Inflation as a window into short distance physics

Strings 2002

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" + Leonard Susskind

Experimental probes of string/M theory are hard to come by.

m_s is high (except for TeV strings).

The Big Bang tells us to expect very high energies in the early universe.

The earliest currently accessible signals, the Cosmic Microwave Background are usually thought to arise from inflation.

Inflation: a period of ~~exponential~~ rapid exponential expansion

$$ds^2 = -dt^2 + a^2(t)\, d\vec{x}^2 \quad \text{de Sitter}$$

$$a(t) = e^{Ht}$$

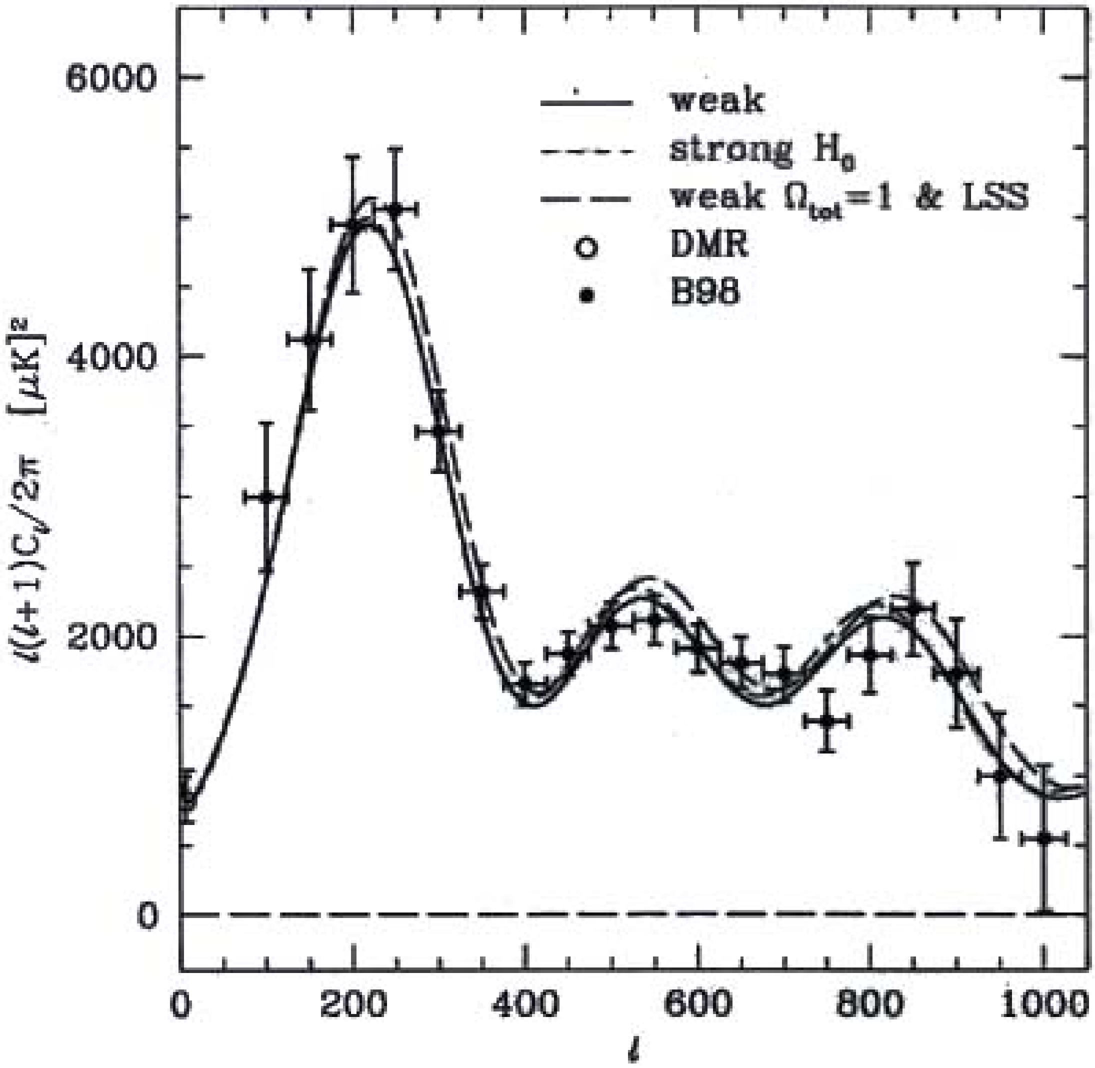
Simplest models of inflation give

$$H \sim 10^{13} - 10^{14} \text{ GeV} \qquad (!)$$

Not necessary (hybrid inflation, $H \sim$ TeV

H measurable. (r for large H) B-mode pol.

Boomerang



$$\sigma_{\text{cosmic variance}} \sim \frac{1}{\sqrt{2l+1}}$$

$\sim .01$ (avged)

($l \sim 1000$)

Reasonable assumptions and current experiments lead to a situation with an immensely powerful 10^{14} GeV thermal "accelerator" in the sky, and detectors capable of 1% measurements on line now

This is too juicy to pass up.

A number of groups have studied the possible effects of new physics characterized by a heavy mass M on the CMB.

Brandenburger, Martin
Kempf, Niemeyer
Easther, Greene, Kinney, Shiu

These groups use simple models to explore qualitative nature of the effects.

They found effects of strength

$$\sim \frac{H}{M} \quad \text{or} \quad \sim \left(\frac{H}{M}\right)^2$$

depending on choices we will discuss later

To resolve open questions and to learn to calculate quantitatively in more realistic models we formulated a systematic calculation.

The ideas are simple:

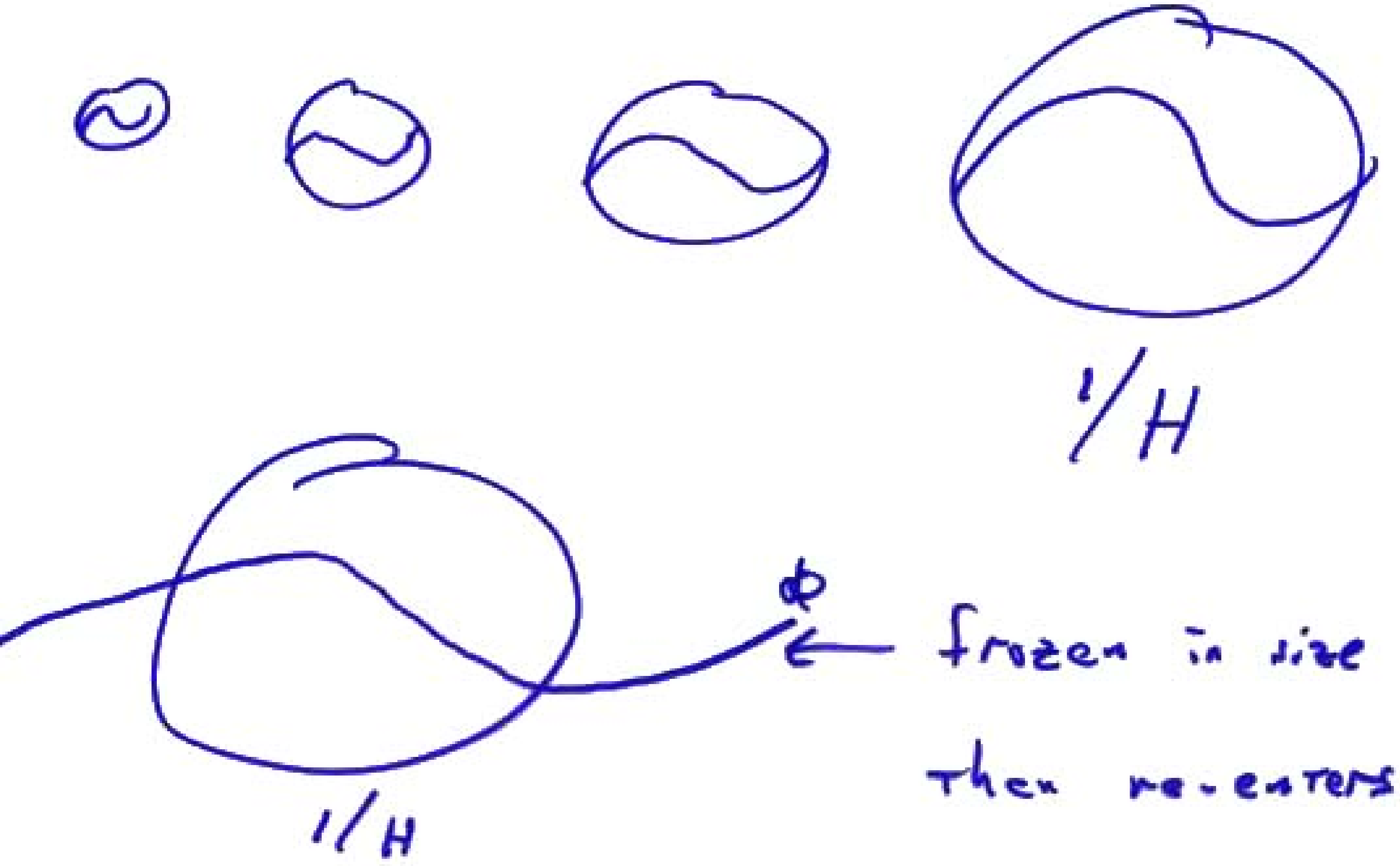
1) Following standard inflationary thinking we argue that rapid expansion effectively dilutes, or erases or inflates away any reasonable excitation above the usual vacuum of the system. For instance 60 e-foldings of inflation will reduce an excess energy density ε to $e^{-240}\varepsilon$. This idea is responsible for the predictivity of inflation. We use it to justify use of the standard vacuum

2) $H < m_p \, , m_s$

so effective field theory description appropriate. (Strings in de Sitter? ...)

3) $\frac{\delta\rho}{\rho}$ (ρ energy)

$\sim \delta\phi$ $\quad \phi$ inflaton field



$\delta\phi$ determined by fluctuations at length scale $1/H$

$$(\delta\phi)^2 \sim \langle \phi(p)\,\phi(-p) \rangle \Big|_{p \sim H}$$

standard field theory quantity at rel. low. energy

4) Write an Effective Field Theory for ϕ assuming heavy scale M (ignore interactions)

$$S_{eff}(\phi) \sim \int d^4_p\ \phi(p)\phi(-p)\left(\frac{p^2}{2} + \frac{c_1}{2}\, p^2 \frac{H^2}{M^2} + \frac{c_2}{2}\frac{p^4}{M^2} + \cdots\right)$$

from

$$(\delta\phi)^2 = \langle \phi(p)\, \phi(-p) \rangle \Big|_{p=H}$$

put $p = H$ into S_{eff} and find

$$(\delta\phi)^2 \sim \frac{H^2}{2} \left(1 + (c_1 + c_2) \frac{H^2}{M^2} + O\left(\frac{H}{M}\right)^4 \right)$$

$$\downarrow \quad \frac{\delta\rho}{\rho} = \text{ordinary} \left(1 + \text{const} \left(\frac{H}{M}\right)^2 + \cdots \right)$$

<u>const</u> calculable. Compute correction in flat space string / M theory to determine c_1, c_2

There has been some disagreement about this line of argument.

Brandenburger, Martin
Danielsson
Easther, Greene, Kinney, Shiu

These groups argue that not all excitations above the usual, "adiabatic" vacuum, inflate away. In particular they discuss a family of de Sitter invariant states first described by Mottola, and by Allen, further discussed by Wald and studied in the context of dS/CFT by Bousso, Maloney, Strominger. These vacua produce effects ~ (H/M)

Our conclusion is that these vacua are unphysical, unacceptable candidates for an inflating universe.

Review basic properties of these (α) vacua.

inflating coords

$$a_k \, | \text{adia} \rangle = 0$$

↓ Bogolubov transform $\qquad \alpha \in \mathbb{C}$

$$N_\alpha \left(a_k - e^{\alpha^*} a_k^+ \right) | \alpha \rangle = 0$$

α indep of k so quanta excited for arb. high k. $|\alpha\rangle$ differs from $|\text{adia}\rangle$ at arb short distances.

$|\alpha\rangle$ dS inv. does not inflate away

$$\langle\alpha| T_{\mu\nu} |\alpha\rangle = \frac{1+\exp(\alpha+\alpha^*)}{1-\exp(\alpha+\alpha^*)} \langle adia| T_{\mu\nu} |adia\rangle$$

So much more zero pt energy in α.
Cannot just subtract off because inflation connects to our world now, where renormalizations must be consistent.
Implies enormous uncancelled, unphysical energies at some point in cosmological evolution.

Static patch picture:

$|adiabatic\rangle \to$ thermal

$|\alpha\rangle \to$ highly excited, strongly interacting (at stretched horizon)

must thermalize back to $|adiabatic\rangle$

isomorphic to info bring away

Results of calculation

CMB expt. $\sim 10^{-2}$ (need tensor model)

$H \sim 10^{14}$ GeV

$\chi \left(\frac{H}{M}\right)^2$	M	$\chi \left(\frac{H}{M}\right)^2$
pert. string theory	$m_s \sim 10^{19}$ GeV	10^{-11}
H.W. $m_{11} \sim 5 \times 10^{16}$ GeV	$M \sim m_{11}$	10^{-7}
G_2/M theory $m_{11} \sim 10^{14}$ GeV	$M \sim m_{11} \sim 10^{14}$ GeV	10^{-1} ✓

Some models that have not yet been ruled out can be probed by CMB and not by other techniques.

But CMB does not hit a "sweet spot" of string phen., perturbative unification.

Another experimental probe of inflation

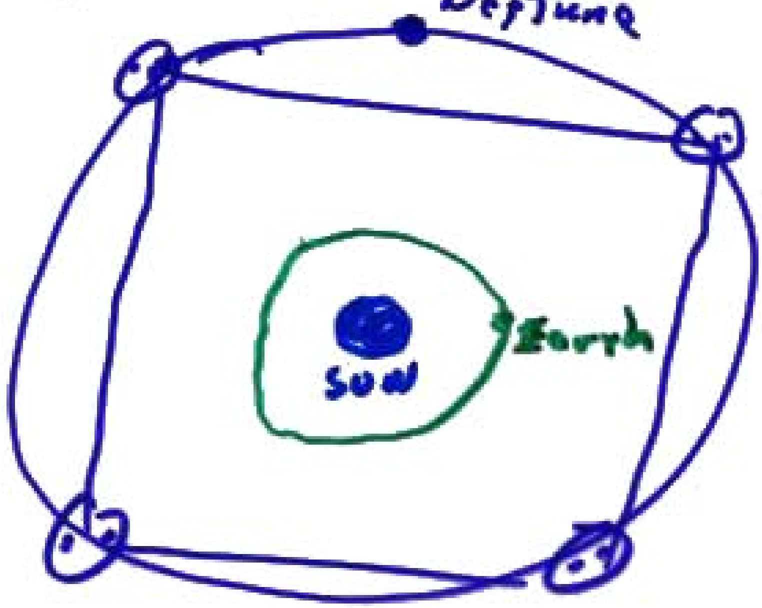
<u>Direct</u> detection of gravitational waves (not polarization of CMB photons)

wavelengths << cosmological, so no cosmic variance constraint (but hard to detect!)

<u>Very</u> optimistic proposal

GREAT project: Cornish, Spergel, Bennett

LISA followup



8 satellites ~10 AU Neptune orbit

Sensitivity ~ 10^{-3} - 10^{-4} Inflation

$\left(\frac{H}{M}\right)^2 \sim 10^{-4} \Rightarrow M \sim 10^{16}$ GeV

Near H.W. !

Note $\frac{H}{M} \sim 10^{-4} \Rightarrow M \sim 10^{18}$ GeV a lot

so this issue is important

Lots of experimental issues to settle but .....

Strings 2052

Neptune