Is Inflation Robust?

Can trans-Planckian Physics be seen in the CMB?

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Outline

- The CMB and Inflation
- Sensitivity to Trans-Planckian Physics?
  - What of Decoupling?
- Two Models
  - Hybrid Inflation
  - Linear Couplings
- Conclusions
The Cosmic Microwave Background

![Microwave Background Image]

- **Brightness $\delta$ (erg cm$^{-2}$ sec$^{-1}$ Hz$^{-1}$)**
- **Frequency [GHz]**
- **Angular scale in degrees**

**Legend**:
- **FIRAS**
- **COBE satellite**
- **CMB**
- **COBE satellite**
- **LPR - Italy**
- **White Mts & South Pole**
- **Princeton ground & balloons**
- **UBC sounding rocket**
- **Cyrusoptical**
- **2.5K blackbody**

**COBE DMR**

- **Temperature fluctuations $\Delta T$ (mK)**
- **Multipole $l$**

10/27/02 Trans-Planckian Inflation
Current precision measurements of the CMB temperature anisotropies begin to redundantly constrain the parameters of the Big Bang Model.

*eg: amplitude of scalar fluctuations*
Inflation and the CMB

Primordial metric fluctuations produced during an early inflationary phase describe well the CMB anisotropy.

\[ n_s = 1 - 6\varepsilon + 2\eta \]

M. Tegmark
Fluctuation Evolution

- Fluctuation amplitudes:
  - Damped oscillations if $\lambda < H^{-1}$
  - Freeze at $H$ if $\lambda > H^{-1}$
- During Inflation:
  $$\lambda \propto a = e^{Ht} \; ; \; H = \text{const.}$$
- Radiation domination:
  $$\lambda \propto a = \sqrt{t} \; ; \; H \propto 1/t$$
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A Window Onto Trans-Planckia?

- At long wavelengths the CMB bears the imprints of initially microscopic fluctuations.
  - Exponentially inflation implies scales which are currently cosmological can have originated as sub-Planckian during Inflation.
- Proposals for sub-Planckian physics:
  - Modified dispersion relations;
  - Modified commutation relations;
  - Modified boundary conditions and non-standard $\alpha$-vacua;.....
A Trans-Planckian Poll

Can Be Seen:

- Martin & Brandenberger, (hepth/0005209, hepth/0005432, astroph/0012031, hepth/0201189);
- Easther, Greene, Kinney & Shiu, (hepth/0104102, hepth/0110226, hepth/0204129);
- Tanaka, (astroph/0012432);
- Danielsson, (hepth/0205227, hepth/0210058);
- Goldstein & Lowe, (hepth/0208167);
- Starobinsky, (astroph/0104043);
- Niemeyer & Parentani, (astroph/0101451);
- Kempf & Niemeyer, (astroph/0103225);
- Bastero-Gil, (hepph/0106133);
- Shiu & Wasserman, (hepth/0203113).

Must be smaller than $H^2/M^2$:

- Kaloper, Kleban, Lawrence & Shenker, (hepth/0201158);
- Kaloper, Kleban, Lawrence, Shenker & Susskind, (hepth/0209231).
What of Decoupling?

- Progress in physics has been possible because short-distance scales decouple from longer-distance physics.
  - *eg:* Atomic physics is insensitive to details of nuclear physics; Cosmology is largely sensitive only to the equation of state of constituent matter,..
  - In practice this allows us to understand nature one scale at a time.
- Does inflation violate this decoupling?
  - If so, are meaningful comparisons with observation possible?
  - If not, how can very-high energies possibly alter the physics of horizon exit?
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Two Models

- Examine the issue within two mundane models:
  - Use of ordinary higher energy physics allows explicit calculation of decoupling issues.
  - By dropping exotic properties can better trace what is required in order to have an influence on inflation.
  - Once trans-Planckian physics is understood, its predictions require a mundane benchmark in order to be interpreted.

\[
L = \partial \phi \partial \phi + \partial \chi \partial \chi - V(\phi, \chi)
\]

\[
V_1 = V(\phi) + \lambda (\chi^2 - \nu^2)^2 + g\chi^2\phi^2
\]

\[
V_2 = V(\phi) + M^2 \chi^2 + g'\chi\phi^2
\]
Model 1: Hybrid Inflation

- Standard Hybrid inflation starts with the inflaton, $\phi$, at the bottom of a steep potential-energy trough.
- Sufficient inflation requires the trough to be steep in transverse directions: $M \gg H$.

$$V_{\text{int}} = g\chi^2 \phi^2$$
Heavy-Field Oscillations

- Variant: start with initial oscillations of the heavy field, $\chi$, about the trough’s bottom.
- Because $M$ is large:
  - The oscillations are not adiabatic.
  - The heavy field does not decouple, since it is a bad approximation to try to integrate it out.
- Could such oscillations be seen in the CMB?
Possible Pre-Inflationary Period

- If the $\chi$ oscillations have a large enough amplitude they can dominate the universe, implying a pre-inflationary phase.
- Initially consider initial amplitudes which are not large enough to do so.
The $\chi$ oscillations are imprinted on the inflaton motion at horizon exit.

- Tends to suppress inflaton fluctuations on large scales.
Observed Features

- Oscillation amplitude damps as $A \approx a^{-3/2}$ and so eventually damps away.
  - Can have up to 14 $e$-foldings before the horizon exit of CMB-relevant scales.

- Dominant effect is large suppression at small $k$.
  - Due to constant in: $\chi^2 \propto \cos^2(Mt) \propto 1 + \cos(2Mt)$

- Amplitude $g\chi^2/H^2 \approx 10^{-5}$ similar to $n=1.05$ tilt.
Implications for the CMB

- Computed using CMBFAST: 
  \( g\chi^2 \) in units of \( H^2 \) at h.e.
- Normalization at \( l=10 \) causes a tilt to the CMB spectrum.
Choosing a trilinear coupling can change the implications for the CMB.

- Can produce an observable effect for up to 30 e-foldings before horizon exit.
- Can produce dominant effects for larger values of $k$.

$$V = V(\phi) + \frac{M^2}{2} \chi^2 + V_{\text{int}}$$

$$V_{\text{int}} = g' \chi \phi^2$$
Model-2 Evolution

- Reduced sensitivity to small $k$: $\delta P_k \approx g' \chi_0 / M^2$.
- Large $k$ limit is $M$ independent.
Implications for the CMB

- Main effects are moved to larger $k$.
- Fast oscillations are washed out, but slower modulations leave their mark on the CMB.
- Due to slower damping of $\phi^2$ coefficient, CMB can be sensitive to up to 30 $e$-foldings before horizon exit.
A pre-inflationary phase with no $g'\chi\Phi^2$ term suppresses fluctuations for largest scales.

The $\chi-\Phi$ couplings can partially compensate for this.
Some trans-Planckian proposals involve the preparation of the inflaton in $\alpha$-vacua.

These states have been criticized as being unphysical, and so not obtainable in principle.

Since these vacua are produced from the standard FRW vacuum by non-adiabatic evolution, our calculation shows that there cannot be problems in principle with having fields prepared in $\alpha$-vacua during inflation, provided this only occurs up to a maximum value for $k$.

$$w_k = u_k \cosh \alpha_k + e^{i\delta} u_k^* \sinh \alpha_k$$
Perturbative Induction of $\alpha$-vacua

$$\delta \varphi_k = \int dt' G_k(t, t') \chi^n_k(t')$$

$$G_k(t, t') = u_k(t) u^*_k(t') - u_k(t') u^*_k(t) \quad t > t'$$

$$= 0 \quad t < t'$$

- Non-adiabatic evolution produces $\alpha$-vacua, but only for those momenta for which $k < M$.
  - $M$ is the scale of the non-adiabatic evolution.
  - Transition from pre-inflationary phase produces $\alpha$-vacua from FRW vacuum for $k < H$ modes (Ford & Vilenkin, 1982).
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Conclusions and Outlook

- Can have our cake and eat it too:
  - No effects for CMB if inflation lasts long enough before horizon exit: *Can sensibly compare standard inflationary predictions with observations.*
  - Not impossible to see higher-energy adiabatic physics: *Should search for deviations from standard predictions.*

- If trans-Planckian physics obeys usual decoupling properties (as string theory seems to do) changes to inflation likely to involve non-adiabatic physics.

- Nonstandard $\alpha$-vacua can make sense for $k$ up to a cutoff.

- Once trans-Planckian calculations become possible, it will be necessary to compare them to ordinary physics like that described here.