Inflationary Cosmology and Particle Physics

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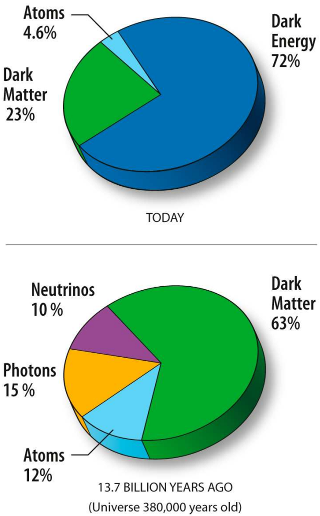
Outline

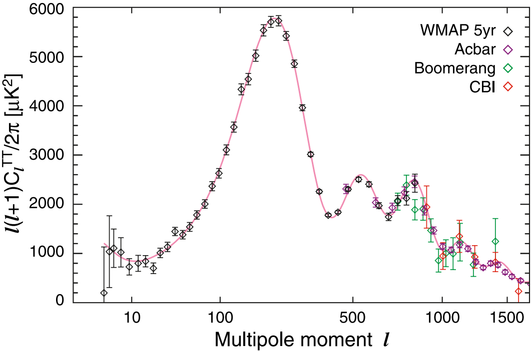
- ΛCDM
- WMAP
- Inflationary Cosmology
- Radiative Corrections and Precision Cosmology
- Non-Supersymmetric Inflation Models
- Supersymmetric Inflation Models
- Standard Model Inflation (?)
- Brane/String Inflation
- Gaussian vs. Non-Gaussian Fluctuations
- Conclusions

WMAP Collaboration 2008



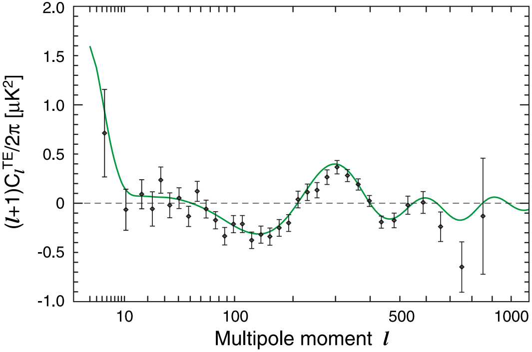
WMAP

- TT power spectrum yields:
  - Scalar spectral index n_s
  - Baryonic and dark matter densities Ω_b, Ω_c
- Deviations from Gaussianity not reflected in power spectrum



Nolta et. al. (WMAP Collaboration), 2008

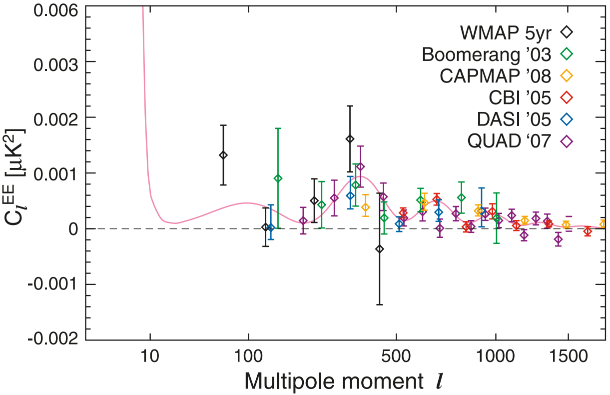
Temperature Anisotropy and CMB Polarization



Nolta et. al. (WMAP Collaboration), 2008

In addition to temperature anisotropy, one expects the CMB to become polarized via Thompson scattering: Linear polarization results from the velocities of electrons and protons. With both the velocity field and temperature anisotropies created by primordial density fluctuations, one expects to see temperature-polarization correlations. ($\langle TT \rangle$, $\langle TE \rangle$, $\langle EE \rangle$, $\langle BB \rangle$)

CMB Polarization



Nolta et. al. (WMAP Collaboration), 2008

Hot Big Bang Cosmology (SM+GR)

Highly successful but it fails to explain

1. Observed Isotropy of CMB (COBE)
2. Origin of $\frac{\delta T}{T}$ (COBE, ..., WMAP)
3. $\Omega_{\text{total}} = 1$ (critical density)
4. $\Omega_{\text{CDM}} = 0.22$ (non-baryonic DM)
5. $n_b/n_\gamma = 10^{-10}$ (baryon asymmetry)

Inflationary Cosmology

- Inflationary Cosmology can take care of (1), (2), (3) and an inflation model can be called "realistic" if it can explain (4) $\rightarrow$ CDM and (5) $\rightarrow n_b/n_\gamma$. Some models also provide a link with (6) $\rightarrow$ neutrino physics.
- Testable predictions?
- Usual paradigm: **slow-roll inflation**
  - Physical quantities expanded in terms of 'slow-roll parameters'

$$\epsilon \equiv \frac{m_P^2}{2}\left(\frac{V'}{V}\right)^2 \quad ; \quad \eta \equiv m_P^2\left(\frac{V''}{V}\right)$$

  - $\epsilon, |\eta| \ll 1$ during inflation
  - Inflation ends when $\epsilon \sim 1$ or $|\eta| \sim 1$

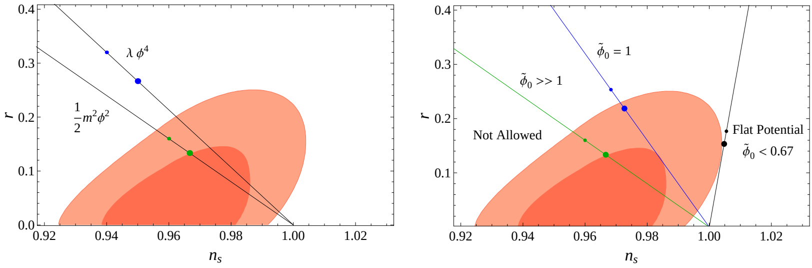
Models of Inflation

- **Chaotic:** potential is quadratic ($V \sim m^2\phi^2$) or quartic ($V \sim \lambda\phi^4$)
  - Simplest (renormalizable) potential
  - Predicts significant primordial gravity waves
- **Hybrid:** inflation driven by ϕ field, vacuum energy provided by second scalar field χ

$$V(\phi,\chi) = \kappa^2 \left(M^2 - \frac{\chi^2}{4}\right)^2 + \frac{m^2\phi^2}{2} + \frac{\lambda^2\chi^2\phi^2}{4}$$

  - Compelling and robust
  - Translates well to SUSY (more on this later)
  - Non-SUSY model results in $n_s > 1$ (unless in chaotic-like regime) — SUSY case can have $n_s < 1$

Tree Level Inflation Models vs. WMAP5

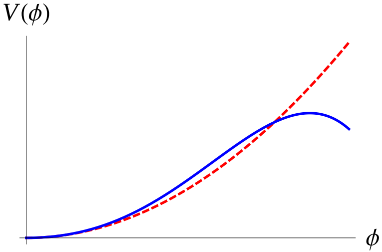


Komatsu et. al. (WMAP Collaboration), 2008

Quadratic: $V(\phi) = \frac{1}{2}m^2\phi^2 \pm A\phi^4 \ln \frac{\phi^2}{\mu^2}$

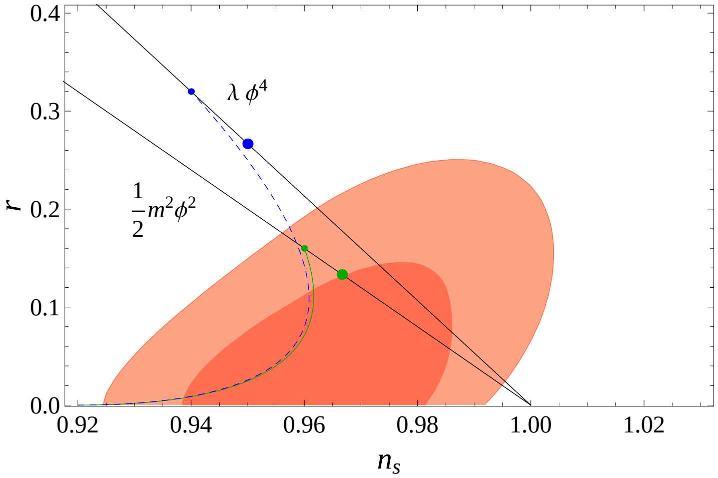
Quartic: $V(\phi) = \lambda\phi^4 \pm A\phi^4 \ln \frac{\phi^2}{\mu^2}$

Fermion-dominated corrections $(-)$ (say from right handed neutrinos)



Radiative Corrections in Chaotic Inflation — Results

[V. N. Senoguz and Q. Shafi, 2008]

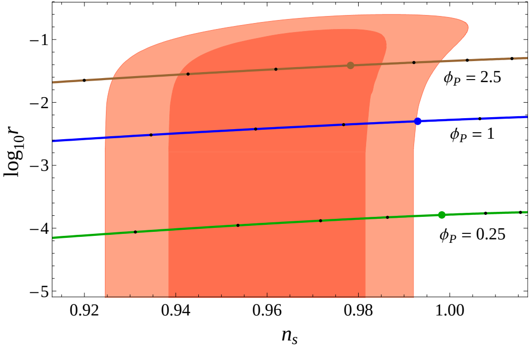


Radiative Corrections in Hybrid Inflation

[M. Rehman, Q. Shafi and J. Wickman, 2009]

$$V(\phi,\chi) = \kappa^2\left(M^2 - \frac{\chi^2}{4}\right)^2 + \frac{m^2\phi^2}{2} + \frac{\lambda^2\chi^2\phi^2}{4} \pm A\phi^4 \ln\left(\frac{\phi}{\phi_c}\right),$$

where $\phi \equiv$ 'inflaton' field, $\chi \equiv$ 'waterfall' field ($\chi = 0$ during inflation)



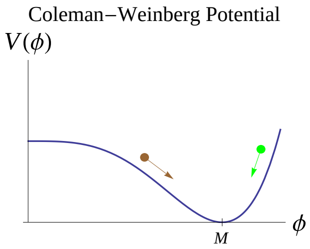
Radiative Corrections/Precision Cosmology

Radiatively-corrected inflation models;

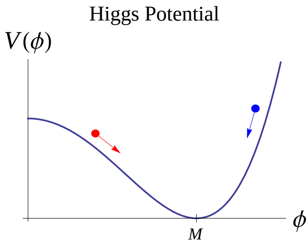
- Chaotic Inflation
  - Permits low values of r (e.g. $0 \lesssim r \lesssim 0.2$ to agree with WMAP5 2σ bound)
- Hybrid Inflation
  - Red spectrum $(n_s < 1)$ can be produced for Planckian or sub-Planckian values of the inflaton
- Better agreement with WMAP5
- Generically 2 solutions of n_s for each A

Non-Supersymmetric GUTs

- Consider Coleman-Weinberg (CW) and Higgs inflation in the context of SO(10) and non-minimal SU(5)



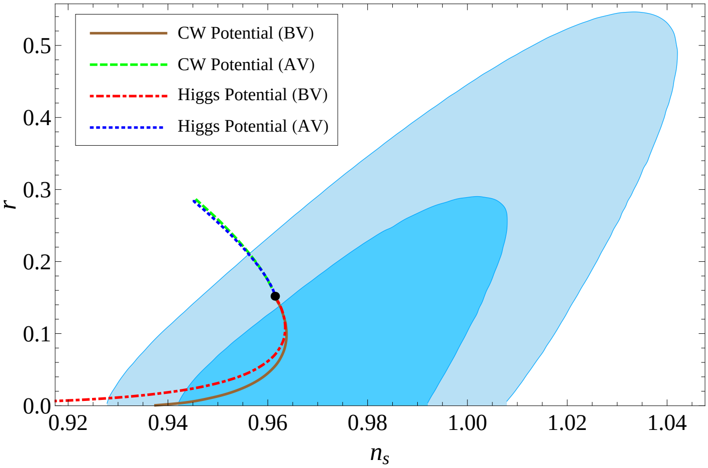
[Rehman, Shafi and Wickman, 08]



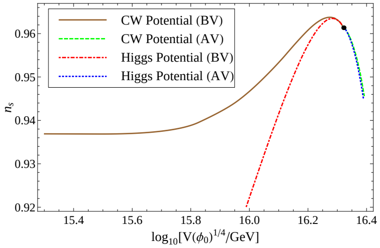
[Kallosh and Linde, 07]

Predictions

[M. Rehman, Q. Shafi and J. Wickman, 2008]



Proton Decay and WMAP5



$V_0^{1/4}$(GeV)	$V(\phi_0)^{1/4}$(GeV)	n_s	r
1.75×10^{16}	1.61×10^{16}	0.9613	0.0538
$2. \times 10^{16}$	1.74×10^{16}	0.9630	0.0730
2.25×10^{16}	1.83×10^{16}	0.9637	0.0889
2.5×10^{16}	1.89×10^{16}	0.9638	0.101
2.75×10^{16}	1.93×10^{16}	0.9636	0.110
$3. \times 10^{16}$	1.96×10^{16}	0.9635	0.117
$4. \times 10^{16}$	2.03×10^{16}	0.9628	0.133
$4. \times 10^{16}$	2.14×10^{16}	0.9607	0.165
$3. \times 10^{16}$	2.17×10^{16}	0.9600	0.174

$$M_X \sim 2\text{-}4\, V_0^{1/4} \sim 10^{16}\,\mathrm{GeV} \qquad \text{(CW model)}$$

$$\Rightarrow \quad \tau_p \sim 10^{34}\text{-}10^{38}\,\mathrm{years} \quad \text{(proton lifetime)}$$

Magnetic Monopoles and Inflation

- Consider the breaking

$$G \equiv SO(10) \to H \to SM$$

where $H \equiv SU(4) \times SU(2) \times SU(2)$.

  - First breaking produces superheavy monopoles carrying one unit of Dirac charge; these will be inflated away.

$$\pi_2(G/H) = Z_2;$$

  - The second breaking at scale M_c produces monopoles which carry two units of Dirac magnetic charge. These are intermediate mass monopoles and they may survive inflation.

Magnetic Monopoles and Inflation

- Consider the quartic coupling $-c\phi^2\chi^\dagger\chi$, with $c \sim (M_c/M)^2$. Here χ vev breaks 4-2-2 to 3-2-1 and ϕ is the inflaton.
- Monopole formation occurs when $c\phi^2 \sim H^2$ $\rightarrow H(t - t_\chi) \equiv \eta \sim 3c/\lambda$.
- Initial monopole number density $\sim H^3$, which gets diluted by inflation down to $H^3 \exp(-3\eta)$; thus, $r_M = n_M/T_R^3 \sim (H/T_R)^3 \exp(-3\eta) \lesssim 10^{-30}$.
- Roughly 25–30 e-folds can yield a flux close to or below the Parker bound.

Supersymmetry and Inflation

- Resolution of the gauge hierarchy problem
- Unification of the SM gauge couplings at

  $M_{GUT} \sim 2 \times 10^{16}$ GeV
- Cold dark matter candidate (LSP)
- Predicts new particles accessible at the LHC

Other good reasons:

- Radiative electroweak breaking
- String theory requires susy

  Leading candidate is the MSSM (Minimal Supersymmetric Standard Model)

MSSM Inflation

[Allahverdi et al]

- Numerous flat dimensions exist in MSSM.

  Utilize UUD and LLE.

  By suitable tuning of soft susy breaking parameters A and m_ϕ, an inflationary scenario may be realized.

- Flat directions lifted by high dimensional operators

$$W = \frac{\lambda\,\Phi^n}{m_P^{n-3}},\ \Phi \text{ is flat direction superfield.}$$

$$V = \frac{1}{2}m_\phi^2\phi^2 + A cos(n\theta + \theta_A)\frac{\lambda_n\,\phi^n}{n m_P^{n-3}} + \frac{\lambda_n^2\,\phi^{2(n-1)}}{m_P^{2(n-3)}}$$

- For $A^2 \geq 8(n-1)m_\phi^2$, there is a secondary minimum at $\phi = \phi_0 \sim (m_\phi m_P^{n-3})^{\frac{1}{(n-2)}} \ll m_p$, with $V \sim m_\phi^2\phi_0^2 \sim m_\phi^2(m_\phi m_P^{n-3})^{\frac{2}{n-2}}$ (this can drive inflation)

MSSM Inflation

$$H_{inf} \sim \frac{(m_\phi \phi_0)}{m_P} \sim m_\phi (\frac{m_\phi}{m_P})^{\frac{1}{(n-2)}} \ll m_\phi$$

- To implement realistic inflation you want both the first and second derivatives of V to vanish at ϕ_0 (saddle point inflation):

  Thus

$$V(\phi) \sim V(\phi_0) + \frac{1}{3!} V'''(\phi_0)(\phi - \phi_0)^3 + \cdots$$

  Using slow roll approximations (take $n = 6$, $\phi_0 \sim 10^{14}$ GeV, $m_\phi \sim 1 - 10$ TeV)

$$n_s \sim 1 - \frac{4}{N} \simeq 0.92$$

$$\frac{dn_s}{dlnk} \simeq -\frac{4}{N^2} \simeq -0.002$$

$$r \sim \frac{H}{m_P} \ll 1$$

Susy Hybrid Inflation

[Dvali, Shafi and Schaefer; Copeland et al. '94]

- SUSY hybrid inflation is defined by the superpotential

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

inflaton (singlet) $= S$, waterfall field $= (\Phi\,,\overline{\Phi}) \in G$

- R-symmetry

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

- Some examples of gauge groups are

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

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

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

$G = SO(10)$, $(\Phi\,,\overline{\Phi}) = (16\,,\overline{16})$

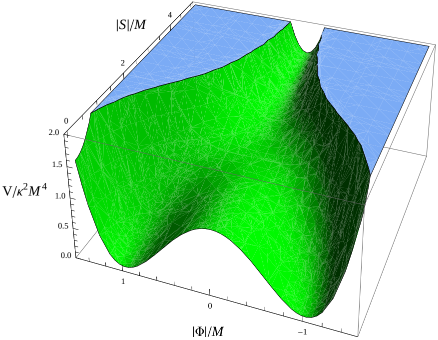
Susy Hybrid Inflation

- SUSY vacua

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

- Potential

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



Susy Hybrid Inflation

- 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

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

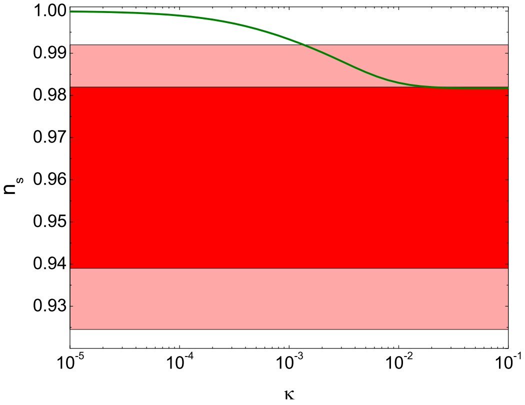
- In the inflationary valley $(\Phi = 0)$

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

where $x = |S|/M$ and

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

Susy Hybrid Inflation

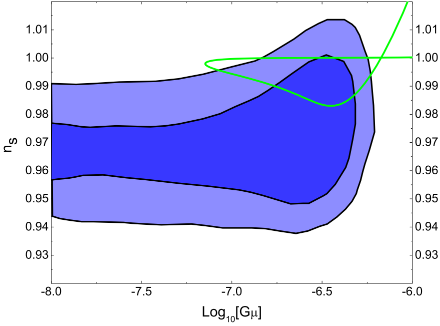


$$n_s \simeq 1 + \left(\frac{m_p}{M}\right)^2 \left(\frac{\kappa^2 \mathcal{N}}{8\pi^2}\right) \partial^2_{x_0} F(x_0) \xrightarrow{x_0 \gg 1} 1 - \frac{1}{N_0} \simeq 0.98$$

WMAP and Cosmic Strings

[Battye, Bjorn, Adam]

Results for a 7 parameter fit to the WMAP5+ACBAR data. The contours are the 68% and 95% confidence levels contours with string contribution included.



$$\frac{\delta T}{T} = \sqrt{\left(\frac{\delta T}{T}\right)^2_{inf} + \left(\frac{\delta T}{T}\right)^2_{cs}}, \qquad \left(\frac{\delta T}{T}\right)_{cs} \propto G\mu$$

- The Kähler potential can be expanded as
  $K = |S|^2 + |\Phi|^2 + \left|\overline{\Phi}\right|^2$
  $+\kappa_S \frac{|S|^4}{4m_p^2} + \kappa_{S\phi} \frac{|S|^2|\Phi|^2}{m_p^2} + \kappa_{S\overline{\phi}} \frac{|S|^2\left|\overline{\Phi}\right|^2}{m_p^2} + \kappa_{SS} \frac{|S|^6}{6m_p^4} + \cdots$
- 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 $z_i \in \{\Phi, \overline{\Phi}, S, ...\}$

Sugra Hybrid Inflation

- Taking also into account the radiative correction and soft SUSY breaking terms, the potential is of the following form

$$V \approx V_F + \Delta V_{\text{1loop}} + V_{soft} =$$
$$\kappa^2 M^4 \left(1 - \kappa_S \left(\frac{M}{m_p}\right)^2 x^2 + \gamma_S \left(\frac{M}{m_p}\right)^4 \frac{x^4}{2} + \frac{\kappa^2 \mathcal{N}}{8\pi^2} F(x)\right) +$$
$$a \kappa M^3 x$$

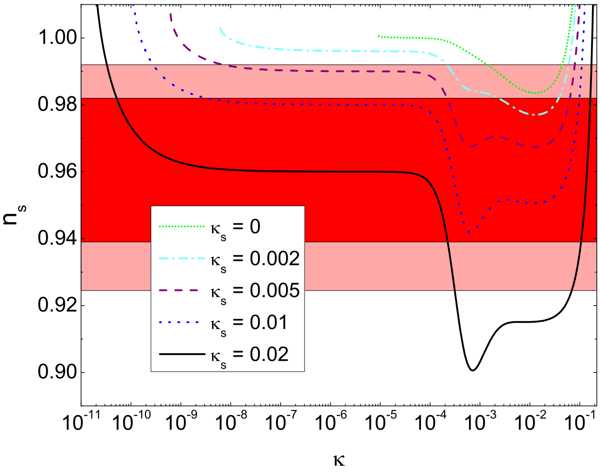
where $\gamma_S = 1 - \frac{7\kappa_S}{2} + 2\kappa_S^2$,

$a = m_{3/2} 2\,|2 - A| \cos[\arg S + \arg(2 - A)]$ and and $S \ll m_P$.

Note: No 'η' problem with minimal Kähler potential

[V. N. Senoguz, and Q. Shafi '04] [M. Bastero-Gil, S. F. King, Q. Shafi 06]

[M. Rehman, V. N. Senoguz, and Q. Shafi [hep-ph/0612023]]



$$n_S = 1 - 2\kappa_S + 6\gamma_S \left(\frac{M}{m_p}\right)^2 x_0^2 + \left(\frac{m_p}{M}\right)^2 \left(\frac{\kappa^2 \mathcal{N}}{8\pi^2}\right) \partial_{x_0}^2 F(x_0)$$

Shifted Hybrid Inflation

[R. Jeannerot, S. Khalil, G. Lazarides, Q. Shafi '2000]

Useful for inflating away troublesome objects.

- Shifted hybrid inflation is defined by the superpotential

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

- Potential

$$V_F = \kappa^2\, (M^2 - |\Phi|^2 + \xi\, |\Phi|^4)^2 + 2\kappa^2 |S|^2 |\Phi|^2\, (M^2 - 2\, \xi\, |\Phi|^2)^2$$

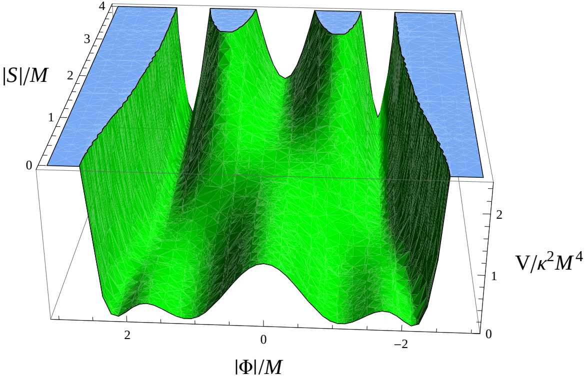
where $\xi = M^2 / \kappa\, M_S^2$

- Inflationary trajectories

$$|\Phi| = 0 \text{ and } |\Phi| = \sqrt{1/2\, \xi}\, M \text{ with } |S| > M$$

Shifted Hybrid Inflation

- Monopoles produced in the shifted directions get inflated away



Shifted Hybrid Inflation

- Including 1-loop radiative corrections in the shifted direction $(|\Phi| = \sqrt{1/2\,\xi}\, M)$

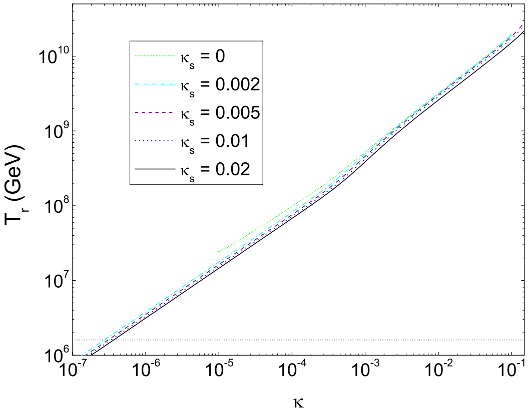
$$V \simeq \kappa^2 M_\xi^4 \left(1 + \frac{\kappa^2 \mathcal{N}}{8\pi^2} F(x_\xi)\right)$$

where $x_\xi = |S|/M_\xi$ and $M_\xi = M\, \sqrt{1/4\,\xi - 1}$

- Same results/predictions are obtained as that of regular SUSY/SUGRA inflation

$$M_\xi \;\Leftrightarrow\; M$$

Reheat Temperature and Non-Thermal Leptogenesis



$$T_r \gtrsim 1.6 \times 10^7 \text{ GeV} \left(\frac{10^{16} \text{ GeV}}{M}\right)^{1/2} \left(\frac{m_{\rm inf}}{10^{11} \text{ GeV}}\right)^{3/4} \left(\frac{0.05 \text{ eV}}{m_{\nu 3}}\right)^{1/2}$$

Standard Model Inflation?

[Shaposhnikov et al., De Simone et al.]

- Consider the following action with non-minimal coupling:

$$S_J =$$
$$\int dx^4 \sqrt{-g}\{|\partial H|^2 + \lambda \left(H^\dagger H - \frac{v^2}{2}\right)^2 - \frac{1}{2} m_P^2 \mathcal{R} - \xi H^\dagger H \mathcal{R}\}$$

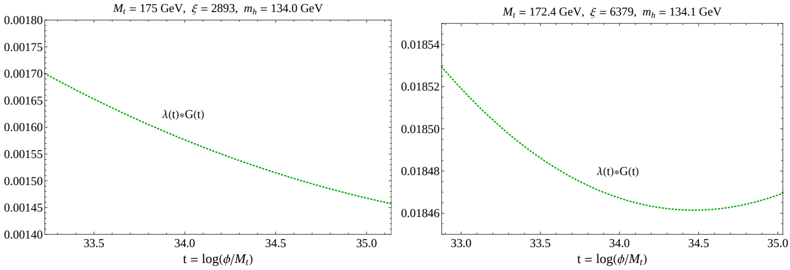
- In the Einstein frame the potential turns out to be:

$$V_E(\phi) \simeq \frac{\frac{\lambda G}{4}\phi^4}{(1+\frac{\xi\phi^2}{m_P^2})^2};\ G(t) = \exp[-4\int_0^t dt' \gamma(t')/(1+\gamma(t'))]$$

where $H^T = \frac{1}{\sqrt{2}}(0, v+\phi)$, $t = \log[\frac{\phi}{M_t}]$ and $\gamma(t)$ is the anomalous dimension of the Higgs field.

- For large ϕ values, $V_E(\phi)$ gives rise to inflation.

Standard Model Inflation?



$\lambda(t)\, G(t)$ vs. t, between pivot-scale $t_0 = \log[\frac{\phi_0}{M_t}]$ and inflation end scale $t_e = \log[\frac{\phi_e}{M_t}]$

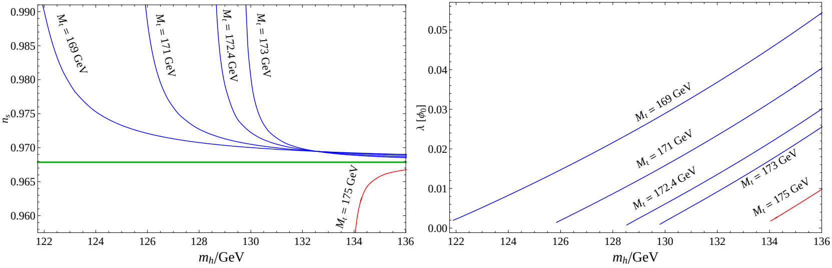
- The spectral index is

$$n_s \simeq 1 - \frac{2}{N_e} + \frac{1}{3}\left(\frac{\partial_{\psi_0}(\lambda\, G)}{(\lambda\, G)}\right); \qquad \psi_0 \equiv \frac{\sqrt{\xi}\,\phi_0}{m_P}$$

with

$$\Delta^2_{\mathcal{R}} \simeq \frac{\lambda\, G}{\xi^2}\frac{N_e^2}{72\pi^2} \;\Rightarrow\; \xi \simeq \left(\frac{N_e}{6\sqrt{2}\,\pi\,\Delta_{\mathcal{R}}}\right)\sqrt{\lambda\, G} \sim 10^4\ (!)$$

Standard Model Inflation?



Green curve is the tree level result (independent of Higgs mass).
Blue and red include quantum corrections.

Challenges for SM inflation

[Burgess et al., Espinosa et al., 2009]

- Consider $g_{\mu\nu} = \eta_{\mu\nu} + \frac{h_{\mu\nu}}{m_P}$, so that the term $\xi\,\phi^2\,\mathcal{R}$ yields

$$\frac{\xi}{m_P}\,\phi^2\,\eta^{\mu\nu}\,\partial^2\,h_{\mu\nu} + \cdots$$

  This suggests an effective cut-off scale $\Lambda \approx \frac{m_P}{\xi} \ll m_P$.

- The energy scale of inflation is estimated to be

$$E_i \simeq V_0^{1/4} = \frac{\lambda^{1/4} m_P}{4^{1/4}\sqrt{\xi}} \gg \Lambda = \frac{m_P}{\xi}.$$

- Hence, it is not easy to see why we should trust this inflationary scenario.

Brane Inflation

- In the simplest brane inflation models the inflaton ϕ is a field which parametrizes the distance r between two brane worlds embedded in the extra dimensions.
- If the distance between these two branes is much bigger than the string scale, the potential between them is essentially governed by the infrared bulk supergravity. Assuming the effects of higher string excitations are decoupled, the potential is expected to be

$$V \sim M_s^4 \left(a - \frac{b}{(M_s r)^{N-2}} \right),$$

where M_s is the string scale, and a, b are constants.

Brane Inflation

- Thus, in this picture inflation in four dimensions is driven by brane motion in the extra-dimensional space.
- Positive powers of ϕ are absent because the inter-brane interaction falls off with the distance.
- For a D_3 brane - anti D_3 brane system, assuming the extra dimensions have been suitably compactified and (say T^6) and remain frozen during inflation,

$$V(\phi) \sim M_s^4 \left(1 - \frac{\alpha}{\phi^4}\right), \; \phi = \sqrt{T_3}\, r, \; \alpha = \frac{T_3}{16\,\pi^2}.$$

(contributions from dilaton, graviton and RR field)

In this case

$\frac{\delta T}{T} \propto M_c/M_P$, $M_c \sim 10^{12}$ GeV (intermediate compactification scale),

$$n_s \simeq 1 - \frac{2}{N_0} \approx 0.96.$$

NOTE: No very compelling/realistic model so far!!

D-brane Inflation

- Brane-Antibrane Dvali & Tye; Alexander; Dvali,Shafi,Solganik; Burgess,Majumdar,Nolte,Quevedo,Rajesh,Zhang.
- Branes at Angles Garcia-Bellido, Rabadan, Zamora; Blumenhagen, Krs, Lst, Ott; Dutta, Kumar, Leblond.
- D3-D7 Dasgupta,Herdeiro,Hirano, Kallosh; Hsu,Kallosh, Prokushkin; Hsu & Kallosh; Aspinwall & Kallosh; Haack, Kallosh, Krause, Linde, Lst, Zagermann.
- warped brane-antibrane Kachru,Kallosh,Linde,Maldacena,L.M.,Trivedi; Firouzjahi & Tye; Burgess,Cline,Stoica,Quevedo; Iizuka & Trivedi,...
- DBI Silverstein & Tong; Alishahiha,Silverstein,Tong; Chen; Chen; Shiu & Underwood; Leblond & Shandera,...
- Monodromy Silverstein & Westphal.

Adapted from McAllister, 2008

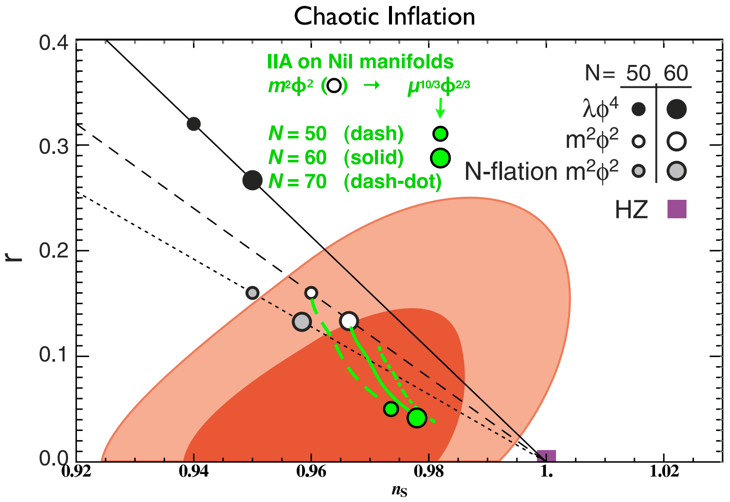
D-brane Inflation

Closed string inflation models, e.g.:

- Racetrack Blanco-Pillado, Burgess, Cline, Escoda, Gomez-Reino, Kallosh, Linde, Quevedo.
- Kähler moduli Conlon & Quevedo.
- N-flation Dimopoulos, Kachru, McGreevy, Wacker; Easther & L.M.

Adapted from McAllister, 2008

[Silverstein, Westphal, 2008]



Brane Inflation and Cosmic Strings

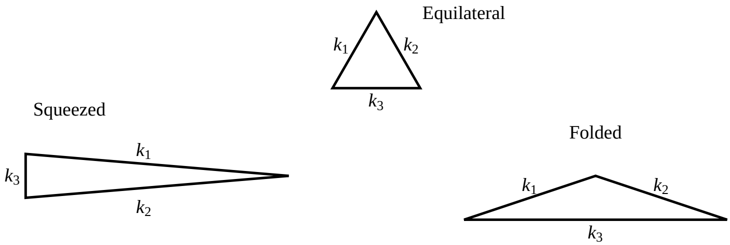
- Prior to brane annihilation the associated gauge symmetry is $U(1) \times U(1)$. One linear combination gives rise to D-strings, while the orthogonal combination is associated with F (fundamental)-strings.
- It has been argued that a substantial fraction of energy of the annihilating branes is used up in the production of a network of cosmic D and F strings.
- If one assumes that brane inflation gives rise to the observed inhomogeneities, estimates suggest that

$$10^{-11} \lesssim G\mu \lesssim 10^{-6}.$$

- With some(?) luck it may be possible to observe these primordial strings with LIGO/LISA.

Gaussianity vs. Non-Gaussianity

- Gaussian fluctuations predicted by slow-roll, single-field inflation
- **Bispectrum:** $\mathcal{B}_{\mathcal{R}}(k_1, k_2, k_3)$
    - 3-point correlation from CMB map
- Momenta form triangles:



New Physics from Significant Non-Gaussianity

- Each triangular formation indicates non-trivial inflationary dynamics
  - **Squeezed:** multi-field inflation
  - **Equilateral:** higher-derivative interactions
  - **Folded:** excited initial state

- *The discovery of primordial non-Gaussianity will rule out the simplest inflation models*

Models of Non-Gaussianity

- Some models/mechanisms predicting large non-Gaussianity:
  - DBI inflation (equilateral)
  - Curvatons (squeezed)
  - Inhomogeneous reheating phase (squeezed)
  - Preheating after inflation

Current Limits (WMAP5)

$$\mathcal{R}(x) = \mathcal{R}_g(x) + \frac{3}{5} f_{\mathsf{NL}}^{\mathsf{local}} \times [\mathcal{R}_g(x)]^2$$

where $f_{\mathsf{NL}} = \frac{5}{18}\frac{\mathcal{B}_{\mathcal{R}}(k,k,k)}{\mathcal{P}_{\mathcal{R}}(k)^2}$ characterizes the amount of non-Gaussianity

WMAP5 measurements (95% CL):

Komatsu et. al. (WMAP Collaboration), 2008

$$\begin{aligned} -9 < \quad & f_{\mathsf{NL}}^{\mathsf{local}} \quad < 111 \\ -151 < \quad & f_{\mathsf{NL}}^{\mathsf{equil}} \quad < 253 \end{aligned}$$

$\Rightarrow$ So far, observations are consistent with Gaussian fluctuations ($f_{\mathsf{NL}} = 0$)

Conclusions

- Inflationary Cosmology is a highly successful extension of Hot Big Bang Cosmology.
- Main Challenges: Where does ΛCDM come from? In particular what makes up the CDM component, and what does Λ stand for?
- Realistic supersymmetric and non-supersymmetric models are readily constructed, with predictions for n_s, r, $\frac{dn_s}{dlnk}$, etc. They also provide dark matter candidates (neutralino, axion, for example) and decent baryogenesis scenarios.

Conclusions

- String Theory Inflation still in the early stages. Many scenarios have been considered but none so far compelling.
- Hopefully, a combination of precision measurements waiting to be delivered by PLANCK and other instruments, LHC, dark matter searches, supernovae observations, etc., will bring us a step closer to answering some of these basic questions.