Which is the best inflation model?

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1. Modular inflation
2. Fixing modular inflation to generate the curvature perturbation
3. Hybrid modular inflation
4. Using the curvaton paradigm to generate the curvature perturbation
5. A tentative ranking
6. Conclusion

1. Modular inflation

Modulus (working definition):

A field with gravitational-strength decay, and potential

$$V(\phi) = M_S^4 f(\phi/M_{\rm P})$$
$$f \sim |f'| \sim |f''| \cdots \sim 1$$

Modular inflation: [Binetruy & Gaillard 1986]

$$\begin{aligned} V(\phi) &= V_0 - \frac{1}{2} m_\phi^2 \phi^2 + \cdots \\ m_\phi &\sim H_* \sim m_{\frac{3}{2}} \end{aligned}$$

giving fastish-roll inflation.

Advantage: uses known field with no fine-tuning.

Disadvantage: curvature perturbation
$\zeta \sim H_*/M_{\rm P} \sim 10^{-15}$ (observation: $\zeta \sim 10^{-5}$).

2. Fixing modular inflation to generate the curvature perturbation

a) [Kodata & Stewart 2003]

(i) Make ϕ complex.

(ii) Assume unsuppressed couplings at $\phi = 0$ giving dip there due to running mass.

(iii) Use both modulus and phase of ϕ

Result: a two-field inflation model which is viable *if* we live in a very special part of the Universe.

b) [Banks 1999]

Use a bulk modulus of Horava-Witten M-theory to raise inflation scale giving big enough curvature perturbation.

Assume $m_\phi^2/H_*^2 \sim 0.1$ giving $n \simeq 0.9$.

Result: viable model *if* assumption is correct, and observation gives $n \simeq 0.9$.

3. Hybrid modular inflation

Hybrid inflation [Linde 1991]

Uses inflation field ϕ *and* ‘waterfall’ field χ. Inflation ends when change in ϕ de-stabilizes χ.

‘Hybrid modular’ inflation: my term, covering **‘supernatural’** inflation [Randall, Soljacic & Guth, 1996] and **running-mass** inflation [Stewart, 1997]

The waterfall field is a modulus with enhanced symmetry at $\chi = 0$. It *doesn’t* inflate after de-stabilization since $m_\chi^2/H_*^2 \gtrsim 2$.

In ‘supernatural’ inflation, small inflaton mass $m_\phi \ll H_*$ put in by hand.

In running-mass inflation, natural value $m_\phi \sim H_*$ assumed at Planck scale, smallness during inflation generated by running. Gives running spectral index, possible conflict with observation.

5. Using the curvaton paradigm to generate the curvature perturbation

Curvaton paradigm [Lyth & Wands 2001; also Mollerach 1990, Linde & Mukhanov 1997]

Inflaton generates *negligible* curvature perturbation.

(i) **During inflation** curvaton σ is light so that the vacuum fluctuation gives perturbation $\delta\sigma_* \sim H_*$ with a flat spectrum.

(ii) **After inflation** curvaton oscillates. Naively,

$$\begin{aligned} \rho_\sigma(\mathbf{x}) &\propto \sigma_*^2(\mathbf{x}) \\ \frac{\delta\rho_\sigma}{\rho_\sigma} &= 2\frac{\delta\sigma_*}{\sigma_*} \\ &\sim \frac{H_*}{\sigma_*} \end{aligned}$$

(iii) **Before BBN** curvaton dominates then decays giving curvature perturbation $\sim H_*/\sigma_*$.

(iv) This naive version of the curvaton paradigm needs $H_* \gtrsim 10^3\,\mathrm{GeV}$. Viable with *bulk*, but not ordinary, modular inflation.

A ranking of existing inflation models

Possible problems for an inflation model (suggested order of importance)

(i) Ruled out by observation.

(ii) *Extreme* fine-tuning, eg. no SUSY or $10^{-\mathrm{many}}$ Yukawas.

(iii) Non-renormalizable terms ignored.

(iv) An unreasonable initial condition for inflation.

(v) Supergravity mass $\sim H_*$ ignored.

(vi) The field theory describing inflation cannot also describe reheating.

Table 1: Suggested ranking of inflation models

Model	Potential	Problems	$n(k)$
NEW INFLATION			
2-field mod.	various	—	1.00?
bulk mod.	$V_0 - m^2\phi^2$	(v)	~ 0.9
p.n.g.b.	$V_0 - M\phi^3$	(iv)	0.92
∼m.s.s.m.	$V_0 - m^2\phi^2 - \lambda\phi^4$	(iii)	1.00
original	$V_0 + \lambda\phi^4 \log(\phi/Q)$	(ii)	0.94
XmodularX	$V_0 - m^2\phi^2$	(i)	~ 0.9
HYBRID INFLATION			
running	$V_0 - m^2\phi^2 \log\phi$	—	$n' > 0$
D to F	various	—	?
p.n.g.b.	various	—	?
F-term	$V_0(1 + g^2 \log\phi)$	—	0.99
coll. brane	various	(vi)	~ 0.97
'supernatural'	$V_0 + m^2\phi^2$	(v)	~ 1.1
quartic	$V_0 + \lambda\phi^4$	(iv)	1.00
dyn. s. b.	$V_0 + c\phi^{-p}$	(iv)	1.00
D-term	$V_0(1 + g^2 \log\phi)$	(iii)	0.99
∼m.s.s.m.	$V_0 \pm m^2\phi^2$	(ii)	1.00
CHAOTIC INFLATION			
quadratic	$m^2\phi^2$	see note	0.96
X?quarticX?	$\lambda\phi^4$	(i)?(ii)	0.94
XEXTENDED INFLATIONX		killed by COBE (1991)	

Notes on Table 1

1. Most models described by Lyth & Riotto hep-ph/9807278. Models often have more than one of the problems (i)–(vi), but only the most serious is indicated. The models in orange are arguably free of all six problems.

2. '$\sim$m.s.s.m.' means 'not far beyond the Minimal Supersymmetry Standard Model'.

3. 'p.n.g.b.' means 'uses a Pseudo Nambu Goldstone Boson to ensure the flatness of the potential'.

4. Predictions for n assume curvature perturbation generated by the inflaton.

5. X means 'conflict with present observation of CMB anisotropy'. Watch out for future conflict!

6. Observable tensor perturbation possible only if non-renormalizable terms absent [Lyth 1997], hence only for the 'chaotic' models. Absence of non-ren. terms justified in the 'gauge inflation' paradigm (Arkani-Hamed et. al. 2003), which however seems to have no string-theoretic realisation (Banks et. al. 2003).

References for Table 1

NEW	
2-field mod.	Kodata & Stewart 2003
Bulk mod.	Banks 1999
p.n.g.b.	Adams, Ross & Sarkar 1997
∼m.s.s.m.	Dine & Riotto 1997
original	Linde 1982, Albrecht & Steinhardt 1982
modular	Binetruy & Gaillard 1986
HYBRID	
running	Stewart 1997
D to F	Copeland, Liddle, Lyth, Stewart & Wands 1994 Gaillard, Lyth & Murayama 1998
F term	CLLSW 1994; Dvali, Schaeffer & Shafi 1994
collid. brane	Dvali & Tye 1998
supernatural	Randall, Soljacic & Guth 1996
p.n.g.b.	Cohn & Stewart 2000
quartic	Linde 1991
dynam. S. B.	Kinney & Riotto 1998
D-term	Stewart 1995; Binetruy & Dvali 1996; Halyo 1996
∼m.s.s.m.	Bastero-Gil & King 1997
CHAOTIC	
quadratic	Linde 1983; Arkani-Hamed, Cheng, Creminelli & Randall 2003
quartic	Linde 1983
EXTENDED	La & Steinhardt 1989

Conclusion

The broad-brush era has gone.

We now have detailed particle physics confronting detailed observations.

The spectral index n will be a powerful discriminator when Planck measures it with $\Delta n \pm 0.01$.

Observation of a tensor signal in the CMB would imply absence of non-renormalizable terms.