Inflation and String Theory

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Based on: Arkani Hamed and JM,
JM and Pimentel
• Inflation is the leading candidate for a theory that produces the primordial fluctuations.
• The scale of inflation can be very high

\[ H \lesssim 10^{14} \text{ Gev} \]

• Are there possible signatures from string theory?
Standard Paradigm

String theory in ten dimensions
Gravity in ten dimensions
Compactify
Four dimensional effective theory

\[ \int R + (\nabla \phi)^2 + V(\phi) + \ldots \]

Constraints on the parameters of the effective theory?

Is there a constraint on r (tensor/scalar ratio)?

Talk by Uranga, axion monodromy...
Main points

• There are terms in the effective theory that can only arise in string theory.

• We could also produce massive string states during inflation with specific signatures.
• Here we are talking about “strings” as a theory of weakly coupled higher spin particles.

• Inflation is very weakly coupled: \( g_{\text{eff}} \sim \frac{H}{M_{\text{pl}}} \)
Energy scales

\[ M_{pl} \]

\[ H \]

\[ \phi \]

\[ \sqrt{\epsilon H} \]
Energy scales

We do not know whether a Model of this sort is possible. It seems difficult.
Energy scales

\[ M_{pl} \sim \frac{\sqrt{V}}{g} M_s \]

\[ M_{KK}, \quad M_{\text{partners}} \]

Quasi-single field inflation

Chen, Wang
Noumi, Yamaguchi, Yokoyama,
Assassi, Baumann, Green, Porto,
Senatore, Silverstein, Zaldarriaga,
Suyama, Yamaguchi,...
Effects of new particles

- Virtual: Integrating them out (classically).

Local terms in the effective theory

\[ \frac{M_{pl}^2}{H^2} \left[ (\nabla \chi)^2 + \frac{H^2}{M_s^2} (\nabla^2 \chi)^2 + \frac{H^2}{M_s^2} (\nabla \chi)^4 + \ldots \right] \]

\[ g_{eff} = \frac{H}{M_{pl}} \]

2pt:
Kaloper, Kleban, Lawrence, Shenker, Susskind.
Easter, Greene, Kinney, Shiu, …

Larger than expected from gravity as an effective theory

\[ M_s \rightarrow M_{pl} \]
Effects of new particles

• Virtual: Integrating them out (classically). Local terms in the effective theory
  \[ \left( \frac{H}{M_s} \right)^n \]

• Real particles which then decay and imprint signatures on the inflaton. Non-local in the effective theory.
  \[ \exp \left( -\frac{M_s}{H} \right) \]

• Producing cosmic strings
  \[ \exp \left( -\frac{M_s^2}{H^2} \right) \]

Copeland, Myers, Polchinski
Virtual corrections

• Are there local corrections that do not arise classically in local gravity theories? (Einstein + QFT)

• Example: Three graviton vertex correction.

\[ A_{grav} \sim \epsilon^3 k^2 , \quad \int R \]

\[ A_{other} \sim \epsilon^3 k^6 , \quad \int R^3 \quad o(H^4/M_s^4) \]
Why is $R^3$ a signature of strings?

- In flat space $\rightarrow$ This leads to an asymptotic causality violation that cannot be fixed (at tree level) by adding new particles with spins $S \leq 2$.

- Need higher spin particles $\rightarrow$ Regge behavior of amplitudes.

Camanho, Edelstein, JM, Zhiboedov
Observability

• The gravity two point function has not yet been observed.

• The three point function is much harder...

• Because gravity is weakly coupled...

\[ g_{eff} \sim \frac{H}{M_{pl}} \]
New particles

• Massless or very light particles (specially spin zero ones) can give rise to large effects:
  - Isocurvature fluctuations
  - Non gaussianities in the squeezed limit.
  - None observed so far…

\[ m \sim \sqrt{\epsilon H} \]
New massive particles

• Are produced for \( m \sim H \)
• Massive particles are rapidly diluted by the expansion of the universe.
• Could lead to interesting effects if they decay to the inflaton.

Quasi-single field inflation

Chen, Wang
Noumi, Yamaguchi, Yokoyama, Assassi, Baumann, Green, Porto, Senatore, Silverstein, Zaldarriaga, Suyama, Yamaguchi,...
Four point function in de Sitter

\[ \langle \zeta(k_1)\zeta(k_2)\zeta(k_3)\zeta(k_4) \rangle \]

\( \vec{k}_I = \vec{k}_1 + \vec{k}_2 \)

Inflaton $\rightarrow$ massless scalar field in de-Sitter.
Cosmological double slit experiment

\[ |\Psi_{\text{nopair}} + \Psi_{\text{pair}}|^2 \]
Interesting limit:

\[ k_I = |k_I| \ll |\vec{k}_i| = k_i, \quad i = 1, 2, 3, 4 \]
\[ \langle 4pt \rangle \propto e^{-\pi \mu} \left[ \left( \frac{k_I^2}{k_1 k_3} \right)^{3/2} + i\mu \right] e^{i\delta} + \left( \frac{k_I^2}{k_1 k_3} \right)^{3/2} e^{-i\delta} \]

\[ \mu = \sqrt{m^2 / H^2 - 9/4} \]
Non trivial power law behavior in the ratio of scales. Oscillatory for real $\mu \rightarrow$ oscillations of the wavefunction

$$\ell = \log \left( \frac{k_{\text{short}}}{k_{\text{long}}} \right) = \text{Time, in e-folds, over which the intermediate particle propagates}$$
\langle 4pt \rangle \propto e^{-\pi \mu} \left[ \left( \frac{k_I^2}{k_1 k_3} \right)^{3/2} + i \mu \right] e^{i\delta} + \left( \frac{k_I^2}{k_1 k_3} \right)^{3/2} - i \mu e^{-i\delta} \]

Oscillatory for real $\mu \rightarrow$ oscillations of the wavefunction
\langle 4pt \rangle \propto e^{-\pi \mu} \left[ \left( \frac{k_I^2}{k_1 k_3} \right)^{\frac{3}{2}} + i \mu \right] e^{i \delta} + \left( \frac{k_I^2}{k_1 k_3} \right)^{\frac{3}{2}} - i \mu e^{-i \delta} \right]

Boltzmann suppression: 
\[ e^{-\frac{m}{2T}} \]

\[ \left| \Psi_{\text{nopair}} + e^{-\pi \mu} \Psi_{\text{pair}} \right|^2 \]
\[ \langle 4pt \rangle \propto e^{-\pi \mu} \left[ \left( \frac{k_I^2}{k_1 k_3} \right)^{3/2} + i\mu \right] e^{i\delta} + c.c. \]

Volume dilution
\[\langle 4pt \rangle \propto e^{-\pi \mu} \left[ \left( \frac{k_I^2}{k_1 k_3} \right)^{\frac{3}{2}} + i\mu \right] e^{i\delta} + \text{c.c.} \]

Explicit phase, function of \(\mu\)

Test of quantum mechanics
Spin

$$\langle 4pt \rangle \sim F(\gamma, \theta, \theta')$$

Further evidence of quantum mechanics! → View it as a measurement of the correlated spins of pair of produced particles.
The answer mainly comes from the two point function from a massive spinning particle $\rightarrow$ fixed by conformal symmetry

$$
\langle \epsilon_1^s \cdot O \epsilon_2^s \cdot O \rangle \sim \frac{[\epsilon_1 \cdot \epsilon_2 - 2(\epsilon_1 \cdot \hat{x})(\epsilon_2 \cdot \hat{x})]^s}{|x|^{2\Delta}}
$$
\[
\frac{\langle 4pt \rangle}{\langle 2pt \rangle^2} \propto \frac{H^2}{M_{pl}^2} e^{-\pi \mu} \left[ \left( \frac{k_I^2}{k_1 k_3} \right)^{3/2} + i \mu \right] e^{i \delta} + c.c.
\]

Overall size is small.

One factor of H/M from each interaction.

Can we find a bigger effect?
Three point functions

• Consider instead the inflationary background.
• Now, we have a time dependent background

$$\phi(t)$$
Only one very small coupling $H/M_{pl}$

Single field inflation

\[ \langle 3pt \rangle \propto \frac{H}{M_{pl}} \frac{\dot{\phi}}{k_1^3 k_3^3} e^{-\pi \mu} \left[ \left( \frac{k_3}{k_1} \right)^{3/2} + i\mu \right] e^{i\delta} + c.c. \]
Spin:

\[ \langle 3 \text{pt} \rangle \propto \frac{\dot{\phi}}{k_1^3 k_3^3} e^{-\pi \mu} \left[ \left( \frac{k_3}{k_1} \right)^{\frac{3}{2}} + i \mu \right] e^{i \delta} + \text{c.c.} \right] P_s (\cos \theta) \]

\[ \times \dot{\phi}(t) \cdot \vec{k}_4 = 0 \]
How difficult is it to detect?

Very
How difficult is it to detect ?

- The standard 3 point function can be viewed as exchanging a graviton.

\[ \langle k_1 k_2 k_3 \rangle \times \dot{\phi}(t) k_4 = 0 \]

JM, Creminelli, Norena, Simonovic, Seery, Sloth, Vernizzi, Kundu, Shukla, Trivedi, Raju,

Talk by Trivedi
How difficult is it to detect?

\[ |\langle 3pt \rangle_{\text{experimental}}^{\text{squeezed}}| \lesssim 5, \]

\[ |\langle 3pt \rangle_{\text{graviton}}^{\text{squeezed}}| \sim |n_s - 1| \sim 0.04 \]
How difficult is it to detect?

\[
\left| \langle 3pt \rangle_\text{massive squeezed} \right| \sim \epsilon e^{-\pi \mu} \left( \frac{k_3}{k_1} \right)^{3/2} \frac{\lambda^2}{M_{pl}^2}
\]

- Assuming gravitational strength couplings \(\rightarrow\) extra small factors.
- Cosmic variance \(\rightarrow\) the number of modes has to grow like the square of the above factor.
- The interactions could be larger than gravitational!
How difficult is it to detect?

Futuristic + luck

Theory with a large $H$ and $M_s$ similar to $H$. Ability to detect vastly more primordial fluctuation modes. e.g. Cosmological 21cm tomography.

Loeb & Zaldarriaga

First non-gaussianity $\rightarrow$ Then squeezed limit and spectrum of particles.
Loops

Faster decay

\[ \left( \frac{k_3}{k_1} \right)^{3+2i\mu} \]

Different volume dilution factor

An extra factor of \( \frac{H^2}{M^2_{\text{pl}}} \)

Higgs, gauge fields, fermions
Some conceptual aspects
Finding new particles: collider physics

• Collider ➔ peaks in the invariant mass distribution.

\[
(\sum k_i)^2
\]
Finding new particles
collider physics

- Collider $\rightarrow$ peaks in the invariant mass distribution.
Cosmological collider physics

- Cosmology $\rightarrow$ peaks in the Fourier transform of the cosmological correlator as a function of

$$\ell = \log\left(\frac{k_{\text{short}}}{k_{\text{long}}}\right)$$

- Spin $\rightarrow$ angular dependence.
De Sitter isometries and conformal symmetry

\[ ds^2 = \frac{-d\eta^2 + dx^2}{\eta^2} \quad \langle O_4(\eta_1, \vec{x}_1) \cdots O_4(\eta_n, \vec{x}_n) \rangle \]

Invariant under de-Sitter isometries.

At late times, de-Sitter isometries act on \( x \) as conformal symmetries.

QFT in a fixed de Sitter background.
Dimensions are quasinormal mode frequencies

\[ ds^2 = \frac{-d\eta^2 + dx^2}{\eta^2} \quad \langle O_4(\eta_1, \vec{x}_1) \cdots O_4(\eta_n, \vec{x}_n) \rangle \]

At late times we can expand

\[ O_4 \sim \sum_i \eta^{\Delta_i} O_{3, i}(\vec{x}) \]

3d operator of conformal dimension \( \Delta_i \)

( Related to conformal dimensions of operator in dual CFT_3 )

Strominger, Witten
Squeezed limit = OPE expansion

\[ O_4 \sim \sum_i \eta^{A_i} O_{3,i}(\vec{x}) \]

Leads to \[ \langle 3pt \rangle \propto \sum_i \left( \frac{k_3}{k_1} \right)^{\Delta_i} c_i \]
Conclusions

• If the string scale was similar to the Hubble scale, then there could be direct signals of string theory in the primordial fluctuations.

• Signals:

• Local effects → terms in the classical lagrangian which are not field theoretic in origin.

• Non-local effects that correspond to real particle production (with spins > 2).
Conclusions

• Requires luck to be observable.

• There are interesting theoretical aspects in how the signal is encoded:
  • Connection between quasinormal frequencies, the dimensions of operators and the squeezed limit of cosmological correlators.
  • Small step towards decoding a cosmological hologram!