String Theory and the Very Early Universe

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February 9, 2009

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   - Review of the Theory of Cosmological Perturbations
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Current Paradigm for Early Universe Cosmology

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

Successes:

- Solves horizon problem
- Solves flatness problem
- Solves size/entropy problem
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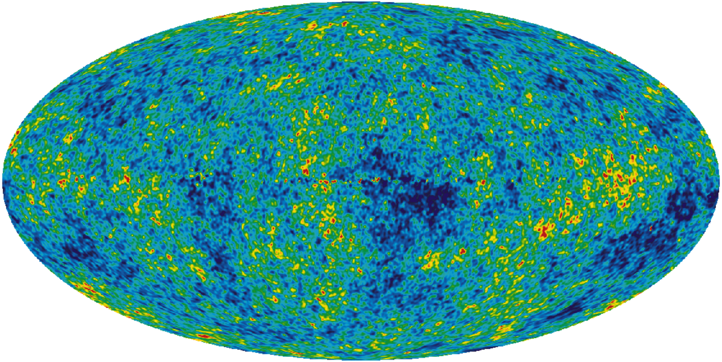
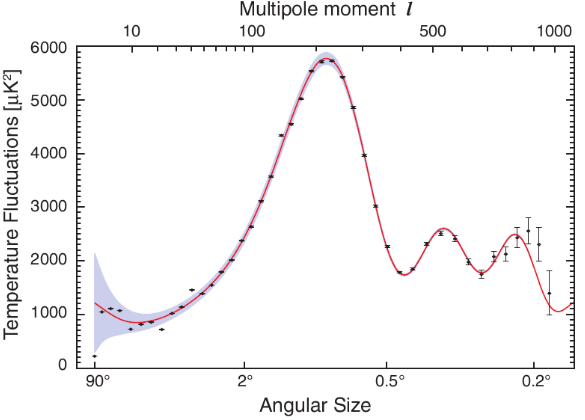


Credit: NASA/WMAP Science Team



Credit: NASA/WMAP Science Team

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

$$\text{Metric}: \; ds^2 = dt^2 - a(t)^2 d\mathbf{x}^2 \qquad (1)$$

Inflation:

- phase with $a(t) \sim e^{tH}$
- requires matter with $p \sim -\rho$
- requires a slowly rolling scalar field φ
- - in order to have a potential energy term
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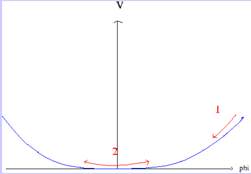
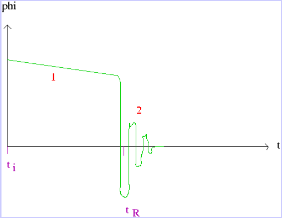
Time line of inflationary cosmology:

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

Matter scalar field:

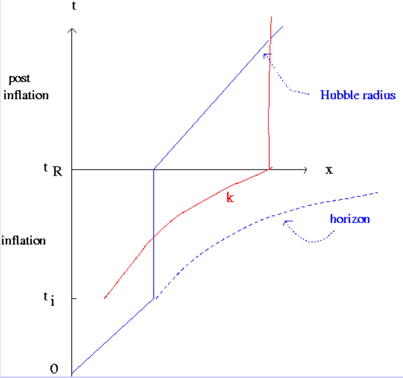


Scalar field evolution:



Review of Inflationary Cosmology II

Space-time sketch of inflationary cosmology:



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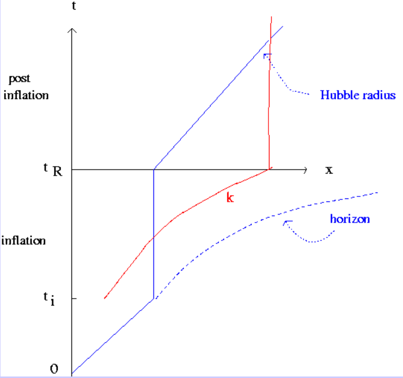

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- classical matter redshifts → matter vacuum remains
- quantum vacuum fluctuations: seeds for the observed structure [Chibisov & Mukhanov, 1981]
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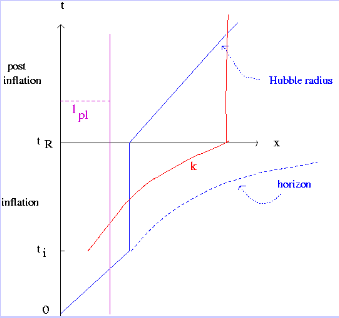
Conceptual Problems of Inflationary Cosmology

- Nature of the scalar field φ (the “inflaton")
- Conditions to obtain inflation (initial conditions, slow-roll conditions, graceful exit and reheating)
- Amplitude problem
- Trans-Planckian problem
- Singularity problem
- Cosmological constant problem
- Applicability of General Relativity

Trans-Planckian Problem

R.B., hep-ph/9910410



- **Success of inflation**: At early times scales are inside the Hubble radius → causal generation mechanism is possible.
- **Problem:** If time period of inflation is more than $70H^{-1}$, then $\lambda_p(t) < l_{pl}$ at the beginning of inflation
- → new physics MUST enter into the calculation of the fluctuations.

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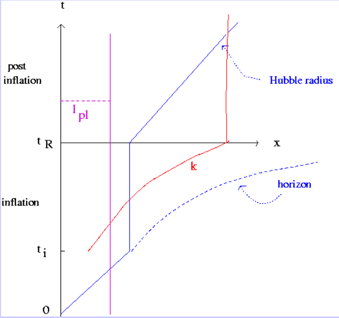

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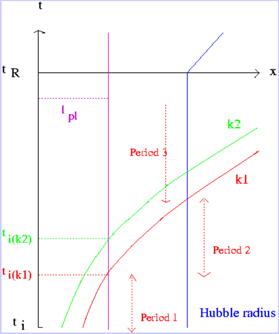
Trans-Planckian Window of Opportunity



- If evolution in Period I is non-adiabatic, then scale-invariance of the power spectrum will be lost [J. Martin and RB, 2000]
- → Planck scale physics testable with cosmological observations!

Singularity Problem

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

Penrose-Hawking theorems:

- Ass: i) Einstein action, 2) weak energy conditions $\rho > 0, \quad \rho + 3p \geq 0$
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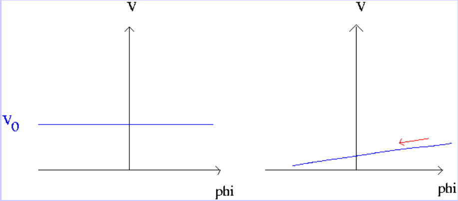

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- Why should the almost constant $V(\varphi)$ gravitate?

$$\frac{V_0}{\Lambda_{obs}} \sim 10^{120} \qquad (2)$$

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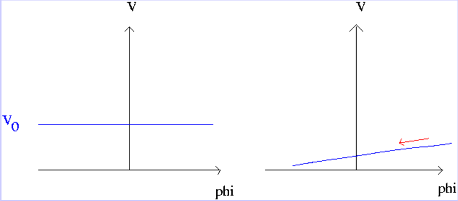

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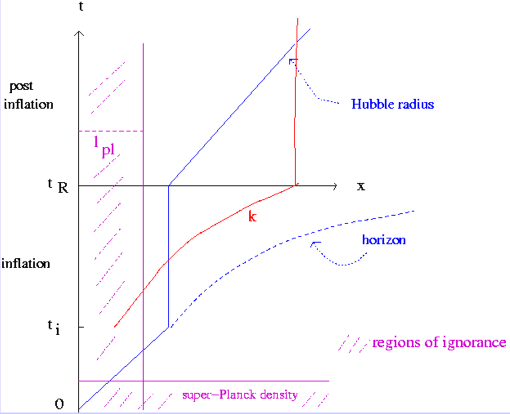
Applicability of GR

- In all approaches to quantum gravity, the Einstein action is only the leading term in a low curvature expansion.
- Correction terms may become dominant at much lower energies than the Planck scale.
- Correction terms will dominate the dynamics at high curvatures.
- The energy scale of inflation models is typically $\eta \sim 10^{16}\text{GeV}$.
- $\rightarrow \eta$ too close to m_{pl} to trust predictions made using GR.

Zones of Ignorance



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].

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]
- Line discontinuities in CMB anisotropy maps [N. Kaiser and A. Stebbins, 1984]
- Line discontinuities may have junctions
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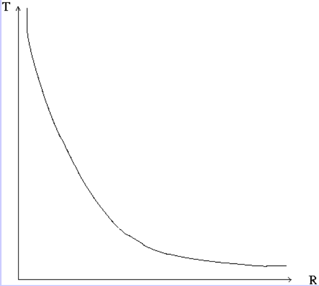
Plan

Singularity Problem in Standard and Inflationary Cosmology

Temperature-size relation in standard cosmology



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
- Leads to a new symmetry: physics at large R is equivalent to physics at small R

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T-Duality

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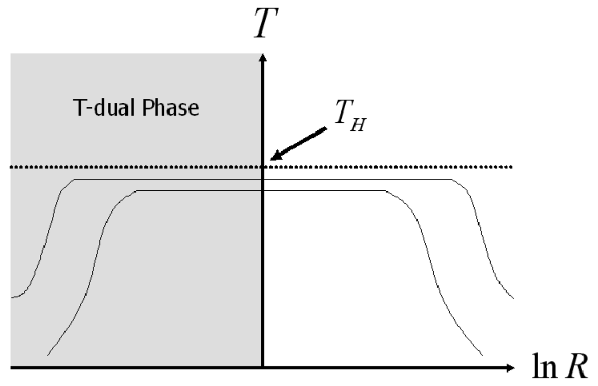
- Momentum modes: $E_n = n/R$
- Winding modes: $E_m = mR$
- Duality: $R \rightarrow 1/R \quad (n, m) \rightarrow (m, n)$
- Mass spectrum of string states unchanged
- Symmetry of vertex operators
- Symmetry at non-perturbative level → existence of D-branes

Adiabatic Considerations

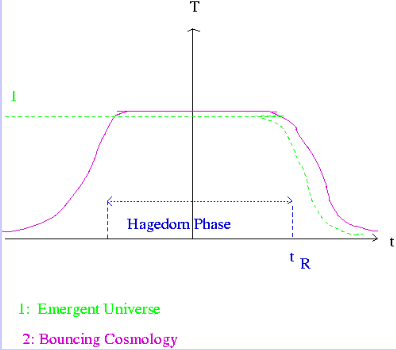
R.B. and C. Vafa, *Nucl. Phys. B316:391 (1989)*

Temperature-size relation in string gas cosmology



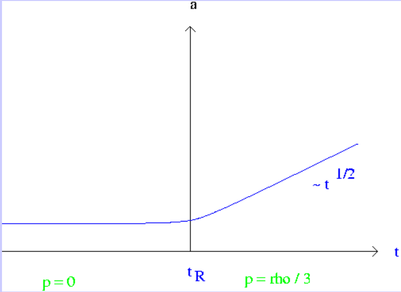
Dynamics

Assume some action gives us $R(t)$



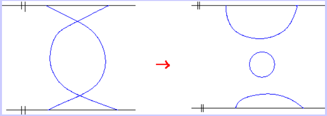
Dynamics II

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 → winding modes about all spatial sections are excited.
- Expansion of any one spatial dimension requires the annihilation of the winding modes in that dimension.



- Decay only possible in three large spatial dimensions.
- → dynamical explanation of why there are exactly three large spatial dimensions.

Note: this argument assumes constant dilaton [R. Danos, A. Frey and A. Mazumdar]

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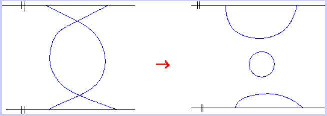

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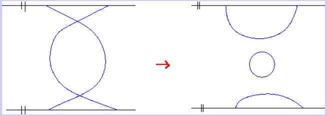

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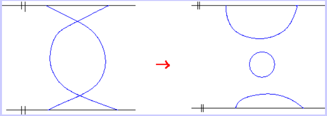

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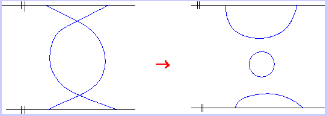

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Moduli Stabilization in SGC

Size Moduli [S. Watson, 2004; S. Patil and R.B., 2004, 2005]

- winding modes prevent expansion
- momentum modes prevent contraction
- $\rightarrow \ V_{eff}(R)$ has a minimum at a finite value of $R, \ \rightarrow \ R_{min}$
- in heterotic string theory there are enhanced symmetry states containing both momentum and winding which are massless at R_{min}
- $\rightarrow V_{eff}(R_{min}) = 0$
- → size moduli stabilized in Einstein gravity background

Shape Moduli [E. Cheung, S. Watson and R.B., 2005]

- enhanced symmetry states
- → harmonic oscillator potential for θ
- → shape moduli stabilized

Dilaton stabilization in SGC

- The only remaining modulus is the dilaton
- Make use of gaugino condensation to give the dilaton a potential with a unique minimum
- $\rightarrow$ diltaton is stabilized
- Dilaton stabilization is consistent with size stabilization [R. Danos, A. Frey and R.B., 2008]

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Theory of Cosmological Perturbations: Basics

Cosmological fluctuations connect early universe theories with observations

- Fluctuations of matter → large-scale structure
- Fluctuations of metric → CMB anisotropies
- N.B.: Matter and metric fluctuations are coupled

Key facts:

- 1. Fluctuations are small today on large scales
- → fluctuations were very small in the early universe
- → can use linear perturbation theory
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Quantum Theory of Linearized Fluctuations

V. Mukhanov, H. Feldman and R.B., *Phys. Rep. 215:203 (1992)*

Step 1: Metric including fluctuations

$$ds^2 = a^2[(1+2\Phi)d\eta^2 - (1-2\Phi)d\mathbf{x}^2] \qquad (3)$$

$$\varphi = \varphi_0 + \delta\varphi \qquad (4)$$

Note: Φ and $\delta\varphi$ related by Einstein constraint equations

Step 2: Expand the action for matter and gravity to second order about the cosmological background:

$$S^{(2)} = \frac{1}{2}\int d^4x\left((v')^2 - v_{,i}v^{,i} + \frac{z''}{z}v^2\right) \qquad (5)$$

$$v = a\left(\delta\varphi + \frac{z}{a}\Phi\right) \qquad (6)$$

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Step 3: Resulting equation of motion (Fourier space)

$$v_k'' + (k^2 - \frac{z''}{z})v_k = 0 \tag{8}$$

Features:

- oscillations on sub-Hubble scales
- squeezing on super-Hubble scales $v_k \sim z$

Quantum vacuum initial conditions:

$$v_k(\eta_i) = (\sqrt{2k})^{-1} \tag{9}$$

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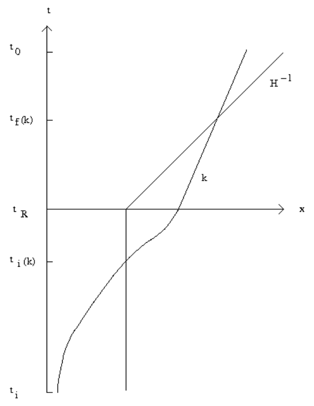
Requirements

Requirements for a model which agrees with observations:

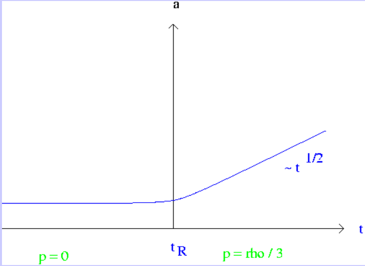
- Scale-invariant spectrum of fluctuations.
- Generation on sub-Hubble scales.
- Frozen propagation on super-Hubble scales.

Structure formation in inflationary cosmology



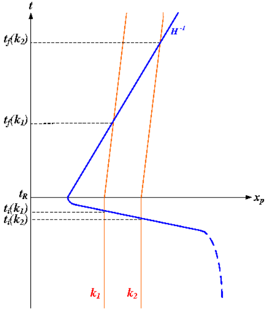
N.B. Perturbations originate as quantum vacuum fluctuations.

Background for string gas cosmology



Structure formation in string gas cosmology

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



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

Method

- 1. Calculate matter correlation functions in the Hagedorn phase (neglecting the metric fluctuations)
- 2. For fixed k, convert the matter fluctuations to metric fluctuations at Hubble radius crossing $t = t_i(k)$
- 3. Evolve the metric fluctuations for $t > t_i(k)$ using the usual theory of cosmological perturbations

Extracting the Metric Fluctuations

Ansatz for the metric including cosmological perturbations and gravitational waves:

$$ds^2 = a^2(\eta)\big((1+2\Phi)d\eta^2 - [(1-2\Phi)\delta_{ij} + h_{ij}]dx^i dx^j\big)\,. \quad (10)$$

Inserting into the perturbed Einstein equations yields

$$\langle|\Phi(k)|^2\rangle = 16\pi^2 G^2 k^{-4}\langle\delta T^0{}_0(k)\delta T^0{}_0(k)\rangle\,, \quad (11)$$

$$\langle|h(k)|^2\rangle = 16\pi^2 G^2 k^{-4}\langle\delta T^i{}_j(k)\delta T^i{}_j(k)\rangle\,. \quad (12)$$

Power Spectrum of Cosmological Perturbations

Key ingredient: For thermal fluctuations:

$$\langle \delta\rho^2 \rangle = \frac{T^2}{R^6} C_V \, . \tag{13}$$

Key ingredient: For string thermodynamics in a compact space

$$C_V \approx 2 \frac{R^2/\ell_s^3}{T(1 - T/T_H)} \, . \tag{14}$$

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Power spectrum of cosmological fluctuations

$$\begin{aligned} P_\Phi(k) &= 8G^2k^{-1} < |\delta\rho(k)|^2 > && (15)\\ &= 8G^2k^2 < (\delta M)^2 >_R && (16)\\ &= 8G^2k^{-4} < (\delta\rho)^2 >_R && (17)\\ &= 8G^2 \frac{T}{\ell_s^3}\frac{1}{1 - T/T_H} && (18) \end{aligned}$$

Key features:

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

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Comments

- 1. Evolution for $t > t_i(k)$: $\Phi \simeq \text{const}$ since the equation of state parameter $1 + w$ stays the same order of magnitude unlike in inflationary cosmology.
- 2. Squeezing of the fluctuation modes takes place on super-Hubble scales like in inflationary cosmology → acoustic oscillations in the CMB angular power spectrum
- 3. In a dilaton gravity background the dilaton fluctuations dominate → different spectrum [R.B. et al, 2006; Kaloper, Kofman, Linde and Mukhanov, 2006]

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R.B., A. Nayeri, S. Patil and C. Vafa, *Phys. Rev. Lett. (2007)*

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Requirements

- Static Hagedorn phase (including static dilaton) → new physics required.
- $C_V(R) \sim R^2$ obtained from a thermal gas of strings provided there are winding modes which dominate.
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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

$$\alpha = 8\pi G\mu \,, \tag{23}$$

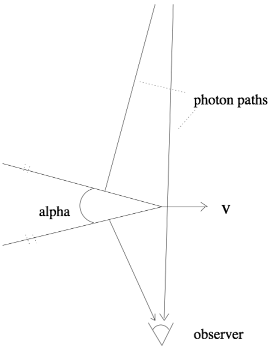
Photons passing by the string undergo a relative Doppler shift

$$\frac{\delta T}{T} = 8\pi\gamma(v)vG\mu \,, \tag{24}$$

→ network of line discontinuities in CMB anisotropy maps

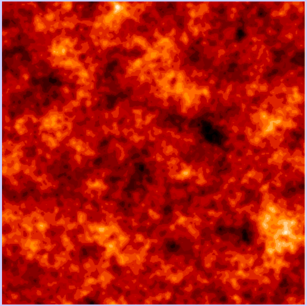
.

N.B. characteristic scale: comoving Hubble radius at the time of recombination → need good angular resolution to detect these edges.


photon paths
alpha
V
observer

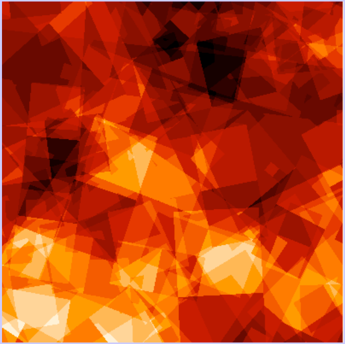
Gaussian temperature map

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



Cosmic string temperature map

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

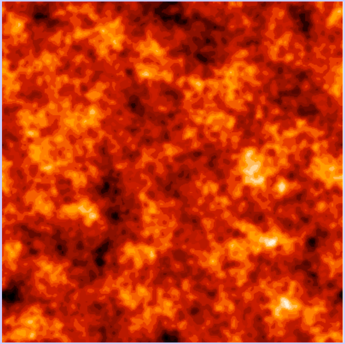


This signal is superimposed on the Gaussian map. The relative power of the string signature depends on $G\mu$ and is bound to contribute less than 10% of the power (L. Pogosian & M. Wyman).

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.

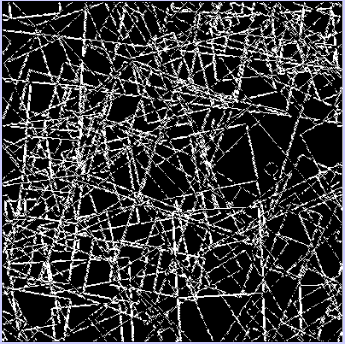
Temperature map Gaussian + strings



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.

Edge map



Preliminary results

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

1. Introduction
    - Motivation
    - Review of Inflationary Cosmology
    - Problems of Inflationary Cosmology
    - Message
2. String Gas Cosmology
    - Principles
    - Features of String Gas Cosmology
3. String Gas Cosmology and Structure Formation
    - Review of the Theory of Cosmological Perturbations
    - Overview
    - Analysis
    - Signatures in CMB anisotropy maps
4. Conclusions and Discussion

Conclusions I

Conclusions :

- The Inflationary scenario, the current paradigm of early universe cosmology, has serious conceptual problems.
- This motivated the search for a new paradigm based on improved fundamental physics.
- String Gas Cosmology: Model of cosmology of the very early universe based on new degrees of freedom and new symmetries of superstring theory.
- SGC $\rightarrow$ nonsingular cosmology
- SGC $\rightarrow$ natural explanation of the number of large spatial dimensions.
- SGC $\rightarrow$ new scenario of structure formation
- Scale invariant spectrum of cosmological fluctuations (like in inflationary cosmology).
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- Holographic scaling of the specific heat capacity.
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