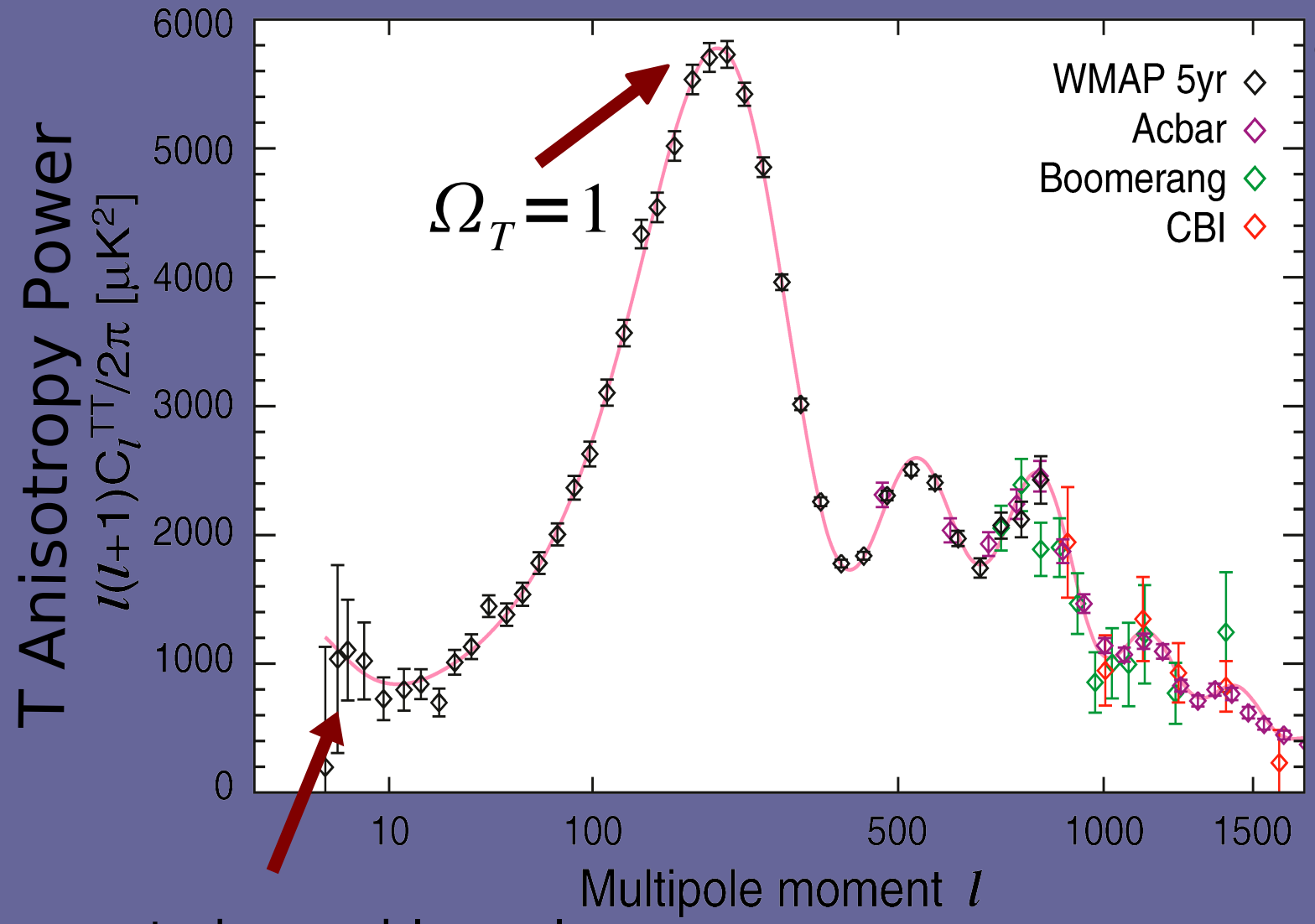
Inflation & CMB

- Cosmological Observations:
  - Why inflation
  - “Slow-roll” inflation
  - Primordial spectrum
- Model building:
  - Susy (sugra) models of inflation:
    - “eta” problem
    - moduli problem
    - Inflation & Shift/Heisenberg sym.
- Summary

Mar Bastero Gil
University of Granada

Cosmic Microwave Background Radiation

Wilkinson Microwave Anisotropy Probe



astro-ph/0803.0593

COBE (1992)
Boomerang
Maxima
DASI
CBI
VSA
.
.
.
PLANCK
(14/05/09)

Largest observable scale
O(3000 Mpc)

Galaxy scale
O(Mpc)

Cosmological Parameters (LCDM)

TABLE 1

Parameter	WMAP5-year	WMAP5+BAO+SN Mean
Homogeneous background		
H_0	$71.9^{+2.6}_{-2.7}$ km/s/Mpc	70.5 ± 1.3 km/s/Mpc
$t_0{}^a$	13.69 ± 0.13 Gyr	13.72 ± 0.12 Gyr
Ω_b (barions)	0.0441 ± 0.0030	0.0456 ± 0.0015
Ω_c (CDM)	0.214 ± 0.027	0.228 ± 0.013
Ω_Λ (DE)	0.742 ± 0.030	0.726 ± 0.015
Curvature ($w \neq -1$)	$-0.063 < \Omega_k < 0.017$	$-0.0179 < \Omega_k < 0.0081$
Dark Energy (Constant w)	$-1.37 < 1 + w < 0.32$	$-0.14 < 1 + w < 0.12$
Primordial spectrum: ~adiabatic, scale-invariant, gaussian		
$\Delta^2_{\mathcal{R}}(k_0{}^b)$	$(2.41 \pm 0.11) \times 10^{-9}$	$(2.445 \pm 0.096) \times 10^{-9}$
n_s	$0.963^{+0.014}_{-0.015}$	0.960 ± 0.013
Gravitational Wave	$r < 0.43$	$r < 0.22$
Running Index (r=0)	$-0.090 < dn_s/d\ln k < 0.019$	$-0.068 < dn_s/d\ln k < 0.012$
Gaussianity: Local	$-9 < f_{NL}^{\rm local} < 111$	
Gaussianity:Equilateral	$-151 < f_{NL}^{\rm equil} < 253$	

[a]The present-day age of the universe
[b]$k_0 = 0.002$ Mpc^{-1}.

Flat Geometry

Tensors?

Gaussian?

WMAP: astro-ph/0803.0547

Expanding Universe

Flatness problem

$\Omega_T = 1 \Rightarrow \Omega_T(t_{nucl}) - 1 \approx 10^{-16}$

Horizon problem

The observable Universe was larger than the **particle horizon** at LSS

Inflation

Early period of accelerated expansion

$\ddot{a} > 0 : P < -\rho/3$

Super-horizon perturbations?

Too small sub-horizon (**causal**) perturbations

Unwanted relics

monopoles, moduli, gravitinos,..

Slow Roll Inflation

Scalar field rolling down its (flat) potential

Energy & pressure

$$\rho = \dot{\phi}^2/2 + V(\phi) \approx V(\phi) \approx Constant$$

$$P = \dot{\phi}^2/2 - V(\phi) \approx -V(\phi)$$

negative pressure

"Flat" potential

The curvature and the slope smaller than the (Hubble) expansion rate

EOM

$$\underline{\ddot{\phi} \ll 3H\dot{\phi}, \dot{\phi}^2 \ll V} \quad \Rightarrow \quad 3H\dot{\phi} \simeq -V_\phi$$

Slow-roll parameters

$$\eta_H \simeq \eta_\phi - \epsilon_\phi$$

$$|\eta_\phi| = m_P^2 \left| \frac{V''}{V} \right| < 1 \qquad \epsilon_\phi = \frac{m_P^2}{2} \left(\frac{V'}{V} \right)^2 < 1$$

$$|\eta_H| = 2 m_P^2 \left| \frac{H''}{H} \right| < 1 \qquad \epsilon_H = 2 m_P^2 \left(\frac{H'}{H} \right)^2 < 1$$

Slow Roll Inflation

- The observable Universe should be within the horizon at the beginning of inflation

No. of e-folds: $N_e \simeq 50-60$

- Quantum fluctuations → Primordial Spectrum

$$P_{\delta\phi} \simeq (H/2\pi)^2_{(k=aH)} \qquad P_R \simeq (H/\dot{\phi})^2 P_{\delta\phi} \simeq (5\times 10^{-5})^2$$

(H ~ constant , P_R~scale invariant)

- Gravitational waves: $ds^2 = dt^2 - a(t)^2(\delta_{ij}(1+2\psi)+h_{ij})dx^i dx^j$

$$P_T \simeq 8(H/(2\pi m_P))^2$$

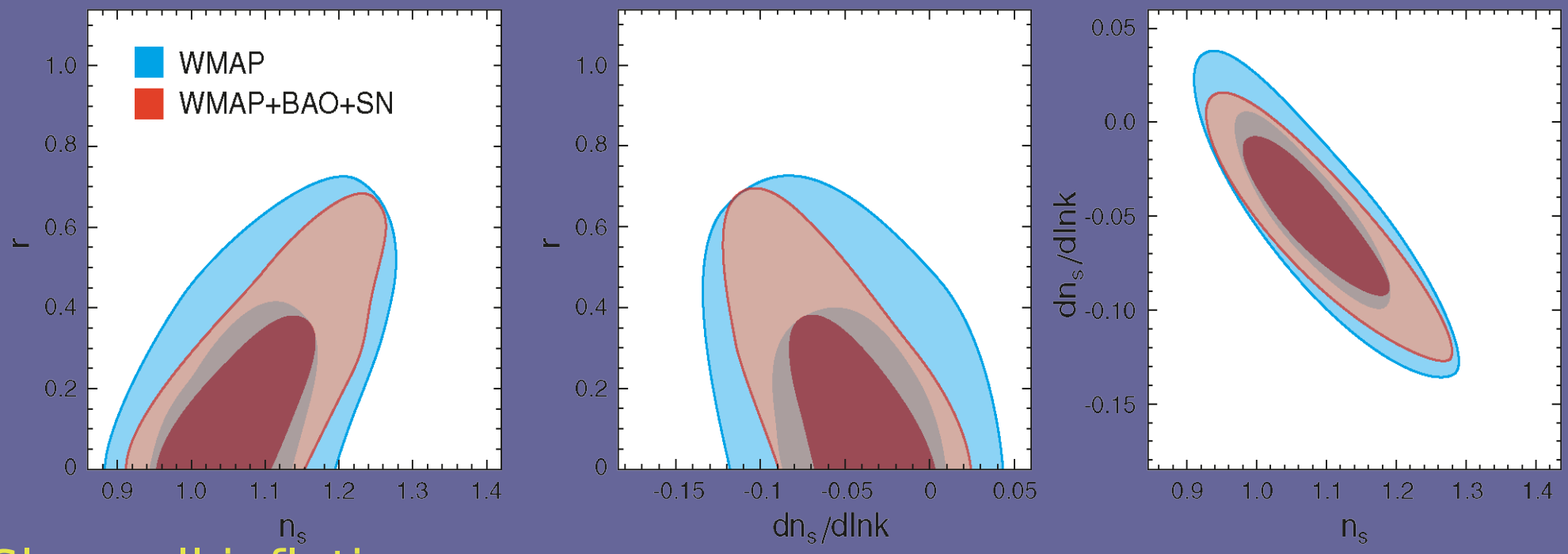
$$r = P_T/P_R \simeq 16\epsilon_\phi$$

Tensor-to-scalar ratio r <1

Primordial Spectrum

$$P_R(k)=P_R(k_0)(k/k_0)^{n_s(k_0)-1+n'_s/2} \qquad P_T(k)=P_T(k_0)(k/k_0)^{n_T}$$

Running: $n'_s=dn_s/d\ln k$ $\qquad (k_0=0.002\,\mathrm{Mpc}^{-1})$



Slow-roll inflation:

$$n_s\simeq 1-6\epsilon_\phi+2\eta_\phi, \quad n_T\simeq -2\epsilon_\phi\simeq -r/8$$

$$n'_s\simeq 2\epsilon_\phi(8\eta_\phi-6\epsilon_\phi+\xi_\phi)$$

$$(\xi_\phi=2m_P^2(V_{\phi\phi\phi}/V_\phi))$$

E. Komatsu et al. (WMAP): astro-ph/0803.0547

$$n_s\simeq 0.96\pm 0.015$$

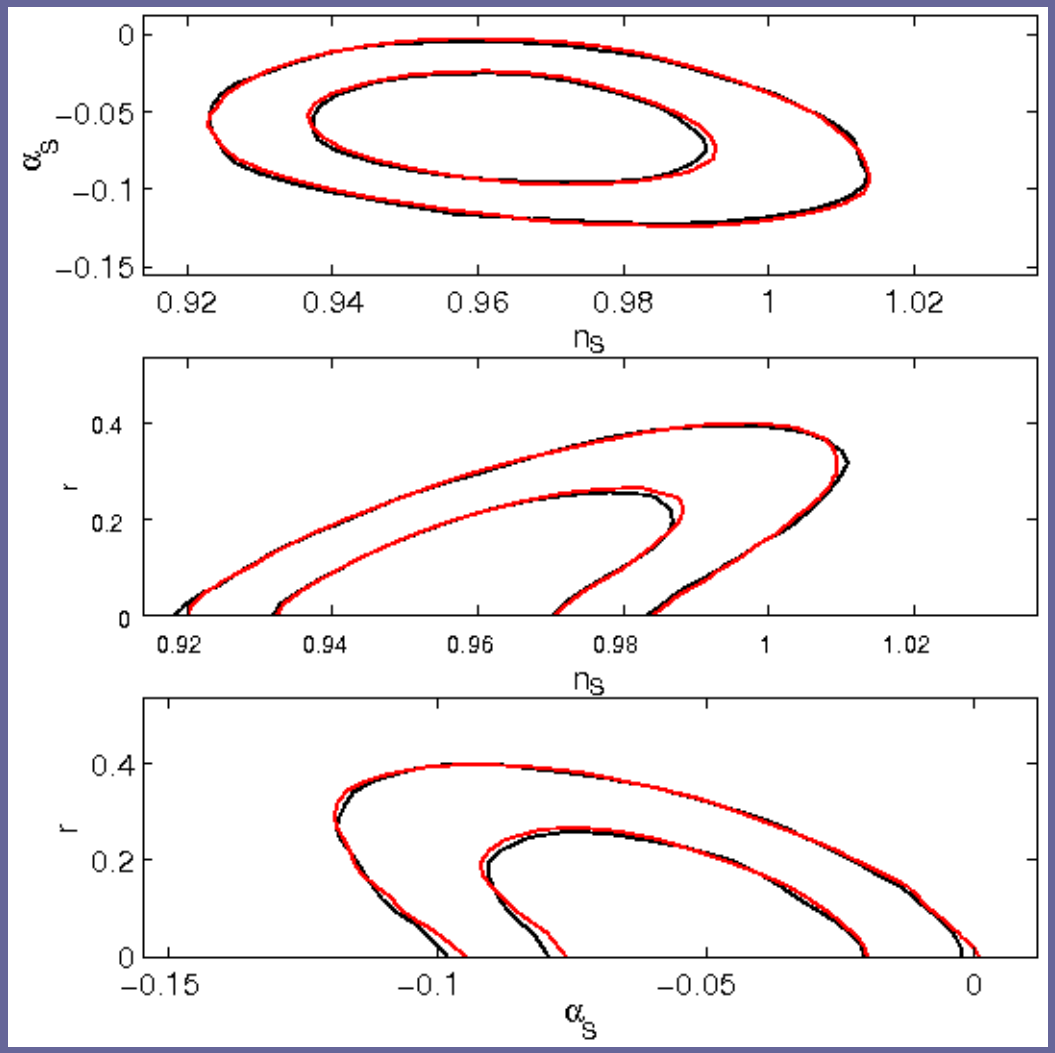
(No tensor, no running)

Primordial Spectrum

$$P_R(k)=P_R(k_0)(k/k_0)^{n_S(k_0)-1+n'_S/2}$$

$$P_T(k)=P_T(k_0)(k/k_0)^{n_T+n'_T/2}$$

$$(k_0=0.002\,\mathrm{Mpc}^{-1})$$



Slow-roll:

Consistency relation

Red Gravity Waves

$$n_T=-r/8-(r/8)(1-n_S-r/8)$$

$$n'_T=r/8(r/8+n_S-1)$$

$$n_S=0.964^{+0.039}_{-0.030}$$

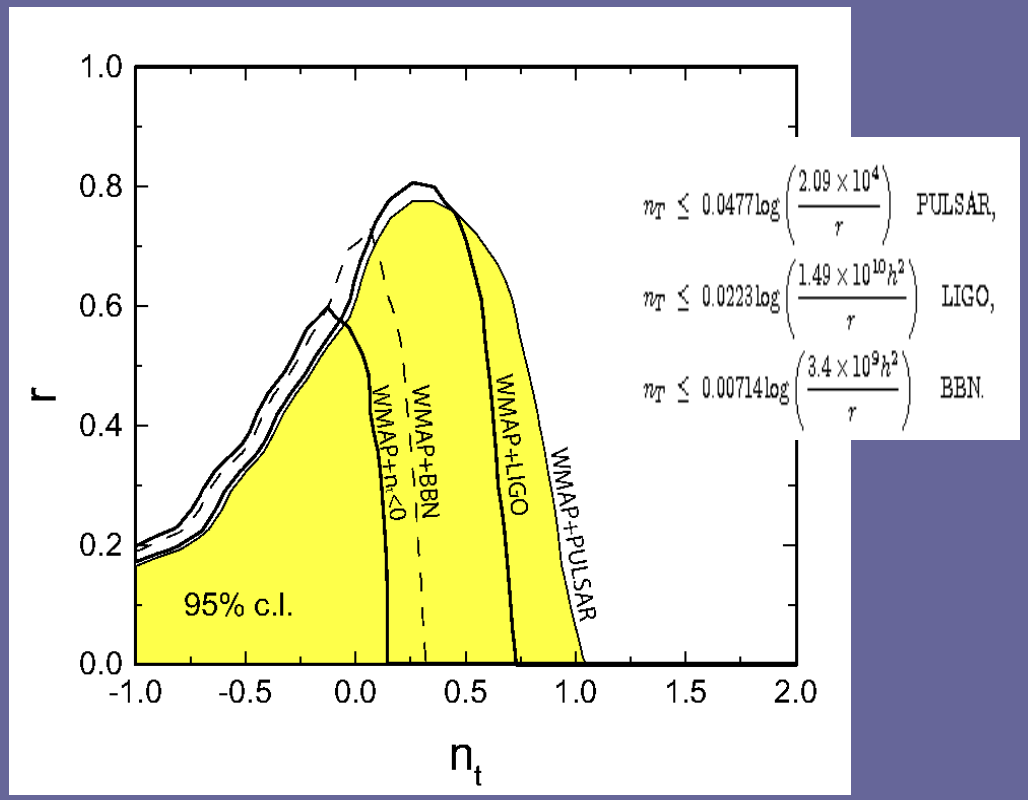
$$r<0.33$$

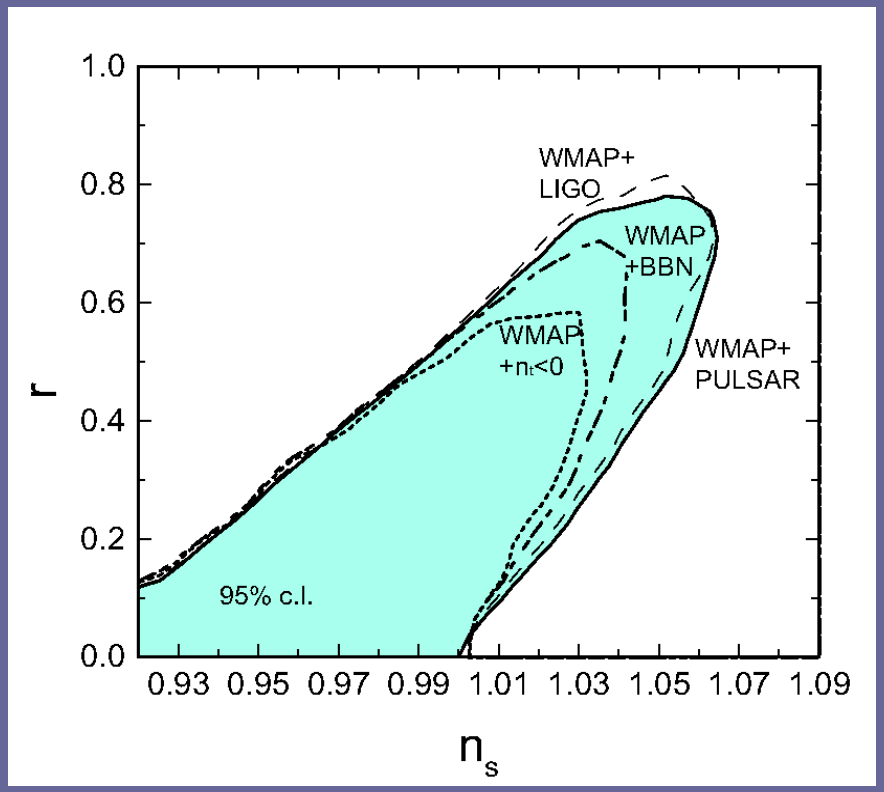
$$\alpha_S=n'_S=-0.063^{+0.061}_{-0.049}$$

F. Finelli et al., 0912.0522 : WMAP + ACBAR + BAO + SN1A

Primordial Spectrum: Blue Gravity Waves?

$$P_R(k)=P_R(k_0)(k/k_0)^{n_S(k_0)-1} \qquad P_T(k)=P_T(k_0)(k/k_0)^{n_T} \qquad (k_0=0.002\,\mathrm{Mpc}^{-1})$$





No priors: **$-1.51 < n_T < 2.62$** ($r > 0.05$)

R. Camerini et al., 0802.1442: WMAP3 + ACBAR

Primordial Spectrum: Quantum corrections

- Correlation functions are **IR (UV) divergent**

$$P_\phi(k) \simeq (H(t_k)/(2\pi))^2 \Rightarrow \langle \delta\phi^2 \rangle = \int \frac{dk}{k} P_\phi(k) \sim P_\phi \ln k$$

- Regularization scheme:

any effect on the primordial spectrum?

(a) Adiabatic subtraction (momentum space)

Parker, 0702216
Agulló et al., 0901.0439

$$\langle \delta\phi^2 \rangle_{ren} = \int \frac{dk}{k} (P_\phi(k) - P_\phi(k)^{ad}) \sim \text{finite}$$

(b) Infrared mode matching

Janssen & Prokopec 0906.0666

$$\delta\phi(t=t_0) = \delta\phi^{(0)}(t=t_0), \quad \langle \delta\phi^{(0)\,2} \rangle \sim \text{finite when } \epsilon = -\dot{H}/H^2 > 3/2$$

(c) The universe in a (comoving) box ~ L (IR cutoff)

Lyth, 0707.0361

$$\langle \delta\phi^2 \rangle = \int_{L^{-1}} \frac{dk}{k} P_\phi(k) \sim P_\phi \ln kL$$

"Minimal Box" $\ln(H_0 L) \sim O(1)$

Primordial Spectrum: Quantum corrections

(a) Adiabatic subtraction (momentum space): $\langle T_{\mu\nu}\rangle_{ren}$ ~ finite

$$\langle \delta\phi^2\rangle_{ren} = \int dk\, k^2 (\phi_k^2 - 1/(\underbrace{2W_k^{ad}}_{\text{Adiabatic invariant (vacuum contrib.)}}))$$

Parker, hep-th/0702216
Agulló et al., 0901.0439

$$W_k^{ad} \simeq (\omega_k^2 - 9H^2/4 - 3\dot{H}/2 + 3(\dot{\omega}_k/\omega_k)^2 - \ddot{\omega}_k/(2\omega_k))^{1/2} \simeq \omega_k (1+\delta(z))^{1/2}$$

(m<<H, ω=H z) (z=k/aH)

- Subtraction at k=aH (z=1):

$$P_T(k) \simeq 8(H/(2\pi m_P))^2 \epsilon_\phi(t_k) \qquad P_R(k) \simeq (H/(2\pi m_P))^2 (\alpha\epsilon_\phi + \beta\eta_\phi)/(2\epsilon_\phi)$$

$$n_T \simeq 2(\epsilon_\phi - \eta_\phi)$$

.

- But when z << 1 ➡ $\delta(z)$ > 1 (IR regime):

$$k^3/W_k^{ad} \simeq H^2 z^4/(z^2 + \epsilon_\phi - 2) \ll k^3/\omega_k$$

Durrer, Marozzi, Rinaldi, 0906.4772

No effect on the primordial spectrum...

Primordial Spectrum: Quantum corrections

(b) Mode matching in the IR: $\langle T_{\mu\nu}\rangle_{ren}$ ~ finite

Janssen & Prokopec 0906.0666

$\langle \delta\phi^2 \rangle$ Is IR finite when $\epsilon = -\dot{H}/H^2 > 3/2$ $(q = \epsilon - 1 > 1/2)$

(deceleration parm.)

$\varepsilon > 3/2$ (RD =2): $\varepsilon < 3/2$: (Inflation <<1)

time t_0

~ No particle production

~ particle production (long wavelength modes)

$a\,\delta\phi_k(t<t_0) = u_k^{(0)}(t)$ → **Bunch-Davies vacuum**

$a\,\delta\phi_k(t>t_0) = \alpha_k u_k(t) + \beta_k \bar{u}_k(t)$ → $|\beta_k|^2 \neq 0$

→ Quantum backreaction negligible at one loop order
When q < -1, equivalent to placing the Universe in a (comoving) box at late times

Non-gaussianity

- **Spectrum:** (beyond linear order)

$$\langle R(k_1)R(k_2)\rangle = (2\pi)^3\delta(k_1+k_2)P_R(k)$$ (Power spectrum)

$$\langle R(k_1)R(k_2)R(k_3)\rangle = (2\pi)^3\delta(k_1+k_2+k_3)B_R(k_1,k_2,k_3)$$ (Bispectrum)

$$\vdots$$

$$\boxed{B_R(k_1,k_2,k_3) = -\frac{6}{5}\mathbf{f_{NL}}(P_R(k_1)P_R(k_2)+\text{permt.})}$$

Non-linearity parameter: $-9 < f_{NL}^{local} < 111$ $(k_3 << k_1 \sim k_2)$

(Planck: $f_{NL} \sim O(10)$) $-151 < f_{NL}^{equil} < 253$ $(k_3 \sim k_1 \sim k_2)$

- **Single field inflation**
- **Canonical kinetic terms**
- **Slow-roll**
- **Initial vacuum state**

$\Big\}$ $f_{NL} \sim O(\varepsilon, \eta)$

Maldacena JHEP '03
Acquaviva et al. NPB '03

Non-gaussianity

- **Large (detectable) f_{NL}:**
  - **Multi-field inflation** — Byrnes, Choi, Hall 0812.0807
  - **Non-canonical kinetic terms** — Seery, Lidsey JCAP '05; Chen et al. JCAP '07
  - **End of inflation** — Bernardeu et al. PRD '04; Lyth JCAP '05
  - **Curvaton** — Lyth et al. PRD '03; Enqvist, Nurmi JCAP '05
  - **Warm inflation** — Moss, Xiong JCAP '07
  - **Slow-roll + loops corrections** — Cogollo et al. 0806.1546
  - **...**

Non-gaussianity

Sloth NPB '06, NPB '07
Byrnes et al., 0705.4096
Seery 0707.3377,0707.3378

- **Loops corrections:**

$$P_\phi(k) \simeq P_\phi^{tree}(k)\left(1 + P_\phi^{tree}\left(\frac{35}{6}\underline{\ln kL} + \beta\right)\right)$$

$$P_R(k) \simeq P_\phi^{tree}(k)\left((\partial_\phi N_e)^2 + \Pi^{loop}\right)$$

Several fields

$$\Rightarrow \quad \Pi^{loop} \sim P_\phi^{tree}(k)(\partial^2_{\phi\phi} N_e)\underline{\ln kL} \quad \Rightarrow \quad (\partial^2_{\alpha\beta} N_e) \sim e^{N_e \eta_\beta}$$

Cogollo et al. 0806.1546
Rodriguez, Valenzuela, 0811.4092

- **2-fields example:**

Φ~ inflaton, σ ~ 0, light field

$$P_R^{tree} \simeq (H/2\pi)^2/(\eta_\phi \phi)^2$$
$$B_R^{tree} \simeq -(P_R^{tree})^2 f(k_i)/\eta_\phi$$

Φ contribution

$$P_R^{loop} \simeq (\eta_\sigma e^{2N_e(\eta_\phi - \eta_\sigma)} P_R^{tree})^2 \ln kL$$
$$B_R^{loop} \simeq (\eta_\sigma e^{2N(\eta_\phi - \eta_\sigma)} P_R^{tree})^3 f(k_i) \ln kL$$

Φ,σ contribution

P_R~ tree-level, B_R~ 1-loop $\Rightarrow$ f_{NL} sizeable

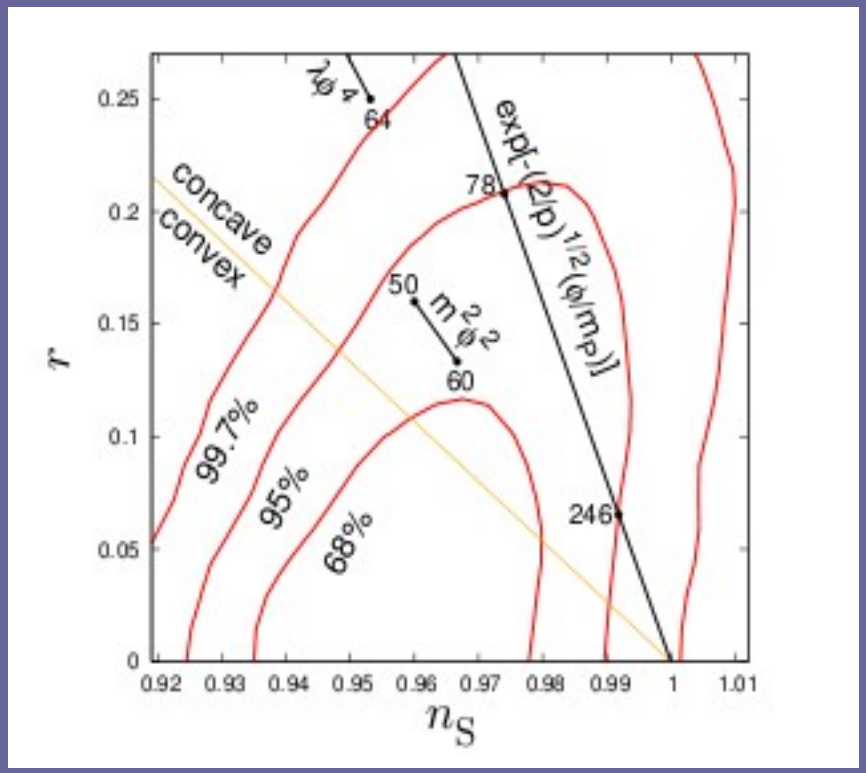
Which (particle) model of inflation?

- Inflationary predictions consistent with observations
- Particle physics model building issues

Large field models (chaotic inflation)

(Linde, PLB'83)

$$V(\phi)=V_0(\phi/M)^p$$



"Slow roll" for large field values
(larger than Planck scale)

$$\eta_\phi = p(p-1)\left(m_P/\phi\right)^2 < 1$$

Tensor-to-scalar: $r \simeq 4p/N_e$

p = 2 $r \simeq 0.13$ **p = 4** $r \simeq 0.3$

p > 2 ruled out:
too large tensor amplitude
(r < 0.33 F. Finelli et al. 0912.0522)

- **p=4 + 1-loop effective potential not excluded** Senoguz & Shafi PLB '08
- **p=4 + "just enough" inflation** Ramirez & Schwarz 0912.4348
- **p=4 + warm inflation** MBG & Berera 0902.0521

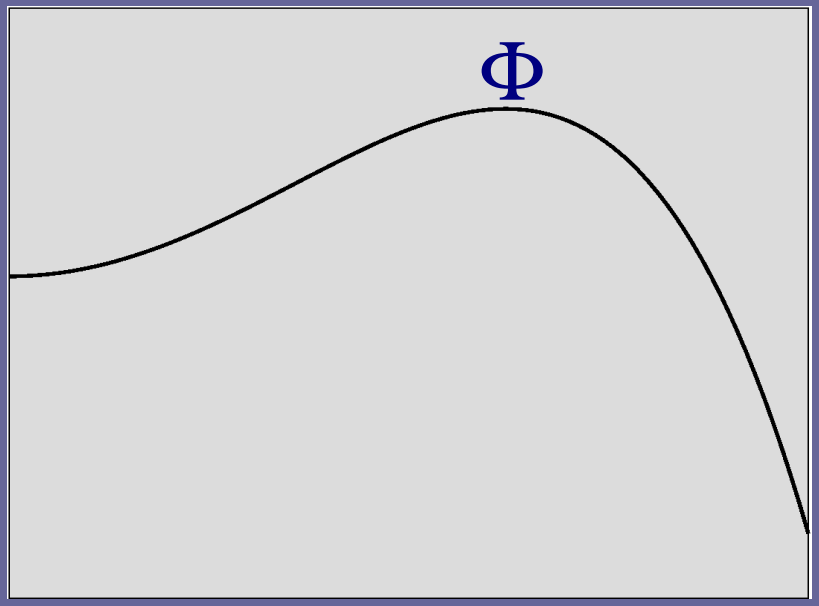
Small field models (false vacuum dominated)

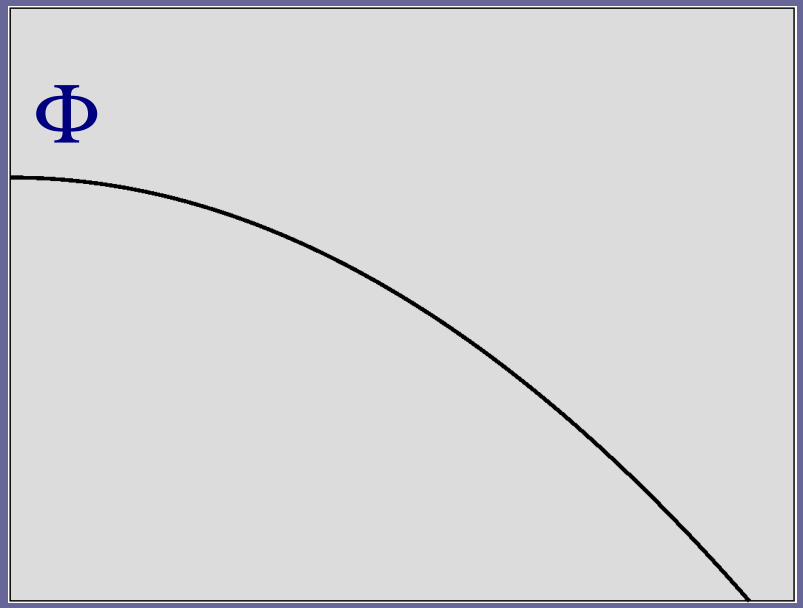
$$V(\phi) = V_0\left(1 \pm \left(\frac{\phi}{M}\right)^p\right) + \cdots$$

Linde PLB '82
Albrecht & Steinhardt PRL '82

"Slow roll" for field values below Planck

$\epsilon_\phi \ll \eta_\phi \rightarrow n_S \simeq 1 + 2\eta_\phi \rightarrow$ Observations: $\eta_\phi < 0 \quad (V'' < 0)$





Cosmological scales leave the horizon near the "top of a hill"

Tensor-to-scalar: $r \ll 1$

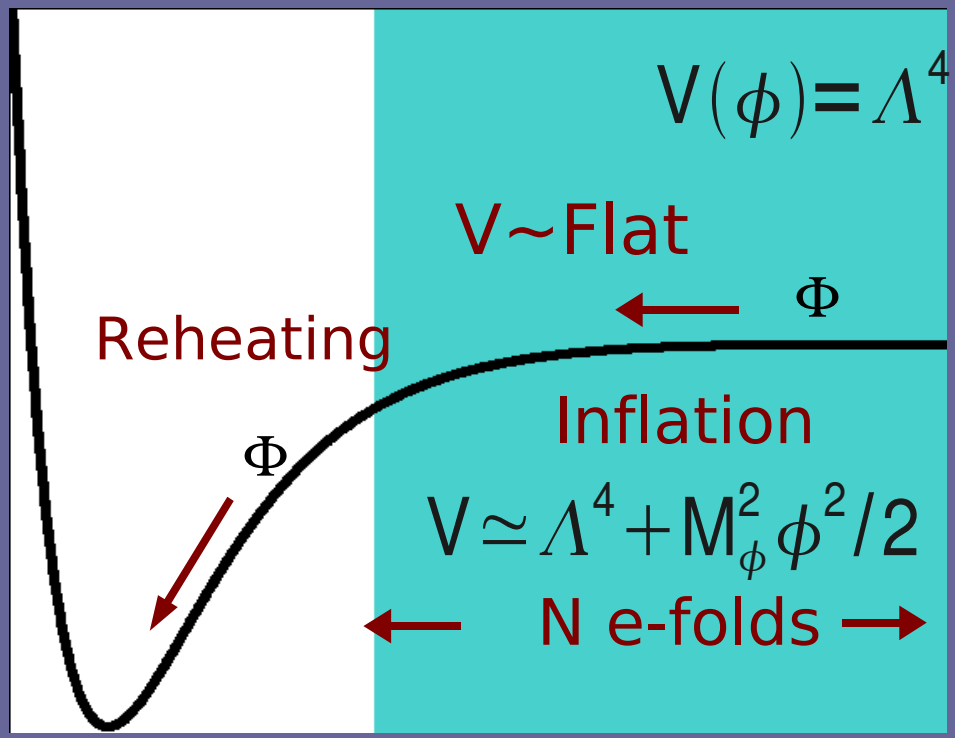
Alabidi & Lyth JCAP '06
Kohri, Lin, Lyth JCAP '07

Hybrid inflation (2 fields models)

Inflation ➡ phase transition ➡ reheating

False vacuum

Global minimum



$$V(\phi) = \Lambda^4 + \frac{M_\phi^2}{2}\phi^2 + \frac{\lambda}{4}\chi^4 + \frac{1}{2}(g^2\phi^2 - \sqrt{\lambda}\,\Lambda^2)\chi^2$$

Inflation: above the critical value

The second field vanishes
Potential ~ vacuum energy

$$V \simeq \Lambda^4 + M_\phi^2\phi^2/2$$

Global minimum: below critical

The second field gets a vev
The potential vanishes

(a) Small (below Planck) field values

(No tensor: r << 1)

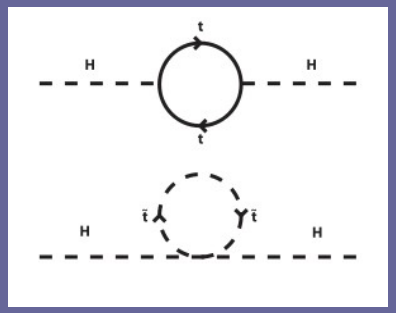
(b) Susy models ⟷ Flat directions

Linde, PLB'90
Copeland et al, PRD'94

Supersymmetry

- **Fermion/boson** symmetry
- **Hierarchy** problem: $m_W / m_P \sim O(10^{-17})$

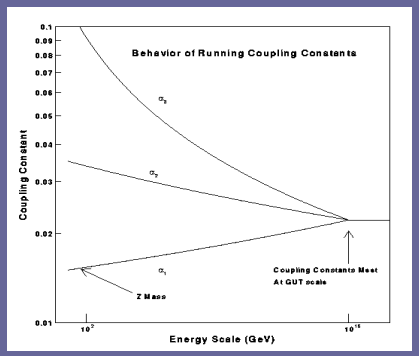
  SM scalar (Higgs) masses are not protected against large (quadratic) radiative corrections



Susy: no rad. Corrections
exact cancelation between fermions/scalars

Soft Susy: no quadratic rad. corrections

- **Grand Unification**:



- **Dark Matter candidate**:
  Lightest **S**upersymmetric **P**article

R-parity: susy particles produced in pairs, stable LSP i

Supersymmetric Hybrid inflation:

Susy superpotential: $W = \kappa \Phi H \bar{H} + \cdots$

Φ = inflaton (gauge singlet) H = GUT fields

$$V = V_F + V_D(H, \bar{H}) = \Sigma \left| W_i^2 \right| + V_D(H, \bar{H})$$

- F-term inflation: $W = \kappa \Phi (H \bar{H} - \underline{M^2})$

Dvali, Shafi, Shraefer PRL '94

$$H = \bar{H} = 0 \Rightarrow V_0 = V_F = \kappa^2 M^4$$

- D-term inflation: $V_D = \frac{g^2}{2} (\underline{\xi_{FI}} + \bar{H}^2 - H^2)^2$

Binetruy & Dvali PLB '96
Halyo PLB '96

$$H = \bar{H} = 0 \Rightarrow V_0 = V_D = \frac{g^2}{2} \xi_{FI}^4$$

- Susy breaking: V lifted by **1-loop rad. correct.**

$$m_H^2(\phi), m_{\bar{H}}^2(\phi) \Rightarrow V = V_0 + \Delta V^{(1)}(\phi)$$

Sugra inflation: "eta" problem:

- Global susy models should be embedded into a local susy (sugra) model

Sugra Potential: superpotential W+ Kähler potential (K)

$$V(\phi)=e^{K}(|W_i+K_iW|K^{-1}_{i\bar{j}}|\bar{W}_{\bar{j}}+K_{\bar{j}}\bar{W}|-3|W^2|)=|F_i|^2-3m^2_{3/2}m^2_P$$

- Sugra corrections problematic for (slow-roll) inflation: they typically induce masses of order H for the scalars

→ **"eta" problem?** (F-term inflation)

$$V(\phi)=e^{K(\phi)/m_P^2}V_0\sim V_0(1+\frac{\phi^2}{m_P^2}+\ldots)\sim V_0+3H^2\phi^2+\ldots$$

→ $\eta_\phi\sim 1$

Copeland et al. PRD '94
Dine, Randall, Thomas PRD '95

- Chaotic models : $V(\phi)=e^{K(\phi)/m_P^2}V_0(\phi)$

too steep for $\phi > m_P$

Sugra F-term Hybrid Inflation

Susy superpotential: $W_H = \kappa \Phi (H\bar{H} - M^2)$

Waterfall (GUT) fields: $H \quad \bar{H}$ Singlet: ϕ

Minimal Kahler potential: $K = |\Phi|^2 + |H|^2 + |\bar{H}|^2$

→ W_H + Minimal Kähler potential: <u>no quadratic term</u>

$$V(\phi) \simeq \kappa^2 M^4 \left(1 + \frac{\phi^4}{8 m_P^4} + \ldots\right) + \Delta V^{(1)}$$

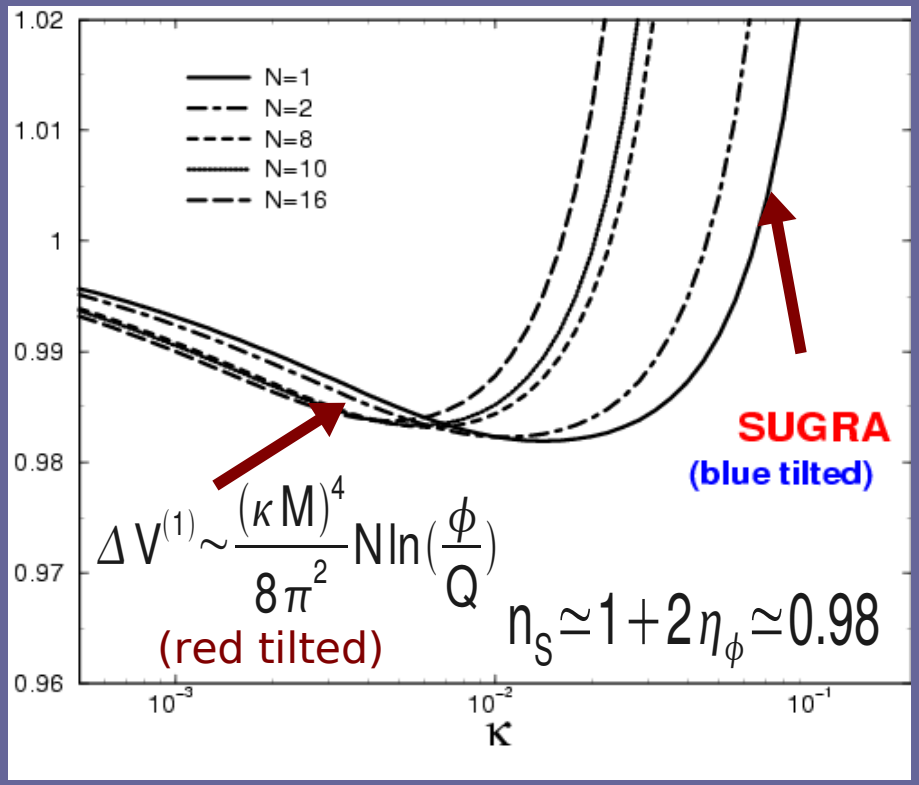
Sugra correction

Copeland et al. PRD '94
Linde & Riotto PRD '97

n_S consistent with observations at 95% CL, but....

<u>WMAP:</u> $n_S \simeq 0.96 \pm 0.015$

(no tensor)



“eta” problem: shift symmetry

- Symmetry of the Kahler potential

$\phi \to \phi + c \longrightarrow K = K(\phi - \bar{\phi})$ does not depend on Re(ϕ)

no quadratic correction from Kahler

- Chaotic inflation:

sym broken by small parameter in W

$W = m\Phi^2 \longrightarrow$ unbounded from below for Im(ϕ)

$W = m\Phi X$ **OK!**

Kawasaki, Yamaguchi, Yanagida PRD'00
Hsu, Kallosh JHEP'04
Brax, Martin PRD'05
Antusch et al. PLB'09

- Hybrid inflation:

$K = -(\phi - \bar{\phi})/2 + |H|^2 + |\bar{H}|^2$

$\longrightarrow$ tachyonic Im(ϕ):

Extra contributions to Kahler required

Sugra inflation: moduli problem(s)

Brunstein, Steinhardt PLB'92; M. Dine PLB'00

- Sugra as the low energy effective theory from strings:

Moduli fields: scalar d. of f. from extra dimensions

Dilaton S, T modulus,.. : $K \sim -\mathrm{Ln}(S + S^*) - 3\,\mathrm{Ln}(T+T^*)$

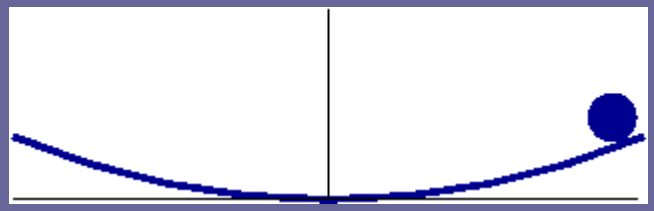
No W, flat V at tree-level, lifted by NP effects

- Long lived light d. of f.: ($m_{3/2} \sim 1$TeV)

must decay before nucleosynthesis

- Potential lifted by susy breaking effects:

Energy due to large amplitude ($\sim m_P$) oscillations may overclose the Universe



- Runaway potential during inflation: $V \sim V_{inf}/(T+\bar{T})^3$

Kinetic energy dominates → **they must be stabilised**

Ellis et al. JCAP'06; Brax et al. JCAP'06; Davis, Postma JCAP'08

Sugra inflation + moduli

- K = K(ϕ) -3 Ln(T+T*) , W=W(ϕ) , shift symmetry K($\phi-\phi*$)

$$V=|F_\Phi|^2/(T+\bar{T})^3 \longrightarrow \eta_T=\epsilon_T>1$$

Ellis et al. JCAP'06

T dynamics dominates and makes inflation impossible

- Generating a potential minimum for T:

F-term stabilisation $W(T)_{KKLT}=W_0+Ae^{-aT}$ Kachru et al. PRD '03

Fluxes instanton effects

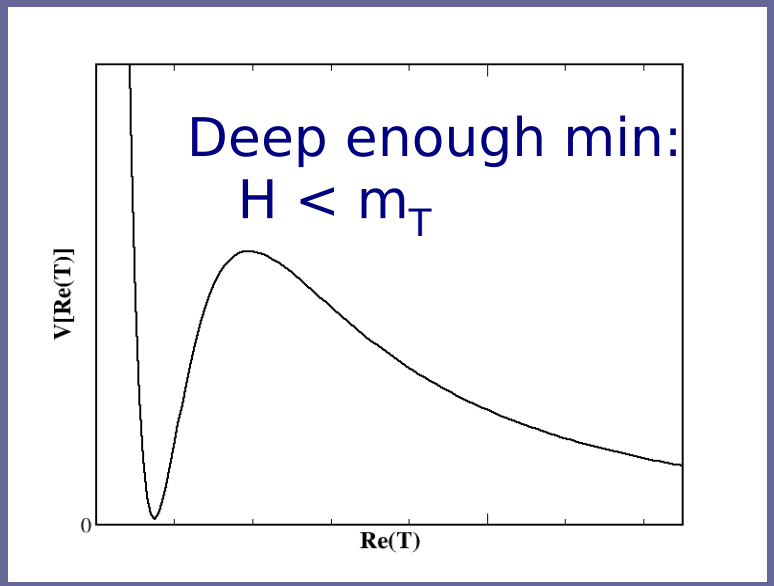
(a) AdS minimum : add $V_{lift}\sim K_T^2/ReT^p$

$\longrightarrow$ dS minimum

(b) $W(T)_{KL}=W_0+Ae^{-aT}+Be^{-bT}$

$\longrightarrow$ Minimum $W=W_T=0$

Kallosh, Linde JHEP '07



Sugra inflation + moduli

- Adding all together: $K = K(\phi - \phi^*) + K(T)$,$W = W(\phi) + W(T)$

$$V \simeq V_0(\Phi) + C(T)\Phi + M(T)^2 \Phi^2/2$$

- T stabilised at T_0 : check $M(T_0) < H$

- Check dynamics: $V \simeq V_{inf}(T_0) + \delta V(\delta T)$

Hybrid (shift sym.) + KKLT/ KL: $\eta \sim -6$ Brax et al. JCAP '06

(Adding Kahler functions: $G = K(\phi) + K(T) + \ln W(T)\, W(\phi)$ $|\eta| < 1$)

Achucarro, Hardeman, Sousa PRD '08

Davis & Postma JCAP'08

Chaotic (shift sym.) + $W = M\, \phi\, X$:

quadratic chaotic model

Sugra inflation + Heisenberg sym.

- Heisenberg symmetry protects flat directions in V

$$\delta T = \epsilon \Phi, \quad \delta \Phi = \epsilon$$

Gaillard, Murayama, Olive '95
Gaillard, Lyth, Murayama PRD '98

Kahler invariant under Heisenberg sym. :

$$K = K(\rho), \quad \boxed{\rho = T + \bar{T} - |\Phi|^2} \qquad (K = -3 \ln \rho)$$ (no scale)

Sym broken in the superpotential : $W = W(\Phi)$

$$V = e^{K(\rho)} \left[\left(K_\rho^2 / K_{\rho\rho} - 3 \right) |W|^2 - |W_\Phi|^2 / K_\rho \right] \qquad (V = |W_\Phi|^2 / (3 \rho^2))$$ (no scale)

The modulus ρ must be <u>stabilised</u> during inflation: $V_\rho(\rho_0) = 0$

$$M^2(\rho_0, \Phi) \simeq \begin{pmatrix} V_{\rho\rho} & -\Phi V_{\rho\rho} \\ -\bar{\Phi} V_{\rho\rho} & |\Phi|^2 V_{\rho\rho} \end{pmatrix} \Rightarrow \mathrm{Det}\, M^2(\rho_0, \Phi) = 0$$

“Kahler” moduli stabilisation

Antusch et al. JCAP'09

Murayama et al. PRD '94

Hybrid model + Heisenberg symmetry: $\rho = T + \bar{T} - |N|^2$

No-scale: an example

$$K = -3\ln\rho + (1 + \kappa_S |S|^2 + \kappa_\rho \rho)|S|^2 + |H|^2$$

$$W = \kappa S (H^2 - M^2) + \lambda N^2 H^2 / \bar{M}$$

$$V = \kappa^2 M^4 e^{K(\rho)} / (1 + \kappa_\rho \rho)$$

-Matter content:

- T : modulus , N: inflaton
- S: singlet $|F_S|^2 \neq 0$, S=0 (vacuum energy)
- H, waterfall field, H=0

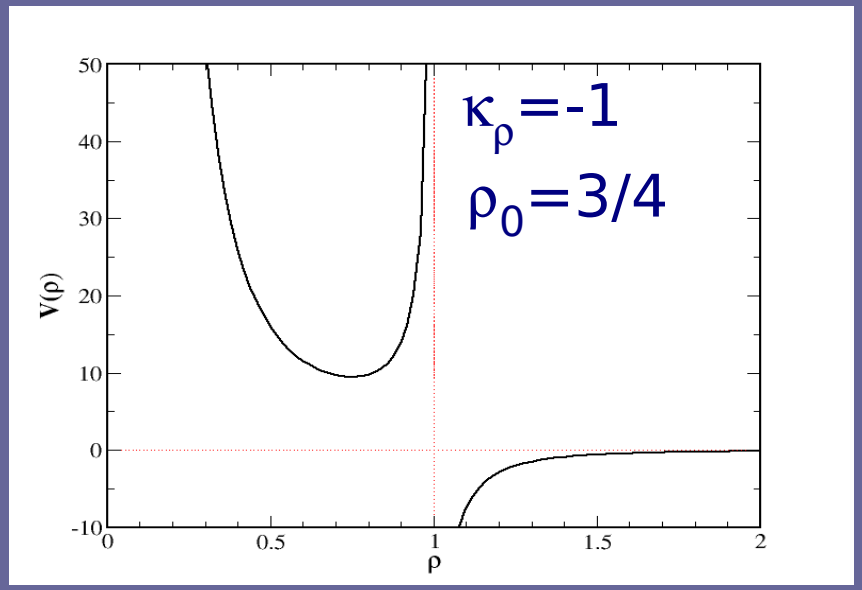
- $m_N < H$
- All other masses > H
- $\kappa_S < 0$

κ_S : S mass contribution

κ_ρ : minimum ρ direction

-V(N) lifted by 1-loop corrections

ρ settles quickly at its minimum

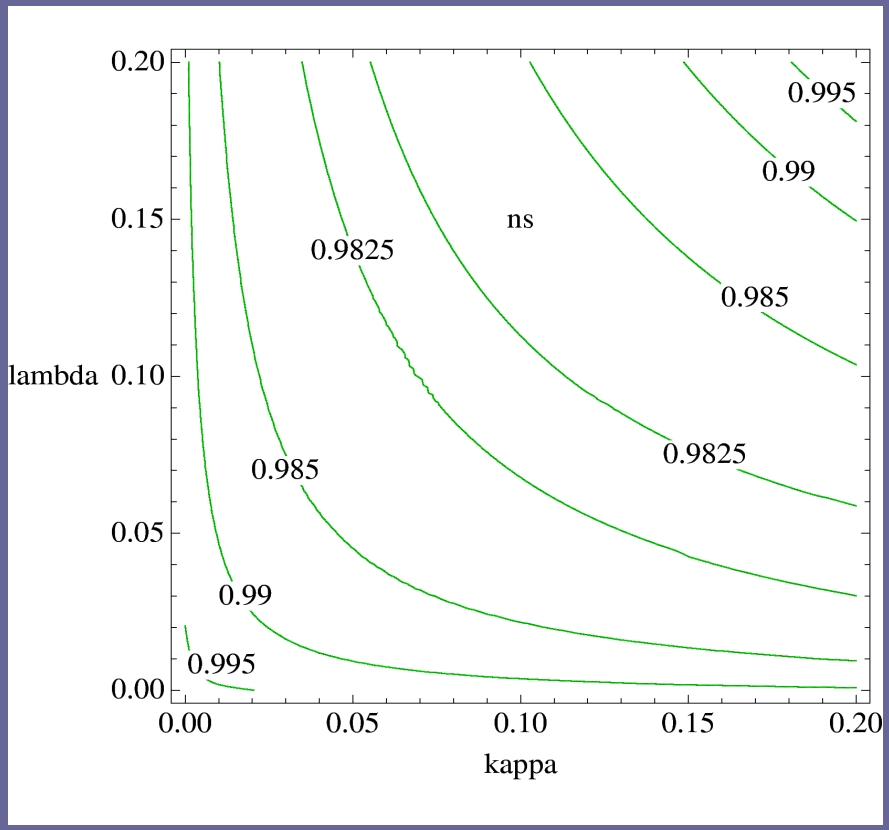


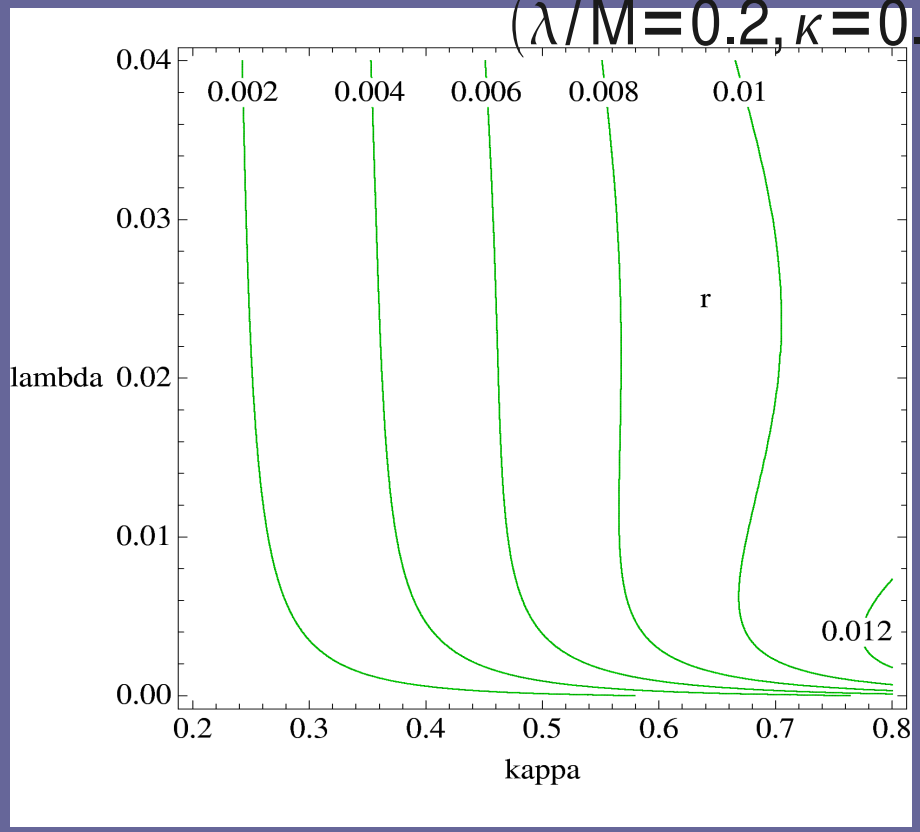
Inflationary predictions

Similar to standard susy hybrid inflation:

$$n_S \simeq 0.98, \quad M \simeq 3\times10^{-3}, \quad r \simeq 10^{-4}, \quad dn_s/d\ln k \simeq -10^{-3}$$

$(\lambda/\bar{M}=0.2, \kappa=0.05)$





- no blue-tilted spectrum
- κ, λ can be larger than in standard susy hybrid inflation:

  $\kappa \sim 0.7$, $\lambda/M \sim 0.05$ ➡ $r \sim 0.01$ (larger tensor contribution)
- $\kappa_{SH} \sim 10$ ➡ $n_S \sim 0.95$

“Kahler” moduli stabilisation

Antusch et al. PLB'09

Chaotic model + Heisenberg symmetry: $\rho = T + \bar{T} - |\Phi|^2$

Matter content:
- T : modulus , Φ: inflaton
- X : $|F_X|^2 \neq 0$ (vacuum energy)

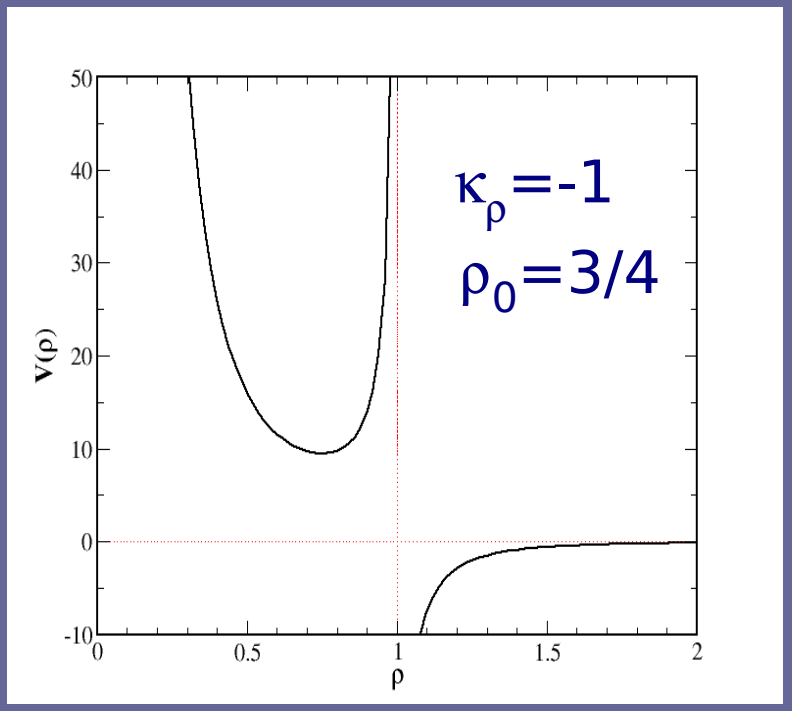
$$K = -3\ln\rho + (1 + \kappa_X |X|^2 + \underline{\kappa_\rho \rho})|X|^2$$

$$W = M\Phi X$$

ρ minimum

$M_X > H$, $k_X < 0$

$$V = M^2|\Phi|^2/(\rho^3(1+\kappa_\rho\rho))$$



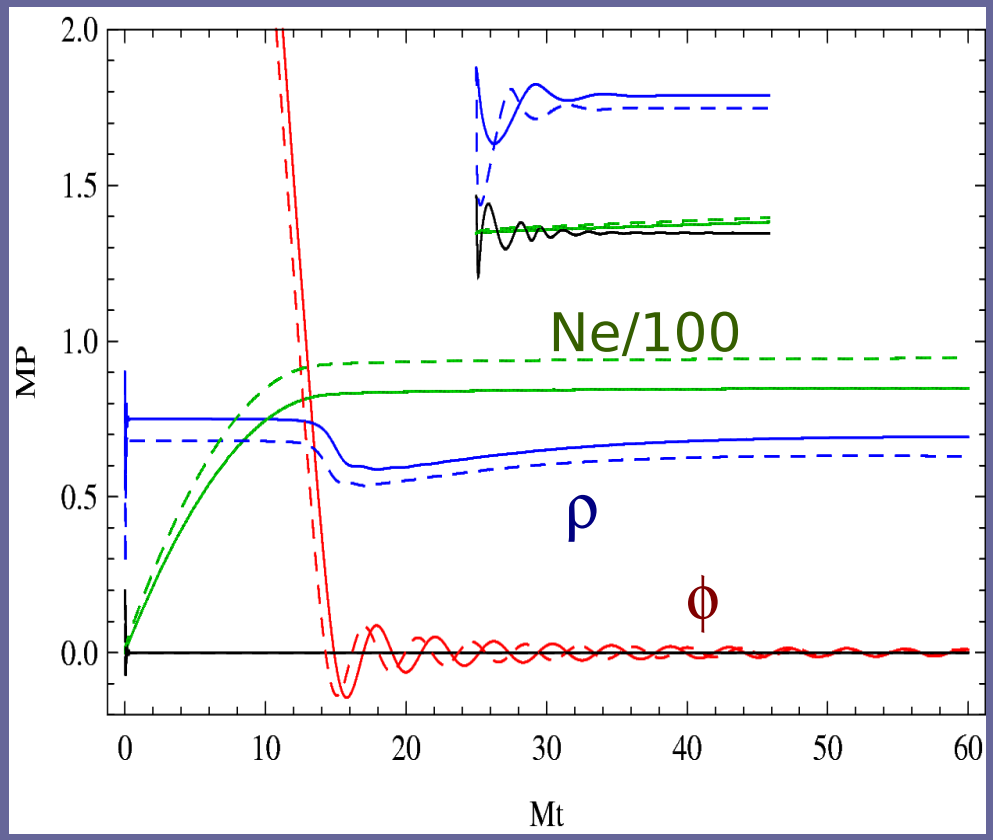
Quadratic model

$n_S \simeq 0.97$

$M/m_P \sim 10^{-5}$

$r \simeq 0.13$

Chaotic model + Heisenberg symmetry: field evolution and 1-loop corrections



Solid: tree-level potential
dashed: + 1-loop potential

1-loop effective potential

$$\Delta V^{(1)} = \frac{\Lambda^2}{32\pi^2}\,\mathrm{Str}\,M_\alpha^2 + \frac{1}{64\pi^2}\,\mathrm{Str}\,M_\alpha^4 \ln\frac{M_\alpha^2}{\Lambda^2}$$

negligible

$$\mathrm{Str}\,M_\alpha^2 \neq 0$$

$$\Delta V^{(1)} \simeq M^2 \Phi^2 \left(C(\rho) - 12\kappa^X\right) / \left(\rho^3 (1+\kappa_\rho \rho)^3\right)$$

$$V + \Delta V^{(1)} = m_{\mathrm{eff}}^2(\rho_0)\,\Phi^2/2$$

1-loop correction: inflaton mass renormalization

Summary

- Observations → Standard Model in Cosmology

  Primordial spectrum? Flatness? Horizon problem?

  → inflation

- Primordial power spectrum:

  Adiabatic?

  Scale invariant?

  Tensors?

  Non-gaussianity?

  } Planck

  → Higher order corrections

  Renormalization issues?

Summary

- Particle physics model of inflation?

  Sugra inflation: "eta" & moduli problems

  - Shift symmetry $K(\phi-\phi^*)$
  - Heisenberg symmetry $K(\rho)$
  - $G(H,l)= G(H) + G(l)$ adding Kahler functions
  - ...

No detection of any (fundamental) scalar...yet...

The Higgs boson still missing
(Electroweak symmetry breaking)

LHC will shed light on physics beyond the SM:

- Higgs physics? Supersymmetry? ...

Summary

- Heisenberg symmetry K(ρ) protects flat directions

$$K = K(\rho), \quad \rho = T + \bar{T} - |\Phi|^2$$

Modulus ρ potential originates from Kahler corrections

$$K = -3\ln\rho + (1 + \kappa_X |X|^2 + \kappa_\rho \rho)|X|^2$$

κ_X: X mass contribution, $|F_X|^2$: vacuum energy

κ_ρ : minimum ρ direction

→ Sugra corrections under control

→ Hybrid model: no blue spectrum for large couplings

→ Chaotic model: quadratic potential for W= M Φ X

No detection of any (fundamental) scalar...yet...

The Higgs boson still missing
(Electroweak symmetry breaking)

LHC will shed light on physics beyond the SM:

- Higgs physics?
- Supersymmetry?
- ...

Planck will improve our knowledge on the cosmological parameters

- Primordial spectrum?
- Polarization? Non-gaussianities?
- ...

Expanding Universe

Hubble's law, 1929

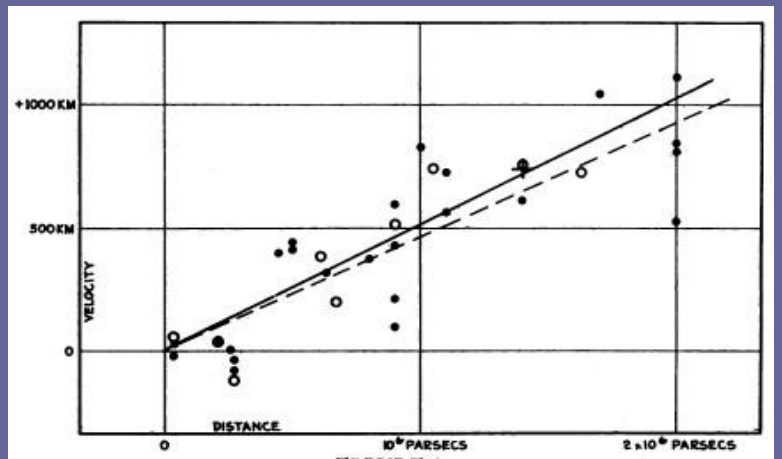


FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.

Radial velocities, corrected for solar motion, are plotted against distances estimated from involved stars and mean luminosities of nebulae in a cluster. The black discs and full line represent the solution for solar motion using the nebulae individually; the circles and broken line represent the solution combining the nebulae into groups; the cross represents the mean velocity corresponding to the mean distance of 22 nebulae whose distances could not be estimated individually.

$$V = H_0 \, D(z)$$

H_0 = Hubble parameter

Einstein's Equations,1917

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G_N T_{\mu\nu}$$

geometry ⟷ "matter"

Cosmological Principle:
The Universe is **homogeneous** and **isotropic** on very large scales

FRW metric:

$$ds^2 = dt^2 - a(t)^2 d\bar{x}^2$$

(a(t)= scale factor)

The rate of expansion (H_0) depends on the matter content

Minimal + small corrections: $K = |\phi|^2 + \kappa_S \frac{|\phi|^4}{4 m_P^2} + \kappa_{SS} \frac{|\phi|^6}{6 m_P^4} + \ldots$

$$V(\phi) \simeq \kappa^2 M^4 \left(1 - \kappa_S \frac{\phi^2}{2 m_P^2} + \gamma_S \frac{\phi^4}{8 m_P^4} + \ldots\right) + \Delta V^{(1)}$$

Eta problem?

Spectral index:

1-loop potential

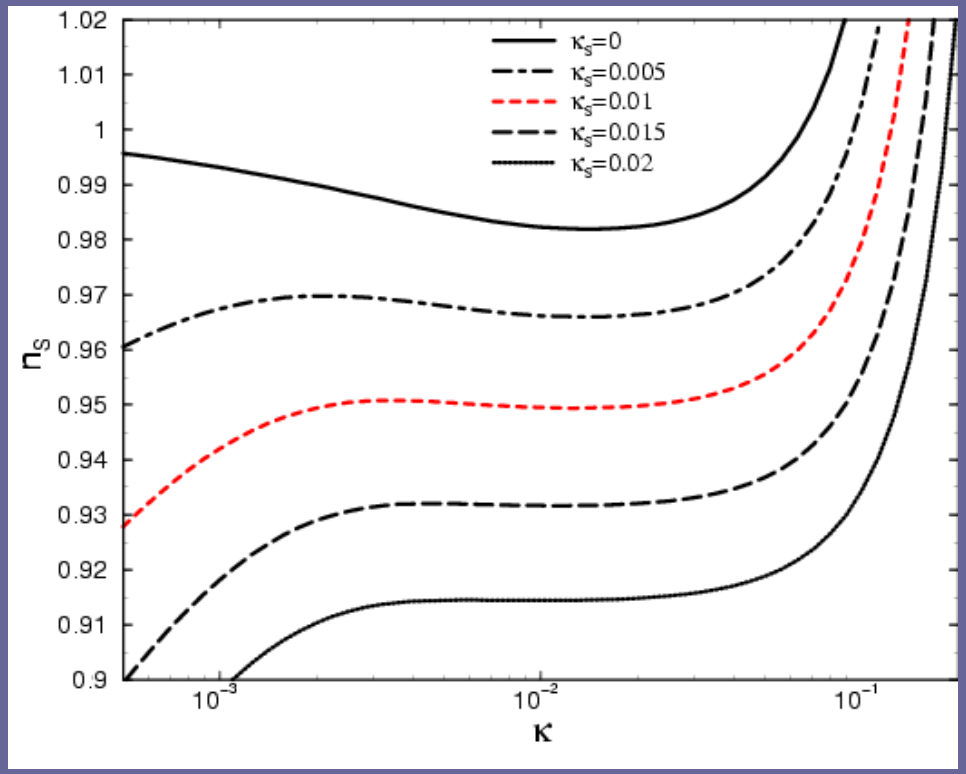
$$n_S \simeq 1 - 2\kappa_S - 2\delta$$

Kähler correction

Flatter potential:

→ ϕ_{N_e} smaller

→ $\delta \sim m_P^2 / \phi_{N_e}^2$ larger



$n_S \simeq 0.95 \quad (\kappa_S \simeq \kappa \simeq 0.01)$

Bastero-Gil, King and Shafi '06
Garbrecht, Pallis, Pilaftsis '06

“Kahler” moduli stabilisation

amics during inflation: ρ, N_R

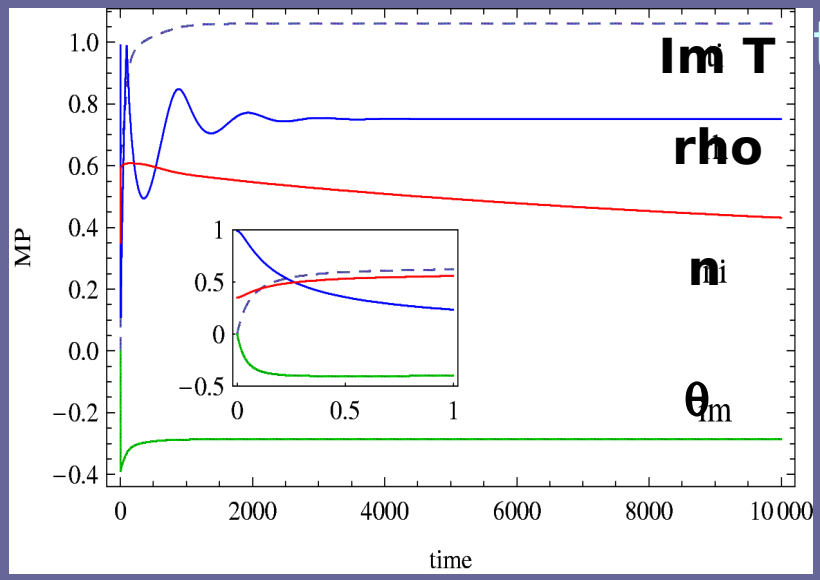
Non-canonical kinetic terms

$$L_{kin} = \frac{K_{\rho\rho}}{4}(\partial_\mu \rho)^2 - \frac{K_\rho}{2}(\partial_\mu N)^2$$

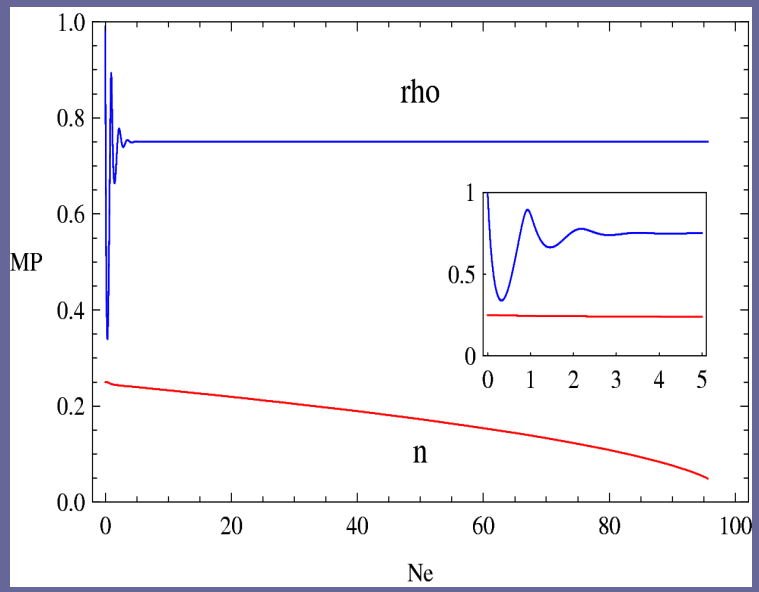
$$V = \kappa^2 M^4 e^{\acute{K}(\rho)} / (1 + \kappa_\rho \rho)$$

$$\ddot{N}_R + 3H\dot{N}_R - \frac{V_N}{K_\rho} = -\frac{K_{\rho\rho}}{K_\rho}\dot{N}_R\dot{\rho}$$

$$\ddot{\rho} + 3H\dot{\rho} + \frac{2V_\rho}{K_{\rho\rho}} = -\frac{K_{\rho\rho\rho}}{2K_{\rho\rho}}\dot{\rho}^2 - \dot{N}_R^2$$



tles quickly at its minimum



Phases set to a constant value at the start of inflation

“Kahler” moduli stabilisation

Antusch et al. '09

otic model + Heisenberg symmetry: $\rho = T + \bar{T} - |\Phi|^2$

Matter content:
- T : modulus , Φ: inflaton

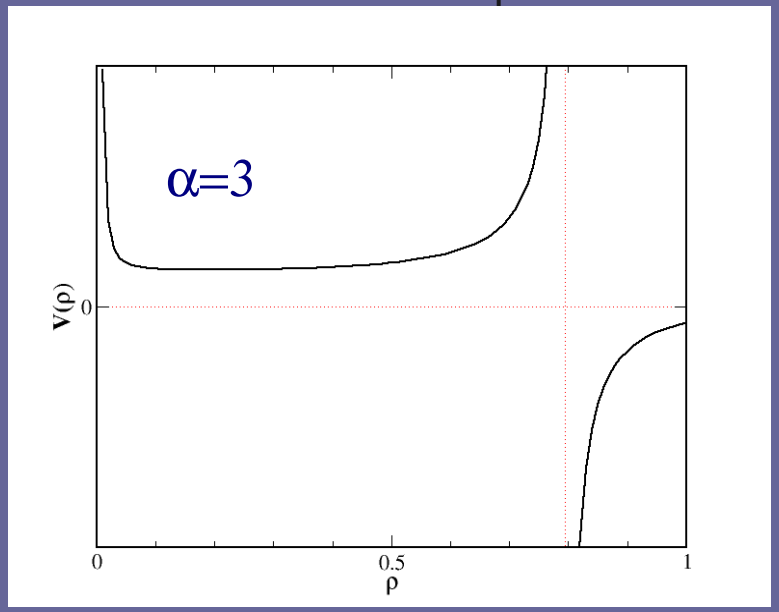
$$K = -3\ln\rho - \rho^{\alpha}$$

$$W = M\Phi^2$$

ρ minimum

$$V = M^2 e^{K(\rho)}\left(A(\rho)\frac{\Phi^4}{m_P^2} + B(\rho)\Phi^2\right)$$

Quartic model



$n_s \simeq 0.95$

$M/m_P \simeq 10^{-7}$

$r \simeq 0.3$

ρ_0 evolves with ϕ

but $\eta_\rho, \varepsilon_\rho < 1$