ORIGIN OF PRIMORDIAL PERTURBATIONS

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LENNY SUSSKIND

OUTLINE

* EFT and the Universe
* Cosmological problems and Inflation
* Emergence of Perturbations
* Perturbations and New Physics
* Summary

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 ℓ_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...

BASIC OBSERVATIONS

THE UNIVERSE IS :

* VERY OLD AND BIG
  ($\tau \sim 14 \cdot 10^9$ YRS & $L \gtrsim 4500$ MPc)

* HOMOGENEOUS AND ISOTROPIC
  (THE SAME FOR ANY OBSERVER AT A GIVEN TIME, WITH ACCURACY $\Delta \sim 10^{-5}$)

* SPATIALLY FLAT
  (WITH SPATIAL GEOMETRY APPROXIMATED BY EUCLIEDEAN GEOMETRY, WITH ACCURACY 1%)

* EXPANDING, WITH $v = HR$
  (HUBBLE'S LAW, $H \simeq 65$ km/s/MPc)

* FILLED WITH MATTER WHICH IS MOSTLY INVISIBLE

  (THE USUAL BARYONS & LEPTONS COMPRISE ONLY ABOUT ~ 1% OF THE UNIVERSE)

CMB ANISOTROPIES

HOWEVER, THE UNIVERSE IS NOT PERFECTLY SMOOTH - THERE ARE "SMALL BLEMISHES" - PERTURBATIONS IN THE DISTRIBUTION OF MATTER

$$\frac{\delta\rho}{\rho} \sim 10^{-5}$$

GALAXIES, CLUSTERS, NEBULAE ...

THEY YIELD THE SMALL TEMPERATURE FLUCTUATIONS IN THE CMB:

$$\frac{\delta T}{T} \sim \frac{\delta\rho}{\rho} \sim 10^{-5}$$ SACHS - WOLFE

MEASURED IN THE CMB!

COBE, 1982

CMB ANISOTROPIES A PERFECT TOOL FOR OBSERVERS!

BOOMERANG, MAXIMA, WMAP, PLANCK, ...

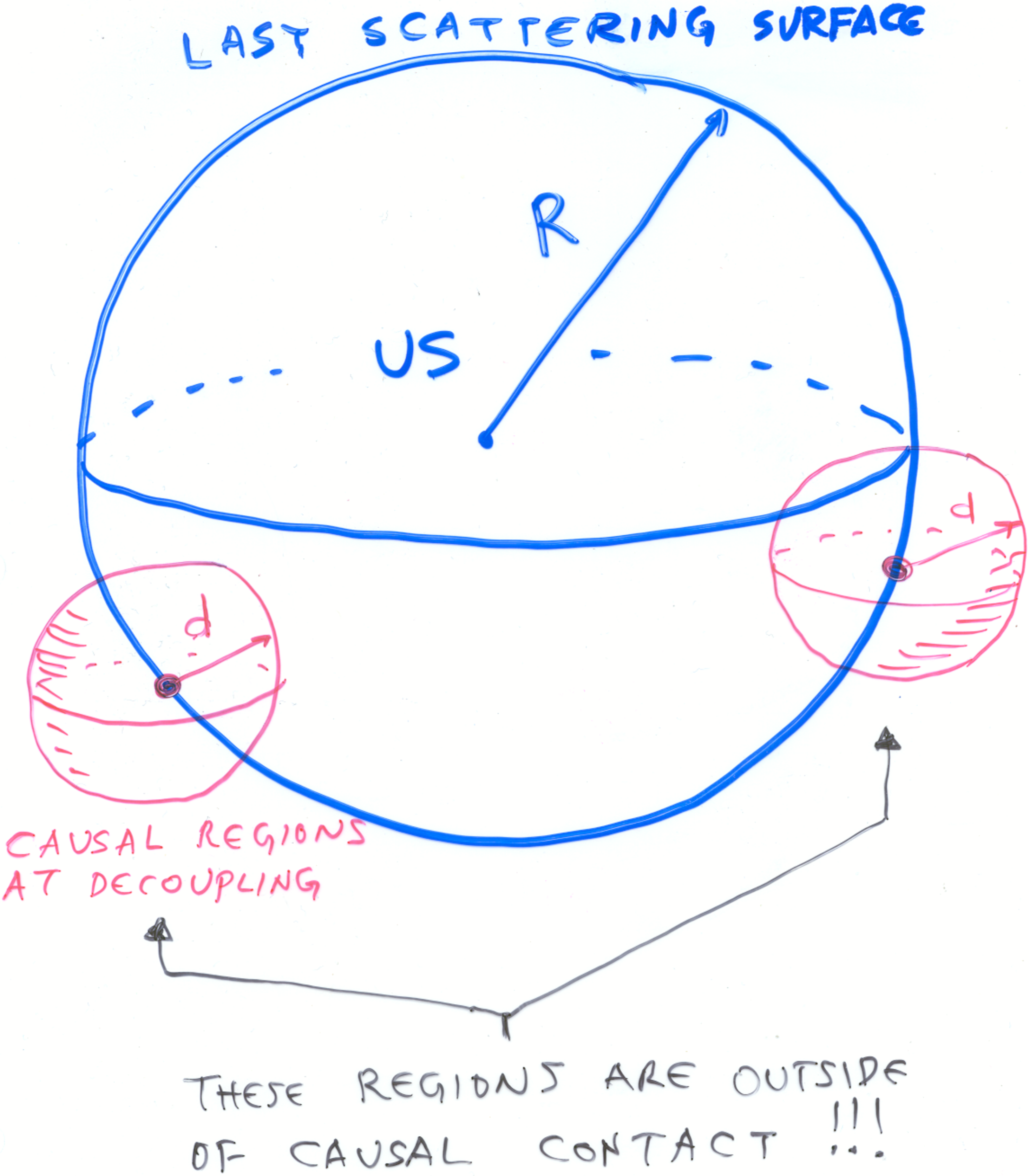
70's HARRISON & ZELDOVITCH

THE OBSERVED STRUCTURES IN THE UNIVERSE (GALAXIES, CLUSTERS, VOIDS ETC) CAN BE EXPLAINED BY GRAVITATIONAL INSTABILITY (→ CLUMPING) IF THERE WAS AN INITIAL SCALE-INVARIANT SPECTRUM OF FLUCTUATIONS

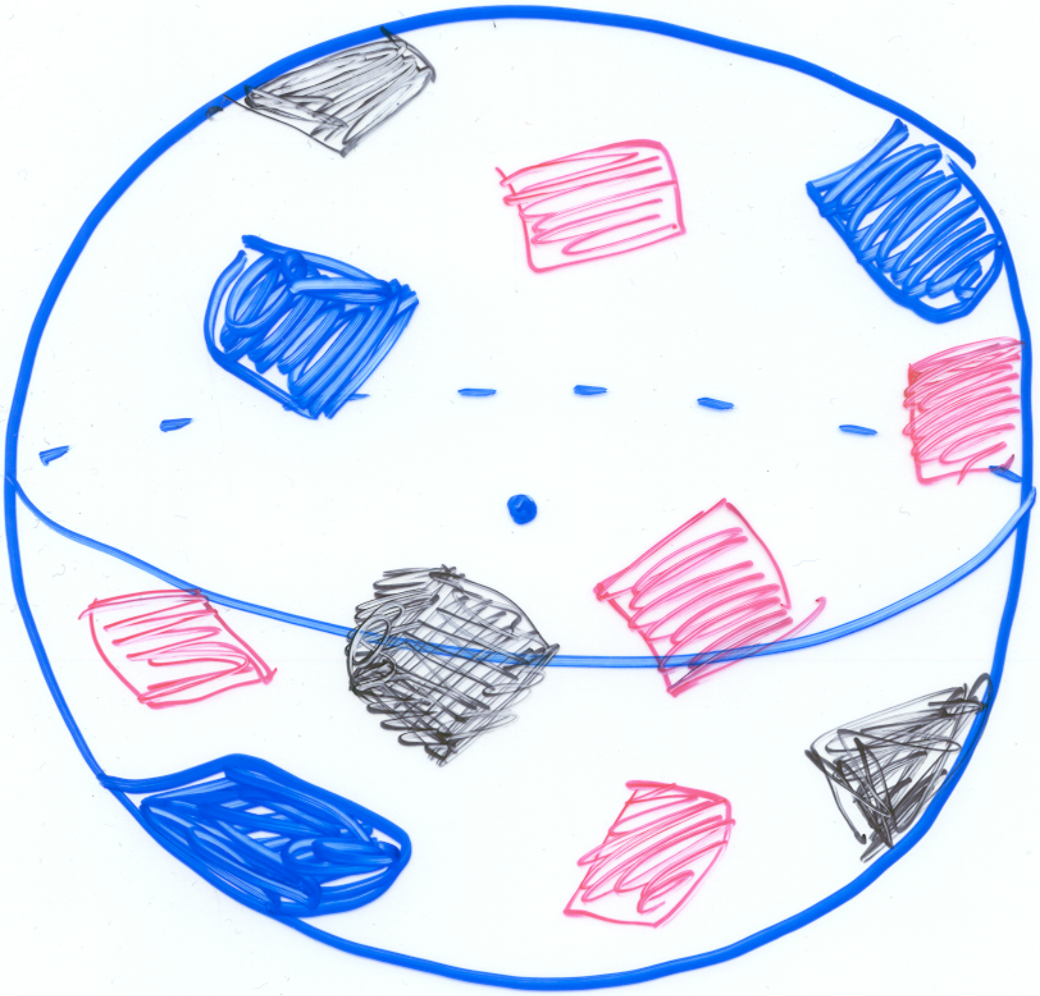
WHAT GAVE RISE TO IT?

THE ANSWER IS RELATED TO THE SOLUTION OF THE OTHER COSMIC CONUNDRA...

HOMOGENEITY, ISOTROPY, AGE, FLATNESS...

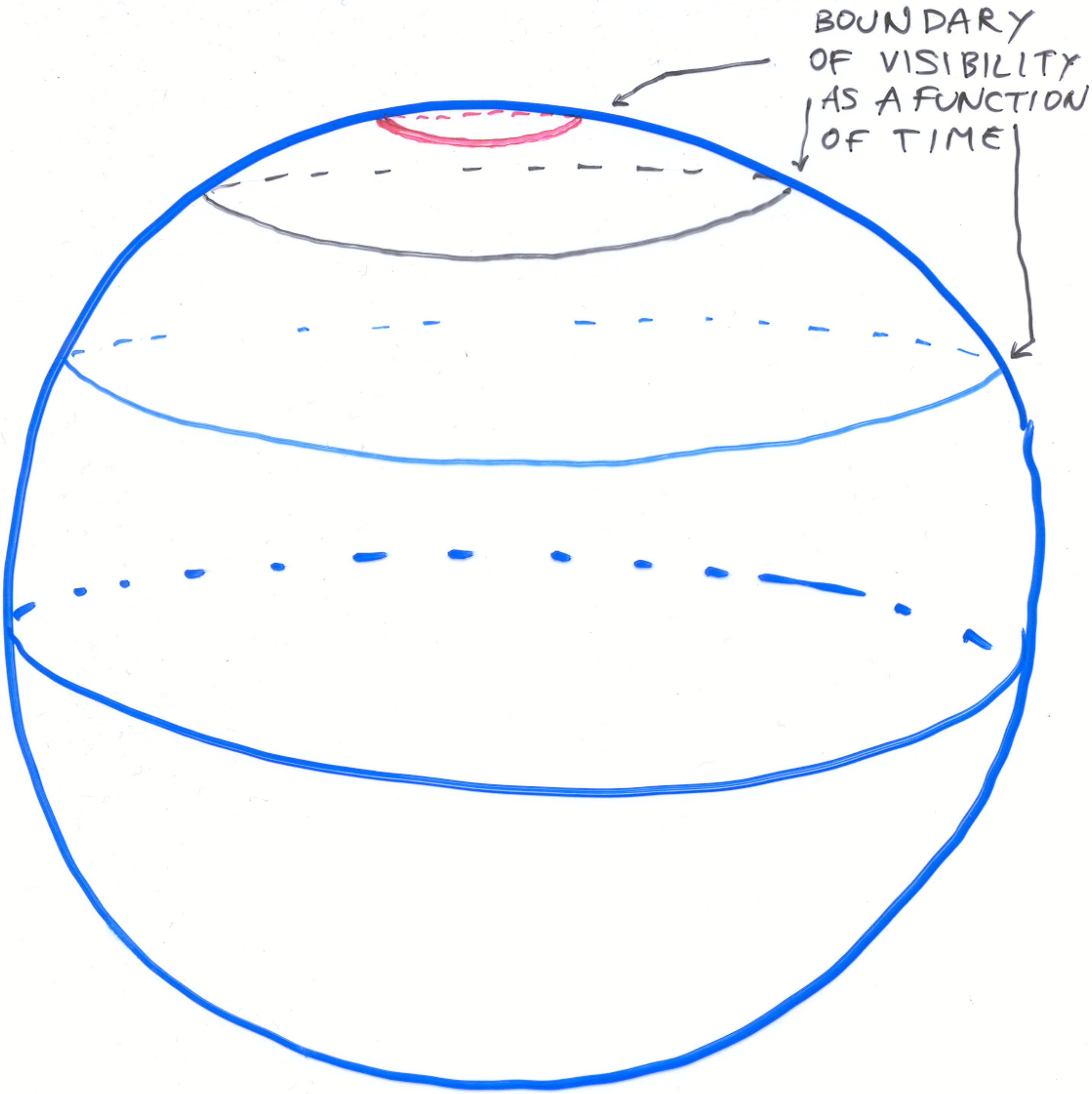

LAST SCATTERING SURFACE
R
US
d
d
CAUSAL REGIONS
AT DECOUPLING
THESE REGIONS ARE OUTSIDE
OF CAUSAL CONTACT !!!

WE SHOULD EXPECT THE UNIVERSE TO LOOK **MUCH MORE** PATCHY!



$$\frac{\Delta T}{T} \sim 1, \text{ NOT } 10^{-5} ?!$$

CURVATURE PROBLEM



WHY IS THE BALOON SO BIG?!

FLATNESS

$$H^2 + \frac{k}{a^2} = \frac{8\pi G_N}{3}\rho$$

DEF: $$\Omega = \frac{\rho}{\rho_c} = \frac{\rho}{\frac{3H^2}{8\pi G_N}}$$

$$\Omega = 1 + \frac{k}{a^2 H^2}$$

TODAY: $H^{-1} \sim 10^{60}\, \ell_P \quad a \gtrsim 10^{60}\, \ell_P$

PLANCK: $H^{-1} \sim \ell_P \quad a \gtrsim 10^{30}\, \ell_P$

$$\therefore \quad \Omega = 1 + 10^{60}(\Omega_P - 1)$$

AT THE PLANCK TIME Ω_P MUST BE 1 WITH THE PRECISION OF ...

1 PART PER 10^{60} !

A SOLUTION:

COSMIC INFLATION

A. GUTH, 81, A. LINDE, 82

A. ALBRECHT & P. STEINHARDT, 82

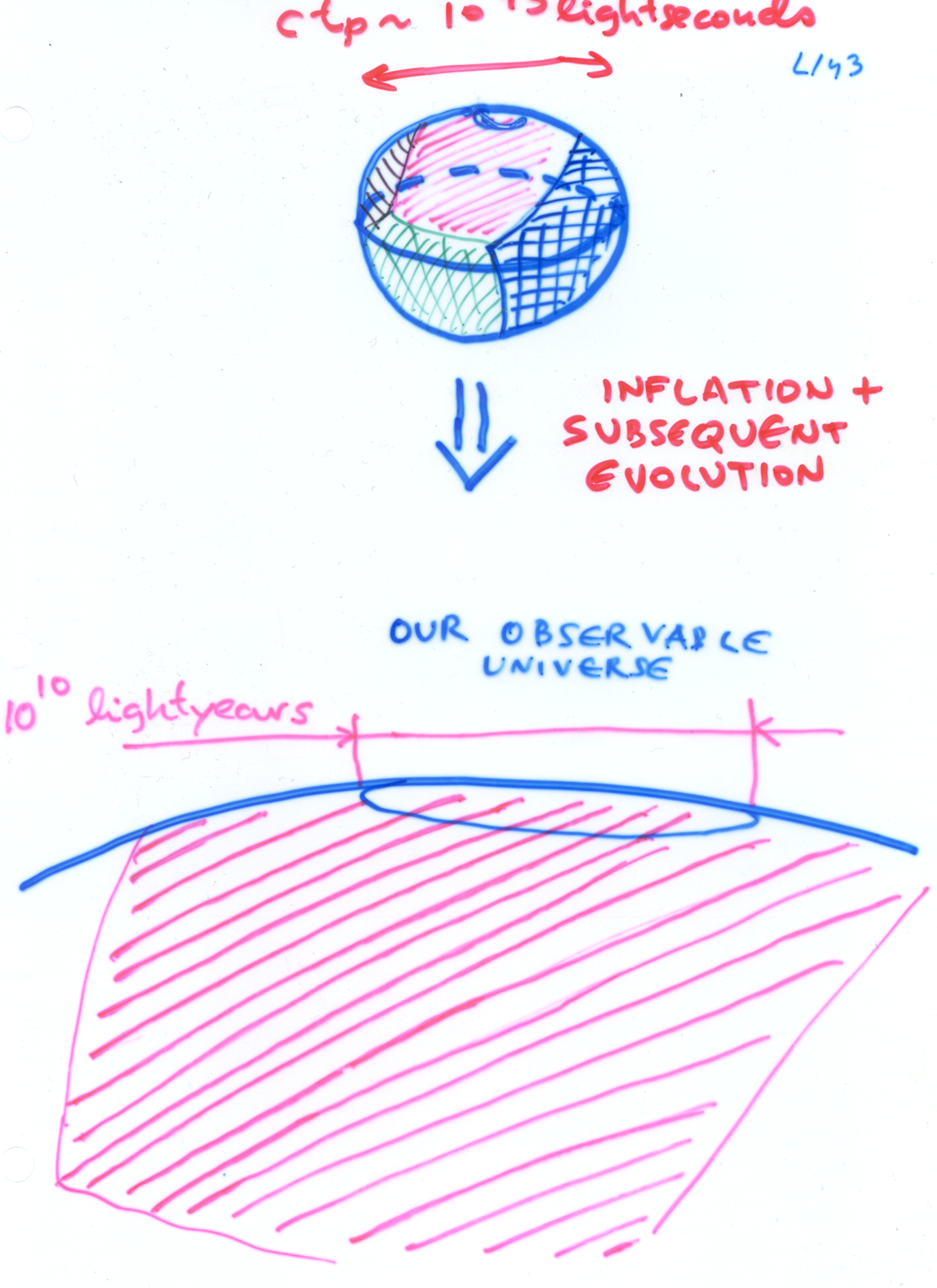
IDEA: THE VERY EARLY UNIVERSE WAS DOMINATED BY DARK ENERGY - A NON-CLUMPING FORM OF MATTER WITH $\rho \sim \text{const}$

THEN

$$3H^2 + 3\frac{k}{R^2} = 8\pi G_N \rho \simeq \text{const}$$

$$\rightarrow \quad H \sim \text{const}, \quad R \sim e^{Ht}$$

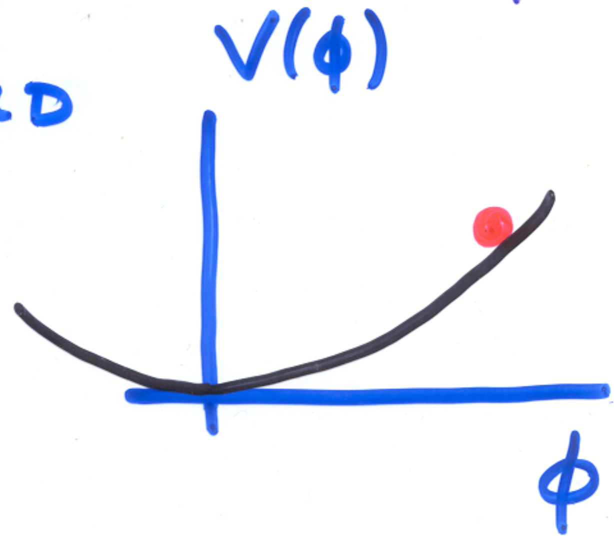
THE COSMIC BALOON STARTED GROWING EXPONENTALLY FAST!


$ct_P \sim 10^{-43}$ lightseconds
INFLATION + SUBSEQUENT EVOLUTION
OUR OBSERVABLE UNIVERSE
10^{10} lightyears

DYNAMICS OF INFLATION

LINDE, '82

ϕ : INFLATON FIELD



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

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

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

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) X (POLARIZATION TENSOR)

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

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

FLUCTUATIONS ≡ PARTICLE PRODUCTION

A PAIR CREATED FROM THE VACUUM CAN

* ANNIHILATE, LEADING TO A BUBBLE DIAGRAM CORRECTION TO λ_4 FINE-TUNED AWAY AS IS USUAL

* PREVENTED FROM ANNIHILATION BY COSMOLOGICAL STRETCHING BOGOLUBOV PARTICLE PRODUCTION $\simeq$ IMPRINTING OF A CLASSICAL WAVE

$$\lambda_{physical} = \frac{a(t)}{k}$$

k : WAVE VECTOR

WHEN $\lambda_{physical} \gtrsim H^{-1}$ MODE "FREEZES" : e.g. DEFINE CONFORMAL TIME $\eta = -\frac{1}{H} e^{-Ht}$ AND $\varphi = \frac{\phi}{\eta}$:

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

SO : WHEN $k^2\eta^2 \lesssim 2 \rightarrow \lambda_{physical} \gtrsim H^{-1}$

MODES BECOME POWER-LAW: $\varphi \rightarrow \frac{A}{\eta} + B\eta^2$

$$\phi \rightarrow A + B e^{-3Ht}$$

FREEZE-OUT!

INDEED: CONSIDER SMALL FLUCTUATIONS

$$\ddot{\phi}_k + 3H\dot{\phi}_k + \left(m^2 + \frac{k^2}{a^2}\right)\phi_k = 0$$

A TECHNICAL ASIDE: FOR SIMPLICITY TAKE $H \simeq$ CONST, $a \simeq a_0 \exp(Ht)$

DEFINE CONFORMAL TIME $\eta = -\frac{1}{H}\exp(-Ht)$

AND REDEFINE THE SCALAR BY $\phi = \eta\varphi$

USING $f' = \frac{df}{d\eta}$,

$$\varphi'' + \left(k^2 - \frac{2 - \frac{m^2}{H^2}}{\eta^2}\right)\varphi = 0$$

IGNORE m^2/H^2; THEN:

1) $\eta^2 \gg \frac{2}{k^2} \rightarrow \varphi \sim A\cos(kt + \delta)$

UV: $\phi_k \sim e^{-Ht}\phi_0 \cos(kt+\delta)$

2) $\eta^2 \ll \frac{2}{k^2} \rightarrow \varphi \sim \frac{A}{\eta} + B\eta^2$

IR: $\phi_k \sim A + B e^{-3Ht}$

INDEED: CONSIDER GAUGE-INVARIANT SMALL FLUCTUATIONS: BARDEEN

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

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

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

CURVATURE PERTURBATION MUKHANOV, '82

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

∴ DURING SLOW ROLL INFLATION, $H \simeq$ CONST,

$a \simeq a_0 \exp(Ht)$, $\eta = -\frac{1}{H}\exp(-Ht)$

as "η" $\to -\infty$!

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

IN THE IR THIS REDUCES TO A BEAUTIFUL PICTURE OF CLASSICAL PARAMETRIC RESONANCE

L. KOFMAN

CURVATURE PERTURBATION

$$\Phi \sim \frac{H}{\dot{\phi}} \left\langle \frac{\varphi}{a} \right\rangle$$

QUANTUM MECHANICS DETERMINES THE NORMALIZATION OF $\left\langle \frac{\varphi}{a} \right\rangle$;

STANDARD RESULT: $\left\langle \frac{\varphi}{a} \right\rangle \sim H$

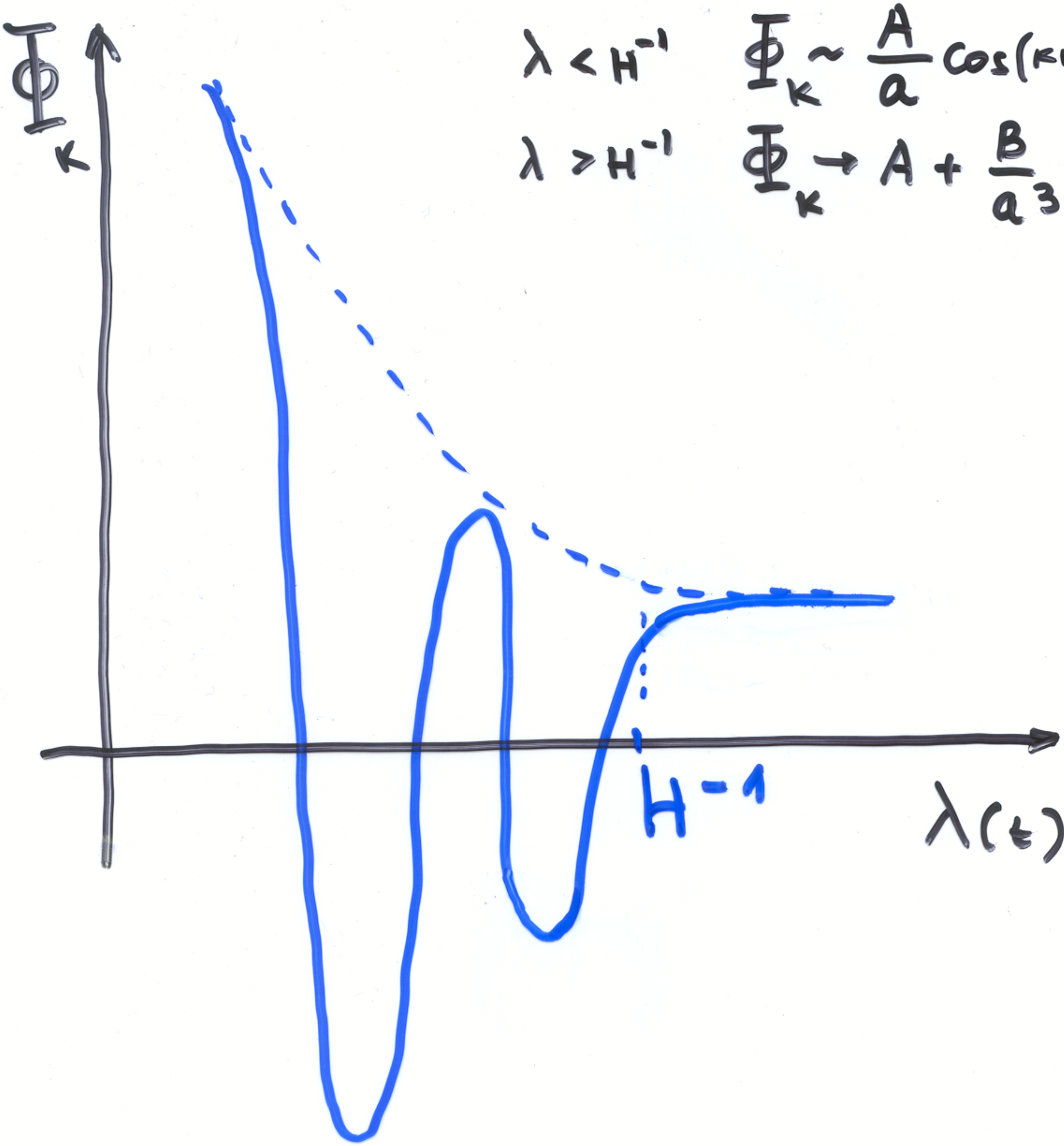
$$\frac{\delta\rho}{\rho} \sim \frac{H^2}{\dot{\phi}}$$

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

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

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

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



TYPICALLY, USING EQS OF MOTION

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

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

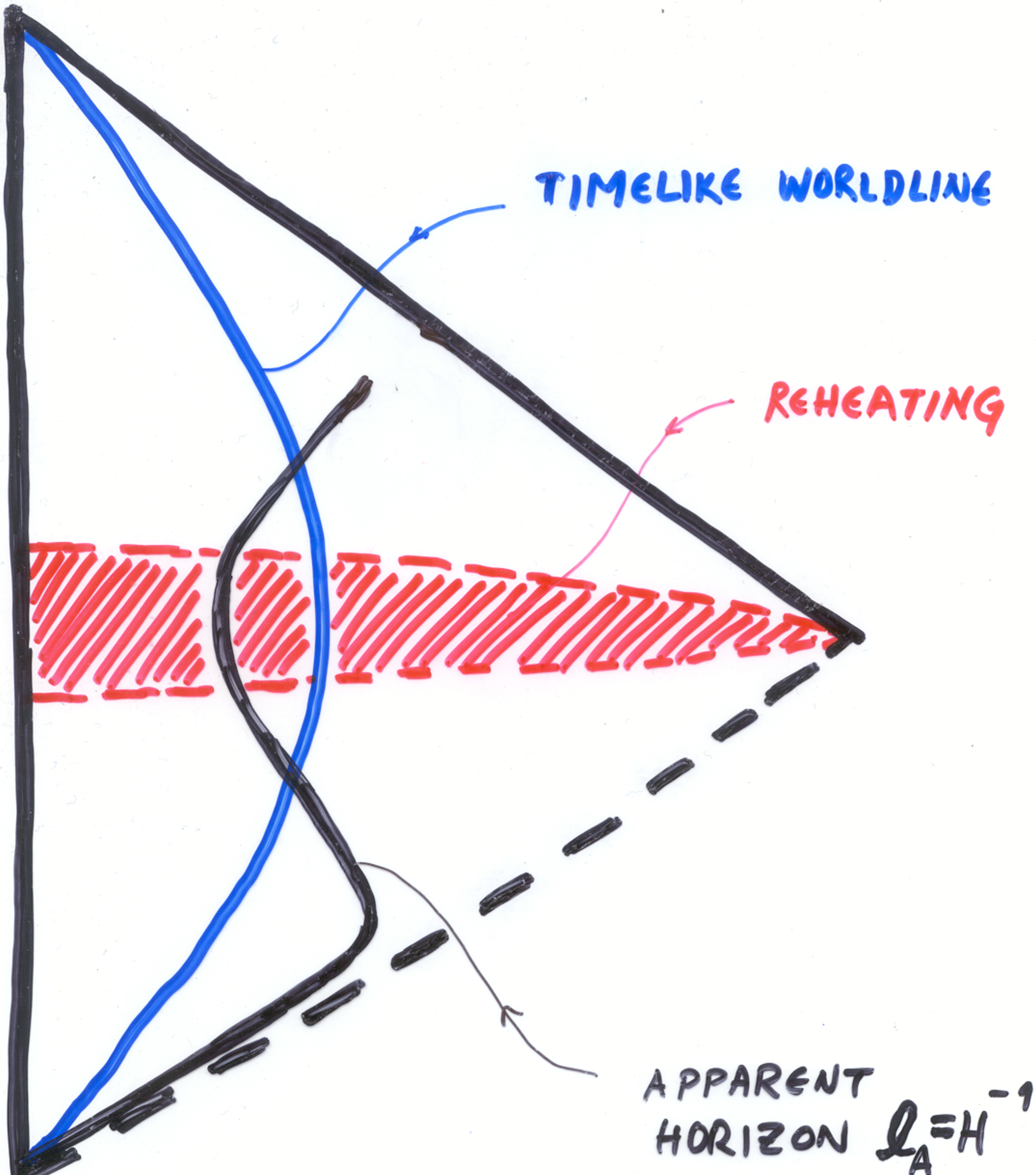
$M = V^{1/4}$: SCALE OF INFLATION

α : LOW INTEGER : 1, 2, ... (MODEL-DEPENDENT)

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

ONE INPUT! SLOW ROLL GUARANTEES SCALE INVARIANE!

KEY PREDICTION ...



KALOPER, KLEBAN, LAWRENCE, SHENKER, 2002

NOTE: $M \sim 10^{-10} M_p - 10^{-5} M_p$

$$M \sim 10^{9}\,\text{GeV} - 10^{14}\,\text{GeV}$$

COULD INFLATIONARY DYNAMICS BE SENSITIVE TO NEW HIGH ENERGY PHYSICS?

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 !

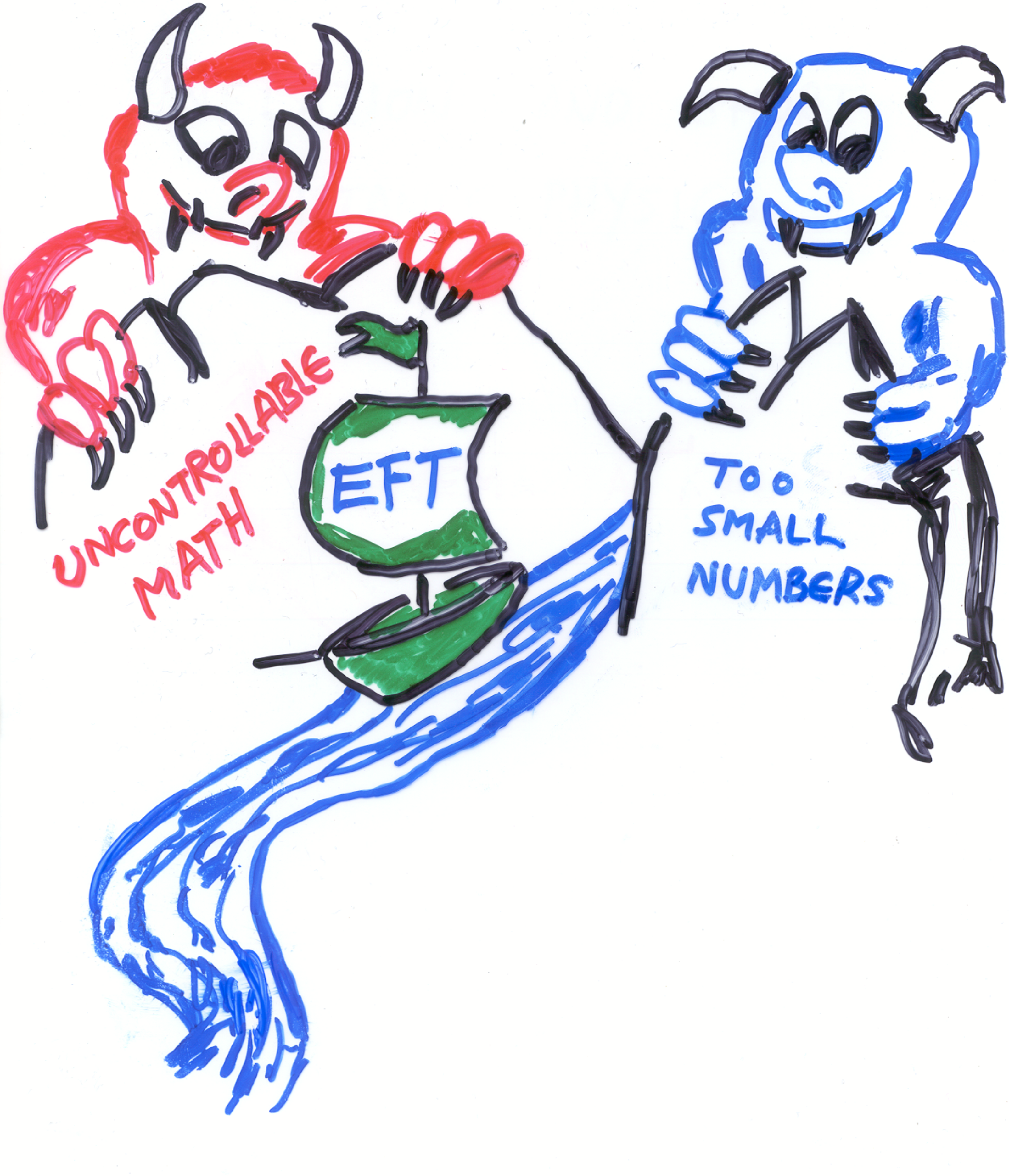
* LARGE X-TRA DIMENSIONS: ALL FORCES BECOME STRONG AT TeV, AND HIERARCHY COMES FROM DILUTION IN X-TRA D

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
HUI & KINNEY
KKLS, KKLSS, KK
DANIELSSON
STAROBINSKY & TKACHOV
BURGESS, HOLMAN, CLINE, LEMIEUX
GIUDICE, KOLB, RIOTTO & TKACHOV
CHUNG, NOTARI, RIOTTO ...


UNCONTROLLABLE MATH
EFT
TOO SMALL NUMBERS

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 !!

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

FREE   INTERACTIONS

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

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

. . .

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

SIMILAR PROCEDURE FOR TENSORS !

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

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

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

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.

KALOPER, KLEBAN, LAWRENCE & SHENKER, 2002
HUI & KINNEY

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

$|\alpha\rangle$

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

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

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

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

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

$\mathrm{Re}\,\alpha < 0$

Chernikov & Tagirov; Geheniau & Schomblond; Schomblond & Spindel; Mottola; Allen; Bousso, Maloney & Strominger

CORRECTIONS TO $\frac{\delta\rho}{\rho} \propto \left(\frac{H}{M} + \cdots\right)$

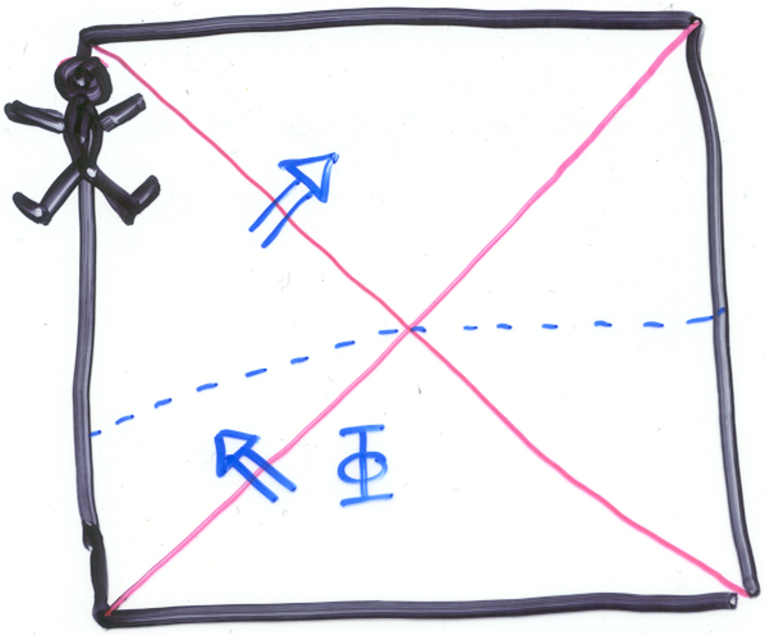
Danielsson; Easther, Greene, Kinney & Shiu

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

KKLSS
BANKS & MANNELLI
EINHORN & LARSEN

POSITIVE MESSAGE: THERMAL VACUUM IS THE RIGHT CHOICE!

THINKING IN A BOX ...

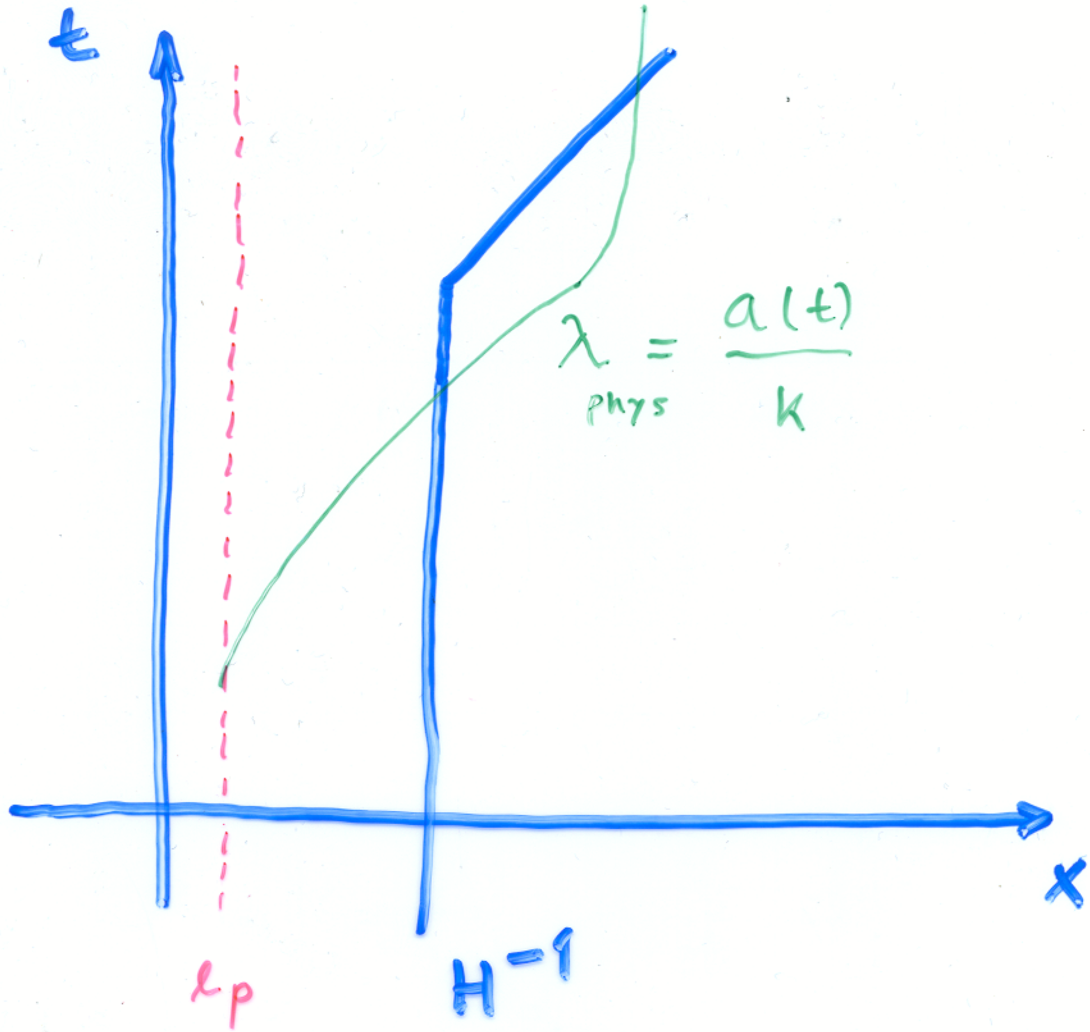


$\Phi = 0$ THERMAL $(\alpha = 0)$ $\Phi \neq 0$ $(\alpha \neq 0)$

$\alpha \neq 0$ LEVEL occupancy $\longrightarrow e^{-\alpha}$ $E > |\alpha| H$

$\therefore$  SEES A SHOWER OF HIGH ENERGY QUANTA $\rightarrow$ AT THE HORIZON THEIR ENERGY $\longrightarrow \infty$ BECAUSE OF BLUESHIFT

WHY WOULD  TRUST EFT OF THE BACKGROUND ??



BUT:

CONSIDER $\Theta = z\,\varphi$ GAUGE INVARIANT CURVATURE PERTURBATION

$\lambda_{phys} > H^{-1}$ $\quad \Theta \to \tilde{A} + \frac{\tilde{B}}{a^3}$ "FREEZE OUT"

$\lambda_{phys} < H^{-1}$ $\quad \Theta \to \frac{A}{a}\cos(k\eta + \delta)$

AT HORIZON CROSSING

$$\lambda_{phys} = \frac{a_0}{k} \sim H^{-1} \quad \rightarrow \quad k \sim a_0 H$$

$$\Theta_0 \sim \frac{A}{a_0} \sim 10^{-5} \quad \text{COBE!}$$

SO: WHEN $\quad \lambda_{phys} \sim \ell_p \sim \frac{a}{k}$

$$\therefore \quad a \sim a_0 H \ell_p \sim a_0 \frac{H}{M_p}$$

THERE: $\quad |\Theta| \sim \frac{A}{a_0 \frac{H}{M_p}} \sim \frac{M_p}{H} \cdot 10^{-5}$

CMB: $\quad H \lesssim 10^{14}\,\text{GeV}$

SO $\quad \frac{M_p}{H} \gtrsim 10^{5}$

THUS: WHEN $\quad \lambda_{phys} \sim \ell_p$,

$$|\Theta| \gtrsim 1$$

BREAKDOWN OF PERTURBATION THEORY!

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 $\varepsilon \lesssim \frac{1}{15}$

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 ϕ TO m_4 †

S. THOMAS

HENCE : $M \sim m_4$

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

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

COMPLETELY UNOBSERVABLE !

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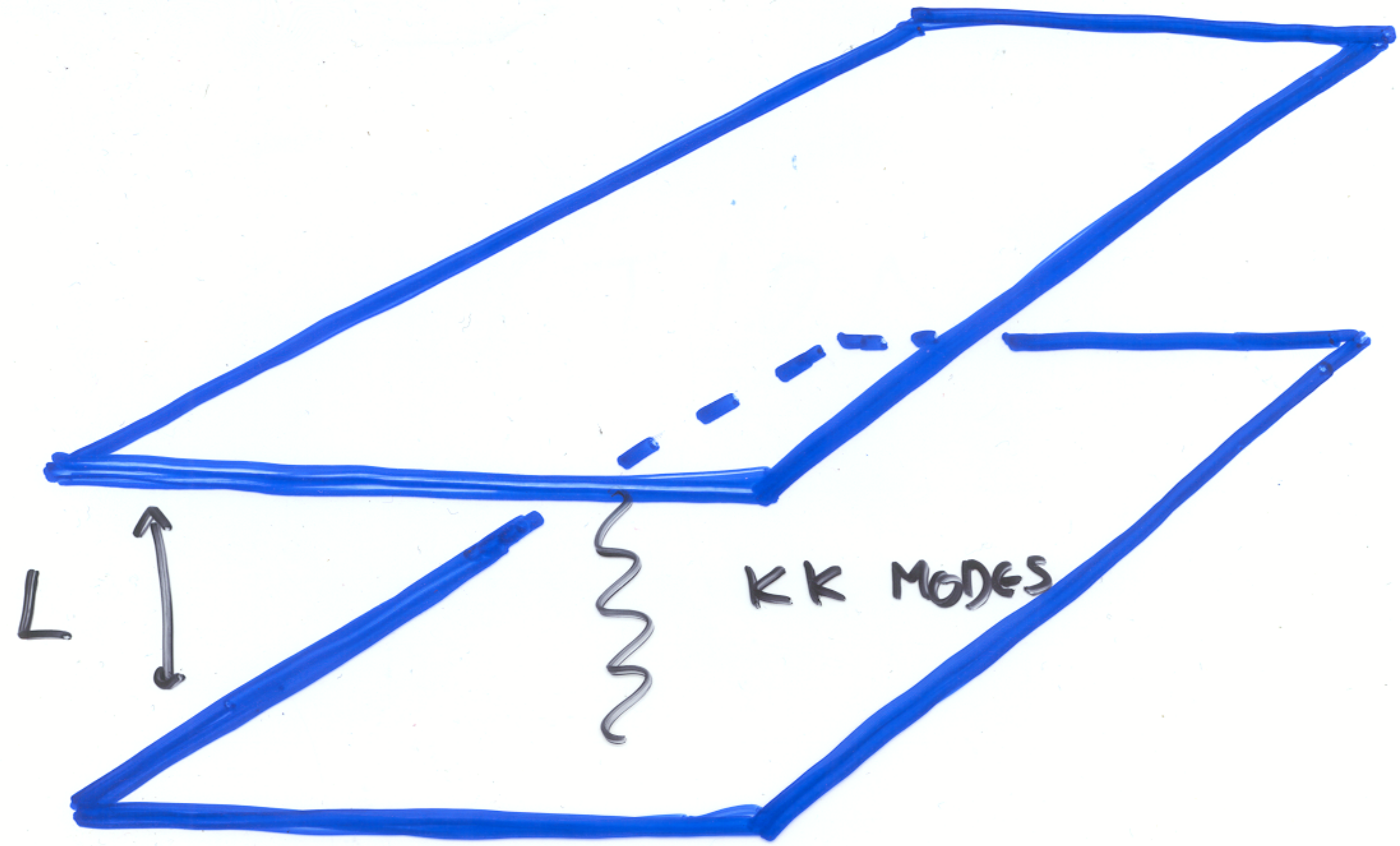
† EXCEPTION: IT IS POSSIBLE TO HAVE COUPLINGS $(\lambda + \phi)\bar{\psi}\psi$ WHICH GIVE $m_\psi \sim 0$ DURING INFLATION – WIMPZILLAS – WILL PRODUCE A BLIP!

LINDE ET AL, CHUNG ET AL

BUT: ∃ MODELS w/ $m_f \ll m_{PL}$!



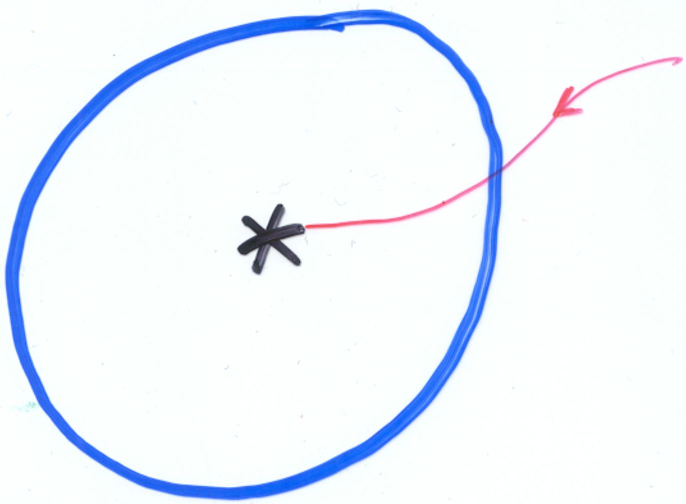
$$\frac{\delta\rho}{\rho}(1) = \sum_{KK} \frac{H^2}{M_{PL}^2}$$

$$= C N \frac{H^2}{M_{PL}^2} = C \frac{H^2}{M_f^2}$$

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



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

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

WARNING: CALCULATIONS IMPRECISE!

MORE PRECISELY:

CONSIDER COMPACTIFICATIONS WITH

- $m_{Pl}^2 = m_{Pl,d}^{d-2} V_{d-4} \simeq (2 \cdot 10^{18} GeV)^2$

- $\alpha_{gauge} = \frac{g^2}{4\pi} \sim \frac{1}{25}$ 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!

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

$$\left(\frac{H}{M}\right)^2 \sim 10^{-4} \implies \text{IF } H \sim 10^{14}\ \text{GeV}$$
$$M \sim 10^{16}\ \text{GeV}$$

GUT SCALE → NEAR HOŘAVA - WITTEN

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

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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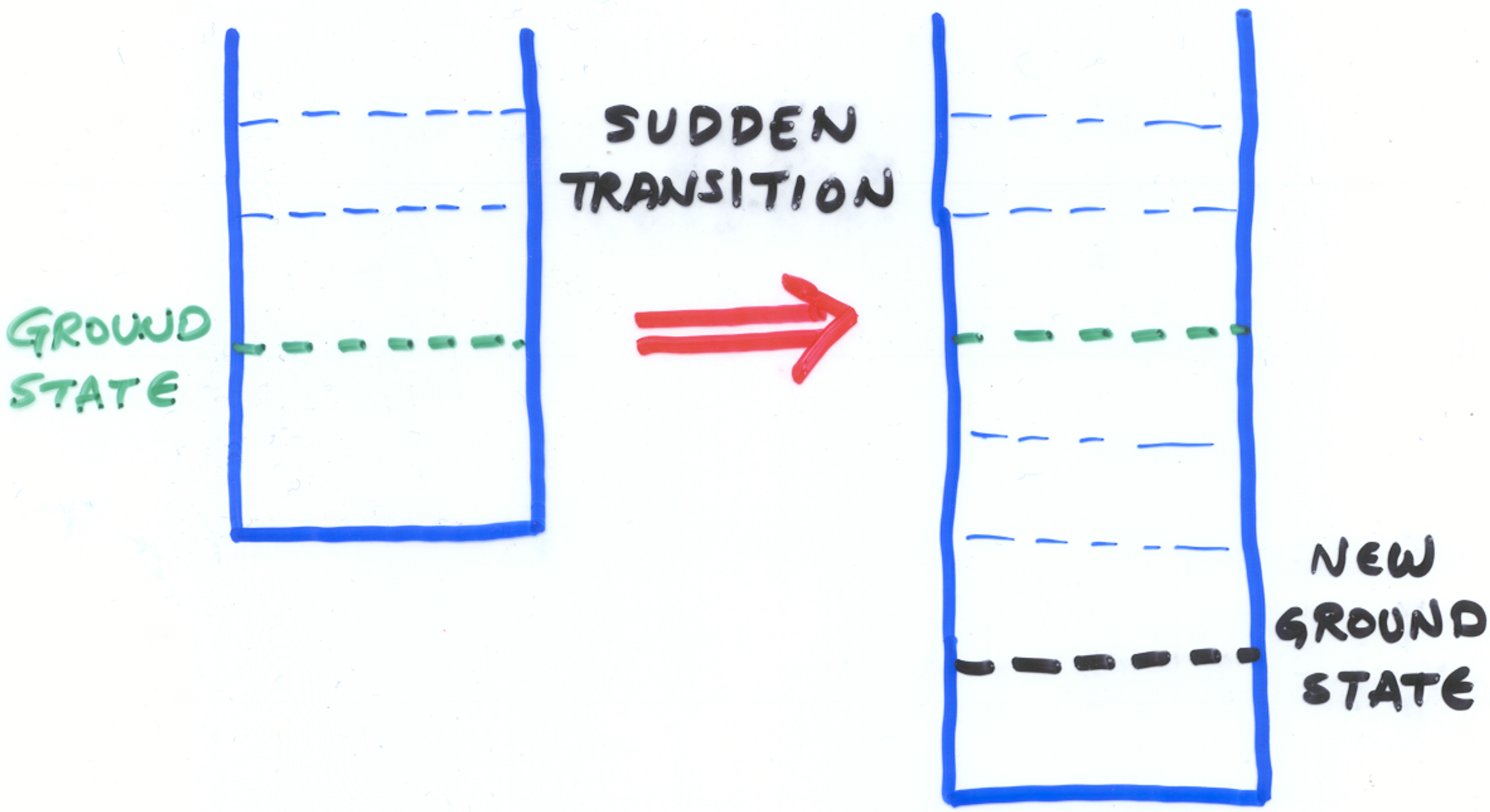
CONSIDER QUANTUM-MECHANICAL ANALOGY:



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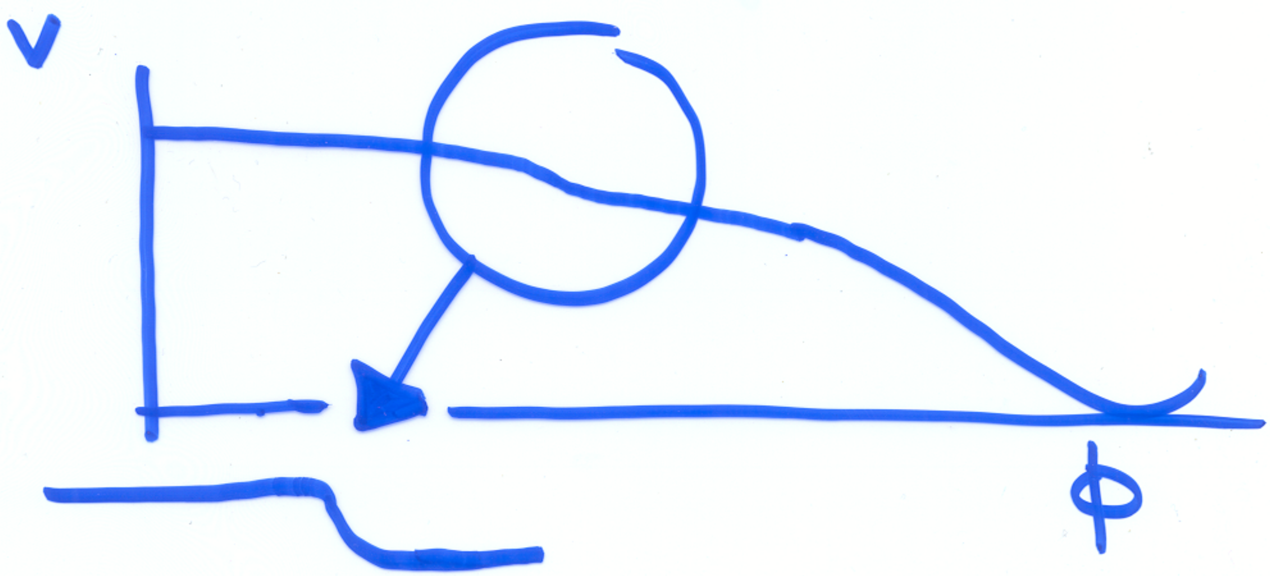
EXAMPLE: CONSIDER A POTENTIAL WHERE THE SLOWROLL PARAMETER $\eta = -\frac{\ddot{\phi}}{H\dot{\phi}}$ JUMPS ~60 EFOLDS BEFORE THE END OF INFLATION, OR WHERE INFLATION WAS SHORT, STARTING FROM SOME NON-VACUUM STATE



USE GAUGE-INVARIANT PERTURBATION THEORY:

MUKHANOV

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

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

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

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

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

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

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

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

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

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

- * VANISHES WHEN $\Delta(\eta-\epsilon)\to 0$
- * VANISHES WHEN $p\to\infty$

NOT AN α-VAC!

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...

SUMMARY

- 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 USUAL 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

The Conclusion

Now, reader, I have told my dream to thee;
See if thou canst interpret it to me,
Or to thyself, or neighbour; but take heed
Of misinterpreting; for that, instead
Of doing good, will but thyself abuse:
By misinterpreting, evil ensues.

Take heed, also, that thou be not extreme,
In playing with the outside of my dream:
Nor let my figure or similitude
Put thee into a laughter or a feud.
Leave this for boys and fools; but as for thee,
Do thou the substance of my matter see.

Put by the curtains, look within my veil,
Turn up my metaphors, and do not fail,
There, if thou seekest them, such things to find,
As will be helpful to an honest mind.

What of my dross thou findest there, be bold
To throw away, but yet preserve the gold;
What if my gold be wrapped up in ore? –
None throws away the apple for the core.
But if thou shalt cast all away as vain,
I know not but 'twill make me dream again.