Thermal and quantum induced superstring cosmology

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Based on

- arXiv:1003.0471 [JE, C. Kounnas, H. Partouche]
- arXiv:0908.1881 [F. Bourliot, JE, C. Kounnas, H. Partouche]
- arXiv:0902.1892 [F. Bourliot, C. Kounnas, H. Partouche]
- arXiv:0710.3895 [T. Catelin-Jullien, C. Kounnas, H. Partouche, N. Toumbas]
- arXiv:0710.3895 [T. Catelin-Jullien, C. Kounnas, H. Partouche, N. Toumbas]

Superstring cosmology overview

- By studying general string models, we may hope to get an understanding of the role vacuum energy and quantum corrections play in cosmology
  - We can compute the vacuum energy unambiguously including quantum corrections
  - derive equation of state from first principles including quantum corrections
- We will find
  - a radiation-like universe connecting the Hagedorn era to the electro-weak era
  - a mechanism for stabilizing certain moduli
  - a dynamical mechanism for generating the hierarchy

$$M_{\text{susy}} \ll M_{\text{Planck}}$$

Superstring cosmology in the intermediate era

- Procedure:
  1. We start with a flat static background and introduce temperature and zero temperature supersymmetry breaking
  2. Working to first order, we compute the free energy density including both thermal and quantum contributions
  3. The back-reaction of the free energy density, under certain conditions, induces a quasi-static evolution corresponding to a radiation-like universe
- Analysis starts after the Hagedorn transition (or re-heating), where we may use canonical ensemble techniques
- Parameterize exit from the Hagedorn transition by allowing arbitrary initial conditions
- As the universe expands and cools, IR effects need to be included
- Masses are generated at the electro-weak phase transition, and afterwards we enter into standard cosmology

Setup

- The canonical partition function can be computed via a Euclidean path integral (with $\beta = 2\pi R_0$) from which one may deduce the energy density and pressure
- We introduce zero temperature supersymmetry breaking via the stringy Scherk-Schwarz mechanism (internal Wilson lines)
- Both temperature and zero temperature supersymmetry breaking may be implemented directly at the string world sheet level
- We assume a homogenous and isotropic space-time and flat spatial curvatures

$$ds^2_{1,3} = -dt^2 + a(t)^2 dx_i^2, \quad \phi(t), \quad \zeta_i(t) \equiv \ln R_i(t), \ldots$$

- Equations of motion can be derived from an effective field theory approach:

$$S = S_{\text{classical}} + S_{1-\text{loop}} \qquad\qquad S_{1-\text{loop}} = \int d^2x \, Z/V_4$$

Explicit toy model - thermal effects only

- Consider $E_8 \times E_8$ Heterotic string on $\mathcal{M}_{1,3} \times T^6$
- For simplicity, take internal moduli fixed near string scale
- Introduce thermal effects via Euclidean time formalism
- Resulting partition function takes the form:

$$Z_{\rm therm} = V_4 n_T (\tfrac{\pi^2}{48}) T^4 + \mathcal{O}(e^{-T_h/T})$$

- n_T is the number of massless degrees of freedom

$$n_T = 2^4([8] + [120+128]_{E_8} + [120+128]_{E_8'}) = 8064$$

- Many purely thermal models will have this form, differing only in the number n_T
- For any value of n_T, we obtain an equation of state $P = \frac{1}{3}\rho$ which leads to a radiation dominated evolution characterized by:

$$T(t) \propto 1/a(t) \propto 1/\sqrt{t}$$

Explicit toy model - thermal and quantum effects

- Pick an S^1 out of the T^6 along which to introduce zero temperature supersymmetry breaking, we denote its radius by R_5
- The partition function at zero temperature takes the form

$$Z_{\rm susy} = n_V (\tfrac{\pi^2}{48}) M_{\rm susy}^4 + \mathcal{O}(e^{-M_h/M})$$

- Examples of supersymmetry breaking schemes:
  - $Q = 0 : n_V = 8064$
  - $Q = Q_{E_8} + Q_{E_8'}$: where Q_{E_8} denotes the charge under an $SO(16)$ decomposition:

$$n_V = 2^4([8] + [120 - 128]_{E_8} + [120 - 128]_{E_8'}) = -128 < 0!$$

The radiation-like era

- Including both thermal effects and zero temperature supersymmetry breaking effects we obtain:

$$Z = V_4 T^4 [n_T\, f_T(M_{\rm susy}/T) + n_V\, f_V(M_{\rm susy}/T)]$$

- Introduce $e^z = M_{\rm susy}/T$, the effective potential $V(z)$ for z is defined by $\partial_z V = \partial_z Z + Z$
- Whenever $-\frac{1}{15} < \frac{n_V}{n_T} < 0$, $V(z)$ has a unique minimum at z_c where z is stabilized (this is a global attractor of the dynamics)
- At $z = z_c$ we find a radiation-like evolution:

$$M_{\rm susy}(t) = e^{z_c} T(t) \propto 1/a(t) \propto 1/\sqrt{t} \propto e^{4\phi(t)}$$

- This is not pure radiation, as $\rho = 4P$. Only after including the kinetic energy of the moduli do we find $\rho_{\rm tot} = 3P_{\rm tot}$
- Gives dynamical explanation of the hierarchy: $M_{\rm susy} \ll M_{\rm Planck}$
- Note that the vacuum energy is large, but not constant and therefore does not contribute to the cosmological constant

Moduli dynamics

- Relax frozen moduli restriction, and allow one of the radii, R_d, of the remaining T^5 to become dynamical and take arbitrary values
- Compute partition function as a function of R_d as well as T and z

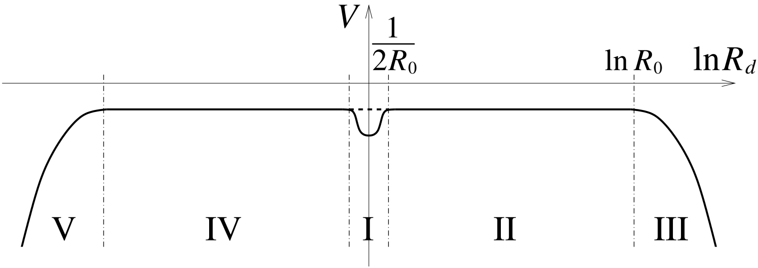
$$Z = V_4 T^4 [n_T(f_T(z) + k_T(T, R_5, R_d, \phi)) + \tilde{n}_T g_T(T, R_5, R_d, \phi)$$

$$+ n_V(f_V(z) + k_V(T, R_5, R_d, \phi)) + \tilde{n}_V g_V(T, R_5, R_d, \phi)] + \mathcal{O}(e^{-T_H/T})$$

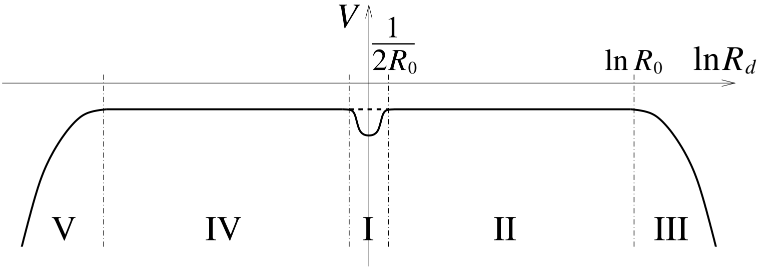
  - $k_{T(V)}$ come from the Kaluza-Klein modes, and are suppressed except when $R_d > R_{0(5)}$ or $R_d^{-1} > R_{0(5)}$
  - $g_{T(V)}$ come from the enhancement of $\tilde{n}_T$ extra massless states at the self-dual point $R_d = 1$, where $U(1) \to SU(2)$, and are suppressed except when $|R_d - 1| < \frac{1}{2R_{0(5)}}$

- Leads to moduli dependent equation of state:

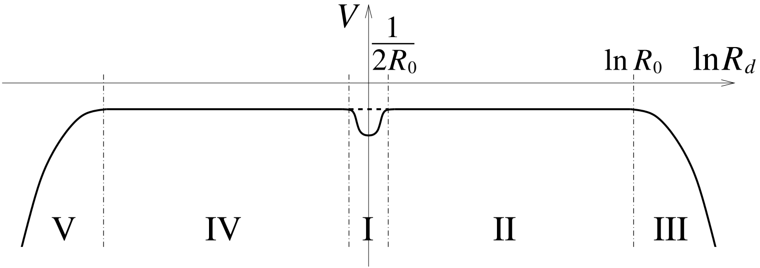
$$P = w(T, R_5, R_d, \phi)\rho$$



- (I): $SU(2)$ region ($g_{T(V)}$ contribute)
  - R_d is stabilized at its self-dual point
  - The mass is of order $M_{R_d}^2 \sim \tilde{n}_T T^2 e^{-\phi} + \tilde{n}_V M_{\rm susy}^2 e^{-\phi}$
  - $\rho_{\rm tot} \sim 3P_{\rm tot} \Rightarrow$ radiation-like dominated evolution
- (II): Modulus region
  - Flat potential, R_d may take any value
  - $\rho_{\rm tot} \sim 3P_{\rm tot} \Rightarrow$ radiation-like dominated evolution



- (III): Five-dimensional region ($k_{T(V)}$ contribute)
  - Large force pushing R_d towards higher values, so five directions are now expanding
  - For $R_d \gg R_0$ we have $\rho_{\text{tot}} \sim 4P_{\text{tot}} \Rightarrow$ radiation-like dominated evolution in five dimensions
  - However, R_0 always expands faster and even though we start with $R_d > R_0$, after a long enough time we have $R_0 > R_d$, after which the expansion of R_d halts (the friction term dominates the potential)



- (IV): T-dual modulus region
- (V): T-dual higher dimensional region ($k_{T(V)}$ contribute)
- String theory smoothly connects regions described by different low energy effective field theories

$\mathcal{N}_4 = 1 \to 0$ models in the intermediate era

- Results naturally generalize to backgrounds with $\mathcal{N}_4 = 1 \to 0$ supersymmetry (for example: heterotic on $\mathcal{M}_{1,3} \times T^6/(\mathbb{Z}_2 \times \mathbb{Z}_2)$)
- The partition function takes the form

$$\mathcal{F} = V_4 T^4 (n_T^u f_T(M_{\text{susy}}/T) + n_V^u f_V(M_{\text{susy}}/T)) + n_T^t c_4 T^4$$

  - n_T^u is the number of degrees of freedom from the un-twisted sector
  - n_T^t is the number from the twisted sector
  - n_V^u is a sum over un-twisted degrees of freedom weighted by $(-1)^Q$
- Dynamics attracted to radiation-like evolution when $n_V < 0$
- The ratio of the supersymmetry breaking scale to the temperature is stabilized $M_{\text{susy}} = e^{z_c} T$
- Moduli can be stabilized at points of enhanced symmetry, with mass scales $M \sim M_{\text{susy}}$

In progress

- Need a mechanism in the IR to exit the radiation-like era
    - Electro-weak symmetry breaking
    - In models with radiative electro-weak symmetry breaking the supersymmetry breaking scale,under certain conditions, can be stabilized around the electro-weak scale [see: S.Ferrara, C.Kounnas, F.Zwirner '98, I.Pavel, C.Kounnas, F.Zwirner '99]
    - The vacuum energy and initial conditions play a key role
    - What will happen with the cosmological constant?
- String-string dualities
    - Can we learn about non-perturbative thermal effects by exploiting string-string dualities?