# Was There A Big Bang?

## Challenges of Early Universe Cosmology

Robert Brandenberger
McGill University

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# Outline

# Plan

# Goals of Early Universe Cosmology



- Understand origin and early evolution of the universe.
- Explain observed large-scale structure.
- Make predictions for future observations.

# Goals of Early Universe Cosmology

Early Universe

R. Brandenberger

Introduction
Motivation
Inflation
Problems
Message

String gas
Principles
Features

Structure
Analysis
Signatures in CMB anisotropy maps

Conclusions

- Understand origin and early evolution of the universe.
- Explain observed large-scale structure.
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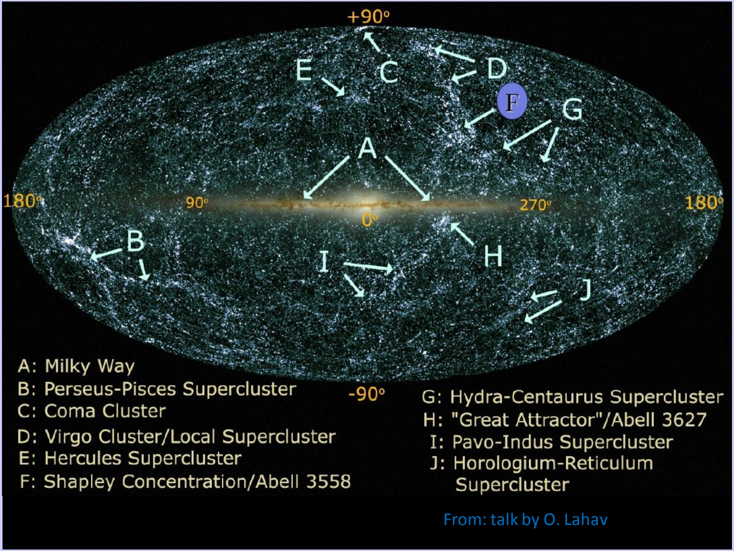
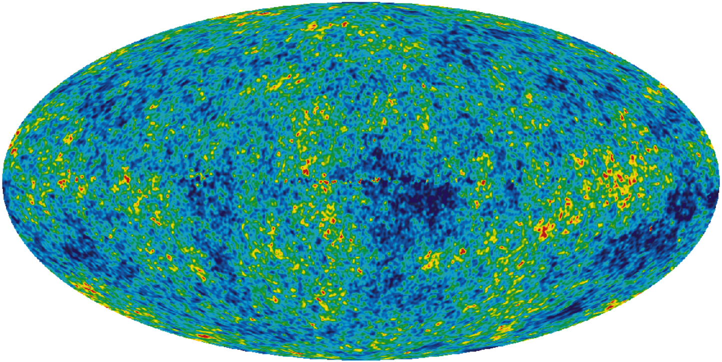
- Explain observed large-scale structure.
- Make predictions for future observations.

# Large-Scale Structure



# Anisotropies in the Cosmic Microwave Background (CMB)

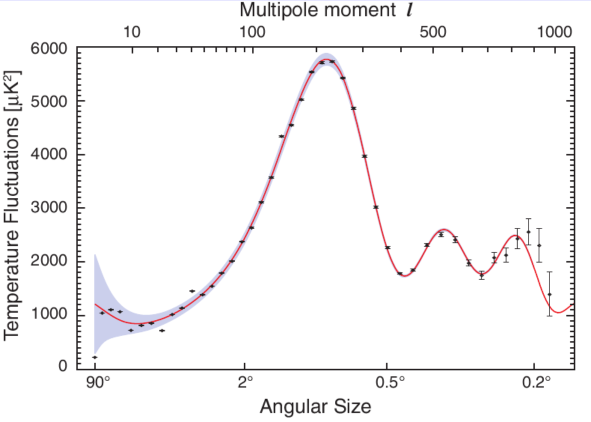




Credit: NASA/WMAP Science Team

# Quantification of the CMB data



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# Framework

- Space-time described by Einstein's theory of General Relativity.
- Space-time dynamical (no longer absolute like in Newtonian theory)
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# Standard Big Bang Cosmology



Standard Big Bang Cosmology (SBB): the old paradigm of cosmology ( 1960).
The SBB is based on:

- Cosmological principle: universe homogeneous and isotropic on large scales.
- Einstein equations governing dynamics of space-time.
- Classical matter as source in the Einstein equations (cold matter + radiation)

# Standard Big Bang Cosmology (ctd.)



- Universe begins as a homogeneous and very hot fireball
- Initially radiation dominates: hot plasma
- Space expands and matter cools
- After about 30,000 years cold matter starts to dominate.
- After about 300,000 years atoms (hydrogen) forms and universe becomes transparent to light
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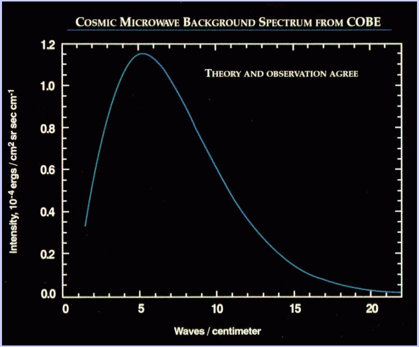
# Successes of the SBB Model

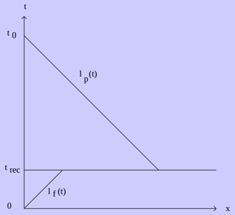


Key success: Existence and black body nature of the CMB.



# Conceptual Problems of the SBB Model

No explanation for the homogeneity, spatial flatness and large size and entropy of the universe.
Horizon problem of the SBB:



# Conceptual Problems of the SBB Model II



No explanation of the observed inhomogeneities in the distribution of matter and anisotropies in the Cosmic Microwave Background possible!

# Current Paradigm for Early Universe Cosmology



The Inflationary Universe Scenario is the current paradigm of early universe cosmology (1980).

Successes:

- Solves horizon problem
- Solves flatness problem
- Solves size/entropy problem
- Provides a causal mechanism of generating primordial cosmological perturbations (Chibisov & Mukhanov, 1981).

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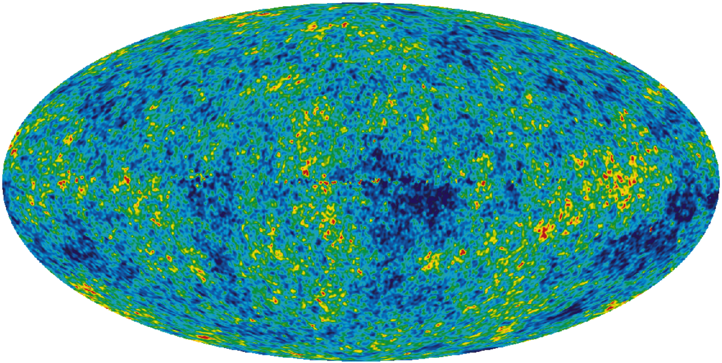

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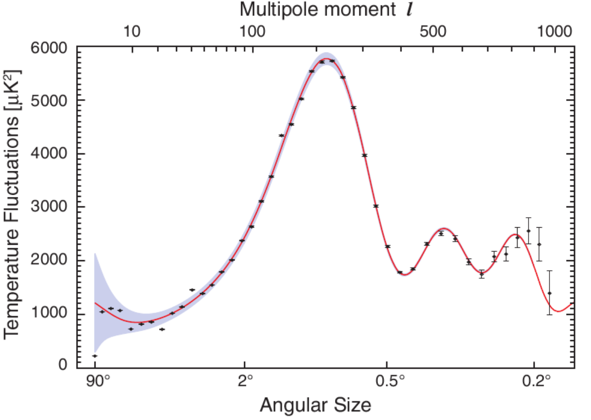


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# Challenges for the Current Paradigm



- In spite of the phenomenological successes, the inflationary scenario suffers from several conceptual problems.
- In light of these problems we need to look for input from new fundamental physics to construct a new theory which will overcome these problems.
- Question: Can Superstring theory lead to a new and improved paradigm?
- Question: Can this new paradigm be tested in cosmological observations?

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# Review of Inflationary Cosmology



Context:

- General Relativity
- Scalar Field Matter

Inflation:

- phase with exponential expansion of space
- requires matter with negative pressure
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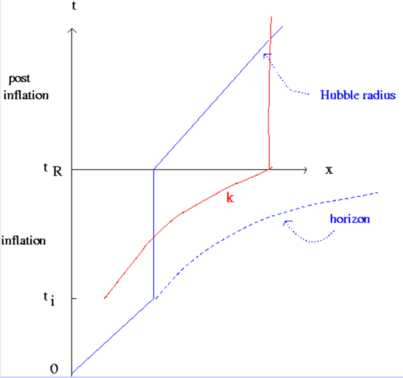
## Time line of inflationary cosmology:


- $t_i$: inflation begins
- $t_R$: inflation ends, reheating

## Space-time sketch of inflationary cosmology:




Note:

- $H = \frac{\dot{a}}{a}$
- curve labelled by $k$: wavelength of a fluctuation

- inflation renders the universe large, homogeneous and spatially flat
- classical matter redshifts → matter vacuum remains
- quantum vacuum fluctuations: seeds for the observed structure [Chibisov & Mukhanov, 1981]

# Conceptual Problems of Inflationary Cosmology



- What is the scalar field?
- Why does it have the special conditions to obtain inflation?
- Trans-Planckian problem
- Singularity problem
- Applicability of General Relativity

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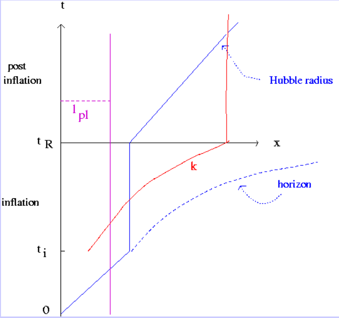
# Trans-Planckian Problem






- **Success of inflation**: At early times scales are inside the Hubble radius → causal generation mechanism is possible.
- **Problem:** If time period of inflation is slightly more than the minimal length it must have, then the wavelength is smaller than the Planck length at the beginning of inflation

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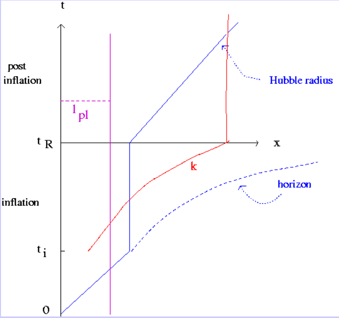


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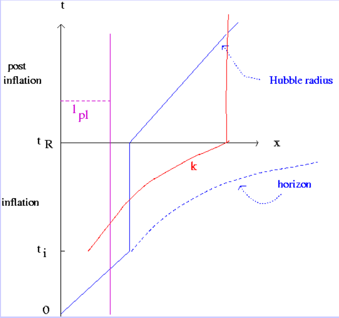


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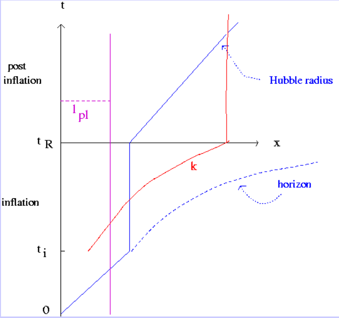


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# Singularity Problem



- Standard cosmology: Penrose-Hawking theorems $\rightarrow$ initial singularity $\rightarrow$ incompleteness of the theory.
- Inflationary cosmology: In scalar field-driven inflationary models the initial singularity persists [Borde and Vilenkin] $\rightarrow$ incompleteness of the theory.

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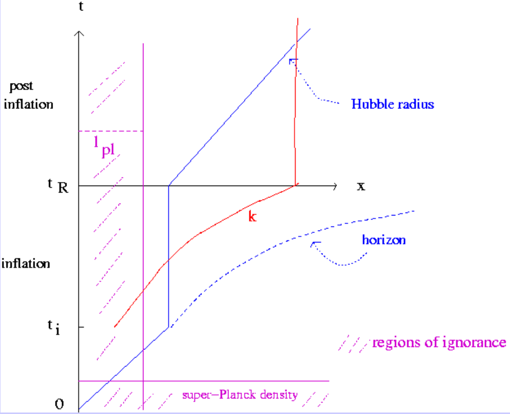

# Message I



- Current realizations of inflation have serious conceptual problems.
- We need a new paradigm of very early universe cosmology based on new fundamental physics.
- Hypothesis: New paradigm based on Superstring Theory.
- The new paradigm of early universe cosmology may not involve inflation.
- New cosmological model motivated by superstring theory: String Gas Cosmology (SGC) [R.B. and C. Vafa, 1989]
- New structure formation scenario emerges from SGC [A. Nayeri, R.B. and C. Vafa, 2006].

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# Message II



String Gas Cosmology makes testable predictions for cosmological observations

- Blue tilt in the spectrum of gravitational waves [R.B., A. Nayeri, S. Patil and C. Vafa, 2006]
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# Plan

# Principles

R.B. and C. Vafa, *Nucl. Phys. B316:391 (1989)*



Idea: make use of the new symmetries and new degrees of freedom which string theory provides to construct a new theory of the very early universe.

Assumption: Matter is a gas of fundamental strings

Assumption: Space is compact, e.g. a torus.

Key points:

- New degrees of freedom: string oscillatory modes
- Leads to a maximal temperature for a gas of strings, the Hagedorn temperature
- New degrees of freedom: string winding modes
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# T-Duality



## T-Duality

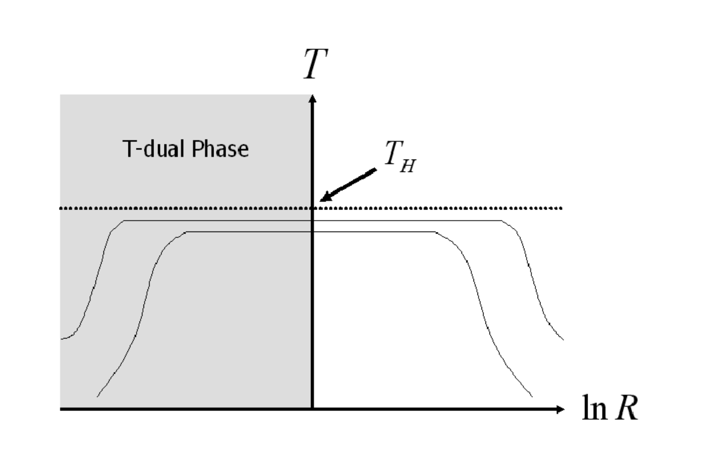
- Momentum modes: $E_n = n/R$
- Winding modes: $E_m = mR$
- Duality: $R \rightarrow 1/R \quad (n, m) \rightarrow (m, n)$
- Mass spectrum of string states unchanged

# Adiabatic Considerations

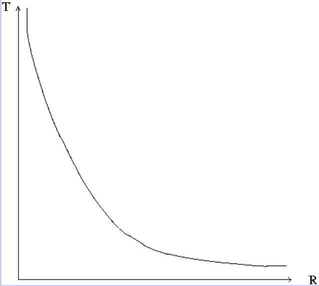
R.B. and C. Vafa, *Nucl. Phys. B316:391 (1989)*



## Temperature-size relation in string gas cosmology

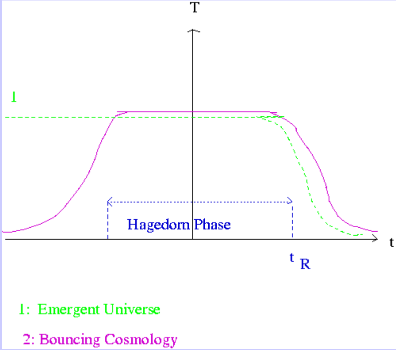


## Temperature-size relation in standard cosmology



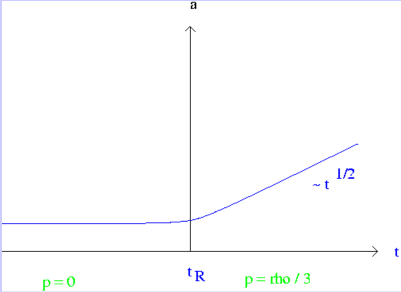
# Dynamics

Assume some action gives us $R(t)$



# Dynamics II

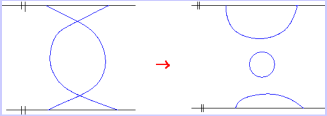
We will thus consider the following background dynamics for the scale factor $a(t)$:



# Dimensionality of Space in SGC



- Begin with all 9 spatial dimensions small, initial temperature close to $T_H$ $\rightarrow$ winding modes about all spatial sections are excited.
- Expansion of any one spatial dimension requires the annihilation of the winding modes in that dimension.



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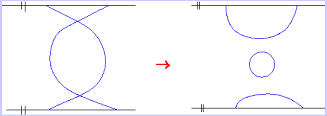

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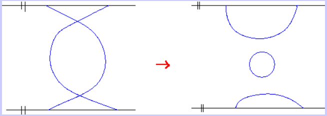

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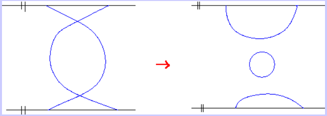

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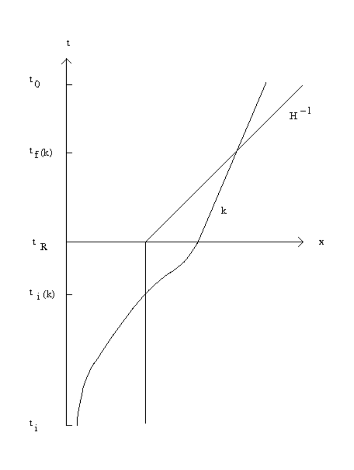
# Plan

# Structure formation in inflationary cosmology

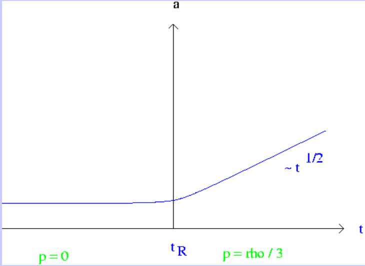





N.B. Perturbations originate as quantum vacuum fluctuations.

# Background for string gas cosmology





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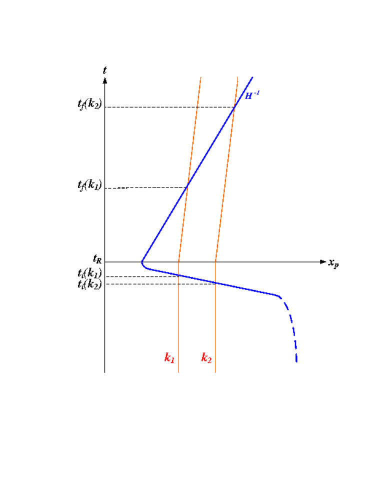
A. Nayeri, R.B. and C. Vafa, *Phys. Rev. Lett. 97:021302 (2006)*






N.B. Perturbations originate as thermal string gas fluctuations.

# Power spectrum of cosmological fluctuations



Key features:

- scale-invariant like for inflation
- slight red tilt like for inflation

# Spectrum of Gravitational Waves

Key features:

- scale-invariant (like for inflation)
- slight blue tilt (unlike for inflation)

# Network of cosmic superstrings



- Remnant of the Hagedorn phase: network of cosmic superstrings
- This string network will be present at all times and will achieve a scaling solution like cosmic strings forming during a phase transition.
- Scaling Solution: The network of strings looks statistically the same at all times when scaled to the Hubble radius.

# Kaiser-Stebbins Effect



Space perpendicular to a string is conical with deficit angle

$$\alpha = 8\pi G\mu \, , \tag{1}$$

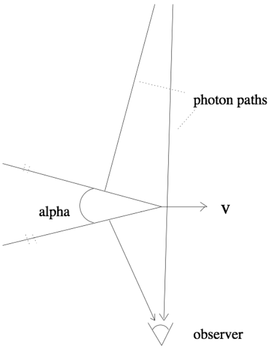
Photons passing by the string undergo a relative Doppler shift

$$\frac{\delta T}{T} = 8\pi\gamma(v)vG\mu \, , \tag{2}$$

$\rightarrow$ network of line discontinuities in CMB anisotropy maps

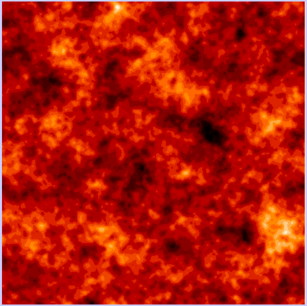
.

*N.B. characteristic scale: one degree in the sky, but to see that there is a sharp temperature jump one needs good angular resolution .*


photon paths
alpha
V
observer

# Gaussian map due to thermal superstring fluctuations

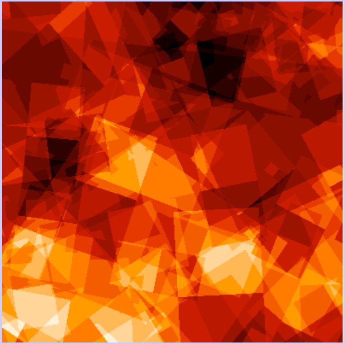
$10'^{0}$ x $10^{0}$ map of the sky at 1.5' resolution (South Pole Telescope specifications)



# Cosmic superstring contribution



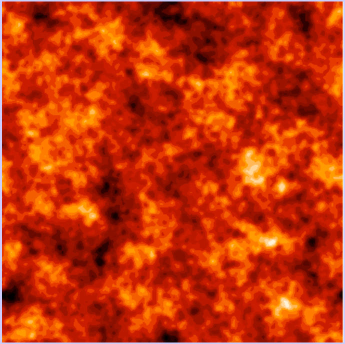
$10^0$ x $10^0$ map of the sky at 1.5’ resolution



This signal is superimposed on the Gaussian map. The relative power of the string signature depends on $G\mu$ and is bound to contribute less than 10% of the power.

# Temperature map Gaussian + cosmic superstrings





# CANNY edge detection algorithm



- Challenge: pick out the string signature from the Gaussian "noise" which has a much larger amplitude
- New technique: use CANNY edge detection algorithm [Canny, 1986]
- Idea: find edges across which the gradient is in the correct range to correspond to a Kaiser-Stebbins signal from a string
- Step 1: generate "Gaussian" and "Gaussian plus strings" CMB anisotropy maps: size and angular resolution of the maps are free parameters, flat sky approximation, cosmic string toy model in which a fixed number of straight string segments is laid down at random in each Hubble volume in each Hubble time step between $t_{rec}$ and $t_0$.

# CANNY algorithm II

- Step 2: run the CANNY algorithm on the temperature maps to produce edge maps.
- Step 3: Generate histogram of edge lengths
- Step 4: Use Fisher combined probability test to check for difference compared to a Gaussian distribution.

# Results

- For South Pole Telescope (SPT) specification: limit $G\mu < 2 \times 10^{-8}$ can be set [R. Danos and R.B., 2008]
- Anticipated SPT instrumental noise only insignficantly effects the limits [A. Stewart and R.B., 2008]

# Results

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# Plan

# Conclusions I

Early Universe

R. Brandenberger

Introduction
- Motivation
- Inflation
- Problems
- Message

String gas
- Principles
- Features

Structure
- Analysis
- Signatures in CMB anisotropy maps

Conclusions

- Cosmology is a vibrant field with lots of observational data
- Paradigms of early universe cosmology have been developed
- Paradigm 1: Standard Big Bang Model
- Paradigm 2: Inflationary Universe scenario - current paradigm
- Paradigm 2 has conceptual problems → motivates the search for an improved paradigm.
- Superstring theory may provide a new paradigm.
- Superstring cosmology may resolve the Big Bang singularity.
- It is possible to observationally probe string cosmology.

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# Conclusions II



- SGC leaves behind a network of cosmic superstrings
- These cosmic superstrings give rise to line discontinuities in CMB anisotropy maps which can be probed using a CANNY edge detection algorithm.
- Undergraduates participate in this cutting edge research!