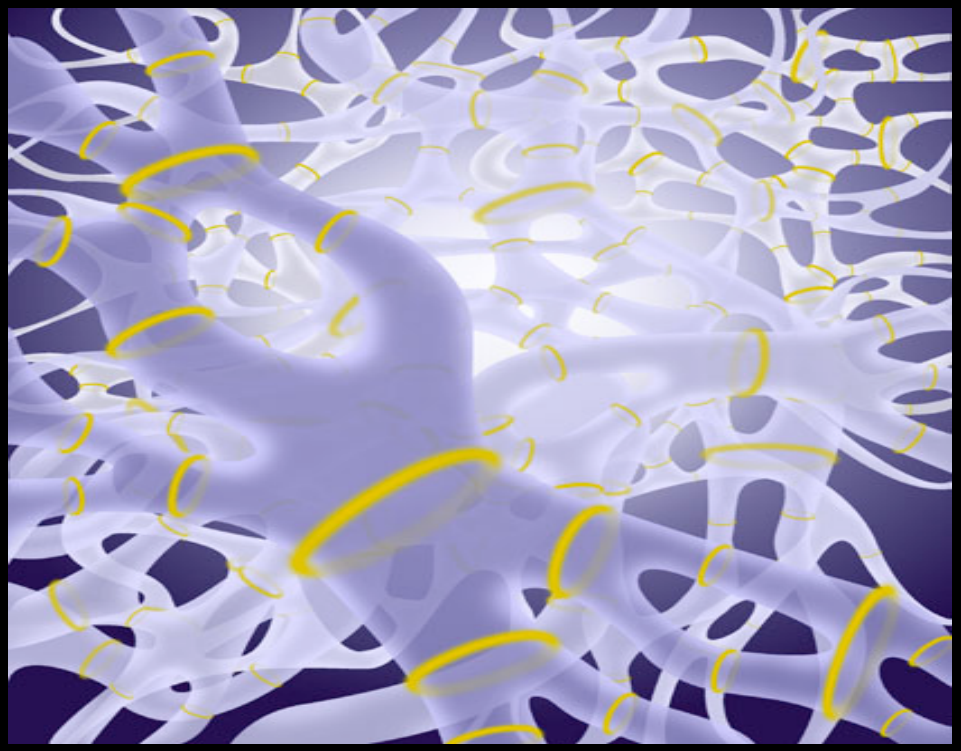
Brane Gas Cosmology



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What is Brane Gas Cosmology (BGC)?

By considering the presence of p-branes and strings (p=1 branes) in the early universe, BGC provides a democratic and robust solution to a number of outstanding problems in cosmology.

BGC Quick Facts:

- Explains (3+1) dimensionality of space-time
- Explains observed isotropy of the Cosmic Microwave Background
- Resolves the initial singularity problem (hep-th/0208188)
- Offers explanation of the stabilization of extra dimensions
- Offers natural solution to the Horizon Problem (hep-th/0109165)
- Branes as sources provide interesting candidates for Dark Energy

Democratic:

- All 10 spatial dimensions are treated equal
- All p-branes are treated equal (No preferred brane as in Brane World Models)

Robust:

- No fine tuning
- Conclusions hold for variety of target space-times (hep-th/0204099)
- Isotropization arises independently of initial conditions (hep-th/0207168)

How does it work?

The BGC model:

- Starting point analogous to Standard Big Bang
  - Small, dense, hot
  - All fundamental degrees of freedom near thermal equilibrium
- Spatial background taken to be T^9 (toroidal) compactified at string scale *
- Universe filled with hot gas of p-branes
- p-branes wrap cycles of the background resulting in a halt to cosmological expansion

* The model can be modified to incorporate more general space-times (hep-th/0204099)

Three factors contribute to the energy of a p-brane: (Let us consider a (p=1) brane or string for simplicity)

Oscillatory Modes (vibrations)

This energy corresponds to the particle spectrum of the string.

Momentum Modes

This energy is related to the center of mass motion of the string and depends on the radius R of the compact dimensions.

$$E_p = \frac{n}{R}$$

n is any integer

R is the radius of the compact dimension

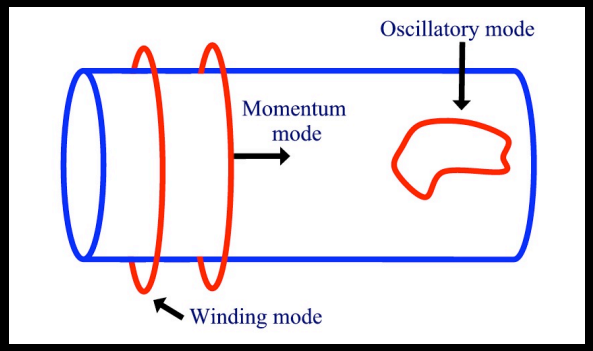
Winding Modes

This energy is associated with the winding of a string around the compact dimensions.

$$E_w = mR$$

m is any integer

R is the radius of the compact dimension



T-Duality

The total energy of the string is given by

$$E = \frac{n}{R} + mR \ + \text{oscillations}$$

Notice the spectrum is unchanged by the interchange

$$R \leftrightarrow \frac{1}{R} \qquad m \leftrightarrow n$$

So we see that strings in small spaces behave like strings in large spaces!

T-Duality and Cosmological Consequences

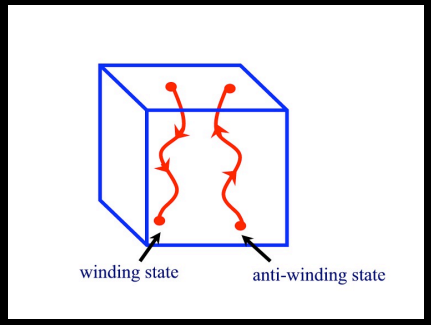
As R approaches the string scale winding modes become energetically favored (lighter). We must use these modes to measure physical distances, since the momentum modes become heavy. This is an example of how T-duality can resolve singularities by letting us use the relation between strings in small spaces and strings in large spaces.

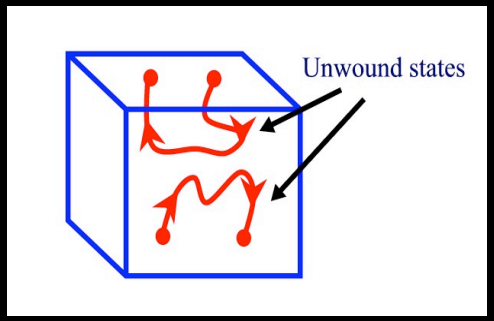
Thus we have, SINGULARITY FREE COSMOLOGY!!!

$$E = \frac{n}{R} + mR \ + \text{oscillations}$$

Winding Modes Keep Dimensions From Expanding!

Winding modes keep the universe from expanding through their confining potential. In this way, the strings wrap the space and keep it from growing larger. However, the wound strings can meet with their anti-wound partners and annihilate letting the dimensions expand.





BGC can explain the dimensionality of space since strings can find their anti-partners in a maximum of 3 spatial dimensions.

For a p-brane, annihilation is probable in a maximum of (2p+1) dimensions.

A p=1 brane (string) is the critical case, since it is the lowest dimensional state that can admit winding modes. (hep-th/0005212).

That is, the dimensionality of the universe is the result of decompactification of 3 of 9 spatial dimensions by winding/anti-winding string annihilation

Equations of BGC

Brane Gas Cosmology is formulated by considering the compactification of M-theory on S^1 which yields Type IIA string theory. The background space is taken to be toroidal (although this can be generalized) with its size determined by self dual point (string scale).

The metric is taken to be $ds^2 = -dt^2 + \sum_{i=1}^{D} e^{2\lambda_i} dx_i^2$ $\quad \lambda_i \equiv \ln(R_i)$ $R_i(t)$: scale factor in ith direction

The equations of motion are found by varying the bulk space action with p-brane sources given by the Dirac-Born-Infeld action.

Equations of Motion

$$-\sum_i \dot{\lambda}_i^{\,2} + \dot{\varphi}^2 = e^{\varphi} E$$

$$-\sum_i \dot{\lambda}_i^{\,2} + \ddot{\varphi} = \frac{1}{2} e^{\varphi} E$$

$$\ddot{\lambda}_i - \dot{\lambda}_i \dot{\varphi} = \frac{1}{2} e^{\varphi} P_i$$

φ: dilaton from M-theory compactification

Energy and Pressure Terms

$$E = \sum_{i=1}^{D} E_W^n + E_{NW}^n + E_M^n$$

$$E_W^n = \sum_{i=1}^{D} \mu NR\ (t) = \sum_{i=1}^{D} \mu N e^{\lambda}$$

$$E_M^n = \sum_{i=1}^{D} \mu NR^{-1}(t) = \sum_{i=1}^{D} \mu N e^{-\lambda}$$

$$P_i = -\mu N \left(e^{\lambda_i} + e^{-\lambda_i} \right)$$

Here we recognize the energy associated with winding modes and momentum modes as discussed earlier. As the radius increases the pressure becomes more negative. This acts as a confining potential to stop the expansion.

Weak Coupling Approximation

We work in the weak limit (small string coupling), which is that of SUSY dilaton gravity. Since the first equation of motion tells us the dilaton doesn't change sign, we can choose to restrict our model to the damping case to maintain the weak limit.

$\varphi \sim g_s$

$\dot{\varphi} > 0$ Boosting

$\dot{\varphi} < 0$ Damping

Notice: Negative Pressure does **NOT** imply Inflation!

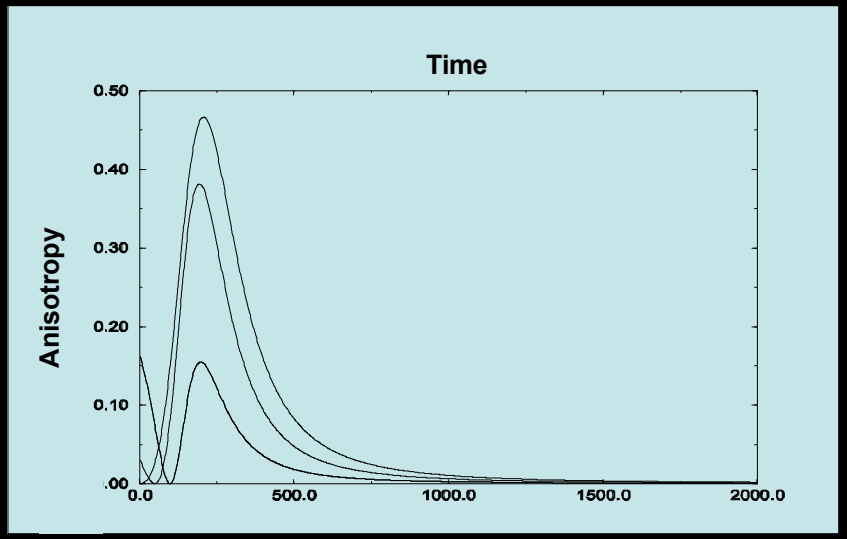
Loitering Universe (hep-th/0109165)

- Loitering is a generic result of the equations of motion.
- Loitering ends in three of the dimensions once winding modes annihilate with anti-winding modes allowing the dimensions to expand.
- Annihilation results in loop production which leads naturally to a three dimensional radiation dominated universe.
- The Horizon Problem is solved during loitering since the three dimensional universe has time to reach thermal equilibrium.

Isotropization (hep-th/0207168)

We might expect that in the three dimensions that grow large strings might annihilate at different rates in different directions. This would lead to an anisotropic universe. However, it is found that given any initial amount of anisotropy the annihilation process will yield an isotropic cosmology.

BGC offers a natural explanation of the observed isotropy of the universe



The Future of Brane Gas Cosmology

Many aspects of BGC are being explored:

- The six dimensions that remain compactified should be stabilized by the balance between momentum and winding modes at the string scale. This is currently under investigation
- Remnant branes and fluxes could play important roles in the early universe (e.g., Dark Energy, Dark Matter).
- BGC can solve the horizon problem, but can it address the other issues to become a replacement for inflation?