CAN COSMOLOGICAL DATA CONTAIN SIGNATURES OF QUANTUM GRAVITY/STRING THEORY?

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with

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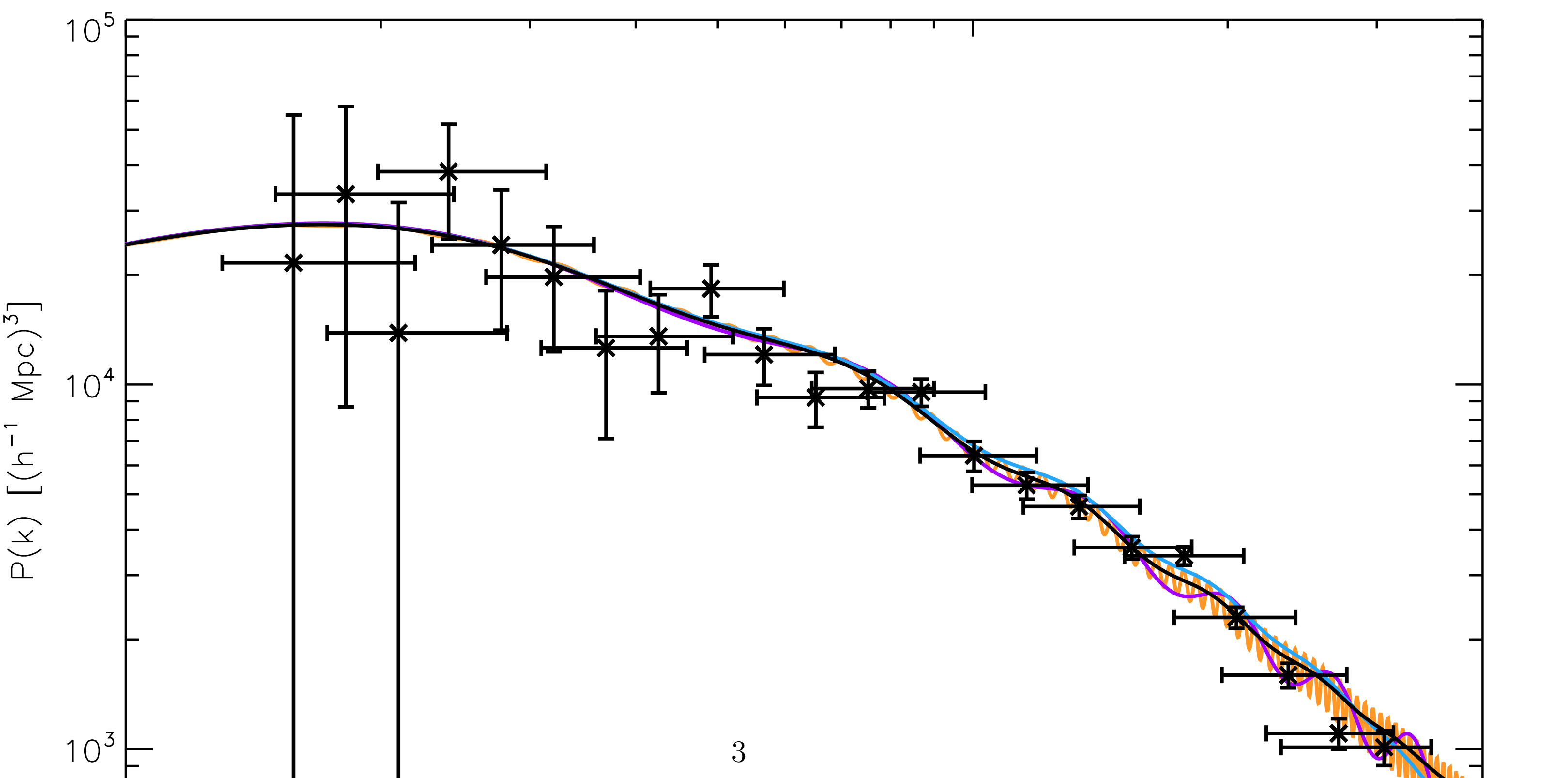
Cosmological Data: linear matter power spectrum


10^5
10^4
10^3
P(k) [(h^-1 Mpc)^3]

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

- **Linear Matter Power spectrum**
  - **Temperature fluctuations in the CMB**
  - **Large Scale Structure**
- **INPUT: Primordial Power Spectrum**

$$\frac{\delta\rho}{\rho} = k^n$$

  - $n = 0$**: SCALE INVARIANCE**

[Harrison, Zeldovich]

Avoid $\frac{\delta\rho}{\rho} \geq 1$**:**

  - $n > 1$**: problematic at high** k **range (BH formation)**
  - $n < 1$**: problematic at low** k **range (homogeneity; data)**

- **NOTE: Early times ⇔ Large Scales**
  Late times ⇔ Small Scales

(Counterintuitive to effective field theory expectations)

- **<u>SBB Cosmology:</u>**
  - $\frac{\delta\rho}{\rho} = k^n$ **INITIAL CONDITION**
  - **Explanation: quantum gravity**
  - **$\Rightarrow$ Horizon Problem**
- **<u>Inflationary Cosmology:</u>**
  - $\frac{\delta\rho}{\rho} = k^n$ **Spontaneous pair creation from vacuum**
  - **Cures SBB problems within GR!**
  - **BIG SUCCESS (COBE, WMAP,. . .)**
  - **Can Cosmological Data contain signatures of Quantum Gravity?**

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BAD NEWS

- **Avoid** $\frac{\delta\rho}{\rho} > 1$**:** **Slow Roll Inflation**

$$\epsilon = \left|\frac{V'}{V}\right|^2 < 1$$
$$\eta = \left|\frac{V''}{V}\right| < 1$$

- **Problems:**

[Brandenberger,...]

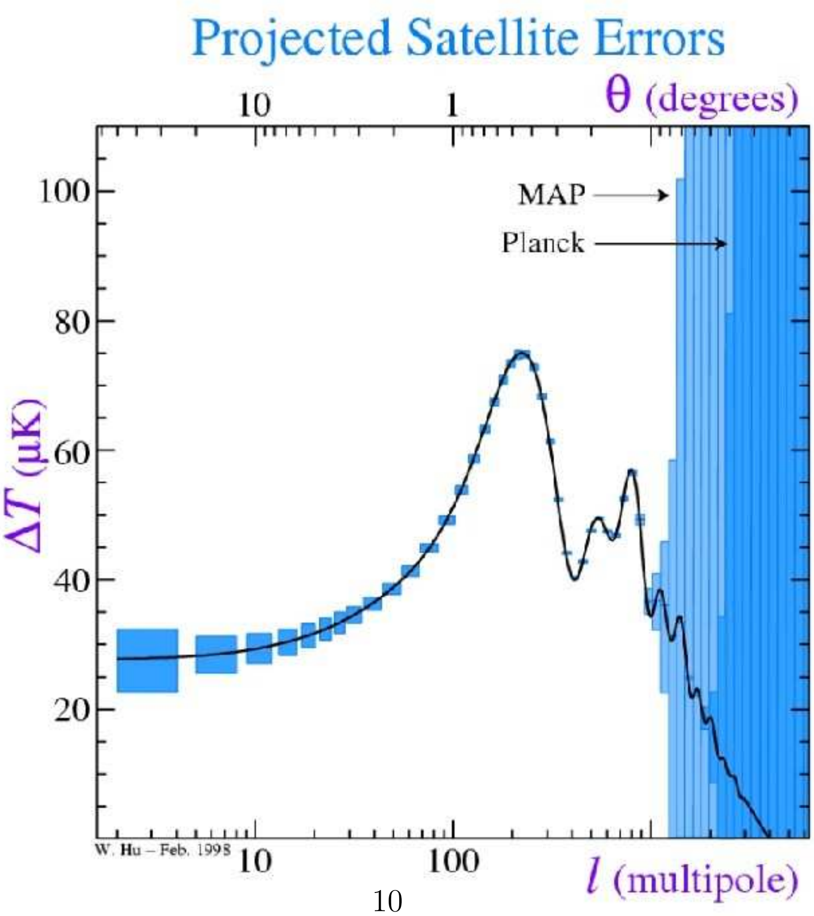
  - **Slow roll** $\Leftrightarrow$ **Very fine tuned action**
  - **What/where is the inflaton?**
  - **Massive redshifts**
    (Transplanckian problem vs. Horizon problem)

$$\frac{a(t_{end})}{a(t_{init})} \geq e^{60} \simeq 10^{20}$$

  - **QFT in cosmological spacetimes**
    Spontaneous pair creation from the vacuum
    $\Rightarrow$ **cosmological vacuum ambiguity/initial state problem**

OPPORTUNITIES TO DETECT QUANTUM GRAVITY REMAIN

Cosmic Variance


Projected Satellite Errors
θ (degrees)
10
1
MAP
Planck
100
80
60
40
20
ΔT (μK)
W. Hu – Feb. 1998
10
100
l (multipole)

Expected errors in the C_ℓ spectrum for the WMAP (light blue) and Planck (dark blue) satellites. (source: W. Hu)

- **Cosmic Variance: Intrinsic Statistics Limited Error of order** 10^{-2}

- **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** $\frac{k^2}{a^2 M^2} \sim \frac{H^2}{M^2} \left(\sim \left(\frac{10^{14}}{10^{16}} \right)^2 \sim 0.01\% \right)$.

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

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

    COSMOLOGICAL VACUUM AMBIGUITY

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

- **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, . . .]

- **Primordial Power Spectrum**

$$
\begin{aligned}
D^\mu D_\mu \Phi_\pm(t,k) &= 0 \\
\phi_b(t,k) &= \Phi_+(t,k) + b(k)\Phi_-(t,k) \qquad \textbf{(b.c./vacuum choice)} \\
P(k) &= \frac{k^3}{2\pi} \lim_{t\to\infty} |\phi_b(t,k)|^2
\end{aligned}
$$

(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**

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

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

[Danielson; Brandenberger; Easther, Greene, Kinney, Shiu; Kempf, Niemayer;....

  - **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 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

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

[Symanzik; .... Schalm,Shiu, vd-Schaar; Porrati]

New physics corrections to the initial state encoded in irrelevant boundary operators

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

- **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**

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

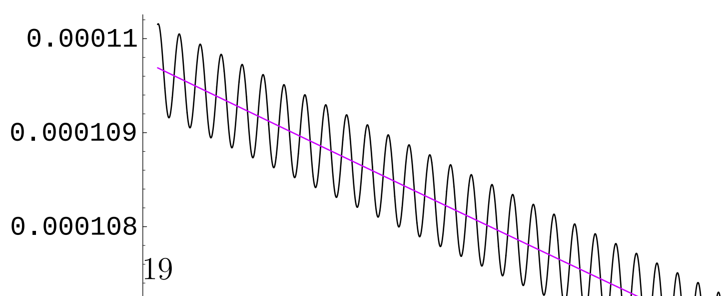
- **Can be shown to be consistent initial conditions**
  - **Backreaction is under control: new boundary couplings absorb $\langle T\rangle_{Cosmo} - \langle T\rangle_{Mink}$ divergences**

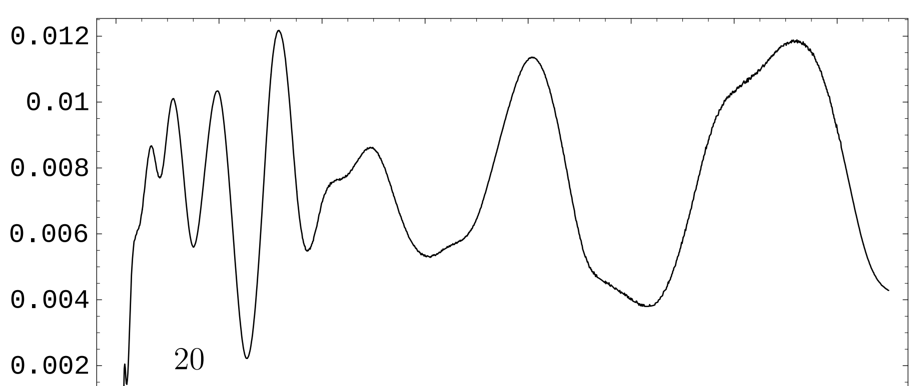
	BEFT	**SL-NPH**
Power Spectrum	$\delta P = P_{BD}\left(\mathcal{A}k\sin\left(\frac{2\pi k}{\mathcal{C}}\right)\right)$	$\delta P = P_{BD}\left(A\sin\left(\frac{2\pi}{C}\ln\frac{k}{k_{piv}}\right)\right)$
Amplitude	$\mathcal{A} = \frac{\beta}{a_0 M}$	$A = \tilde{\beta}\frac{H}{M}$
Period	$\Delta k = \mathcal{C}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

  $\Rightarrow k_{max} < \pi M\mathcal{C}/H$
- **Qualitative difference** $\Leftarrow$ **Symmetries**
  - **Linear**$_{BEFT}$ **vs. Log**$_{SL-NPH}$ **periodicity**
- **Preliminary studies (SL-NPH)**
  - **Observable if** $\frac{\beta H}{M} \sim 1\%$.

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

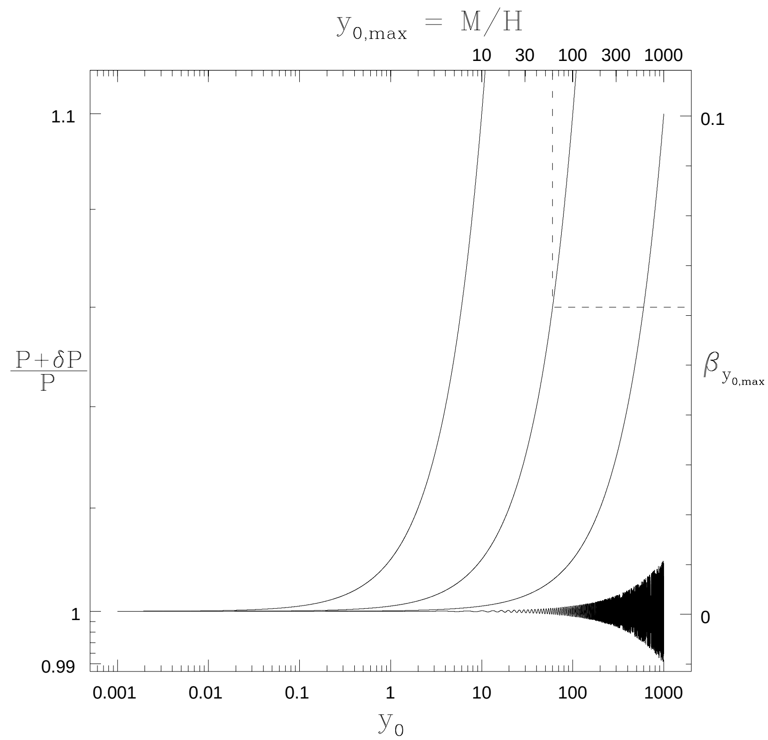

0.00011
0.000109
0.000108

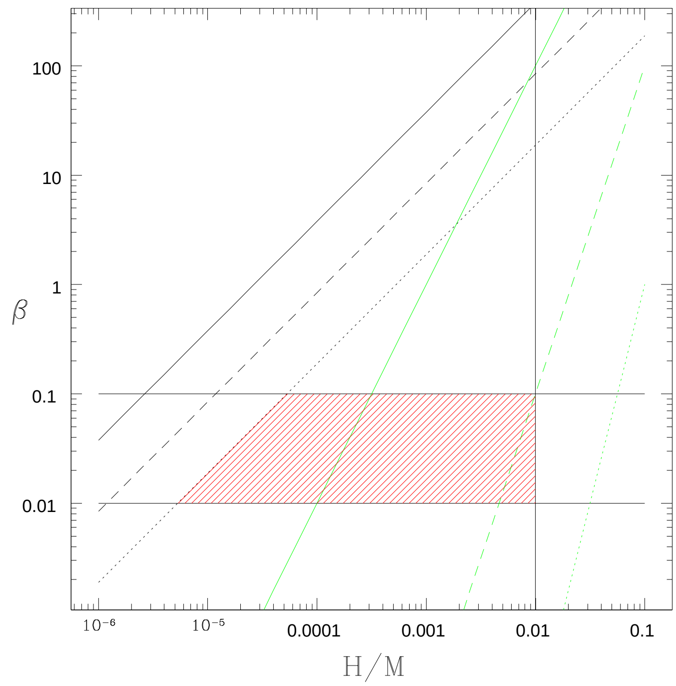

0.012
0.01
0.008
0.006
0.004
0.002

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

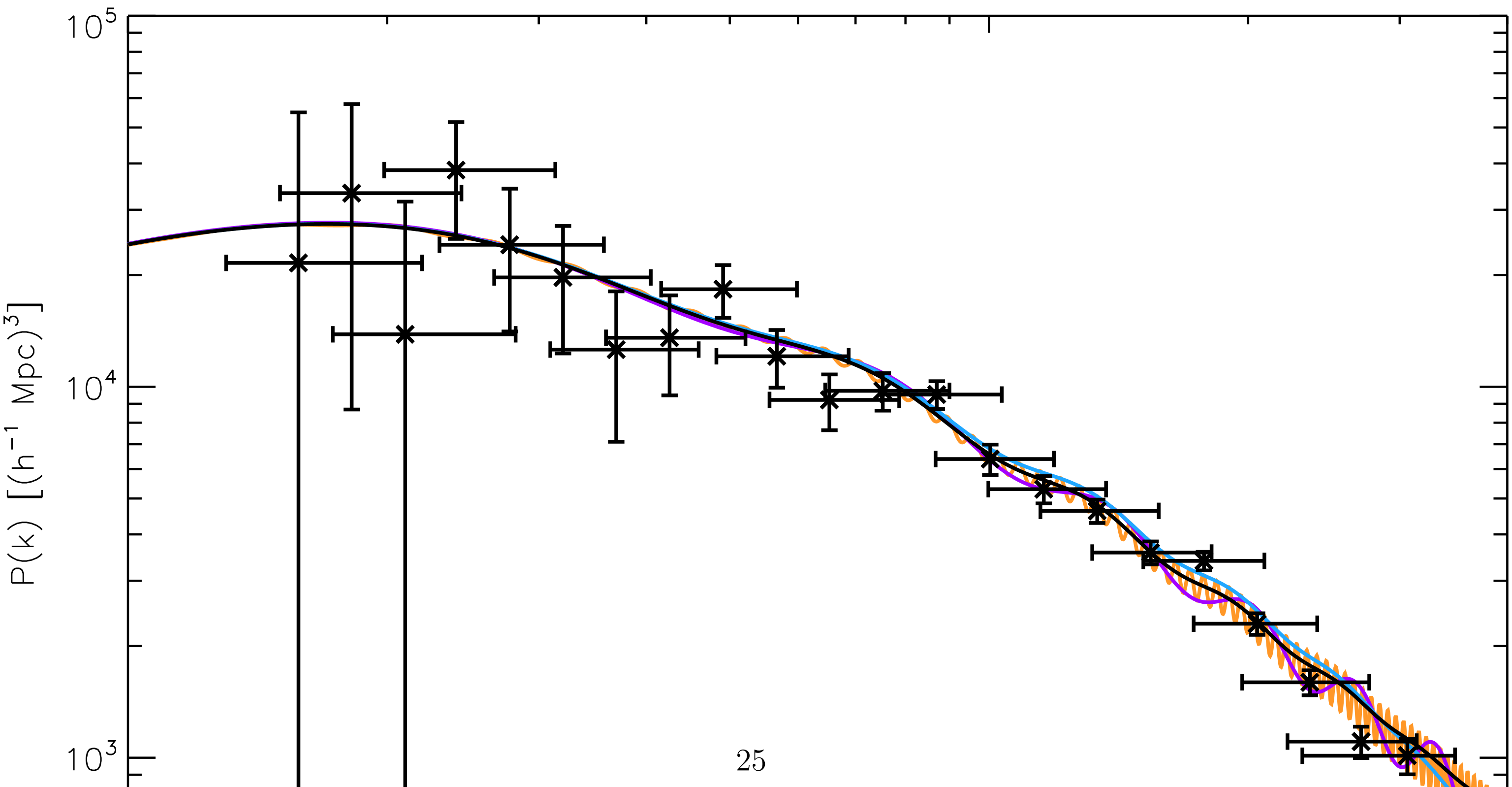




A. Generic change in the power spectrum from initial state effects as deduced with boundary EFT.

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

Linear matter power spectrum II



10^5
10^4
10^3
P(k) [(h^{-1} Mpc)^3]

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 suggests irrelevance of BEFT to observed cosmology.**
- **NOTE:** **Early times $\Leftrightarrow$ Large Scales**
  Late times $\Leftrightarrow$ Small Scales
  (Counterintuitive to effective field theory expectations)
  BEFT CONUNDRUM

- **Initial states in Effective Field Theory**
  - **Phenomenological SL-NPH approach**
    - Intuitively sensible; lacks interpretation/consistency
    - Indicates moderately large H/M corrections
  - **Theoretically controlled boundary action formalism**
    - Manifest scaling behaviour: boundary RG-flow
    - dressing of initial state;
    - preferred b.c. are RG-fixed points.
    - 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**
    - Preference?
    Bunch-Davies, transparent, adiabatic, thermal, etc.
    - Generically receive H/M corrections!
  - **Parameters encoding initial data are phenomenologically constrained.**
  - **Connections with holography?**
  - **Earliest time in cosmology**
    $\Rightarrow$ "guarantee" irrelevant boundary corrections.
  - **Are quantum gravity contributions decipherable in cosmological data?**

- **Measured (indirectly)**
  - **Spatial curvature fluctuations**

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

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

  - **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 observed**].

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

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

    ⇒ Can deduce scale M of new physics.

    -String theory?

    -Intermediate new scale physics (GUT)?

- **To distinguish various models, need more information.**
  - **GATHER ONE PIECE AT A TIME**