Probing Fundamental Physics with Cosmological Observations

Cosmology of the Very Early Universe

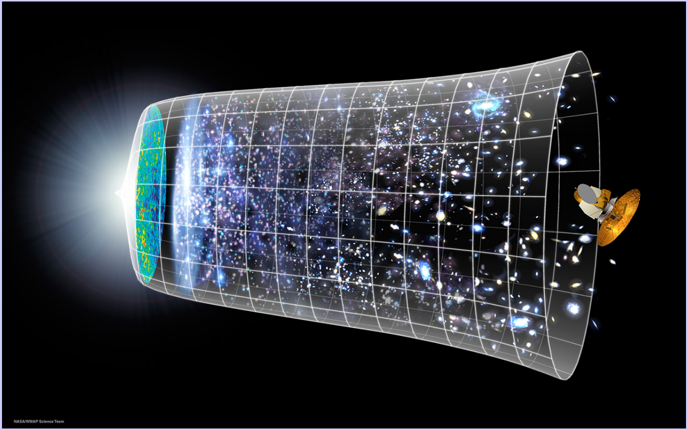
Robert Brandenberger, McGill University

January 9, 2014

Outline

Plan

Context: The Expanding Universe

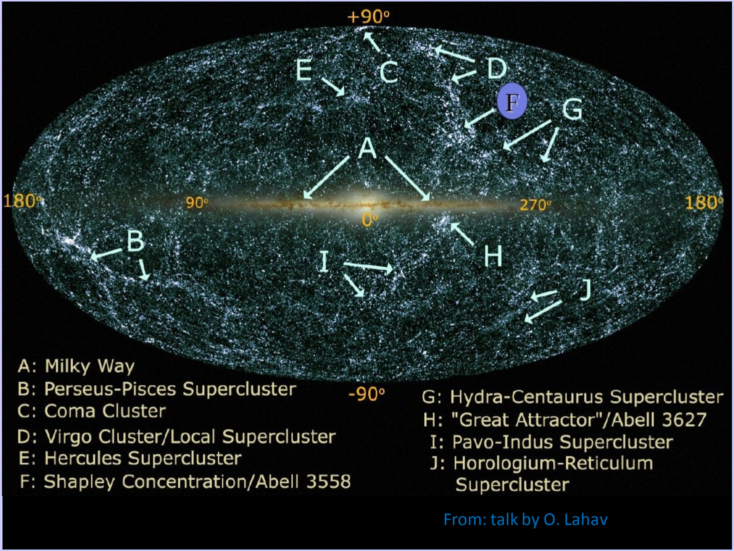


Credit: NASA/WMAP Science Team

Optical Telescopes: Gemini Telescope

Galaxies: Building Blocks of the Cosmology

Large-Scale Structure



Power Spectrum of Density Fluctuations

Early Universe

R. Brandenberger

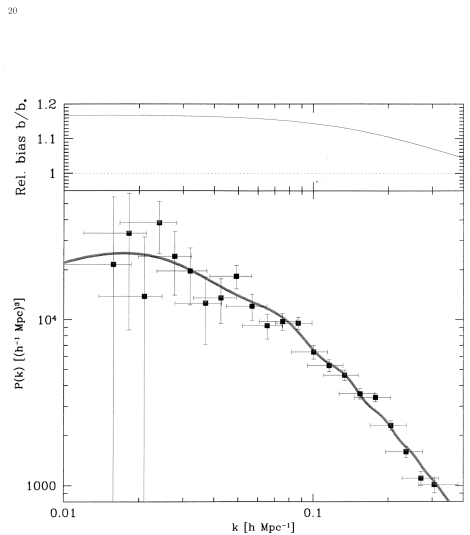
Observations

Fluctuations
- Theory
- Criteria
- Realizations

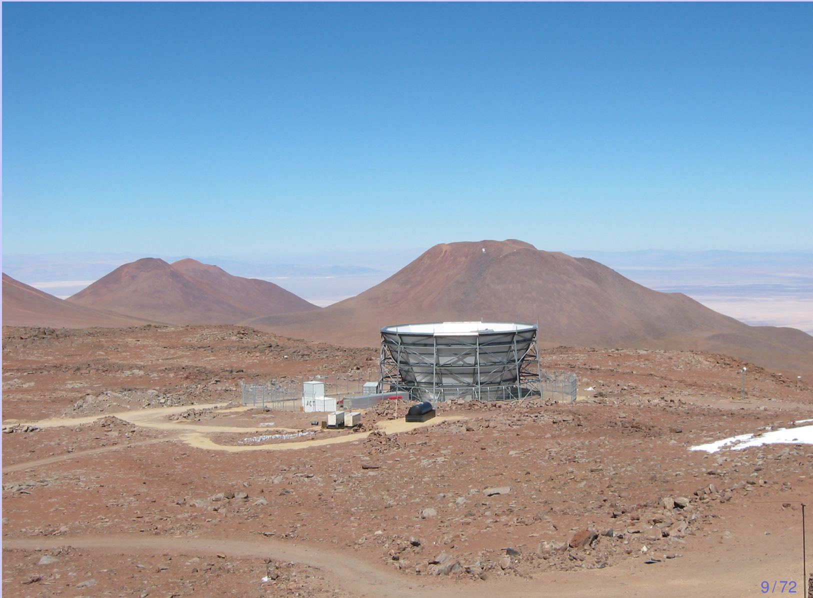
Fundamental Physics

Particle Physics
- Cosmic Strings
- Structure
- Signatures

Conclusions

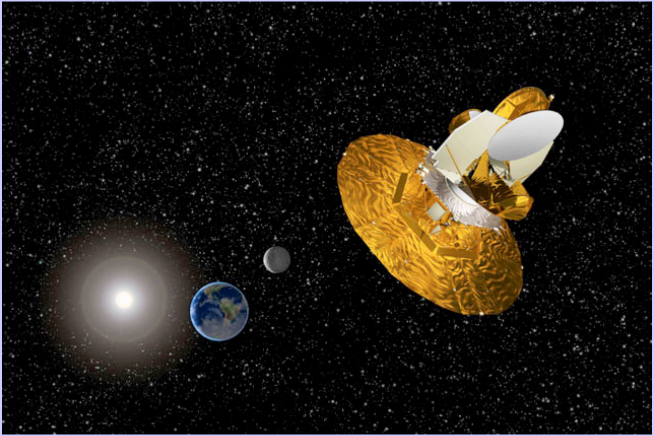


Microwave Telescopes on the Earth: ACT Telescope

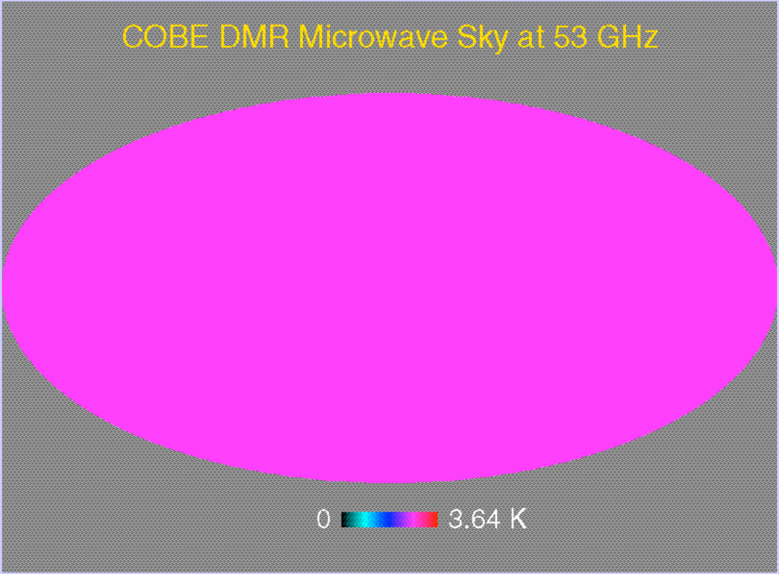


Microwave Telescopes on the Earth: SPT Telescope

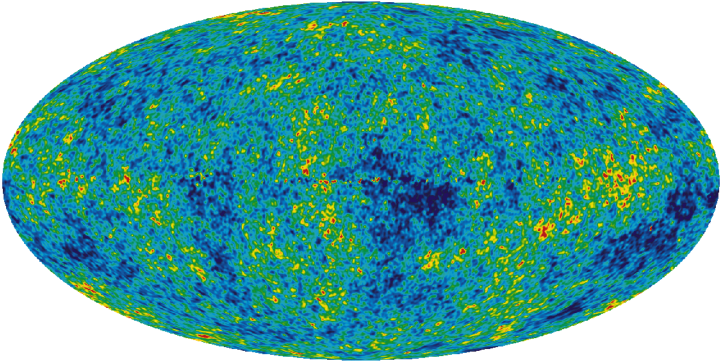
Microwave Telescopes in Space: WMAP Telescope



Isotropic CMB Background

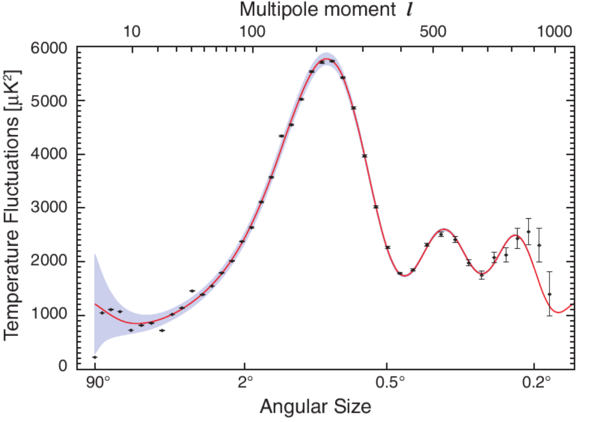


Map of the Cosmic Microwave Background (CMB)



Credit: NASA/WMAP Science Team

Angular Power Spectrum of CMB Anisotropies



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New Window: CMB Polarization

- CMB radiation can be polarized.
- e.g. CMB photons passing through a gas cloud are polarized by Thompson scattering.
- Two polarization modes: E mode and B mode.
- E mode has been detected, for B mode only upper limits exist.
- Primordial adiabatic fluctuations produce no B modes. B modes only induced by gravitational waves.
- Detection of B mode polarization: main goal for the near future.
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- Baryonic matter dominated by neural H for $z_{rec} > z > z_{rein}$.
- Neutral H has 21cm hyperfine transition line.
- Inhomogeneities in the distribution of neutral H $\rightarrow$ inhomogeneities in 3-d redshift map of 21cm: extra absorption/emission.
- 21cm redshift surveys $\rightarrow$ information about the distribution of baryons in the “dark ages".
- 21cm telescopes exist, e.g. LOFAR, ambitious project in planning SKA.
- NB: These telescopes have many other applications.

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Fluctuation Problem in Standard Cosmology

- Fluctuations on large scales were outside the horizon at t_{eq} (the time when structures can start growing).
- Seeds for the current fluctuations had to have been present at t_{eq}
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Key Realization

R. Sunyaev and Y. Zel'dovich, Astrophys. and Space Science **7**, 3 (1970); P. Peebles and J. Yu, Ap. J. **162**, 815 (1970).

- Given a scale-invariant power spectrum of adiabatic fluctuations on "super-horizon" scales before t_{eq}, i.e. standing waves.
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1970 paper

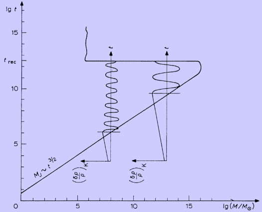

Fig. 1a. Diagram of gravitational instability in the 'big-bang' model. The region of instability is located to the right of the line $M_J(t)$; the region of stability to the left. The two additional lines of the graph demonstrate the temporal evolution of density perturbations of matter: growth until the moment when the considered mass is smaller than the Jeans mass and oscillations thereafter. It is apparent that at the moment of recombination perturbations corresponding to different masses correspond to different phases.

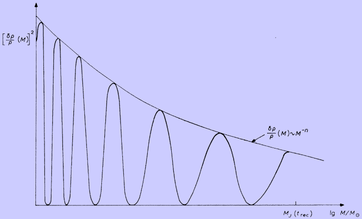

Fig. 1b. The dependence of the square of the amplitude of density perturbations of matter on scale. The fine line designates the usually assumed dependence $(\delta\varrho/\varrho)_M \sim M^{-n}$. It is apparent that fluctuations of relic radiation should depend on scale in a similar manner.

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Hubble Radius vs. Horizon

- Horizon: Forward light cone of a point on the initial Cauchy surface.
- Horizon: region of causal contact.
- Hubble radius: $l_H(t) = H^{-1}(t)$ inverse expansion rate.
- Hubble radius: local concept, relevant for dynamics of cosmological fluctuations.
- In Standard Big Bang Cosmology: Hubble radius = horizon.
- In any theory which can provide a mechanism for the origin of structure: Hubble radius $\neq$ horizon.

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Theory of Cosmological Perturbations: Basics

Cosmological fluctuations connect early universe theories with observations

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

Key facts:

- Fluctuations are small today on large scales
- $\rightarrow$ fluctuations were very small in the early universe
- $\rightarrow$ 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

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\begin{aligned}
ds^2 &= a^2[(1+2\Phi)d\eta^2 - (1-2\Phi)d\mathbf{x}^2] \\
\varphi &= \varphi_0 + \delta\varphi
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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:

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Step 3: Resulting equation of motion (Fourier space)

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

Features:

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

Quantum vacuum initial conditions:

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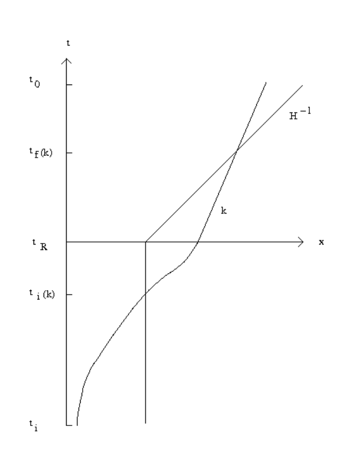
Criteria

- Horizon $\gg$ Hubble radius.
- Fluctuation modes have $\lambda \gg H^{-1}$ for a long period of time $\rightarrow$ squeezing.
- Mechanism producing scale-invariant primordial spectrum.

Structure formation in inflationary cosmology



N.B. Perturbations originate as quantum vacuum fluctuations.

Origin of Scale-Invariance in Inflation I

- Scenario A: Initial vacuum spectrum of ζ ($\zeta \sim v$): (Chibisov and Mukhanov, 1981).

$$P_\zeta(k) \equiv k^3|\zeta(k)|^2 \sim k^2$$

- $v \sim z \sim a$ on super-Hubble scales
- At late times on super-Hubble scales

$$P_\zeta(k,t) \equiv P_\zeta(k,t_i(k))\left(\frac{a(t)}{a(t_i(k))}\right)^2 \sim k^2 a(t_i(k))^{-2}$$

- Hubble radius crossing: $ak^{-1} = H^{-1}$
- $\rightarrow P_\zeta(k,t) \sim \mathrm{const}$

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Origin of Scale-Invariance in Inflation II

- Scenario B: Thermal matter fluctuations during inflation: ("Warm Inflation", Berera, 1995; Berera and Fang, 1995).
- Energy density fluctuations time independent on Hubble scale.
- $\rightarrow$ power spectrum of Φ independent of time on Hubble scale.
- $\rightarrow$ power spectrum of Φ independent of k at and after reheating.
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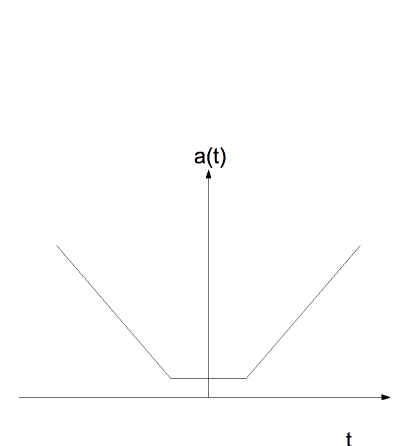
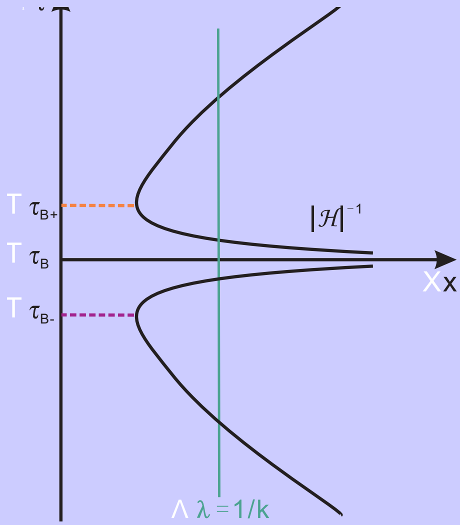
Matter Bounce Cosmology

D. Wands, Phys. Rev. D **60**, 023507 (1999): F. Finelli and R.B. Phys. Rev. D **65**, 103522 (2002).

Idea: Non-singular bouncing cosmology with a matter-dominated phase of contraction, can be realized in the context of Horava-Lifshitz gravity [R.B., arXiv:0904.2835].



Structure Formation in a Bouncing Cosmology



Origin of Scale-Invariance in Matter Bounce

- Vacuum spectrum of ζ ($\zeta \sim v$):

$$P_\zeta(k) \equiv k^3 |\zeta(k)|^2 \sim k^2$$

- To produce a scale-invariant spectrum a mechanism to boost long wavelength modes relative to short wavelength modes is needed.
- In a contracting phase ζ grows on super-Hubble scales.
- Dominant mode in the contracting phase in a matter universe:

$$v_k(\eta) \sim \eta^{-1} \text{ where } a(\eta) \sim \eta^2$$

- Hubble radius crossing condition:

$$k^{-1} a(\eta_H(k)) = t(\eta_H(k)) \rightarrow \eta_H(k) \sim k^{-1}$$

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- Thus the power spectrum becomes

$$P_\zeta(k,\eta) \sim k^3 z(\eta)^{-2} |v_k(\eta_H(k))|^2 \left(\frac{v_k(\eta)}{v_k(\eta_H(k))}\right)^2$$
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- Thus, a scale-invariant spectrum of curvature fluctuations results.
- The fluctuations can be followed through the bouncing phase, modeled as $a(\eta) = 1 + c\eta^2$.
- Use Hwang-Vishniac (Deruelle-Mukhanov) matching conditions at the two surfaces (between contracting matter and bounce phase, and between bounce phase and expanding matter phase) to complete the evolution of ζ.

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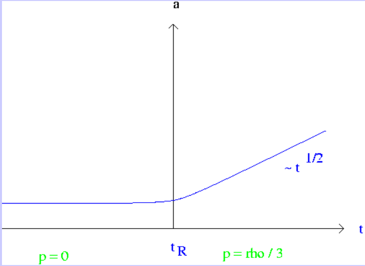
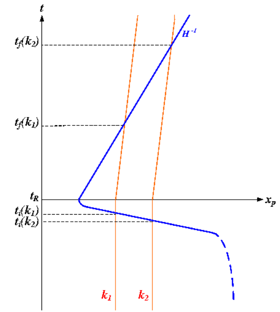
Background for string gas cosmology



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.

Origin of Scale-Invariance in String Gas Cosmology: Method

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

Origin of Scale-Invariance in String Gas Cosmology: Basics I

Ansatz for the metric including cosmological perturbations and gravitational waves:

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

Inserting into the perturbed Einstein equations yields

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

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

Origin of Scale-Invariance in String Gas Cosmology: Basics II

Key ingredient: For thermal fluctuations:

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

Key ingredient: For string thermodynamics in a compact space

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

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Origin of Scale-Invariance in String Gas Cosmology: Power Spectrum

Power spectrum of cosmological fluctuations

$$
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P_\Phi(k) &= 8G^2 k^{-1} < |\delta\rho(k)|^2 > \\
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\end{aligned}
$$

Key features:

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

Origin of Scale-Invariance in String Gas Cosmology: Power Spectrum

Power spectrum of cosmological fluctuations

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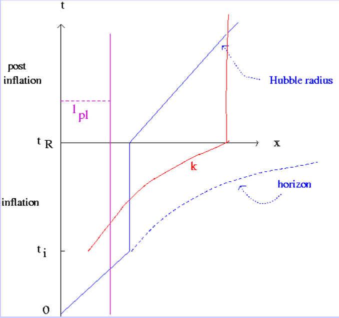
Plan

Trans-Planckian Window in Inflationary Cosmology



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

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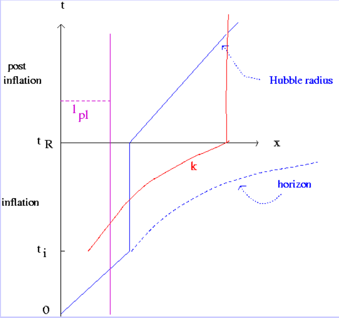

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- Example: R. Easther et al (hep-th/0104102): Inflation in the context of space-space noncommutativity $\rightarrow$ characteristic oscillations in $P(k)$.
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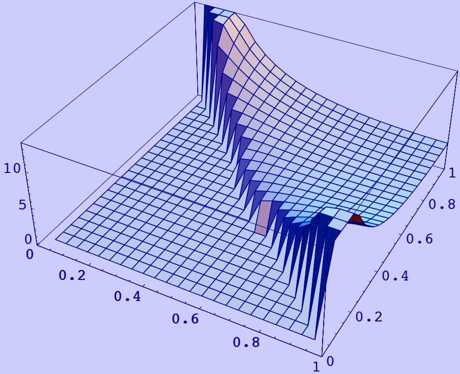
Prediction of a Bouncing Cosmology

Y. Cai, W. Xue, R.B. and X. Zhang, JCAP **0905**, 011 (2009)

Distinctive shape of the bispectrum:



Spectrum of Gravitational Waves in String Gas Cosmology

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

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P_h(k) &= 16\pi^2 G^2 k^{-1} < |T_{ij}(k)|^2 > \\
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Key ingredient for string thermodynamics

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< |T_{ij}(R)|^2 > \sim \frac{T}{l_s^3 R^4}(1 - T/T_H)
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Plan

Cosmic Strings

T. Kibble, J. Phys. A **9**, 1387 (1976); Y. B. Zeldovich, Mon. Not. Roy. Astron. Soc. **192**, 663 (1980); A. Vilenkin, Phys. Rev. Lett. **46**, 1169 (1981).

- Cosmic string = linear topological defect in a quantum field theory.
- 1st analog: line defect in a crystal
- 2nd analog: vortex line in superfluid or superconductor
- Cosmic string = line of trapped energy density in a quantum field theory.
- Trapped energy density $\rightarrow$ gravitational effects on space-time $\rightarrow$ important in cosmology.

Relevance to Particle Physics and Cosmology

- Cosmic strings are predicted in many particle physics models beyond the "Standard Model".
- In models which admit cosmic strings, cosmic strings inevitably form in the early universe and persist to the present time.
- Cosmic strings are characterized by their tension μ which is associated with the energy scale η at which the strings form ($\mu \sim \eta^2$).
- Searching for the signatures of cosmic strings is a tool to probe physics beyond the Standard Model at energy ranges complementary to those probed by the LHC.
- Cosmic strings are constrained from cosmology: strings with a tension which exceed the value $G\mu \sim 1.5 \times 10^{-7}$ are in conflict with the observed acoustic oscillations in the CMB angular power spectrum (Dvorkin, Hu and Wyman, 2011).

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Criterium for the Existence of Strings

- Consider models with spontaneous symmetry breaking.
- Space of ground states $\mathcal{M}$
- $\Pi_1(\mathcal{M}) \neq 1$ is the criterium for the existence of cosmic strings.
- Example: Broken $U(1)$ symmetry $\rightarrow$ strings exist.

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Formation of Strings

T. Kibble, Phys. Rept. **67**, 183 (1980).

- By causality, the values of ϕ in $\mathcal{M}$ cannot be correlated on scales larger than t.
- Hence, there is a probability $\mathcal{O}(1)$ that there is a string passing through a surface of side length t.
- Causality $\rightarrow$ network of cosmic strings persists at all times.
- Correlation length $\xi(t) < t$ for all times $t > t_c$.
- Dynamics of $\xi(t)$ is governed by a Boltzmann equation which describes the transfer of energy from long strings to string loops
- Result: $\xi(t) \sim t$ for all $t \gg t_c$

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Scaling Solution

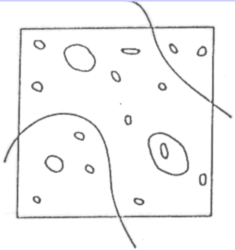


Figure 39. Sketch of the scaling solution for the cosmic string network. The box corresponds to one Hubble volume at arbitrary time t.

Geometry of a Straight String

A. Vilenkin, Phys. Rev. D **23**, 852 (1981).

Space away from the string is locally flat (cosmic string exerts no gravitational pull).

Space perpendicular to a string is conical with deficit angle

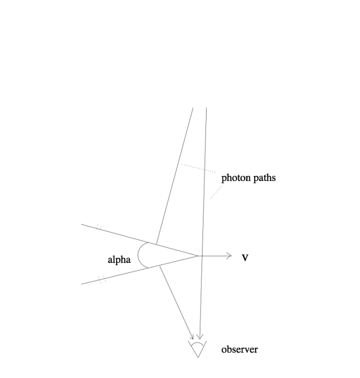
$$\alpha = 8\pi G\mu \, ,$$

Kaiser-Stebbins Effect

N. Kaiser and A. Stebbins, Nature **310**, 391 (1984).

Photons passing by the string undergo a relative Doppler shift

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

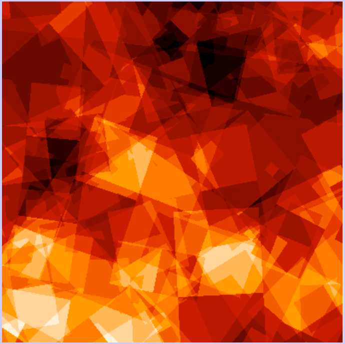


- $\rightarrow$ network of line discontinuities in CMB anisotropy maps.
- *N.B. characteristic scale: comoving Hubble radius at the time of recombination $\rightarrow$ need good angular resolution to detect these edges.*
- Need to analyze position space maps.

Signature in CMB temperature anisotropy maps

R. J. Danos and R. H. Brandenberger, arXiv:0811.2004 [astro-ph].

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

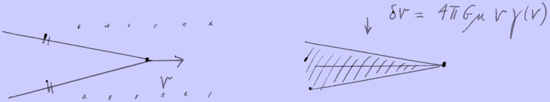


Cosmic String Wake

J. Silk and A. Vilenkin, Phys. Rev. Lett. **53**, 1700 (1984).

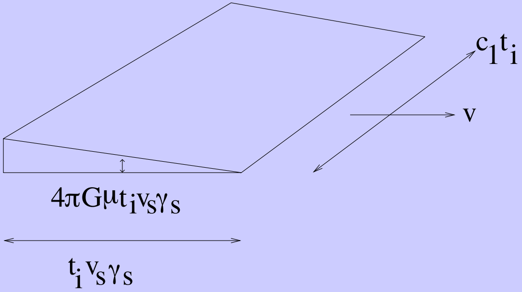
Consider a cosmic string moving through the primordial gas:

Wedge-shaped region of overdensity 2 builds up behind the moving string: wake.



Closer look at the wedge

- Consider a string at time t_i $[t_{rec} < t_i < t_0]$
- moving with velocity v_s
- with typical curvature radius $c_1 \, t_i$



Gravitational accretion onto a wake

L. Perivolaropoulos, R.B. and A. Stebbins, Phys. Rev. D **41**, 1764 (1990).

- Initial overdensity $\rightarrow$ gravitational accretion onto the wake.
- Accretion computed using the Zeldovich approximation.
- Focus on a mass shell a physical distance $w(q,t)$ above the wake:
- Turnaround shell: $q_{nl}(t)$ for which $\dot{w}(q_{nl}(t),t) = 0$
- Result: $q_{nl}(t) \sim a(t)$
- Yields thickness of the gravitationally bound region (wake thickness).

Signature in CMB Polarization

R. Danos, R.B. and G. Holder, arXiv:1003.0905 [astro-ph.CO].

- Wake is a region of enhanced free electrons.
- CMB photons emitted at the time of recombination acquire extra polarization when they pass through a wake.
- Statistically an equal strength of E-mode and B-mode polarization is generated.
- Consider photons which at time t pass through a string segment laid down at time $t_i < t$.

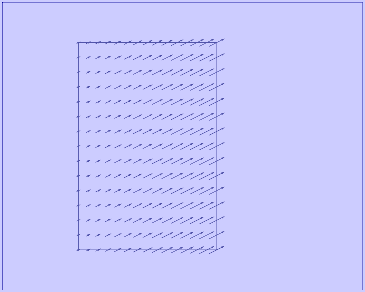
$$\frac{P}{Q} \simeq \frac{24\pi}{25}\left(\frac{3}{4\pi}\right)^{1/2}\sigma_T f G\mu v_s \gamma_s$$
$$\times \Omega_B \rho_c(t_0) m_p^{-1} t_0 \left(z(t)+1\right)^2 \left(z(t_i)+1\right)^{1/2} .$$

Signature in CMB Polarization II

Inserting numbers yields the result:

$$\frac{P}{Q} \sim fG\mu v_s \gamma_s \Omega_B \left(\frac{z(t)+1}{10^3}\right)^2 \left(\frac{z(t_i)+1}{10^3}\right)^{1/2} 10^7 \,.$$

Characteristic pattern in position space:



Is B-mode Polarization the Holy Grail of Inflation?

R.B., arXiv:1104.3581 [astro-ph.CO].

- Cosmic strings produce direct B-mode polarization.
- $\rightarrow$ gravitational waves not the only source of primordial B-mode polarization.
- Cosmic string loop oscillations produce a scale-invariant spectrum of primordial gravitational waves with a contribution to $\delta T/T$ which is comparable to that induced by scalar fluctuations (see e.g. A. Albrecht, R.B. and N. Turok, 1986).
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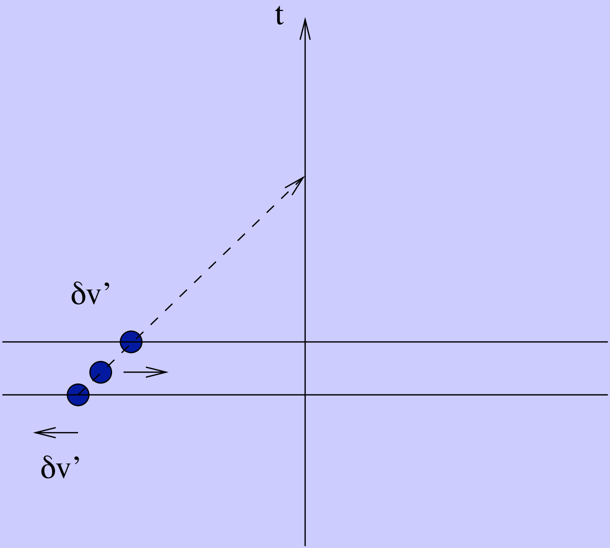
21cm Signals from Cosmic String Wakes

R.B., D. Danos, O. Hernandez and G. Holder, arXiv:1006.2514; O. Hernandez, Yi Wang, R.B. and J. Fong, arXiv:1104.3337.

- 21 cm surveys: new window to map the high redshift universe, in particular the “dark ages".
- Cosmic strings produce nonlinear structures at high redshifts.
- These nonlinear structures will leave imprints in 21 cm maps. (Khatri & Wandelt, arXiv:0801.4406, A. Berndsen, L. Pogosian & M. Wyman, arXiv:1003.2214)
- 21 cm surveys provide 3-d maps $\rightarrow$ potentially more data than the CMB.
- $\rightarrow$ 21 cm surveys is a promising window to search for cosmic strings.

The Effect

- $10^3 > z > 10$: baryonic matter dominated by neutral H.
- Neutral H has hydrogen hyperfine absorption/emission line.
- String wake is a gas cloud with special geometry which emits/absorbs 21cm radiation.
- Whether signal is emission/absorption depends on the temperature of the gas cloud.


t
δv'
δv'

Key general formulas

Brightness temperature:

$$T_b(\nu) \; = \; T_S\left(1 - e^{-\tau_\nu}\right) + T_\gamma(\nu) e^{-\tau_\nu} \, ,$$

Spin temperature:

$$T_S \; = \; \frac{1 + x_c}{1 + x_c T_\gamma / T_K} T_\gamma \, .$$

T_K: gas temperature in the wake, x_c collision coefficient

Relative brightness temperature:

$$\delta T_b(\nu) \; = \; \frac{T_b(\nu) - T_\gamma(\nu)}{1 + z}$$

Optical depth:

$$\tau_\nu = \frac{3c^2 A_{10}}{4\nu^2}\left(\frac{\hbar\nu}{k_B T_S}\right)\frac{N_{HI}}{4}\phi(\nu),$$

$N_{HI} \sim G\mu$ column number density of hydrogen atoms.
Line profile:

$$\phi(\nu) = \frac{1}{\delta\nu} \sim (\mathrm{width})^{-1} \sim (G\mu)^{-1}$$

$\rightarrow$ pixel 21cm intensity independent of $G\mu$.

Frequency dispersion (thickness in redshift direction) $\sim G\mu$.

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Application to Cosmic String Wakes

Wake temperature T_K:

$$T_K \simeq [20\ \mathrm{K}](G\mu)_6^2 (v_s\gamma_s)^2 \frac{z_i + 1}{z + 1},$$

determined by considering thermalization at the shock which occurs after turnaround when $w = 1/2 w_{max}$ (see Eulerian hydro simulations by A. Sornborger et al, 1997).

Thickness in redshift space:

$$\frac{\delta\nu}{\nu} = \frac{24\pi}{15} G\mu v_s\gamma_s (z_i + 1)^{1/2} (z(t) + 1)^{-1/2}$$
$$\simeq 3 \times 10^{-5} (G\mu)_6 (v_s\gamma_s),$$

using $z_i + 1 = 10^3$ and $z + 1 = 30$ in the second line.

Relative brightness temperature:

$$\delta T_b(\nu) = [0.07\,\mathrm{K}]\frac{x_c}{1+x_c}(1-\frac{T_\gamma}{T_K})(1+z)^{1/2}$$
$$\sim 200mK \quad \text{for} \quad z+1=30\,.$$

Signal is emission if $T_K > T_\gamma$ and absorption otherwise.

Critical curve (transition from emission to absorption):

$$(G\mu)_6^2 \simeq 0.1(v_s\gamma_s)^{-2}\frac{(z+1)^2}{z_i+1}$$

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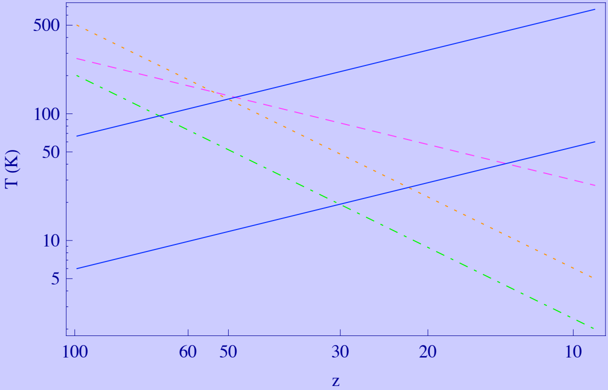
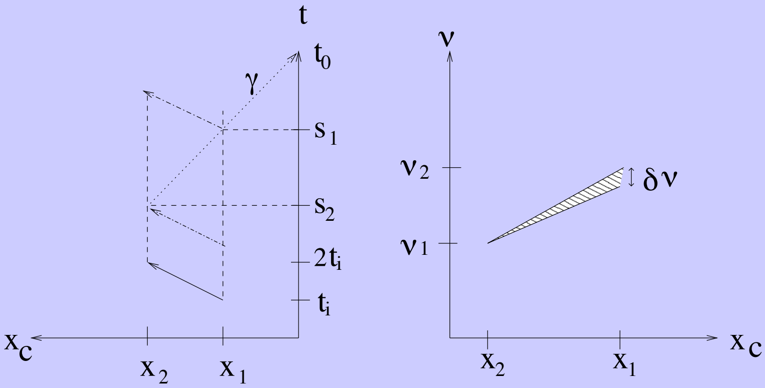
Scalings of various temperatures



Top curve: $(G\mu)_6 = 1$, bottom curve: $(G\mu)_6 = 0.3$

Geometry of the signal



Plan

Conclusions

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- Origin of structure: very early universe.
- Physics of the very early universe can be tested by means of cosmological observations.
- Several theoretical paradigms of early universe cosmology exist, inflation not the unique scenario.
- In this context, fundamental physics can be tested with cosmological observations.
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