Transplanckian Physics and the CMB: A Status Report

Brian Greene
Columbia University
Institute for Strings, Cosmology, and Astroparticle Physics

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Basic Questions

- We all hope LHC will give insight into string theory.
- But is it our only hope for contact with data?
- Can string/planck-scale physics leave an imprint on the CMB?
- Can observations of CMB give insight/information about string/planck-scale physics?

Why Think Possible?

Inflation Post-inflation

- Expansion Factor at *least* $(e^{60})(10^{28}) = 10^{54}$

  Size of Universe = 10^{10} light-years = 10^{61} Planck Lengths

- Ripples we see began sub-Planckian; Planckian imprint?

- Only way to know:

  Calculate perturbations standard way.

  See if string/quantum gravity modifies in significant way.

Outline

I. Brief Review of Standard Calculation.

II. Possible Modifications; Affect on CMB.

III. Observational opportunities.

I. Spectrum: Standard Results

- Perturb metric/scalar fields.
- Calculate equation of motion.
- Calculate power in quantum fluctuations: 2-pt function

I. Spectrum: Standard Results

- Consider Tensor Modes: Perturb Metric.

$$ds^2 = a^2(\eta)(d\eta^2 - (\delta_{ij} + h_{ij})dx^i dx^j)$$

- Expand in Traceless Symmetric Modes:

$$h_{ij}(\eta, x) = h_+ e_{ij}{}^+ + h_\times e_{ij}{}^\times$$

- Equations of Motion:

$$u_k'' + (k^2 - a''/a)u_k = 0$$

$$(u_k = a(\eta)h_k)$$

I.Spectrum: Standard Results

- Quantum Mechanics:

$$\hat{u}(\eta, x) = 1/(2\pi)^{3/2} \int d^3k [\hat{a}_k(\eta) e^{ikx} + \hat{a}_k{}^{+}(\eta) e^{-ikx}]$$

Express operators in terms of basis at a fixed reference time.

$$\hat{a}_k(\eta) = \alpha_k(\eta)\hat{a}_k(\eta_i) + \beta_k(\eta)\hat{a}_{-k}{}^{+}(\eta_i)$$

$$\hat{a}_k(\eta) \rightarrow (\alpha_k + \beta_k{}^{*})(\eta)\hat{a}_k(\eta_i) = u_k(\eta)\hat{a}_k(\eta_i)$$

- Measure of Fluctuation: Power Spectrum/Two Point Fcn

$$P(k) = \frac{k^3}{2\pi^2 a^2} \langle 0 | \hat{u}_k(\eta) \hat{u}_k{}^{+}(\eta) | 0 \rangle_{LateTime} = \frac{k^3}{2\pi^2} \left| \frac{u_k}{a} \right|^2$$

I.Spectrum: Standard Results

- Tensor Perturbations:

$$u_k'' + (k^2 - \frac{a''}{a})u_k = 0$$

- Power Spectrum:

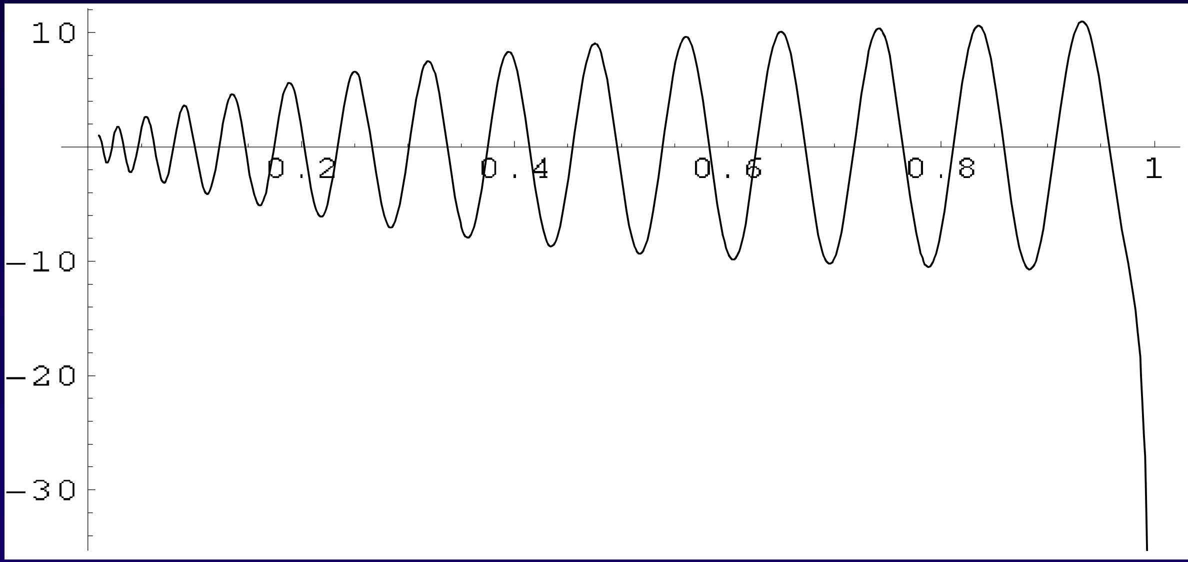
$$P^{1/2}(k) = \sqrt{\frac{k^3}{2\pi^2}}\left|\frac{u_k}{a}\right|_{k=aH}$$

- Boundary Conditions: Arbitrarily early times/short scales modes behave as in Minkowski space:

$$u_k(\eta) \to \frac{1}{\sqrt{2k}} e^{-ik\eta}$$

I.Spectrum: Standard Results

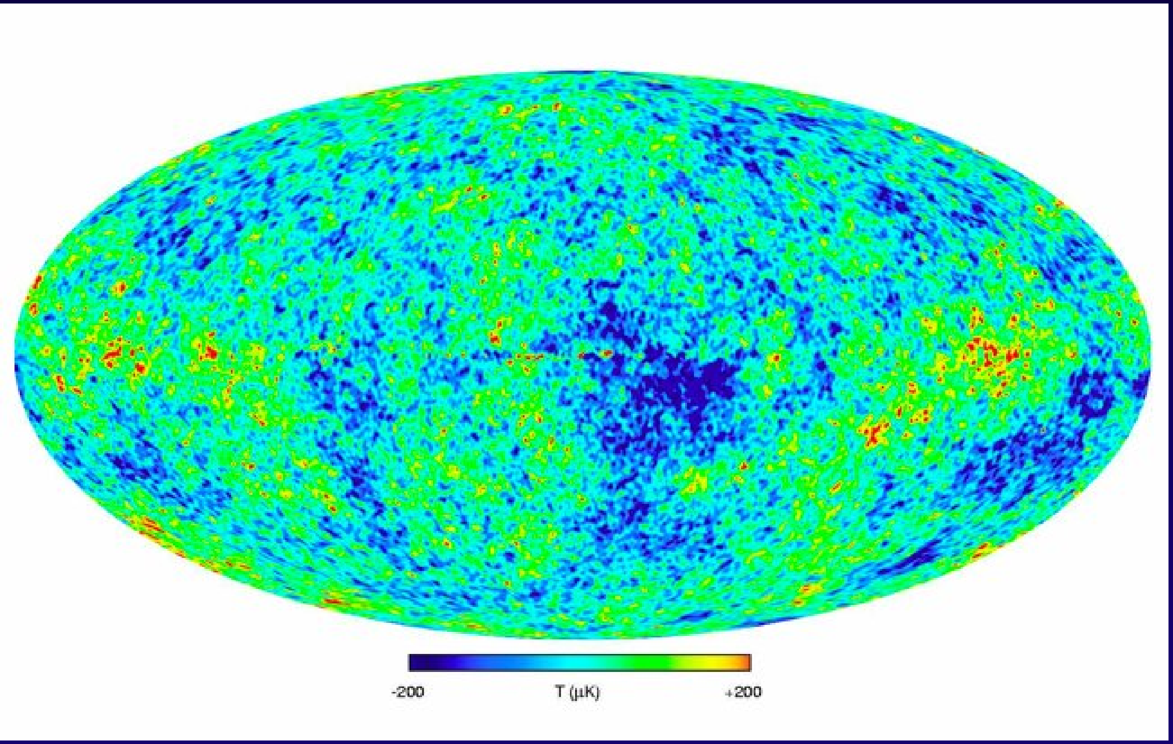
- Mode Solutions:



- Early time: a”/a << k^2 ⟶ Oscillation.
- Late time: a”/a >> k^2 ⟶ Freeze out.

I.Spectrum: Standard Results

Density Perturbations: CMB



I.Spectrum: Standard Results

- Tensor Perturbations:

$$u_k'' + (k^2 - \frac{a''}{a})u_k = 0$$

- Power Spectrum:

$$P^{1/2}(k) = \sqrt{\frac{k^3}{2\pi^2}}\left|\frac{u_k}{a}\right|_{k=aH}$$

- Boundary Conditions: Early times/short scales—Minkowskian:

$$u_k(\eta) \to \frac{1}{\sqrt{2k}} e^{-ik\eta}, \eta \to -\infty$$

- Assumption: Standard QFT applies unmodified on arbitrarily short scales. What if it doesn't?

II. Imprints of modified Short Scale Physics?

- No complete, first principles calculation.
- Parameterize Possibilities via:
  - Modified Dynamics
  - Modified Boundary Conditions

II. SHORT SCALE IMPRINTS
A Brief History

- Modify Dispersion Relations:
  - Brandenberger and Martin astro-ph/0005432, hep-th/0005209, hep-th/0201189
- Short Scale Noncommutativity:
  - Chu, BRG, Shiu hep-th/0011241
  - Lizzi, Mangano, Miele, Peloso hep-th/0203119
  - Tsujikawa, Maartens, Brandenberger hep-th/0307016
- Introduce minimum length*:*
  - Kempf and Niemeyer astro-ph/0103225
  - Easther,BRG, Shiu, Kinney hep-th/0104102, hep-th/0110226
- Higher Order Operators in Dynamics:
  - Kaloper, Kleban, Lawrence, Shenker hep-th/0201158
  - Shiu, Wasserman hep-th/0203113

II. SHORT SCALE IMPRINTS
A Brief History

- Modify Short Scale Boundary Conditions:
  - Easther,BRG, Shiu, Kinney hep-th/0104102, hep-th/0110226
  - U. Danielsson,hep-th/0203198
  - Easther, BRG, Kinney, Shiu hep-th/0204129
  - Goldstein, Lowe hep-th/0208167
  - Martin, Brandenberger hep-th0305161
- Controlled Effective Field Theories:
  - Burgess, Cline, Lemieux, Holman hep-th/0210233
  - Burgess, Cline, Holman hep-th/0306079
  - Kaloper, Kaplinghat hep-th/0307016
  - Schalm, Shiu, Van der Schaar hep-th/0401164
  - BRG, Schalm, Shiu, Van der Schaar hep-th/0411217
  - BRG, Parikh, Van der Schaar, JHEP 0604 (2006) 057

II.Philosophy

- Question: How far do we need to deviate from conventional physics to yield a (potentially) observable imprint on the CMB?
- Question: Is the required deviation remotely sensible?
- Related Approach: Let CMB speak for itself.

II. Parameterized Modifications:
Representative Examples

- I. Modify Dynamics *and* Boundary Condtions:(Easther, BRG, Kinney, Shiu)
  - Dynamics: String Uncertainty principle. $$[x, p] = i\frac{h}{2\pi}(1 + (L^2{}_{string})p^2); \Delta x_{\min} \sim L_{string}$$
  - Boundary Conditions: ***Modes physical iff wavelength larger than string length. Set boundary conditions there. Choose state of zero particle number wrt pos/neg frequency solutions to new EOM.***
  - Found: O(H/M) modulation to P(k).
- II. Modify Only Boundary Condtions:(Danielsson)
  - Boundary Conditions: ***Same prescription as I, wrt pos/neg frequency solutions to standard EOM.***
  - Found: O(H/M) modulation to P(k). Same origin as I; easier to analyse.
- III. Modify Only Dynamics:(Kaloper, Kleban,Lawrence,Shenker)
  - Dynamics: ***Include next order operators in EFT derivative expansion.***
  - Found: O($(H/M)^2$) shift to P(k). (Smaller effect; no iconic modulation.)

II. Parameterized Modifications:

Representative Examples: Estimates

- I. / II. O(H/M):
  - $a_{NEW} = a_{ORIGINAL} + O(H/M)\, a^{\dagger}_{ORIGINAL}$
  - P(k): Cross term in 2-point function picks up O(H/M) contribution.
  - Generic modification to vacuum/boundary data (will return to this).

For realistic H/M, potentially observable.

- III. $O((H/M)^2)$:
  - Leading irrelevant operator in EFT for scalar/tensor modes: Dimension 6.
  - P(k) picks up $O((H/M)^2)$ contribution (will return to this).

For realistic H/M, unlikely to be observable.

II. Calculating Modifications:
Boundary Conditions

- Usual Case:

$$\hat{u}(\eta, x) = 1/(2\pi)^{3/2} \int d^3k [\hat{a}_k(\eta) e^{ikx} + \hat{a}_k^{+}(\eta) e^{-ikx}]$$

$$\hat{a}_k(\eta) = \alpha_k(\eta)\hat{a}_k(\eta_i) + \beta_k(\eta)\hat{a}_{-k}^{+}(\eta_i)$$

$$\hat{a}_k(\eta) \to (\alpha_k + \beta_k^{*})(\eta)\hat{a}_k(\eta_i) = u_k(\eta)\hat{a}_k(\eta_i)$$

$$\beta_k(\eta) = 0, as\, \eta \to -\infty, u_k(\eta) \to \frac{1}{\sqrt{k}} e^{-ik\eta}$$

- Modify:

$$\beta_k(\eta_k) = 0, when: \frac{k}{a(\eta_k)} = M_{string} \Rightarrow \eta_k = -\frac{M}{Hk}; |A_k|^2 - |B_k|^2 = 1$$

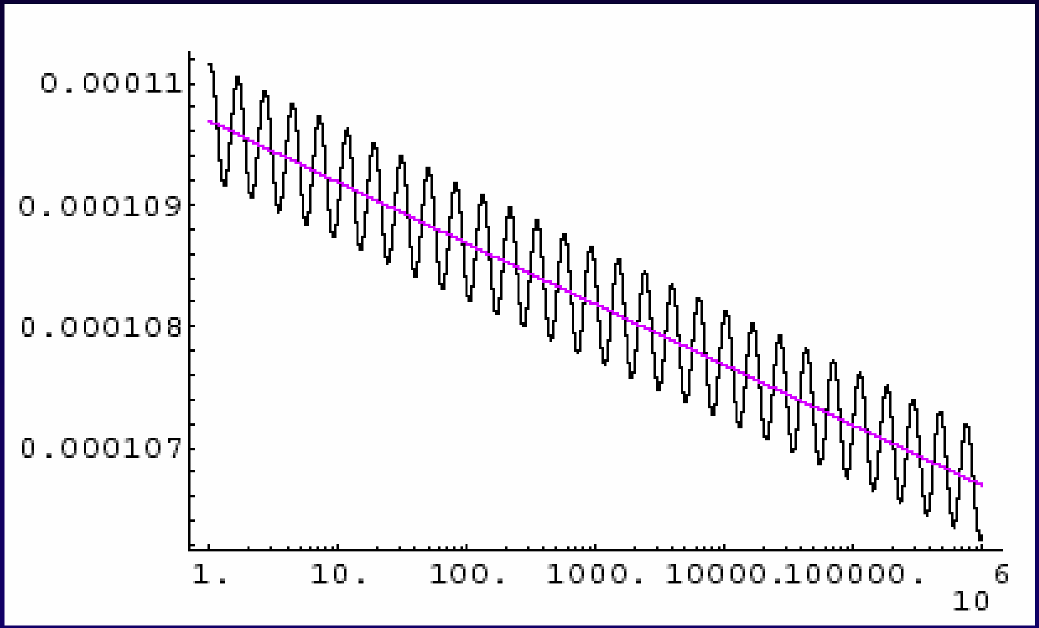
$$u^{\text{mod}}{}_k(\eta) = A_k u_k(\eta) + B_k u_k^{*}(\eta) \qquad |A_k|^2 = (1 - |(1 - 2ki\eta_k)^{-1}|)^{-1}$$

- Spectrum:

DeSitter Space: Shift (Danielsson)
General Slow Roll: Modulation (Easther, BRG, Kinney, Shiu)

$$P_k = (\frac{H}{2\pi})^2 (1 - \frac{H}{M_{st}} \sin(\frac{2}{H/M_{st}}))$$

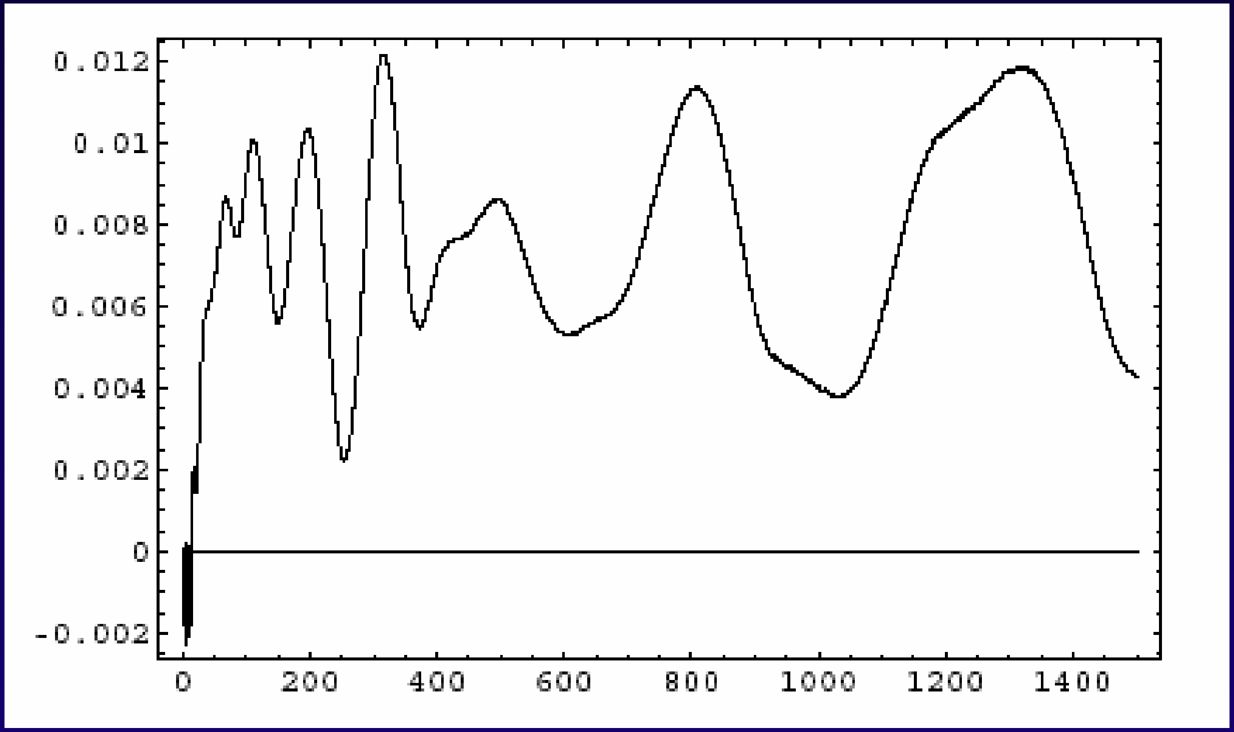
II. Short Scale Modifications to CMB



- $L_{string} = 100L_{planck}$, power law inflation, exponent = 500
- Roughly normalized to CMB
- Size of deviation: $O((H/M_{string})^1)$

II. Impact on Observations

- $\Delta C_l / C_l$



II. Criticisms/Responses

- Large backreaction I: (Tanaka; Goldstein, Lowe):
  - Issue: E(fluctuations)—relative to BD vacuum—on order of V(field).
  - Energy of modes with wavelengths less than Hubble radius, at end of inflation, relative to BD vacuum large—collapse.
  - Resolution: $(M_{string})^4 \ (H/M_{string})^2 < (M_{planck})^2 H^2$, i.e. $M_{string} < M_{planck}$
- Large backreaction II: **(Kleban, Kaloper, Lawrence, Shenker, Susskind)**
  - What are modes doing “before” creation? (Looking inside box.)
  - Need to modify modes up to $e^{65} M_{string}$. Large backreaction.
  - Responses: Only think outside the box; Ignorance of subplanck Physics; Degree of fine tuning; Look for signature.

- Boundary Effective Field Theory: Control Backreaction

II. Boundary Effective Field theory and the CMB

- Encode Boundary Conditions in Boundary Effective Field Theory
  (Schalm, Shiu, Van der Schaar; Poratti; BRG, Schalm, Shiu, Van der Schaar)
  - Boundary data: Specified on spacelike hypersurface, **$t = t_0$, for all modes**.
  - Previous approach: Specified on fixed energy surface:
    New Physics Hypersurface (NPH)—**different times for diff modes.**
- $S = S_{Boundary} + S_{BULK}$
  - Choose $S_{boundary}$ to encode BD boundary conditions.

$$S^{BD}_{Bound} = \int_{t=t_0} d^3x\sqrt{g^{(3)}}\left(-\frac{1}{2}\mu_{BD}\phi^2\right)$$

  - One-loop corrections:

    S_{BULK}: $O((H/M)^2)$ (dim 6 op.)

    $S_{BOUNDARY}$: $O(H/M)$. (3d QFT, dim 4 op.)

$$\mu^{Corrected}_{BD} = \mu_{BD} + \frac{\beta}{M}\left(\frac{k^2}{a(t_0)^2}\right)$$

- Contriubtion to P(K):

$$P(k) = P(k)_{BD}\left(1+\beta\frac{k}{a(t_0)M}\sin\left(\frac{2k}{a(t_0)H}\right)\right)$$

II. Boundary Effective Field theory and the CMB

- Comparison:
  - Boundary EFT: $$P(k) = P(k)_{BD}(1+\beta \frac{k}{a(t_0)M} \sin(\frac{2k}{a(t_0)H}))$$
  - NPH: $$P(k) = P(k)_{BD}(1-\frac{H}{M_{st}} \sin(\frac{2}{H/M_{st}}))$$
- EFT: explicit scale dependence (at fixed t, can distinguish diff k modes).
- . NPH: scale dependence only from background (H(K))
- EFT: Larger k, larger amplitude (large k, closer to boundary).
- NPH: Larger k, smaller amplitude (large k, late exit, small H).

II. Parameterized Modifications:

Final Example: Generic Deviation from Thermality

(BRG, Parikh, Van der Schaar)

- Black Holes are not precisely thermal (Parikh, Wilczek)
  - Radiation constituents have $M < M_{black\ hole}$ ⇨ truncated thermal tail.
  - $T = T(r_{horizon})$; $r_{horizon}$ changes as radiation emitted ⇨ violation of strict thermality.
- BD Vacuum:
  - BD vacuum *is* precisely thermal.
  - Physically: DeSitter Vacuum state **NOT** precisely thermal:
    - ✓ Truncated thermal tail no thermal emission with $M>M_{narai\ Black\ Hole}$
    - ✓ Desitter Horizon backreacts from emission as in black hole case.

$$e^{-\frac{E}{T}} = e^{-\frac{2\pi E}{H}} \rightarrow e^{-\frac{2\pi E}{H}(1+\frac{EH}{8\pi M_{Planck}^2})}$$

- **Implication: BD vacuum receives universal correction.**
  - **Result:**

$$P_{BD}(k) \rightarrow P_{BD}(k)(1+\frac{1}{4e^{\pi}}(\frac{H(k)}{M_{Planck}})^2)$$

II. Summary of Corrections

Correction Type	Change to Spectrum
New Physics Energy Hypersurface	$O(H/M_{string})$
Boundary Effective Field Theory	$O(H/M_{string})$
Bulk Effective Field Theory	$O((H/M_{string})^2)$
Universal Thermal Correction	$O((H/M_{Planck})^2)$

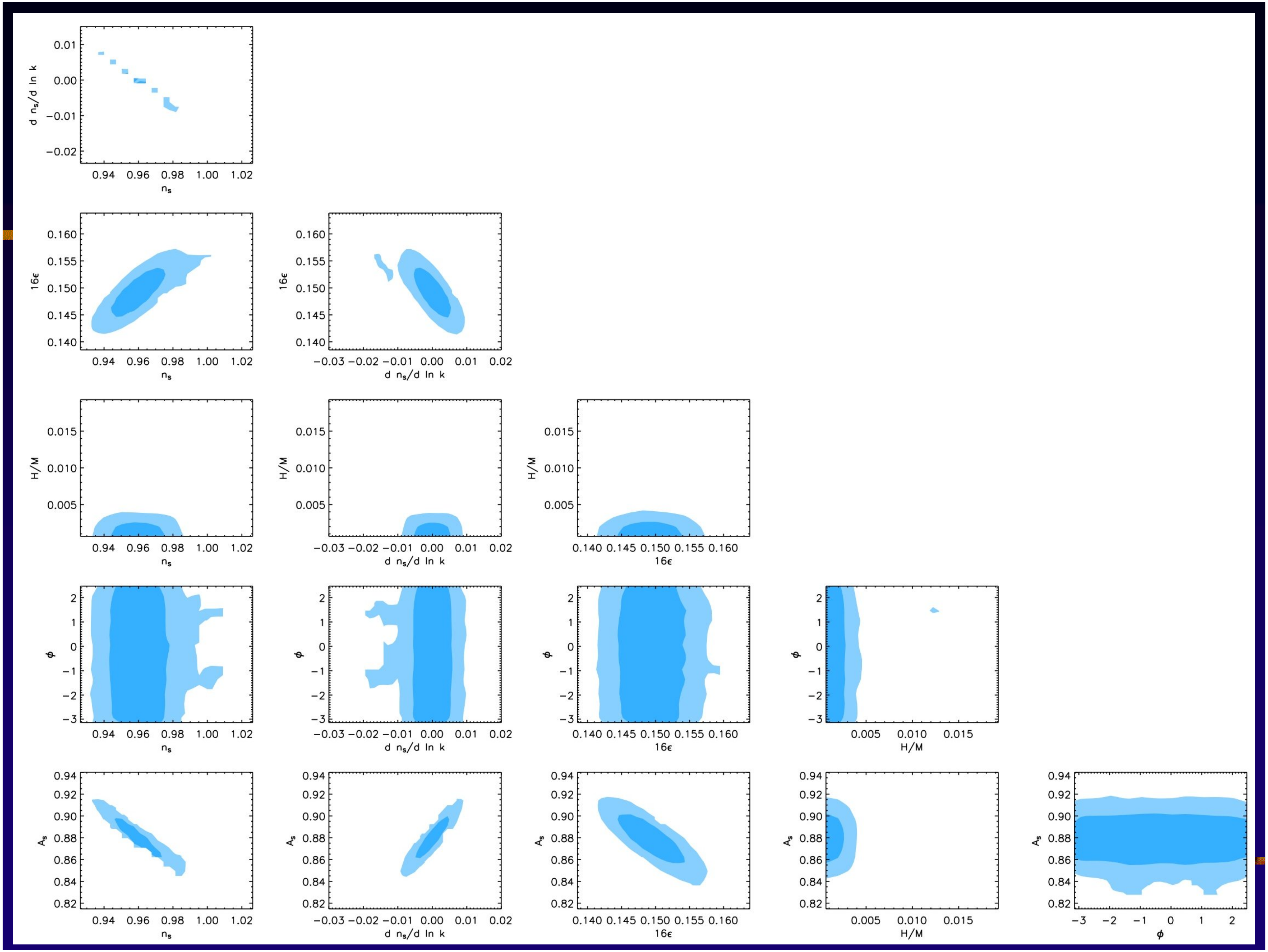
III. OBSERVATIONS

- Can these corrections be seen/measured?

(Bergstrom, Danielsson; Elgaroy, Hannestad; Okamoto, Lim; Martin, Ringeval; Verde, et. al.; Spergel, et. al.; Easther, Kinney, Peiris).

- Tight connection between observing tensor mode and TP Physics (Easther, Kinney, Peiris)

- Representative case (EKP): NPH
  - High Scale Inflation/Large Tensor Mode Signal (r=.15)
    Transplanck signature detectable for H/M >.004
  - Low Scale Inflation/Small Tensor Mode Signal (r=.00013)
    Transplanck signature detectable for H/M >.03


d n_s/d ln k
n_s
16ε
d n_s/d ln k
H/M
ϕ
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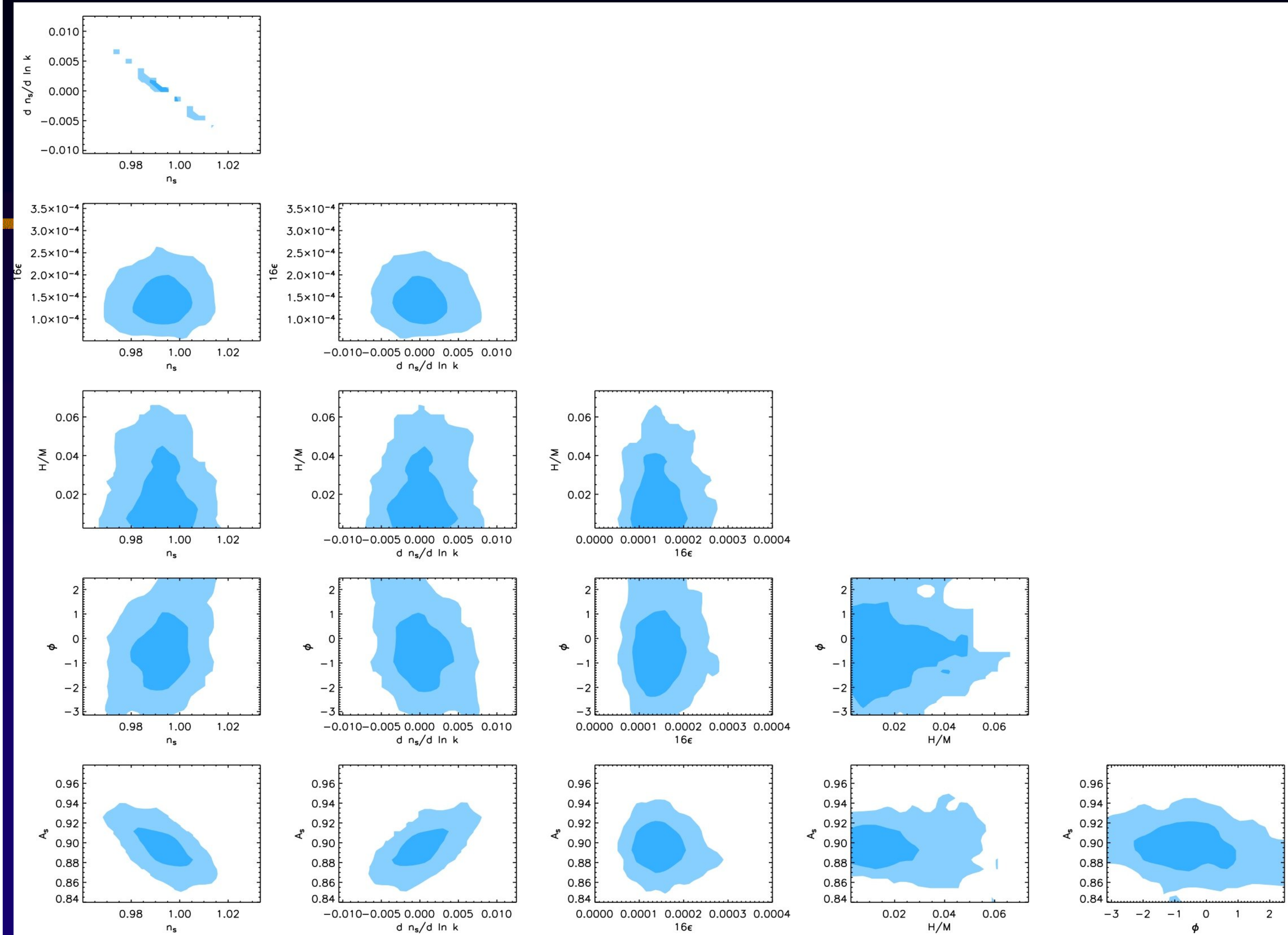

d n_s/d ln k
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16ε
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H/M
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Conclusions

- Modifications to vacuum can yield effects sensitive to first order variation from standard vacuum choice.
- Conclusions sensitive to assumptions about initial conditions and overall model.
- Overall Point: Cosmological window on Planckian Physics is a promising alternative approach—by refining these rough ideas we just might one day make experimental contact.
- Stringy effects may be closer to the surface in cosmology than in particle physics.