# INFLATION AND SHORT DISTANCE PHYSICS

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# SCALES IN NATURE

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

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

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 ?

E.G. 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
  - Easther Greene, Kinney & Shiu
  - Kempf & Niemeyer
  - Hui & Kinney
  - KKLS
  - Danielsson
  - Guidice, Kolb, Riotto & Thacker

# COSMOLOGY

**RECOURSE TO EFFECTIVE FIELD THEORY:**
CLASSICAL GR IS NOT A STAND-ALONE THEORY BECAUSE IT IS NOT UV COMPLETE

... LOOP DIVERGENCES!

INSTEAD: A THEORY WITH A CUTOFF :

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

WORKS WONDERFULLY AT DISTANCES LONG COMPARED TO $\ell_p$ DECOUPLING

**IN COSMOLOGY:** PHYSICS AT SCALES $L$ IS INDEPENDENT TO LEADING ORDER OF THE PHYSICS AT SCALES $\ell \ll L$
**LOCALITY, CAUSALITY & COVARIANCE!**

**CAVEAT:** COSMOLOGICAL CONSTANT PROBLEM SO FAR DEFIED ALL ATTEMPTS TO SOLVE IT WITHIN A LOCAL, CAUSAL, COVARIANT FRAMEWORK. DOES THIS SUGGEST OUR ASSUMPTIONS ARE WRONG?

WE WILL CONTINUE TO IGNORE THIS...

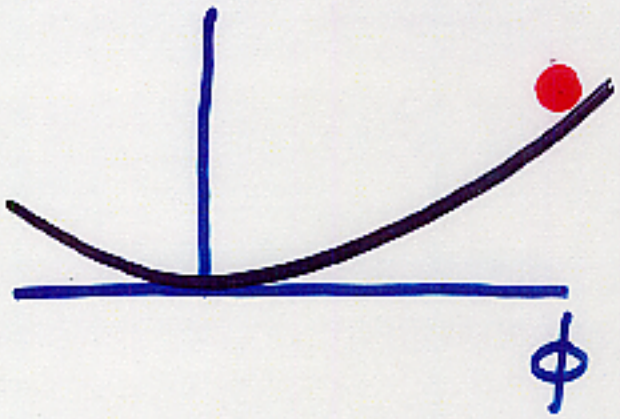
# INFLATION

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

THE BENCHMARK THEORY IS INFLATION.

$\phi$ : INFLATON

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

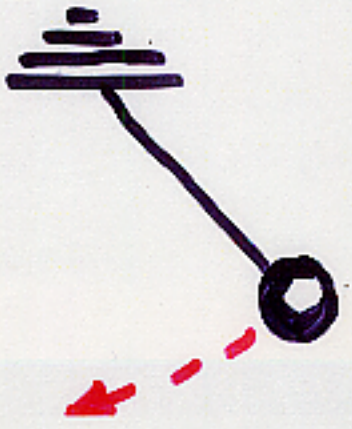



$$3H^2 = 8\pi G_N \left( \frac{\dot{\phi}^2}{2} + V(\phi) \right)$$

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

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!

# QUANTUM FLUCTUATIONS

QUANTUM FLUCTUATIONS OF THE INFLATON ARE IMPRINTED ON THE BACKGROUND AS SMALL RIPPLES ON THE SPACE-TIME → SO THEY PRODUCE DENSITY FLUCTUATIONS

THE OVERDENSE REGIONS WILL EVENTUALLY BEGIN TO COLLAPSE BY JEANS INSTABILITY THE ORIGIN OF STRUCTURE: GALAXIES ETC...

## HEURISTIC "DERIVATION"

$$\delta\rho \sim H\rho\,\delta\tau$$

$$\delta\phi \sim \dot{\phi}\,\delta\tau$$

$$\frac{\delta\rho}{\rho} = \frac{H}{\dot{\phi}}\delta\phi$$

BACKGROUND METRIC ALSO FLUCTUATES
→ TENSOR GRAVITON MODES ARE GETTING EXCITED

TO COMPUTE: GO TO THE AXIAL GAUGE (TRANSVERSE-TRACELESS) AND RECALL THAT EACH GRAVITON POLARIZATION IS A (SCALAR FIELD) × (POLARIZATION TENSOR)

$$\therefore \quad \frac{\delta\rho_g}{\rho} = 2\frac{\delta h}{M_p}$$

TO LEADING ORDER BOTH $\delta\phi$ AND $\delta h$ ARE FIELDS WHICH HAVE WEAK SELFINTERACTIONS AND COUPLE TO THE BACKGROUND → TREAT THEM AS ESSENTIALLY FREE FIELDS IN INFLATING SPACETIME

**FLUCTUATIONS ≡ PARTICLE PRODUCTION**

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

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

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

$$\dots$$

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

TO LEADING ORDER, THIS IS JUST HAWKING RADIATION $\rightarrow$ $\phi$ LIVING IN A THERMAL CAVITY

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

$$\delta_s = \frac{1}{\sqrt{75\pi}} \frac{V^{\frac{3}{2}}}{m_{PL}^3 \partial_\phi V} \left(1 + c_s \frac{H^2}{M^2} + \ldots\right)$$

$$\delta_T = \frac{1}{\sqrt{60\pi}} \frac{V^{\frac{1}{2}}}{m_{PL}^2} \left(1 + c_T \frac{H^2}{M^2} + \ldots\right)$$

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

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

OUR RESULT ( $\propto \frac{H^2}{M^2}$ ) DEPENDS CRUCIALLY ON VACUUM CHOICE : THERMAL (AKA ADIABATIC, BUNCH-DAVIES...) VACUUM

OTHER CHOICES : INFLATION APPROX DE SITTER $\Rightarrow$ VACUUM (APPROX) DS INVARIANT

IN DS $^3$ CONTINUOUS $\infty$ OF INVARIANT STATES!

$$a_k^\alpha |\alpha\rangle = 0$$

$$a_k^\alpha = N_\alpha \left(a_k - e^{\alpha^*} a_k^\dagger\right), \quad N_\alpha = \frac{1}{\sqrt{1-\exp(\alpha+\alpha^*)}}$$

Allen; Mottola; Bousso, Maloney & Strominger

CORRECTIONS TO $\frac{\delta\rho}{\rho} \propto \frac{H}{M}$ Danielsson; Easther, Greene, Kinney & Shiu

**BUT:** BACKREACTION HUGE, ATTEMPTS TO CONTROL IT BREAK LOCALITY, DECOUPLING...

KKLSS, TO APPEAR
BANKS & Mannelli

* SEE THE TALK BY ALBION LAWRENCE

# 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 TO $n_T$ MUST BE $> 0.01$ TO BE OBSERVABLE!

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

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 $\phi$ TO $m_4$ †

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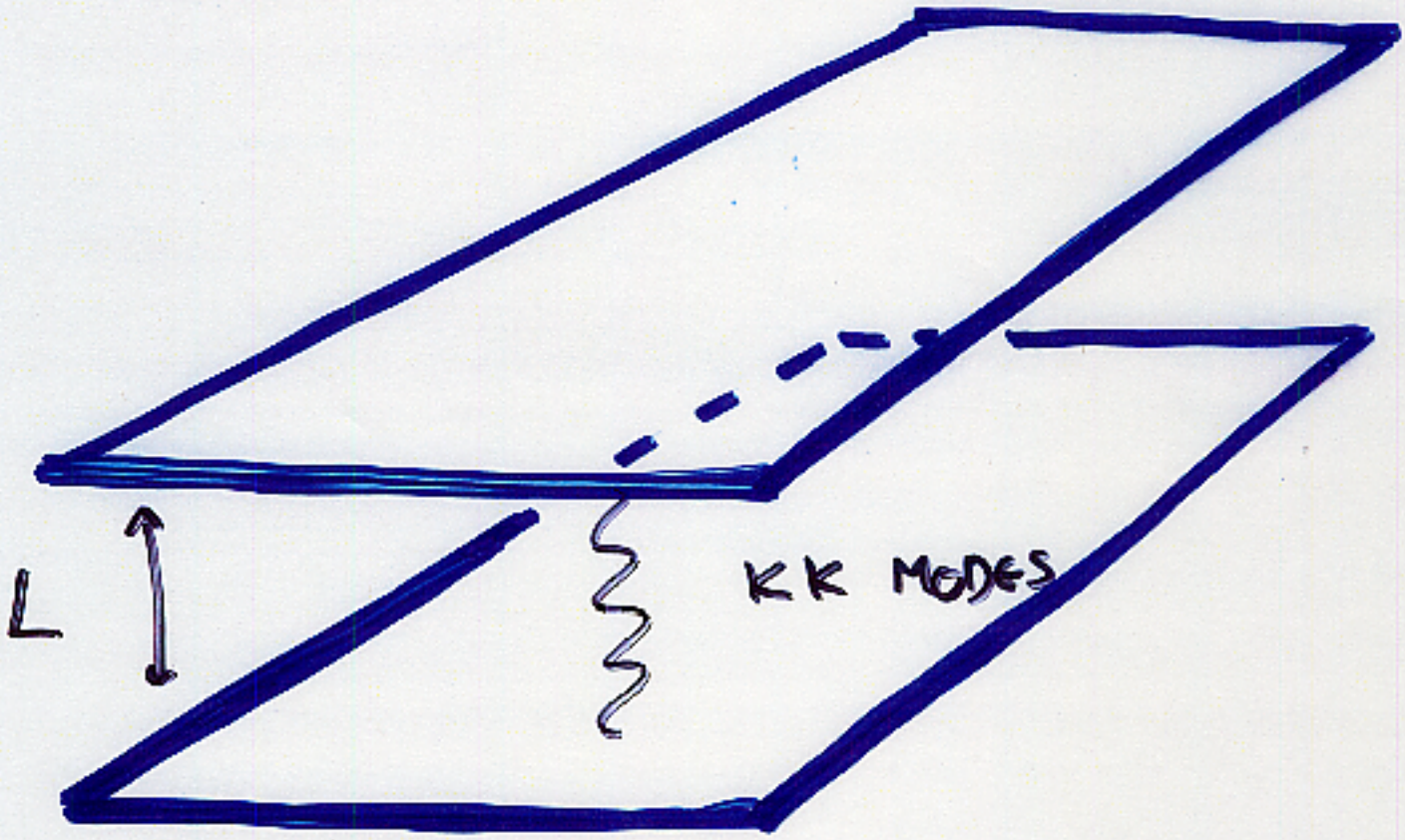
† EXCEPTION: IT IS POSSIBLE TO HAVE COUPLINGS $(\lambda + \phi)\bar{\psi}\psi$ WHICH GIVE $m_\psi \sim 0$ DURING INFLATION - WIMPZILLAS - WILL PRODUCE A BLIP!
LINDE ET AL, CHUNG ET AL

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

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. $\frac{H^2}{M_{Pl,d}^2} \sim \frac{\rho_d}{M_{Pl,d}^d} \lesssim O(1)$

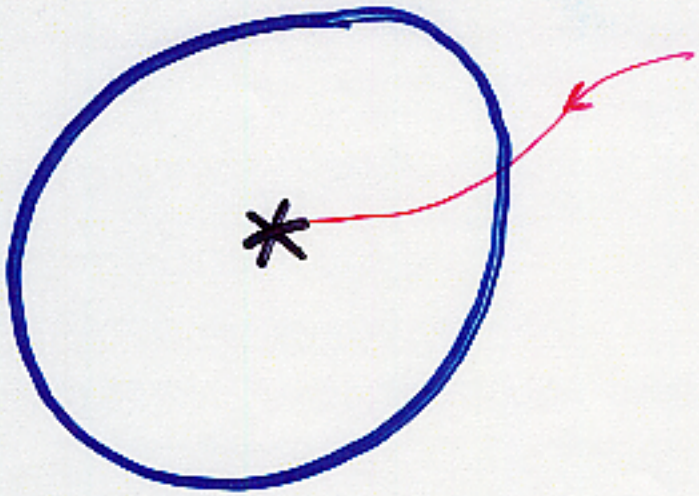
S.T. HIGHER-DIMENSIONAL SUGRA IS VALID!

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

2) PROTON DECAY PROBLEMS

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

e.g., MANIFOLDS @ $G_2$ HOLONOMY



SINGULARITY GIVING RISE TO $G_2$ HOLONOMY GROUP

CODIMENSION 4

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

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

WARNING: CALCULATIONS IMPRECISE!

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

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

$$M \sim 10^{16}\ \text{GeV}$$

GUT SCALE → NEAR HOŘAVA-WITTEN

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

# CONCLUSIONS

- MODELS WHICH CAN LEAVE OBSERVABLE SIGNATURE IN THE CMB EXIST, BUT...
- THEY REQUIRE SPECIAL CHOICE OF SCALES AND A DIFFERENT RATIONALE FOR UNIFICATION
- THERE MAY BE COMPETING EFFECTS; EG. MODELS WITH MULTIPLE SCALARS MAY ALSO VIOLATE INFLATIONARY CONSISTENCY CONDITIONS BUT NEED TO BE FINE-TUNED
- NEED BETTER CALCUCATIONAL CONTROL, MORE PRECISE ESTIMATES...
- ULTIMATELY, ALTHOUGH DIFFICULT (BY CURRENT LORE) THIS POSSIBILITY IS WORTH CONSIDERING SINCE IF THERE REALLY ARE HIGH SCALES IN NATURE, IT MIGHT BE ONE OF VERY FEW CHANCES WE GET TO PROBE THEM! DIRECT GRAVITY WAVE DETECTION MIGHT REVEAL THEM SOME DAY ...