Transplanckian Physics and the CMB

Discussion Session

KITP

September 16, 2003

Basic Question

- 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?

- 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. Leave Imprint?
- Only way to know for sure:
  Calculate perturbations standard way.
  See if string/quantum gravity modifies in significant way.

Outline

- Standard Calculation.
- Possible Modifications. Affect on CMB.
- Criticisms/Responses.

Spectrum: Standard Results

- Consider Tensor Modes:

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

- Expand in Traceless Symmetric Modes:

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

- Equations of Motion:

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

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

Spectrum: Standard Results

- Quantum Mechanics:

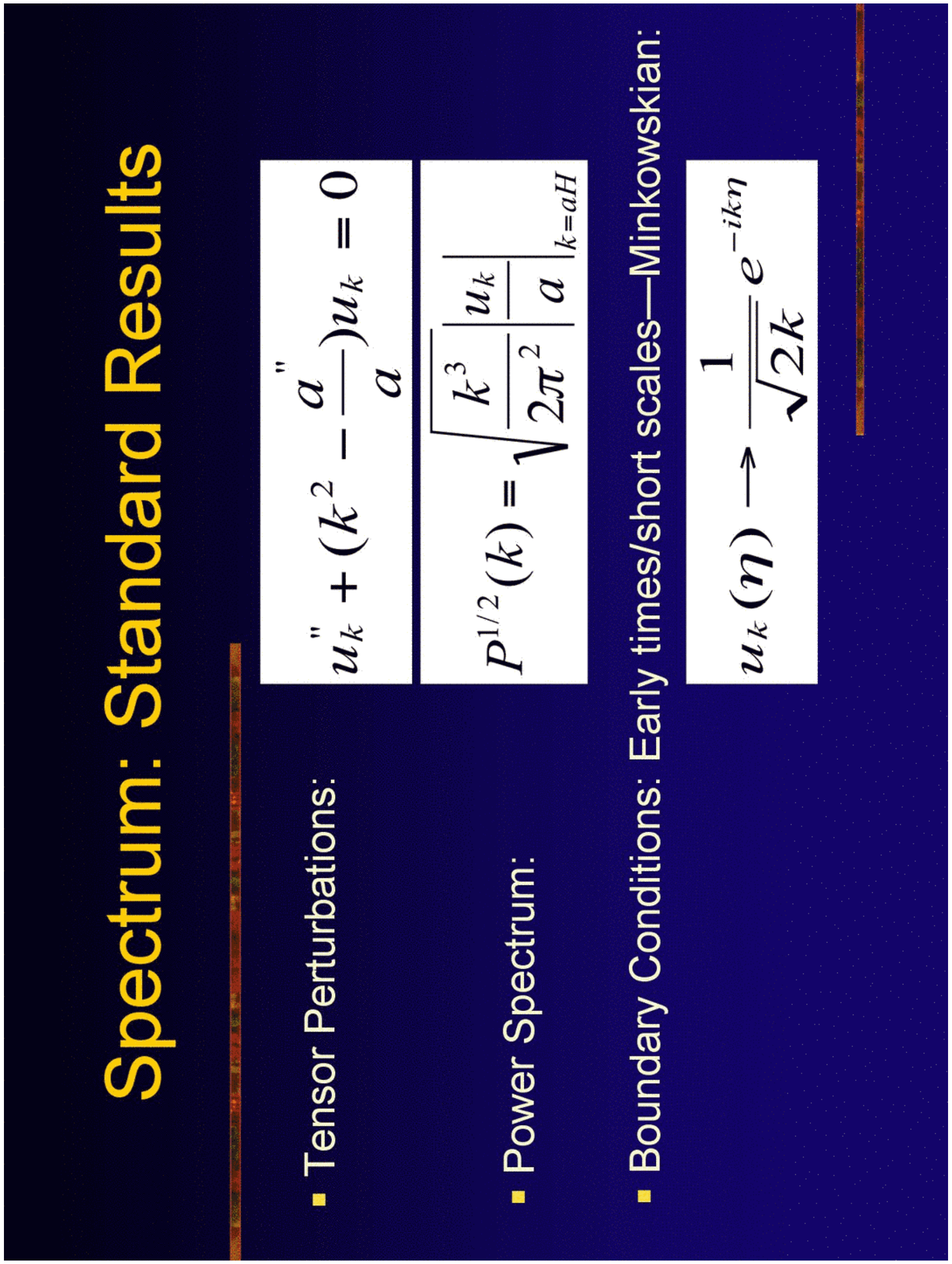
$$\hat{u}(\eta, x) = 1/(2\pi)^{3/2} \int d^3k[\hat{a}_k(\eta)e^{ikx} + \hat{a}_k^{\ +}(\eta)e^{-ikx}]$$

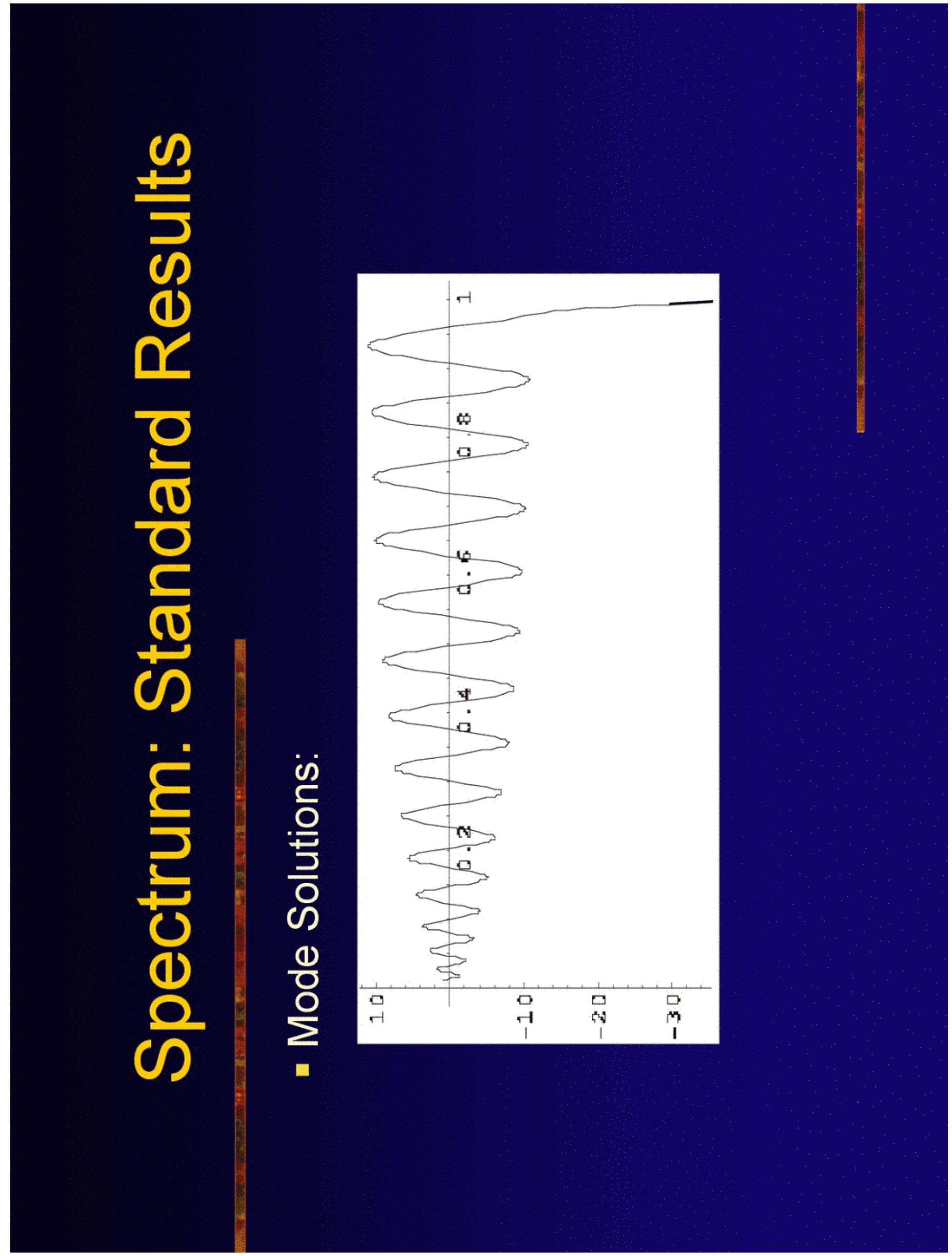
$$\hat{a}_k(\eta) = \alpha_k(\eta)\hat{a}_k(\eta_i) + \beta_k(\eta)\hat{a}_{-k}^{\ +}(\eta_i)$$

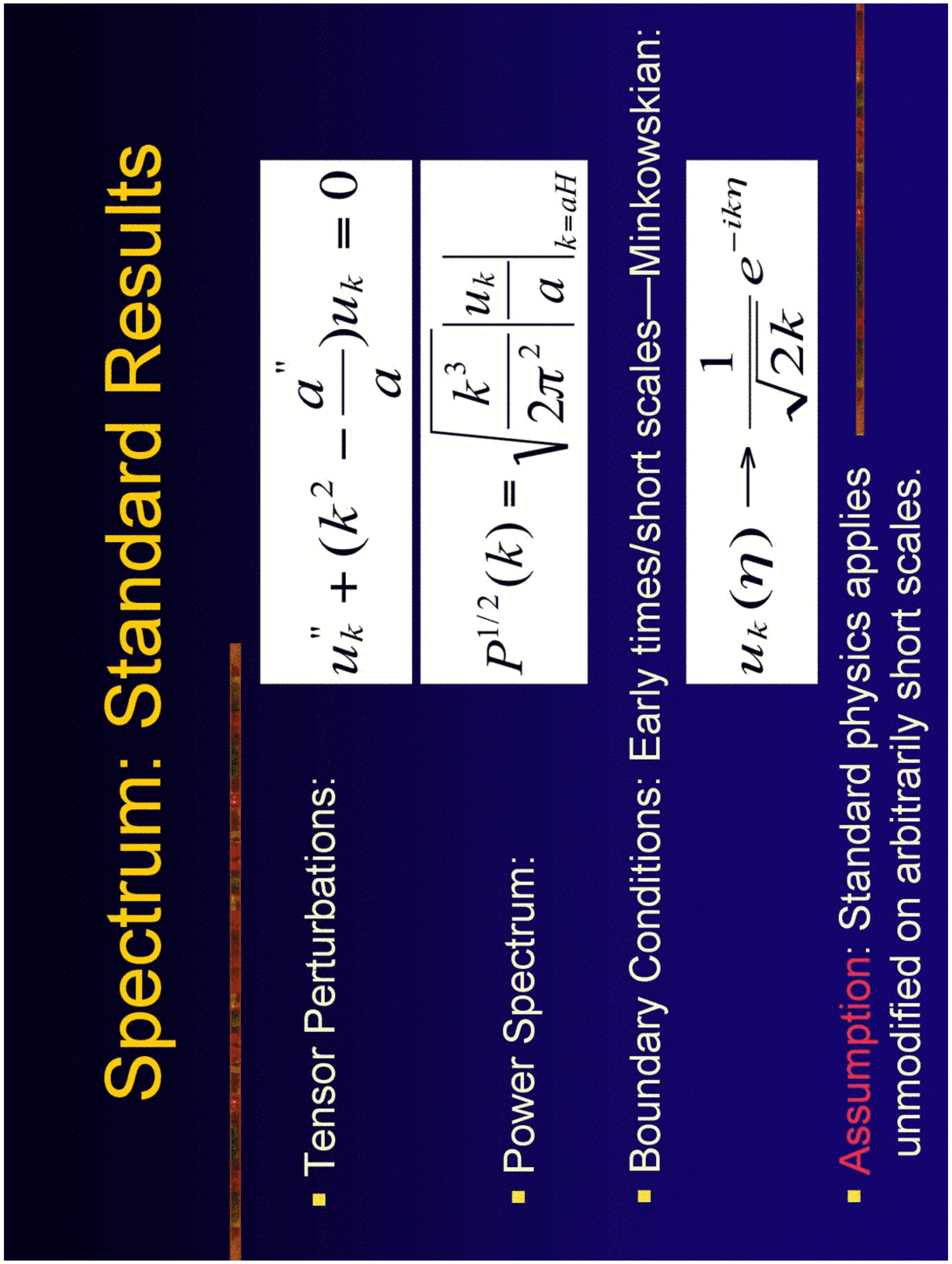
$$\hat{a}_k(\eta) \rightarrow (\alpha_k + \beta_k^{\ *})(\eta)\hat{a}_k(\eta_i) = u_k(\eta)\hat{a}_k(\eta_i)$$

- Measure of Fluctuation: Power Spectrum/Two Point Fcn

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


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


Spectrum: Standard Results
Mode Solutions:
0.2
0.4
0.6
0.8
1
10
-10
-20
-30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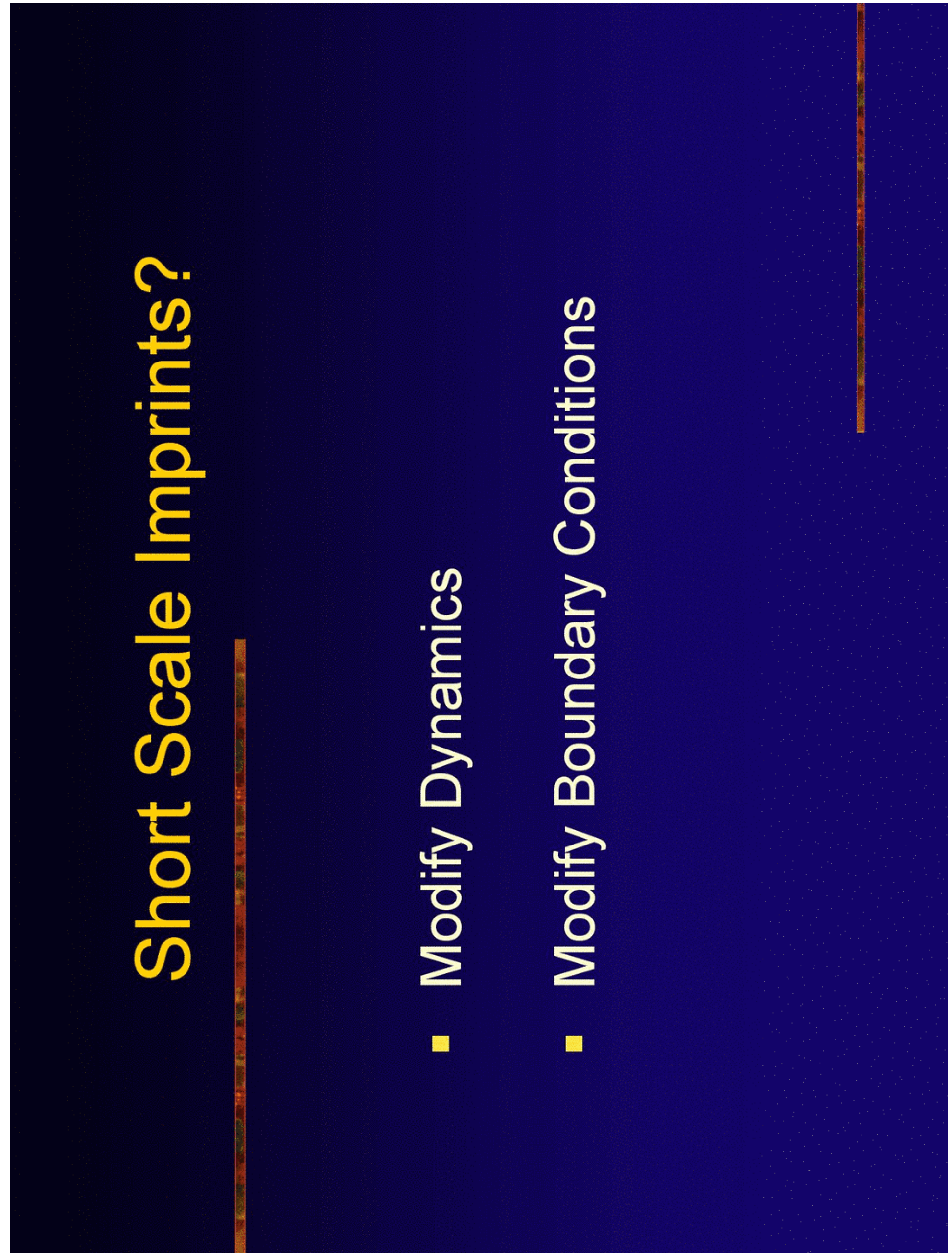
Boundary Conditions: Early times/short scales—Minkowskian:
$u_k(\eta) \to \frac{1}{\sqrt{2k}} e^{-ik\eta}$
Assumption: Standard physics applies unmodified on arbitrarily short scales.


Short Scale Imprints?
Modify Dynamics
Modify Boundary Conditions


SHORT SCALE IMPRINTS
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


SHORT SCALE IMPRINTS
Modify Short Scale Boundary Conditions:
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

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.

Modify Initial State

- Usual Case:

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

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

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

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

- Modify: $\beta_k(\eta_k) = 0$

$$u^{\text{mod}}{}_k(\eta) = A_k u_k(\eta) + B_k u_k^{*}(\eta)$$

Short Scale Modifications to CMB

- Vacuum: For each k, set vacuum at critical time
  $\eta = \eta_k$ when $k/a = p = 1/L_{st}$; $\eta_k = -1/(L_{st}Hk)$
- Condition: $\beta_k = 0$ at $\eta = \eta_k$. (Danielsson)
  That is: $|A_k|^2 = 1/(1-|b_k|^2)$ with $b_k = -1/(-1+2ki\,\eta_k)$
- Then:

$$P_k = \frac{k^3}{2\pi^2}\frac{|u_k|^2}{|a|^2} = \left(\frac{H}{2\pi}\right)^2\left(1+|b_k|^2 - b_k e^{-2ik\eta_k} - b_k^* e^{2ik\eta_k}\right)\frac{1}{1-|b_k|^2}$$

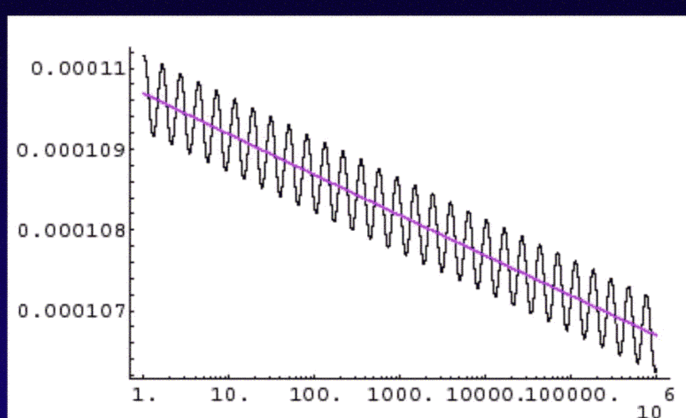
$$P_k = \left(\frac{H}{2\pi}\right)^2\left(1-\frac{H}{M_{st}}\sin\left(\frac{2}{H/M_{st}}\right)\right)$$

- As $\eta_k \to -\infty$ we recover standard result

- (Easther,BRG,Kinney,Shiu)

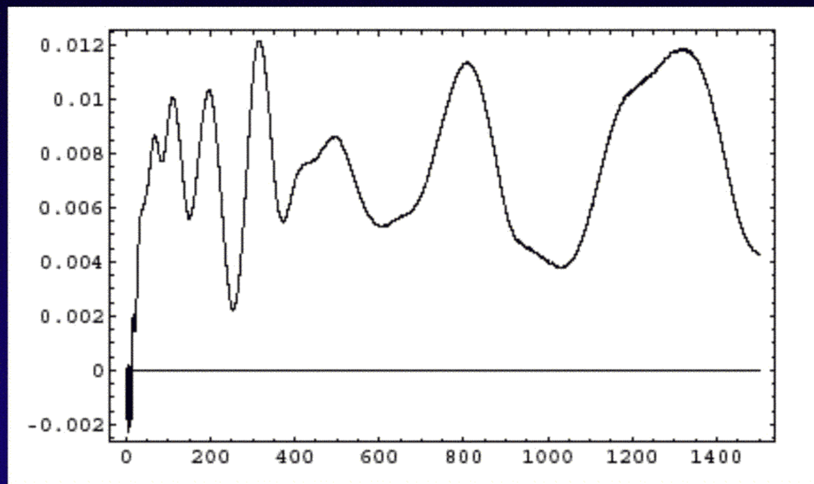
If not in deSitter space, modulation in k. Effects are $O(H/M_{st})$.

Short Scale Modifications to CMB



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

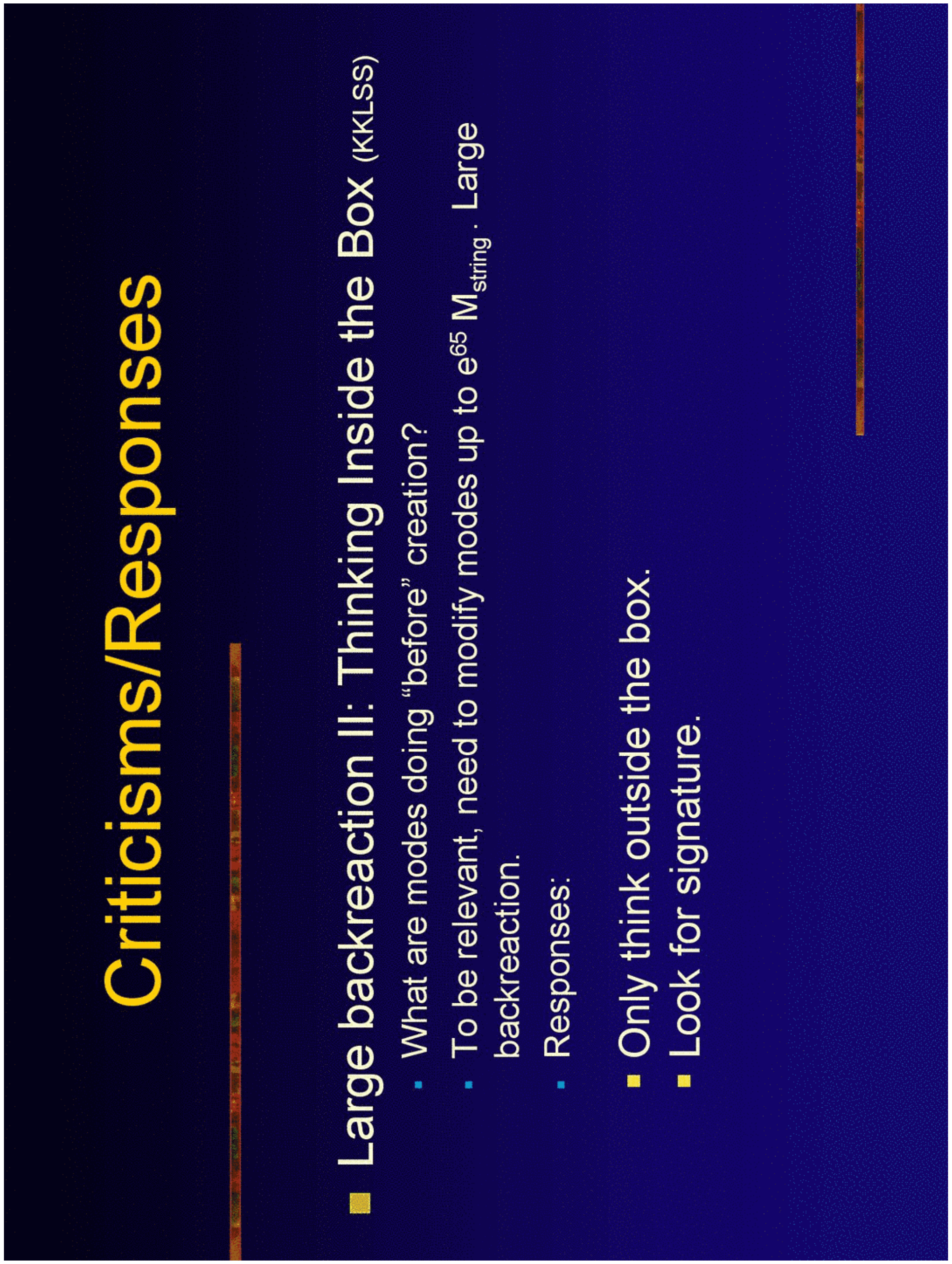
Impact on Observations



- $\Delta C_l / C_l$

Criticisms/Responses

- Problems with α-vacua.
  - Not relevant: only modify of sufficiently long wavelength.
  - Problems addressed (?)
- Large backreaction (Tanaka,hep-th/0112431; 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. $M_{string} < M_{planck}$


Criticisms/Responses
Large backreaction II: Thinking Inside the Box (KKLSS)
What are modes doing "before" creation?
To be relevant, need to modify modes up to e^{65} M_{string} . Large backreaction.
Responses:
Only think outside the box.
Look for signature.