Title: Cosmological Effective Actions imply new physics in the CMB

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Abstract:

String Theory & Experiment

- Characteristic scale

String Theory = Quantum Gravity

$$M_{pl} \equiv \frac{1}{\sqrt{8\pi G_N}} \sim 10^{19}\,\mathrm{GeV}$$

derived

$$M_{string} \equiv \frac{1}{\sqrt{\alpha'}} \sim 10^{16}\,\mathrm{GeV}$$

- How to test strings?

flux-tube

"elementary"

Duality!

- Strings on AdS_{d+1} $\simeq$ CFT on $\mathcal{M}_d$

$\Downarrow$

- Strings on $X_{d+1}^{\Lambda\neq 0}$ $\simeq$ QFT on Y_d

Natural extreme energies

- Cosmic Rays
- Cosmic Strings
- Black Holes

- Early Universe - Big Bang

& String Theory / Quantum Gravity Inflationary Cosmologies

- Inflation

  - Gravitational redshift in an expanding universe

$$ds^2_{FRW} = -dt^2 + a^2(t)\, dx_3^{\,2} = g_{\mu\nu}^{FRW} dx^\mu dx^\nu$$

$$\Rightarrow \frac{\Delta x(t_f)}{\Delta x(t_i)} \sim \frac{a(t_f)}{a(t_i)}$$

  - Inflation:

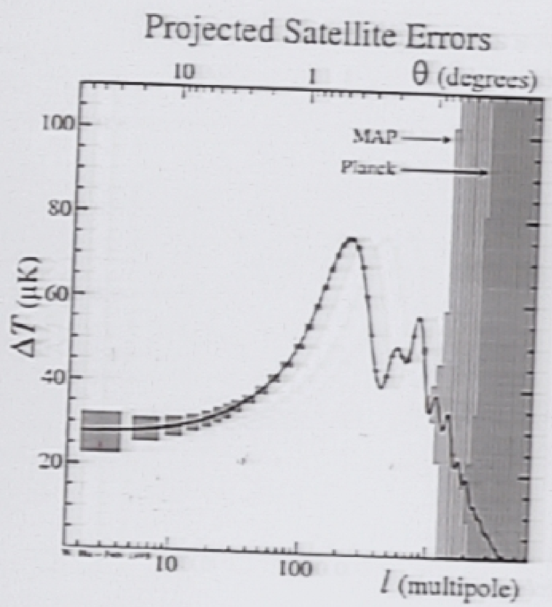
    - Period with $\ddot{a} > 0$
    - Max. distance a particle can travel: proportional to Hubble radius $H \equiv \dot{a}/a$
    - Equivalent definition $\frac{d}{dt}\frac{1}{aH} < 0$
    - If $\frac{a(t_f)}{a(t_i)} \gtrsim e^{60} \simeq 10^{20}$

String Theory / QG & Inflation II

- Inflation and Transplanckian Physics
    - Tremendous redshift

$$\frac{a(t_f)}{a(t_i)} \gtrsim e^{60} \simeq 10^{20}$$

    - Any present scale (GeV) was transplanckian ($> 10^{19}$ GeV) at the onset of inflation
    - Energies occur for which GR is not a valid description $\Rightarrow$ String Theory in $\Lambda > 0$ backgrounds?
- Transplanckian window of opportunity
    - Do present day features reflect transplanckian characteristics?



Error :
STATISTICS ⇒
Limited

Figure 1: Expected errors in the C_ℓ spectrum for the MAP (light blue) and Planck (dark blue) satellites. (Source W. Hu http://background.chicago.edu/.)

- Multipole moments of Temperature fluctuations in the CMB

→ constant variance

- Input : Primordial Gaussian Power spectrum
- Inflation : 1. Gaussianity ~~due to~~ quantum fluctuations

- Measured : fluctuations

String Theory / QG & Inflation III

Scale of New Physics

• GR is an effective field theory for $p \equiv \frac{\vec{k}}{a(t)} \leq M$

• Do present day cosmological features reflect $\boxed{\text{transplanckian}}$ characteristics ?

MISNOMER

• YES : Bound $p(t) = M$ yields an earliest time (different for each $\vec{k}$)

Easther, Greene, Kinney, Shiu, Danielsson, Kempf, Niemeyer ⋮

• Demand that at smallest scale $\left(t_{\vec{k}}^{\text{earliest}}\right)$ "recover" flat space (Minkowski vacuum)

$\boxed{\text{COSMOLOGICAL VACUUM AMBIGUITY}}$

⇒ NEW effects :

Expansion in $\frac{H}{M} \left(\sim \frac{10^{14}}{10^{16}} = 1\% \right)$

CMB density fluctuations

• "NO" : Effects of high energy physics encoded in irrelevant, higher derivative operators

Kaloper, Kleban, Lawrence, Shenker

• Leading term

$$S^{hd} = \frac{1}{M^2} \int \left[D_\mu D_\nu \varphi \, D^\mu D^\nu \varphi + \ldots \right.$$

UNOBSERVABLE

String Theory / QG & Inflation V

- Do present day cosmological features reflect new physics?
  - Is the effect $\frac{H}{M}$ or $\frac{H^2}{M^2}$
    nonstandard vacuum
  - COSMOLOGICAL VACUUM CHOICE AMBIGUITY
    $E \neq$ global ; $E|vac\rangle = E_{MIN}$?
- Are non-standard vacua consistent ?
  - PROBLEM: Non-standard vacua in cosmology are difficult to square with decoupling
  - tend to be non-local at scale H (specific examples)

$\boxed{\text{• Backreaction } \langle vac| T_{\mu\nu} |vac\rangle - T_{\mu\nu}^{Mink, bare} \text{ diverges.}}$

- EXPLICIT EXAMPLES
  - suggest they are consistent

Vilenkin Ford
Burgess Cline Holman

DEBATED ⇒ Kaloper et al, Banks, Larsen, Einhorn, Brandenberger

Initial States in QFT & Decoupling

- Language
  - Vacuum / Initial State $\longrightarrow$ Hamiltonian (operators)
  - Effective Field Theory $\longrightarrow$ Lagrangian (path integral)
    Decoupling and Symmetries
- Translation
  - Ham : vacuum $\Longleftrightarrow$ Lag : boundary conditions
- Boundary conditions (Initial States) in QFT_{eff}
  - Any* b.c. can be incorporated in a boundary action.
  - The location of this boundary action is arbitrary
  - Boundary actions are subject to renormalization
  - Apply to cosmology

Summary of Results

- Boundary actions are subject to <u>RENORMALIZATION</u>
  - Long known
  - Irrelevant boundary operators

homogeneous & isotropic $\Updownarrow$ no intrinsic scale

$$S_{bnd} = \oint \left[-\frac{\beta_{\parallel}}{2M} (\partial_i \varphi)^2 - \frac{\beta_{\perp}}{2M} (\partial_n \varphi)^2 - \frac{\beta_c}{2M} \varphi \partial_n^2 \varphi \right]$$

- Application in Cosmology
  - Parametrize Cosmological Vacuum Ambiguity
  - Any * b.c. is consistent → beyond Hadamard
  - Recover known ones

- Effects on CMB Predictions
  - Power Spectrum

$$P = P^{(0)} \left(1 + \frac{f(\gamma_0)}{H} \left[\frac{k^2}{a_0^2 M} (\beta_{\parallel} - \beta_c) + \frac{g(\gamma_0)}{M} \left(\beta_{\perp} g(\gamma_0) - 3\beta_c H \right) \right] \right)$$

- <u>PHENOMENOLOGICAL</u> Backreaction constraints: MILD

Boundary Conditions from Boundary actions

- Scalar field theory

$$S = \int -\frac{(\partial_\mu \varphi)^2}{2} - \frac{m^2\varphi^2}{2} - \frac{\lambda \varphi^4}{4!}$$

$$+ \oint_{y_0} -\frac{\mu}{2}\varphi\, \partial_n \varphi - \frac{\kappa}{2}\varphi^2 \qquad + \text{nonrenorm.}$$

- Calculus of variations

  - $(\Box - m^2)\varphi = \frac{\lambda \varphi^3}{3!}$
  - $\left(\frac{\mu+2}{2}\right)\partial_n \varphi\Big|_{y=y_0} = -\kappa\varphi\Big|_{y=y_0}$
  - $\mu\, \varphi\, \partial_n \delta\varphi\Big|_{y=y_0} = 0 \quad \Rightarrow \quad \mu = 0\ ??$

- Field redefinition

distributions $\partial_n \delta^\kappa = -\kappa\delta^\kappa$

$$\varphi \to \varphi + \alpha\,\vartheta(y_0 - y)\,\varphi$$

$$\kappa' \equiv \kappa + \kappa\left(\alpha + \frac{\alpha^2}{4}\right) + \delta(0)\left(\frac{\kappa}{2}^2 - \mu\alpha - \frac{\mu\alpha^2}{2}\right)$$

$$\alpha = \frac{2\mu}{2-\mu}$$

MEANING OF "ANY *"

Freedom of Boundary Location

- Solutions to EOM

$$(\Box - \omega^2)\varphi = 0$$

two solutions $\Phi_+ \; ; \; \Phi_- = (\Phi_+)^*$

- Boundary Conditions

$$\partial_n \varphi(y_0) = -k\varphi(y_0)$$

for each frequency ω independently

$$\Rightarrow \Phi_{sol} = \Phi_+ + b_k \, \Phi_-$$

$$b_k = - \frac{k\,\Phi_{+,0} + \partial_n \Phi_{+,0}}{k\,\Phi_{-,0} + \partial_n \Phi_{-,0}}$$

- Freedom of Location y_0

  - Initial Conditions for 2^{nd} order PDE

    $\Rightarrow b_k \Rightarrow$ determines physics

$y_0 \to y_0 + \xi$

$k \to k + \delta k$

$$b_{k+\delta k}(y_0 + \xi) = b_k(y_0)$$

Boundary conditions in Cosmological Lagrangians.

- Preliminaries

  - FRW in conformal gauge

$$ds^2 = a^2(\eta)\left(-d\eta^2 + dx_3^{\,2}\right)$$

  - Restrict attention to de Sitter

$$a = -\frac{1}{H\eta} \qquad \frac{\partial H}{\partial \eta} = 0$$

not too limiting ; results generalize to power-law inflation

  - Solution to the field equation

Hankel function

$$\Phi_+ = (-\vec{k}\eta)^{3/2}\sqrt{\frac{\pi}{4\vec{k}}}\left(\frac{H}{\vec{k}}\right)\bar{H}_\nu(-\vec{k}\eta)$$

$$\nu = \sqrt{\frac{(d-1)^2}{4} - \frac{m^2}{H^2}}$$

  - Subtlety boundary condition

$$\partial_n \varphi\big| = -\kappa\varphi\big| \quad \Rightarrow \quad \frac{1}{a(\eta_0)}\partial_\eta \varphi(\eta_0) = -\kappa\varphi(\eta_0)$$

Harmonic Oscillator & Shortest length b.c.

- Covariantize "Mink" boundary conditions
  - Recall $\kappa_M = -i\omega = -i\sqrt{\vec{k}^2 + m^2}$
  - In FRW $\kappa_{HO} = -i\sqrt{\frac{\vec{k}^2}{a_0^2} + m^2}$

    $h^{ij}\partial_i\partial_j$ with $h_{ij} = g_{\mu\nu}\partial_i x^\mu \partial_j x^\nu$

- Shortest length boundary conditions
  - Impose κ_{HO} at earliest time $\frac{|\vec{k}|}{a} = M$
    $\Rightarrow$ momentum-dependent location $\eta_0 = -\frac{M}{H|\vec{k}|}$ $\quad a = \frac{-1}{H\eta}$
  - Physically relevant parameter

$$b_k^{SL} = \text{constant} = \frac{H}{2M} e^{2i\frac{M}{H}} + \dots$$

  - "<u>Nicer</u>" interpretation (more correct in the formalism)

    b_k^{SL} follows from a momentum-independent boundary location η_0' with a coupling

$$\kappa_{SL} = -\frac{\partial\Phi_+(\eta_0') + b^{SL}\,\partial\Phi_-(\eta_0')}{\Phi_+(\eta_0') + b^{SL}\,\Phi_-(\eta_0')}$$

Bunch - Davies (Adiabatic) boundary conditions

- Bunch - Davies boundary conditions
  - Reproduce G^{Mink} for $\frac{|\vec{k}|}{a} \gg H$
  - In our basis : $b_k^{BD} = 0$

$$\kappa_{BD} = - \frac{\partial_n \Phi_+(\eta_0)}{\Phi_+(\eta_0)}$$

relevant local

  - For very high momenta $\frac{|\vec{k}|}{a} \gg H$

$$\lim_{\frac{|\vec{k}|}{aH} \to \infty} \kappa_{BD}(\vec{k}) = \kappa_{HO}(\vec{k})$$

- Adiabatic, transparent, thermal B.C. ; fixed pts of RG flow
  - Adiabatic : Number operator changes slowest under cosmic evolution ($\neq$ RG flow !)

    Hamiltonian
  - Transparent : Notion of in- and outgoing waves
  - Thermal : Cosmic Horizon

Location & Earliest Time

- Expectation: Cosmological effective GR breaks down at $t = \frac{1}{M_P}$

Effective bulk action

$$\frac{|\vec{k}|}{a(\eta)} \leq M \Rightarrow p(\eta) \leq M$$

Effective bdy action

$$\frac{|\vec{k}|}{a(\eta_0)} \leq M$$

$\overset{?}{\Rightarrow}$ Earliest time EGKS

$$a(\eta_0) = \frac{\vec{k}}{M}$$

Given a (co)-moving momentum $\vec{k}$, the action is only valid for dynamics later than $a(\eta_0)$

[Despite the presence of the shift symmetry !]

New Physics in the CMB

- Leading irrelevant operators

covariant

$$S = \oint \left[- \frac{\beta_{\parallel}}{2M} (\partial_i \varphi)^2 - \frac{\beta_{\perp}}{2M} (\partial_n \varphi)^2 - \frac{\beta_c}{2M} \varphi D_n \partial_n \varphi \right]$$

- Two terms with normal derivatives
  $\Rightarrow$ can be removed by field redefinition

$$k_{eff} = k_0 + \frac{\vec{k}^2}{a_0^2 M} (\beta_{\parallel} - \beta_c) + \frac{k_0^2 \beta_{\perp}}{M} - 3 k_0 \frac{\beta_c H}{M}$$

- Power Spectrum of density fluctuations

$\equiv$ Spontaneous pair creation from vacuum

$$F^{-2\rho} = \oint$$

$$= \mathrm{Im} \langle \varphi(t)\, \varphi(t) \rangle$$

$$= \frac{k^3}{2\pi^2} \left| \Phi_b \right|^2$$

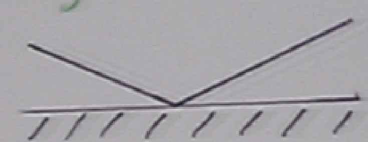
New Physics in the CMB II

pheno-input

- Perturbation theory around Bunch - Davies

$$S = \int - \kappa_{BD} \frac{\varphi^2}{2} - \delta\kappa \frac{\varphi^2}{2}$$

- Feynman diagram

$$\delta P = \mathrm{Im} \Big(\quad$$  $$\Big)$$

- Corrections to Power Spectrum

$$y_0 = \frac{k}{a_0 H}$$

$$P = P_{BD} \left(1 - \frac{\pi}{4H} \left[\frac{H_\nu(y_0)}{i} \left(\kappa_{eff} - \kappa_{BD} \right) + c.c. \right] \right)$$

$$\kappa_{eff} \simeq \kappa_{BD} + \frac{k^2}{a_0^2 M} \beta_1 + \frac{\kappa_{BD}^2 \beta_2}{M} - 3 \kappa_{BD} \beta_3 \frac{H}{M}$$

- Corrections suppressed by single power of M

$$\delta P \sim \frac{H}{M} \sim 0.01 \, P$$

Summary: Backreaction and Initial Conditions

THEORETICAL

- Conventional Wisdom
  - Only Hadamard States consistent

$$\Rightarrow \langle Had | T_{\mu\nu} | Had \rangle - \langle Mink | T_{\mu\nu} | Mink \rangle \equiv \text{FINITE}$$

- Boundary action formulation
  - New boundary couplings

    $\Rightarrow$ can absorb additional infinities

PHENOMENOLOGICAL

- For small deviations $\kappa = \kappa_{BD} + \frac{\beta k^2}{a_0^2 M}$

- $\langle \delta T \rangle^{1ST\ ORDER} = \text{LOCALIZED}$

- $\langle \delta T \rangle^{2ND\ ORDER} \ll \langle T \rangle$

Cosmo-
Calisthenics

cal·is·then·ics noun
rythmic exercises
without apparatus

Deciphering New Physics

- Characteristic signature initial state effects
    - Mode "mixing"

$$\varphi(k) = \Phi_+(k) + b(k)\,\Phi_-(k)$$

- results in oscillations

$$\delta P = P_{BD}\left(b(k) + b^*(k) \right)$$
$$= P_{BD}\,|b(k)|\cos\alpha(k)$$

- Boundary EFT
  Symmetries : Homogeneity & Isotrop

$$b(k) = \left[i a_0^3 \Phi_{+,0}^2 \right]\left(\frac{\beta k^2}{a_0^2 M} \right)$$

non-generic
subset

- Shortest Length (NPH)
  Symmetries : H & I & "Scale" invari

$$b(k) = -i\,\frac{\tilde{\beta}\,H(k)}{2M}\,e^{-2i\frac{M}{H(k)}}$$

Deciphering New Physics

	BEFT	SL-NPH
Power Spectrum	$SP = P_{BD}\left(\mathcal{A}\, k \sin\left(\frac{2\pi k}{\mathcal{C}}\right)\right)$	$SP = P_{BD}\left(A \sin\left(\frac{2\pi}{C} \ln \frac{k}{k_{piv}}\right)\right)$
Amplitude	$\mathcal{A} = \beta / a_0 M$	$A = \tilde{\beta}\, H/M$
Period	$\Delta k = \mathcal{C} = \pi a_0 H$	$\Delta \ln k/k_{piv} = C = \frac{\pi H}{M \varepsilon_H}$
# of Osc	$\mathcal{N} \leq \frac{M}{\pi H}$	$N \simeq \varepsilon \frac{M}{\pi H} \ln \frac{k_{max}}{k_{min}}$
Ratio Scales	$\mathcal{A} \cdot \Delta k = \beta \frac{H}{M}$	$A = \tilde{\beta} \frac{H}{M}$; $\frac{\varepsilon_H C}{\pi} = \frac{H}{M}$

- BEFT bound $k_{max} < a_0 M$

  $\Rightarrow k_{max} < \pi \frac{M}{H} C$

- Qualitative difference $\Leftarrow$ Symmetries

  Linear$_{BEFT}$ vs Log$_{SL\text{-}NPH}$ Period

CMB Density Fluctuations

- Measured (indirectly)

  - Spatial Curvature fluctuations

$$P_R = \frac{P}{M_{pl}^2\, \varepsilon} \quad \text{slow roll parameter} \quad H \sim y^{-\varepsilon}$$

$$\overset{BD}{\Longrightarrow} \frac{H^2}{M_{pl}^2\, \varepsilon}$$

[~ 10^{-10} COBE WMAP]

  - Primordial Gravitational Waves

$$P_T = \frac{P}{M_{pl}^2}$$

$$\overset{BD}{\Longrightarrow} \frac{H^2}{M_{pl}^2}$$

- measures $\frac{H}{M}$ directly! [not yet observed]

Conclusion & Outlook

- Initial states in QFT
  - ⇒ boundary action
  - ⇒ location is arbitrary !!
- Scaling behaviour
  - ⇒ boundary RG-flow & boundary irrelevant operators dressing of initial state
- Application to cosmological vacuum selection
  - ⇒ preferred b.c. are RG-fixed points
  - ⇒ Bunch-Davies ? Hamm-Osc ? Transparent ? Thermal ? Adiabatic ?
  - ⇒ No matter which, generically there are $\frac{H}{M}$ corrections to the CMB power spectrum of fluctuations
- Can we actually decipher these corrections from the data ? YES if $\frac{H}{M} \sim 1\%$
- Connections with holography
  - de Sitter has a dual boundary theory
- Earliest time in Cosmology ?
  - → "guarantee" irrelevant corrections

New CMB Physics and String Theory

- If observed, what can we learn about quantum gravity / string theory
  - Observe effect of leading irrelevant operator in LEEA

$\Downarrow$

Can deduce scale M of new physics

↳ string theory?

Intermediate / GUT physics?

- to distinguish various models need more information
  - GATHER ONE PIECE AT A TIME