Title: Cosmological Effective Actions Imply New Physics in the CMB

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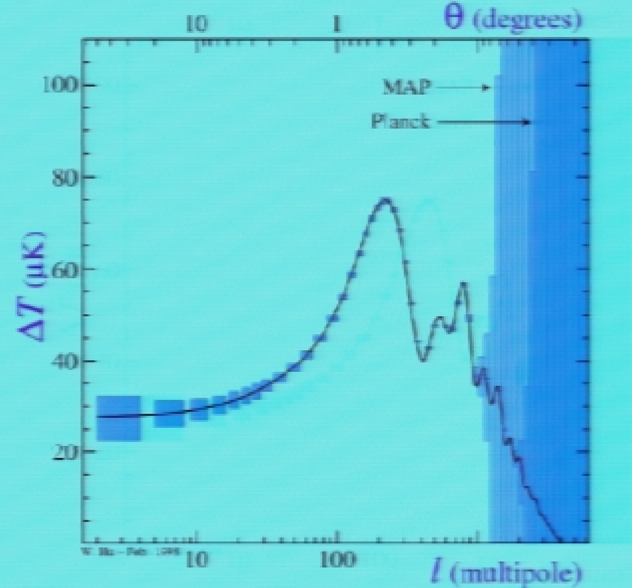
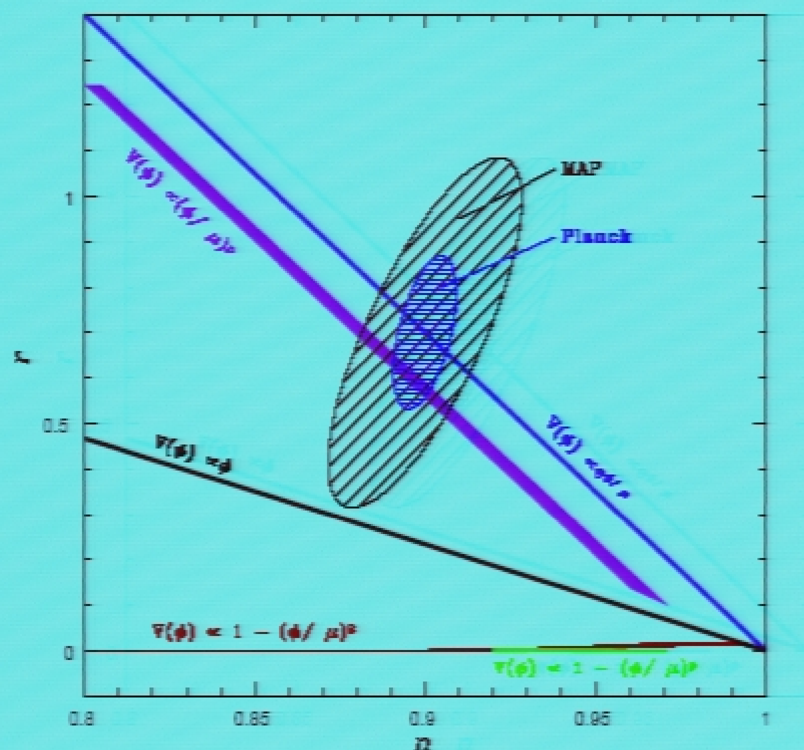
Abstract:

Projected Satellite Errors



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

- Multipole moments of Temperature fluctuations in the CMB
  - Input: Primordial Gaussian power spectrum
  - Inflation:
    - Gaussianity due to quantum fluctuations
    - Measured fluctuations from $e^{50} - e^{40} < t_{end}^{infl}$
- Error: STATISTICS limited (Cosmic Variance)



Error bars in the $r = C_2^{Tensor}/C_2^{Scalar}$, n plane for WMAP and Planck. These ellipses show the expected 2σ errors. The lines on the plot show the predictions for various inflaton potentials. Note that these are error bars based on *synthetic* data: the size of the error is meaningful, but not the location on the plot. The best fit for r and n from real date is likely to be somewhere else on the plot. (Source W. Kinney, astro-ph/9806259, astro-ph/0301448)

- Initial conditions
  - Primordial power spectrum is based on a homogeneous solution to the wave equation

$$P(k) = k^3 \langle \phi\phi \rangle \ , \qquad (D^2 - m^2)\langle \phi^2 \rangle = 0$$

  - 2nd order PDE ⇒ needs initial conditions!
  - standard choice: Bunch-Davies state.

    (only truly justified by observation)

- "Transplanckian" problem
  - Dynamics effectively free (slow roll)
  - Energy content in $P(k)$ blueshifts towards the past.
  - Energies occur for which GR is not a valid description (Long Inflation)

    String theory in $\Lambda > 0$ backgrounds?

  - Transplanckian window of opportunity

    ⇒ Do present features reflect transplanckian characteristics?

MISNOMER → Any new scale.

- GR is an effective field theory for $p \equiv \frac{\vec{k}}{a(t)} \leq M$
- Do present day cosmological features reflect transplanckian characteristics?

- "YES" : Bound $p(t) = M$ yields an earliest time (different for each $\vec{k}$)
  - Demand that at smallest scale $\left(t_{\vec{k}}^{earliest}\right)$ "recover" flat space (Minkowski vacuum)

    COSMOLOGICAL VACUUM AMBIGUITY

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

  [Easther, Greene, Kinney, Shiu; Danielsson; Kempf, Niemeyer; ...]

- "NO" : Effects of high energy physics encoded in irrelevant, higher derivative operators.
  - Leading term:

$$S^{irr.op.} = \frac{1}{M^2}\int [D_\mu D_\nu \phi D^\mu D^\nu \phi + \ldots]$$

  [Kaloper, Kleban, Lawrence, Shenker; ...]

  - Leading effect of order $\frac{k^2}{a^2 M^2} \sim \frac{H^2}{M^2} (\sim 0.01\%)$.
    (standard vacuum)

    ⇑ UNOBSERVABLE

Effective Action

Relevant Operators

- Universal
- mildly dependent on $E > M_{new}$ physics

Irrelevant Operators

- encode $E > M_{new}$ physics

Potential Irr. Op.

- slow roll inflation: ϵ, η phenomenologically determined

Kinetic Irr. Op.

- Clear consequence: breakdown of scalar tensor consistency relation (not unique reason)

(non-trivial BG [Shiu, Wasserman,...])

Dynamics

[KKLS,...]

$$S \sim \frac{1}{M^2}\int D_\mu D_\nu \phi D^\mu D^\nu \phi$$

$p \sim H \Rightarrow$ Effect $\dfrac{H^2}{M^2} \sim 0.01\%$

(unobservable)

Initial Conditions

[EGKS,D,KN,...]

- Set at time $p(t) = M$.
- Effect $\dfrac{H}{M} \sim 1\%$.

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Initial Conditions

[EGKS,D,KN,...]

- Set at time $p(t) = M$.
- Effect $\frac{H}{M} \sim 1\%$.

- Do present day cosmological features reflect new physics ?
  - Is the effect $\frac{H}{M}$ or $\frac{H^2}{M^2}$?
  - COSMOLOGICAL VACUUM AMBIGUITY

$$E \neq \text{global} \; ; \qquad E|\text{vac}\rangle = E_{min} \; ?$$

- Are non-standard vacua consistent?
  - PROBLEM: Non-standard vacua in cosmology are difficult to square with decoupling.
    - tend to be non-local with scale H
    - (specific examples)

    Backreaction

    $$\langle vac|T_{\mu\nu}|vac\rangle - T_{\mu\nu}^{Mink,bare}$$

    diverges.
  - EXPLICIT EXAMPLES:
    - suggest they are consistent

    [Vilenkin Ford,
    Burgess, Cline, Holman;
    Kaloper, Kaplinghat,
    ...]

→ **HOTLY DEBATED** → [KKLS; Banks; Larsen-Einhorn; Brandenberger, EGKS, ...]

- Language
  - Vacuum/Initial state ⟶ Hamiltonian
  - Effective field theory. ⟶ Lagrangian
    Decoupling and symmetries.
- Translation
  - Ham: vacuum ⇔ 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 group flow.
  - Apply to Cosmology
    - Recover known b.c.
    - Computation of corr. to CMB spectra.

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- ANY* b.c. can be incorporated in a boundary action
  - QM transition amplitude ⟶ path integral.
- The LOCATION of this boundary action is arbitrary.
  - "Symmetry" location ⇔ boundary couplings.
- Boundary actions are subject to renormalization group flow.
  - Long known
  - Irrelevant boundary operators

homogeneous & isotropic = no intrinsic scale

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

- Application in Cosmology
  - Parameterize Cosmological Vacuum Ambiguity
  - Any* b.c. is consistent ⟶ go beyond Hadamard.
  - Recover known b.c.
- Effects on CMB predictions
  - Power spectrum

$$P = P^{(0)}\left(1 + \frac{f(y_0)}{H}\left[\frac{k^2}{a_0^2 M}(\beta_{\|} - \beta_c) + \frac{g(y_0)}{M}(\beta_{\perp} g(y_0) - 3\beta_c H)\right]\right)$$

  - PHENOMENOLOGICAL backreaction constraints: MILD.

- **Scalar field theory**

$$S = \int -\frac{1}{2}(\partial_\mu\phi)^2 - \frac{1}{2}m^2\phi^2 - \frac{\lambda}{4!}\phi^4$$

$$+ \oint_{y_0} -\frac{\mu}{2}\phi\partial_n\phi - \frac{\kappa}{2}\phi^2 \quad + \ \mathrm{non-renorm.}$$

- **Calculus of variations**
  - $(\partial^2 - m^2)\phi = \frac{\lambda}{3!}\phi^3$
  - $\left(\frac{\mu+2}{2}\right)\partial_n\phi\Big|_{y=y_0} = -\kappa\phi\big|_{y=y_0}$
  - $\mu\phi\partial_n\delta\phi\big|_{y=y_0} = 0$

- **Field redefinition**

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

$$\phi \longrightarrow \phi + \alpha\theta(y-y_0)\phi$$

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

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

- **Boundary conditions** (all relevant possibilities: Z_2 scalar QFT)

$$\partial_n\phi(y_0) = -\kappa'\phi(y_0)$$

- MEANING OF "ANY*"

- **Solutions to EOM**

$$(\partial^2 - \omega^2)\phi = 0$$

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

- **Boundary conditions**

$$\partial_n \phi(y_0) = -\kappa \phi(y_0)$$

$$\Rightarrow \quad \Phi_{sol} = \Phi_+ + b_\kappa \Phi_-$$

$$b_\kappa = -\frac{\kappa \Phi_{+,0} + \partial_n \Phi_{+,0}}{\kappa \Phi_{-,0} + \partial_n \Phi_{-,0}} \quad \longleftarrow$$

for each frequency ω independently

- **Freedom of location y_0.**
  - Initial conditions for 2nd order PDE
  $\Rightarrow b_\kappa \Rightarrow$ determines physics.

$$y_0 \to y_0 + \xi \qquad \kappa \to \kappa + \delta\kappa \qquad b_{\kappa+\delta\kappa}(y_0 + \xi) = b_\kappa(y_0)$$

domain

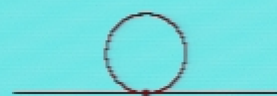
$\Rightarrow$ **ALL PHYSICS IS INVARIANT***

- **RG: Anything that is not forbidden, WILL happen.**
  - in a bounded space, expect to generate

$$S^{counter}_{bdy} = \oint -\frac{\mu}{2}\phi\partial_n\phi - \frac{\kappa}{2}\phi^2$$

[Symanzik; Deutsch, Candelas; Barton; . . . Many recent articles]

- **Example** $\kappa = 0$ (Neumann) **in** $\lambda\phi^4$



$$= \lambda \int^{\Lambda} d^4k \frac{1}{k^2 + m^2} + \frac{e^{ik_y(2y_0 - y)}}{\bar{k}^2 + k_y^2 + m^2}$$

$$= \text{bulk} + \lambda\Lambda\delta(y - y_0)$$

$\Rightarrow$ boundary counterterm

(Lorentz invariance broken)

- **Fixed points**
  - β-function $\qquad \beta^{1-loop}_{\kappa} = \lambda\Lambda$

$\Rightarrow$ IR: Dirichlet.

- **Interpretation**
  - Dressing of initial state

$\Rightarrow$ Vacua $\stackrel{?}{=}$ fixed pt.

- Effective field theory
  - Integrating out high energy d.o.f.
    $\Rightarrow$ RG-flow + irrelevant operators
    (higher derivative corrections).

    $\Rightarrow$ Effective bdy Lagrangian

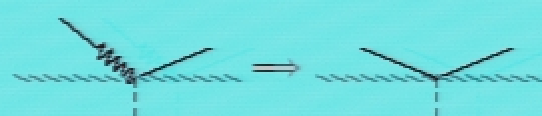
- Z_2 Scalar field theory

$$S_{bnd} = \oint \left[-\frac{\beta_4}{2M}\phi^4 - \frac{\beta_\parallel}{2M}(\partial_i\phi)^2 - \frac{\beta_\perp}{2M}(\partial_n\phi)^2 - \frac{\beta_c}{2M}\phi\partial_n^2\phi \right]$$

- Example:
  - Two scalars $\chi,\ \phi$ with $M_\chi^2 \gg m_\phi^2$.

$$S^{int} = -\int g\chi\phi - \oint \gamma\chi\phi$$

  - Effective interaction $|k| \ll M_\chi$.



$$\oint \gamma g\phi \frac{1}{\partial^2 - M_\chi^2}\phi \quad \Longrightarrow \quad \frac{1}{M_\chi^2}\oint \gamma g\phi \frac{k^2}{M_{chi}^2}\phi$$

- Flat space: VACUUM is unique
  - Recall $\kappa = -i\omega$ cancels the physical pole. Hence

$$G^{\kappa=-i\omega}(x,x') = G^{Mink}(x,x')$$

Thus all divergences are <u>bulk</u>

$\kappa = -i\omega$ (restores Lorentz)

- Irrelevant corrections to Mink vacuum are absent!
  - Example:

$$S^{int} = -\int g\chi\phi - \oint \gamma\chi\phi$$

$$\Rightarrow \partial_n \chi_0 = -\kappa\chi_0 - \gamma\phi$$

(γ breaks Lorentz)

Lorentz symmetry should guarantee that high energy corrections to low-energy Minkowski boundary conditions are absent

- Cosmology preview:
  - EFT Rule: everything that is allowed by the symmetries ought to be considered.

- **Preliminaries**
  - FRW in conformal gauge

$$ds^2 = a^2(\eta)(-d\eta^2 + dx_3^2)$$

  - Restrict attention to de Sitter

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

    - (easily generalized to power-law and slow-roll inflation)
  - Solution to field equation

Hankel function

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

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

  - Subtlety: boundary condition

$$\partial_n\phi| = -\kappa\phi| \;\Rightarrow\; \frac{1}{a(\eta_0)}\partial_\eta\phi(\eta_0) = -\kappa\phi(\eta_0)$$

- Covariantize Minkowski (harm. osc.) 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 $\frac{|\vec{k}|}{a} = M$ } $a = \frac{-1}{H\eta}$

    $\Rightarrow$ momentum-dependent location $\eta_0 = -\frac{M}{H|\vec{k}|}$
  - Physically relevant parameter

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

  - Nicer interpretation (in boundary EFT formalism)

    $b_{\kappa_{SL}}$ follows from a momentum-*independent* boundary location η' with boundary coupling

$$\kappa_{SL} = -\frac{\partial_n \Phi_+(\eta'_0) + b_{SL}\partial_n \Phi_-(\eta'_0)}{\Phi_+(\eta'_0) + b_{SL}\Phi_-(\eta'_0)}$$

- Bunch-Davies boundary conditions
  - Reproduce $G^{Mink}(x,x')$ for $\frac{|\vec{k}|}{a} \gg H$.
  - In our basis: $b_{\kappa_{BD}} = 0$.

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

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

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

- Adiabatic, transparent, thermal b.c.; fixed point of bdy RG-flow.
  - Adiabatic: Number operator changes slowest under cosmic evolution
  - Transparent: Notion of in- and out-going waves
  - Thermal: cosmic horizon
  - <u>Fixed points of boundary RG-flow!</u>

- Leading irrelevant operators

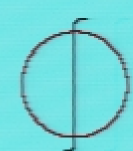
$$S_{bnd} = \oint \left[-\frac{\beta_\parallel}{2M}(\partial_i\phi)^2 - \frac{\beta_\perp}{2M}(\partial_n\phi)^2 - \frac{\beta_c}{2M}\phi D_n \partial_n \phi \right]$$

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

$$\kappa_{eff} = \kappa_0 + \frac{\vec{k}^2}{a_0^2 M}(\beta_\parallel - \beta_c) + \frac{\kappa_0^2}{M}\beta_\perp - \frac{3\kappa_0 H}{M}\beta_c$$

- Power spectrum of density fluctuations
  $\equiv$ Spontaneous pair creation from the vacuum

$$P^{0\to 2\phi} =$$



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

$$= \frac{k^3}{2\pi^2}\frac{|\Phi_+ + b_{\kappa_{eff}}\Phi_-|^2}{1-|b_{\kappa_{eff}}|^2}$$

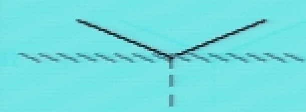
- Perturbation theory around Bunch-Davies

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

phenomenological input

  - Feynman diagrams

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



- Corrections to Power spectrum $\left(y_0 = \frac{k}{a_0 H}\right)$

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

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

  - Corrections suppressed by single power of the new scale M.

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

- Boundary conditions parameterize vacuum ambiguity
  - Harmonic oscillator b.c.

$$\kappa_{HO} = -i\sqrt{\frac{\kappa^2}{a_0^2} + m^2}$$

  - Shortest length b.c.

$$b_{SL} = \text{constant} \sim \frac{H}{2M}$$

  - Bunch-Davies b.c.

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

  - Adiabatic, thermal, transparent; fixed pts. ...

- Corrections to CMB spectra

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

$$\simeq P_{BD}\left(1 + \frac{\beta k}{a_0 M}\sin(2\frac{k}{a_0 H})\right)$$

CORRECTIONS OF ORDER $H/M \sim 1\%$
FROM UNKNOWN UV PHYSICS

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- Conventional wisdom:
  - In a gravitational background, zero-point energy has to be renormalized away:

$$\langle T_{\mu\nu}^{ren}\rangle = \langle T_{\mu\nu}^{bare}\rangle - T_{\mu\nu}^{counter}$$

  - In flat space $|\vec{k}| \gg H)$, we know the counterterm:

$$T_{\mu\nu}^{counter} = T_{\mu\nu}^{Mink}$$

$\Rightarrow$ Only those vacua for which

$$\langle T_{\mu\nu}^{bare}\rangle - T_{\mu\nu}^{Mink} = \boxed{\text{finite}}$$

are consistent.

Hadamard condition

- QFT with Initial states
  - New divergences, but all are located on the boundary.

  $\Rightarrow$ dress the initial state.
  - For $\vec{k}/a \gg H$,

$$\Phi_{\pm,dS} \longrightarrow \Phi_{\pm,Mink}$$

then

$$\lim_{k/aH\to\infty} b_\kappa = -\frac{a_0\kappa + i\vec{k} + a_0H}{a_0\kappa - i\vec{k} + a_0H} e^{2i\vec{k}\eta_0}$$

$\Rightarrow$ should subtract Mink divergences with κ the same.

- No backreaction problems for κ_{BD} (Bunch-Davies) [...; Birrell, Davies; ...]
  - Hadamard ⟶ by definition
- Ought to be no problem for $\kappa_{BD} + \Delta\kappa_{relevant}$
  - New divergences viz. κ_{BD}
  - New boundary couplings κ can absord divergences
  - Finite ambiguity fixed by ren. prescription

Observation!

- Here we wish to know $\kappa_{BD} + \Delta\kappa_{irrelevant}$.

$$\Delta\kappa_{irr} = \frac{\beta k^2}{a_0^2 M}$$

  - irrelevant ⟶ non-renormalizable!
  - not subject to ambiguities

⇒ PHENOMENOLOGICAL CONSTRAINTS

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[. . . ; Birrell, Davies; . . .]

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  - irrelevant $\longrightarrow$ non-renormalizable!
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$\Rightarrow$ PHENOMENOLOGICAL CONSTRAINTS

- 1-loop stress tensor

$$\Delta T_{bulk} \sim \int dk\, k\, \delta P(k)$$

$$\Delta T_{boundary} \sim \text{UNMEASURABLE}$$

- First-order correction (in $\delta\kappa$)

$$\Delta T_{bulk} \sim \frac{\beta}{M a_0 a^4} \int dk k^4 \sin(2k(\eta - \eta_0)) e^{-\frac{k^2}{2M^2}}$$

$$\sim M^4 e^{-2M^2(\eta-\eta_0)^2}$$

- FINITE: as $M \to \infty$, except when $\eta = \eta_0$
- LOCALIZED: on $\eta = \eta_0$ within the cut-off scale M.
- MIXES: with unobservable $\Delta T_{boundary}$.

- 1-loop second-order (in $\delta\kappa$) backreaction

$$\Delta T^{(2)}_{bulk} = \frac{1}{3(4\pi)^2}\beta^2 M^4 e^{-4H(\eta-\eta_0)} + \ldots$$

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COSMO - CALISTHENICS

cal•is•then•ics : *noun*
rythmic exercises without apparatus

- Characteristic signature initial state effects
  - Mode "mixing"

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  - results in oscillations

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- Boundary EFT
  - Symmetries: homogeneity and isotropy

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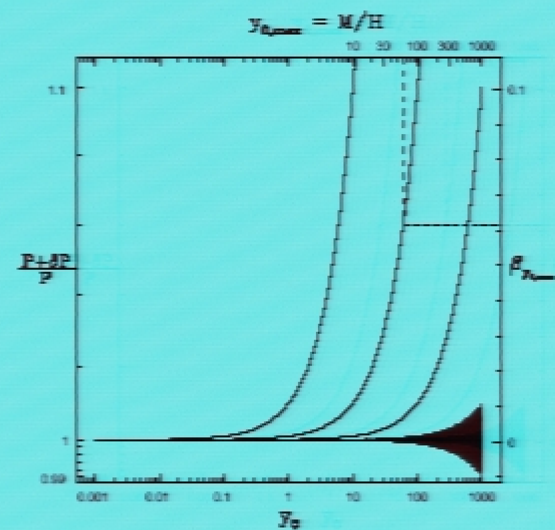
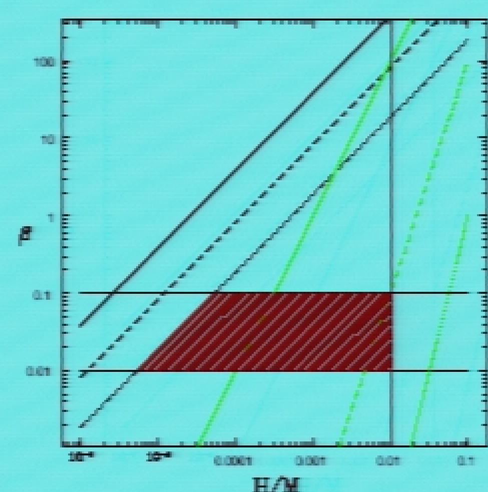
$$b(k) = -i\frac{\tilde{\beta} H(k)}{2M} e^{-2i\frac{M}{H(k)}}$$

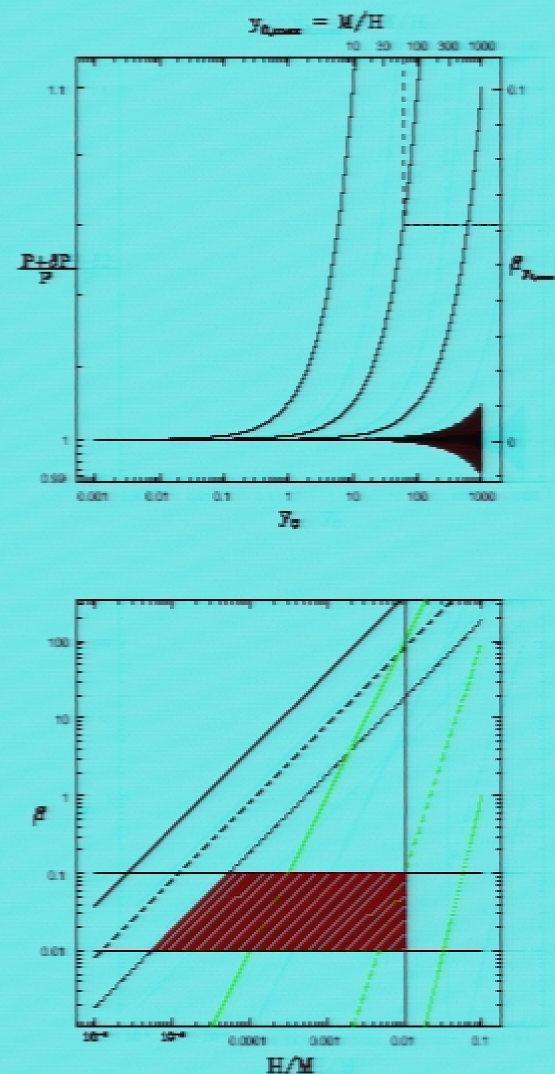
Signature of BEFT corrections





A. Generic change in the power spectrum from initial state effects as deduced with boundary EFT.

B. A refined estimate of the sensitivity of the CMB to new physics.



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# of Osc.	$\mathcal{N} \leq \frac{M}{\pi H}$	$N \simeq \epsilon_H \frac{M}{\pi H}\ln\frac{k_{max}}{k_{min}}$
Ratio of scales	$\mathcal{A}\cdot\Delta k = \frac{\beta}{H}M$	$A = \tilde{\beta}\frac{H}{M}$, $\frac{\epsilon_H C}{\pi} = \frac{H}{M}$

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[Bergstrom, Danielsson; Elgaroy, Hannestad; Okamoto, Lim; Martin, Ringeval; Sriramkuma Padmanabd Eas- ther, Kinney, Peiris]

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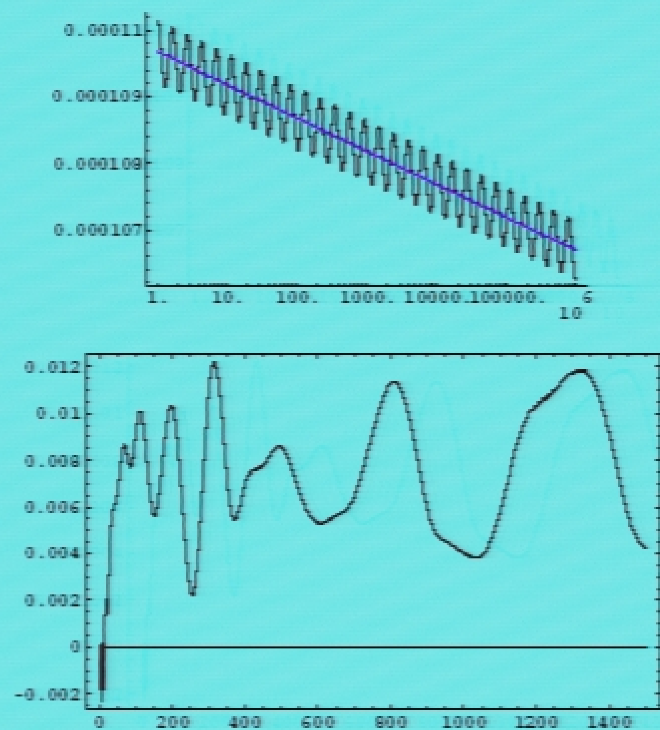

A. The modified perturbation spectrum $P(\vec{k})$ (for a power-law inflationary model) as a function of the momentum for a nearly "scale invariant" change in the initial conditions compared to Bunch-Davies.

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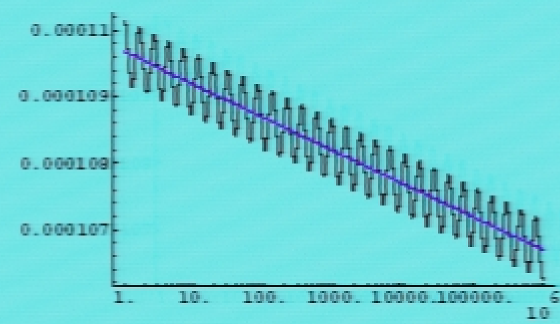

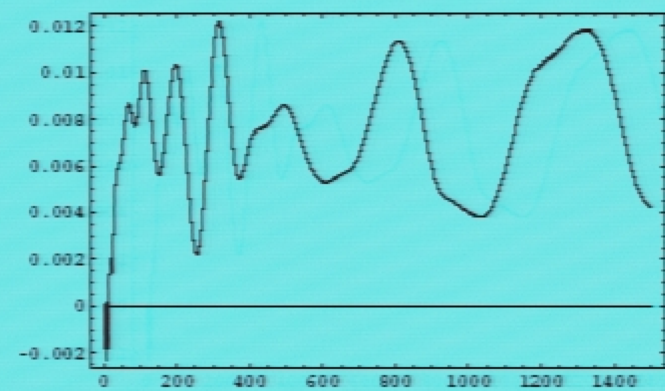

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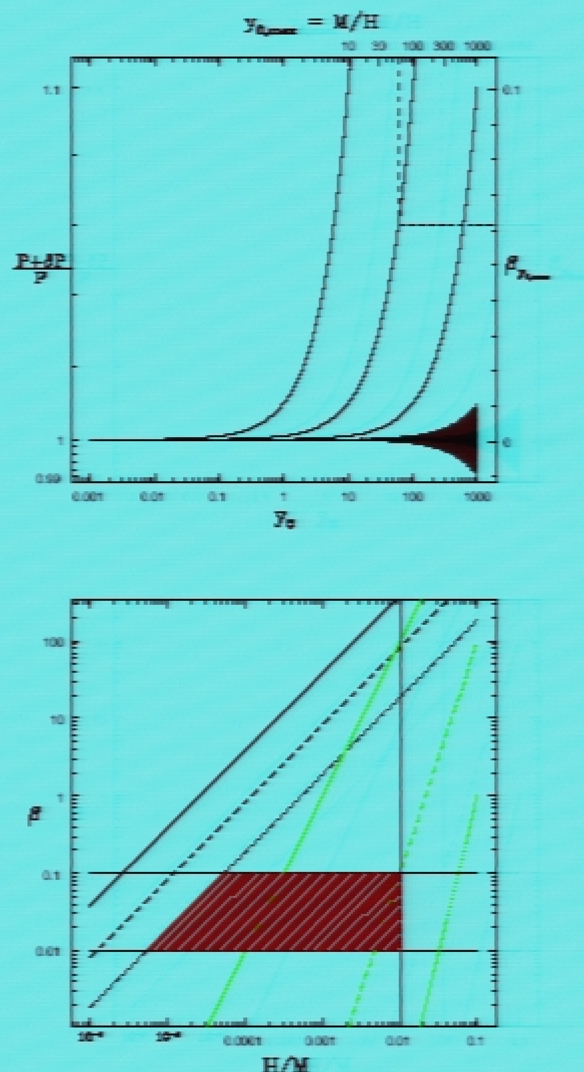
- **Initial states on Effective Field Theory**
  - Theoretically controlled boundary action formalism: location of boundary arbitrary.
  - Scaling behaviour: boundary RG-flow
    - dressing of initial state;
    - preferred b.c. are RG-fixed points.
- **Application to Cosmology**
  - Parametrize the cosmological vacuum ambiguity
    - Preference?
      Bunch-Davies, transparent, adiabatic, thermal, etc.
    - Generically receive H/M corrections!
  - Parameters encoding initial data are phenomenologically constrained.
  - Connections with holography?
    de Sitter is conjectured to have a dual boundary theory
  - Earliest time in cosmology
    $\Rightarrow$ "guarantee" irrelevant boundary corrections.
  - Are leading bdy. irr. op. contributions decipherable in CMB data?

If $H/M \simeq 1\%$ $\Leftrightarrow$ primordial gravity waves observed, then initial state effects in the CMB due to UV physics are (potentially) observable



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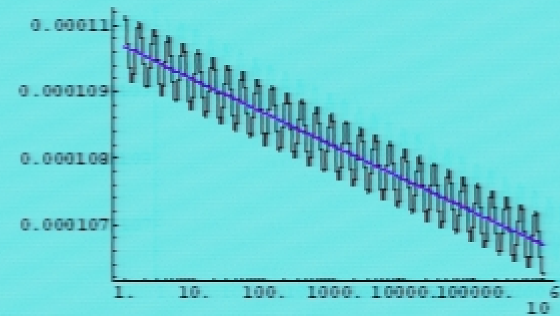

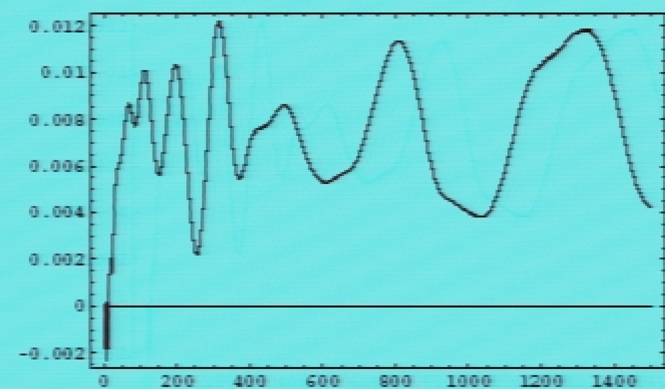

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- Conventional wisdom:
  - In a gravitational background, zero-point energy has to be renormalized away:

$$\langle T_{\mu\nu}^{ren}\rangle = \langle T_{\mu\nu}^{bare}\rangle - T_{\mu\nu}^{counter}$$

  - In flat space $(|\vec{k}| \gg H)$, we know the counterterm:

$$T_{\mu\nu}^{counter} = T_{\mu\nu}^{Mink}$$

$\Rightarrow$ Only those vacua for which

$$\langle T_{\mu\nu}^{bare}\rangle - T_{\mu\nu}^{Mink} = \boxed{\text{finite}}$$

are consistent.

Hadamard condition

- QFT with Initial states
  - New divergences, but all are located on the boundary.

    $\Rightarrow$ dress the initial state.
  - For $\vec{k}/a \gg H$,

$$\Phi_{\pm,dS} \longrightarrow \Phi_{\pm,Mink}$$

then

$$\lim_{k/aH\to\infty} b_\kappa = -\frac{a_0\kappa + i\vec{k} + a_0 H}{a_0\kappa - i\vec{k} + a_0 H} e^{2ik\eta_0}$$

$\Rightarrow$ should subtract Mink divergences with κ the same.

- Leading irrelevant operators

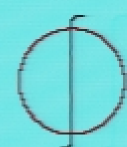
$$S_{bnd} = \oint \left[-\frac{\beta_\parallel}{2M}(\partial_i\phi)^2 - \frac{\beta_\perp}{2M}(\partial_n\phi)^2 - \frac{\beta_c}{2M}\phi D_n \partial_n \phi \right]$$

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

$$\kappa_{eff} = \kappa_0 + \frac{\vec{k}^2}{a_0^2 M}(\beta_\parallel - \beta_c) + \frac{\kappa_0^2}{M}\beta_\perp - \frac{3\kappa_0 H}{M}\beta_c$$

- Power spectrum of density fluctuations
  $\equiv$ Spontaneous pair creation from the vacuum

$P^{0\to 2\phi}$ =



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

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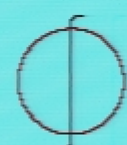

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