String Cosmology

SSI 2005

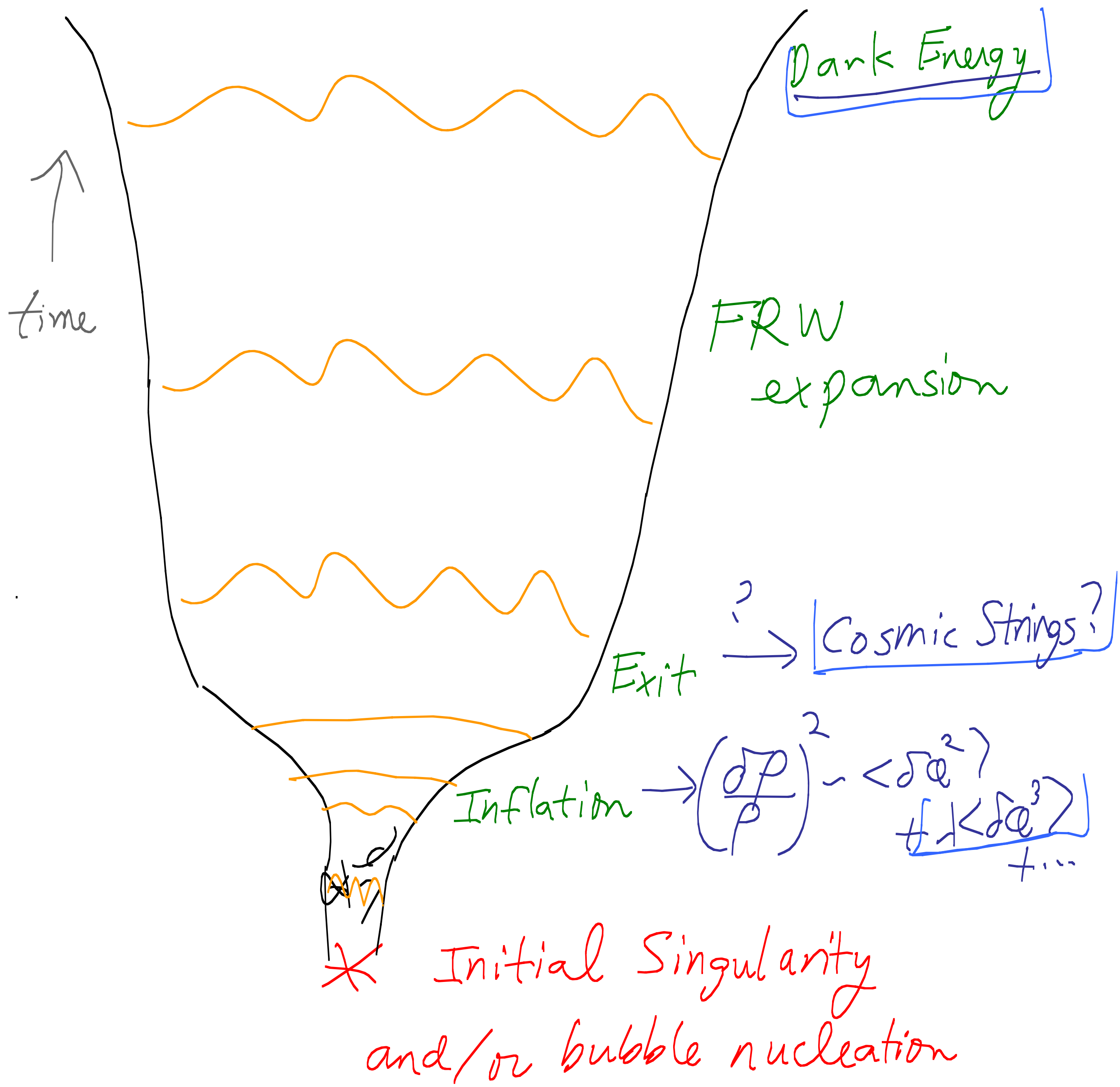
I. Broad Intro Strings, Gravity, Cosmo.

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)



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 $M_{GUT} \sim 10^{15}\,\text{GeV} \ll M_s$

And many "fundamental" processes are hidden behind horizons and/or diluted by inflation,

Conceptual —[1] and even observational —[2] connections between string theory and cosmology are possible.

① "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?

⋮
Horowitz et al
LMS
Shenker et al
McGreevy & ES
⋮

- 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

⋮
BP
MSS
KKLT
Susskind et al
⋮

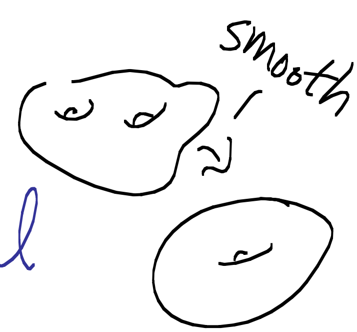
- Microscopic Gravity :
  - black hole physics
    - entropy $S = \dfrac{A}{4G_N}$

count microscopically in some cases *Strominger-Vafa*

- unitarity ?, singularity ?

→ "holography" : area not volume's worth of degrees of freedom *Maldacena 't Hooft – Susskind*

- topology change



GR : $g_{\mu\nu}$ dynamical

QG : topology dynamical

AGM, W, GMS, ..., ALMSS ...

⋮

② 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.

Albrecht
Guth
Linde
Steinhardt
⋮
Mukhanov
|

From the Friedmann eqn

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_N}{3}\rho - \frac{k}{a^2}$$

(k ← curvature; ρ ← energy density)

$$\rho = V(\Phi_i) + \rho_{kinetic}$$

Φ_i: scalar field inflaton(s)

$\rho_{kinetic}$: $\dot{\Phi}_i^2 + \lambda \dot{\Phi}^4 + \dots$

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

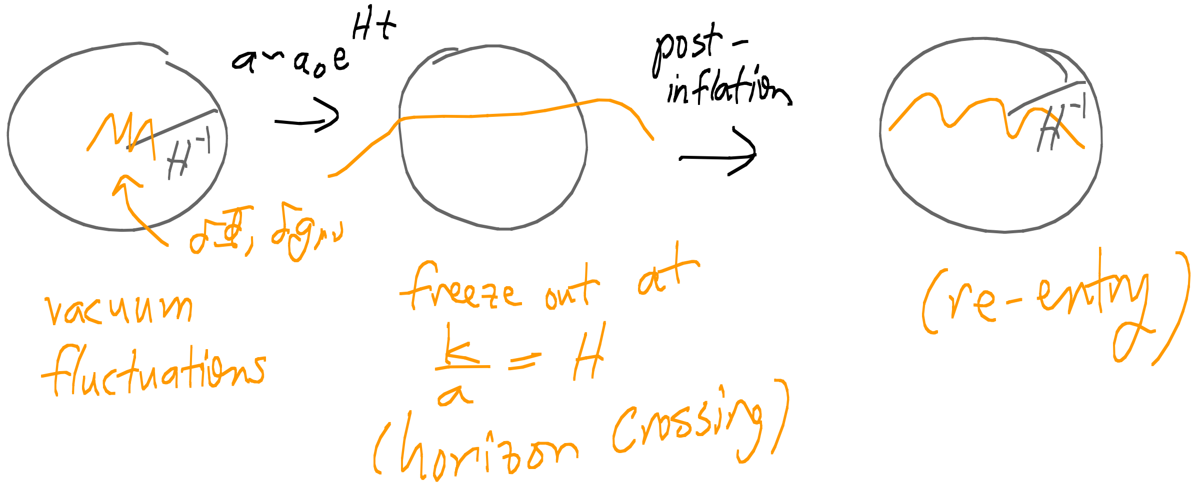
$$H = \frac{\dot{a}}{a} = \sqrt{\frac{8\pi G_N}{3} V_0} \rightarrow a = a_0 e^{Ht}$$

This dilutes spacetime curvature and matter, and generates primordial density perturbations (cf Buonanno, Church, ... lectures describing δg_{ij} component)

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

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

↳ potential + kinetic energy lanscape on a subspace of which inflation occurs.



For a given mode $k_{phys} = \frac{k}{a(t)}$, 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.)

Lawrence Shenker Susskind et al

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

dominates at late times $\frac{a}{k} > H^{-1}$ (no dilution)

dominates at early times: $\frac{k}{a} \sim \frac{k}{a_0}\left(1 - H\Delta t + \ldots\right)$

$\rightarrow \frac{1}{\sqrt{2\omega}} e^{-i\frac{k}{a_0}\Delta t}$ Minkowski mode sol'n

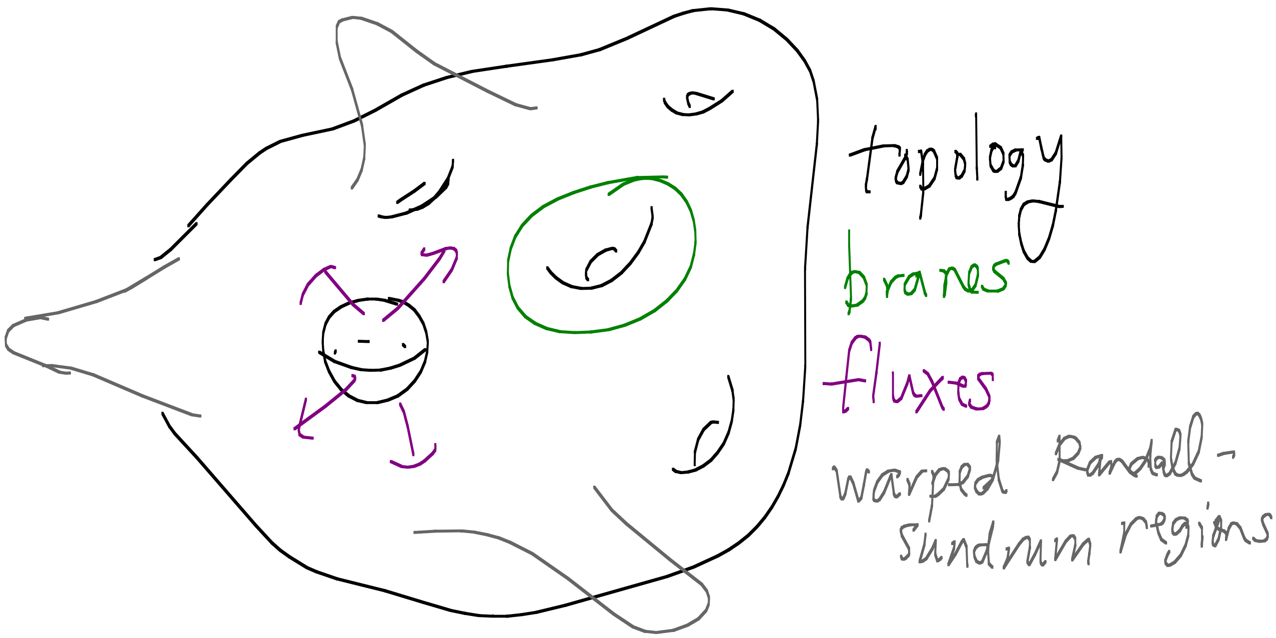
Exit from inflation is rich source of observables:

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 inflaton sector), polarization (scale of $V(\Phi_I)$), ...

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)

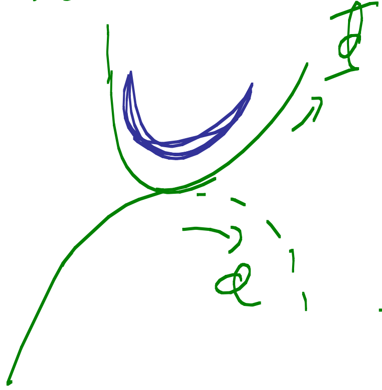


→ huge potential (& kinetic) energy "landscape": e.g. potential energy

$V(\Phi^I)$ ← 4d scalar "moduli" from higher-dimensional metric, brane positions, form fields → axions, ...

This low-energy theory has metastable solutions which can model dark energy, as well as corners in which inflationary expansion takes place.

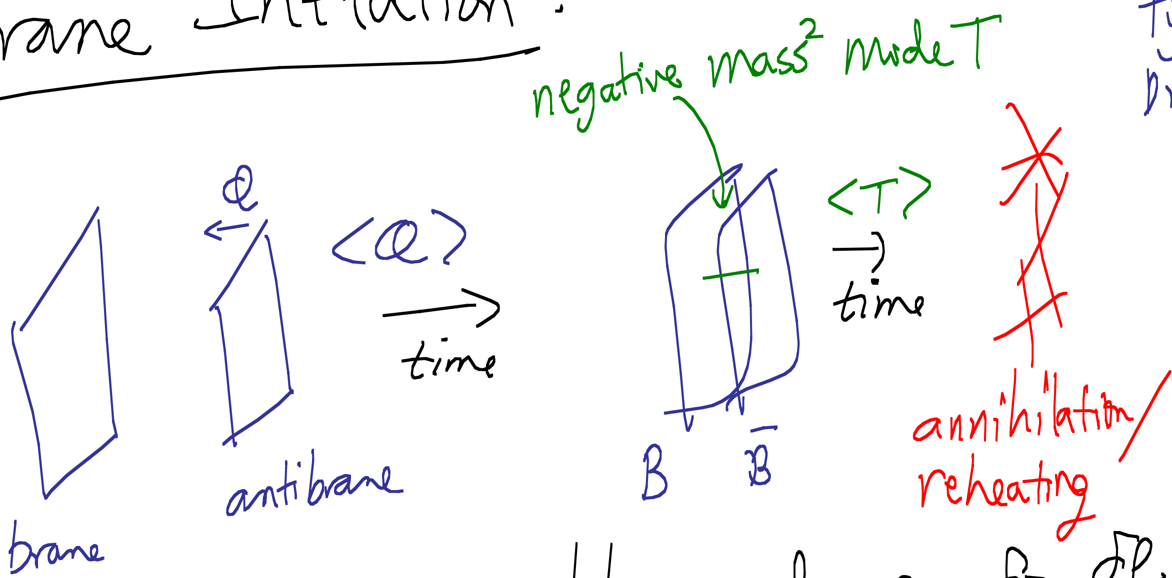
- "N-flation" : many (N) axions inflationary potential energy scales up with N while V', V'' fixed flat potential → slow roll — DKMW
- "New Old" inflation — Dvali/Kachru



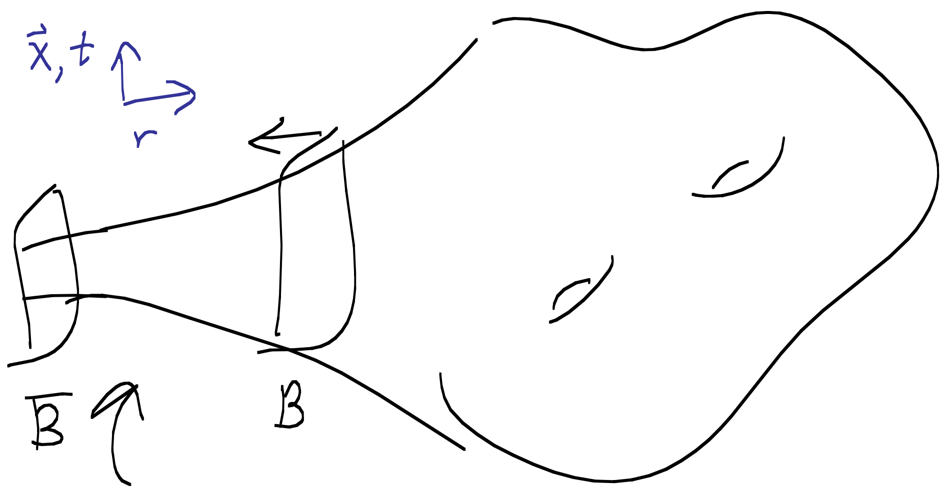
saddle point : Φ oscillates rapidly at large V_0 until finds exit.

Brane Inflation: (cf hybrid inflation)

Tye et al
Dvali et al



This produces reasonable scales e.g. for $\frac{\delta\rho}{\rho}$, $V(\Phi)$ inside a warped throat (RS-like model)



$$ds^2 = \underbrace{r^2}_{\text{warp factor (gravitational redshift)}} \underbrace{\left(-dt^2 + d\vec{x}^2\right)}_{4d} + L^2 \frac{dr^2}{r^2} + f(r)\, ds_\perp^2$$

The brane motion is governed by the Lagrangian

$$\mathcal{L} = \frac{\phi^4}{\lambda}\sqrt{1 - \frac{\lambda\dot{\phi}^2}{\phi^4}} - V(\phi ; \Phi_J) + \cdots$$

$\lambda = \left(\frac{L}{\ell_s}\right)^4$

ϕ: brane position

Φ_J: other moduli

Inflation has been obtained in 2 regimes: (also variants with other brane combos, e.g. D3/D7 Kallosh et al)

① $\frac{\lambda\dot{\phi}^2}{\phi^4} \ll 1$, V flat (mild tuning)

"KKLMMT Model"
Kachru Kallosh Linde Maldacena McAllister Trivedi

② $\frac{\lambda\dot{\phi}^2}{\phi^4} \to 1$ $\phi \to 0$ V can be steep; λ huge

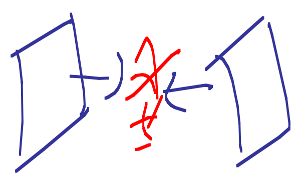
"DBI Inflation"
E.S. & Tong
Alishahiha, ES, Tong; Chen

→ falsifiable prediction of non-Gaussianity

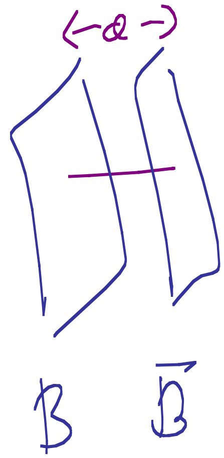
cf Creminelli, Zaldarriaga, ...

some cases: cosmic string signatures (for ① and ②)
Tye et al
Copeland Myers Polchinski

Case ① is a stringy version of hybrid inflation, consistent with moduli stabilization, with the inflaton sector conveniently annihilating* during exit, as the brane and antibrane collide.



Actually more generically the annihilation of the 3-branes leaves behind cosmic strings (1-branes) which for appropriate models survive to late times → gravity wave signatures



spectrum of open strings includes negative mode ("tachyon") T for small separation

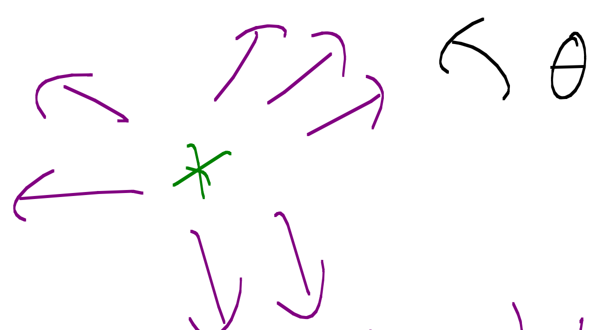
$$\mathcal{L}_T = (\partial T)^2 + (m_0^2 - \ell^2) T^2$$

$$\Rightarrow T \sim T_0 \, e^{|m| t}$$

↑ complex field charged under U(1) gauge symmetry

Kibble

↪ T_0 points in different directions

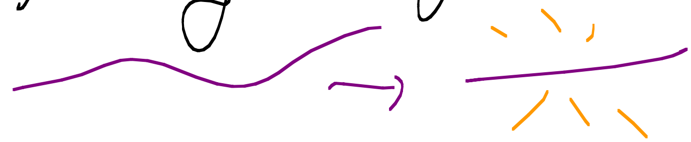


$T_0 \sim e^{i\theta n}$ ⇒ 1-dimensional (string) topological defect

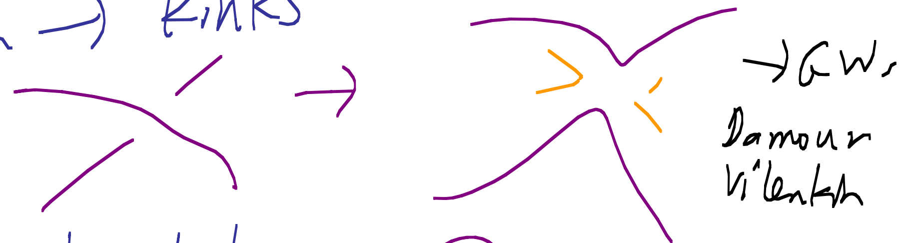
The network evolves, losing energy to GWs

via

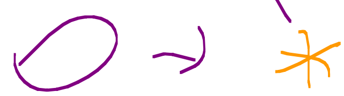
- straightening



- interaction → kinks



- decay of closed loops



Simulations → scaling solution

$$\frac{\rho_s}{\rho_{\text{matter or radiation}}} \sim 10^2 \, G\mu < 10^2 \; 10^{-(6 \text{ or } 7)}$$

$G\mu$ ↑ string tension (depends on model parameters)

$10^{-(6 \text{ or } 7)}$ ↑ bounds from CMBR (shape and non-Gaussianity of power spectrum); Stochastic GW background

In the warped $B-\bar{B}$ inflation models, strings can (model dependently) 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/Myers/Polchinski suggest a representative range

$$10^{-10} \lesssim G\mu \lesssim 10^{-7}$$

↑ otherwise difficult to get $\delta\rho/\rho$ ↖ observational bound

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 Φ, coupled to many other degrees of freedom χ:

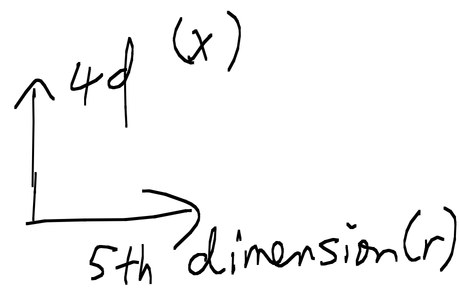
$$\mathcal{L} = \mathcal{L}_{kinetic} + \lambda \Phi^2 \sum_{I=1}^{N} \chi_I^2$$

As $\Phi \to 0$, the χ degrees of freedom become light.

* $\Phi = 0$

* They slow down Φ'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:



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

(r^2 ↑ warp factor)

motion of 3-brane is <u>bounded</u> by causality! → $\left(\frac{L^4}{\ell_s^4}\right) \frac{\dot{\Phi}^2}{\Phi^4} < c$

(velocity^2 of probe brane)

$\Rightarrow$ Φ rolls slowly as $\Phi \to 0$

In the velocity $\to c$ regime

$$\left(\dot{\Phi}^2 \to \left(\frac{L}{l_s}\right)^4 \Phi^4\right),$$ the

dynamics of Φ requires the full relativistic "DBI" action

$$\mathcal{L}_{kin} = \Phi^4 \left(\frac{l_s}{L}\right)^4 \sqrt{1 - \left(\frac{L}{l_s}\right)^4 \frac{\dot{\Phi}^2}{\Phi^4}}$$

including $\left(\frac{v}{c}\right)$ corrections ↑

Given the resulting inflationary background, one can compute $\frac{\delta\rho}{\rho}$ by expanding

$$\mathcal{L}_{kin} = \Phi^4 \left(\frac{l_s}{L}\right)^4 \sqrt{1 - \left(\frac{L}{l_s}\right)^4 \frac{(\partial\Phi)^2}{\Phi^4}}$$

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

$$\delta\mathcal{L}_{kin} \propto \underbrace{\left(\frac{1}{\sqrt{1-\left(\frac{L}{l_s}\right)^4 \frac{\dot{\Phi}^2}{\Phi^4}}}\right)^3}_{\gamma^3} \delta\dot{\Phi}^2 (\ldots) + \gamma^5 \delta\dot{\Phi}^3 (\ldots)$$

Magnitude $\frac{\mathcal{L}_3}{\mathcal{L}_2} \sim (0.2)\,\gamma^2$

$\rightarrow \quad 5 \lesssim \gamma \lesssim 22$

↑ DBI mechanism ↖ current bounds (naive 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 NG bounds in the data, optimizing for model (types). Maldacena, Creminelli, Zaldarriaga, et al

Other (string) theory ⟺ data cosmological connections include:

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

- $\Lambda \neq 0$ can be accomodated via tuning compactification ingredients, while $\Lambda = 0$ $M_{SUSY} \gtrsim$ TeV not obtained (so far) (see S. Kachru talk here)

  Bousso - Polchinski
  MSS
  KKLT
  ⋮

  ⟷ many solutions

- Bubble nucleation connecting solutions suggests negative spatial curvature in our patch

  Freivogel, Kleban, Susskind

- Depending on masses & couplings, moduli might be detectable

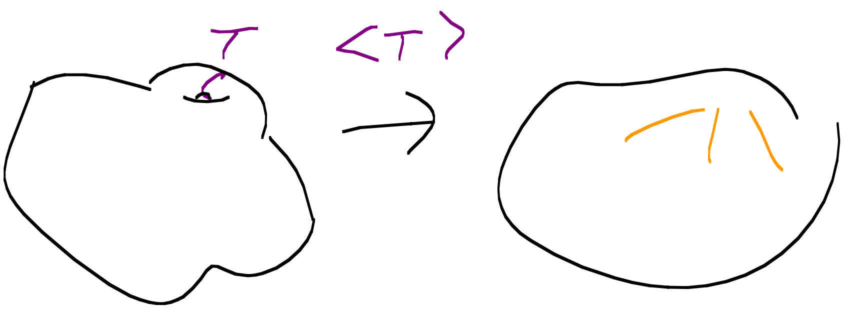
  Dimopoulos
  Dine ...

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



Conceivably survive to imprint GW or γ-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, ...