String Cosmology

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I. Broad Intro: Strings, Gravity, Cosmo.

II. String (or String-Inspired) Models of inflation, including some with distinctive observational signatures (CMBR non-Gaussianity; cosmic strings...)

III. Outlook

Note: incomplete referencing (large subject...
Schematic Big Picture: (our patch)

↑

time

Dark Energy

FRW expansion

Exit

Inflation \rightarrow (\frac{\partial P}{\partial \phi})^2 <\delta \phi^2> + ... + ...

* Initial Singularity

and/or bubble nucleation
Although the separation of scales between known physics and quantum/string gravity effects is daunting (string mass scale $M_s$:

$$\text{TeV} < M_s \lesssim 10^{18} \text{ GeV}$$

e.g. warped or large dimensions  

e.g. SUSY GUTs

$M_{\text{GUT}} \sim 10^6 \text{ GeV}$

$\ll M_s$
And many “fundamental” processes are hidden behind horizons and/or diluted by inflation, conceptual — and even observational — connections between string theory and cosmology are possible.
"Conceptual" Issues

* Initial Singularity: GR breaks down. Ongoing work using dynamics of strings and/or dual descriptions to get a handle on the physics of spacelike singularities
  - What states are consistent?
  - How can time start?

* Global Structure of spacetime:
  Accelerated expansion, including bubble nucleation mixing vacua, or eternal inflation, can yield classically causally disconnected patches. Microphysical structure of solutions, and formulation of physical quantities, under investigation.
• Microscopic Gravity:
  - black hole physics

• entropy $S = \frac{A}{4\ell}n$

  count microscopically in some cases

• unitarity?, Singularity?

  $\Rightarrow$ "holography": area not volume's worth of degrees of freedom

  - topology change

  GR: gmun dynamical
  QG: topology dynamical

  $\Rightarrow$ AGN, W, C.M.S..., ALMS5
Observational consequences of novel string (or string-inspired) phenomena in specific models.

Inflation provides an effective field theory solution to flatness, horizon, monopole, ... problems, while providing a theory of the origin of all structure via expansion of basic zero-point quantum fluctuations. Let us work in this framework.
From the Friedmann eqn

\[(\frac{\dot{a}}{a})^2 = \frac{8\pi G_N}{3} \rho - \frac{k}{a^2}\]

\[\rightarrow\]

energy density

\[\rho = V(\Phi) + P_{\text{kinetic}}\]

scalar field

inflaton(s)

\[\dot{\Phi}^2 + V + \cdots\]

Accelerated expansion occurs if the potential energy dominates, and is slowly changing:

\[H = \frac{\dot{a}}{a} = \sqrt{\frac{8\pi G_N}{3} V_0} \rightarrow a = a_0 e^{Ht}\]
This dilutes spacetime curvature and matter, and generates primordial density perturbations (cf. Buonanno, Church, ... lectures describing $\delta g_{ij}$ component).

Inflationary potential energy source is its modeled in effective field theory by scalar (inflaton) sector:

$$
\mathcal{L} = \mathcal{L}_{\text{kinetic}} - V(\Phi)
$$

& potential + kinetic energy landscape on a subspace of which inflation occurs.
For a given mode $k_{\text{phys}} = \frac{k}{a(t)}$, start in Minkowski (Bunch-Davies) vacuum at early $t$ when $\frac{k}{a(t)} \gg H$.

(Note: this conservative assumption yields no "trans-Planckian" information.)

Modes $\propto \frac{H}{\sqrt{2k^3}} (i + \frac{k}{aH}) e^{\frac{i k}{aH}}$

$\left \{ \begin{array}{l}
\text{dominates at early times: } \frac{k}{a} = \frac{k}{a_0} (1 - Ht) + \ldots \\
\text{late times: } \frac{k}{a} > H^{-1} \text{ (no dilution)} \end{array} \right.$

$\rightarrow \frac{1}{\sqrt{2\omega}} e^{-i \frac{1}{a_0} \omega t}$  Minkowski mode soln
Exit from inflation is rich source of observables:

1) Primordial fluctuation modes re-enter horizon and seed density perturbations observable in the CMBR. Models predict parameters in power spectrum such as tilt (level of scale-invariance), non-Gaussianity (level of nonlinear interactions in inflation sector), polarization (scale of $V^{1/4}$),...

2) In some models, the exit produces interesting defects (e.g. cosmic strings) observable by e.g. gravity waves.
Before getting to some specific stringy models with distinctive signatures, let me survey more broadly some new classes of models.
String Compactifications are rich (a.k.a. complicated)

→ huge potential (a.kinetic) energy "landscape": e.g., potential energy

$V(\Phi_I)$

* 4d scalar "moduli" from higher-dimensional metric, brane positions, form fields $\rightarrow$ actions, ...
This low-energy theory has metastable solutions which can model dark energy, as well as corners in which inflationary expansion takes place.

- "N-flation": many (N) axions in inflationary potential energy scales up with N while V, V' fixed flat potential $\rightarrow$ slow roll

- "New Old" inflation
  - Saddle point: oscillates rapidly at large $V_0$ until finds exit
Brane Inflation:

\[ ds^2 = \sqrt{r^2 (-dt^2 + d\vec{x}^2)} + \frac{L^2}{r^2} dr^2 + f(r) ds_{\perp}^2 \]

This produces reasonable scales e.g. for \( \frac{d^2}{dt^2} V(\phi) \) inside a warped throat (RS-like model).

\[ \dot{x},t \xrightarrow{r} \]

\( B \uparrow \quad B \)

\( \downarrow \quad \text{brane} \)

\( \uparrow \quad \text{antibrane} \)

\( \langle \phi \rangle \xrightarrow{\text{time}} \langle T \rangle \)

\( \text{negative mass}^2 \text{ mode T} \)

\( \text{annihilation/ reheating} \)

Tye et al

Dvali et al
The brane motion is governed by the Lagrangian

\[ L = \frac{\alpha^4}{4} \sqrt{1 - \frac{\dot{\alpha}^2}{\alpha^4}} - V(\alpha; \frac{\partial^2}{\partial y_j^2}) + \ldots \]

\[ \alpha = \left( \frac{L}{l_s^4} \right)^{1/4} \]

Inflation has been obtained in 2 regimes: (also variants with other brane combos, e.g. D3/0; Kallosh et al.)

1. \( \frac{\dot{\alpha}^2}{\alpha^4} < 1 \), \( V \) flat (mild tuning) "KKLMNT Model"
   Kachru, Kallosh, Lindeløv, Maldecena, McAllister, Trivedi

2. \( \frac{\dot{\alpha}^2}{\alpha^4} \rightarrow 1 \) \( \alpha \rightarrow 0 \) \( V \) can be steep, \( V \) huge
   "DBI Inflation"
   E.S. & Tong
   Alishahiya, E.S., Tong, & Chen

Some cases: cosmic string signatures
Tye, et al.
Copeland, Lyons, Polchinski

Falsifiable prediction of non-Gaussianity
of Creminelli, Faldasti...
Case 0 is a stringy version of hybrid inflation, consistent with moduli stabilization, with the inflaton sector conveniently annihilating during exit, as the brane and anti-brane collide.

Actually more generically, the annihilation of the 3-branes leaves behind cosmic strings (1-branes) which for appropriate models survive to late times $\rightarrow$ gravity wave signatures
spectrum of open strings includes negative mode ("tachyon") $T$ for small separation

$$L_T = (\partial T)^2 + (m_0^2 - \phi^2)T^2$$

$|m|/t$

$\Rightarrow T \sim T_0 \exp{\gamma}$

complex field charged under U(1) gauge symmetry

Kibble

$\Rightarrow T_0$ points in different directions

$T_0 \sim e^{i\theta}$

$1$-dimensional (string) topological defect
The network evolves, losing energy to GWs via:
- straightening
- interaction → kinks
- decay of closed loops

Simulations → scaling solution

\[
\frac{\rho_s}{\rho_{\text{matter}} + \rho_{\text{rad}}} \sim 10^2 \text{ G}\mu \lesssim 10^2 10^{-6}\text{Hz}
\]

string tension (depends on model parameters)

bounds from CMBR (shape and non-Gaussianity of power spectrum);
Stochastic GW background
In the warped $\mathcal{B}$-$\mathcal{B}$ inflation models, strings can naturally appear which (a) survive but (b) are at low enough scales to be consistent with bounds and (c) are at high enough scales to be observable.

Tye et al.; Copeland/Hyeon/Polchinski suggest a representative range

$$10^{-10} \leq \sigma \lambda \leq 10^{-7}$$

otherwise difficult observational bound to get $\sigma$
Case 2, DBI inflation, arises from relativistic brane motion (equivalent via AdS/CFT to scalar field dynamics in strongly coupled QFT), and as we will see yields falsifiable predictions of CMBR non-Gaussianity.
Consider a rolling scalar field $\Phi$, coupled to many other degrees of freedom $X$:

$$L = L_{\text{kinetic}} + \lambda \Phi^2 \sum_{i=1}^{N} x_i^2$$

As $\Phi \rightarrow 0$, the $X$ degrees of freedom become light.

* $\Phi = 0$

* They slow down $\Phi$'s motion, via particle production and/or renormalization effects.
Using the AdS/CFT duality relating large $N$ field theory to gravity (string theory) in warped backgrounds, this translates to:

$$ds^2 = r^2 dx^2 + \frac{dr^2}{r^2} L^2$$

Motion of 3-brane is bounded by causality! $\rightarrow \left( \frac{L^4}{L_s^4} \right) \frac{\dot{\Phi}^2}{\Phi^4} < c$

Velocity$^2$ of probe brane

$\Rightarrow \Phi$ rolls slowly as $\Phi \rightarrow 0$
In the velocity $\to c$ regime
\[
(\vec{a}^2 \to \left( \frac{L}{l_s} \right)^4 \vec{a}^4)
\]
the dynamics of $\vec{a}$ requires the full relativistic "DBI" action

\[
L_{\text{kin}} = \frac{\Phi^4}{\left( \frac{L}{l_s} \right)^4} \sqrt{1 - \left( \frac{L}{l_s} \right)^4 \vec{a}^2}
\]

including $\left( \frac{L}{c} \right)$ corrections
Given the resulting inflationary background, one can compute $\Delta$ by expanding

$$L = \mathcal{H}^4 \left( \frac{\epsilon}{k} \right)^4 \sqrt{1 - \left( \frac{L}{k} \right)^4 \frac{2 \epsilon_0}{\epsilon^4}}$$

in perturbations. For a simple reason (related to the physics of the model), the non-Gaussian component is relatively large:

$$\int L_{\text{kin}} \sim \left( \frac{L}{\sqrt{1 - \left( \frac{\epsilon}{k} \right)^4 \frac{2 \epsilon_0}{\epsilon^4}}} \right)^3 \sqrt{\frac{2}{y^2}} \ldots + y^5 \sqrt{\frac{2}{y^2}} \ldots$$
Magnitude \( \frac{L^3}{\tilde{L}^2} - (0.2) \gamma^2 \)

\[ \Rightarrow \quad 5 \leq \gamma \leq 22 \]

DBI mechanism \( \sim \) current bounds (naïve WMAP)

This (as well as another recent model, "ghost inflation" (Arkani-Hamed et al.), and earlier higher derivative analysis (Creminelli)) \( \Rightarrow \)

1. Inflation \( \not\Rightarrow \) Gaussianity of perturbations

2. It is worth improving the N6 bounds in the data, optimizing for model (types). Maldacena, Creminelli, Grabowski, et al
Other (string) theory \iff data cosmological connections include:

- dark matter candidates, e.g. from low energy SUSY, a natural corner of string theory.

- $\Lambda \neq 0$ can be accommodated via tuning compactification ingredients, while $\Lambda = 0 \Rightarrow M_{\text{Susy}} \geq \text{Tev}$

- not obtained (so far) \cite{Bonanno:2001ki, MSS, KKLMT}

- \cite{Kachru:2002gs} many solutions

- Bubble nucleation connecting solutions suggests negative spatial curvature in our patch \cite{Friedan:1980uk, Kachru:2003sx, Susskind}

- Depending on masses & couplings, moduli might be detectable \cite{Dimopoulos:1981zb}
III. Outlook:

- Connections to observation are obviously model-dependent.

As we learn more about the theory, new phenomena appear whose connection to observation can be assessed, as in warped/DBI inflation etc.

E.g., string-theoretic effects lead to simple topology changing processes

\[ T \xrightarrow{\text{?}} \]

Conceivably survive to imprint GW or x-ray or... signals?
- Conceptual developments continue — may remain shrouded from observation by horizons, scale mismatch, inflationary dilution etc., but still instructive. e.g. theory of black holes, singularities, holography, ...