INFLATIONARY MODELS AND FUNDAMENTAL PHYSICS FROM WMAP DATA

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LPTHE - PARIS

9/12/04

8th PARIS COSMOLOGY COLLOQUIUM

THE HISTORY OF THE UNIVERSE

IS A HISTORY OF EXPANSION

AND COOLING DOWN

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

EXPANSION : THE SPACE ITSELF

EXPANDS WITH TIME.

$a(t)$ = SCALE FACTOR

THE LENGTHS SCALES AS $a(t)$ WHICH GROWS WITH TI

UNIVERSE : HOMOGENEOUS AND ISOTROPIC

COOLING : TEMPERATURE DECREASES

AS $1/a(t)$: $T(t) \sim \dfrac{1}{a(t)}$

WAVELENGTH OF AN ELECTROMAGNETIC WAVE EMITTED AT $t=1$

$$\lambda(t) = a(t) \frac{\lambda(1)}{a(1)}$$

RED SHIFT z

$$T(t) = \frac{1}{a(t)} T(1)\, a(1)$$

IT IS NOT AN EXPANSION IN A PRE-EXISTING

TIME	$1\,GeV = 1{,}16\,10^{15}\,K$ TEMPERATURE		$1+z$ $= a(now)$
10^{-44} sec	10^{19} GeV	QUANTUM STRING THEORY, GRAVITY INFLATION	FACTOR 10^{26} $\sim e^{Ht}$ $\gtrsim 10^{2}$
10^{-30} sec	$\sim 10^{12}$ GeV	INFLATION ENDS	$\sim 10^{20}$
		PARTICLE CREATION STARTS – GUT PHASE REHEATING TRANSITION, MATTER DOMINATED? HOT BIG BANG = THERMALIZATION	$\sim \sqrt{t}$
10^{-10} sec	10^{3} GeV	ELECTRO-WEAK PHASE TRANSITION	
	10^{2} GeV	BARYON ASYMMETRY ORIGINATES? BARYOGENESIS	RADIATION
10^{-4} sec 10^{-2} sec	1 GeV 0.1 GeV	QUARK-HADRON AND CHIRAL PHASE TRANSITIONS	DOMINAT
	10 MeV	$\gamma, \nu, e, \bar{e}, m, p$ in thermal equilibrium	
	$1\,MeV = 10^{-3}$ GeV	NEUTRINOS DECOUPLE	
1 sec.			
100 sec	~ 0.1 MeV	NUCLEOSYNTHESIS CREATION OF LIGHT ELEMENTS	$\sim 10^{4}$
0000 years		STRUCTURE FORMATION BEGINS ONSET OF GRAVITATIONAL INSTABILITY	$\sim t^{2/3}$
10^{5} yr		ATOMS FORM	$\sim 10^{3}$
		PHOTON DECOUPLING UNIVERSE BECOMES TRANSPARENT	
10^{9} yr	first bound structures	GALAXY FORMATION	
		SOLAR SYSTEM FORMATION	COLD MATTER
		QUASARS	DOMINATED

FIELD THEORY

MICROSCOPIC THEORY: A GUT mode

GAUGE SYMMETRY: O(10), SU(6), ?

GAUGE FIELDS + GUT FERMIONS + GUT HIGG
γ, W, Z, ... leptons, quarks, ... Higgs, —

THE INFLATON IS A SCALAR FIELD
THAT CAN DESCRIBE A FERMION-ANTIFERM
PAIR.

ELEVANT EFFECTIVE THEORIES IN PHYSICS:

GINSBURG-LANDAU THEORY OF
SUPERCONDUCTIVITY. IT IS AN EFFECTIVE
EORY FOR COOPER PAIRS IN THE MICROSCOP
CS THEORY OF SUPERCONDUCTIVITY.

) THE O(4) SIGMA MODEL FOR PIONS,
GMA AND PHOTONS AT LOW ENERGIES $\lesssim$ 1 G
ICROSCOPIC THEORY IS QCD (quarks and gl

SCALAR FIELD THEORIES (λ = self co

FOR HIGH ENERGY DENSITIES: $\varepsilon \sim \frac{M^4}{\lambda}$

AND LARGE FIELD AMPLITUDES: $\langle \Phi \rangle \sim \frac{M}{\sqrt{\lambda}}$

NON PERTURBATIVE METHODS ARE NEEDED

LARGE N: $\vec{\Phi} = (\phi_1, \dots, \phi_N)$, $\lambda = \frac{g}{N}$ $N \to \infty$ $g = $ fix

HARTREE , ONE-LOOP EFFECTIVE APPROX.

PROPAGATION IN A DENSE MEDIUM

NON-LINEARITY OF FIELDS $\longleftrightarrow$ SELF-CONSISTENT TREATMENT
$\updownarrow$
NEEDED TO DETERMIN THE MEDIUM PROPERT

— · — — —

Φ^4 MODEL

$$\frac{a^2}{2}\dot{\vec{\Phi}}^2 - \frac{1}{2}(\nabla\vec{\Phi})^2 - a^2\frac{m^2}{2}\vec{\Phi}^2 - \frac{g}{N}a^2\left(\vec{\Phi}^2\right)^2\Big]a(t)$$

TRASLATIONAL INVARIANT STATES $\hat{e} = (1, 1, \dots, 1)$
O(N) INVARIA

$$\mathrm{Tr}\left[\hat{\rho}(t)\,\Phi_i(\vec{x},t)\right] = \delta_{i1}\,\varphi(t) = \text{FIELD EXPECTATION VALUE}$$

$$\vec{\Phi}(\vec{x},t) = \varphi(t)\,\hat{e}_1 + \vec{\Psi}(\vec{x},t)$$ operator fiel

CREATION - ANNIHILATION OPERATORS $\langle \Psi(\vec{x},t) \rangle = 0$

$$(\vec{x},t) = \int \frac{d^3k}{(2\pi)^3\sqrt{2\omega_k}}\left[\vec{\alpha}_k\,\varphi_k^*(t)\,e^{i\vec{k}\cdot\vec{x}} + \vec{\alpha}_k^{\dagger}\,\varphi_k(t)\,e^{-i\vec{k}\cdot\vec{x}}\right]$$

MODE FUNCTIONS

$\sim e^{i\omega_k t}$ for the vaccuum. $\omega_k = \sqrt{k^2 + m^2}$

T_0 = INITIAL

DIMENSIONLESS VARIABLES $\tau = m_R t$

$h = \frac{H}{m_R}$, $q = \frac{k}{m_R}$, $\eta(\tau) = \sqrt{\frac{g}{2}}\,\frac{\phi(t)}{m}$, $h =$

$\Sigma(\tau) = \frac{1}{2m_R^2} \langle \vec{\Psi}^2(\vec{x},t) \rangle$, $\xi_R = 0$

$+$ UNBROKEN SY
$-$ BROKEN SYM

effective mass squared $\mathcal{M}^2(\tau) = \pm 1 + \eta(\tau)^2 + g\,\Sigma(\tau)$

CLAS $\leftrightarrow$ QUANT
COUPLED

$h = \dot{a}/a$

EVOLUTION

$\ddot{\eta} + 3h\dot{\eta} + \mathcal{M}^2(\tau)\,\eta(\tau) = 0$

EQUATION

$\left[\frac{d^2}{d\tau^2} + 3h\frac{d}{d\tau} + \frac{q^2}{a(\tau)^2} + \mathcal{M}^2(\tau)\right]\varphi_q(\tau) = 0$ (MATTER + GEOMETR

$h(\tau)^2 = L^2\,\epsilon_R(\tau)$, $L^2 = \frac{16\pi m_R^2 N}{3g M_{pl}^2}$

renormalized quantum fluctuations

$\Sigma(\tau) = \int_0^\infty q^2 dq \left\{ |\varphi_q(\tau)|^2 - \underbrace{\frac{1}{q\,a(\tau)^2} + \frac{\theta(q-K)}{2q^3 a(\tau)^2}\left[\mathcal{M}(\tau)^2 - \frac{R}{6}\right.}_{\text{renormalization subtr}}\right.$

- covariant conservation

$\dot{\epsilon}_R + 3h(p+\epsilon_R) = 0$

$\epsilon_R(\tau) = \frac{\dot{\eta}^2}{2} + \frac{\mathcal{M}(\tau)^4}{4} + \frac{g}{2}\int_0^\infty q^2 dq \left\{ |\dot{\varphi}_q(\tau)|^2 + \frac{q^2}{a^2(\tau)}|\varphi_q(\tau)|^2 \right.$

Renormalized energy

$\frac{q}{4} - \frac{h(\tau)^2}{\ldots} - \theta(q-K)\left[\mathcal{M}(\tau)^2 - R + 4h(\tau)^2 + 6\dot{h}\right](\mathcal{M}^2 R$

INFLATON

AFTER THE MODES THAT DOMINATE THE ENERGY CROSS THE HORIZON

$$\left(\frac{k}{a(t)}\right)^2 << 1$$

CAN BE NEGLECTED.

ALL MODES BEHAVE AS ZERO MODE

A CONDENSATE EMERGES

$$\varphi_{eff}(\tau) = \sqrt{N} \sqrt{\eta^2(\tau) + \int \frac{d^3q}{2(2\pi)^3} |\varphi_q(\tau)|^2}$$

IT OBEYS

$$\ddot{\varphi}_{eff} + 3h\,\dot{\varphi}_{eff} \pm \varphi_{eff} + \lambda\,\varphi_{eff}^3 = 0$$

$$h^2 = L^2 \left\{ \frac{1}{2}\dot{\varphi}_{eff}^2 \pm \frac{1}{2}\varphi_{eff}^2 + \frac{\lambda}{4}\varphi_{eff}^4 \right\}$$

$\lambda = \frac{\cdot}{2}$

THE EVOLUTION IS DESCRIBED BY A CLASS FIELD.

THE INITIAL CONDITIONS FOR φ_{eff} ARE DEFINED BY THE PREVIOUS QUANTUM EVOLUTION.

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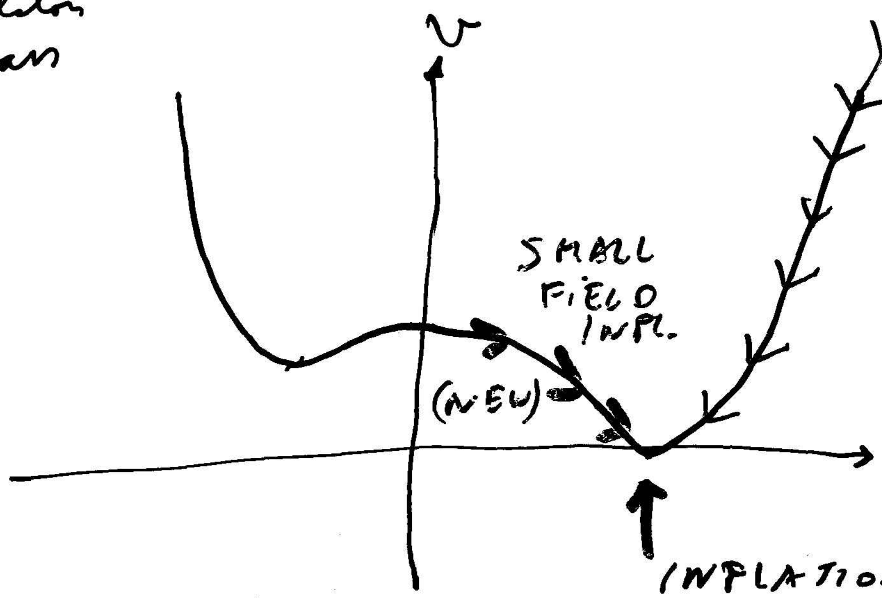
$$V(\phi) = |m|^2 M_{pl}^2 \, v\left(\frac{\phi}{M_{pl}}\right) \qquad \frac{|m|}{M_{pl}} \sim 1$$

$|m|$ inflaton mass



$v(\text{MIN}) = v'(\text{MIN}) = 0 \Rightarrow$ INFLATION ENDS AFTE A FINITE NUMBER OF EFOLD

$v''(0)$, $v'''(0)$, etc of order ONE

$\boxed{\text{NO FINE TUNNING ON } v(\varphi).}$

γ, χ = ORDER ONE

$\chi > 0$, γ either sign

$$v(\varphi) = v_0 \pm \frac{\varphi^2}{2} + \frac{2}{3}\gamma\varphi^3 + \frac{\chi\varphi^4}{32} + \text{higher order}$$

eventually

DEGREE ≤ 4

$$c = 1\,m/t$$

$$h = \frac{\dot a}{a}$$

$$\ddot\varphi + 3h\dot\varphi + v'(\varphi) = 0$$

$$h^2 = \frac{1}{3}\left[\frac{\dot\varphi^2}{2} + v(\varphi)\right]$$

$\varphi, v(\varphi)$ = DIMENSIONLES

SLOW ROLL APPROXIMATION $\quad |\ddot\varphi| \ll |\dot\varphi| h$

OF EFOLDS FROM TIME τ TILL END OF INFLATION

$$N(\tau) = \log \frac{a_{END}}{a(\tau)} = \int_{\tau}^{END} h(\tau')\, d\tau' = -\int_{\varphi(\tau)}^{\varphi_{END}} \frac{v(\varphi)}{v'(\varphi)}\, d\varphi$$

RIMORDIAL POWER SPECTRUM

$$P(k) = A\, k^{n_s - 1}$$

$$\underbrace{45 \lesssim N(\tau) \lesssim 55}_{\text{slow roll is valid}}$$

$$n_s = 1 - 3\left(\frac{v'(\varphi)}{v(\varphi)}\right)^2 + \frac{2v''(\varphi)}{v(\varphi)}$$

$$|\delta^{(S)}_{k\,ad}|^2 = \frac{1}{12\pi^2}\frac{(m)^2}{M_{Pl}^2}\frac{v^3(\varphi)}{v'^2(\varphi)}$$

AMPLITUDE OF ADIABATIC SCALAR PERTURBATIONS

$$r = \left|\frac{\delta^{(T)}_k}{\delta^{(S)}}\right|^2 = 8\left(\frac{v'(\varphi)}{v(\varphi)}\right)^2$$

RATIO OF TENSOR

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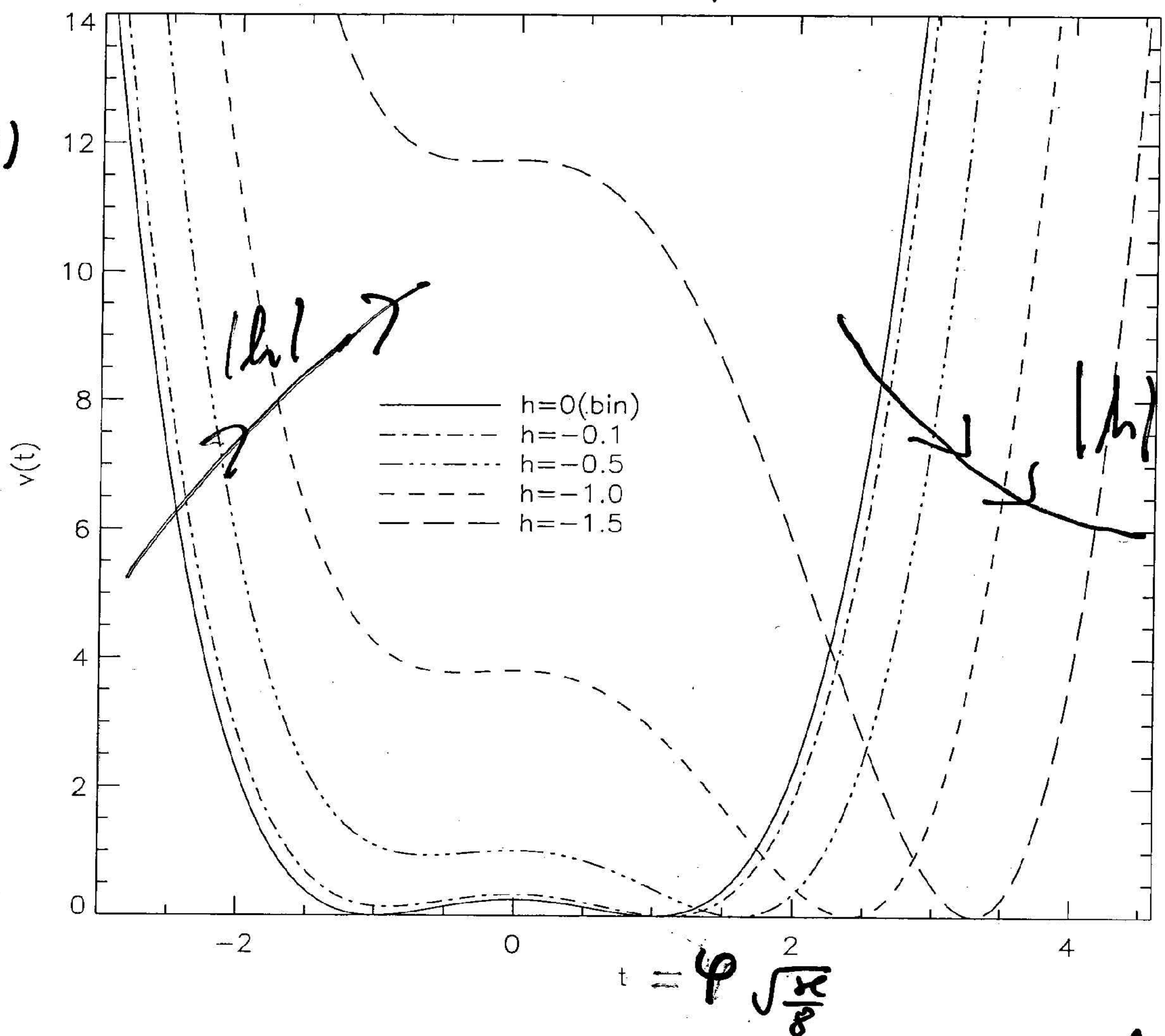


$h < 0$

$$v(\varphi) = -\frac{\varphi^2}{2} + \frac{2}{3}\gamma\varphi^3 + \frac{\chi}{32}\varphi^4 + v_0$$

$$v(0) = v'(0) = 0$$

THE TRINOMIAL POTENTIAL

$$h = \gamma\sqrt{\frac{8}{\chi}} = \underline{\text{ASYMMETRY}} \text{ OF } v(\varphi)$$

INVARIANCE PROPERTY:

PARAMETRIC FORMULAS FOR:

$$\boxed{N,\ n_s,\ |\delta^s_{hor}|^2,\ r}$$

in terms of $t \equiv \sqrt{\frac{\varkappa}{8}}\,\varphi$ ← THE FIELD AT 1st HO CROSSI

$\varkappa$ = quartic coupling

$h = \gamma\sqrt{\frac{8}{\varkappa}}$ asymmetry of $v(\varphi)$

$\Delta \equiv \sqrt{h^2+1}$, $w(h) = \frac{8}{3}h^4 + 4h^2 + 1 + \frac{8}{3}|h|\Delta^3$,

$N = t^2 - 2h^2 - 1 - 2|h|\Delta + \frac{4}{3}|h|(|h|+\Delta-t) - 2w(h)\ln[t(\Delta$

$\frac{16}{3}|h|(\Delta+|h|)\Delta^2 \log\frac{1}{2}\left(1+\frac{t-|h|}{\Delta}\right)$.

Define t as a functi of N

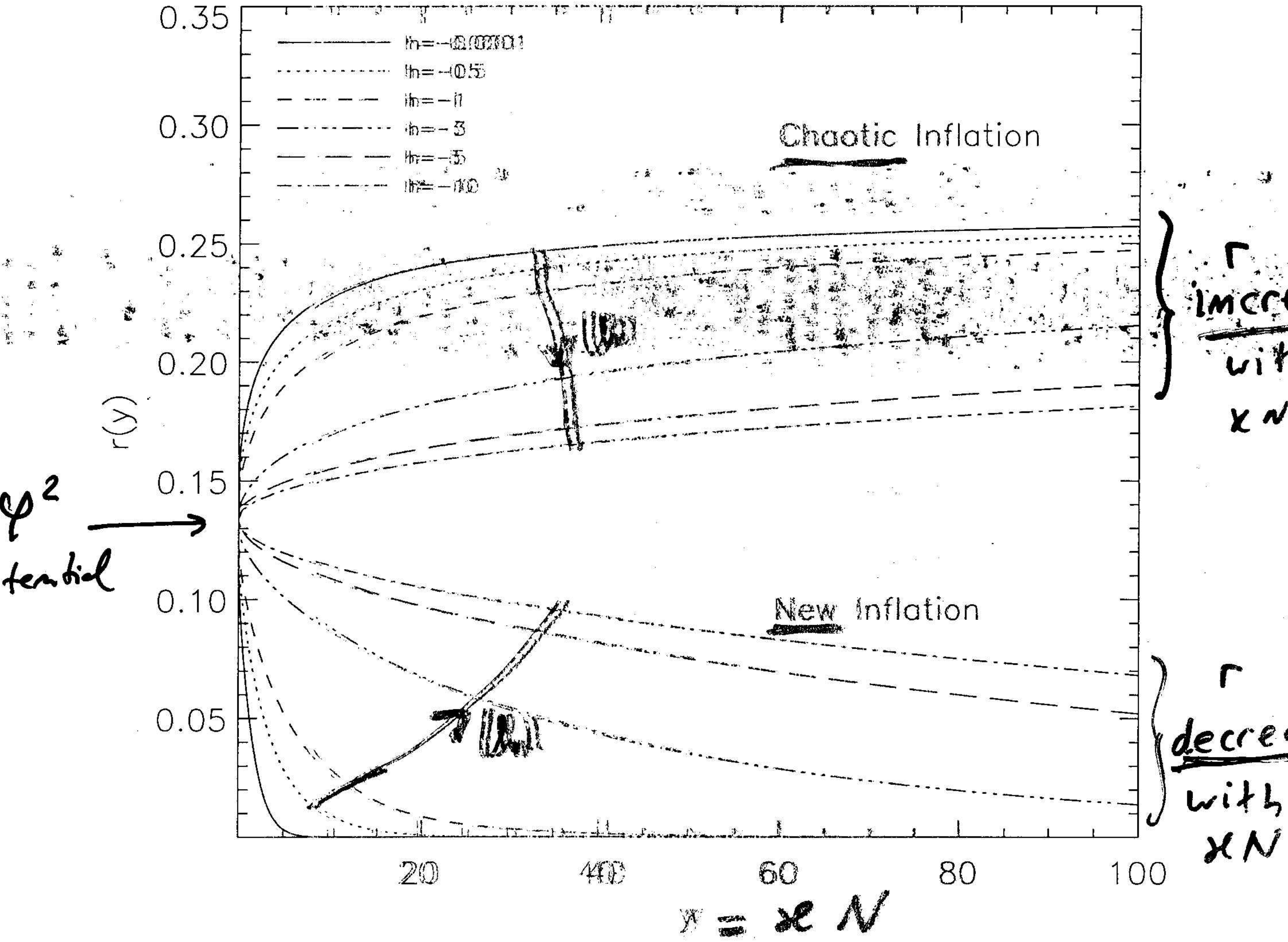
$D \equiv w(h) - 2t^2 + \frac{8}{3}ht^3 + t^4$

$V \equiv t(t^2 - 2ht - 1)$

$$n_s = 1 - 6\varkappa\left(\frac{N}{D}\right)^2 + \frac{\varkappa}{D}\frac{dN}{dt}$$

$r = 16\varkappa\left(\frac{N}{D}\right)^2$, $|\delta_k^{(s)}|^2 = \frac{1}{12\pi^2}\frac{|m|^2}{M_{Pl}^2\varkappa^2}\left(\frac{D}{N}\right)^2$

FROM HERE WE EXPRESS $|m|$



TRINOMIAL POTENTIAL

CHAOTIC INFLATION: $\overset{\varphi^2}{0.16 \simeq \frac{8}{N}} \leq r \leq \overset{\varphi^4}{\frac{16}{N}} \simeq 0.32$

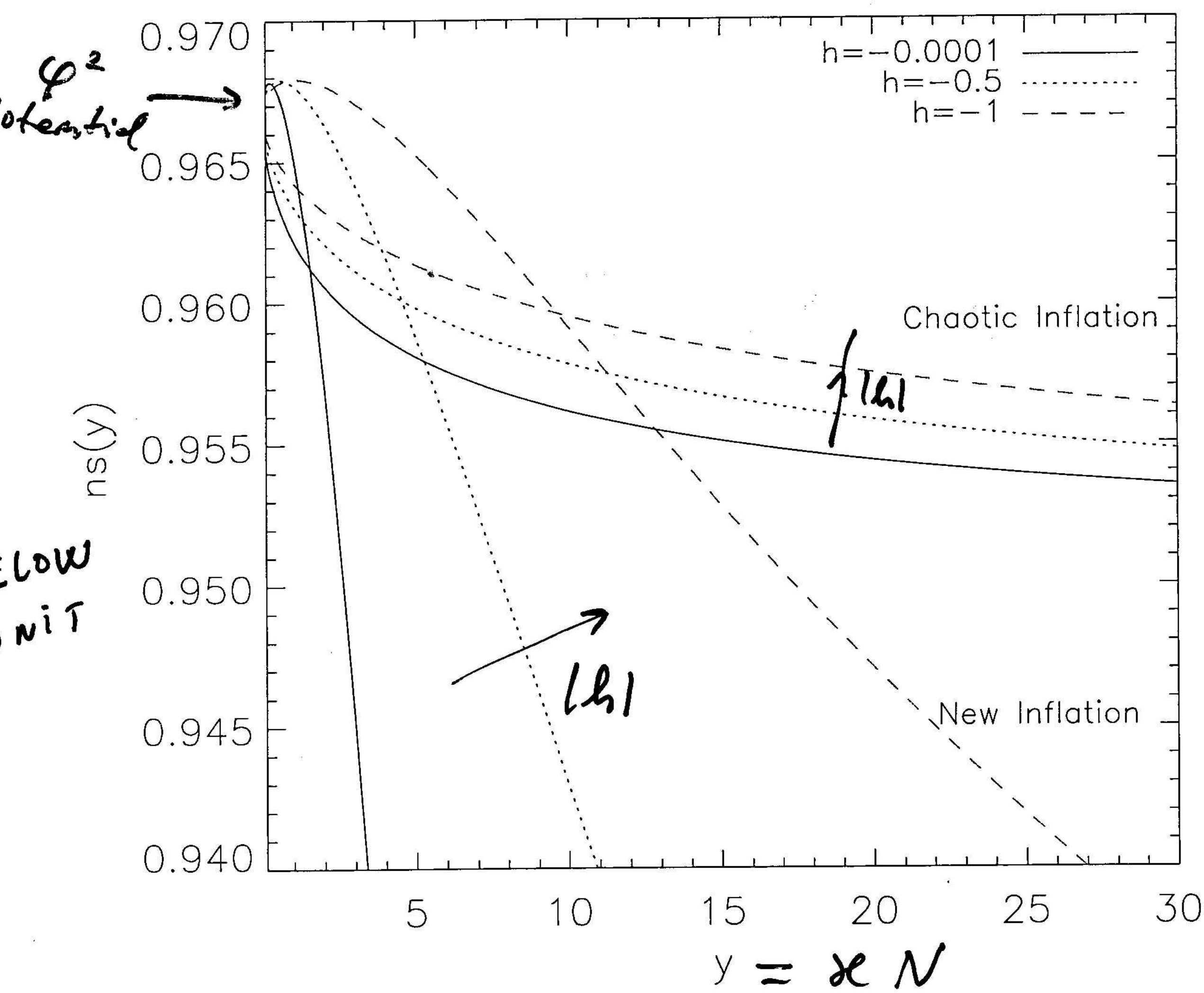
<u>LOWER BOUND</u>

NEW INFLATION:

NO LOWER BOUND

$r \leq \overset{\varphi^2}{\frac{8}{N}} \simeq 0.16$

UPPER BOUN



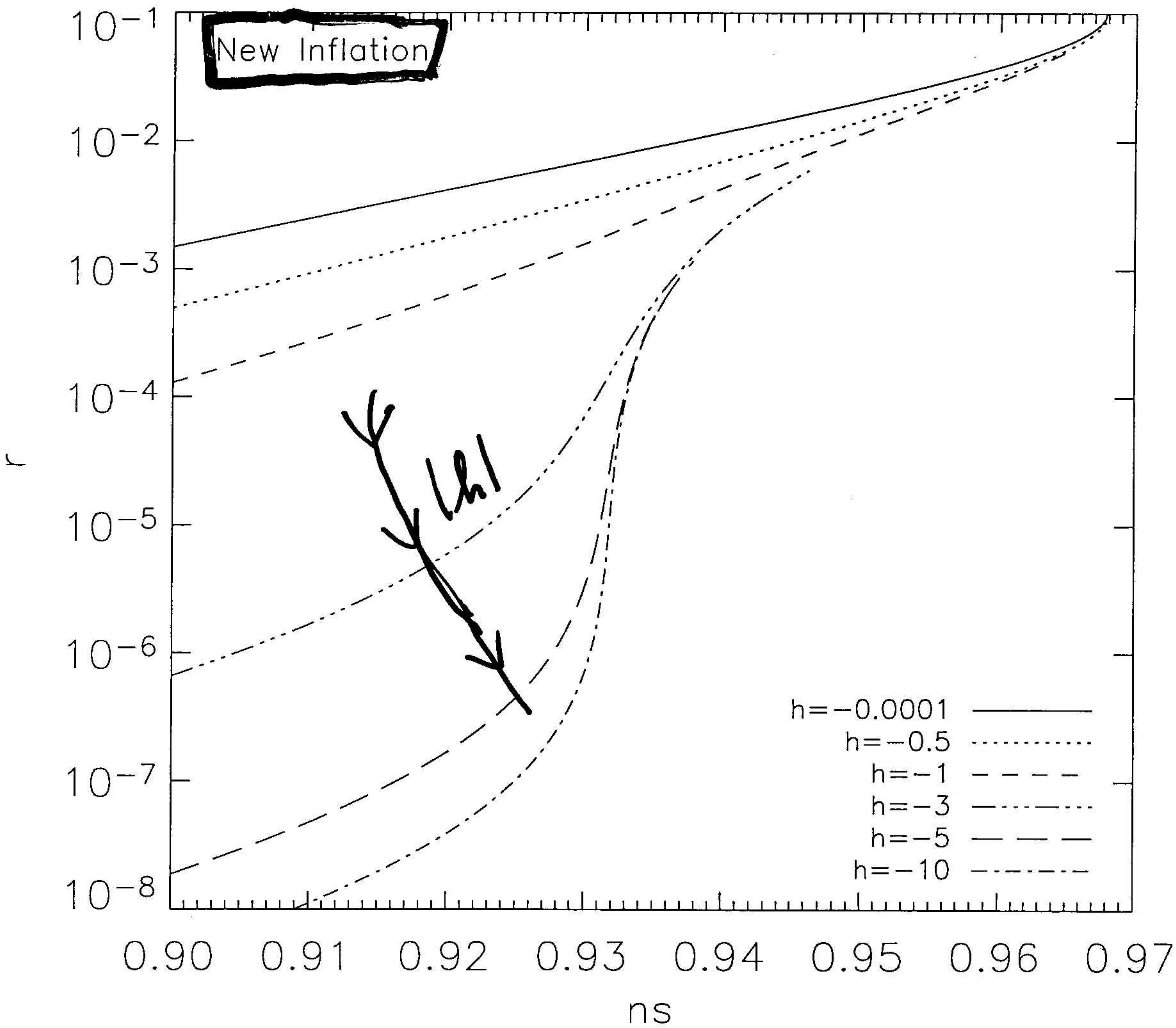
SPECTRAL INDEX OF SCALAR PERTURBA

TRINOMIAL POTENTIAL $h < 0$

$\boxed{n_s \text{ DECREASES WITH } \varkappa \text{ FOR FIXED } h < 0}$

$$n_s \lesssim 1 - \underbrace{\frac{2}{N}}_{\text{quadratic monomial}} \simeq 0.96$$

$\boxed{n_s \text{ GROWS WITH } |h| \text{ FOR FIXED } \varkappa}$



r VS. n_s

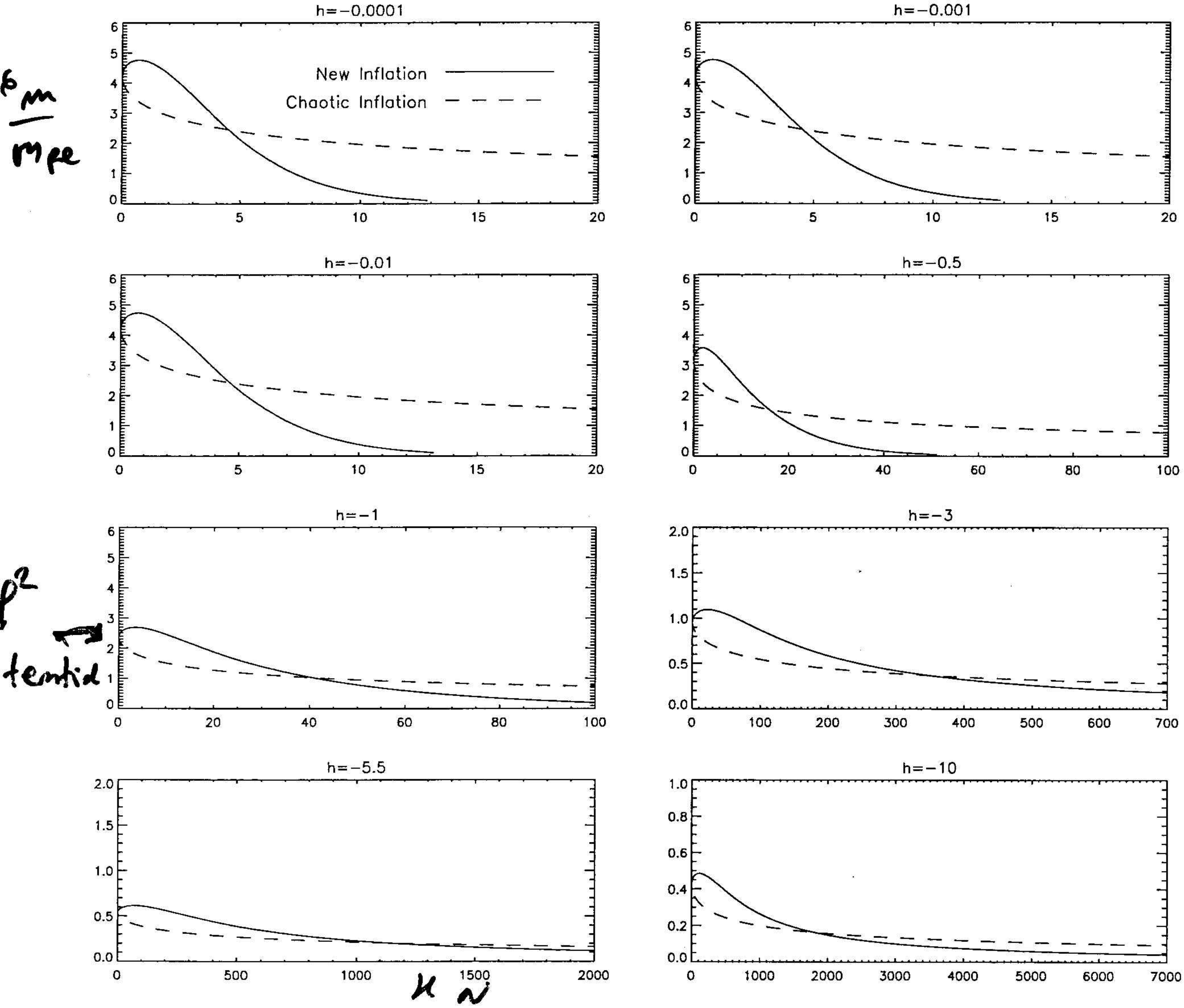
TRINOMIAL POTENTIAL

$\Rightarrow$ r GROWS WITH n_s AT FIXED h

$\Rightarrow$ r DECREASES WITH $|h|$ AT FIXED n_s

LARGE $|h|$ GIVES VERY SMALL r
WITH n_s CLOSE TO UNIT.

INFLATON MASS VS. κN_{efol}



NEW INFLATION ————

TRINOMIAL POTENTIAL

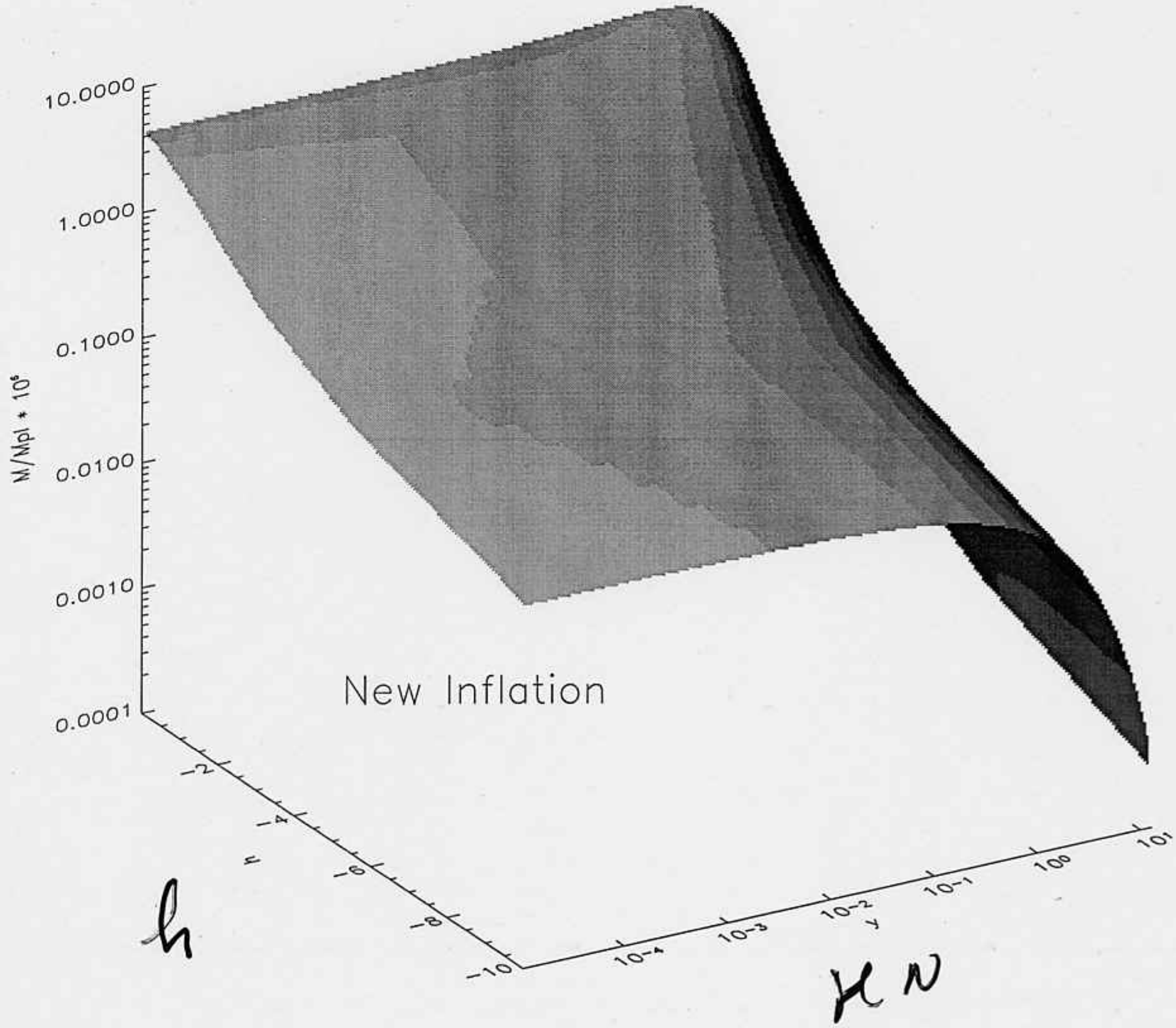
CHAOTIC INFLATION - - - - —

TWO BRANCHES OF THE SAME FUNCTION

$h < 0$

USING THE WMAP VALUE FOR $|\delta_k^{(S)}|$

$10^4 \, |\delta_k^{(S)}| = 0.467 \pm 0.023 \quad (\pm 5\%)$



TRINOMIAL POTENTIAL

$\frac{m}{M_{pl}} 10^6$ VS. κN and $h < 0$

$$\boxed{10^6 \frac{m}{M_{pl}} = 12\cancel{7}\sqrt{r(1-n_s)}}$$

VALID FOR SMALL r and SMALL $1-n_s$

↓ THIS COEFFICIENT

RELEVANT REGIME: $\Lambda \gg \varphi^2$

$$n_s > 1 \quad ,$$

$$n_s = 1 + \frac{4}{\Lambda} - \frac{3}{8} r \quad , \quad r = 32 \frac{\varphi^2}{\Lambda} \ll 1$$

$$10^6 \frac{m}{M_{pl}} = 127 \sqrt{r \left(n_s - 1 + \frac{3}{8} r\right)}$$

a) FOLLOWS FROM WMAP AMPLITUDE

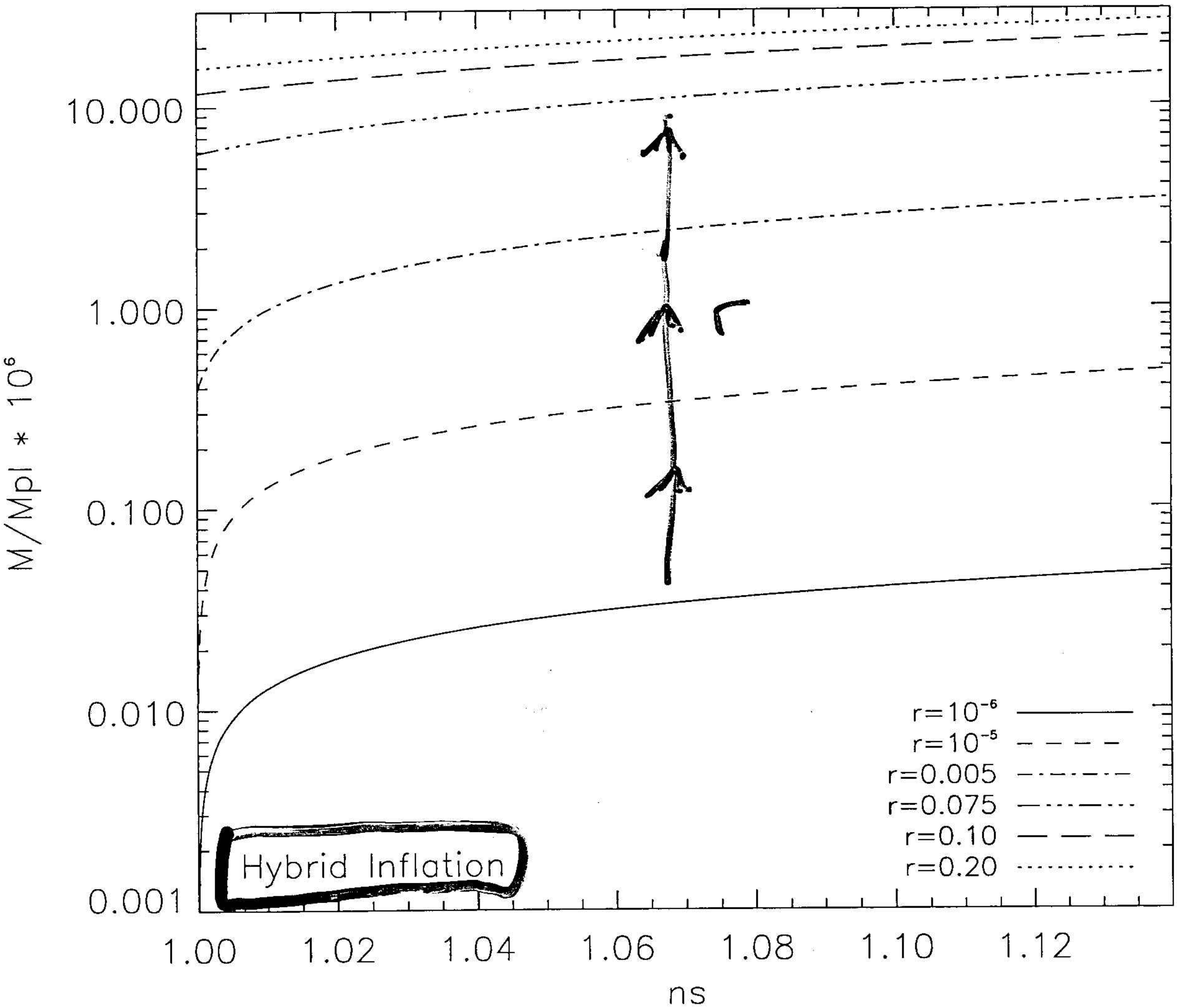
b) EXPRESSION VERY SIMILAR FOR NEW INFLATION

FURTHERMORE:

$$\frac{\Lambda_0}{M_{pl}^4} = 0.329 \times 10^{-7} r$$

$$\frac{\Lambda_0}{m^2 M_{pl}^2} < \frac{2}{n_s - 1}$$

UPPER BOUND FOR THE PRIMORDIAL COSMOLOGICAL CONSTANT

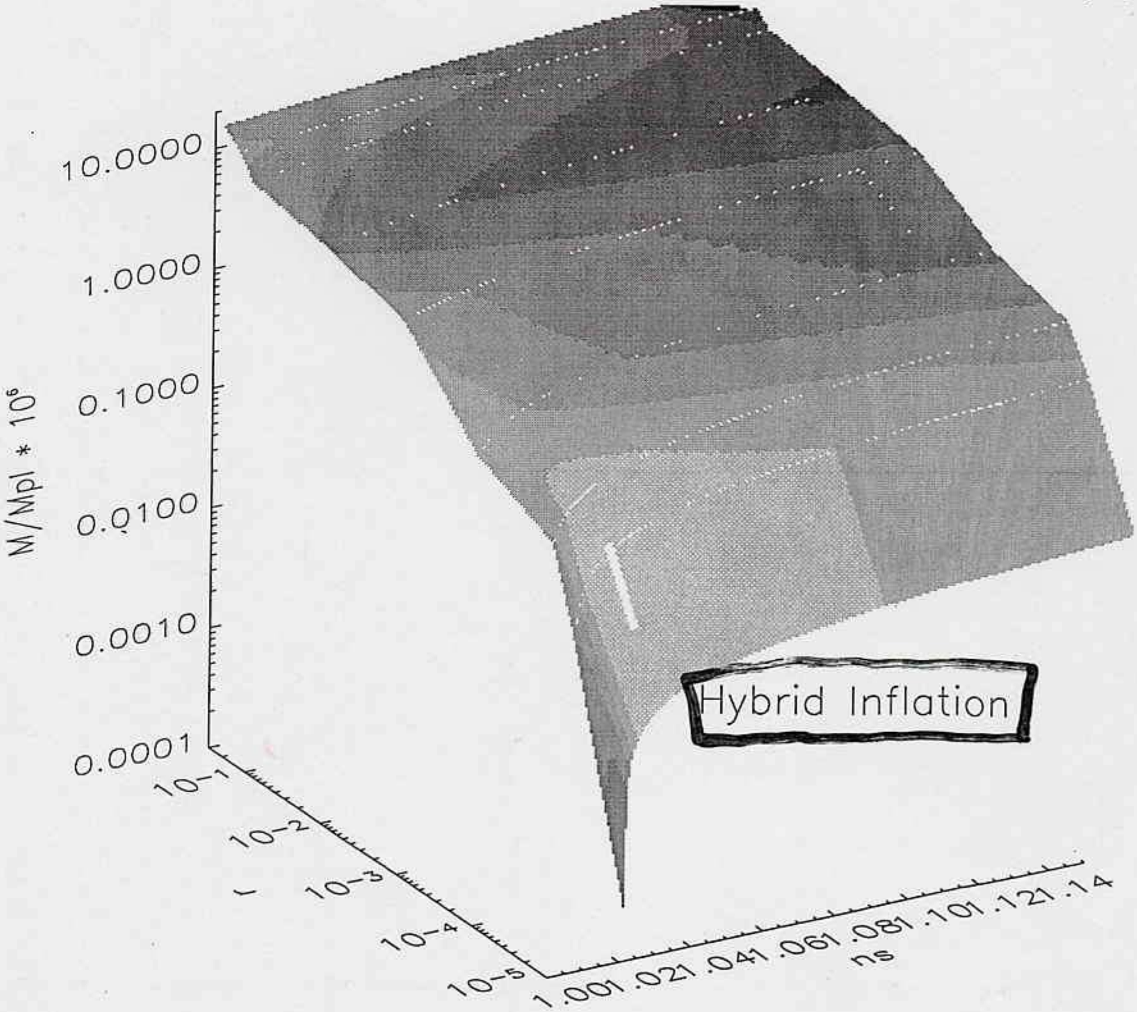


INFLATON MASS RATIO $\frac{m}{M_{pl}} 10^6$ VS. n_s FOR VARIOUS $r = \frac{|\delta_T|^2}{|\delta_S|^2}$

$$10^6 \frac{m}{M_{pl}} = 127 \sqrt{r \left(n_s - 1 + \frac{3}{8} r\right)}$$

vs.

r &



$$10^6 \frac{m}{M_{pe}} = 127 \sqrt{r \left(n_s - 1 + \frac{3}{8} r \right)}$$

SUMMARY

PURE $\lambda \phi^4$ **DISFAVOURED** BY WMAP (2006)

IMPLIES IN OUR GINSBURG-LANDAU APPROACH THAT $m^2 \phi^2$ **MUST BE PRESENT**! $m^2 \neq 0$.

MORE PRECISELY: $|m| \simeq 10^{13}$ GeV

BEST FIT (2003)

1) FOR $n_s < 1$ and $|n_s - 1| \lesssim 0.1$

$r \lesssim 0.1$

NEW INFLATION WITH THE TRINOMIAL POTENTIA

2) FOR $n_s > 1$ and $|n_s - 1| \lesssim 0.1$

$r \lesssim 0.1$

HYBRID INFLATION

*) CHAOTIC INFLATION IMPLIES $r \geq \frac{8}{N} \simeq 0.16$

Grand Unification Idea (GUT)

RENORMALIZATION GROUP RUNNING OF ELECTROMAGNETIC, WEAK AND STRONG COUPLINGS SHOWS THAT THEY **MEET** AT $M_1 \sim 10^{16}$ GeV

) NEUTRINO MASSES (from ν OSCILLATIONS) RE EXPLAINED BY THE SEE-SAW MECHAN

$$\boxed{\Delta m_\nu \sim \frac{M_{Fermi}^2}{M_2}}$$

$\sim 0.05\,eV$

$M_{Fermi} \sim 250$ GeV (weak interaction

$M_2 \sim 10^{16}$ GeV

WE SAW THAT THE INFLATON POTENTI S

$$\underbrace{m^2 M_{pe}^2}_{M_3^4} \, v\left(\frac{\Phi}{M_{pe}}\right)$$

$m \sim 10^{13}$ GeV

$M_{pe} \simeq 10^{19}$ GeV

HENCE, $M_3 \simeq 10^{16}$ GeV $\quad m = \frac{M_3^2}{M_{pe}} =$ AGA SEE SA TYP

<u>CONCLUSION</u>: $M_1 = M_2 = M_3 = M_{GUT} = 10^{16}$ GeV

IN ORDER TO HAVE INFLATION, THE

MASS SCALE $m \sim \dfrac{M_{GUT}^2}{M_{pl}}$ MUST BE PRESENT

IN THE MODEL.

STRING THEORY ONLY KNOWS ABOUT M_{pl}.

DILATON, GRAVITON AND ANTISYMMETRIC FIELDS

ARE MASSLESS. OTHER FIELDS HAS MASS $\sim M_{p}$

m AND M_{GUT} MUST BE GENERATED

DYNAMICALLY. MAY BE FROM THE STRIN

VACUA (LANDSCAPE).

OPEN PROBLEM, FAR FROM BEING SOLVED

INFLATION FROM STRING THEORY STILL TO COM

EFFECTIVE DESCRIPTION OF INFLATION IN STRING T

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LECTURES ON STRING THEORY IN CURVED SPACETIMES

CHALONGE SCHOOL 1995, hep-th/9512074, NATO A. 476 Kl

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CONCLUSIONS

- INFLATION : EFFECTIVE MODEL (PRINCIPLE) DERIVABLE FROM Grand Unified Theo

- INFLATION ABLE TO REPRODUCE PRESENT DATA : $n_s, r, |\delta_s^{ad}|^2$

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- QUANTUM FIELD THEORY EFFECTS ; INFLATON DECAY DURING FIRST HORIZON CROSSING CAN AFFECT CMB ANISOTROPIES AND PRODUCE NON-GAUSSIANITIES

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astro-ph/0409406

D. BOYANOVSKY, H.J. DE VEGA, Phys. Rev. D70, 06350 (2004)