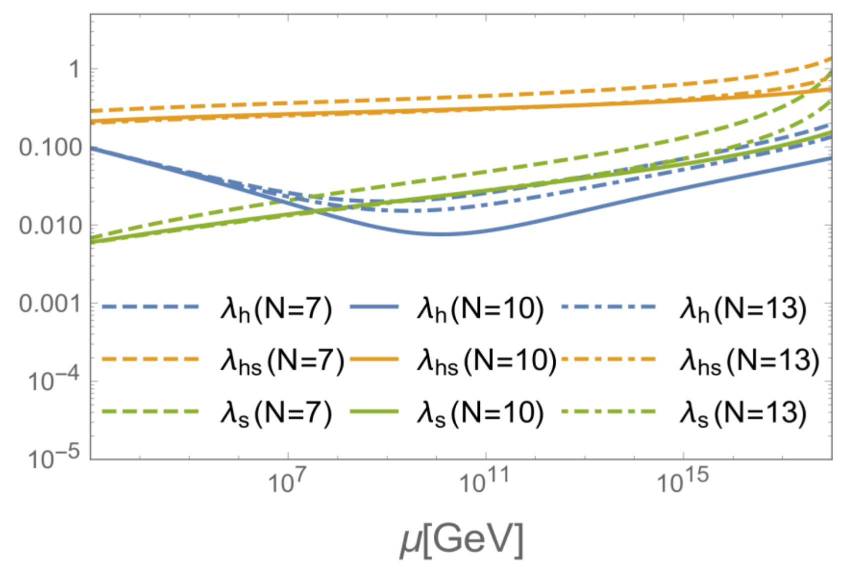


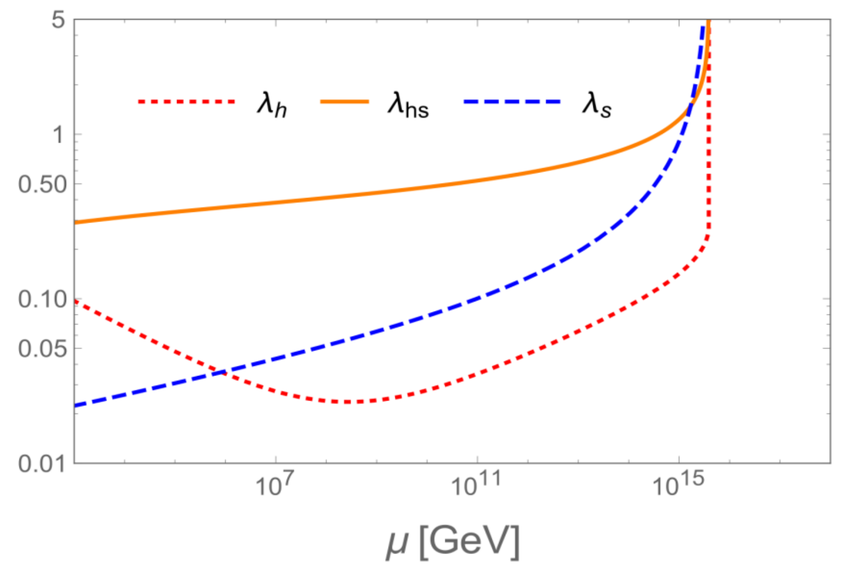
N are 11 → 15

Inflation feasible $(\lambda_s, \lambda_{hs})$ plane for different N with in O(N) scalar model, the larger N is shown by the deeper color.

3.1.1 O(N) scenario

RG running of couplings

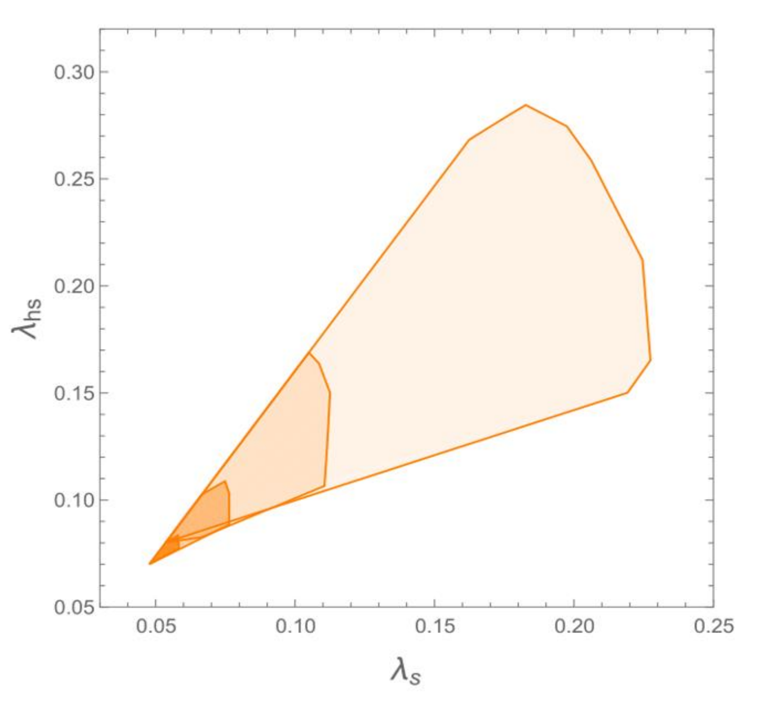


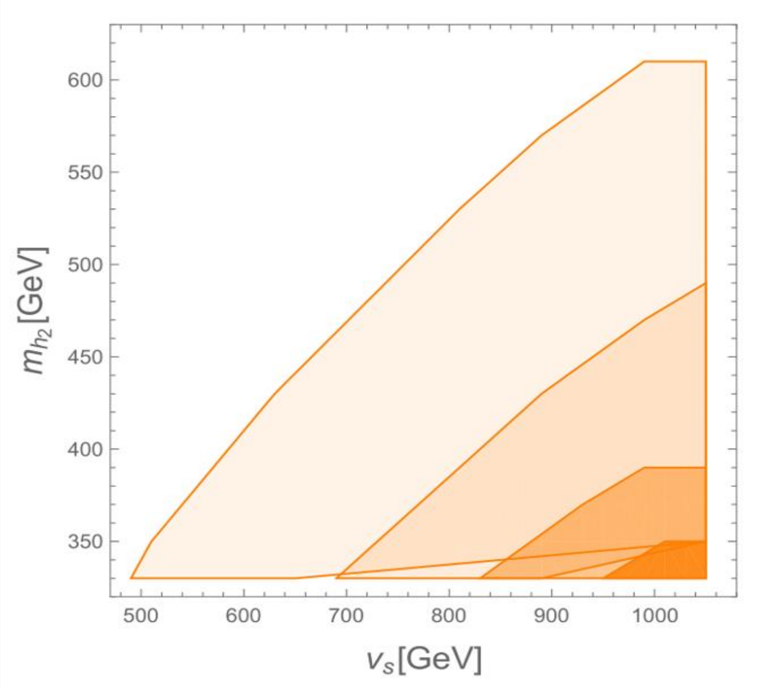


The quartic couplings where the inflation is valid.

The quartic couplings lives in the parameter region where the inflation is invalid.

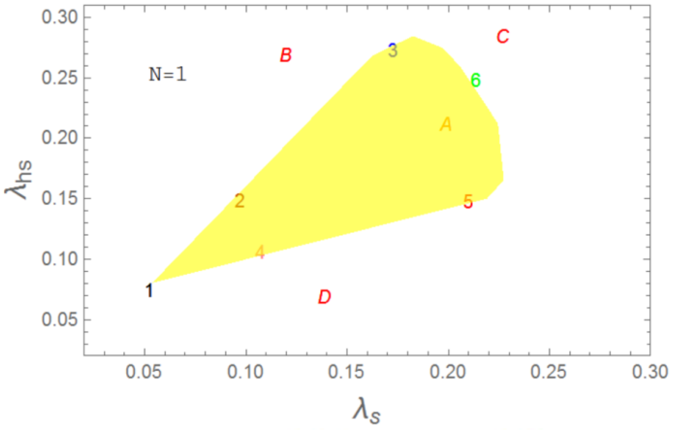
3.1.2 O(N → N−1) scenario





Inflation feasible (λ_s, λ_{hs}) and (v_s, m_{h_2}) plane
for different N within O(N → N −1) scalar model, a deeper color
corresponds to a larger N, the corresponding N are 1, 2, 3 and 4, respectively.

3.1.2 O(N → N−1) scenario



1 m_{h_2}=330[GeV],v_s=1000[GeV]

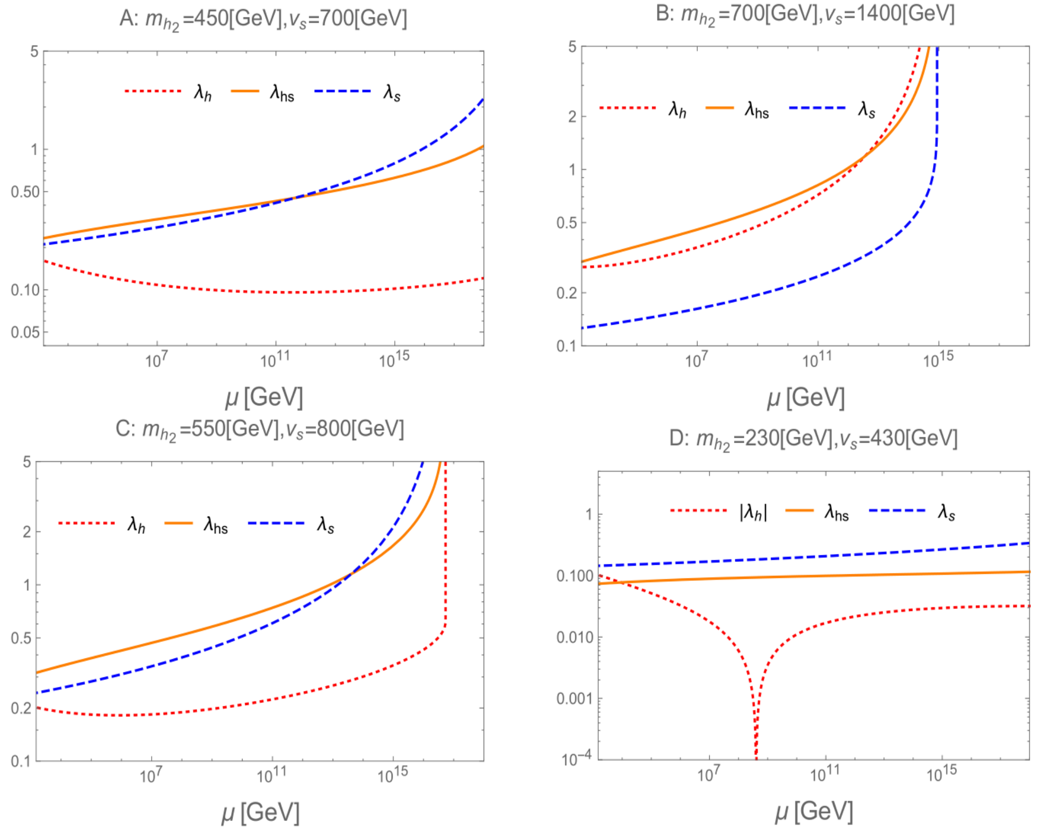
2 m_{h_2}=450[GeV],v_s=1000[GeV]

3 m_{h_2}=600[GeV],v_s=1000[GeV]

4 m_{h_2}=330[GeV],v_s=700[GeV]

5 m_{h_2}=330[GeV],v_s=500[GeV]

6 m_{h_2}=500[GeV],v_s=750[GeV]



3.2 Electroweak phase transitions

The effective potential:

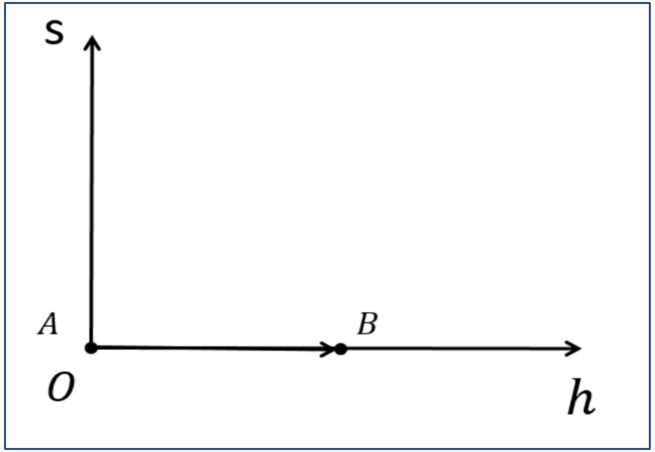
Coleman-Weinberg potential

$$V(h,s,N,T) = V_0(h,s) + V_{CW}(h,n) + V_T(h,n,T) + V_{ring}(h,N,T),$$

Tree level scalar potential

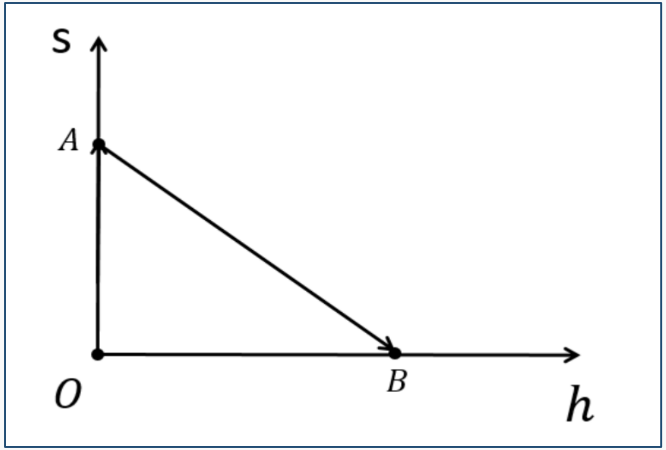
Finite temperature corrections

3.2.1 O (N) scenario



One-step EWPT type

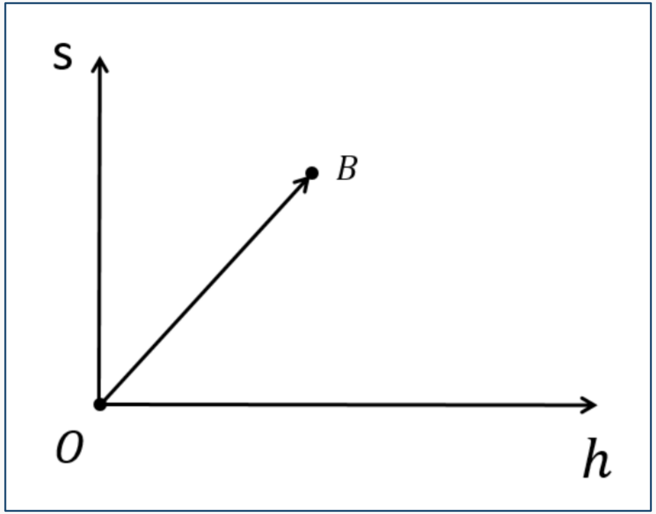
$$V(0,0,N,T_C) = V(h_C^B,0,N,T_C)\ ,$$
$$\frac{dV(h,0,N,T_C)}{dh}\Big|_{h=h_C^B} = 0\ ,$$



Two-step EWPT type

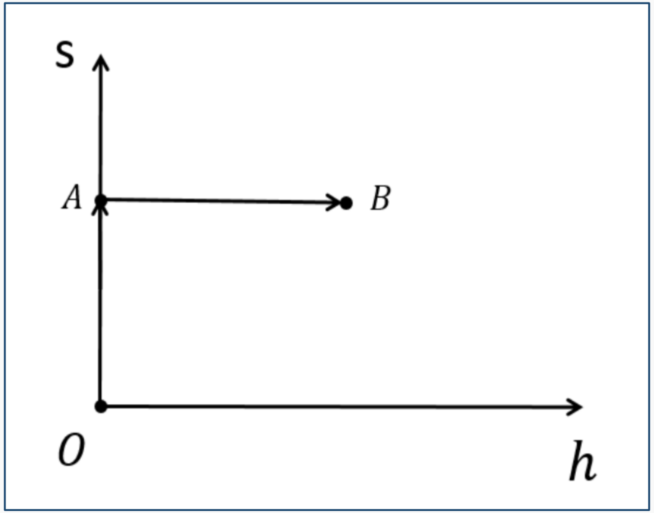
$$V(0,s_C^A,N,T_C) = V(h_C^B,0,N,T_C)\ ,$$
$$\frac{dV(h,0,N,T_C)}{dh}\Big|_{h=h_C^B} = 0\ ,$$

3.2.2 O(N → N−1) scenario



One-step EWPT type

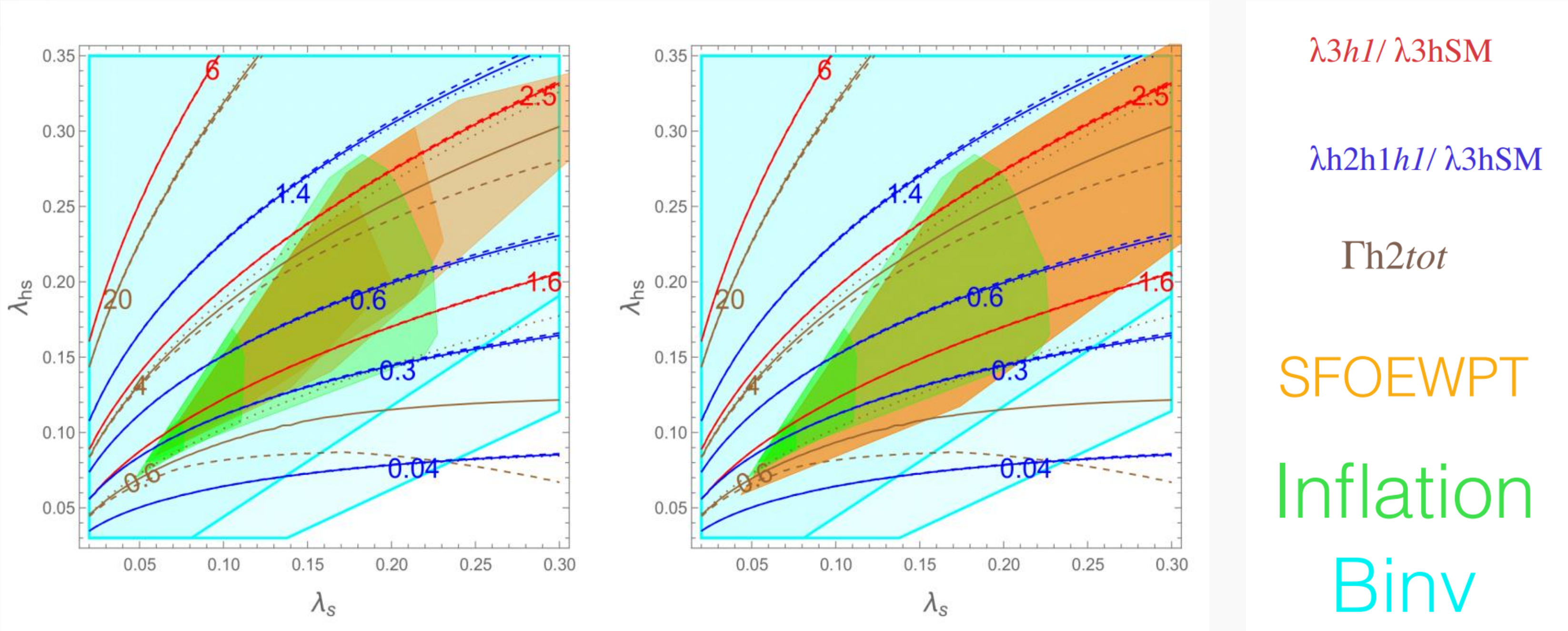
$$V(0,0,N,T_C) = V(v_C^B, s_C^B, N, T_C),$$
$$\frac{dV(h,s,N,T_C)}{dh}|_{h=h_C^B, s=s_C^B} = 0,$$
$$\frac{dV(h,s,N,T_C)}{ds}|_{h=h_C^B, s=s_C^B} = 0.$$



Two-step EWPT type

$$V(0,s_C^A,N,T_C) = V(h_C^B, s_C^B, N, T_C),$$
$$\frac{dV(h,s,N,T_C)}{dh}|_{h=h_C^B, s=s_C^B} = 0,$$
$$\frac{dV(h,s,N,T_C)}{ds}|_{h=h_C^B, s=s_C^B} = 0.$$

3.2.2 O(N → N−1) scenario



One-step

Two-step

5.Summary

- The Higgs inflation and the cosmological electroweak phase transition are studied with the N-scalars extended standard model of particle physics (SM).

- Two scenario of N singlet scalar extended standard models are discussed in detail. One is the N singlet scalar invariant under O(N) symmetry, the other one is the N singlet scalar s_i with O(N) being spontaneously broken to O(N-1) symmetry.

- O(N) can not explain the inflation and EWPT simultaneously, while $O(N \rightarrow N-1)$ can realize at the same time.

THANKS