Higgs Inflation: an update

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PPC 2014, University of Guanajuato, Mexico, June 23-27, 2014

The Standard Big-Bang Cosmology

The success of the Standard Big-Bang Cosmology

Expansion law: $$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3M_{Pl}^2}\rho$$

Continuity equation: $$\dot{\rho} + 3H(\rho + p) = 0$$

- Hubble expansion

  Hubble's law: expansion of the Universe

- Cosmic Microwave Background (CMB)

  2.725K radiation, Planck distribution

- Big-Bang nucleosynthesis

  Success in synthesizing light nuclei in the early Universe

Problems of Big-Bang Cosmology

Big-Bang Cosmology: $$\frac{\ddot{a}}{a} = -\frac{4\pi}{3M_{Pl}^2}(\rho + 3p) = -\frac{4\pi}{3M_{Pl}^2}(1+w)\rho$$

w=1/3 : radiation
w=0 : matter

$$\boxed{\ddot{a} < 0}$$

Decelerating expansion

Flatness problem

Fine-tuning of density parameter is necessary

Horizon problem

Observed CMB is isotropic
nevertheless two regions have never contacted with each other

Origin of density fluctuation

need the seed of density fluctuation for the large scale structure formation of the Universe

Basic Idea of Inflationary Universe

Suppose the existence of a stage in the early universe with $\ddot{a} > 0$

``Inflation'' **Accelerating Expansion**

Simple example: de Sitter space

Positive cosmological constant (vacuum energy)

ρ_Λ $\boxed{w = -1} \rightarrow p = -\rho_\Lambda$

Expansion law: $H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3M_{Pl}^2}\rho$

Continuity equation: $\dot{\rho} + 3H(\rho + p) = 0$

$\Rightarrow$

$a \propto e^{H_I t}$

$\rho_\Lambda = \text{const.}$

Exponential expansion (Inflation) solves

- flatness problem ← spatial curvature flattened
- horizon problem ← small causal region expanded

Simple realization: slow-roll inflation

Scalar field called ``inflaton''

Quantum fluctuation of inflaton
→ origin of primordial density fluctuation

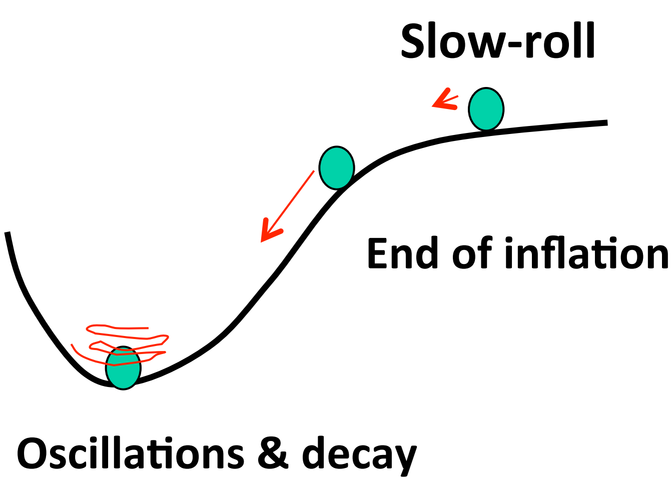
Simple inflation model

The picture we seek….

Inflation before Big-Bang → Big-bang cosmology

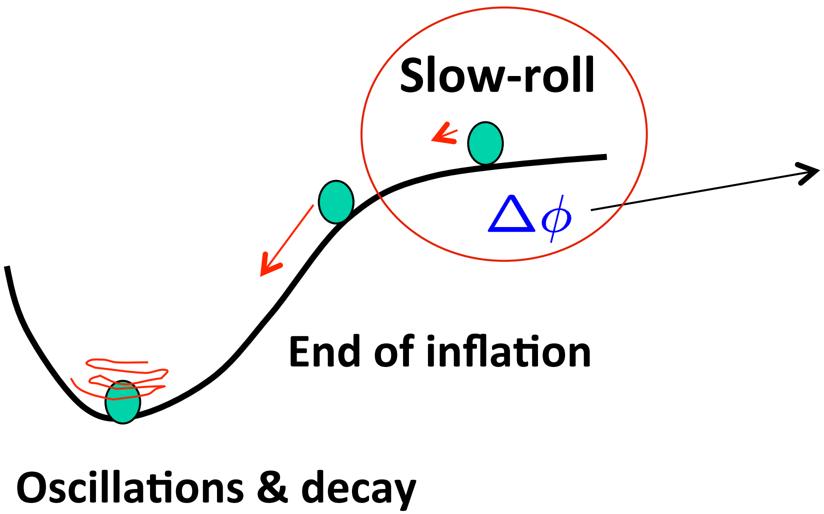
Slow-roll inflation

A scalar field (inflaton) slowly-rolling down to its potential minimum



1. Inflation at slow-roll era (E =K+ V~V)
2. End of Inflation (K ~ V)
3. Coherent oscillations
4. Decays to Standard Model particles
5. Reheating → Big-Bang Cosmology

Primordial density fluctuation



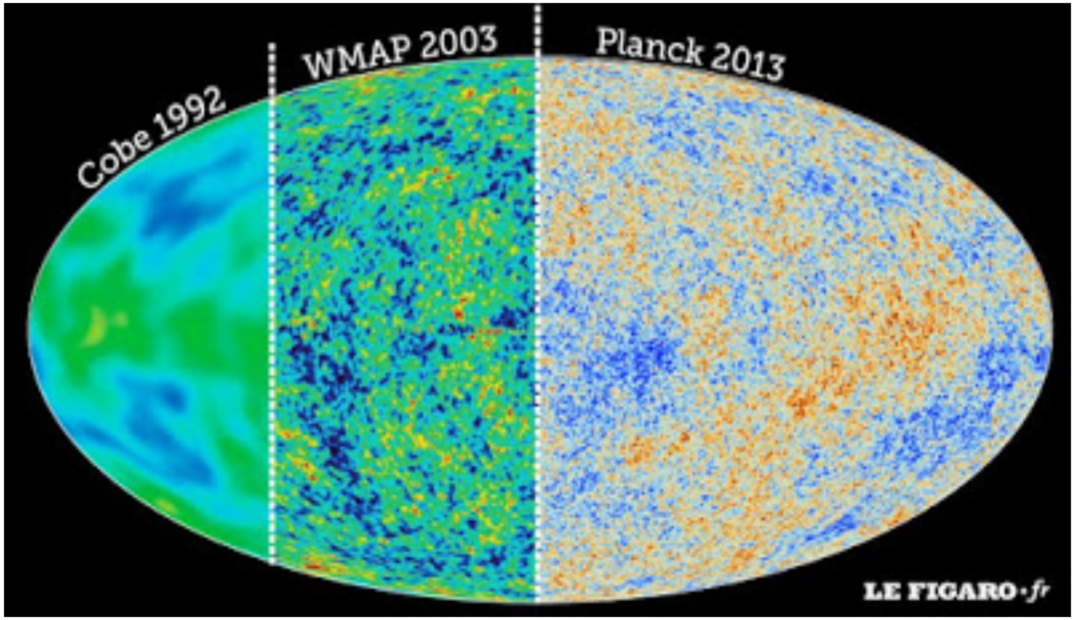
quantum fluctuation is magnified to cosmic scale by inflation

$$a \propto e^{H_I t}$$

Inflaton fluctuation → curvature fluctuation
→ structure formation, CMB anisotropy

- ❑ Inflaton fluctuation → inflaton potential, parameters
- ❑ CMB anisotropy observations → constraints on inflationary scenario

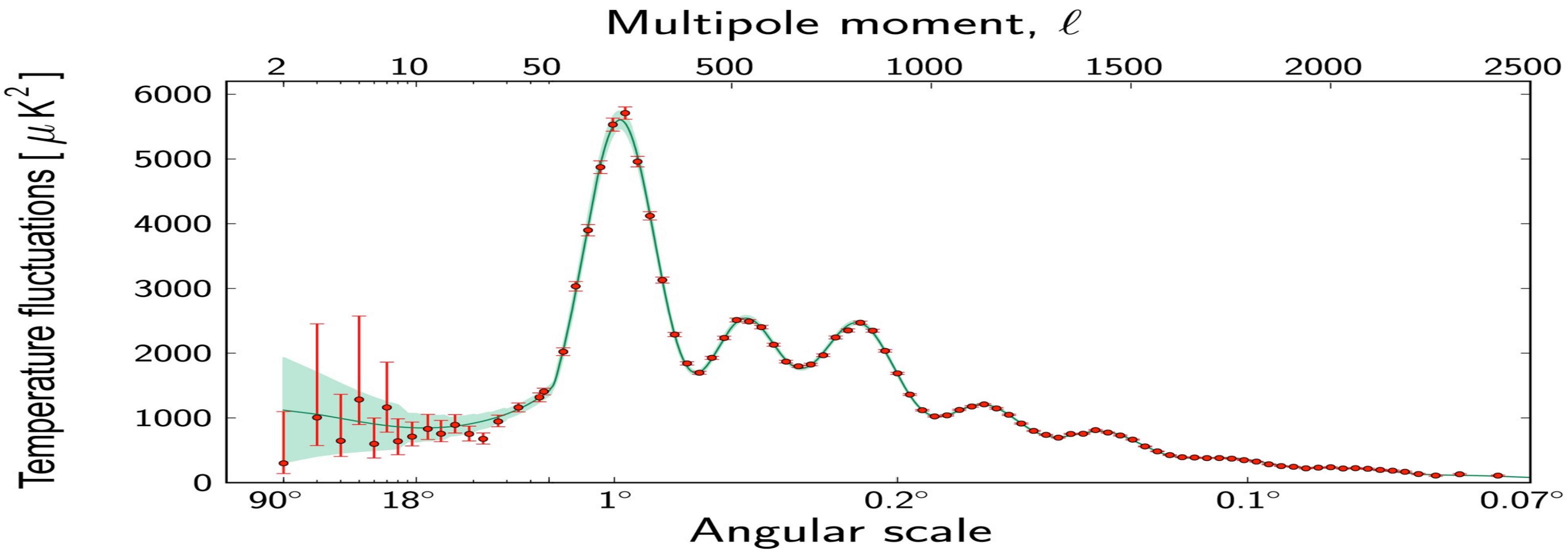
CMB Observations: WMAP & Planck



$$T = 2.725 \text{ K}$$

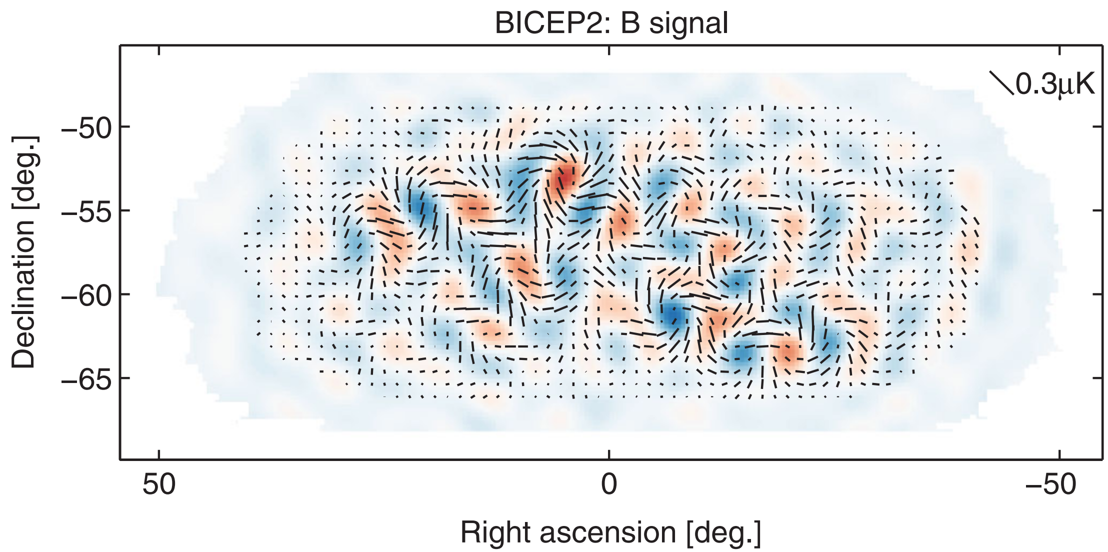
$$\frac{\delta T}{T} \sim 10^{-5}$$

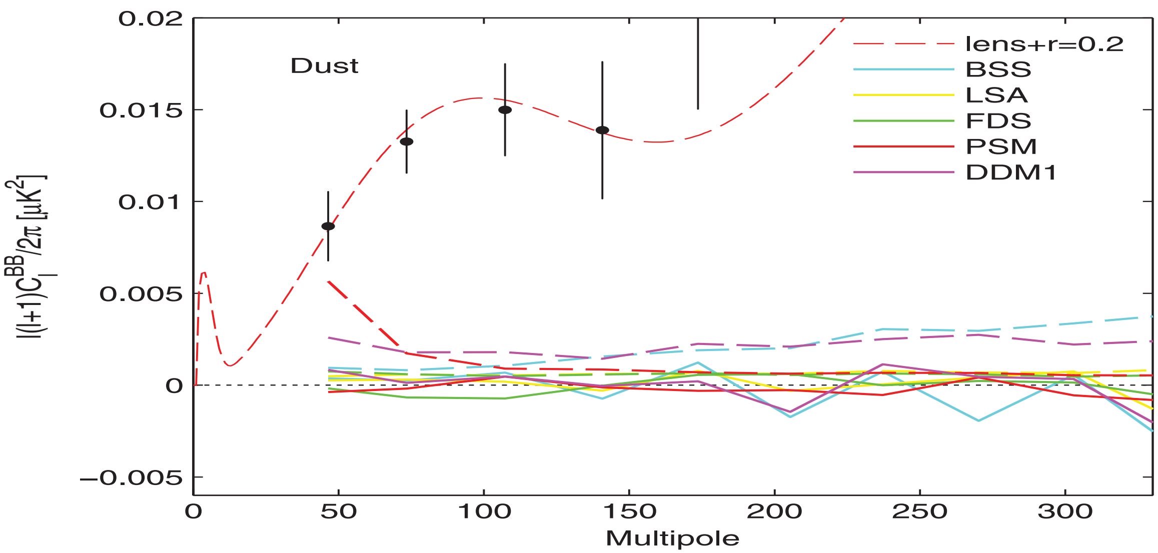
The observational cosmology is now a precision science!



Observation of CMB B-mode polarization

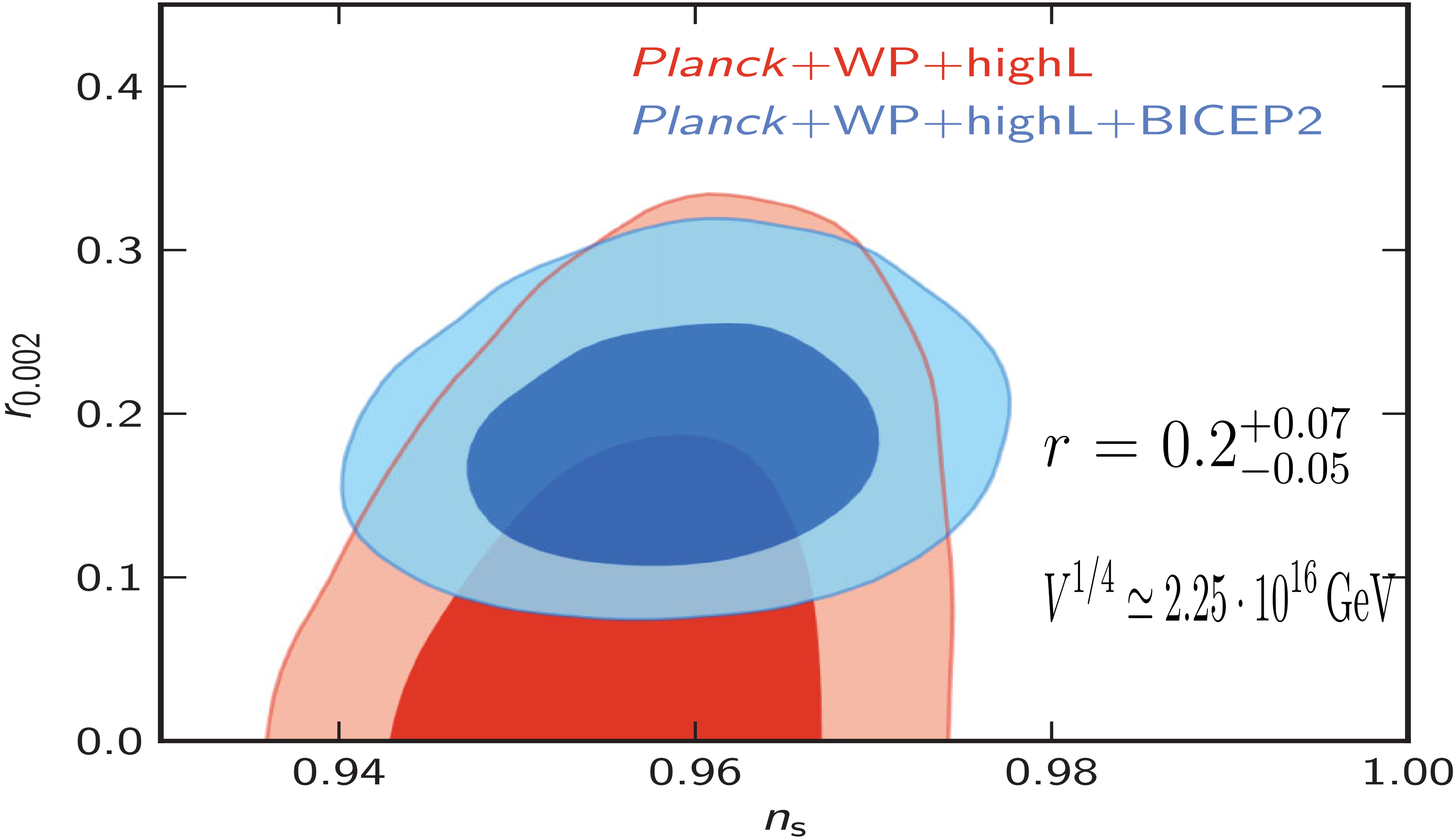
BICEP2 collaboration: PRL 112, 241101 (2014)





well fit by r=0.2 !

Indirect constraints on the inflationary predictions by Planck+WP+highL+BICEP2



Caveat

- Tension with the upper bound on $r < 0.11$ by Planck satellite
- A negative running of the spectral index ~ $O(0.01)$ needs to reconcile BICEP2 and Planck data
- Dust uncertainty may be higher than that modeled in BICEP2 analysis

Mortonson & Seljak, 1405.5857
Flauger, Hill & Spargel, 1405.7351

More data by upcoming measurements such as Planck and Keck Array are required to resolve this situation!

Inflationary predictions

Slow-roll parameters (Planck unit)

$$\epsilon = \frac{1}{2}\left(\frac{V'}{V}\right)^2, \quad \eta = \frac{V''}{V}, \quad \zeta^2 = \frac{V'V'''}{V^2}$$

Constraints

- Amp of curvature perturbation $\Delta_{\mathcal{R}} = \frac{1}{2\sqrt{3}\pi}\frac{V^{3/2}}{|V'|}$ to be compared with Planck measurement

  $\Delta_{\mathcal{R}}^2 = 2.215 \times 10^{-9}$ with a pivot scale $k_0 = 0.05\ \mathrm{Mpc}^{-1}$
- e-folding number

$$N = \int_{\phi_e}^{\phi_0} \frac{V\mathrm{d}\phi}{V'}$$ ***= 50-60***

Inflationary predictions

Spectral index: $n_s = 1 - 6\epsilon + 2\eta$

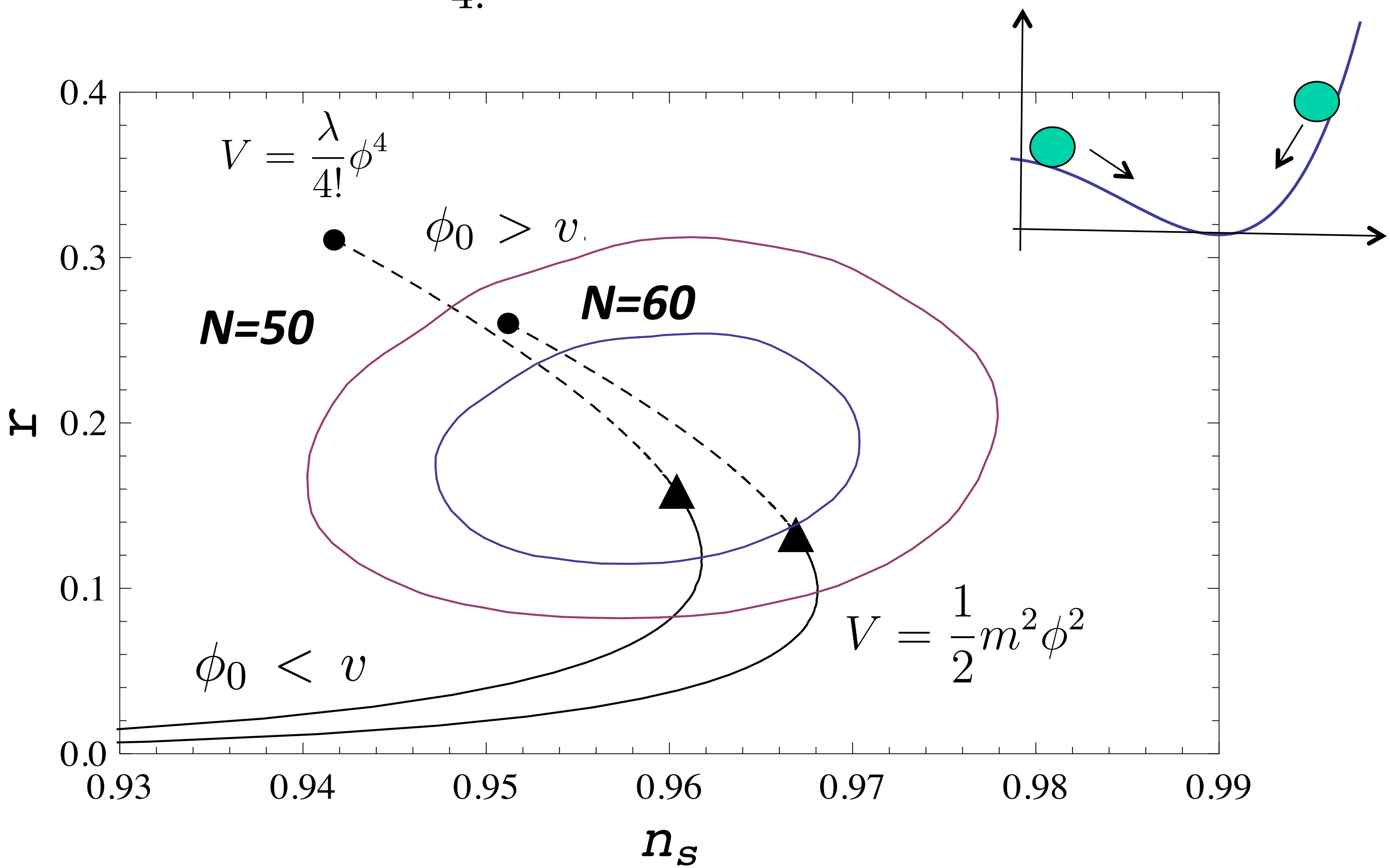
Tensor-to-scalar ratio: $r = 16\epsilon$

Running of spectral index: $\alpha = 16\epsilon\eta - 24\epsilon^2 - 2\zeta^2$

Simple inflationary models in light of BOCEP2: an update

N.O., Senoguz & Shafi, 1403.6493

Higgs potential: $V = \frac{\lambda}{4!}\left(\phi^2 - v^2\right)^2$



Quartic potential with non-minimal gravitational coupling

Jordan frame:

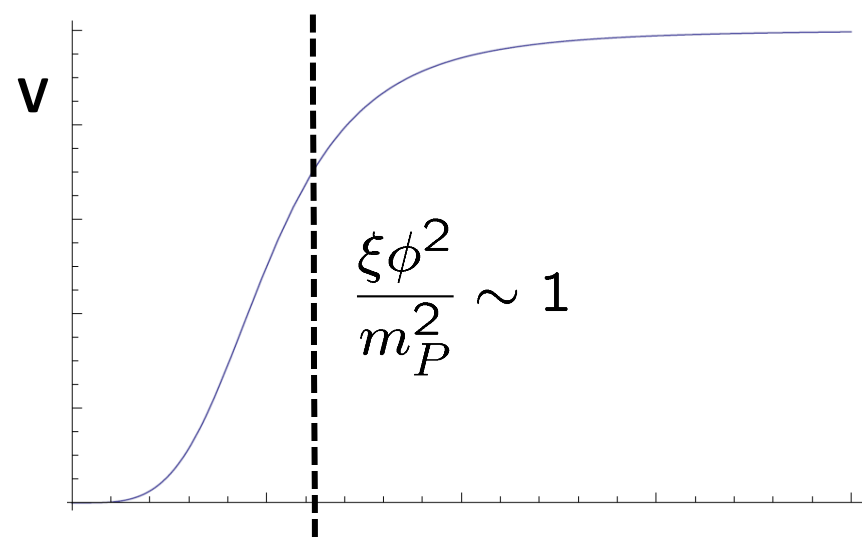
$$S_J^{\mathrm{tree}} = \int d^4x\sqrt{-g}\left[-\left(\frac{1+\boxed{\xi}\phi^2}{2}\right)\mathcal{R} + \frac{1}{2}(\partial\phi)^2 - \frac{\lambda}{4!}\phi^4\right]$$

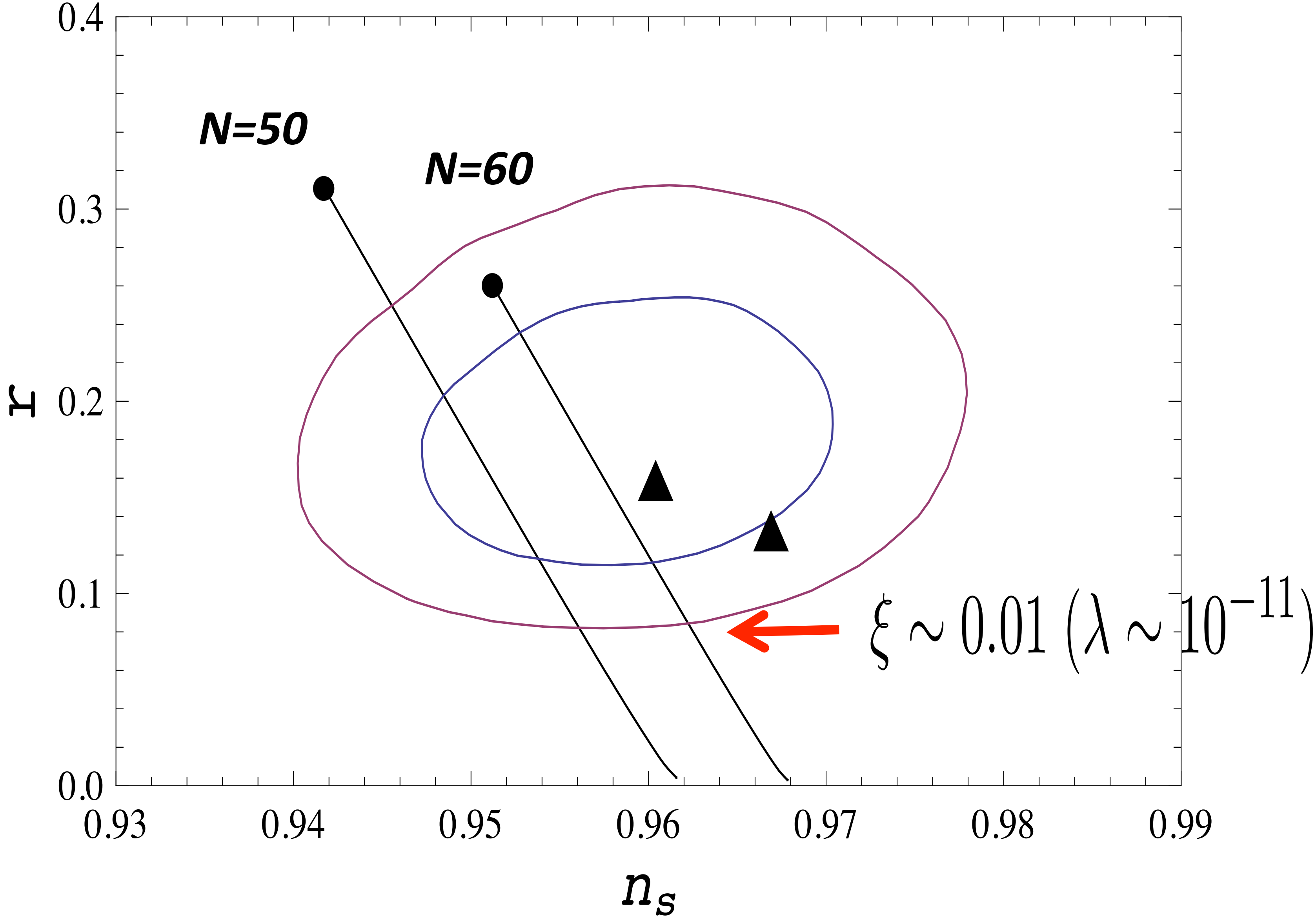
Einstein frame:

$$S_E = \int d^4x\sqrt{-g_E}\left[-\frac{1}{2}\mathcal{R}_E + \frac{1}{2}(\partial_E\sigma_E)^2 - V_E(\sigma_E(\phi))\right]$$

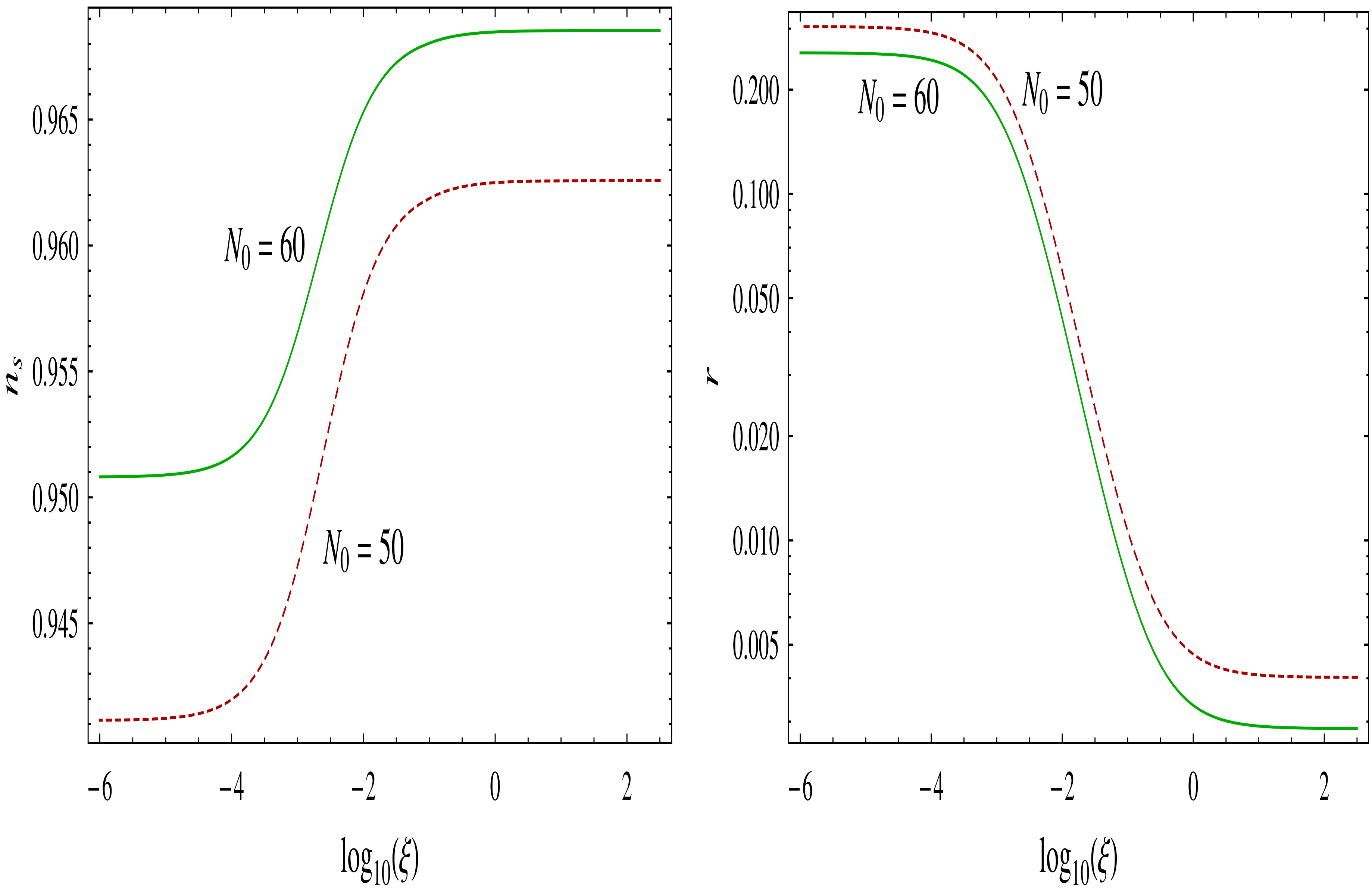
$$\left(\frac{d\sigma}{d\phi}\right)^{-2} = \frac{\left(1+\xi\phi^2\right)^2}{1+(6\xi+1)\xi\phi^2}$$

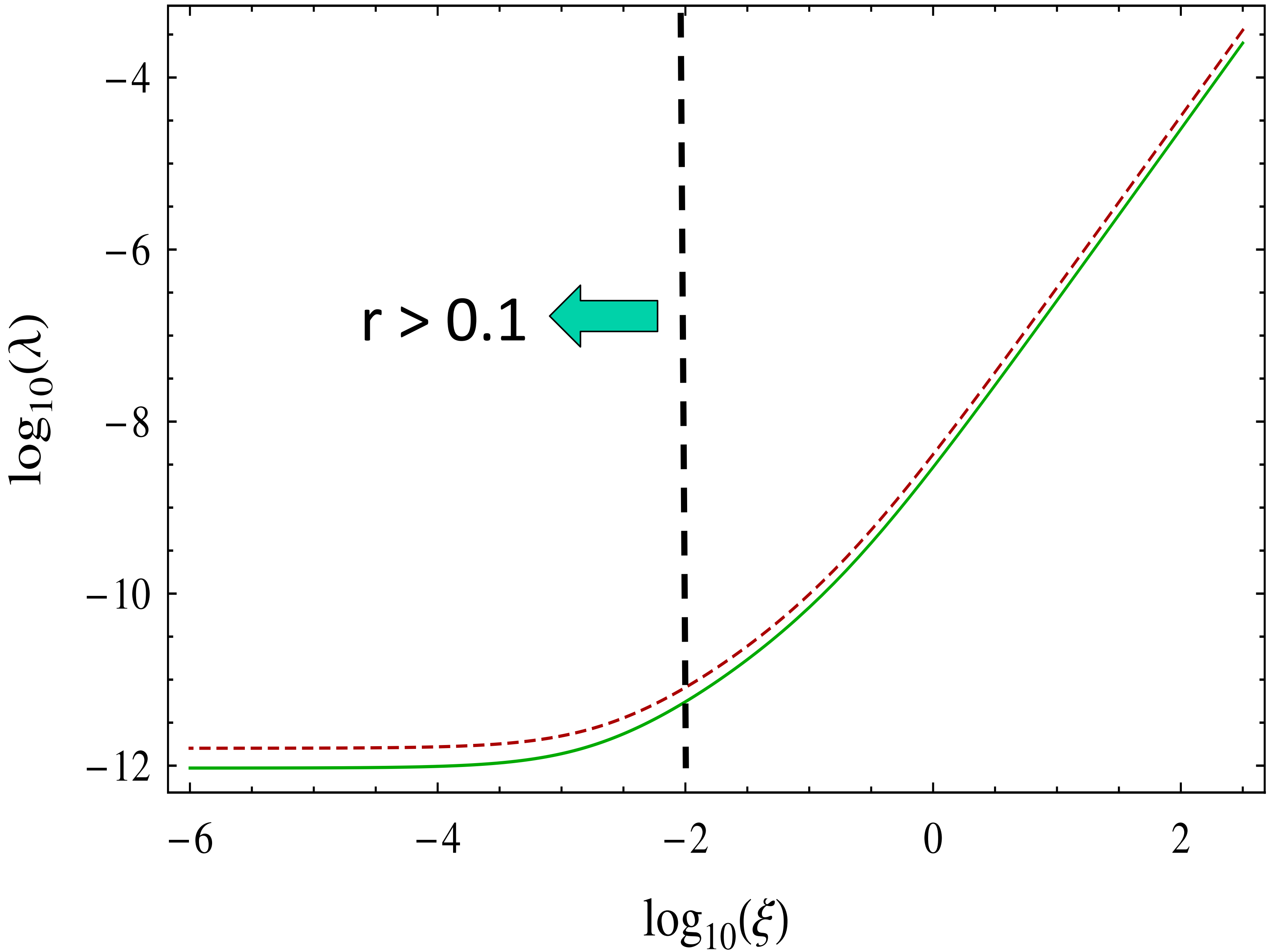
$$V_E = \frac{\frac{1}{4!}\lambda\phi^4}{\left(1+\frac{\xi\phi^2}{m_P^2}\right)^2}$$




N=50
N=60
$\xi \sim 0.01\,(\lambda \sim 10^{-11})$
r
n_s
0.0
0.1
0.2
0.3
0.4
0.93
0.94
0.95
0.96
0.97
0.98
0.99

N. O.,Rehman & Shafi, Phys. Rev. D 82, 043502 (2010)





r > 0.1
−4
−6
−8
−10
−12
$\log_{10}(\lambda)$
−6
−4
−2
0
2
$\log_{10}(\xi)$

Higgs Inflation

Can SM Higgs doublet play the role of inflaton?

- NO!

Quartic potential model: $V = \lambda \left(H^\dagger H - \frac{v_{\mathrm{EW}}}{2} \right)^2 \sim \lambda (H^\dagger H)^2$

Planck measurement: $\lambda \sim 10^{-12} \rightarrow m_h \sim 100 \text{ keV}$

Any idea to realize Higgs Inflation?

(1) $m_h \sim 100 \text{ GeV} \rightarrow \lambda \sim 0.1$

but, consistent with Planck measurement?

(2) RGE effect? $\lambda(M_Z) \neq \lambda(\phi_0 \sim 20 M_P) \sim 10^{-12}$?

Higgs Inflation (before Higgs discovery)

Bezrukov & Shaposhnikov, PLB 659 (2008) 703; JHEP 07 (2009) 089

quartic potential model with non-minimal gravitational coupling

$$S_J^{\mathrm{tree}} = \int d^4x\sqrt{-g}\Big[-\Big(\frac{m_P^2 + \xi\phi^2}{2}\Big)\mathcal{R} + \frac{1}{2}(\partial\phi)^2 - \frac{\lambda}{4!}\phi^4\Big]$$

$$\phi^2 \to H^\dagger H = \frac{1}{2}\varphi^2$$

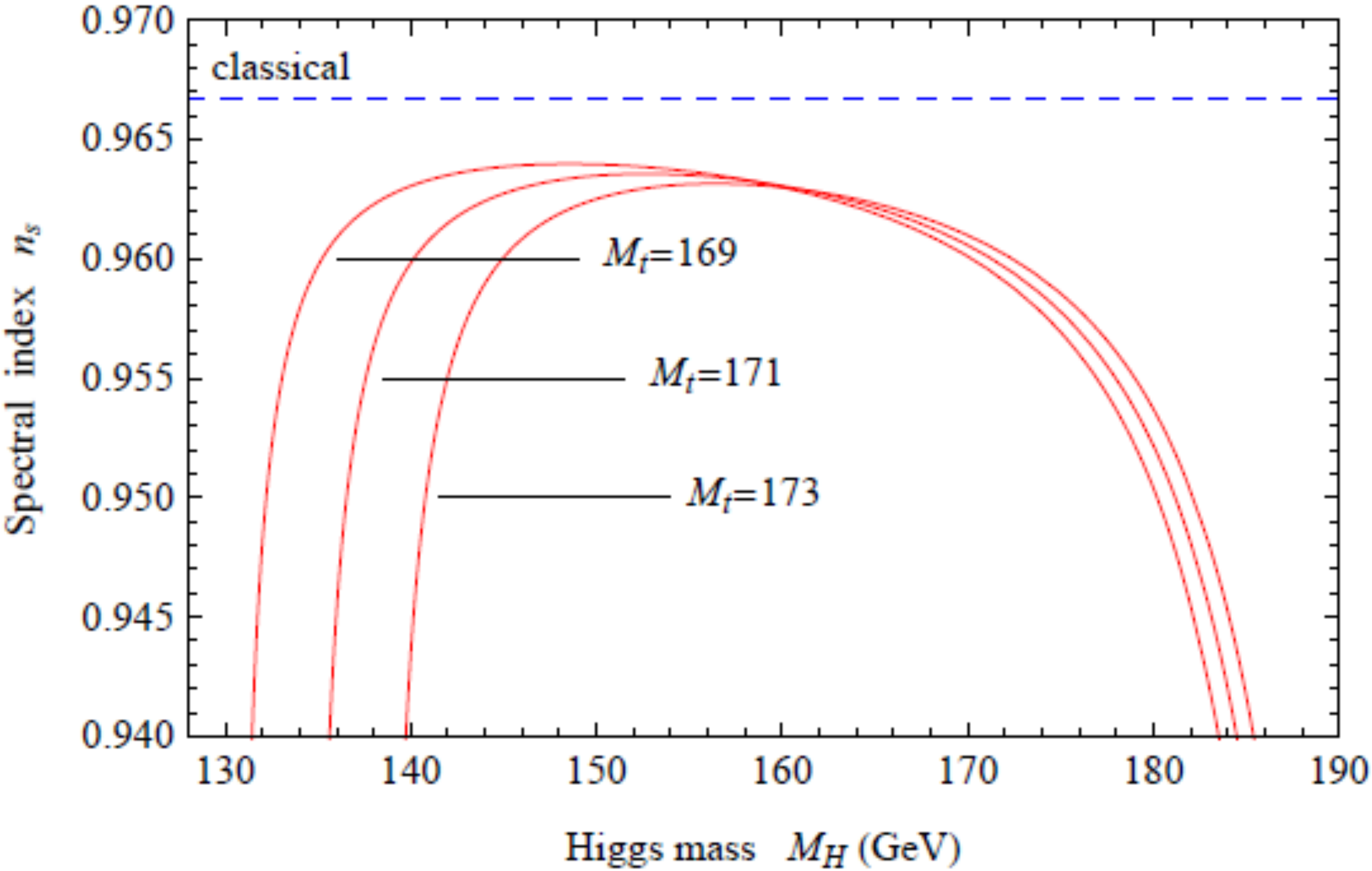
Quartic coupling suitable for a suitable Higgs mass of O(100 GeV) is realized with a large non-minimal coupling

$$m_h \sim 100 \text{ GeV} \to \lambda \sim 0.1 \leftrightarrow \xi \sim 10000$$

Note: predicted r value is very small, r ~0.001

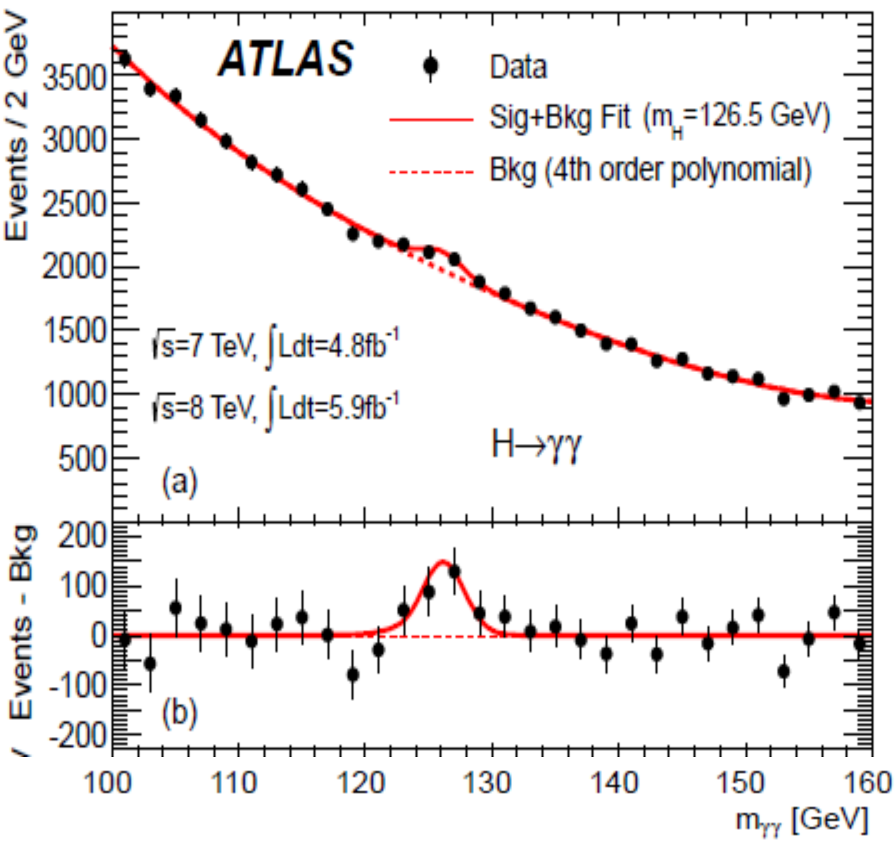
Analysis beyond tree-level (RGE improved effective potential at 2-loop level)

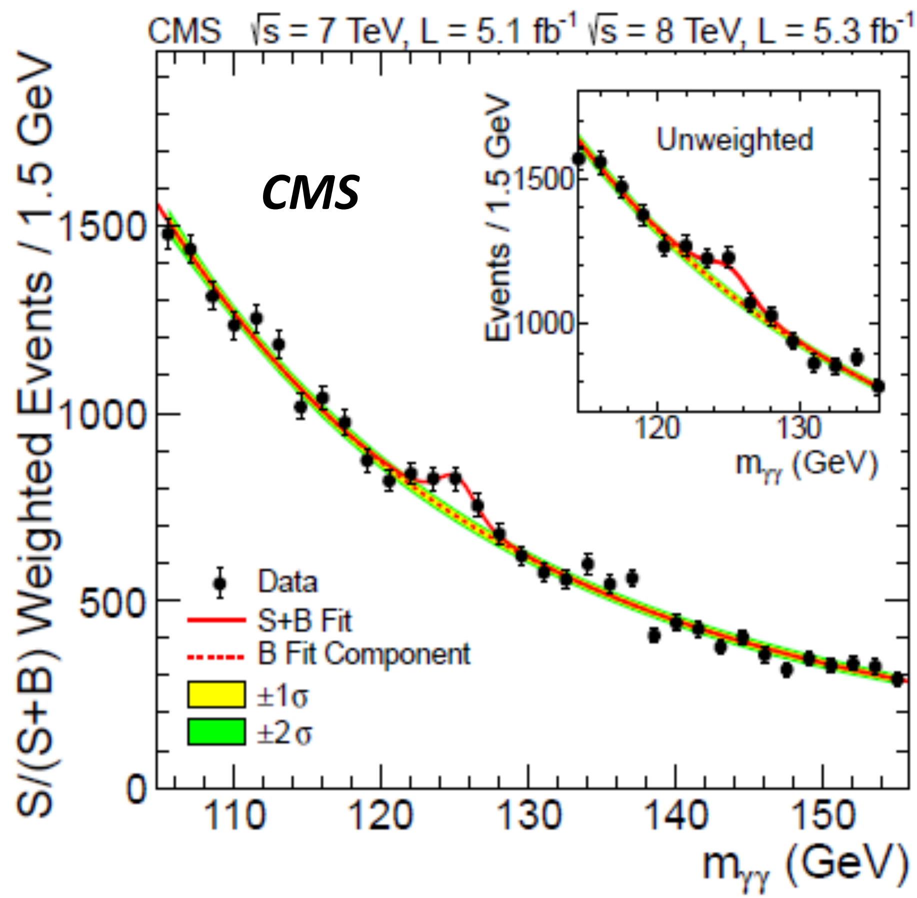
De Simone, Hertzberg & Wilczek, PLB 678 (2009)1; Barvinsky et al., JCAP 0912 (2009) 003



Discovery of Higgs boson at LHC !   **7/04/2012**

A new scalar particle, most likely Standard Model Higgs boson has been discovered at LHC through a variety of decay modes.





$$m_h = 126.0 \pm 0.4(\text{stat.}) \pm 0.4(\text{syst.})\,\text{GeV} \qquad m_h = 125.3 \pm 0.4(\text{stat.}) \pm 0.5(\text{syst.})\,\text{GeV}$$

Higgs Inflation (after Higgs discovery at LHC)

Impact of Higgs mass: $m_H = 125 - 126 \text{ GeV}$

- quartic coupling at EW scale is fixed
- extrapolation to the Planck scale

Update of RGE analysis (@ 3-loop level) **Buttazzo et al., JHEP 12 (2013) 089**

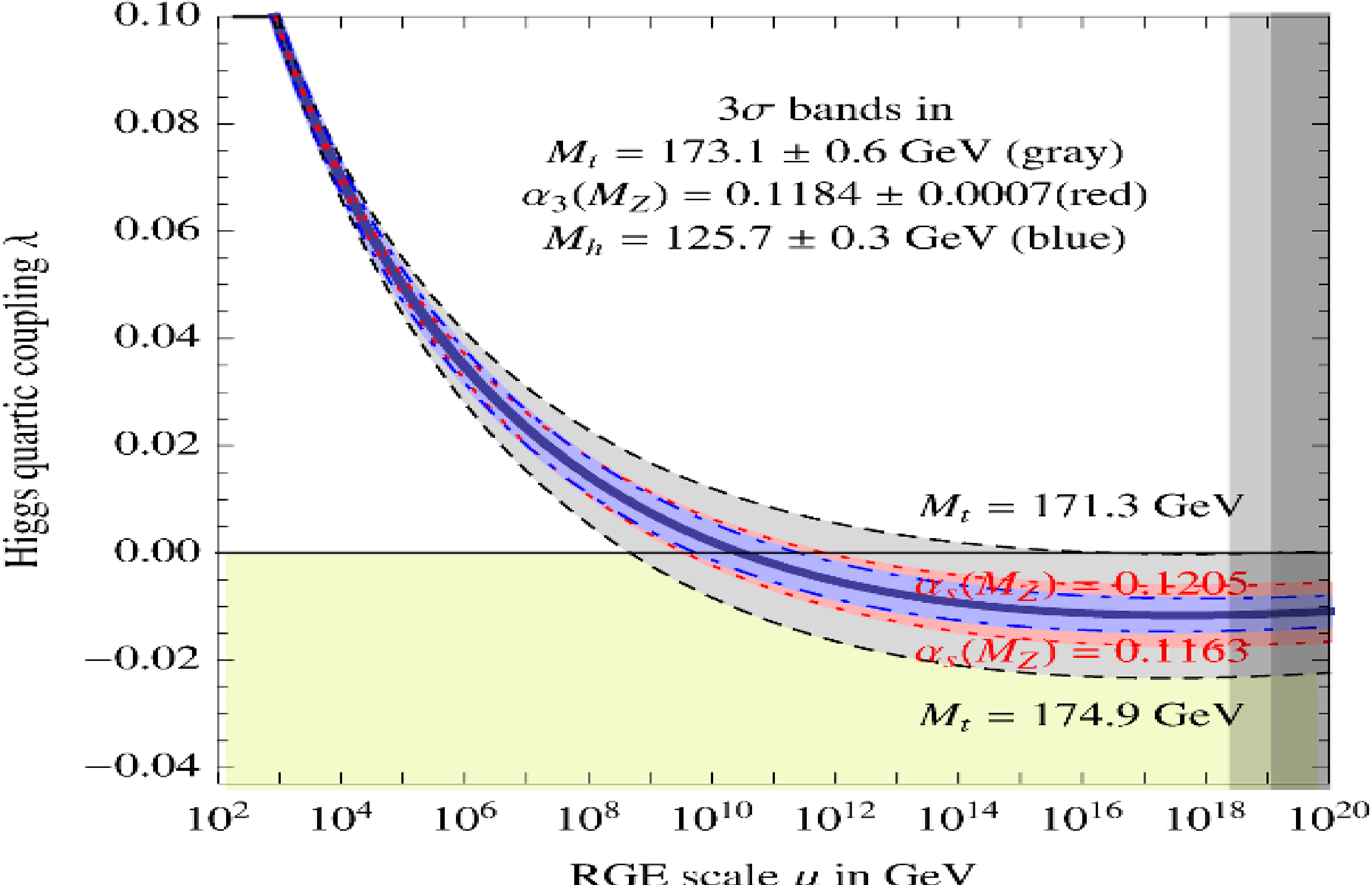
- Instability problem with $m_H = 125 - 126 \text{ GeV}$

Quartic coupling is running to negative below Planck mass

*But, this result is very sensitive to other inputs (top pole mass, QCD coupling)

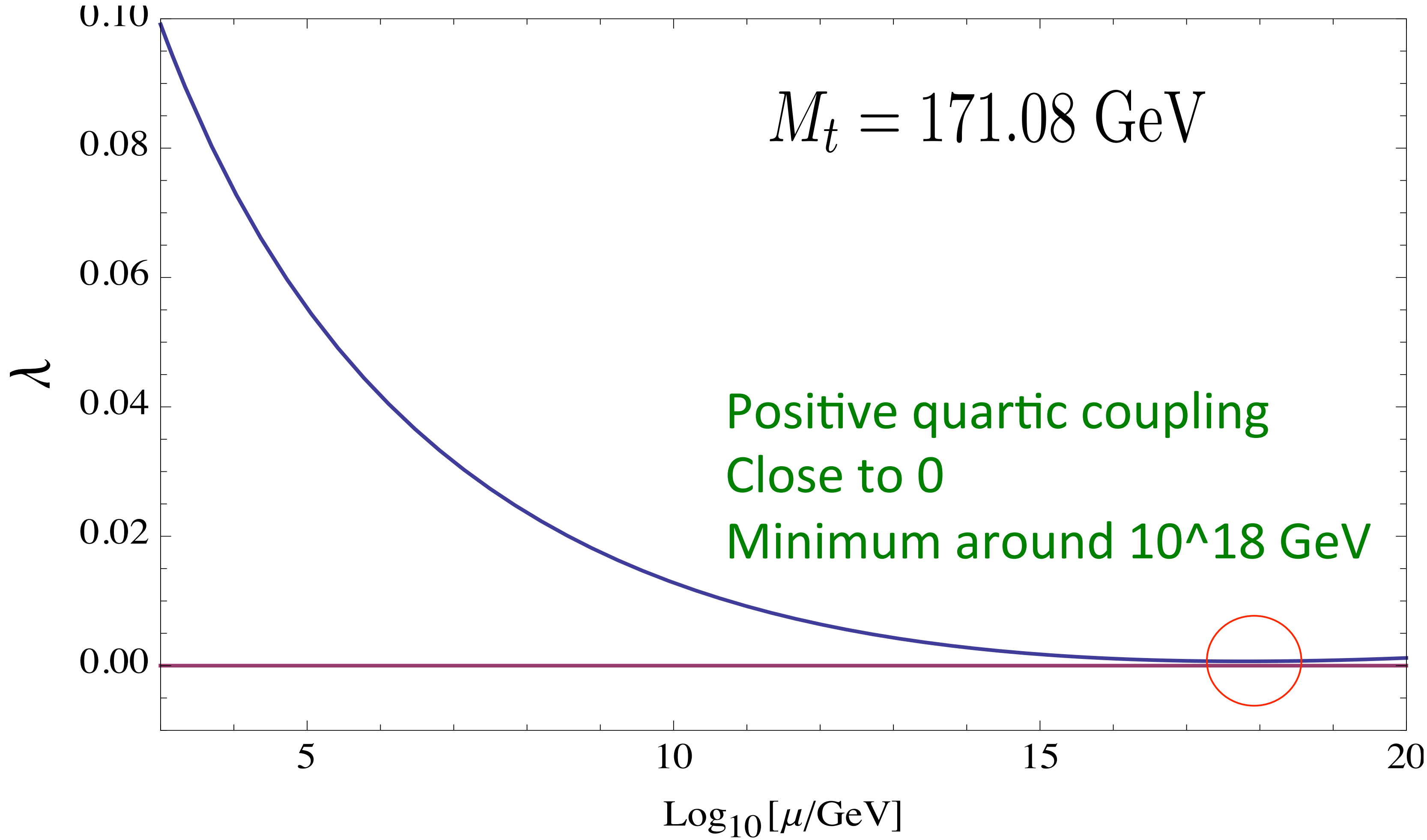
Update of RGE analysis (@ 3-loop level)

Buttazzo et al., JHEP 12 (2013) 089



Two ways to avoid the instability problem

(1) Use input top pole mass as low as possible

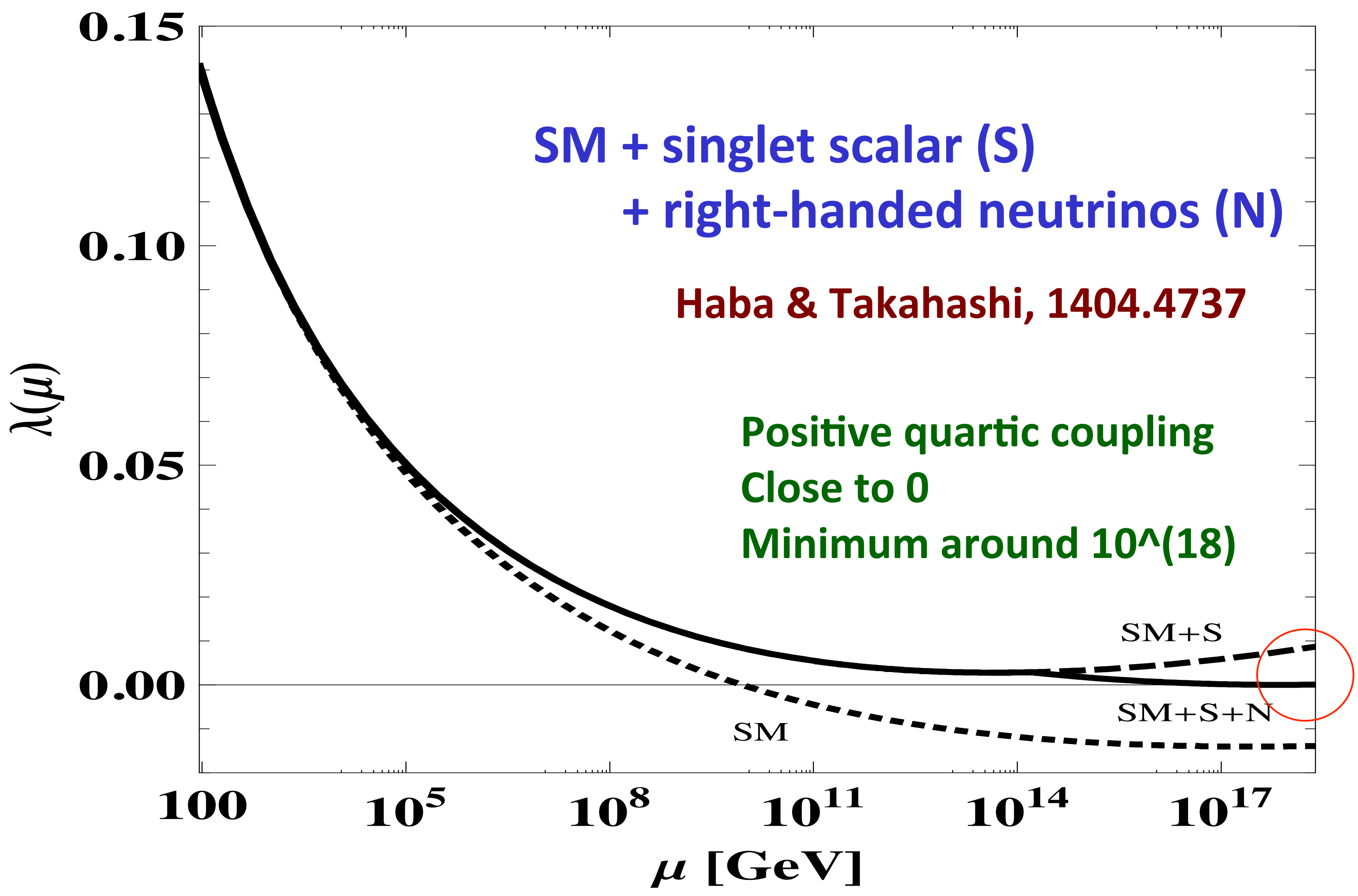


*** Combined LHC & Tevatron (1403.4427) :** $M_t = 173.34 \pm 0.76$ GeV

Two ways to avoid the instability problem

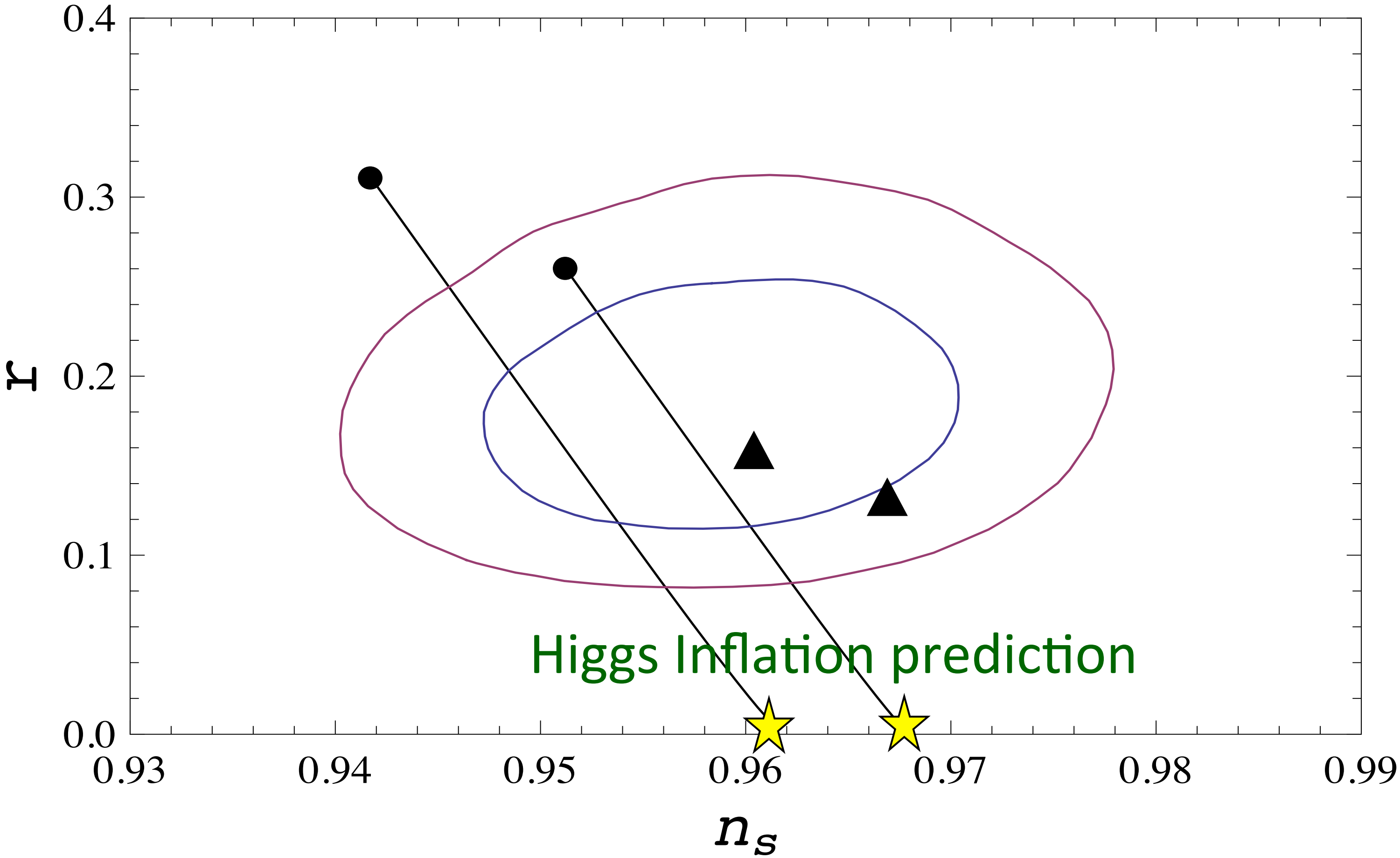
(2) SM supplemented by new physics

Combined LHC & Tevatron (1403.4427) : $M_t = 173.34 \pm 0.76\ \mathrm{GeV}$



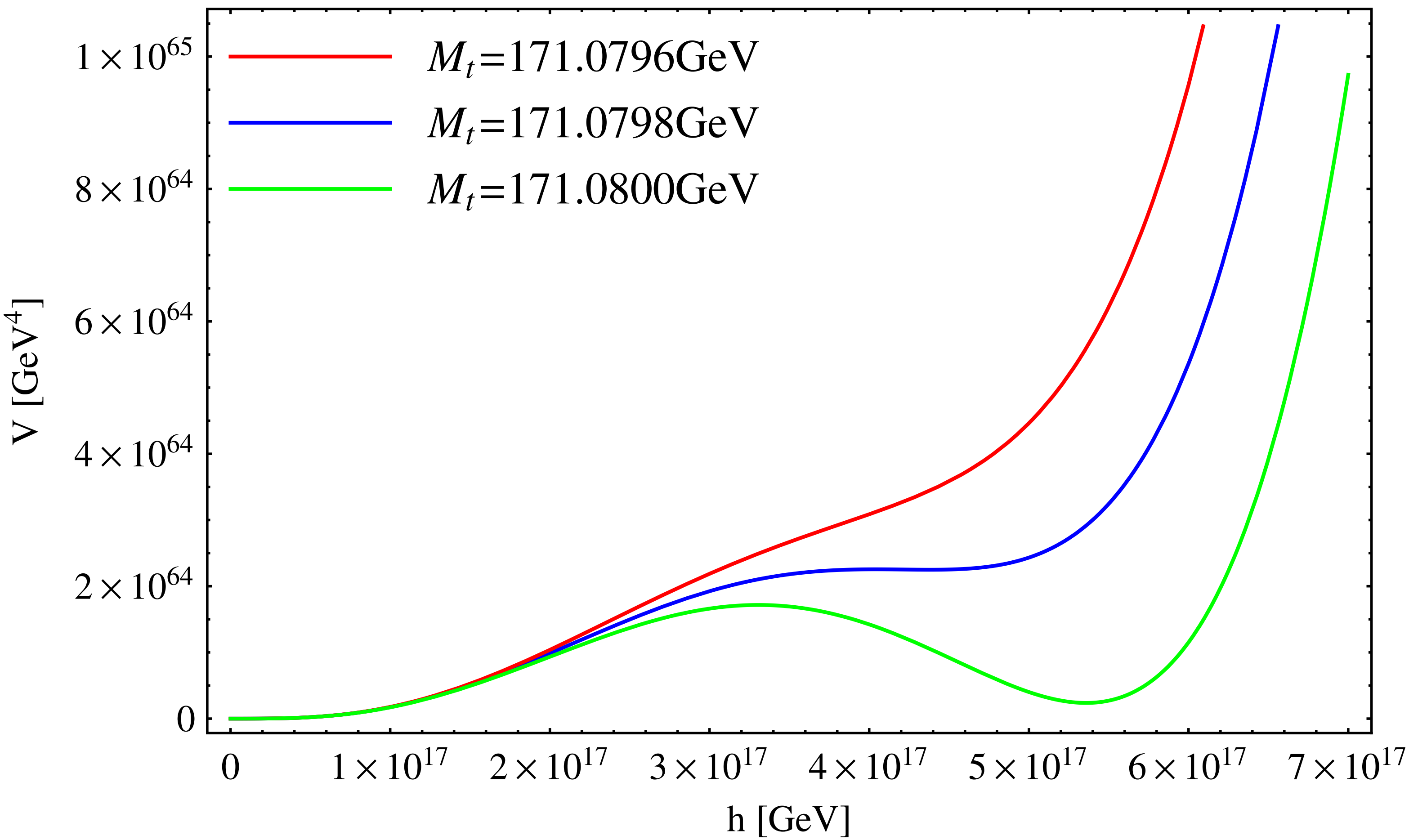
Impact of BICEP2 result on Higgs Inflation

- Avoiding the instability is not enough
- Quartic coupling is not that small (10^(-12)), so that r << 0.1 by simple analysis

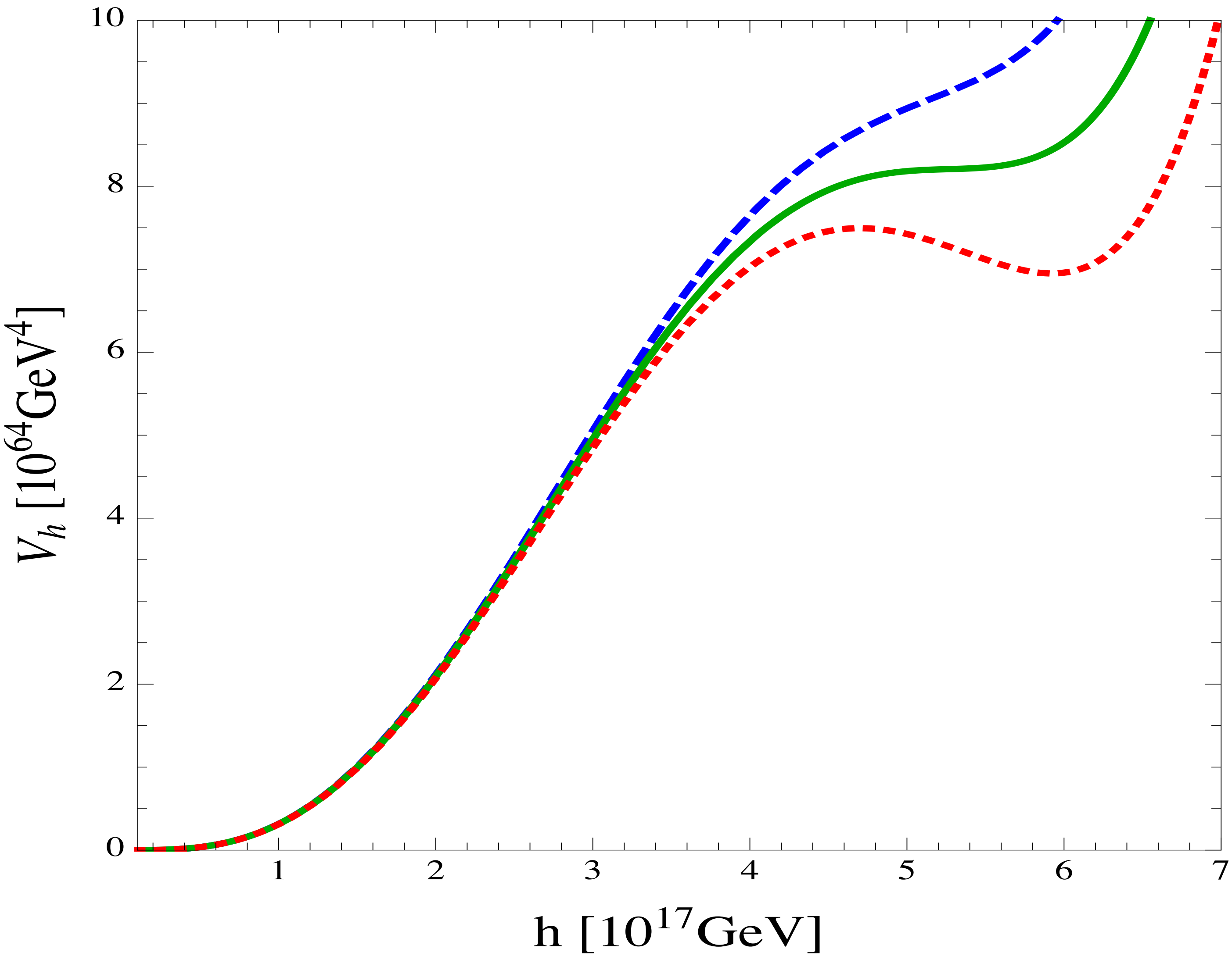


Changing a potential shape by RGE running with tuning of Input parameters (both (1) & (2))

$$V_{\text{eff}} = \lambda(\phi)\phi^4$$



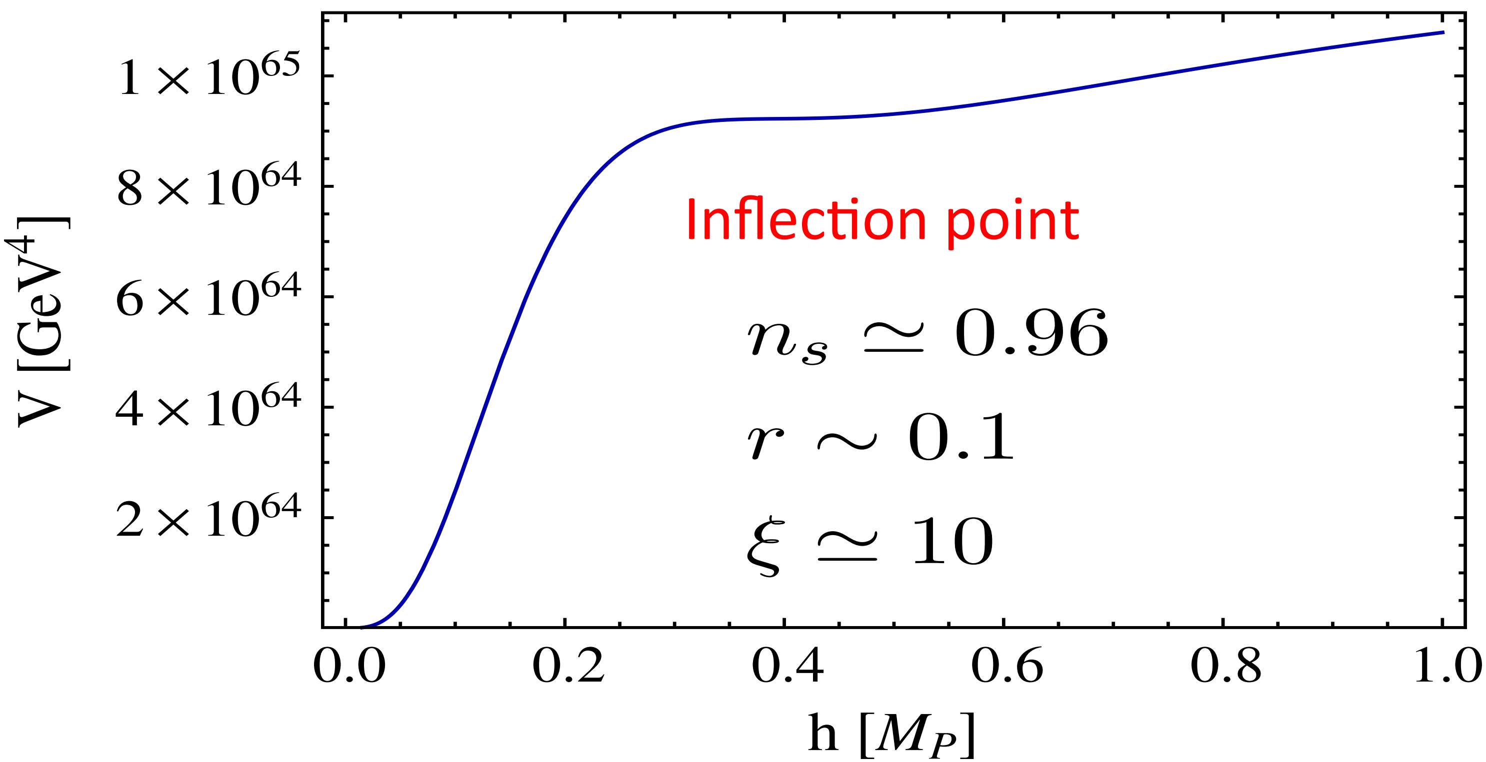
Then, introduction of non-minimal gravitational coupling

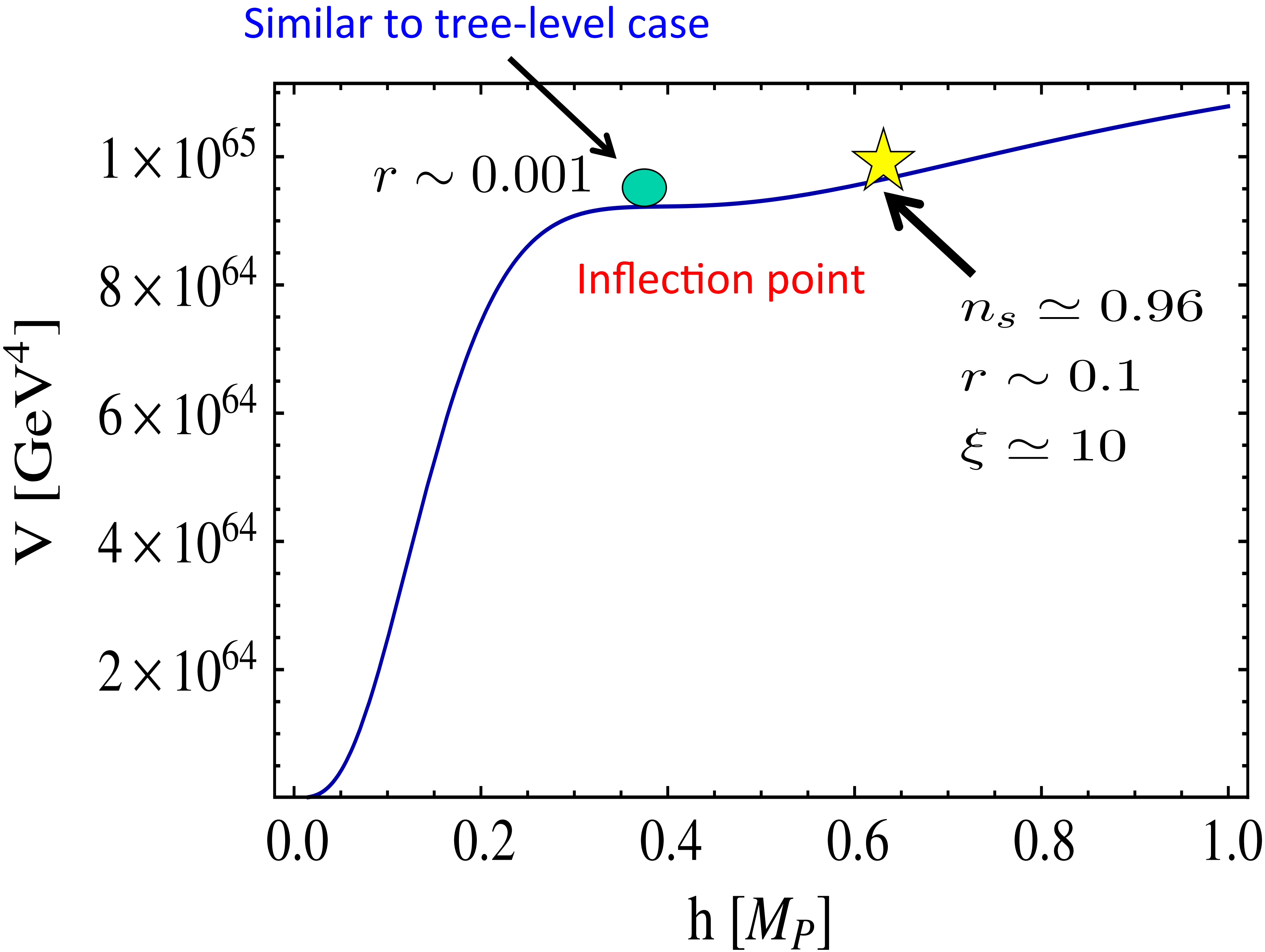


Workable case

(1) SM with a low Mt: Hamada, Kawai, Oda & Park, PRL 112 (2014) 241301
Bezrukov & Shaposhnikov, 1403.6078

(2) Supplement by NP: Haba & Takahashi, 1404.4737)
Ko & Park, 1405.1635)




Similar to tree-level case
$r \sim 0.001$
Inflection point
$n_s \simeq 0.96$
$r \sim 0.1$
$\xi \simeq 10$
1×10^{65}
8×10^{64}
6×10^{64}
4×10^{64}
2×10^{64}
V [GeV^4]
0.0
0.2
0.4
0.6
0.8
1.0
h [M_P]

Higgs Inflation after the Higgs discovery & BICEP2 result

Higgs Inflation scenario is still a viable scenario by

- Avoiding the instability problem in SM or SM + X+Y..
- Introducing Non-minimal gravitational coupling
- Tuning input parameters to realize the inflection point
- Arrange initial inflaton VEV bit higher

Doable, but technically complicated……

SUSY extension of the Higgs Inflation Scenario

SUSY (Supergravity)

- Well-motivated to stabilize the EW scale
- Dark matter candidates (neutralino, gravitino, sneutrino etc.
- Quantum corrections are more controllable
- Local SUSY (supergravity) includes gravity

Difference from non-SUSY case

- Not only one Higgs doublet
- D-flat direction → inflaton is a linear combination of Higgses & other scalars
- Not easy to make inflaton potential flat

Simple realization of Higgs inflation in SUGRA

NMSSM Ferrara, Kallosh, Linde, Marrani & Van Proeyen, Phys.Rev. D82 (2010) 045003

Superconformal framework of SUGRA
(superfield formalism of SUGRA)

Compensating multiplet: $\Sigma = 1 + \theta^2 F_\Sigma$

$$\mathcal{L} = \int d^4\theta \Sigma^\dagger \Sigma \left(-3\Phi\right) + \left[\int d^2\theta \Sigma^3 W + \text{h.c.}\right] \Rightarrow -\frac{1}{2}\Phi\mathcal{R} + \text{kinetic terms} - \sum_i \left|\frac{\partial W}{\partial \phi_i}\right|^2$$

NMSSM

$$\Phi = 1 \underbrace{- \frac{1}{3}\left(|H_u|^2 + |H_d|^2 + |S|^2\right)}_{\text{canonical kinetic terms}} + \underbrace{\frac{\gamma}{2}\left(H_u H_d + \text{h.c.}\right)}_{\text{new term}}$$

$$W = y S H_u H_d$$

D-flat direction: $H_u = \frac{1}{2}\begin{pmatrix} 0 \\ \varphi \end{pmatrix},\ H_d = \frac{1}{2}\begin{pmatrix} \varphi \\ 0 \end{pmatrix}$

$$S = 0$$

$$-\frac{1}{2}\Phi\mathcal{R} + \text{kinetic terms} \Rightarrow -\frac{1}{2}\left(1+\xi\varphi^2\right)\mathcal{R} + \frac{1}{2}(\partial\varphi)^2$$

with $\xi = \frac{\gamma}{4} - \frac{1}{6}$

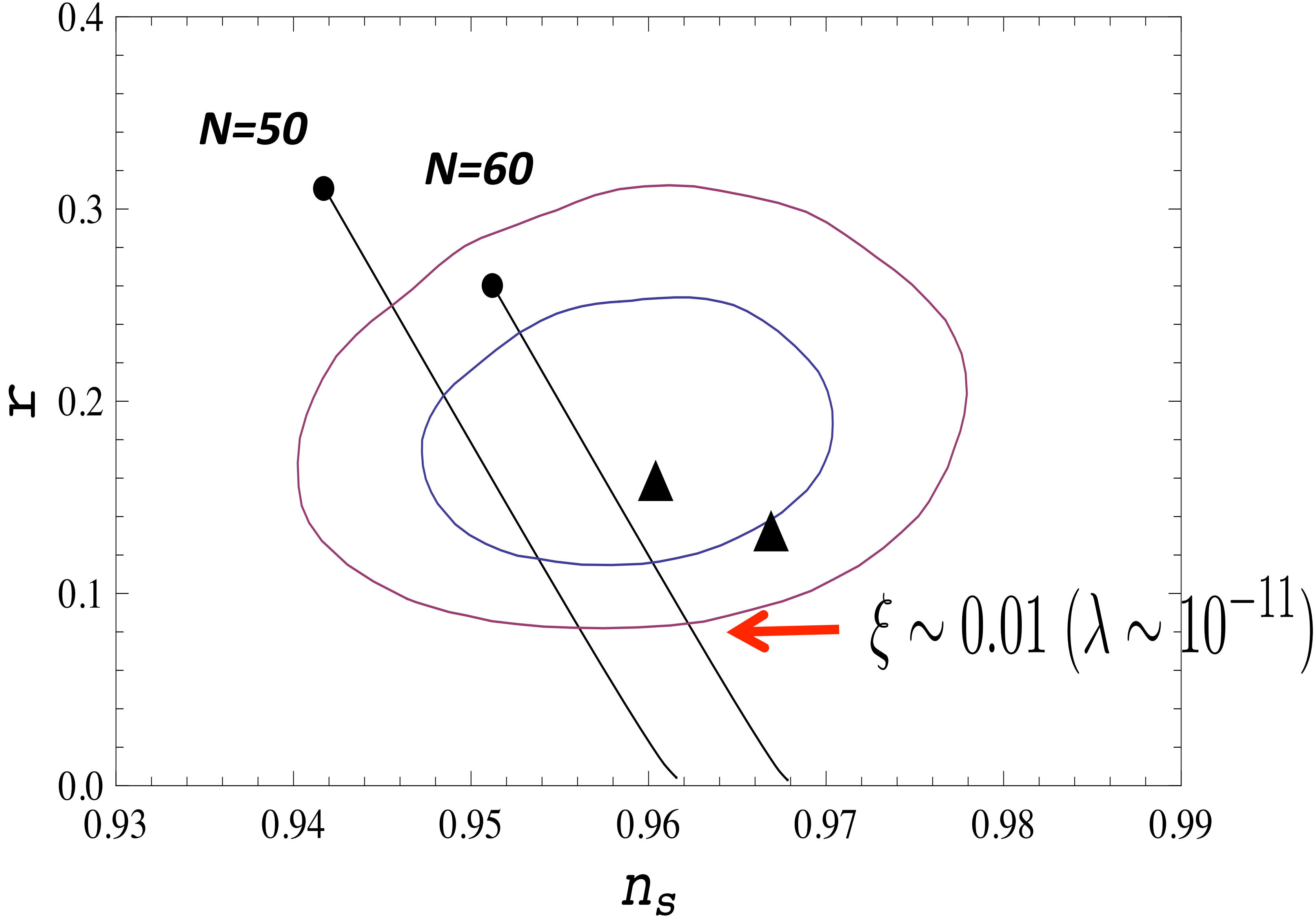
$$W = ySH_uH_d \Rightarrow V = \frac{y^2}{16}\varphi^4$$

Nothing but the quartic potential model with non-minimal coupling!

- SUSY nature: quartic coupling is not a fundamental parameter

$$y^2 \leftrightarrow \lambda$$

Useing a suitable y value



Same structure but more motivated extension of MSSM?

HL-inflation
In Seesaw Extended MSSM

Kawai & N.O., 1404.1450, to appear in PLB

Basic idea → replacement

$$H_d \to L = \frac{1}{2}\begin{pmatrix} \varphi \\ 0 \end{pmatrix}$$

$S \to N^c$: SM singlet (type I seesaw)

or

T^c : SU(2) triplet (type III seesaw)

Type I seesaw case:

$$\Phi = 1 - \frac{1}{3}\left(|H_u|^2 + |L|^2 + |N^c|^2\right) + \frac{\gamma}{2}\left(H_u L + \mathrm{h.c.}\right)$$

$$W = y_D N^c H_u L + \frac{1}{2} M N^c N^c$$

Type III seesaw case:

$$\Phi = 1 - \frac{1}{3}\left(|H_u|^2 + |L|^2 + \mathrm{tr}[|T^c|^2]\right) + \frac{\gamma}{2}\left(H_u L + \mathrm{h.c.}\right)$$

$$W = y_D H_u T^c L + \frac{1}{2} M \,\mathrm{tr}\left[T^c T^c\right]$$

Structure for the inflations are the same

What is interesting?

- Seesaw mechanism: $m_\nu = \frac{y_D^2}{M} v_u^2 \simeq \frac{y_D^2}{M} v^2$

  In normal hierarchy, we may use

  $$m_\nu^2 = \Delta m_{23}^2 = 2.32 \times 10^{-3}\ \mathrm{eV}^2$$

  so that $$y_D = \left(\frac{M}{6.29 \times 10^{14}\ \mathrm{GeV}} \right)^{1/2}$$

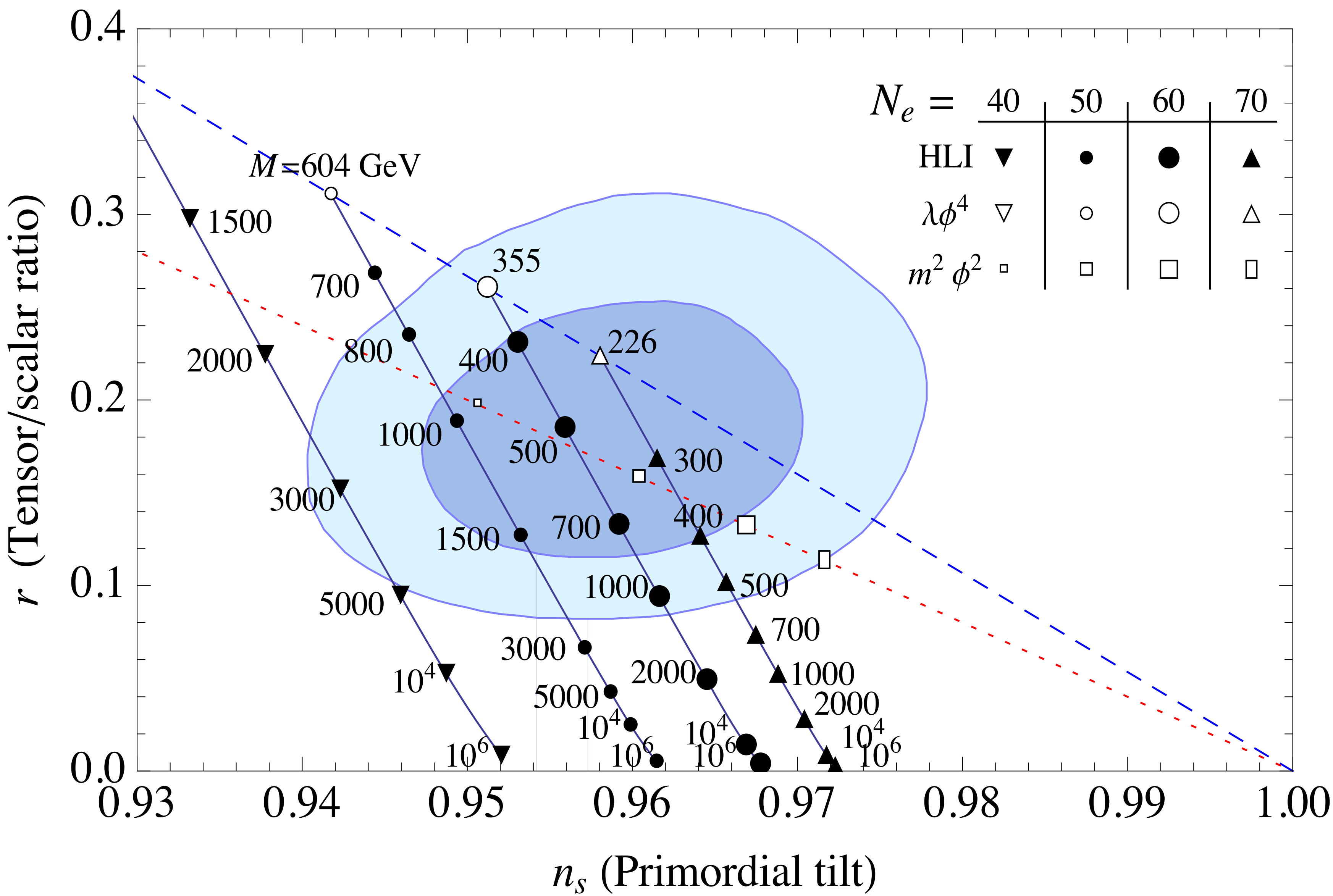
- In quartic potential model with non-minimal coupling, inflationary predictions ←→ quartic coupling

- In the seesaw extended model,

$$\lambda = y_D^2 = \frac{M}{6.29 \times 10^{14}\ \mathrm{GeV}}$$

BICEP2 result constrains the seesaw scale!

Kawai & N.O., 1404.1450, to appear in PLB



BICEP2 bounds on singlet/triplet RH neutino masses

N=50

$$927\ \text{GeV} < M < 1.62\ \text{TeV} \qquad (68\%\ \text{CL})$$
$$751\ \text{GeV} < M < 2.37\ \text{TeV} \qquad (95\%\ \text{CL})$$

N=60

$$391\ \text{GeV} < M < 795\ \text{GeV} \qquad (68\%\ \text{CL})$$
$$355\ \text{GeV} < M < 1.10\ \text{TeV} \qquad (95\%\ \text{CL})$$

- Current LHC bound on triplet mass, M > 254 GeV, (95% CL, ATLAS collaboration with 8 TeV LHC, 5.8/fb)
- Search reach of 14 TeV LHC is M=750 GeV

del Aguila & Aguilar-Saavedra, NPB 813 (2009) 22

More on HL-Inflation phenomenology

- Reheating through Higgs boson decay, $T_{\rm rh} \lesssim 10^7 \ \mathrm{GeV}$

- Baryogenesis via resonant leptogenesis @ TeV

- R-parity violating bilinear term via SUSY breaking

$$\int d^4\theta \Sigma^\dagger \Sigma \frac{\gamma}{2} L H_u \to \int d^2\theta \frac{\gamma}{2} F_\Sigma L H_u \sim \int d^2\theta m_{3/2} L H_u$$

Cosmological bound: $m_{3/2} \lesssim 1 \ \mathrm{MeV}$

- Gravitino dark matter

Summary

- Inflationary universe is the standard paradigm in modern cosmology and consistent with the current observations
- Inflation takes place at very high energy and it should be interesting if inflationary scenario has some relations to low energy physics
- In Higgs inflation, Higgs plays the role of inflaton and offers relations between EW observables and inflationary predictions
- After the Higgs boson discovery and BICEP2 result, realization of Higgs inflation is possible but (technically) non-trivial

Summary (cont'd)

- We have also discussed SUSY extension of Higgs inflation, which is in fact very simple, but we need to extend MSSM
- HL-Inflation is a scenario realized in seesaw extended MSSM
- Via seesaw mechanism and the neutrino oscillation data, inflationary predictions are controlled by the seesaw scale
- BICEP2 result constrains right-handed neutrino mass,
- In type III seesaw extension, a large potion of the parameter space consistent w/ BICEP2 can be explored by 14 TeV LHC
- Implications to cosmology (leptogenesis, DM)

Thank you very much

for your attention!