INFLATION AND SHORT DISTANCE PHYSICS

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ON THE SIGNATURES OF NEW PHYSICS IN THE CMB

* MOTIVATION & PHILOSOPHY OF THE CALCULATION
* REVIEW OF THE STANDARD RESULT
* RADIATIVE EFFECTS IN EFT $O\left(\frac{H^2}{M^2}\right)$
* ENVIRONMENTAL EFFECTS $O\left(\frac{H}{P}\right)$
* SUMMARY

SCALES IN NATURE

WE DEDUCE THE INFORMATION ABOUT THE SCALES IN NATURE FROM THE STRENGTH OF FORCES WE MEASURE

WEAK: $\mathcal{L}_I \sim G_F (\bar{\Psi}\gamma^\mu\bar{\Psi})^2$

GRAVITY: $\mathcal{L}_I \sim G_N^{1/2}\gamma_{\mu\nu}T^{\mu\nu}$.

DIMENSIONLESS STRENGTH:

$$\alpha = G E^2$$

$$\alpha \sim 1 \Rightarrow E \sim \frac{1}{\sqrt{G}}$$

WEAK: $E \sim TeV$

GRAVITY: $E \sim M_{PL} \sim 10^{19}\,GeV$

WHICH SCALES ARE FUNDAMENTAL?

EG: GAUGE HIERARCHY PROBLEM: WHY ARE THERE SUCH DISPARATE SCALES WHERE DIFFERENT FORCES BECOME STRONG?

* DESERT PARADIGM: ALL FORCES UNIFY NEAR $M_{GUT} \sim 10^{16}\,GeV$ AND THE TeV-M_{GUT} DESERT IS PROTECTED BY SUSY, BROKEN AT TeV

REALLY HIGH SCALES IN NATURE!

* LARGE X-TRA DIMENSIONS: ALL FORCES BECOME STRONG AT TeV, AND HIERARCHY COMES FROM DILUTION IN X-TRA D

LOW ENERGY INDICATIONS OF HIGH SCALES ARE A MIRAGE!

TESTS:

* PROTON DECAY - IRRELEVANT OPERATORS
* RG RUNNING - LOG. UNIFICATION
* COSMOLOGY - INFLATION

BRANDENBERGER & MARTIN
TANAKA
EASTHER, GREENE, KINNEY, SHIU
KEMPF & NIEMEYER
HUIE & KINNEY
KKLS
DANIELSSON
STAROBINSKY & TEACHOU
BURGESS, HOLMAN, CLINE, LEMIEUX
GIUDICE, KOLB, RIOTTO & TEACHOU
CHUNG, NOTARI, RIOTTO ...

GRAVITY AS AN EFT

CLASSICAL GR NOT A **STAND-ALONE** THEORY - **NOT** UV-COMPLETE !

... LOOP DIVERGENCES!

INSTEAD: A THEORY WITH A CUTOFF: WORKS WONDERFULLY AT DISTANCES

$$\ell > \ell_p = M_p^{-1}$$

IN COSMOLOGY: PHYSICS AT SCALES L IS - TO LEADING ORDER - INDEPENDENT OF THE PHYSICS AT SCALES $\ell \ll L$

LOCALITY, CAUSALITY & COVARIANCE!

CAVEAT: COSMOLOGICAL CONSTANT PROBLEM SO FAR DEFIED ALL ATTEMPTS TO SOLVE IT WITHIN THE EFT LORE. DOES THIS SUGGEST THAT OUR ASSUMPTIONS ARE WRONG ?

WE WILL CONTINUE TO IGNORE THIS...

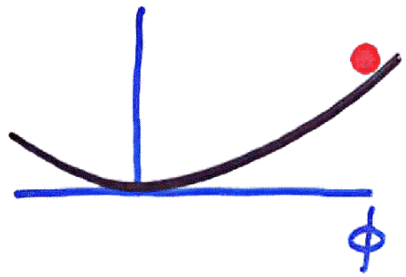
INFLATION

WE LIVE IN A LARGE, FLAT, HOMOGENEOUS, OLD UNIVERSE. WHY ?

THE BENCHMARK THEORY IS INFLATION.

ϕ : INFLATON

$H = \frac{\dot{a}}{a}$ HUBBLE

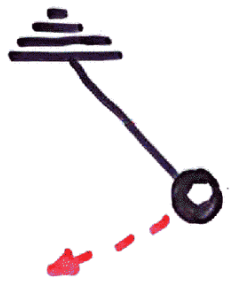


$$3H^2 = 8\pi G_N \left(\frac{\dot{\phi}^2}{2} + V(\phi) \right)$$

$$\ddot{\phi} + 3H\dot{\phi} + \frac{\partial V}{\partial \phi} = 0$$

INFLATION OCCURS WHEN THE FRICTION TERMS DOMINATE OVER THE ACCELERATION TERMS: SLOW ROLL

ANALOGY: PENDULUM IN A VERY VISCOUS MEDIUM



OVERDAMPED!

BUT: IN QM IT FLUCTUATES!

INDEED: CONSIDER GAUGE-INVARIANT SMALL FLUCTUATIONS:

$$ds^2 = a^2\left(-(1-2\Phi)d\eta^2 + (1+2\Phi)d\vec{x}^2\right)$$

$$\phi = \phi(\eta) + \delta\phi(\eta, \vec{x})$$

@ $$\phi'\delta\phi = -2M_p^2\left(\Phi' + \frac{a'}{a}\Phi\right)$$

CURVATURE PERTURBATION MUKHANOV, '82

$$\varphi = a\delta\phi - \frac{a\phi'}{a'/a}\Phi$$

∴ DURING SLOW ROLL INFLATION, $H \approx$ CONST,
$a \simeq a_0 \exp(Ht)$, $\eta = -\frac{1}{H}\exp(-Ht)$

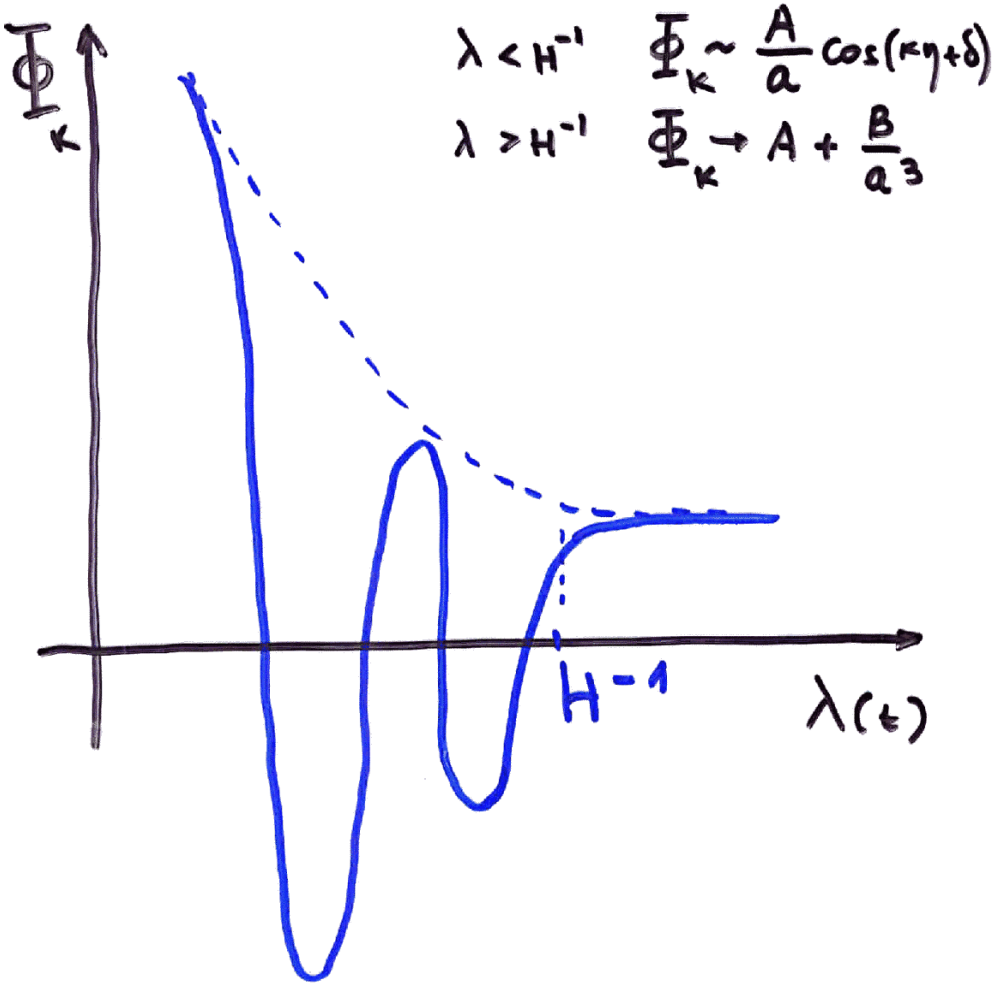
$$\varphi_k'' + \left(k^2 - \frac{2+\ldots}{\eta^2}\right)\varphi_k = 0$$

$$\Phi \sim \frac{\varphi}{a}$$

$$\lambda(t) = \lambda_0 a(t) \propto e^{Ht}$$

$\lambda < H^{-1}$ $\Phi_k \sim \frac{\hat{A}}{a}\cos(k\eta + \delta)$

$\lambda > H^{-1}$ $\Phi_k \to A + \frac{B}{a^3}$



CURVATURE PERTURBATION

$$\Phi \sim \frac{H}{\dot\phi} < \frac{\varphi}{a} >$$

QUANTUM MECHANICS DETERMINES THE NORMALIZATION OF $< \frac{\varphi}{a} >$;

STANDARD RESULT: $< \frac{\varphi}{a} > \sim H$

$$\frac{\delta\rho}{\rho} \sim \frac{H^2}{\dot\phi}$$

ALMOST INDEPENDENT OF K (i.e. ϵ) SINCE $H \simeq$ CONST., $\phi \simeq$ CONST. DURING SLOW ROLL REGIME

TYPICALLY, USING EQS OF MOTION

$$H \sim \frac{\sqrt{V}}{M_p} \qquad \dot\phi \sim \frac{1}{H}\frac{\partial V}{\partial\phi}$$

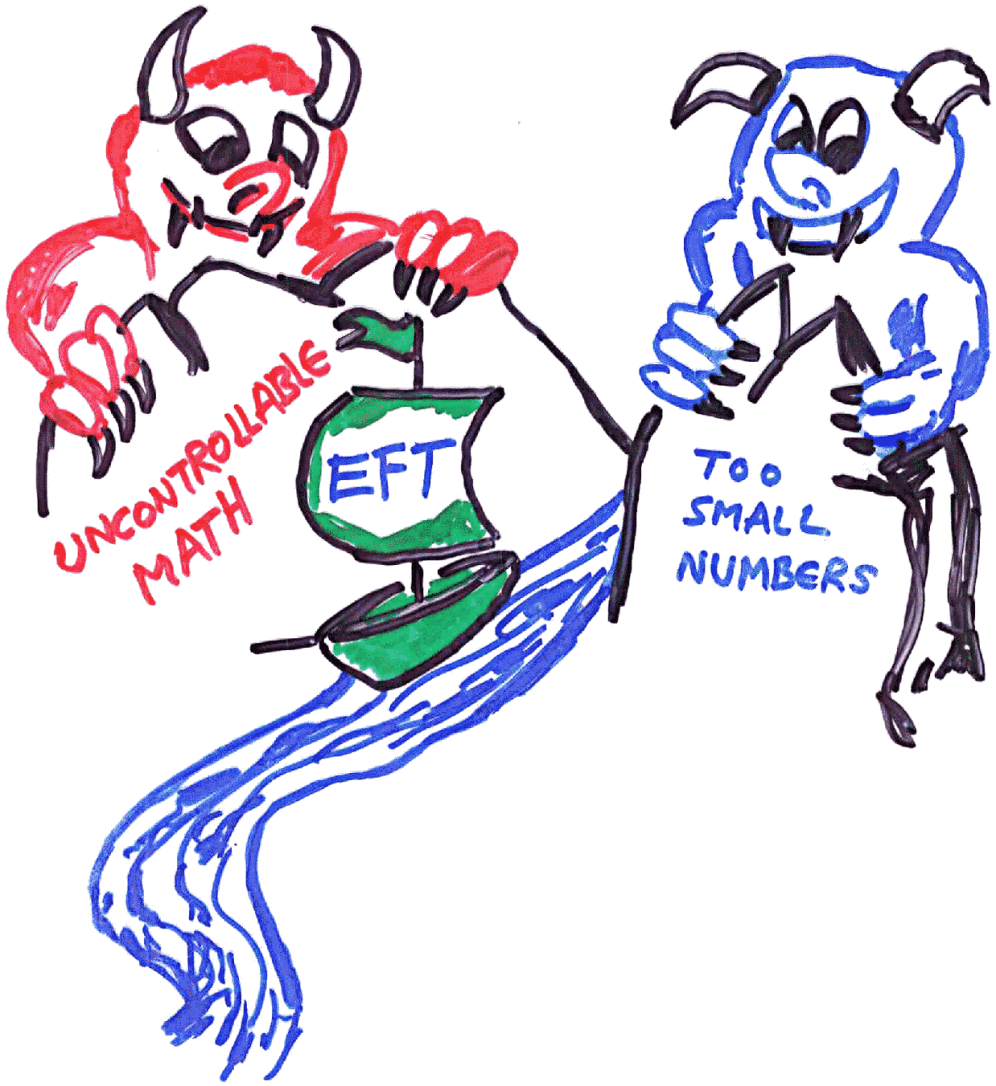
$$\therefore \quad \frac{\delta\rho}{\rho} \sim \frac{V^{3/2}}{M_p^3 V'} \sim \left(\frac{M}{M_p}\right)^{\alpha}$$

$M = V^{1/4}$: SCALE OF INFLATION

α : LOW INTEGER: 1, 2, ... (DEPENDING ON THE MODEL)

FROM $\frac{\delta\rho}{\rho} \sim 10^{-5} \rightarrow M \sim 10^{-10} M_p - 10^{-5} M_p$

COULD INFLATIONARY DYNAMICS BE SENSITIVE TO NEW HIGH ENERGY PHYSICS ?



TO CALCULATE FLUCTUATIONS: USE EFFECTIVE FIELD THEORY!

THERE ARE 4 SCALES IN THE IN ASCENDING ORDER

$$m < H < M < \sqrt{\dot{\phi}}$$

INFLATON MASS — HUBBLE SCALE — SCALE OF NEW PHYSICS — SCALE OF INFLATON KINETIC ENERGY

SPLIT THE THEORY AS BACKGROUND + FLUCTUATIONS AND ORGANIZE IT BY THESE SCALES

FLUCTUATIONS LIGHT: $m < H$

NEW PHYSICS HEAVY: $M > H$ INTEGRATE OUT!

RESULT: EFFECTIVE ACTION FOR FLUCTUATIONS ON TOP OF THE INFLATING BACKGROUND!

BACKGROUND "DECOUPLED": $\sqrt{\dot{\phi}} > M > H > m$

SO IT IS MERELY A SPECTATOR (ONCE ONE ENSURES THAT RADIATIVE CORRECTIONS DO NOT LIFT THE INFLATON POTENTIAL!)

CALCULATION: RECALL $\frac{\delta\rho}{\rho} = \frac{H\,\delta\phi}{\dot{\phi}}$

QUANTUM MECHANICS PROVIDES THE CORRECT NORMALIZATION FOR THESE MODES

MUST QUANTIZE IN CURVED SPACE-TIME

CHOICE OF VACUUM !!

$$\delta\phi = \delta\phi_0 + \delta\phi_1 + \delta\phi_2 + \dots$$

FREE INTERACTIONS

$$\delta\phi_0 = \langle\phi\phi\rangle^{\frac{1}{2}} = \frac{H}{2\pi}$$

$$\delta\phi_1 = \langle\phi\chi_I\phi\rangle^{\frac{1}{2}} = \frac{H}{2\pi} c\frac{H^2}{M^2}$$

. . .

$$\delta\phi = \frac{H}{2\pi}\left(1 + c\,\frac{H^2}{M^2} + \dots\right)$$

SIMILAR PROCEDURE FOR TENSORS !

THIS LEADS TO (def: $\delta_s = \frac{2}{5}\frac{\delta\rho}{\rho}$)

$$\delta_s = \frac{1}{\sqrt{75}\,\pi}\,\frac{V^{\frac{3}{2}}}{m_{Pl}^3\,\partial_\phi V}\left(1 + C_s\frac{H^2}{M^2} + \dots\right)$$

$$\delta_T = \frac{1}{\sqrt{60}\,\pi}\,\frac{V^{\frac{1}{2}}}{m_{Pl}^2}\left(1 + C_T\frac{H^2}{M^2} + \dots\right)$$

def: $n_T = 2\,\frac{\partial \ln \delta_T}{\partial \ln k}$ TENSOR TILT

$\epsilon = \frac{3\dot\phi^2}{2V}$ SLOW ROLL PARAMETER

$$n_T + 2\left(\frac{\delta_T}{\delta_s}\right)^2 = -2\epsilon C_s\frac{H^2}{M^2} + O(\epsilon^2)$$

AN IN-PRINCIPLE EFFECT OF NEW PHYSICS WHICH LEADS TO DEVIATIONS AWAY FROM THE STANDARD INFLATIONARY CONSISTENCY CONDITION TO SUBLEADING ORDER IN P.T.

HUI & KINNEY
KKLS

WITHOUT δ_T, WE COULD REINTERPRET $\propto C_s\frac{H^2}{M^2}$ AS A DIFFERENT POTENTIAL

WHAT CAN ACTUALLY BE SEEN ?

NEED TO OBSERVE TENSORS → E.G. BY CMB POLARIZATION MEASUREMENTS

THE WORST OBSTACLE COSMIC VARIANCE

TO MEASURE $\frac{\delta T}{T}$ WE SAMPLE $\lesssim 1000$ REGIONS OF THE SKY; STATISTICAL VARIANCE IS $\sigma \sim \frac{1}{\sqrt{2\ell+1}} \sim \frac{1}{\sqrt{1000}} \sim \%$

HENCE: ANY CORRECTION MUST BE > 0.01 TO BE OBSERVABLE

@ SLOW-ROLL PARAMETER $\epsilon \lesssim \frac{1}{15}$

MUST HAVE

$$c_s \frac{H^2}{M^2} \gtrsim 0.1 - 1$$

TO BE OBSERVABLE !

IN ALL ESSENTIALLY 4D MODELS (w $M_4 \sim 10^{19}$ GeV (E.G. WEAKLY COUPLED HETEROTIC STRING THEORY @ $g_s^2 \sim 0.1$, $M_s \sim 10^{19}$ GeV)

ANY NEW PHYSICS WILL EITHER :

* CONTRIBUTE AT THE CUTOFF $\sim M_4$
* GET HIGGSED BY ϕ TO m_4 †

S. THOMAS

HENCE : $M \sim m_4$

(w SCALE OF INFLATION $H < 10^{14}$ GeV

$$\frac{H^2}{M^2} \lesssim 10^{-11}$$

COMPLETELY UNOBSERVABLE !

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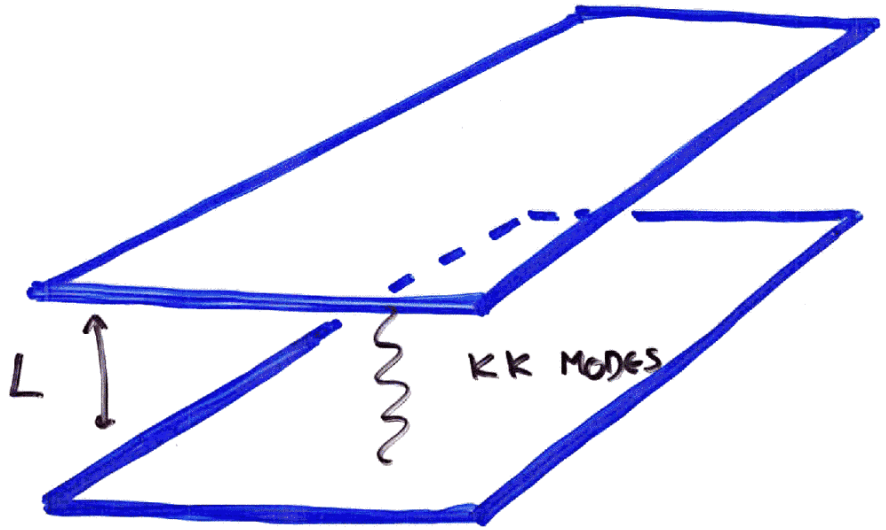
† EXCEPTION: IT IS POSSIBLE TO HAVE COUPLINGS $(\lambda + \phi)\bar{\Psi}\Psi$ WHICH GIVE $m_\psi \sim 0$ DURING INFLATION - WIMPZILLAS - WILL PRODUCE A BLIP!

LINDE ET AL, CHUNG ET AL

BUT: $\exists$ MODELS @ $m_f \ll m_{Pl}$!



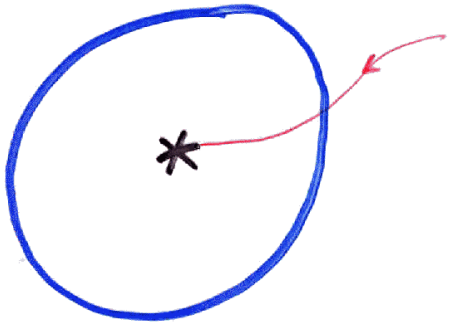
$$\frac{\delta\rho}{\rho}(1) = \sum_{KK} \frac{H^2}{M_{Pl}^2}$$

$$= cN \frac{H^2}{M_{Pl}^2} = c \frac{H^2}{M_f^2}$$

BY GAUSS LAW: $N = (M_f L)^n = \frac{M_{Pl}^2}{M_f^2}$

WITH THIS, $\exists$ MODELS WITH OBSERVABLE SIGNATURES IN THE CMB.

e.g., MANIFOLDS @ G_2 HOLONOMY



$$M_f \sim m_{11} \sim 4 \cdot 10^{13}\ \text{GeV}$$

$$c \frac{H^2}{M_f^2} \sim 0.1$$

WARNING: CALCULATIONS IMPRECISE!

MORE PRECISELY:

CONSIDER COMPACTIFICATIONS WITH

- $m_{Pl}^2 = m_{Pl,d}^{d-2} V_{d-4} = (2 \cdot 10^{18} GeV)^2$
- $\alpha_{gauge} = \frac{g^2}{4\pi} \sim \frac{1}{25}$ SO THAT RG RUNNING PRODUCES THE RIGHT VALUE AT TeV
- $\frac{1}{H} > (V_{d-4})^{\frac{1}{d}}$ 4D DESCRIPTION
- $\rho_{4D} \simeq \rho_d V_{d-4}$ SUB-PLANCKIAN:

i.e. $\frac{H^2}{m_{Pl,d}^2} \sim \frac{\rho_d}{m_{Pl,d}^4} \lesssim O(1)$

S.T. HIGHER-DIMENSIONAL SUGRA IS VALID!

SIGNAL COULD BE CRANKED UP!

NOTE: 1) GIVES UP 4D UNIFICATION, AS $M_{Pl,d} \sim H \sim 10^{14} GeV$

2) PROTON DECAY PROBLEMS

POSSIBLE IMPROVEMENT: DIRECT GRAVITY WAVE DETECTION SINCE $\lambda \ll H^{-1}$, THERE ARE NO COSMIC VARIANCE CONSTRAINTS

BUT: HARD TO DETECT (WEAKNESS OF GRAVITY...)

AN OPTIMISTIC PROPOSAL: GREAT MISSION

CORNISH, SPERGEL & BENNETT

SENSITIVITY $\sim 10^{-3} - 10^{-4}$ INFLATION

$\left(\frac{H}{M}\right)^2 \sim 10^{-4} \Rightarrow$ IF $H \sim 10^{14} GeV$

$M \sim 10^{16} GeV$

GUT SCALE → NEAR HOŘAVA-WITTEN

... THIS WOULD BE FAR IN THE FUTURE, BUT AT LEAST IS POSSIBLE IN PRINCIPLE...

OUR RESULT ($\propto \frac{H^2}{M^2}$ AND) DEPENDS CRUCIALLY ON LOCALITY AND DECOUPLING !

⇓

VACUUM CHOICE !

WE CHOOSE: THERMAL (A.K.A. ADIABATIC, BUNCH-DAVIES) VACUUM

OTHER CHOICES? INFLATION APPROXIMATELY DESITTER → VACUUM SHOULD BE DE SITTER INVARIANT (APPROX!)

IN DS $\exists$ CONTINUOUS ∞ OF INVARIANT STATES !

CHOOSE THOSE?

Chernikov & Tagirov
Allen
MoHola
Bousso, Maloney, Strominger
DANIELSSON

$$a^{\alpha}_{(k)} = N_{\alpha}\left(a_{(k)} - e^{\alpha^*} a^{\dagger}_{(k)}\right)$$

$$a^{\alpha}_{(k)} |\alpha\rangle = 0$$

PROBLEMS: BACKREACTION HUGE, ATTEMPTS TO RENORMALIZE IT BREAK LOCALITY, DECOUPLING ...

KKLSS
BANKS & MANELLI
EINHORN & LARSEN
COLLINS, HOLMAN & MARTIN
GOLDSTEIN & LOWE
STAROBINSKY

WHAT IF INFLATION WERE SHORT, OR THERE WERE SIGNIFICANT FEATURES IN THE INFLATON DYNAMICS ~60 e-FOLDS BEFORE THE EXIT ?

BURGESS, CLINE, HOLMAN, LEMIEUX

SIGNAL COULD BE PARAMETRICALLY SLIGHTLY LARGER: $\propto \frac{H}{M}$ INSTEAD OF $\left(\frac{H}{M}\right)^2$

BUT: THIS IS STILL A LOW-ENERGY EFFECT, HAVING NOTHING TO DO WITH TRANSPLANCKIAN SCALES

INFLATON FLUCTUATIONS ARE PRODUCED IN A STATE WHICH IS NOT THE THERMAL VACUUM BUT SOME "EXCITED" STATE GENERATED BY "ENVIRONMENTAL" CIRCUMSTANCES

INFLATION WITH A HICKUP

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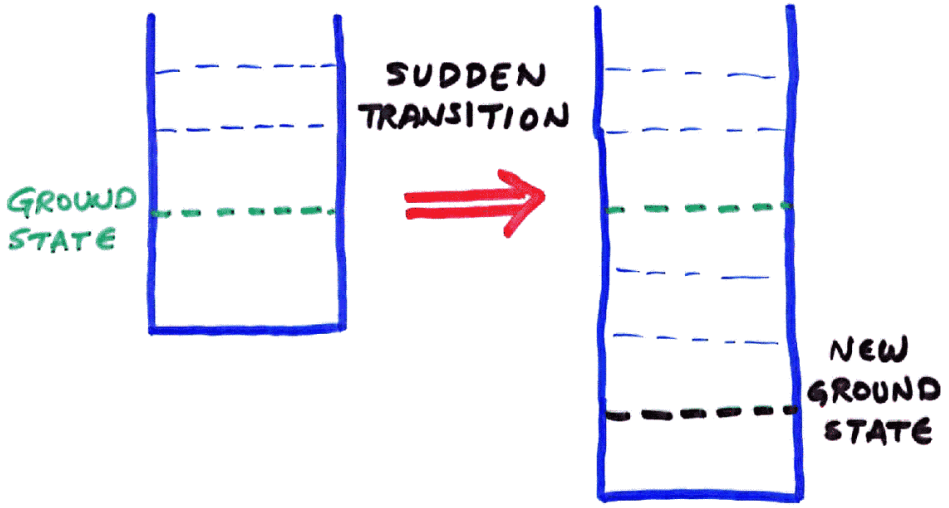
HEP-TH/0307013

CONSIDER QUANTUM-MECHANICAL ANALOGY:



IF TRANSITION SHARP, THE SYSTEM REMAINS IN THE STATE IT OCCUPIED BEFORE THE TRANSITION WHICH IS NOT A VACUUM ANYMORE!

THIS STATE IS A SQUEEZED STATE ON TOP OF THE THERMAL VACUUM AND THE INFLATON FLUCTUATIONS ARE PRODUCED IN IT. THEY CARRY THE INFORMATION ABOUT THE DEVIATION OF THIS STATE FROM THE VACUUM, CORRECTING THE THERMAL VACUUM RESULT FOR $\delta\rho/\rho$

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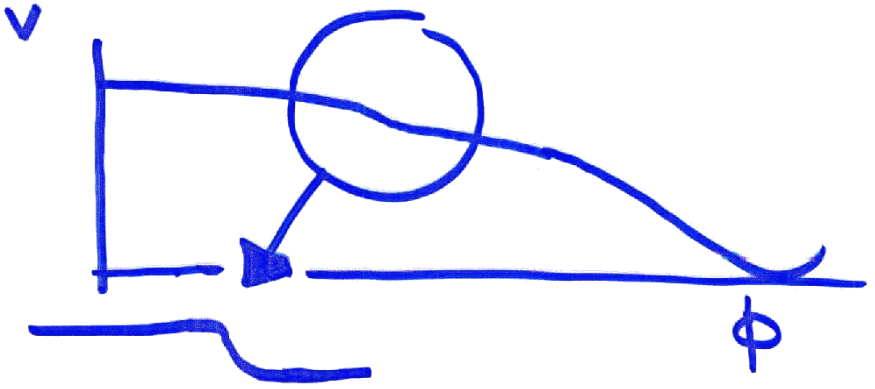
EXAMPLE: CONSIDER A POTENTIAL WHERE THE SLOWROLL PARAMETER $\eta = -\frac{\ddot{\phi}}{H\dot{\phi}}$ JUMPS ~ 60 EFOLDS BEFORE THE END OF INFLATION, OR WHERE INFLATION WAS SHORT, STARTING FROM SOME NON-VACUUM STATE



USE GAUGE-INVARIANT PERTURBATION THEORY:

$$\varphi = a\delta\phi - \frac{a\phi'}{a'/a}\,\Phi$$

$$\varphi_k'' + \left(k^2 - \frac{z''}{z}\right)\varphi_k = 0$$

$$\frac{z''}{z} = \frac{2}{\eta^2} + \frac{1}{2}\left(\frac{\epsilon'}{\epsilon}\right)' + \ldots \qquad \epsilon = \frac{\phi'^2}{2M_p^2 H^2}$$

A JUMP IN $\eta = -\frac{\phi''}{\mathcal{H}\phi'}$ PRODUCES A CANONICAL TRANSFORMATION:

$$\varphi_k(\eta_0^+) = \varphi_k(\eta_0^-)$$

$$\pi_k(\eta_0^+) = \pi_k(\eta_0^-) - \Delta(\eta-\epsilon)\,\mathcal{H}_0\,\varphi_k$$

BOGOLIUBOV TRANSFORMATION IN THE PERTURBATIVE HILBERT SPACE - THE STATE OF THE INFLATON DIFFERENT FROM THE THERMAL VACUUM AFTER THE TRANSITION

$\therefore$ INFLATON ENDS UP IN THE STATE OBEYING

$$b_k(\eta_0^+)\,|I\rangle = -i\,\Delta(\eta-\epsilon)\,\frac{\mathcal{H}_0}{2k}\,b_{-k}^\dagger(\eta_0^+)\,|I\rangle$$

SQUEEZED STATE!

ORGANIZE THE RESULT AS A TRIPLE SERIES:

ϵ, η	$\Delta(\eta-\epsilon)\frac{H}{p}$	$\frac{H^2}{p^2}$
SLOW ROLL	SUDDEN	ADIABATIC

$$\frac{\delta\rho}{\rho} \sim \frac{H^2}{\dot\phi}\left(1 + \frac{1}{2}\mathcal{D}\right)$$

$$\mathcal{D} = \Delta(\eta-\epsilon)\frac{H}{p}\sin\left(\frac{2p}{H}\right) + \frac{H^2}{p^2}\cos\left(\frac{2p}{H}\right) + 2(2-\ln 2-\gamma)(2\epsilon-\eta) - 2\epsilon$$

FOCUS ON $O\left(\frac{H}{p}\right)$:

$$\Delta(\eta-\epsilon)\,\frac{H}{p}\,\sin\left(\frac{2p}{H}\right)$$

* VANISHES WHEN $\Delta(\eta-\epsilon)\to 0$ NOT AN α-VAC!
* VANISHES WHEN $p\to\infty$

QUANTUM NO-HAIR THM!

IF THE TRANSITION OCCURED ~60 e-FOLDS BEFORE THE EXIT, THIS COULD BE $\gtrsim$ FEW %

CAN BE VIEWED AS A POTENTIAL DIAGNOSTIC OF SHORT INFLATION ...

ALSO SEE:
CONTALDI, PELOSO, KOFMAN & LINDE
CLINE, CROTTY & LESGOURGUES
ADAMS, CRESSWELL & EASTHER

CONCLUSIONS

- THERE EXIST MODELS WHICH LEAVE OBSERVABLE SIGNATURES IN THE CMB!
- ALTHOUGH THEY MAY REQUIRE SPECIAL PARTICLE PHYSICS (CHOICE OF SCALES, RATIONALE FOR UNIFICATION, NEW PHYSICS ~60 e-FOLDS BEFORE THE EXIT), THEY ARE FULLY CONSISTENT WITH EFT

  LOCAL, CAUSAL, TACHYON-FREE, OBEYING OSUAL DECOUPLING
- IF ONE ABANDONS EFT, ONE CAN GET LARGER SIGNALS, BUT IT IS NOT CLEAR ONE CAN TRUST IT
- HEDGING STRATEGY: THIS MAY BE WORTH PURSUING SINCE IT COULD BE ONE OF FEW CHANCES WE GET TO SEE REALLY HIGH ENERGY PHYSICS