Topological Gravity as the Early Phase of our Universe

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with Agrawal, Gukov and Vafa
Outline

- Motivation
- Dualities
- Observations
- String Gas Cosmology
- Topological Scenario
- Phenomenology: comparison with inflation
- An Analogy with particle physics
Motivation: Dualities

- Ubiquitous in string theory
- Essential when parameters are taken to extreme limits
- No effective theory is valid in all of parameter space
- New light modes appear in extreme limits (e.g. distance conjecture)

[Ooguri, Vafa '06]
Early Universe is an extreme limit

\[ T \to \infty, \quad a \to 0 \]

Therefore, it is natural to expect that there is a dual description for the early universe.
Observations: Cosmological puzzles

- Can be rephrased as certain vanishing statements:
  - Horizon problem (homogeneity): $\partial_i \rho(x) = 0$
  - Flatness: $[D_i, D_j] = 0$
  - Nearly scale invariant fluctuations:
    $$\langle \delta(x)\delta(y) \rangle \sim 10^{-10} |x - y|^{0.03}$$
  - Hint at an early universe that is independent of position
Motivation: String gas cosmology

\[ |\tilde{x}\rangle = \sum_w e^{iw\tilde{x}} |w\rangle, \quad |x\rangle = \sum_p e^{ipx} |p\rangle \]

Motivated by T-duality:

\[ p = n/L, \quad w = mL \]

\[ L \leftrightarrow 1/L, \quad n \leftrightarrow m \]

[Brandenberger, Vafa ’89]
[Tseytlin, Vafa ’92] …
Motivation: String gas cosmology

\[ |\tilde{x}\rangle = \sum_w e^{iw\tilde{x}} |w\rangle, \quad |x\rangle = \sum_p e^{ipx} |p\rangle \]

The early universe is $x$-independent (i.e. topological) from the point of view of the operators relevant today.
Duality in the Early Universe

- Proposal: this holds more generally than T-duality/SGC
- Suppose we have two phases/frames (call them I & II)
- We do not know the nature of phase I but we know it is topological from our perspective
Topological Theory

- Even gravity is topological since the graviton of phase I is different from the graviton of phase II.
- Horizon problem (homogeneity) is automatically solved because the topological theory is not sensitive to positions.
- For other aspects we need to know more about the topological phase.
- Consider Witten’s 4d topological gravity as one realization.

[Witten ’88]
Witten’s 4d topological gravity

- Gravity action contains a scale-invariant term:

\[ S \supset \int \frac{1}{g^2} W^2 \]

- Backgrounds that preserve topological invariance have:

\[ W = 0 \]

- Additional sector that contains a BRST-invariant massless field \( \Phi \)
## Phenomenology

### Inflationary Model & Topological Scenario

<table>
<thead>
<tr>
<th>Inflation</th>
<th>Topological Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Homogeneity/Isotropy/Flatness</strong></td>
<td>dS bkg</td>
</tr>
<tr>
<td><strong>(Near) Scale-inv.</strong></td>
<td>Topological phase</td>
</tr>
<tr>
<td><strong>Red Tilt</strong></td>
<td>(quasi-)dS bkg</td>
</tr>
<tr>
<td><strong>Non-Gauss.</strong></td>
<td>(Weakly-broken) Topological phase</td>
</tr>
<tr>
<td><strong>Tensor modes</strong></td>
<td>Positivity of conformal anomaly coefficient ( c ) (due to unitarity)</td>
</tr>
<tr>
<td>( O(\epsilon) ) in simple models*</td>
<td>( O(1) ) for four- and higher-point functions*</td>
</tr>
<tr>
<td>Present due to massless graviton</td>
<td>Absent since graviton is not dynamical in topological phase</td>
</tr>
</tbody>
</table>
Analogy with QCD: Particle Physics

**QCD with 2 flavors**

\[ SU(3)_c \times SU(2)_L \times SU(2)_R \]

Form a condensate \( \langle \bar{q}q \rangle \neq 0 \)

Break \( SU(2)_L \times SU(2)_R \rightarrow SU(2)_V \)

Low energy spectrum contains pions

No spin-1 gauge bosons

**LoSOM**

\[ SU(3)_c \times SU(2)_L \times SU(2)_R \]

Break \( SU(2)_L \times SU(2)_R \rightarrow SU(2)_V \)

Higgs \( SU(3)_c \rightarrow U(1)^2 \)

Low energy spectrum contains pions

2 spin-1 gauge bosons
**Analogy with QCD: Cosmology**

- **Topological Scenario**
  - FLRW Regime
  - Additional sector gives a scalar mode
  - No graviton (no tensor modes)
  - Symmetry breaking pattern dictates behavior of the scalar mode.
  - (cf. EFT of inflation)

- **Inflation**
  - FLRW Regime
  - Inflaton gives scalar mode
  - Graviton present (tensor modes)
  - Inflate

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[Cheung et al. '08]
Conclusions

- String theory dualities lead us to believe that the early universe is described by a dual theory

- Early universe looks topological from our perspective; in particular it is not sensitive to our position variable

- Study cosmology in Witten’s 4d topological gravity as an example

Future directions:

- Other realizations of topological gravity in 4d
- Deeper understanding of the breaking of topological invariance
- Develop tools to systematically compute observables such as non-Gaussianities
Thank you!
Analogy: Scalar gravity

Consider a spontaneously broken CFT (⟨ϕ⟩ = M)

Goldstone boson: the dilaton

We can define a `metric' \( g_{\mu\nu} \equiv \phi^2 \eta_{\mu\nu} \) and write the dilaton action in generally covariant form:

\[
S \sim \int d^4x \sqrt{-g} \left( M^2 R + \mathcal{L}_m + \ldots \right)
\]

See e.g. [Sundrum ’03] and references therein