Standard Model Inflation and Beyond

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ΛCDM Model (current paradigm)

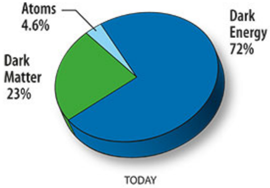
Λ stands for Dark Energy with Einstein's cosmological constant being the leading candidate

($P_\Lambda = w_\Lambda \rho_\Lambda$, with $w_\Lambda = -1$)

$$\rho_{Total} = \rho_\Lambda + \rho_{CDM} + \rho_M \approx \rho_c$$

$$\rho_\Lambda \approx 10^{-120} m_P^4$$ ⟵ Fine tuning?

CDM denotes 'cold dark matter' (particle have tiny velocities)



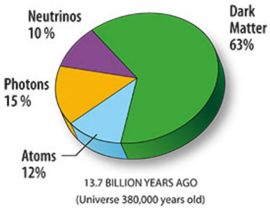
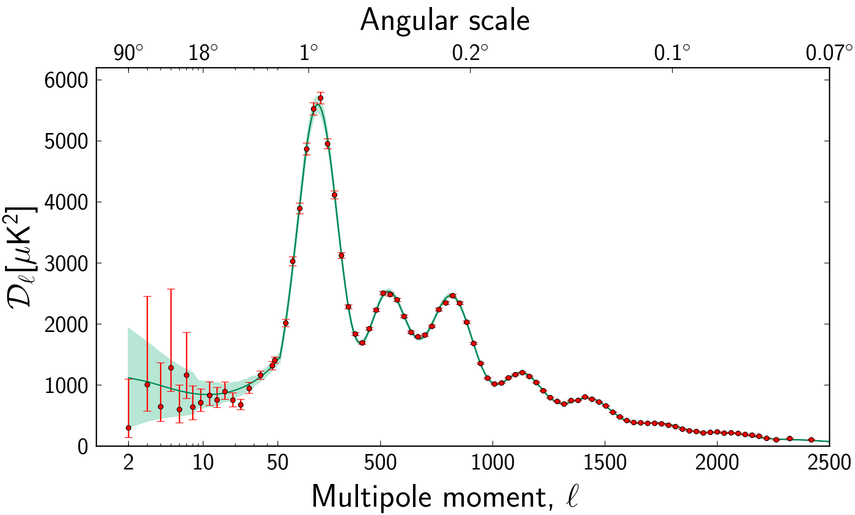


Image courtesy of NASA / WMAP Science Team

Where does ΛCDM come from?



Planck 2013 (arXiv:1303.5075), Planck 2015 in preparation.

Cosmological Problems

- Flatness Problem

Present energy density of the universe is determined to be equal to its critical value corresponding to a flat universe. This means that in the early universe

$$\Omega - 1 = \frac{k}{(aH)^2} \propto t \qquad \text{(for a radiation dominated universe)}$$

$$\Rightarrow \quad |\Omega_{BBN} - 1| \leq 10^{-16} \qquad \left(|\Omega_{GUT} - 1| \leq 10^{-55} \right)$$

How does this come about?

Horizon Problem

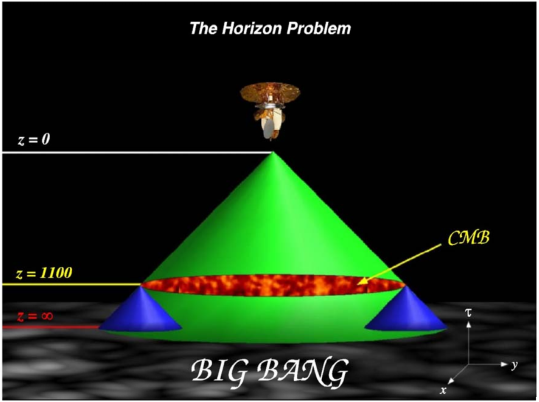


Image courtesy of W. Kinney

Why the CMB is so uniform on large scales?

- Origin of primordial density fluctuation which lead to Large Scale Structure and also explain

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

observed by COBE/WMAP and other experiments?

- Origin of baryon asymmetry ($n_b/n_\gamma \sim 10^{-10}$)?

Inflationary Cosmology

[Guth, Linde, Albrecht & Steinhardt, Starobinsky, Mukhanov, Hawking, . . .]

Successful Primordial Inflation should:

- Explain flatness, isotropy;
- Provide origin of $\frac{\delta T}{T}$;
- Offer testable predictions for n_s, r, $dn_s/d\ln k$;
- Recover Hot Big Bang Cosmology;
- Explain the observed baryon asymmetry;
- Offer plausible CDM candidate;

Physics Beyond the SM?

Cosmic Inflation

- Inflation can be defined as:

$$\frac{d}{dt}\left(\frac{1}{aH}\right) < 0,$$ a decreasing comoving horizon

$$\ddot{a} > 0,$$ an accelerated expansion

$$P < -\rho/3,$$ a negative pressure → repulsive gravity → drives inflation

- Consider a scalar field ϕ

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi) \approx V,$$

$$a(t) \approx e^{Ht}$$ → inflation

Slow rolling scalar field acts as an inflaton

Cosmic Inflation

Tiny patch ~10^{-28} cm ⇨ > 1 cm after 60 e-foldings (time constant ~10^{-38} sec)

Inflation over ⇨ radiation dominated universe (hot big bang)

Quantum fluctuations of inflation field give rise to nearly scale invariant, adiabatic, Gaussian density perturbations

⇨ Seed for forming large scale structure

- Solution to the Flatness Problem $\left(\Omega - 1 = \frac{k}{(aH)^2}\right)$

$$\boxed{\left|\Omega_f - 1\right| = \left|\Omega_i - 1\right| e^{-2N} \to 0,}$$

where $N = H\Delta t \geq 50$

- Solution to the Horizon Problem

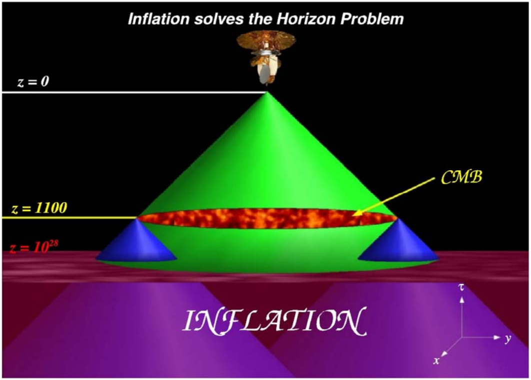


Image courtesy of W. Kinney

Slow-roll Inflation

- Inflation is driven by some potential $V(\phi)$:
- Slow-roll parameters:

$$\epsilon = \frac{m_p^2}{2}\left(\frac{V'}{V}\right)^2, \ \eta = m_p^2\left(\frac{V''}{V}\right).$$

- The spectral index n_s and the tensor to scalar ratio r are given by

$$n_s - 1 \equiv \frac{d\ln\Delta_{\mathcal{R}}^2}{d\ln k}, \ r \equiv \frac{\Delta_h^2}{\Delta_{\mathcal{R}}^2},$$

  where Δ_h^2 and $\Delta_{\mathcal{R}}^2$ are the spectra of primordial gravity waves and curvature perturbation respectively.
- Assuming slow-roll approximation (i.e. $(\epsilon, |\eta|) \ll 1$), the spectral index n_s and the tensor to scalar ratio r are given by

$$n_s \simeq 1 - 6\epsilon + 2\eta, \ r \simeq 16\epsilon.$$

- The tensor to scalar ratio r can be related to the energy scale of inflation via

$$V(\phi_0)^{1/4} = 3.3 \times 10^{16}\, r^{1/4} \text{ GeV}.$$

- The amplitude of the curvature perturbation is given by

$$\Delta^2_{\mathcal{R}} = \frac{1}{24\pi^2}\left(\frac{V/m_p^4}{\epsilon}\right)_{\phi=\phi_0} = 2.43 \times 10^{-9} \text{ (WMAP7 normalization)}.$$

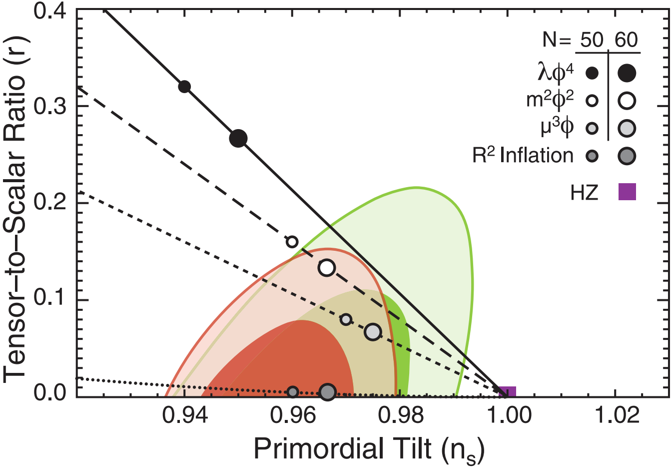
- The spectrum of the tensor perturbation is given by

$$\Delta^2_h = \frac{2}{3\,\pi^2}\left(\frac{V}{m_P^4}\right)_{\phi=\phi_0}.$$

- The number of e-folds after the comoving scale $l_0 = 2\,\pi/k_0$ has crossed the horizon is given by

$$N_0 = \frac{1}{m_p^2}\int_{\phi_e}^{\phi_0}\left(\frac{V}{V'}\right) d\phi.$$

Inflation ends when $\max[\epsilon(\phi_e), |\eta(\phi_e)|] = 1$.

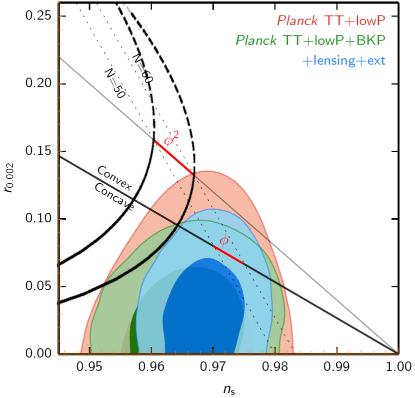


WMAP nine year data

BICEP 2 Result

- BICEP 2 a few months ago surprised many people with their results that $r \sim 0.2$ (0.16).
- Some tension with the Planck upper bound $r < 0.11$.
- Somewhat earlier WMAP 9 stated that $r < 0.13$.

Radiatively Corrected ϕ^2 Potential:



n_s vs. r for radiatively corrected ϕ^2 potential, superimposed on Planck and Planck+BKP 68% and 95% CL regions taken from arXiv:1502.01589. The dashed portions are for $\kappa < 0$. N is taken as 50 (left curves) and 60 (right curves).

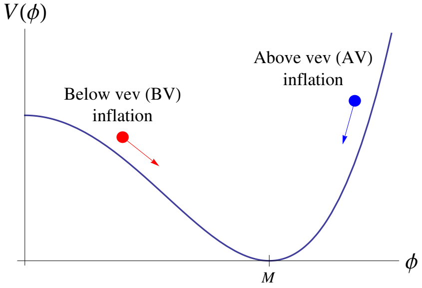
Tree Level Gauge Singlet Higgs Inflation

[Kallosh and Linde, 07; Rehman, Shafi and Wickman, 08]

- Consider the following Higgs Potential:

$$V(\phi) = V_0 \left[1 - \left(\frac{\phi}{M}\right)^2\right]^2 \quad \longleftarrow \text{(tree level)}$$

Here ϕ is a gauge singlet field.

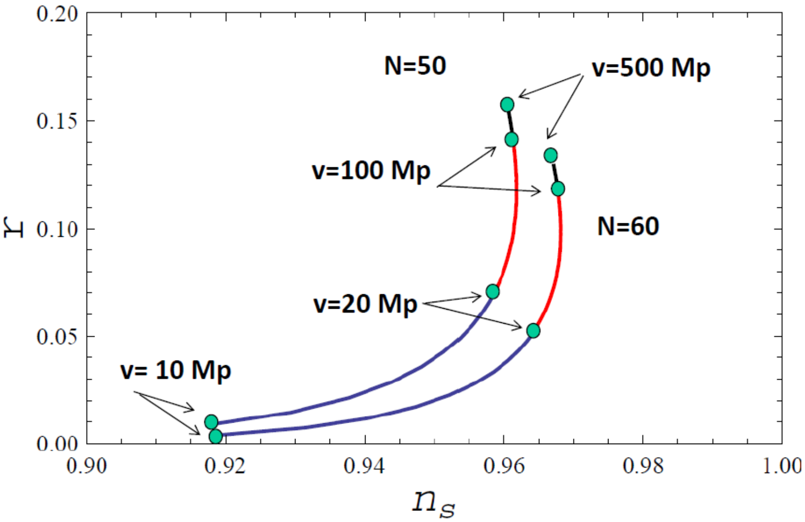


- WMAP/Planck data favors BV inflation ($r \lesssim 0.1$).

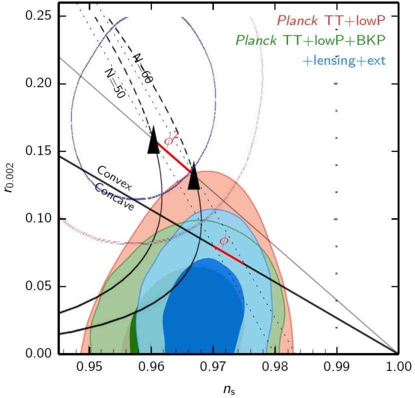
Inflation of the B-L scalar field:

$$V = \frac{1}{4}\lambda(\phi^2 - v^2)^2 \text{ , where } \phi/\sqrt{2} = \mathcal{R}[\phi]$$

We consider inflation with the initial inflation VEV: $\phi < v$

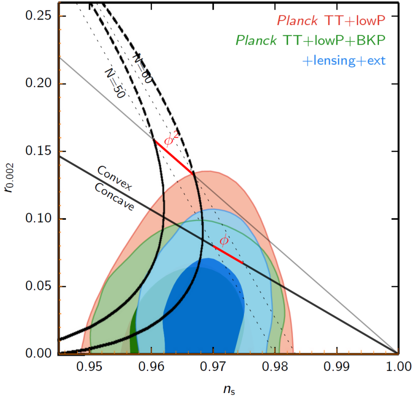


Higgs Potential:



n_s vs. r for Higgs potential, superimposed on Planck and Planck+BKP 68% and 95% CL regions taken from arXiv:1502.01589. The dashed portions are for $\phi > v$. N is taken as 50 (left curves) and 60 (right curves).

Coleman–Weinberg Potential:

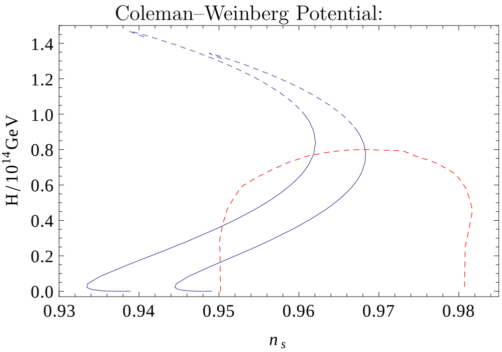


n_s vs. r for Coleman–Weinberg potential, superimposed on Planck and Planck+BKP 68% and 95% CL regions taken from arXiv:1502.01589. The dashed portions are for $\phi > v$. N is taken as 50 (left curves) and 60 (right curves).

Coleman–Weinberg Potential:

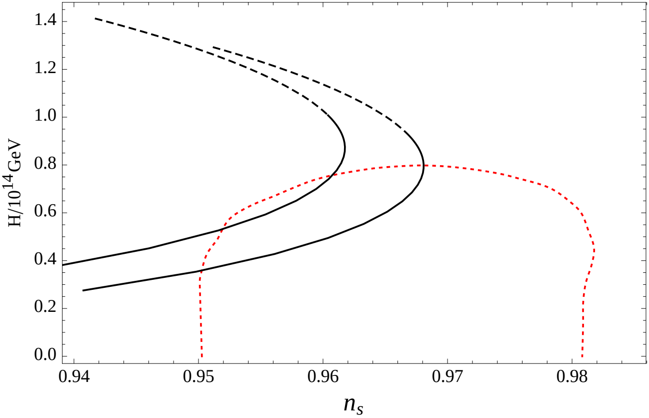
n_s ($N = 50$)	r ($N = 50$)	n_s ($N = 60$)	r ($N = 60$)
0.935	0.00112	0.946	0.00112
0.952	0.026	0.961	0.0254
0.958	0.0498	0.966	0.0471
0.961	0.0712	0.968	0.0652
0.961	0.141	0.968	0.119
0.96	0.161	0.967	0.134
0.956	0.208	0.964	0.171
0.951	0.256	0.959	0.211
0.94	0.324	0.95	0.27
0.939	0.33	0.949	0.276
0.94	0.32	0.95	0.268

- Where does ϕ come from?
  (1) Associated with spontaneous breaking of global $U(1)_{B-L}$, $U(1)_X$ in $SU(5)$, or $U(1)_L$ (majoran dark matter);
  (2) Breaks gauged $U(1)_{B-L}$ (in this case B-L gauge coupling should be $\lesssim 10^{-3}$);
  (3) Associated with $U(1)_{PQ}$ if we employ non-minimal coupling to gravity.
- Topological Defects:
  Cosmic strings and magnetic monopoles may survive inflation if the symmetry breaking scale is comparable to H (Hubble constant) during inflation.
- Example: $SO(10) \to SU(4)_C \times SU(2)_L \times SU(2)_R \to SU(3)_C \times SU(2)_L \times U(1)_Y$.
  Second breaking yields monopoles carrying two units of Dirac magnetic charge.



n_s vs. H for Coleman–Weinberg potential, superimposed on Planck TT+lowP+BKP 95% CL region taken from arXiv:1502.02114. The dashed portions are for $\phi > v$. N is taken as 50 (left curves) and 60 (right curves).

Higgs Potential:



Quartic potential with non-minimal gravitational coupling

Jordan frame:

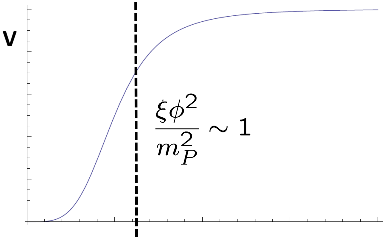
$$S_J^{\rm tree} = \int d^4x\sqrt{-g}\left[-\left(\frac{1+\xi\phi^2}{2}\right)\mathcal{R} + \frac{1}{2}(\partial\phi)^2 - \frac{\lambda}{4!}\phi^4\right]$$

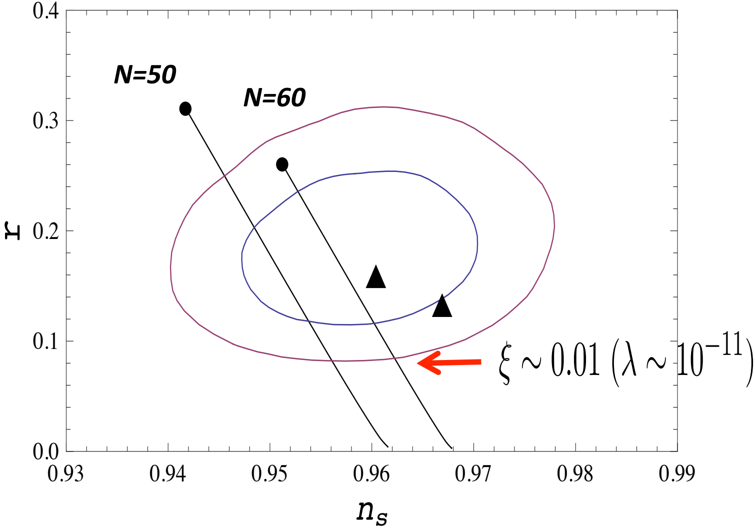
Einstein frame:

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

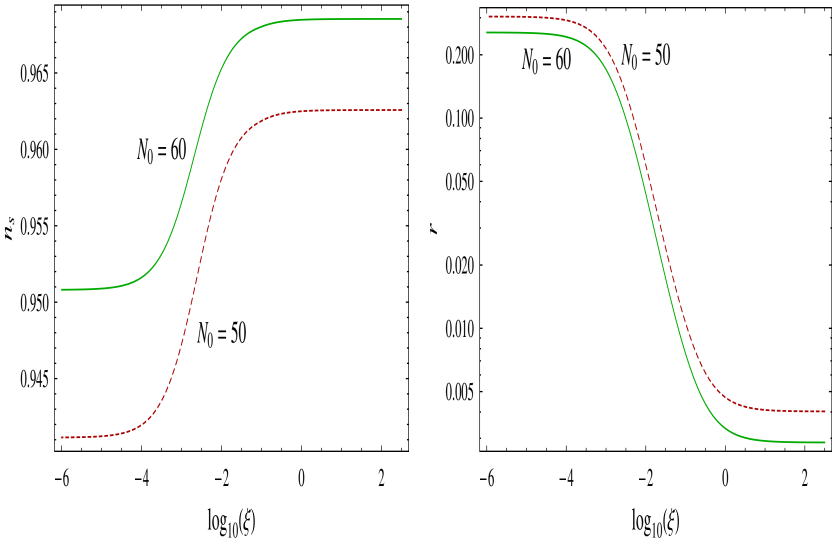
$$\left(\frac{d\sigma}{d\phi}\right)^{-2} = \frac{\left(1+\xi\phi^2\right)^2}{1+(6\xi+1)\xi\phi^2}$$

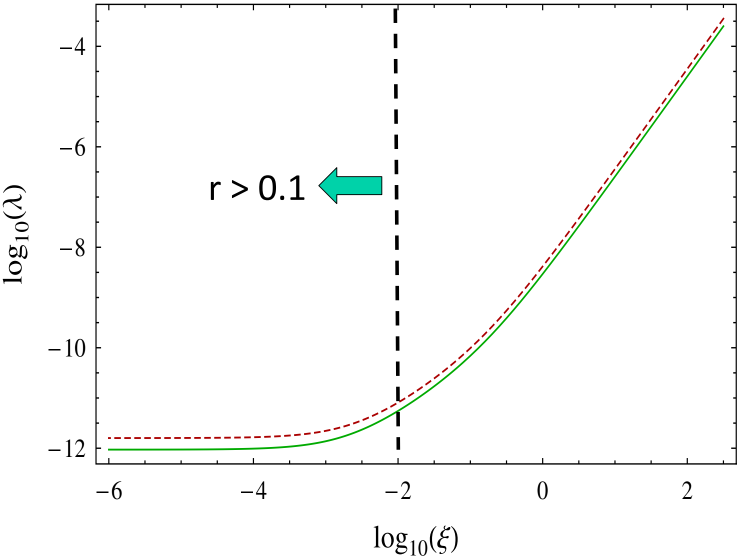
$$V_E = \frac{\frac{1}{4!}\lambda\phi^4}{\left(1+\frac{\xi\phi^2}{m_P^2}\right)^2}$$




N=50
N=60
$\xi \sim 0.01 \; (\lambda \sim 10^{-11})$
r
n_s
0.4
0.3
0.2
0.1
0.0
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
log10(λ)
log10(ξ)
−4
−6
−8
−10
−12
−6
−4
−2
0
2

Higgs Inflation (before Higgs discovery)

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

quartic potential model with non-minimal gravitational coupling

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

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

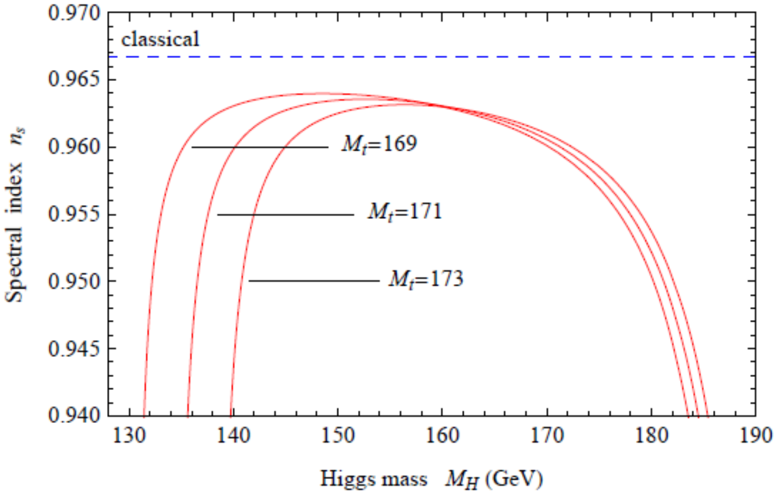
Quartic coupling suitable for a suitable Higgs mass of O(100 GeV) is realized with a large non-minimal coupling

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

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

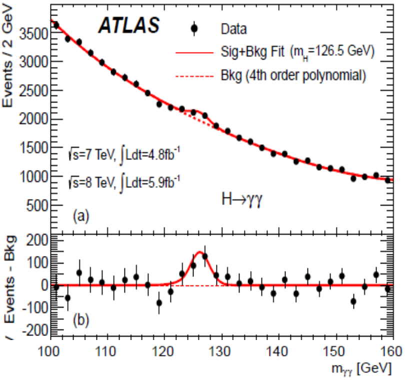
Analysis beyond tree-level (RGE improved effective potential at 2-loop level)

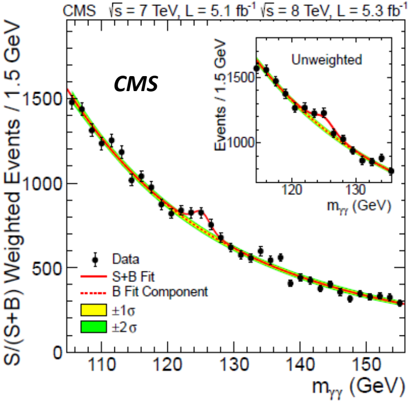
De Simone, Hertzberg & Wilczek, PLB 678 (2009)1; Barvinsky et al., JCAP 0912 (2009) 003



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.





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

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

Higgs Inflation (after Higgs discovery at LHC)

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

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

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

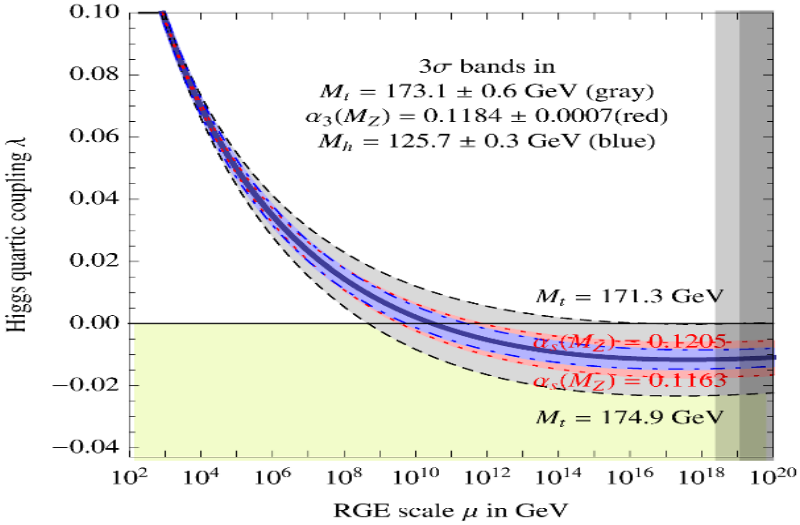
- Instability problem with $m_H = 125 - 126\ \mathrm{GeV}$

Quartic coupling turns negative below Planck mass ;

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

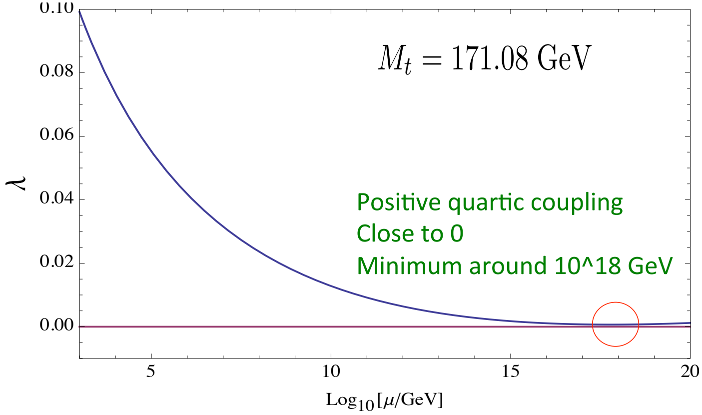
Update of RGE analysis (@ 3-loop level)

Buttazzo et al., JHEP 12 (2013) 089



Two ways to avoid the instability problem

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

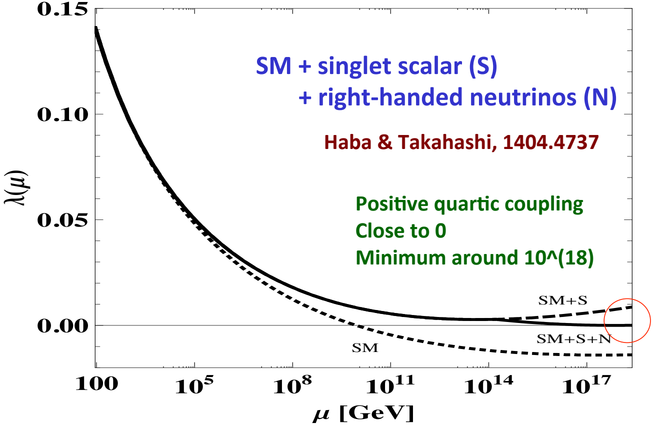


*** Combined LHC & Tevatron (1403.4427) :** $M_t = 173.34 \pm 0.76$ GeV

Two ways to avoid the instability problem

(2) SM supplemented by new physics

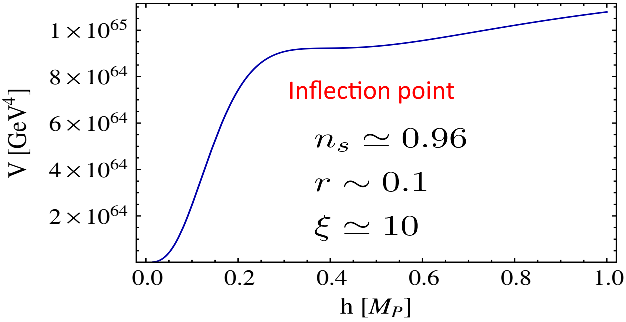
Combined LHC & Tevatron (1403.4427) : $M_t = 173.34 \pm 0.76$ GeV

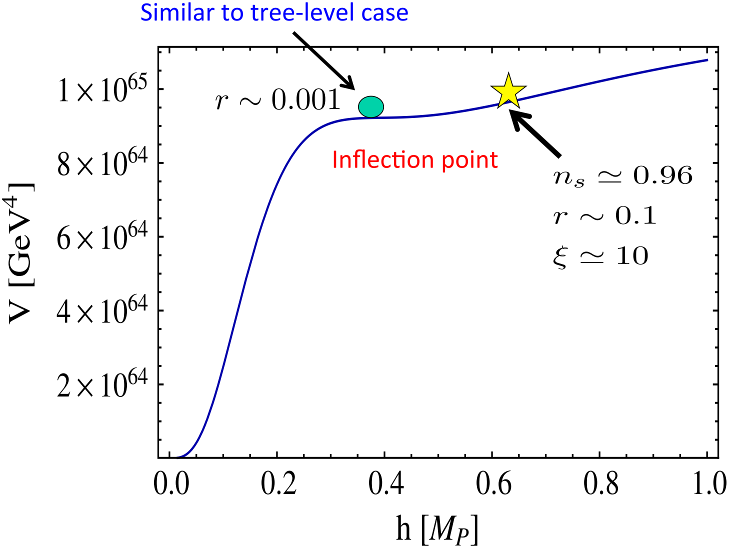


Workable case

(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

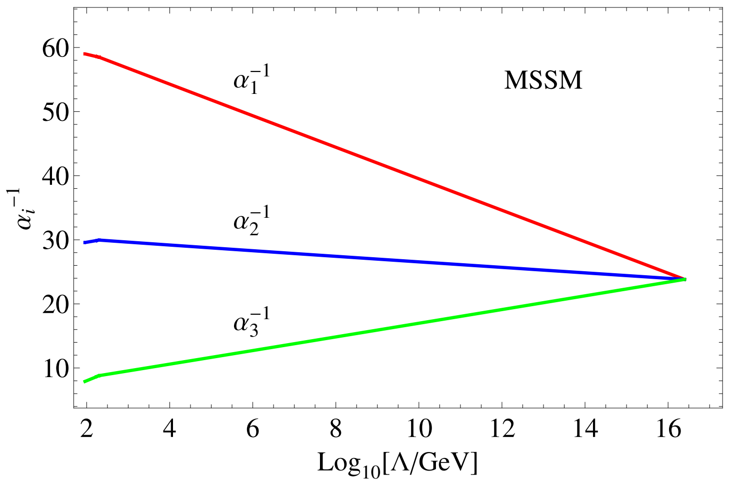
Doable, but technically complicated……

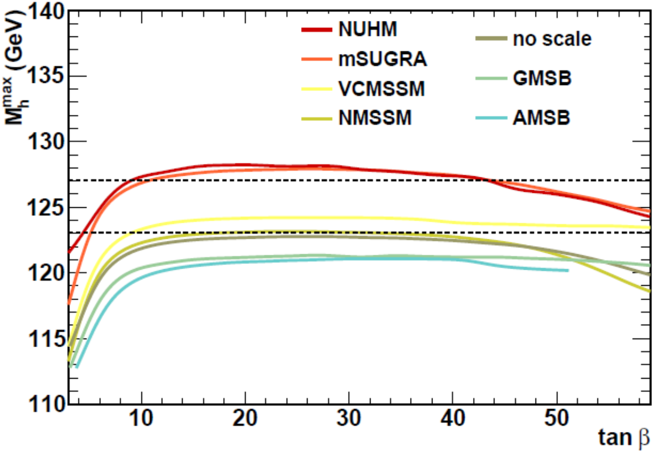
Supersymmetry

- Resolution of the gauge hierarchy problem
- Predicts plethora of new particles which LHC should find
- Unification of the SM gauge couplings at $M_{GUT} \sim 2 \times 10^{16}$ GeV
- Cold dark matter candidate (LSP)
- Radiative electroweak breaking
- String theory requires supersymmetry (SUSY)

Alas, SUSY not yet seen at LHC

Why Supersymmetry?





A. Arbey, M. Battaglia, A. Djouadi, F. Mahmoudi and J. Quevillon, Phys. Lett. B **708**, 162 (2012)

The Bets

Venedig, Feb 23, 2005

1st Bet

Manfred Lindner & Jogesh Pati: NO!

Antonio Masiero, Qaisar Shafi, [signature]: ← say that Higgs will be found at ≤ 130 GeV.

(Within 2σ)

2nd Bet

Jogesh Pati says that neutron dipole moment will be discoverd with a factor 10 improvement (over today's ~~value~~ limit) [signature]

Manfred Lindner, Antonio Masiero, Qaisar Shafi SAY NO!

3rd Bet

Mille + Jogesh yes; Manfred, Antonio, Qaisar NO | $\mu \to e\gamma$ will be found at 10^{-12}

Winning Bet gets dinner at a fine restaurant

Qaisar Shafi (23 Feb, 05)

[signature] -a- [signature]

[signature] 23 Feb. 05

[signature] "

[signature]

SUSY Higgs (Hybrid) Inflation

[Dvali, Shafi, Schaefer; Copeland, Liddle, Lyth, Stewart, Wands '94]

[Lazarides, Schaefer, Shafi '97][Senoguz, Shafi '04; Linde, Riotto '97]

- Attractive scenario in which inflation can be associated with symmetry breaking $G \longrightarrow H$
- Simplest inflation model is based on

$$W = \kappa\, S\, (\Phi\, \overline{\Phi} - M^2)$$

S = gauge singlet superfield, $(\Phi\,, \overline{\Phi})$ belong to suitable representation of G

- Need $\Phi\,, \overline{\Phi}$ pair in order to preserve SUSY while breaking $G \longrightarrow H$ at scale $M \gg$ TeV, SUSY breaking scale.
- R-symmetry

$$\Phi\, \overline{\Phi} \rightarrow \Phi\, \overline{\Phi}, \;\; S \rightarrow e^{i\alpha}\, S, \;\; W \rightarrow e^{i\alpha}\, W$$

$\Rightarrow \quad W$ is a unique renormalizable superpotential

- Some examples of gauge groups:

$$G = U(1)_{B-L},\ \text{(Supersymmetric superconductor)}$$

$$G = SU(5) \times U(1),\quad (\Phi = 10),\quad \text{(Flipped } SU(5)\text{)}$$

$$G = 3_c \times 2_L \times 2_R \times 1_{B-L},\ (\Phi = (1,1,2,+1))$$

$$G = 4_c \times 2_L \times 2_R,\ (\Phi = (\overline{4},1,2)),$$

$$G = SO(10),\ (\Phi = 16)$$

- At renormalizable level the SM displays an 'accidental' global $U(1)_{B-L}$ symmetry.

- Next let us 'gauge' this symmetry, so that $U(1)_{B-L}$ is now promoted to a local symmetry. In order to cancel the gauge anomalies, one may introduce 3 SM singlet (right-handed) neutrinos.

  This has several advantages:

- See-saw mechanism is automatic and neutrino oscillations can be understood.

- RH neutrinos acquire masses only after $U(1)_{B-L}$ is spontaneously broken; Neutrino oscillations require that RH neutrino masses are $\lesssim 10^{14}\mathrm{GeV}$.

- RH neutrinos can trigger leptogenesis after inflation, which subsequently gives rise to the observed baryon asymmetry;

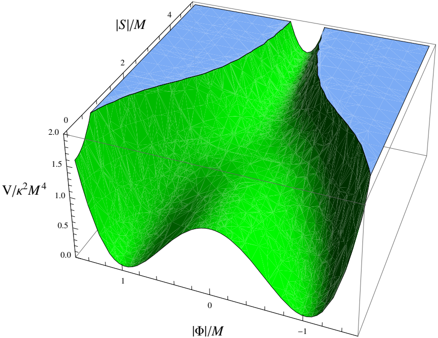
- Last but not least, the presence of local $U(1)_{B-L}$ symmetry enables one to explain the origin of Z_2 'matter' parity of MSSM. (It is contained in $U(1)_{B-L} \times U(1)_Y$, if $B-L$ is broken by a scalar vev, with the scalar carrying two units of $B-L$ charge.)

- Tree Level Potential

$$V_F = \kappa^2 \left(M^2 - |\Phi^2|\right)^2 + 2\kappa^2 |S|^2 |\Phi|^2$$

- SUSY vacua

$$|\langle\overline{\Phi}\rangle| = |\langle\Phi\rangle| = M, \ \langle S\rangle = 0$$



Take into account radiative corrections (because during inflation $V \neq 0$ and SUSY is broken by $F_S = -\kappa M^2$)

- Mass splitting in $\Phi - \overline{\Phi}$

$$m_{\pm}^2 = \kappa^2 S^2 \pm \kappa^2 M^2, \quad m_F^2 = \kappa^2 S^2$$

- One-loop radiative corrections

$$\Delta V_{\text{1loop}} = \frac{1}{64\pi^2} \text{Str}[\mathcal{M}^4(S)(\ln \frac{\mathcal{M}^2(S)}{Q^2} - \frac{3}{2})]$$

- In the inflationary valley ($\Phi = 0$)

$$V \simeq \kappa^2 M^4 \left(1 + \frac{\kappa^2 \mathcal{N}}{8\pi^2} F(x)\right)$$

where $x = |S|/M$ and

$$F(x) = \frac{1}{4}\left(\left(x^4+1\right)\ln\frac{\left(x^4-1\right)}{x^4} + 2x^2 \ln\frac{x^2+1}{x^2-1} + 2\ln\frac{\kappa^2 M^2 x^2}{Q^2} - 3\right)$$

Full Story

Also include supergravity corrections + soft SUSY breaking terms

- The minimal Kähler potential can be expanded as

$$K = |S|^2 + |\Phi|^2 + |\overline{\Phi}|^2$$

- The SUGRA scalar potential is given by

$$V_F = e^{K/m_p^2}\left(K_{ij}^{-1} D_{z_i} W D_{z_j^*} W^* - 3 m_p^{-2} |W|^2\right)$$

where we have defined

$$D_{z_i} W \equiv \frac{\partial W}{\partial z_i} + m_p^{-2} \frac{\partial K}{\partial z_i} W;\ K_{ij} \equiv \frac{\partial^2 K}{\partial z_i \partial z_j^*}$$

and $z_i \in \{\Phi, \overline{\Phi}, S, ...\}$

[Senoguz, Shafi '04; Jeannerot, Postma '05]

- Take into account sugra corrections, radiative corrections and soft SUSY breaking terms:

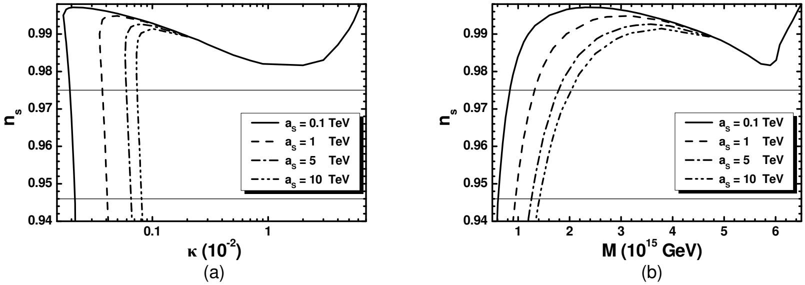
$$V \simeq \kappa^2 M^4 \left(1 + \left(\frac{M}{m_p}\right)^4 \frac{x^4}{2} + \frac{\kappa^2 \mathcal{N}}{8\pi^2} F(x) + a_s \left(\frac{m_{3/2} x}{\kappa M}\right) + \left(\frac{m_{3/2} x}{\kappa M}\right)^2\right)$$

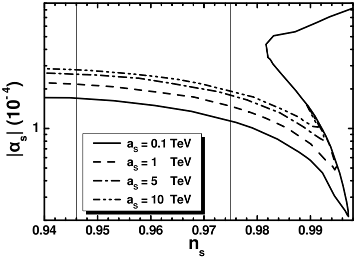
where $a_s = 2\,|2 - A| \cos[\arg S + \arg(2 - A)]$, $x = |S|/M$ and $S \ll m_P$.

Note: No 'η problem' with minimal (canonical) Kähler potential !

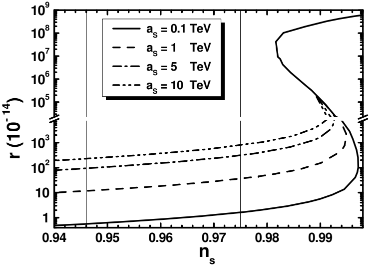
Results

[Pallis, Shafi, 2013; Rehman, Shafi, Wickman, 2010]

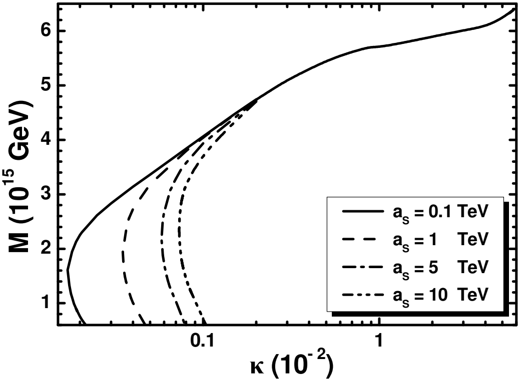



|α_s| (10^-4)
1
0.94 0.95 0.96 0.97 0.98 0.99
n_s
a_s = 0.1 TeV
a_s = 1 TeV
a_s = 5 TeV
a_s = 10 TeV

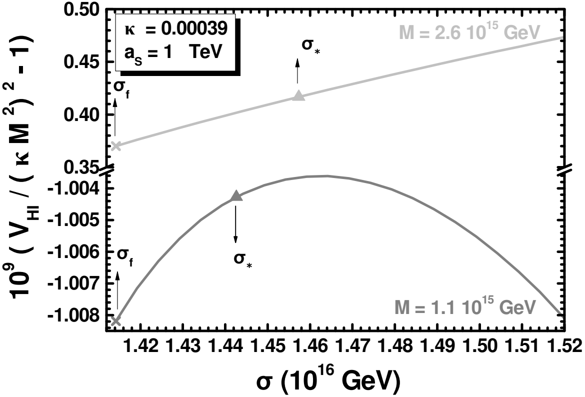
(a)

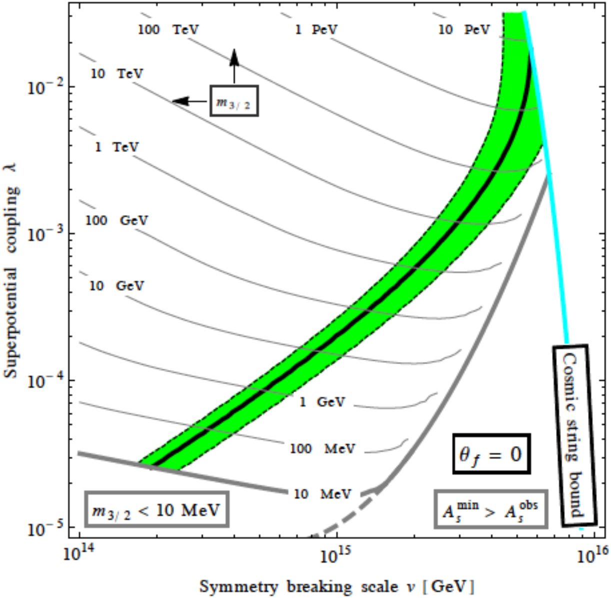

r (10^-14)
10^9
10^8
10^7
10^6
10^5
10^3
10^2
10
1
0.94 0.95 0.96 0.97 0.98 0.99
n_s
a_s = 0.1 TeV
a_s = 1 TeV
a_s = 5 TeV
a_s = 10 TeV

(b)



6
5
4
3
2
1
M (10^15 GeV)
0.1
1
κ (10^-2)
a_s = 0.1 TeV
a_s = 1 TeV
a_s = 5 TeV
a_s = 10 TeV


κ = 0.00039
a_S = 1 TeV
M = 2.6 10^{15} GeV
M = 1.1 10^{15} GeV
σ_*
σ_f
10^9 (V_{HI} / (κ M^2) ^{2} - 1)
σ (10^{16} GeV)
0.50
0.45
0.40
0.35
-1.004
-1.005
-1.006
-1.007
-1.008
1.42 1.43 1.44 1.45 1.46 1.47 1.48 1.49 1.50 1.51 1.52



100 TeV
1 PeV
10 PeV
10 TeV
$m_{3/2}$
1 TeV
100 GeV
10 GeV
1 GeV
100 MeV
10 MeV
$m_{3/2} < 10$ MeV
$\theta_f = 0$
$A_s^{min} > A_s^{obs}$
Cosmic string bound
Superpotential coupling λ
Symmetry breaking scale v [GeV]
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{14}
10^{15}
10^{16}

Non-Minimal SUSY Hybrid Inflation and Tensor Modes

- Minimal SUSY hybrid inflation model yields tiny r values $\lesssim 10^{-10}$
- A more general analysis with a non-minimal Kähler potential can lead to larger r-values;
- The Kähler potential can be expanded as:

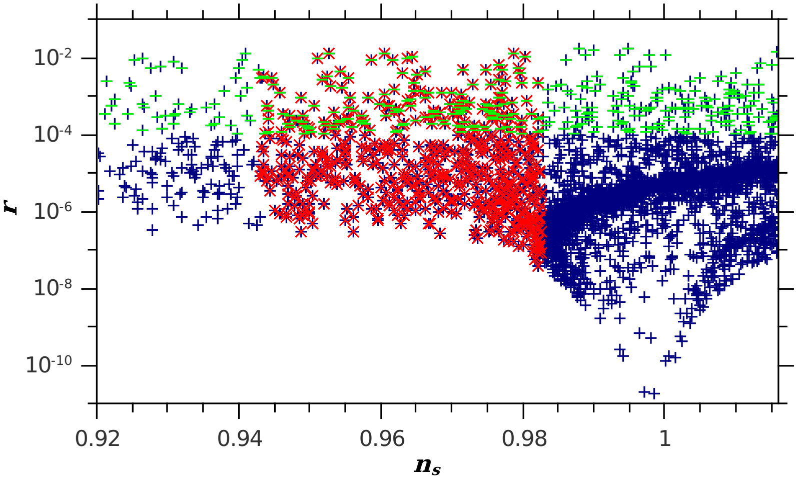
$$K = |S|^2 + |\Phi|^2 + |\overline{\Phi}|^2 + \frac{\kappa_S}{4}\frac{|S|^4}{m_P^2} + \frac{\kappa_\Phi}{4}\frac{|\Phi|^4}{m_P^2} + \frac{\kappa_{\overline{\Phi}}}{4}\frac{|\overline{\Phi}|^4}{m_P^2} + \kappa_{S\Phi}\frac{|S|^2|\Phi|^2}{m_P^2} + \kappa_{S\overline{\Phi}}\frac{|S|^2|\overline{\Phi}|^2}{m_P^2} + \kappa_{\Phi\overline{\Phi}}\frac{|\Phi|^2|\overline{\Phi}|^2}{m_P^2} + \frac{\kappa_{SS}}{6}\frac{|S|^6}{m_P^4} + \cdots ,$$

The scalar potential becomes

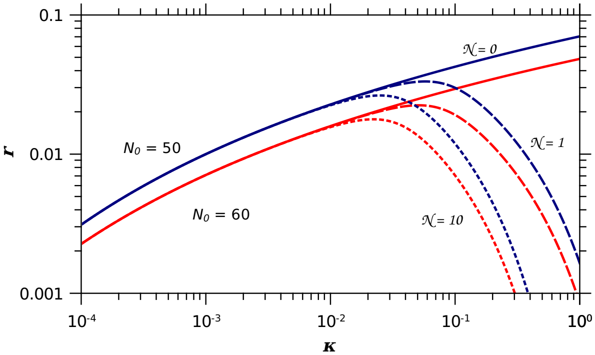
$$V \simeq \kappa^2 M^4 \left(1 - \kappa_S \left(\frac{M}{m_P}\right)^2 x^2 + \gamma_S \left(\frac{M}{m_P}\right)^4 \frac{x^4}{2} + \frac{\kappa^2 \mathcal{N}}{8\pi^2} F(x) + a \left(\frac{m_{3/2}\, x}{\kappa\, M}\right) + \left(\frac{M_S\, x}{\kappa\, M}\right)^2\right)$$

with (leading order) non-minimal Kähler, SUGRA, radiative, and soft SUSY-breaking corrections, and where

$$\gamma_S \equiv 1 - \frac{7}{2}\kappa_S + 2\kappa_S^2 - 3\kappa_{SS}$$



10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
r
0.92
0.94
0.96
0.98
1
n_s



While radiative corrections are subdominant at large r, they play a crucial role in limiting the size of r. This limiting behavior comes in *indirectly* via the number of e-foldings N_0.

MSSM μ-Problem and Inflation

1. $U(1)_R$ symmetry prevents a direct μ term but allows the superpotential coupling

$$\lambda H_u H_d S$$

Since $\langle S \rangle$ acquires a non-zero VEV $\propto m_{3/2}$ from supersymmetry breaking, the MSSM μ term of the desired magnitude is realized.

2. Another option is to introduce a $U(1)$ axion symmetry that is compatible with $U(1)_R$. For instance,

$$H_u H_d \frac{N^2}{M_*} \text{ where } \langle N \rangle \sim (m_{3/2} M_*)^{1/2} \sim 10^{11} \text{ GeV}$$

This can also resolve the μ-problem.

Summary

- If $r \sim 0.1 - 0.02$, then inflation models based on the Higgs / Coleman-Weinberg potentials can provide simple / realistic frameworks for inflation, with minimal coupling to gravity.
- There is a lower bound on H (Hubble constant) in these models. This is important for topological defects in GUT models involving intermediate scales.
- If $r \lesssim 0.01$, then supersymmetric hybrid inflation models are especially interesting. These work with inflaton field values below $M_{\rm Planck}$, and supergravity corrections are under control. The simplest versions employ TeV scale SUSY, and hopefully LHC 14 will find it.