Inflation & Cosmic Strings

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Outline

- Inflationary Cosmology
- Tree Level Gauge Singlet Higgs Inflation
- Quantum Smearing / B-L Inflation
- SUSY Higgs (Hybrid) Inflation
- Cosmic Strings & Inflation

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?

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

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

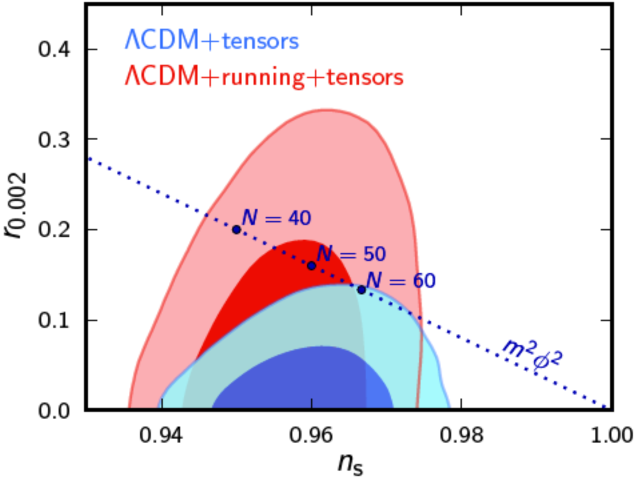
- The spectrum of the tensor perturbation is given by

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

- 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 $\max[\epsilon(\phi_e), |\eta(\phi_e)|] = 1$.



Constraints (68% and 95%) on n_s and the tensor-to-scalar ratio $r_{0.002}$ for $\Lambda_{\rm CDM}$ models with tensors (blue) and additionally with running of the spectral index (red). The dotted line show the expected relation between r and n_s for a $V(\phi) \propto \phi^2$ inflationary potential. N is the number of inflationary e-foldings.

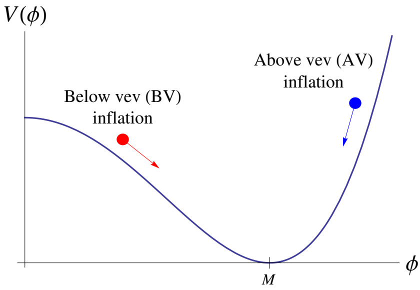
Tree Level Gauge Singlet Higgs Inflation

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

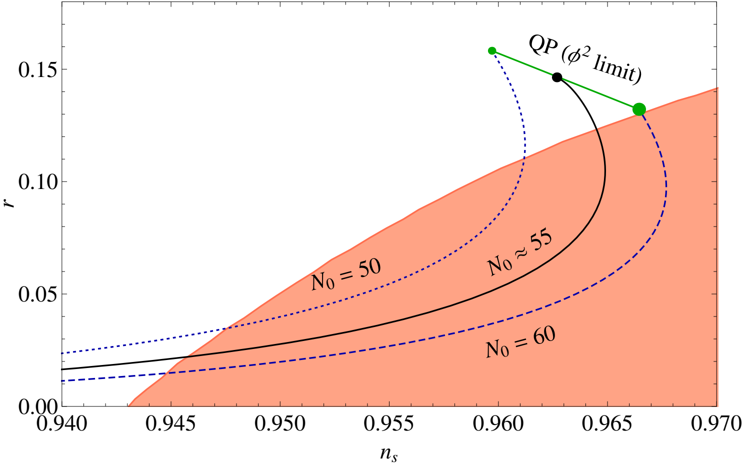
- Consider the following Higgs Potential:

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

Here ϕ is a gauge singlet field.



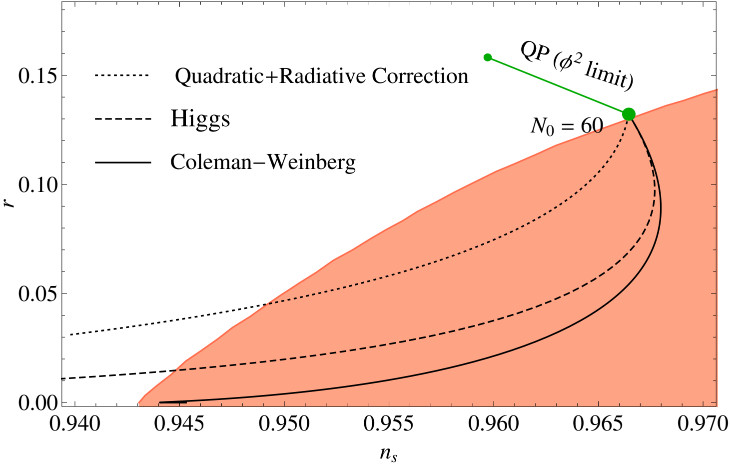
- WMAP/Planck data favors BV inflation.



QP (ϕ^2 limit)
$N_0 = 50$
$N_0 \approx 55$
$N_0 = 60$
0.15
0.10
0.05
0.00
r
0.940
0.945
0.950
0.955
0.960
0.965
0.970
n_s

Quantum Smearing

$$V = \frac{1}{4}\lambda(\phi^2 - v^2)^2 + \frac{C}{16\pi^2}\phi^4 \log\left[\frac{\phi}{v}\right] + \text{const.},$$



- 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.)

$U(1)_{B-L}$ Non-SUSY Inflation (with N. Okada)

Minimal gauged B-L extension of the Standard Model model

Particle contents:

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-L}$
q_L^i	**3**	**2**	$+1/6$	$+1/3$
u_R^i	**3**	**1**	$+2/3$	$+1/3$
d_R^i	**3**	**1**	$-1/3$	$+1/3$
ℓ_L^i	**1**	**2**	$-1/2$	-1
ν_R^i	**1**	**1**	0	-1
e_R^i	**1**	**1**	-1	-1
H	**1**	**2**	$-1/2$	0
Φ	**1**	**1**	0	$+2$

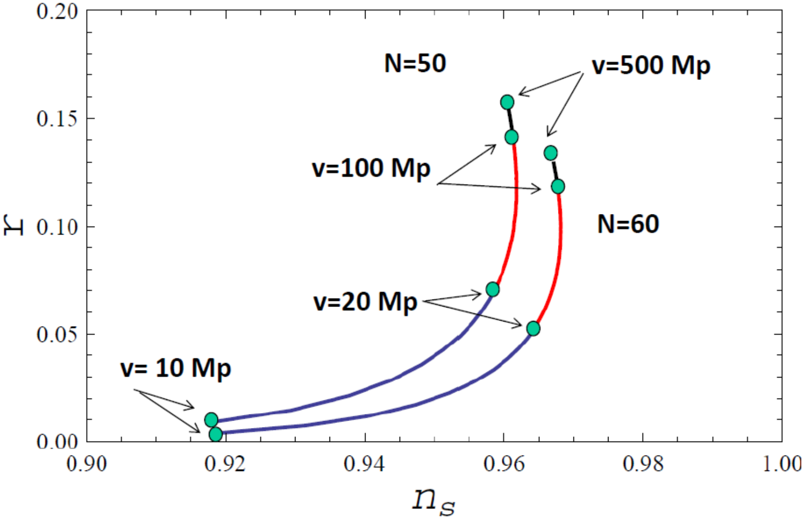
Lagrangian relevant to the seesaw mechanism

$$\mathcal{L} \supset -Y_D^{ij}\overline{\nu_R^i}H^\dagger \ell_L^j - \frac{1}{2}Y_N^i \Phi \overline{\nu_R^{ic}}\nu_R^i + \text{h.c.}$$

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: $\phi < v$



Quantum effects for inflationary predictions

We employ renormalization group improved effective potential and parameterize the potential as

$$V = \frac{1}{4}\lambda\left(\phi^2 - v^2\right)^2 + \frac{C}{16\pi^2}\log\left[\frac{\phi}{v}\right]\phi^4 + const.,$$

where

$$C = 20\lambda^2 + 2\lambda_{mix}^2 + 2\lambda\left(\sum_i (Y_N^i)^2 - 24 g_{BL}^2\right) + 96 g_{BL}^4 - \sum_i (Y_N^i)^4$$

is a solution to RGE of the quartic coupling at leading log approximation, and ``const'' is added to obtain a vanishing cosmological constant at vacuum.

$$V \supset \lambda_{mix}|\Phi|^2|H|^2$$

In analysis, it is convenient to parameterize the potential as

$$V = \lambda \left[\frac{1}{4} \left(\phi^2 - v^2 \right)^2 + a \log \left[\frac{\phi}{v} \right] \phi^4 + const. \right],$$

$$a = \frac{C}{16\pi^2 \lambda}$$

Free parameters involved in analysis: $\{\lambda, v, a\}$

The quartic coupling is determined by $\Delta_{\mathcal{R}}^2(k_0) = 2.43 \times 10^{-9}$

$\{n_s, r\}$ are controlled by $\{v, a\}$

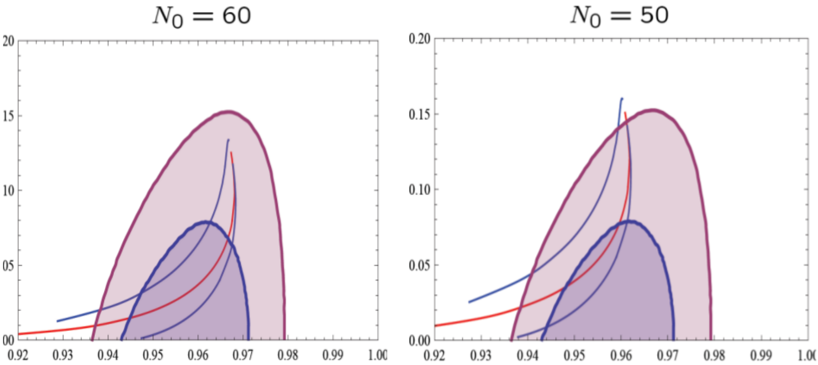
<u>Results along with WMAP 9</u>

$a = -0.2$(top), 0(middle), 50(bottom)

$10M_P \le v \le 100M_P$

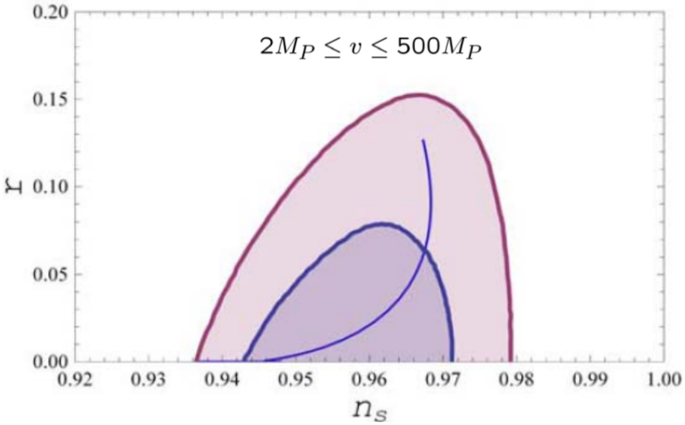
For too small negative a, local minimum disappears

a >> 1 corresponds to Colman-Weinberg potential



Mass spectrum

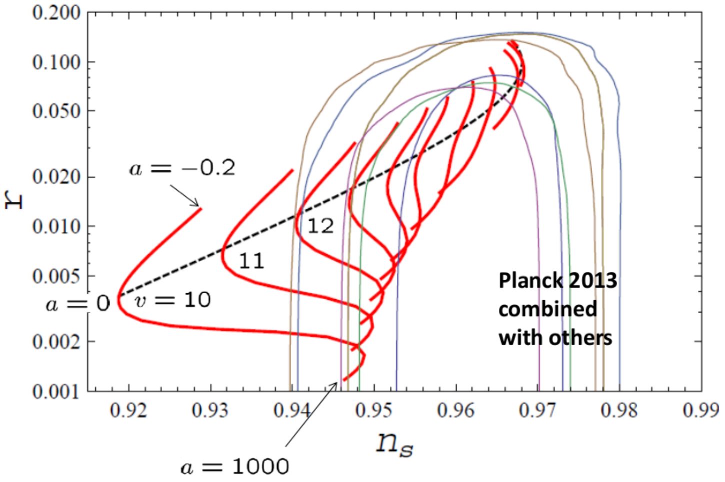
For a=100 fixed (Coleman-Weinberg limit), we obtain the inflationary predictions as a function of VEV (N=60):



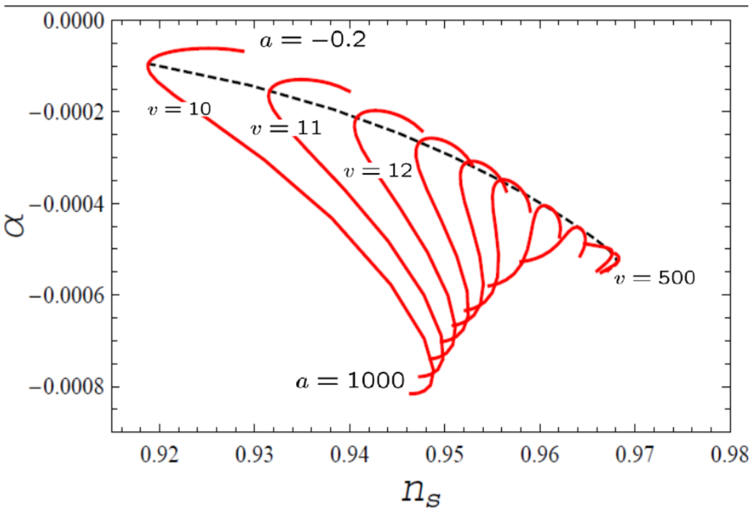
Results along with Planck 2013 $(N_0 = 60)$

For various values of $-0.2 \leq a \leq 1000$

$v = 10, 11, 12, 13, 14, 15, 17, 20, 30, 50, 100$



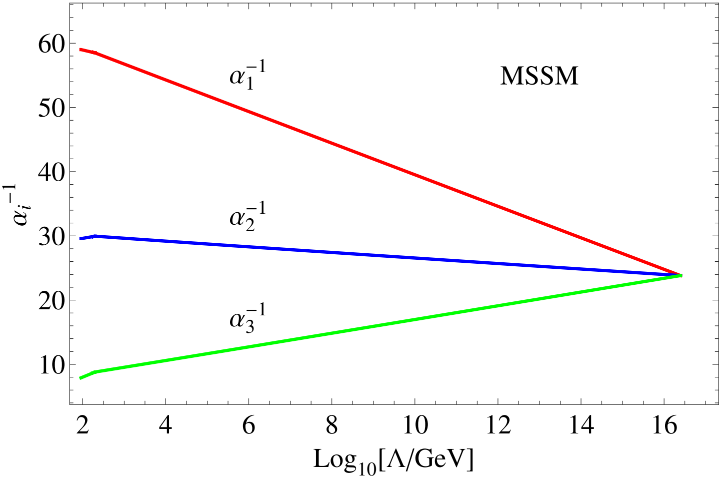
Running of spectral index



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


MSSM
α_1^{-1}
α_2^{-1}
α_3^{-1}
α_i^{-1}
60
50
40
30
20
10
2
4
6
8
10
12
14
16
Log$_{10}$[Λ/GeV]

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

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

$\Rightarrow$ W is a unique renormalizable superpotential

- Some examples of gauge groups:

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

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

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

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

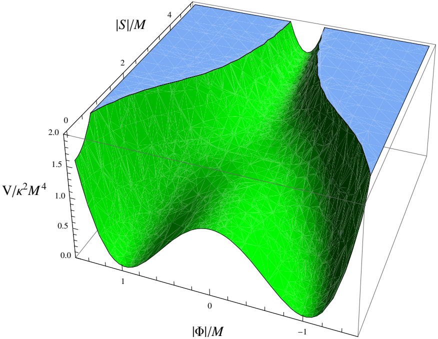
$$G = SO(10), \ (\Phi = 16)$$

- 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

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

- 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

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

- The Sugra scalar potential is given by

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

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 $z_i \in \{\Phi, \overline{\Phi}, S, \ldots\}$

Full Story

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

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

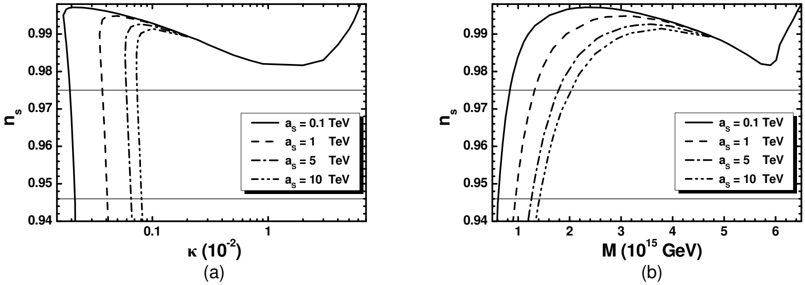
$$V \simeq \kappa^2 M^4 \left(1 + \left(\frac{M}{m_p}\right)^4 \frac{x^4}{2} + \frac{\kappa^2 \mathcal{N}}{8\pi^2} F(x) + a_s \left(\frac{m_{3/2} x}{\kappa M}\right) + \left(\frac{m_{3/2} x}{\kappa M}\right)^2\right)$$

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

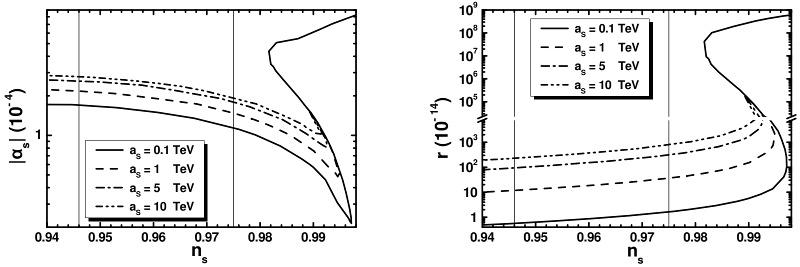
Note: No 'η problem' with minimal (canonical) Kähler potential !

Results

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



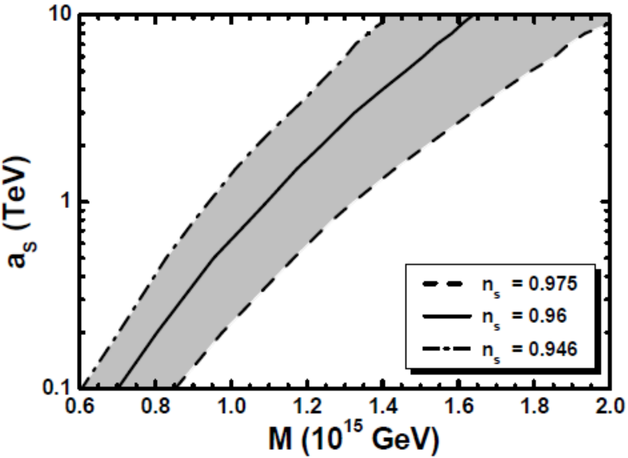
Results



$|\alpha_s|$ (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
r (10^{-14})
10^9
10^8
10^7
10^6
10^5
10^3
10^2
10
1

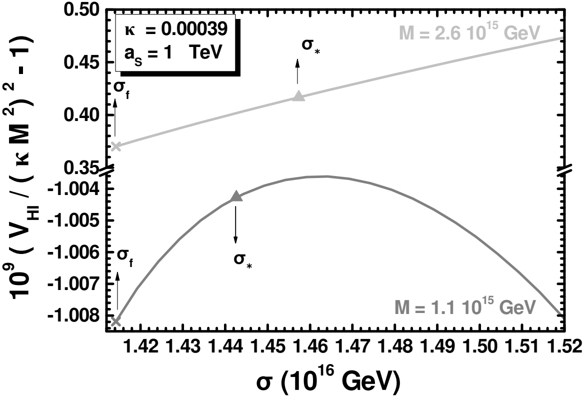
(a) (b)

Results



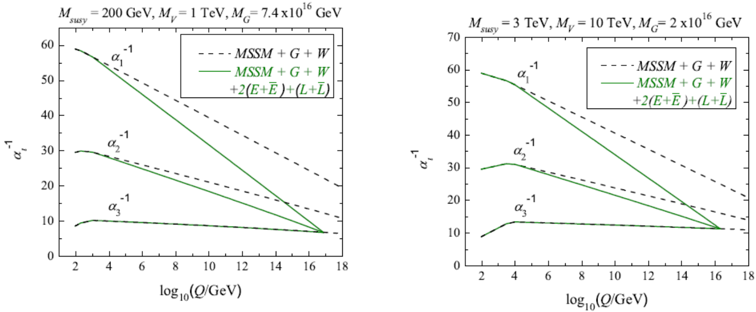
10
1
0.1
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
a_S (TeV)
M (10^15 GeV)
n_s = 0.975
n_s = 0.96
n_s = 0.946

Results


κ = 0.00039
a_S = 1 TeV
M = 2.6 10^15 GeV
M = 1.1 10^15 GeV
σ_*
σ_f
σ_*
σ_f
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
σ (10^16 GeV)
10^9 (V_HI / (κ M^2)^2 - 1)

For $G = SU(5)$ (Khalil et. al.) greater care is required because of monopole problem.

(For $SO(10)$ see G. Cacciapaglia and M. Sakellariadou, arXiv:1306.3242 [hep-ph].)

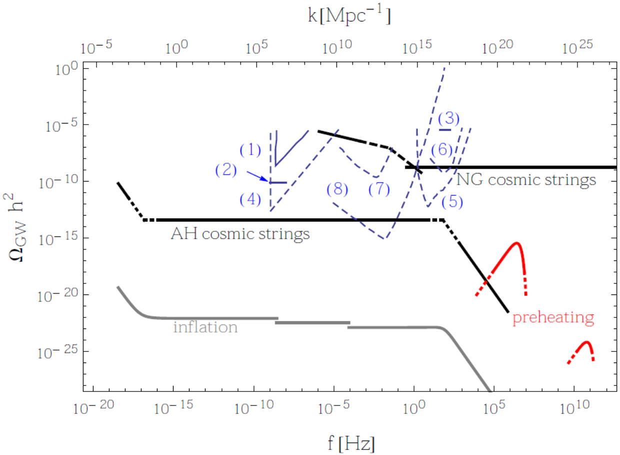


Gauge coupling evolution with effective SUSY breaking scale $M_{\rm susy} = 200$ GeV (left panel), $M_{\rm susy} = 300$ GeV (right panel) and $\tan\beta = 10$. Dotted (solid) lines correspond to $MSSM + G + W$ $(MSSM + G + W + (L + \bar{L}) + 2(E + \bar{E}))$. The masses of G, W and extra vectorlike particles are set equal to $M_V = 1$ TeV (left panel), $M_V = 10$ TeV (right panel).

Local $U(1)_{\mathrm{B-L}}$ symmetry provides a compelling extension of the SM:

- It enables, via seesaw physics, an elegant explanation of the observed neutrino oscillations;
- The observed baryon asymmetry can be realized leptogenesis;
- Supersymmetric version contains LSP neutralino dark matter;
- Last, but by no means least, minimal B-L inflation predicts the presence of cosmic strings of mass scale $\sim 10^{15}$ GeV.

W. Buchmüller, V. Domcke, K. Kamada and K. Schmitz, arXiv:1309.7788v1 [hep-ph]



Predicted gravity wave (GW) spectrum and the expected sensitivity of current and upcoming experiments. The GW spectrum due to inflation (gray), preheating (red), AH and NG cosmic strings (black) for $v_{B-L} = 5 \times 10^{15}$ GeV, $M_1 = 10^{11}$ GeV, $m_S = 3 \times 10^{13}$ GeV, and $\alpha = 10^{-2}$. The current bounds on the stochastic GW spectrum (1) from milisecond pulsar timing, (2) from EPTA, (3) from LIGO, (4) from SKA, (5) from ET, (6) from advanced LIGO, (7) from eLISA, (8) from BBO and DECIGO.