Title: Effective actions for gravity

Date: Sep 07, 2006 09:00 AM

URL: http://pirsa.org/06090033

Abstract:

EFFECTIVE ACTIONS FOR GRAVITY

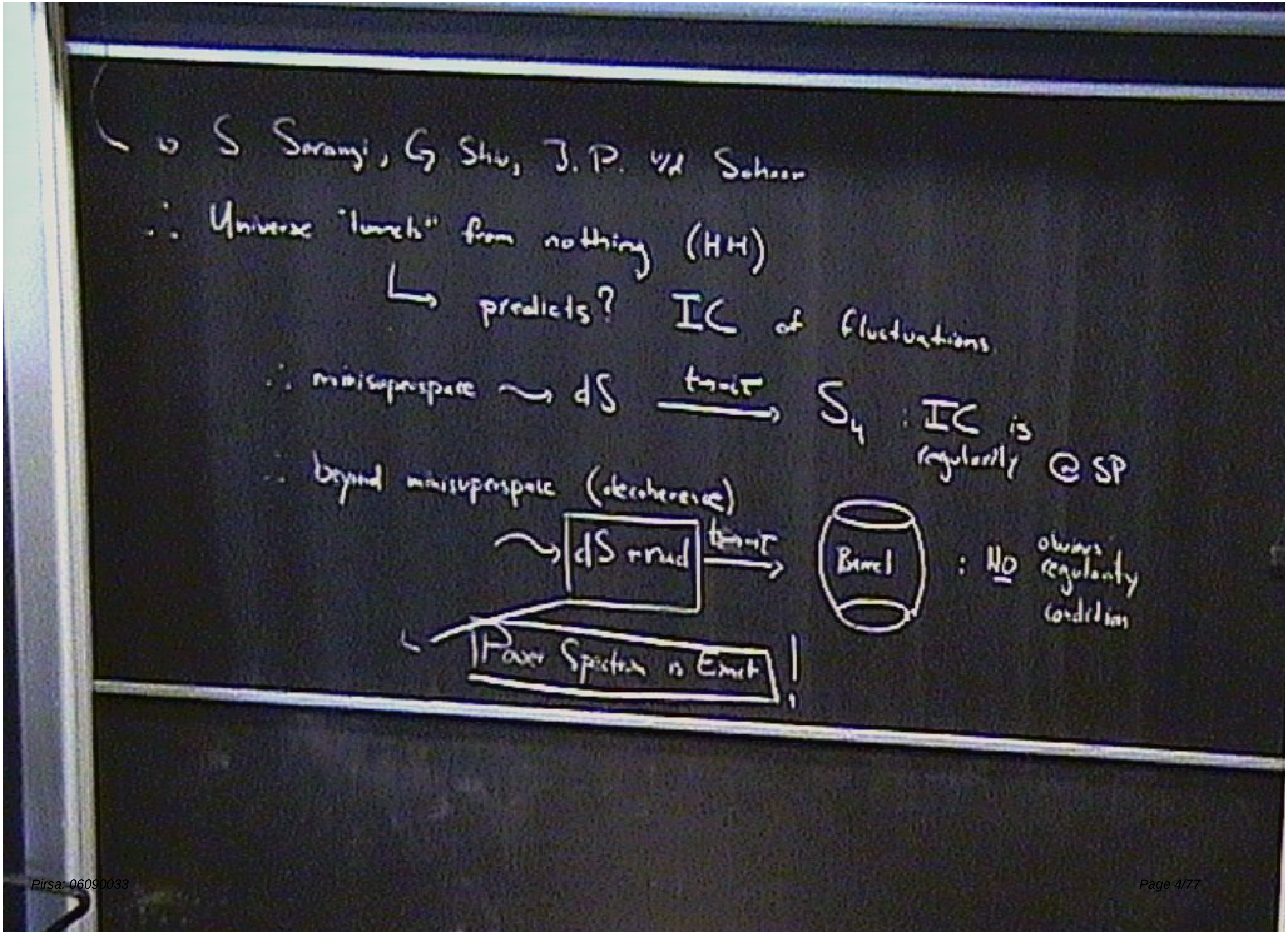
Koenraad Schalm

University of Amsterdam

EFFECTIVE ACTIONS FOR GRAVITY

Koenraad Schalm

University of Amsterdam

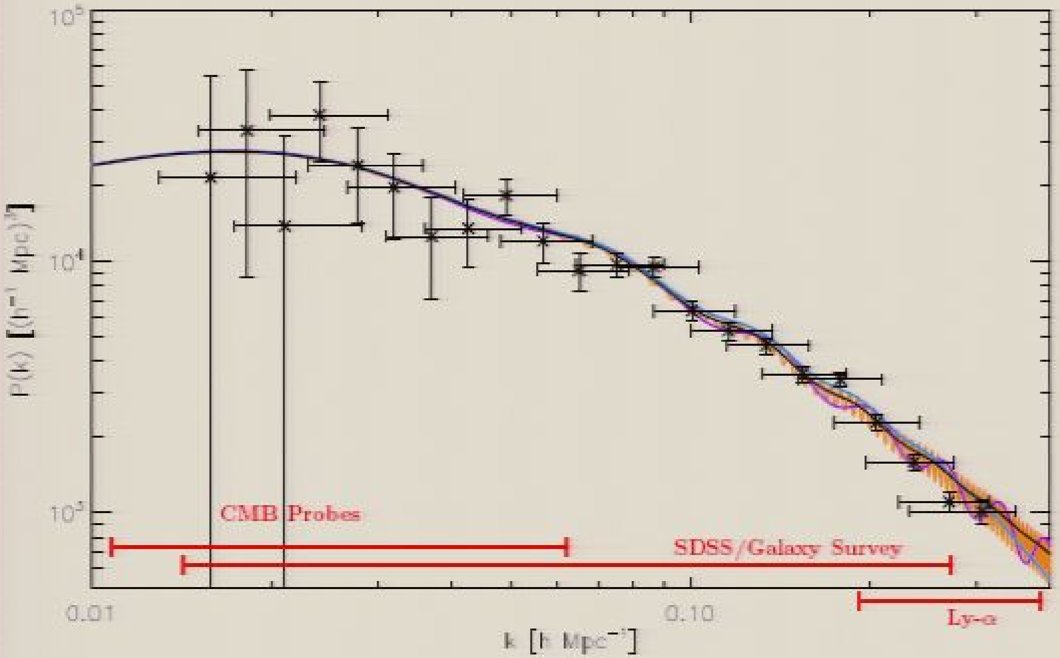

S Sarangi, G Shiu, J.P. v/d Schaar
∴ Universe "tunnels" from nothing (HH)
↳ predicts? IC of fluctuations
∴ minisuperspace ~ dS → S_4 : IC is regularity @ SP
∴ beyond minisuperspace (decoherence)
~ dS mod → Barrel : NO always regularity condition
Power Spectrum is Exact !

EFFECTIVE ACTIONS FOR GRAVITY

Koenraad Schalm

University of Amsterdam

Experiment: Cosmological Data



Linear matter power spectrum (source: Easther, Kinney, Peiris)

- Projected accuracy 10^{-6} [Spergel]
- Ratio of scales $H_{infl}/M_{Pl} \sim 10^{-5}$ ...
- NOTE: Early times ⇔ Large Scales
  Late times ⇔ Small Scales
  (Counterintuitive to effective field theory expectations)

Theory:

- <u>Effective action:</u>
  - **Controlled theoretical error**
  - **Predictability**
    - finite number of undetermined parameters
  - **"Identifies the small parameter"** E/M **;**
    - consistent up to arbitrary precision in this parameter.
    - Need a UV completion beyond scale M to describe physics for $E/M > 1$ (includes fluctuations beyond M).
  - **Action:**

$$S = \int d^4x M^4 \mathcal{O}^{(0)} + M^3 \mathcal{O}^{(1)} + \ldots + \mathcal{O}^{(4)} + \frac{1}{M}\mathcal{O}^{(5)} + \ldots$$

$\mathcal{O}^{(n)}$:all operators of dimension n allowed by the symmetries (modulo field redefinitions/total derivatives)

- $\mathcal{O}^{(n<4)}$: relevant; renormalizable
- $\mathcal{O}^{(n=4)}$: marginal; renormalizable
- $\mathcal{O}^{(n>4)}$: irrelevant; non-renormalizable (coupling constant has negative dimension)

- <u>Physical principles underlying effective actions</u>
  - **Decoupling (separation of scales)**
  - ***Energy conservation* implicit!**

Theory:

- **Effective action:**
  - **Controlled theoretical error**
  - **Predictability**
    - finite number of undetermined parameters
  - **"Identifies the small parameter"** E/M **;**
    - consistent up to arbitrary precision in this parameter.
    - Need a UV completion beyond scale M to describe physics for $E/M > 1$ (includes fluctuations beyond M).
  - **Action:**

$$S = \int d^4x M^4 \mathcal{O}^{(0)} + M^3 \mathcal{O}^{(1)} + \ldots + \mathcal{O}^{(4)} + \frac{1}{M} \mathcal{O}^{(5)} + \ldots$$

$\mathcal{O}^{(n)}$:all operators of dimension n allowed by the symmetries (modulo field redefinitions/total derivatives)

- $\mathcal{O}^{(n<4)}$: relevant; renormalizable
- $\mathcal{O}^{(n=4)}$: marginal; renormalizable
- $\mathcal{O}^{(n>4)}$: irrelevant; non-renormalizable (coupling constant has negative dimension)

- **Physical principles underlying effective actions**
  - **Decoupling (separation of scales)**
  - ***Energy conservation* implicit!**

Effective actions for gravity:

- **General Relativity:**

$$S = \frac{1}{2\kappa}^2 \int d^4x \sqrt{g} g^{\mu\nu} R_{\mu\nu}(g) + \dots$$

Coupling constant $\kappa \sim M_{pl}^{-2}$ has negative dimension.

- **Can consistently describe physics in terms of** $E/M_{pl} < 1$ [Burgess hep-th/0311082]
- **Need a UV completion (Quantum gravity) beyond** M_{pl}
  - Difficult: NEW!

    In FT a UV completion is 'easy'

    (remember the days before asymptotic freedom)...
  - Hints that the UV completion of gravity is "unique"
    - (String theory ...) [Vafa, Ooguri hep-th 0605264]
    - AdS/CFT:

      UV gravity = IR gauge theory

      (only described in terms of the relevant parameters; RG-flow)

      Corollary: (asymptopia!!)

      IR gravity = UV gauge theory

Keep this in mind!!

Theory:

- <u>Effective action:</u>
  - **Controlled theoretical error**
  - **Predictability**
    - finite number of undetermined parameters
  - **"Identifies the small parameter"** E/M **;**
    - consistent up to arbitrary precision in this parameter.
    - Need a UV completion beyond scale M to describe physics for $E/M > 1$ (includes fluctuations beyond M).
  - **Action:**

$$S = \int d^4x M^4 \mathcal{O}^{(0)} + M^3 \mathcal{O}^{(1)} + \ldots + \mathcal{O}^{(4)} + \frac{1}{M}\mathcal{O}^{(5)} + \ldots$$

$\mathcal{O}^{(n)}$:all operators of dimension n allowed by the symmetries (modulo field redefinitions/total derivatives)

- $\mathcal{O}^{(n<4)}$: relevant; renormalizable
- $\mathcal{O}^{(n=4)}$: marginal; renormalizable
- $\mathcal{O}^{(n>4)}$: irrelevant; non-renormalizable (coupling constant has negative dimension)

- <u>Physical principles underlying effective actions</u>
  - **Decoupling (separation of scales)**
  - ***Energy conservation* implicit!**

Effective actions for gravity:

- **General Relativity:**

$$S = \frac{1}{2\kappa}^2 \int d^4x \sqrt{g} g^{\mu\nu} R_{\mu\nu}(g) + \ldots$$

Coupling constant $\kappa \sim M_{pl}^{-2}$ has negative dimension.

- **Can consistently describe physics in terms of** $E/M_{pl} < 1$ [Burgess hep-th/0311082]
- **Need a UV completion (Quantum gravity) beyond** M_{pl}
  - Difficult: NEW!

    In FT a UV completion is 'easy'

    (remember the days before asymptotic freedom)...
  - Hints that the UV completion of gravity is "unique"
    - (String theory ...) [Vafa, Ooguri hep-th 0605264]
    - AdS/CFT:

UV gravity = IR gauge theory

(only described in terms of the relevant parameters; RG-flow)

Corollary: (asymptopia!!)

IR gravity = UV gauge theory

Keep this in mind!!

Effective actions in gravity/cosmology

- BUT, axiom "Energy is conserved" does not always hold;

⇒ ***No clean separation of scales***

- (Possible) Exception: spacetimes with a time-like Killing vector

  .... It works ...

- (Possible) Exception: adiabatically evolving spacetimes:

  .... It works ...

- (Possible) Exception: adiabatic ground state fluctuations

  .... It works ...

⇒ ***What is the small parameter?***

- By the same effective action logic we expect a quantitatively controlled expansion in $\dot{\omega}/\omega^2$.

- SUCH AN EFFECTIVE THEORY IS THE TEMPLATE AGAINST WHICH TO COMPARE COSMOLOGICAL MEASUREMENTS.

Effective Actions and Cosmology

- GR is an effective field theory for $p \equiv \frac{\vec{k}}{a(t)} \leq M$
- Effects of high energy physics encoded in irrelevant higher derivative operators. [Kaloper, Kleban, Lawrence, Shenker;...]
  - Leading term:
  $$S^{irr.op.} = \frac{1}{M^2} \int [D_\mu D_\nu \phi D^\mu D^\nu \phi + \ldots]$$
  - Leading effect of order $\frac{k^2}{a^2 M^2} \sim \frac{H^2}{M^2}$. UNOBSERVABLE
- Phenomenological models/Toy studies
  - Cut-off $p(t) = M$ means an earliest time (different for each $\vec{k}$) [Easther, Greene, Kinney, Shiu; Danielsson; Kempf, Niemeyer; ...]
  - Demand that at smallest scale $\left(t_{\vec{k}}^{earliest}\right)$ "recover" flat space (Minkowski vacuum)

COSMOLOGICAL VACUUM AMBIGUITY

$\Rightarrow$ NEW effects:
  - Leading effect of order $\frac{H}{M}$

The Cosmological Vacuum Ambiguity

- **Can cosmological data contain signatures of new physics ?**

  - Dominant effect $\frac{H}{M}$ arises from

    COSMOLOGICAL VACUUM AMBIGUITY

    $$\Delta E \neq 0 \; ; \quad E|\mathbf{vac}\rangle = E_{min} \, ?$$

- **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, Kapling-hat; ...]

  [KKLS; Banks; Larsen-Einhorn; Brandenberger, EGKS, ...]

Deciphering Initial State Physics

- **Primordial Power Spectrum**

$$D^\mu D_\mu \Phi_\pm(t,k) = 0$$

$$\phi_b(t,k) = \Phi_+(t,k) + b(k)\Phi_-(t,k) \qquad \text{(b.c./vacuum choice)}$$

$$P(k) = \frac{k^3}{2\pi} \lim_{t\to\infty} |\phi_b(t,k)|^2$$

(Choose basis where $b(k) = 0$ standard Bunch-Davies vacuum)

- **Characteristic signature initial state effects**
  - Mode "mixing"

$$\phi(k) = \Phi_+(k) + b(k)\Phi_-(k)$$

  - results in oscillations

$$\delta P = P_{BD}(b(k) + b^*(k))$$

$$= 2P_{BD}|b(k)|\cos\alpha(k) \qquad b = |b|e^{i\alpha}$$

Phenomenological NPH Approach

- **Shortest length b.c. (New Physics Hypersurface)**
  [Danielson; Brandenberger; Easther, Greene, Kinney, Shiu; Kempf, Niemeyer;....]
  - Boundary conditions "imposed" at

$$p(t) = k/aH = M$$

  - Symmetries: homogeneity, isotropy and "scale" invariance

$$b(k) = \tilde{\beta}\frac{H(k)}{2iM}e^{-2i\frac{M}{H(k)(1-\epsilon)}}$$

  - Slow roll

$$H = k^{-\epsilon}$$

  - Power Spectrum

$$P(k) = P_{BD}(k)\left[1 + \tilde{\beta}\frac{H(k)}{M}\sin\left(\frac{M}{H(k)}\right)\right]$$

Deciphering Initial State Physics

- **Primordial Power Spectrum**

$$D^\mu D_\mu \Phi_\pm(t,k) = 0$$

$$\phi_b(t,k) = \Phi_+(t,k) + b(k)\Phi_-(t,k) \qquad \text{(b.c./vacuum choice)}$$

$$P(k) = \frac{k^3}{2\pi} \lim_{t\to\infty} |\phi_b(t,k)|^2$$

(Choose basis where $b(k) = 0$ standard Bunch-Davies vacuum)

- **Characteristic signature initial state effects**
  - Mode "mixing"

$$\phi(k) = \Phi_+(k) + b(k)\Phi_-(k)$$

  - results in oscillations

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

$$= 2P_{BD}|b(k)|\cos\alpha(k) \qquad b = |b|e^{i\alpha}$$

Phenomenological NPH Approach

- **Shortest length b.c. (New Physics Hypersurface)**
  [Danielson; Brandenberger; Easther, Greene, Kinney, Shiu; Kempf, Niemeyer;....]
  - Boundary conditions "imposed " at

    $$p(t) = k/aH = M$$

  - Symmetries: homogeneity, isotropy and "scale" invariance

    $$b(k) = \tilde{\beta}\frac{H(k)}{2iM}e^{-2i\frac{M}{H(k)(1-\epsilon)}}$$

  - Slow roll

    $$H = k^{-\epsilon}$$

  - Power Spectrum

    $$P(k) = P_{BD}(k)\left[1 + \tilde{\beta}\frac{H(k)}{M}\sin\left(\frac{M}{H(k)}\right)\right]$$

Boundary Effective Field Theory

- **Boundary conditions can be encoded in a boundary action**

$$S = \int (D\phi)^2 + \oint \kappa\phi^2$$

$$\Rightarrow D^2\phi = 0$$

$$\partial_n\phi = -\kappa\phi$$

Connection with Hamiltonian approach

$$b(k) = -\frac{\kappa\Phi_+(t_0) + \partial_n\Phi_+(t_0)}{\kappa\Phi_-(t_0) + \partial_n\Phi_-(t_0)}$$

New physics corrections to the initial state encoded in irrelevant boundary operators [**Symanzik; .... Schalm,Shiu, vd-Schaar; Porrati**]

$$S^{irr}_{bnd} = \oint \frac{\beta}{M}(\vec{\partial}\phi)^2$$

- **Boundary EFT parametrizes cosmological vacuum ambiguity**

  - Symmetries: homogeneity and isotropy

$$b(k) = \left[ia_0^3\Phi^2_{+,0}\right]\left(\frac{\beta k^2}{a_0^2 M}\right)$$

  - Power Spectrum

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

Boundary Effective Field Theory II

- Can be shown to be consistent initial conditions
  - Backreaction is under control: new boundary couplings absorb $\langle T \rangle_{Cosmo} - \langle T \rangle_{Mink}$ divergences

Deciphering New Physics

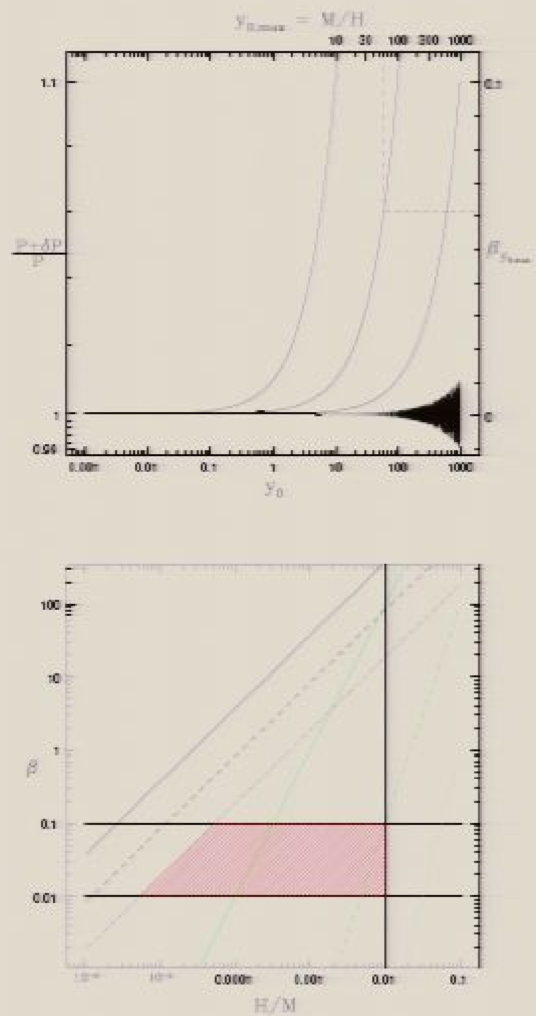
	BEFT	SL-NPH
Power Spectrum	$\delta P = P_{BD}\left(\mathcal{A}k\sin\left(\frac{2\pi k}{\mathcal{C}}\right)\right)$	$\delta P = P_{BD}\left(A\sin\left(\frac{2\pi}{C}\ln\frac{k}{k_{piv}}\right.\right.$
Amplitude	$\mathcal{A} = \frac{\beta}{a_0 M}$	$A = \tilde{\beta}\frac{H}{M}$
Period	$\Delta k = \mathcal{C} = \pi a_0 H$	$\Delta\ln\frac{k}{k_{piv}} = C = \frac{\pi H}{M\epsilon_H}$
# 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	$\mathcal{A}\cdot\Delta k = \frac{\beta}{H}M$	$A = \tilde{\beta}\frac{H}{M}, \quad \frac{\epsilon_H C}{\pi} = \frac{H}{M}$

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

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

  [Bergstrom, Danielsson; Elgaroy, Hannestad; Okamoto, Lim; Martin, Ringeval; Sriramkumar, Padmanabdan; Easther, Kinney, Peiris]
- **Qualitative difference** $\Leftarrow$ **Symmetries**
  - Linear$_{BEFT}$ vs. Log$_{SL-NPH}$ periodicity
- **Preliminary studies (SL-NPH)**
  - Observable if $\frac{\beta H}{M} \sim 1\%$.

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.

BEFT CONUNDRUM

Phenomenological NPH Approach

- **Shortest length b.c. (New Physics Hypersurface)**
  [Danielson; Brandenberger; Easther, Greene, Kinney, Shiu; Kempf, Niemeyer;....]

  - Boundary conditions "imposed" at

  $$p(t) = k/aH = M$$

  - Symmetries: homogeneity, isotropy and "scale" invariance

  $$b(k) = \tilde{\beta}\frac{H(k)}{2iM}e^{-2i\frac{M}{H(k)(1-\epsilon)}}$$

  - Slow roll

  $$H = k^{-\epsilon}$$

  - Power Spectrum

  $$P(k) = P_{BD}(k)\left[1 + \tilde{\beta}\frac{H(k)}{M}\sin\left(\frac{M}{H(k)}\right)\right]$$

Deciphering Initial State Physics

- **Primordial Power Spectrum**

$$D^\mu D_\mu \Phi_\pm(t,k) = 0$$

$$\phi_b(t,k) = \Phi_+(t,k) + b(k)\Phi_-(t,k) \qquad \text{(b.c./vacuum choice)}$$

$$P(k) = \frac{k^3}{2\pi} \lim_{t\to\infty} |\phi_b(t,k)|^2$$

(Choose basis where $b(k) = 0$ standard Bunch-Davies vacuum)

- **Characteristic signature initial state effects**
  - Mode "mixing"

$$\phi(k) = \Phi_+(k) + b(k)\Phi_-(k)$$

  - results in oscillations

$$\delta P = P_{BD}\left(b(k) + b^*(k)\right)$$
$$= 2P_{BD}|b(k)|\cos\alpha(k) \qquad b = |b|e^{i\alpha}$$

Phenomenological NPH Approach

- **Shortest length b.c. (New Physics Hypersurface)**

  [Danielson; Brandenberger; Easther, Greene, Kinney, Shiu; Kempf, Niemeyer;....]

  - Boundary conditions "imposed" at

  $$p(t) = k/aH = M$$

  - Symmetries: homogeneity, isotropy and "scale" invariance

  $$b(k) = \tilde{\beta}\frac{H(k)}{2iM}e^{-2i\frac{M}{H(k)(1-\epsilon)}}$$

  - Slow roll

  $$H = k^{-\epsilon}$$

  - Power Spectrum

  $$P(k) = P_{BD}(k)\left[1 + \tilde{\beta}\frac{H(k)}{M}\sin\left(\frac{M}{H(k)}\right)\right]$$

Deciphering Initial State Physics

- **Primordial Power Spectrum**

$$D^\mu D_\mu \Phi_\pm(t,k) = 0$$

$$\phi_b(t,k) = \Phi_+(t,k) + b(k)\Phi_-(t,k) \qquad \text{(b.c./vacuum choice)}$$

$$P(k) = \frac{k^3}{2\pi}\lim_{t\to\infty} |\phi_b(t,k)|^2$$

(Choose basis where $b(k)=0$ standard Bunch-Davies vacuum)

- **Characteristic signature initial state effects**

  - Mode "mixing"

$$\phi(k) = \Phi_+(k) + b(k)\Phi_-(k)$$

  - results in oscillations

$$\delta P = P_{BD}(b(k) + b^*(k))$$

$$= 2P_{BD}|b(k)|\cos\alpha(k) \qquad b = |b|e^{i\alpha}$$

Boundary Effective Field Theory

- **Boundary conditions can be encoded in a boundary action**

$$S = \int (D\phi)^2 + \oint \kappa\phi^2$$
$$\Rightarrow D^2\phi = 0$$
$$\partial_n \phi = -\kappa\phi$$

Connection with Hamiltonian approach

$$b(k) = -\frac{\kappa\Phi_+(t_0) + \partial_n\Phi_+(t_0)}{\kappa\Phi_-(t_0) + \partial_n\Phi_-(t_0)}$$

New physics corrections to the initial state encoded in irrelevant boundary operators [**Symanzik; .... Schalm,Shiu, vd-Schaar; Porrati**]

$$S_{bnd}^{irr} = \oint \frac{\beta}{M}(\vec{\partial}\phi)^2$$

- **Boundary EFT parametrizes cosmological vacuum ambiguity**

  - Symmetries: homogeneity and isotropy

$$b(k) = \left[ia_0^3\Phi_{+,0}^2\right]\left(\frac{\beta k^2}{a_0^2 M}\right)$$

  - Power Spectrum

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

Phenomenological NPH Approach

- **Shortest length b.c. (New Physics Hypersurface)**
  [Danielson; Brandenberger; Easther, Greene, Kinney, Shiu; Kempf, Niemeyer;....]
  - Boundary conditions "imposed" at

    $$p(t) = k/aH = M$$

  - Symmetries: homogeneity, isotropy and "scale" invariance

    $$b(k) = \tilde{\beta}\frac{H(k)}{2iM}e^{-2i\frac{M}{H(k)(1-\epsilon)}}$$

  - Slow roll

    $$H = k^{-\epsilon}$$

  - Power Spectrum

    $$P(k) = P_{BD}(k)\left[1 + \tilde{\beta}\frac{H(k)}{M}\sin\left(\frac{M}{H(k)}\right)\right]$$

Boundary Effective Field Theory

- **Boundary conditions can be encoded in a boundary action**

$$S = \int (D\phi)^2 + \oint \kappa\phi^2$$
$$\Rightarrow D^2\phi = 0$$
$$\partial_n\phi = -\kappa\phi$$

Connection with Hamiltonian approach

$$b(k) = -\frac{\kappa\Phi_+(t_0) + \partial_n\Phi_+(t_0)}{\kappa\Phi_-(t_0) + \partial_n\Phi_-(t_0)}$$

New physics corrections to the initial state encoded in irrelevant boundary operators [**Symanzik; .... Schalm,Shiu, vd-Schaar; Porrati**]

$$S_{bnd}^{irr} = \oint \frac{\beta}{M}(\vec{\partial}\phi)^2$$

- **Boundary EFT parametrizes cosmological vacuum ambiguity**

  - Symmetries: homogeneity and isotropy

$$b(k) = \left[ia_0^3\Phi_{+,0}^2\right]\left(\frac{\beta k^2}{a_0^2 M}\right)$$

  - Power Spectrum

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

Boundary Effective Field Theory II

- Can be shown to be consistent initial conditions
  - Backreaction is under control: new boundary couplings absorb $\langle T \rangle_{Cosmo} - \langle T \rangle_{Mink}$ divergences

Boundary Effective Field Theory

- **Boundary conditions can be encoded in a boundary action**

$$S = \int (D\phi)^2 + \oint \kappa\phi^2$$

$$\Rightarrow D^2\phi = 0$$

$$\partial_n\phi = -\kappa\phi$$

Connection with Hamiltonian approach

$$b(k) = -\frac{\kappa\Phi_+(t_0) + \partial_n\Phi_+(t_0)}{\kappa\Phi_-(t_0) + \partial_n\Phi_-(t_0)}$$

New physics corrections to the initial state encoded in irrelevant boundary operators [**Symanzik; .... Schalm,Shiu, vd-Schaar; Porrati**]

$$S^{irr}_{bnd} = \oint \frac{\beta}{M}(\vec{\partial}\phi)^2$$

- **Boundary EFT parametrizes cosmological vacuum ambiguity**

  - Symmetries: homogeneity and isotropy

$$b(k) = \left[ia_0^3\Phi^2_{+,0}\right]\left(\frac{\beta k^2}{a_0^2 M}\right)$$

  - Power Spectrum

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

Phenomenological NPH Approach

- Shortest length b.c. (New Physics Hypersurface)

  [Danielson; Brandenberger; Easther, Greene, Kinney, Shiu; Kempf, Niemeyer;....]

  - Boundary conditions "imposed " at

  $$p(t) = k/aH = M$$

  - Symmetries: homogeneity, isotropy and "scale" invariance

  $$b(k) = \tilde{\beta}\frac{H(k)}{2iM}e^{-2i\frac{M}{H(k)(1-\epsilon)}}$$

  - Slow roll

  $$H = k^{-\epsilon}$$

  - Power Spectrum

  $$P(k) = P_{BD}(k)\left[1 + \tilde{\beta}\frac{H(k)}{M}\sin\left(\frac{M}{H(k)}\right)\right]$$

Deciphering Initial State Physics

- **Primordial Power Spectrum**

$$D^\mu D_\mu \Phi_\pm(t,k) = 0$$

$$\phi_b(t,k) = \Phi_+(t,k) + b(k)\Phi_-(t,k) \qquad \text{(b.c./vacuum choice)}$$

$$P(k) = \frac{k^3}{2\pi} \lim_{t\to\infty} |\phi_b(t,k)|^2$$

(Choose basis where $b(k) = 0$ standard Bunch-Davies vacuum)

- **Characteristic signature initial state effects**

- Mode "mixing"

$$\phi(k) = \Phi_+(k) + b(k)\Phi_-(k)$$

- results in oscillations

$$\delta P = P_{BD}(b(k) + b^*(k))$$

$$= 2P_{BD}|b(k)|\cos\alpha(k) \qquad b = |b|e^{i\alpha}$$

The Cosmological Vacuum Ambiguity

- **Can cosmological data contain signatures of new physics** ?
  - Dominant effect $\frac{H}{M}$ arises from

    COSMOLOGICAL VACUUM AMBIGUITY

    $$\Delta E \neq 0 \; ; \quad E|\mathbf{vac}\rangle = E_{min} \; ?$$

- **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; ...]

[KKLS; Banks; Larsen-Einhorn; Brandenberger, EGKS, ...]

Deciphering Initial State Physics

- **Primordial Power Spectrum**

$$D^\mu D_\mu \Phi_\pm(t,k) = 0$$

$$\phi_b(t,k) = \Phi_+(t,k) + b(k)\Phi_-(t,k) \qquad \text{(b.c./vacuum choice)}$$

$$P(k) = \frac{k^3}{2\pi} \lim_{t\to\infty} |\phi_b(t,k)|^2$$

(Choose basis where $b(k) = 0$ standard Bunch-Davies vacuum)

- **Characteristic signature initial state effects**

  - Mode "mixing"

$$\phi(k) = \Phi_+(k) + b(k)\Phi_-(k)$$

  - results in oscillations

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

$$= 2P_{BD}|b(k)|\cos\alpha(k) \qquad b = |b|e^{i\alpha}$$

The Cosmological Vacuum Ambiguity

- **Can cosmological data contain signatures of new physics ?**

  - Dominant effect $\frac{H}{M}$ arises from

    COSMOLOGICAL VACUUM AMBIGUITY

$$\Delta E \neq 0 \; ; \quad E|\mathbf{vac}\rangle = E_{min} \; ?$$

- **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; ...]

[KKLS; Banks; Larsen-Einhorn; Brandenberger, EGKS, ...]

Effective actions for gravity:

- <u>General Relativity:</u>

$$S = \frac{1}{2\kappa}^{2} \int d^4x \sqrt{g} g^{\mu\nu} R_{\mu\nu}(g) + \ldots$$

Coupling constant $\kappa \sim M_{pl}^{-2}$ has negative dimension.

- **Can consistently describe physics in terms of** $E/M_{pl} < 1$ **[Burgess hep-th/0311082]**
- **Need a UV completion (Quantum gravity) beyond** M_{pl}
  - Difficult: NEW!

    In FT a UV completion is 'easy'

    (remember the days before asymptotic freedom)...
  - Hints that the UV completion of gravity is "unique"
    - (String theory ...) [Vafa, Ooguri hep-th 0605264]
    - AdS/CFT:

UV gravity = IR gauge theory

(only described in terms of the relevant parameters; RG-flow)

Corollary: (asymptopia!!)

IR gravity = UV gauge theory

Keep this in mind!!

Theory:

- Effective action:
  - **Controlled theoretical error**
  - **Predictability**
    - finite number of undetermined parameters
  - **"Identifies the small parameter"** E/M ;
    - consistent up to arbitrary precision in this parameter.
    - Need a UV completion beyond scale M to describe physics for $E/M > 1$ (includes fluctuations beyond M).
  - **Action:**

$$S = \int d^4x M^4 \mathcal{O}^{(0)} + M^3 \mathcal{O}^{(1)} + \ldots + \mathcal{O}^{(4)} + \frac{1}{M} \mathcal{O}^{(5)} + \ldots$$

$\mathcal{O}^{(n)}$:all operators of dimension n allowed by the symmetries (modulo field redefinitions/total derivatives)

- $\mathcal{O}^{(n<4)}$: relevant; renormalizable
- $\mathcal{O}^{(n=4)}$: marginal; renormalizable
- $\mathcal{O}^{(n>4)}$: irrelevant; non-renormalizable (coupling constant has negative dimension)

- Physical principles underlying effective actions
  - **Decoupling (separation of scales)**
  - ***Energy conservation* implicit!**

Boundary Effective Field Theory II

- Can be shown to be consistent initial conditions
  - Backreaction is under control: new boundary couplings absorb $\langle T \rangle_{Cosmo} - \langle T \rangle_{Mink}$ divergences

Deciphering New Physics

	BEFT	SL-NPH
Power Spectrum	$\delta P = P_{BD}\left(\mathcal{A} k \sin\left(\frac{2\pi k}{\mathcal{C}}\right)\right)$	$\delta P = P_{BD}\left(A \sin\left(\frac{2\pi}{C} \ln \frac{k}{k_{piv}}\right.\right.$
Amplitude	$\mathcal{A} = \frac{\beta}{a_0 M}$	$A = \tilde{\beta}\frac{H}{M}$
Period	$\Delta k = \mathcal{C} = \pi a_0 H$	$\Delta \ln \frac{k}{k_{piv}} = C = \frac{\pi H}{M \epsilon_H}$
# 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	$\mathcal{A} \cdot \Delta k = \frac{\beta}{H} M$	$A = \tilde{\beta}\frac{H}{M}, \quad \frac{\epsilon_H C}{\pi} = \frac{H}{M}$

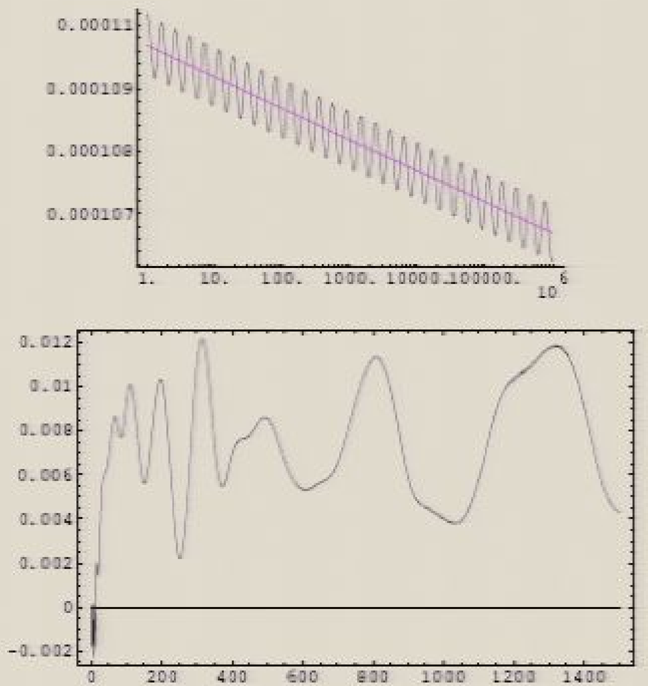
- **BEFT bound** $k_{max} < a_0 M$

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

  [Bergstrom, Danielsson; Elgaroy, Hannestad; Okamoto, Lim; Martin, Ringeval; Sriramkumar, Padmanabdan; Easther, Kinney, Peiris]

- **Qualitative difference** $\Leftarrow$ **Symmetries**
  - Linear$_{BEFT}$ vs. Log$_{SL-NPH}$ periodicity
- **Preliminary studies (SL-NPH)**
  - Observable if $\dfrac{\beta H}{M} \sim 1\%$.

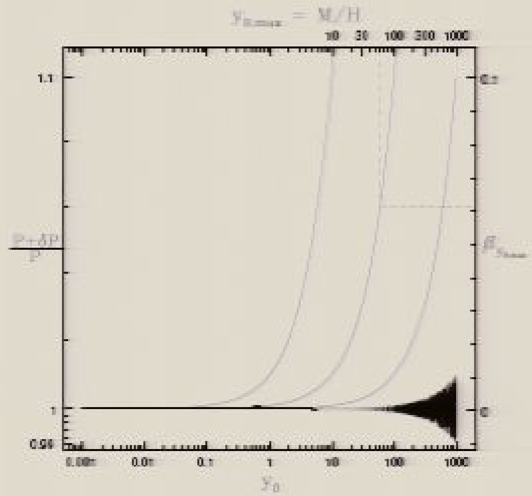
Signature of SL-NPH corrections

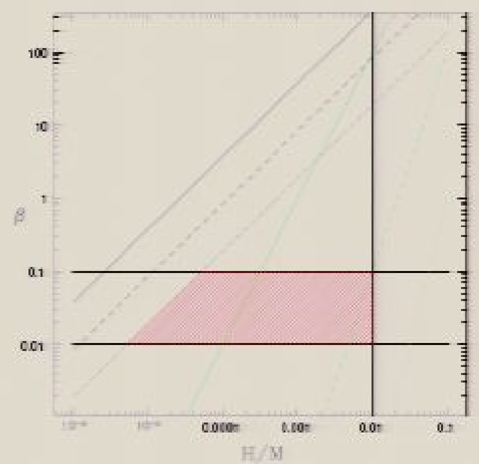


A. The modified perturbation spectrum $P(\vec{k})$ (for a power-law inflationary model) as a function of the momentum for a nearly "scale invariant" change in the initial conditions compared to Bunch-Davies.

B. The percentage change in the observed spherical harmonic coefficients C_ℓ, $P(|\vec{k}|, \theta, \phi) = \sum_{\ell,m} C_\ell(|\vec{k}|) Y^\ell_m(\theta, \phi)$ for a canonical cosmological constant cold dark matter model. (Source Easther et.al. hep-th/0110226)

Signature of BEFT corrections

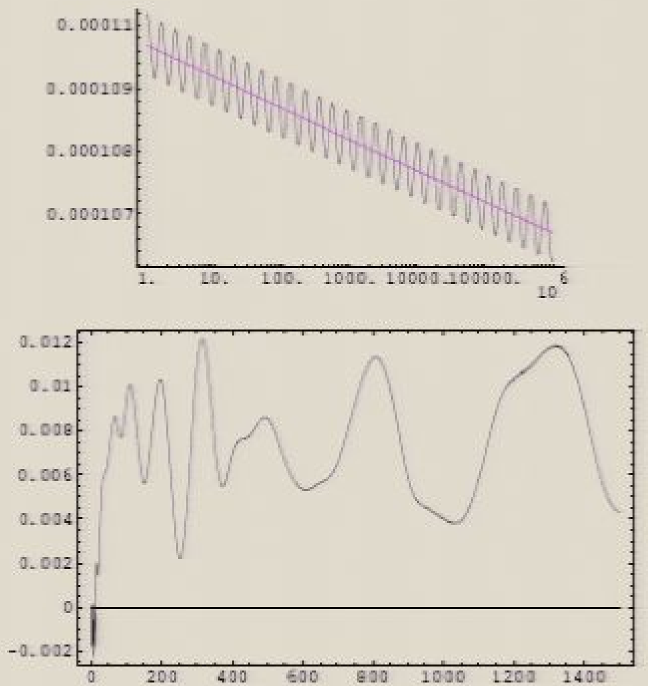




A. Generic change in the power spectrum from initial state effects as deduced with boundary EFT.

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

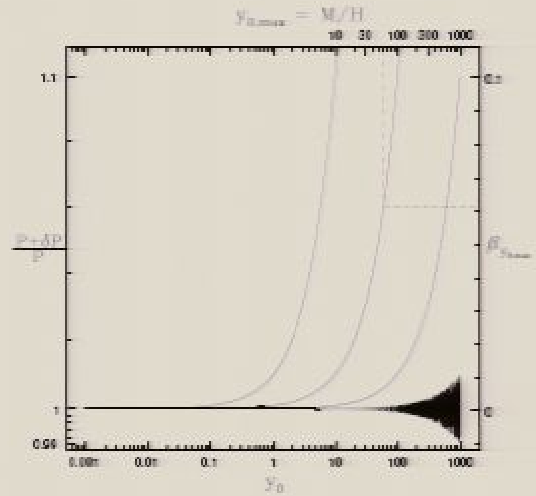
Signature of SL-NPH corrections

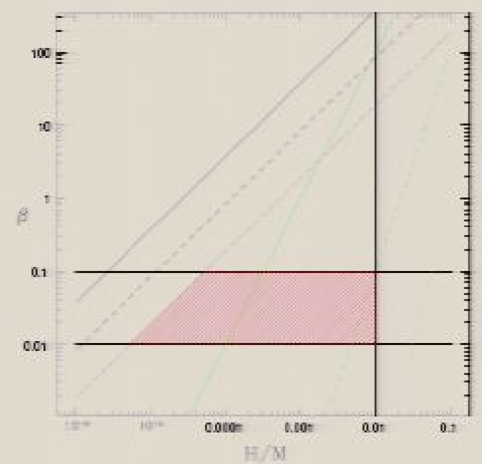


A. The modified perturbation spectrum $P(\bar{k})$ (for a power-law inflationary model) as a function of the momentum for a nearly "scale invariant" change in the initial conditions compared to Bunch-Davies.

B. The percentage change in the observed spherical harmonic coefficients C_ℓ, $P(|\bar{k}|, \theta, \phi) = \sum_{\ell,m} C_\ell(|\bar{k}|) Y^\ell_m(\theta, \phi)$ for a canonical cosmological constant cold dark matter model. (Source Easther et.al. hep-th/0110226)

Signature of BEFT corrections

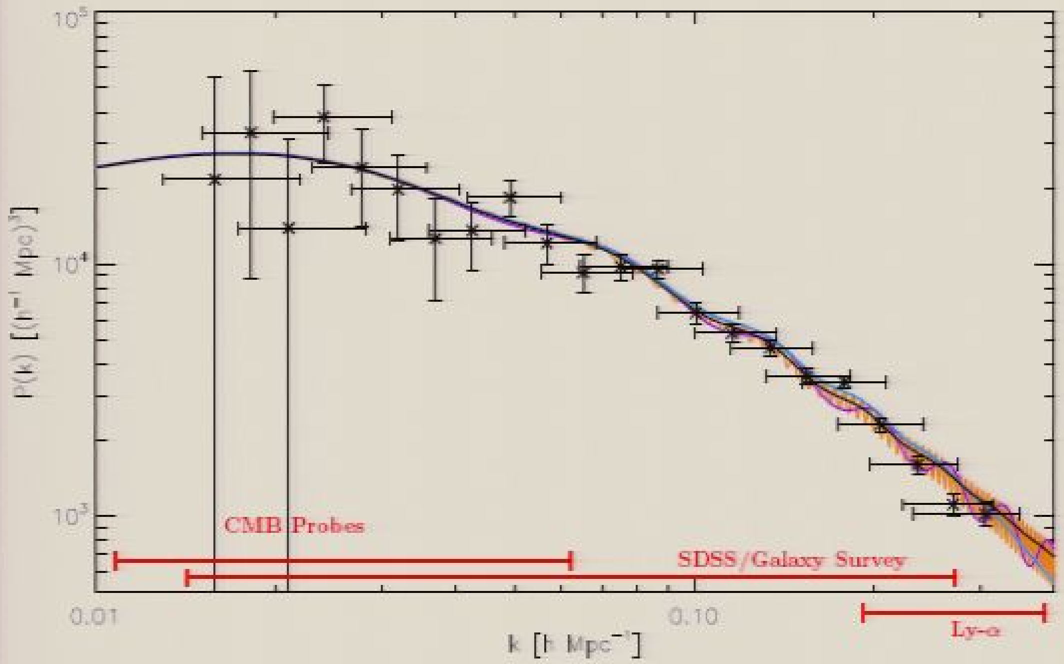




A. Generic change in the power spectrum from initial state effects as deduced with boundary EFT.

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

Linear matter power spectrum II



BEFT corrections to linear matter power spectrum
(source: Easther, Kinney, Peiris)

- Growth of BEFT corrections with $\vec{k}$:
  - suggests LSS- Ly α searches
- $\Leftrightarrow$ Absence in Data:
  - suggests irrelevance of BEFT to observed cosmology.
- **NOTE:** **Early times $\Leftrightarrow$ Large Scales**
  Late times $\Leftrightarrow$ Small Scales
  (Counterintuitive to effective field theory expectations)

Summary: Quantum Field theory in curved spacetimes

- **Are quantum gravity contributions decipherable in cosmological data?**
- **Initial states in Effective Field Theory**
  - Phenomenological SL-NPH approach
    - Intuitively sensible; lacks interpretation/consistency
    - Indicates moderately large H/M corrections for *any* model
  - Theoretically controlled boundary action formalism
    - but, growth with $\vec{k} \Rightarrow$ LSS data suggests irrelevant
  - Best of Both "Universes" approach?
    - Cosmological Effective Field theory (in progress)
- **Application to Cosmology**
  - Parametrize the cosmological vacuum ambiguity
  - Generically receive H/M corrections!
  - Parameters encoding initial data are phenomenologically constrained.
  - Earliest time in cosmology
    $\Rightarrow$ "guarantee" irrelevant boundary corrections.

Summary: Quantum Field theory in curved spacetimes

- **Are quantum gravity contributions decipherable in cosmological data?**
- **Initial states in Effective Field Theory**
  - Phenomenological SL-NPH approach
    - Intuitively sensible; lacks interpretation/consistency
    - Indicates moderately large H/M corrections for *any* model
  - Theoretically controlled boundary action formalism
    - but, growth with $\vec{k} \Rightarrow$ LSS data suggests irrelevant
  - Best of Both "Universes" approach?
    - Cosmological Effective Field theory (in progress)
- **Application to Cosmology**
  - Parametrize the cosmological vacuum ambiguity
  - Generically receive H/M corrections!
  - Parameters encoding initial data are phenomenologically constrained.
  - Earliest time in cosmology

    $\Rightarrow$ "guarantee" irrelevant boundary corrections.

Summary: New Physics in Cosmology:

- Are quantum gravity contributions decipherable in cosmological data?
- Measured (indirectly)
  - Spatial curvature fluctuations

$$P_{\mathcal{R}} = \frac{P}{M_p^2 \epsilon}$$

$$\stackrel{BD}{\Rightarrow} \frac{H^2}{M_p^2 \epsilon} \qquad \left[\sim 10^{-10} \quad \begin{matrix}\text{COBE} \\ \text{WMAP}\end{matrix}\right]$$

  - Primordial Gravitational Waves

$$P_{\mathcal{T}} = \frac{P}{M_p^2}$$

$$\stackrel{BD}{\Rightarrow} \frac{H^2}{M_p^2}$$

– measures $\frac{H}{M_p}$ directly! [not yet observe

If $H/M \simeq 1\%$ $\Leftrightarrow$ primordial gravity waves observed, there is good reason to search for effects of new physics in the data

ON THE IR STRUCTURE OF GRAVITY AND HOLOGRAPHY

Koenraad Schalm

with

Justin Khoury

hep-th/060soon

Summary: New Physics in Cosmology:

- **Are quantum gravity contributions decipherable in cosmological data?**
- Measured (indirectly)
  - Spatial curvature fluctuations

$$P_{\mathcal{R}} = \frac{P}{M_p^2 \epsilon}$$

$$\overset{BD}{\Rightarrow} \frac{H^2}{M_p^2 \epsilon} \qquad \left[\sim 10^{-10} \quad \begin{matrix}\text{COBE}\\ \text{WMAP}\end{matrix}\right]$$

  - Primordial Gravitational Waves

$$P_{\mathcal{T}} = \frac{P}{M_p^2}$$

$$\overset{BD}{\Rightarrow} \frac{H^2}{M_p^2}$$

– measures $\frac{H}{M_p}$ directly! [not yet observe

If $H/M \simeq 1\%$ $\Leftrightarrow$ primordial gravity waves observed, there is good reason to search for effects of new physics in the data

Gravity in the IR

- Standard GR $\Leftrightarrow$ W/O | Dark Energy / Dark Matter |

$$1 \text{ mm} < r < \text{Galactic scale} \sim 10^{22}\text{m}$$

- MODIFY GRAVITY IN THE IR??

  - MOND [Milgrom,Bekenstein,...]

$$\mu(\frac{a}{a_0})a = \nabla\Phi_N \qquad \begin{array}{ll} \mu(x) \to 1 & x \gg 1 \\ \mu(x) \to 0 & x \ll 1 \end{array}$$

  Phenomenologically succesful (until recently...)

  - DGP [Dvali,Gabadadze,Porrati; Vainsthein]

$$S = M_5^3 \int R^{(5)} + M_4^2 \int R^{(4)}$$

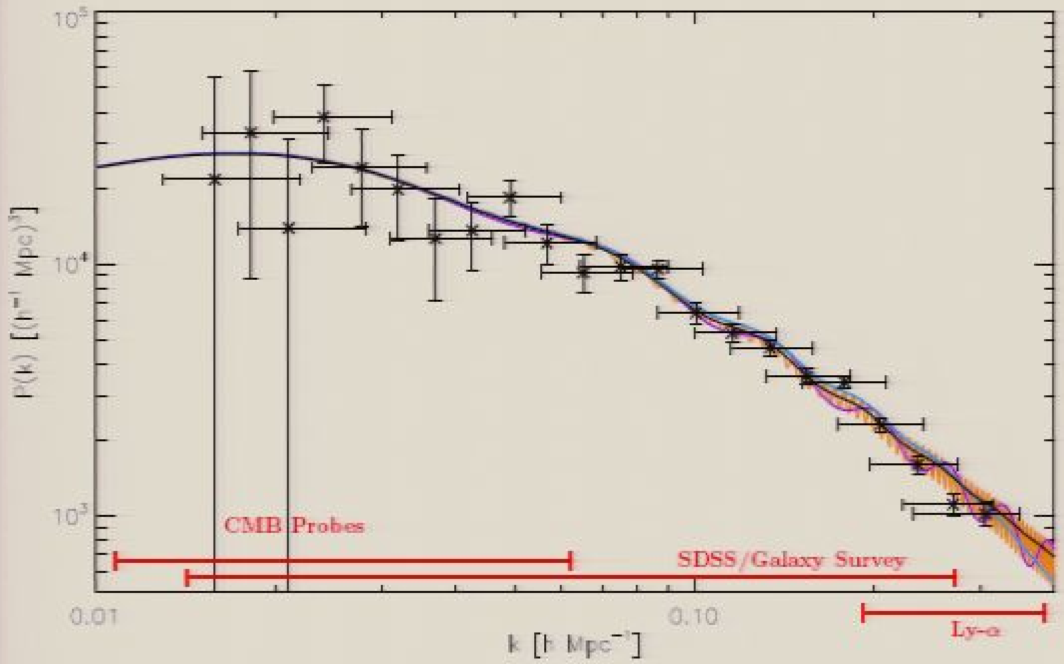
  - Higgsed Gravity [Arkani-Hamed et al.]

$$S = M_4^2 \int R^{(4)} + (\partial\phi)^2$$

$$\langle\dot{\phi}\rangle \neq 0$$

  - ...

Linear matter power spectrum II



BEFT corrections to linear matter power spectrum (source: Easther, Kinney, Peiris)

- Growth of BEFT corrections with $\vec{k}$:
  - suggests LSS- Ly α searches
- $\Leftrightarrow$ Absence in Data:
  - suggests irrelevance of BEFT to observed cosmology.
- **NOTE: Early times $\Leftrightarrow$ Large Scales**
  Late times $\Leftrightarrow$ Small Scales
  (Counterintuitive to effective field theory expectations)

Summary: Quantum Field theory in curved spacetimes

- **Are quantum gravity contributions decipherable in cosmological data?**
- **Initial states in Effective Field Theory**
  - Phenomenological SL-NPH approach
    - Intuitively sensible; lacks interpretation/consistency
    - Indicates moderately large H/M corrections for *any* model
  - Theoretically controlled boundary action formalism
    - but, growth with $\vec{k}$ $\Rightarrow$ LSS data suggests irrelevant
  - Best of Both "Universes" approach?
    - Cosmological Effective Field theory (in progress)
- **Application to Cosmology**
  - Parametrize the cosmological vacuum ambiguity
  - Generically receive H/M corrections!
  - Parameters encoding initial data are phenomenologically constrained.
  - Earliest time in cosmology

    $\Rightarrow$ "guarantee" irrelevant boundary corrections.

Summary: Quantum Field theory in curved spacetimes

- **Are quantum gravity contributions decipherable in cosmological data?**
- **Initial states in Effective Field Theory**
  - Phenomenological SL-NPH approach
    - Intuitively sensible; lacks interpretation/consistency
    - Indicates moderately large H/M corrections for *any* model
  - Theoretically controlled boundary action formalism
    - but, growth with $\vec{k}$ $\Rightarrow$ LSS data suggests irrelevant
  - Best of Both "Universes" approach?
    - Cosmological Effective Field theory (in progress)
- **Application to Cosmology**
  - Parametrize the cosmological vacuum ambiguity
  - Generically receive H/M corrections!
  - Parameters encoding initial data are phenomenologically constrained.
  - Earliest time in cosmology
    $\Rightarrow$ "guarantee" irrelevant boundary corrections.

ON THE IR STRUCTURE OF GRAVITY AND HOLOGRAPHY

Koenraad Schalm

with

Justin Khoury

hep-th/060soon

Gravity and Effective Actions Revisited

- **Physics: What is the relevant scale?**
  - Decoupling
  - Effective action

$\Rightarrow$ Theory vs. Measurement $\Leftarrow$

- **Gravity: [Cosmology]**

ΛCDM Concordance Model

$1 \text{ mm} < r < \Lambda_{today}$

Two "obscure" ingredients:

- Dark Energy $(\rho = -p)$ ~70%
- Dark Matter $(p = 0)$ ~25%

- Evidence: - Cosmic Expansion (CMB/LSS)
  - Gravitational Lensing
  - (DE) Supernova Standard Candles
  - (DM) Galactic rotation Curves

Gravity in the IR

- Standard GR $\Leftrightarrow$ W/O Dark Energy, Dark Matter

$$1 \text{ mm} < r < \text{Galactic scale} \sim 10^{22}\text{m}$$

- MODIFY GRAVITY IN THE IR??
  - MOND [Milgrom,Bekenstein,...]

$$\mu\left(\frac{a}{a_0}\right)a = \nabla\Phi_N \qquad \begin{array}{ll} \mu(x) \to 1 & x \gg 1 \\ \mu(x) \to 0 & x \ll 1 \end{array}$$

    Phenomenologically succesful (until recently...)

  - DGP [Dvali,Gabadadze,Porrati; Vainsthein]

$$S = M_5^3 \int R^{(5)} + M_4^2 \int R^{(4)}$$

  - Higgsed Gravity [Arkani-Hamed et al.]

$$S = M_4^2 \int R^{(4)} + (\partial\phi)^2$$

$$\langle\dot{\phi}\rangle \neq 0$$

  - ...

An UV effective action?

- Different IR extensions
  $\Rightarrow$ GR for scales $r <$ Galactic

$$\mathrm{GR} + \frac{\Lambda_{IR}}{r} + \frac{\Lambda_{IR}^2}{r^2} + \ldots$$

- **Lift to an action?**
  - Λ_{IR}: IR Cut-off/IR scale

$$\Lambda_{IR} \sim H_{today}? \quad \text{Asymptopia}$$
$$\sim \text{Horizon} \quad \text{Observer dependent}$$

  - Physics independent of Λ_{IR}

An IR RG?

  - Connections with Holography?
    - IR Cutoff $=$ Boundary? (Just one type IR regulator)
    - $\Lambda = 0$? $\Lambda > 0$?

Why an UV-effective action could exist

- **Wilsonian RG a la Polchinski**
  - Pick an arbitrary separation scale Λ ;
    Demand physics does not depend on the cutoff

$$\frac{d}{d\Lambda} Z = 0$$

In terms of the effective action:

$$\frac{\partial S^{eff}}{\partial \Lambda} = \frac{1}{2}\frac{\partial S^{eff}}{\partial \phi}\frac{\partial G}{\partial \Lambda}\frac{\partial S^{eff}}{\partial \phi} - \frac{\partial S^{eff}}{\partial \phi}\frac{\partial \ln G}{\partial \Lambda}\phi$$

  - ϕ can be either UV or IR excitation

$$G \sim \frac{1}{\Box}\mathcal{F}(\Box/\Lambda) \to 0 \qquad \begin{cases} \Box \gg \Lambda, & \phi_{IR} \\ \Box \gg \Lambda, & \phi_{UV} \end{cases}$$

  - Generates all relevant and irrelevant operators plus RG-flow (classical/quantum)
    - UV: irrelevant $\ldots \to$ non-local?
    - IR: irrelevant $\leftrightarrow$ higher derivative
  - Example: $\lambda\phi^4$ (isn't gravity special?)

An UV effective action?

- Different IR extensions
  $\Rightarrow$ GR for scales $r <$ Galactic

$$\text{GR} + \frac{\Lambda_{IR}}{r} + \frac{\Lambda_{IR}^2}{r^2} + \dots$$

- **Lift to an action?**

  - Λ_{IR}: IR Cut-off/IR scale

    $\Lambda_{IR} \sim H_{today}$? Asymptopia
    $\sim$ Horizon Observer dependent

  - Physics independent of Λ_{IR}

    An IR RG?

  - Connections with Holography?

    - IR Cutoff $=$ Boundary? (Just one type IR regulator)
    - $\Lambda = 0$? $\Lambda > 0$?

Why an UV-effective action could exist

- **Wilsonian RG a la Polchinski**
  - Pick an arbitrary separation scale Λ ;
    Demand physics does not depend on the cutoff

$$\frac{d}{d\Lambda} Z = 0$$

    In terms of the effective action:

$$\frac{\partial S^{eff}}{\partial \Lambda} = \frac{1}{2}\frac{\partial S^{eff}}{\partial \phi}\frac{\partial G}{\partial \Lambda}\frac{\partial S^{eff}}{\partial \phi} - \frac{\partial S^{eff}}{\partial \phi}\frac{\partial \ln G}{\partial \Lambda}\phi$$

  - ϕ can be either UV or IR excitation

$$G \sim \frac{1}{\Box}\mathcal{F}(\Box/\Lambda) \to 0 \qquad \begin{cases} \Box \gg \Lambda, & \phi_{IR} \\ \Box \gg \Lambda, & \phi_{UV} \end{cases}$$

  - Generates all relevant and irrelevant operators plus RG-flow (classical/quantum)
    - UV: irrelevant $\ldots \longrightarrow$ non-local?
    - IR: irrelevant $\longleftrightarrow$ higher derivative
  - Example: $\lambda\phi^4$ (isn't gravity special?)

Consistency of UV-effective actions

- **IR-effective action**

$$S^{eff} = S + \frac{\Box}{\Lambda^2} + \left(\frac{\Box}{\Lambda^2}\right)^2 + \dots$$

Extra terms: irrelevant, non-renorm, higher-derivative operators

- **UV-effective action**

$$?? \quad S^{eff} = S + \frac{\Lambda^2}{\Box} + \left(\frac{\Lambda^2}{\Box}\right)^2 + \dots \quad ??$$

Extra terms: NON-LOCAL?

⇒ Correlated Problem: Sources and Sinks

- IR-Effective action: $J_{UV} = 0 \longrightarrow$ Energy conservation
- UV-Effective action: SOFT EMISSION?

⇒ Possible solution: **smeared wavefunctions**

IR-effective action:	UV-effective action:
Lattice/graining in x-space	coherent sum $0 < p < \Lambda$ emissions
discretize x	discretize p (∼ finite volume IR-cutoff)

ERG for (pure) gravity

- **GR-ERG equation:**

$$\frac{\partial S^{eff}}{\partial \Lambda} = \frac{\partial S^{eff}}{\partial g^{\mu\nu}}\frac{\partial G^{\mu\nu\rho\sigma}}{\partial \Lambda}\frac{\partial S^{eff}}{\partial g^{\rho\sigma}} + \frac{\partial S^{eff}}{\partial g^{\mu\nu}}\frac{\partial \ln G^{\mu\nu\rho\sigma}}{\partial \Lambda} g_{\rho\sigma}$$

Last term renormalizes G_N/M_{pl} .

- **Let** $G^{\mu\nu\rho\sigma} = \tilde{G}^{\mu\nu\rho\sigma}\mathcal{F}\left(\frac{\Box}{\Lambda}\right)$
with

$$\begin{cases} \mathcal{F}(x) \to 0 & \text{as} \quad x \to 0 \\ \mathcal{F}(x) \to 1 & \text{as} \quad x \to \infty \end{cases}$$

- **Solution:** $(\mathcal{F} \ll 1)$

$$S = \int \sqrt{g}\left(R + G^{\mu\nu}\frac{1-\mathcal{F}}{\Box}R_{\mu\nu} + \dots\right)$$

- Leading irrelevant operator [see Barvinsky]
- Theory is still pure GR!

Leading order correction of Einstein-Hilbert

- Naive expectation: (NOT REALIZED)

$$S = \int \sqrt{g}\left(R + \alpha R\frac{1}{\Box}R + \gamma R^{\mu\nu}\frac{1}{\Box}R_{\mu\nu} + \epsilon R^{\mu\nu\rho\sigma}\frac{1}{\Box}R_{\mu\nu\rho\sigma} + \ldots\right.$$

  - vDVZ discontinuity: $\alpha = -\gamma/2$; $\epsilon = 0$ [Barvinsky]
  - beyond symmetry

- Integrated full UV effective action to order R^2

$$S = \int \sqrt{g}\left(R + G^{\mu\nu}\frac{\mathcal{F}^{-1} - 1}{\Box}R_{\mu\nu} + \ldots\right)$$

  - $\Rightarrow$ **EOM**

$$\mathcal{F}^{-1}G_{\mu\nu} = T_{\mu\nu}$$

Filter function: Λ **does not gravitate** [Arkani-Hamed, Dimopoulos, Dvali, Gabadadze; Barvinsky]

ERG for (pure) gravity

- **GR-ERG equation:**

$$\frac{\partial S^{eff}}{\partial \Lambda} = \frac{\partial S^{eff}}{\partial g^{\mu\nu}} \frac{\partial G^{\mu\nu\rho\sigma}}{\partial \Lambda} \frac{\partial S^{eff}}{\partial g^{\rho\sigma}} + \frac{\partial S^{eff}}{\partial g^{\mu\nu}} \frac{\partial \ln G^{\mu\nu\rho\sigma}}{\partial \Lambda} g_{\rho\sigma}$$

Last term renormalizes G_N / M_{pl} .

- **Let** $G^{\mu\nu\rho\sigma} = \tilde{G}^{\mu\nu\rho\sigma} \mathcal{F}\left(\frac{\Box}{\Lambda}\right)$
with

$$\begin{cases} \mathcal{F}(x) \to 0 & \text{as} \quad x \to 0 \\ \mathcal{F}(x) \to 1 & \text{as} \quad x \to \infty \end{cases}$$

- **Solution:** $(\mathcal{F} \ll 1)$

$$S = \int \sqrt{g} \left(R + G^{\mu\nu} \frac{1 - \mathcal{F}}{\Box} R_{\mu\nu} + \ldots \right)$$

- Leading irrelevant operator [see Barvinsky]
- Theory is still pure GR!

Leading order correction of Einstein-Hilbert

- **Naive expectation: (NOT REALIZED)**

$$S = \int \sqrt{g}\left(R + \alpha R\frac{1}{\Box}R + \gamma R^{\mu\nu}\frac{1}{\Box}R_{\mu\nu} + \epsilon R^{\mu\nu\rho\sigma}\frac{1}{\Box}R_{\mu\nu\rho\sigma} + \dots\right.$$

  - vDVZ discontinuity: $\alpha = -\gamma/2$; $\epsilon = 0$ [Barvinsky]
  - beyond symmetry

- **Integrated full UV effective action to order R^2**

$$S = \int \sqrt{g}\left(R + G^{\mu\nu}\frac{\mathcal{F}^{-1} - 1}{\Box}R_{\mu\nu} + \dots\right)$$

  - $\Rightarrow$ EOM

$$\mathcal{F}^{-1}G_{\mu\nu} = T_{\mu\nu}$$

Filter function: Λ **does not gravitate** [Arkani-Hamed, Dimopoulos, Dvali, Gabadadze; Barvinsky]

Universality of the UV-effective action

- Different IR extensions (consistent ...)
  $\Rightarrow$ different coefficients of irrelevant operators

$$S^{irr} = \int \sqrt{g} \left(\alpha R \frac{\mathcal{F}}{\Box} R + \gamma R^{\mu\nu} \frac{\mathcal{F}}{\Box} R_{\mu\nu} + \epsilon R^{\mu\nu\rho\sigma} \frac{\mathcal{F}}{\Box} R_{\mu\nu\rho\sigma} + \dots \right.$$

- DGP

$$\overset{4D}{r} < \frac{M_4}{M_5^2} < \overset{4D+\text{scalar}}{r} < \frac{M_4^2}{M_5^3} < \overset{5D}{r}$$

  - (in progress) $(\alpha = -3/2;\ \gamma = 1;\ \epsilon = 0)$
  - vDVZ !
  - Analytic?

$$\mathcal{F} = \frac{1}{r_c \sqrt{\Box}} \quad (?)$$

- MOND

Scalar+Vector+Gravity Cf. Brans-Dicke-like

$$S = \int (1+\phi) R + \frac{1}{2} \phi \Box \phi$$

- Higgsed Gravity

Cf. K-inflation

$$S = \int \sqrt{g} R + P\left((\partial\phi)^2 \right)$$

Cosmological solution

- **IR-Cutoff:** screening of Λ_{CC}
- **BUT:effective action $\Leftrightarrow$ physics "same"**
- **Self-gravitating solutions: (Brans-Dicke)**
  - DGP (Exact) [See, however, Charmousis, Gregory, Kaloper, Padilla]

$$H^2 - \frac{H}{r_c} = \frac{8\pi G}{3}\rho$$

$$r_c \sim H_{today}$$

(Generic?), (Dimensional analysis)

- Quantitative agreement???

Observational constraints

- Constraints on $\alpha,\ \gamma,\ \epsilon$.
  - for DGP [Maartens, Majoretto; Ishak, Spergel, Upadhye; Sanichi, Carroll]

•

•

•

(in progress)

Open questions

- **Is a UV-effective action truly consistent?**

  Locality?

  Universality?

- **(Non)-uniqueness of IR-completions of Gravity**
- **Connection with Holography**

AdS-CFT: boundary IR cutoff $\simeq$ Gauge theory UV cutoff

- independence of the choice of cutoff function?
- non-aAds spaces
- Horizon physics?
- ...

- **Unifies open ideas in universal physical concept**

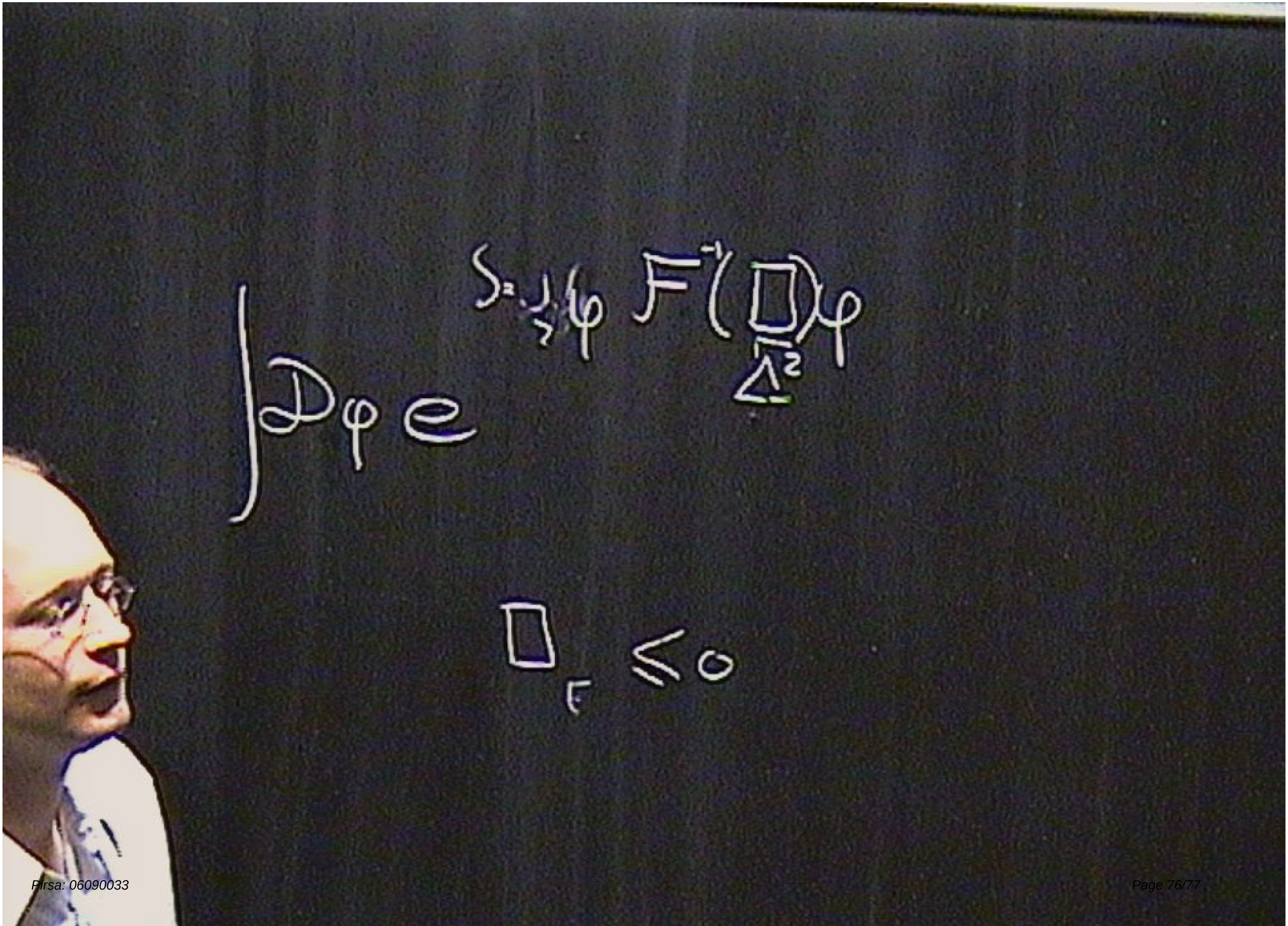
  - MOND-like and/or IR modifications
  - Filters CC
  - Barvinsky's action explained

Conclusions

- **Consistent effective action framework is still lacki**
  - Evidence that both a IR and a UV-effective action should exist.
  - As data improves, these effective actions will be necessary

$$\int \mathcal{D}\varphi \, e^{S = \frac{1}{2}\varphi \, F^{-1}\left(\frac{\Box}{\Delta^2}\right)\varphi}$$

$$\Box$$


$\int D\varphi\, e^{S=\frac{1}{2}\varphi F^{-1}(\Box/\Delta^2)\varphi}$
$\Box_E \leq 0$

Open questions

- **Is a UV-effective action truly consistent?**

  Locality?

  Universality?

- **(Non)-uniqueness of IR-completions of Gravity**
- **Connection with Holography**

AdS-CFT: boundary IR cutoff $\simeq$ Gauge theory UV cutoff

- independence of the choice of cutoff function?
- non-aAds spaces
- Horizon physics?
- ...

- **Unifies open ideas in universal physical concept**

  - MOND-like and/or IR modifications
  - Filters CC
  - Barvinsky's action explained