Searching for Cosmic Strings in New Observational Windows

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Outline

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 → gravitational effects on space-time → important in cosmology.

Relevance to Particle Physics and Cosmology I

- Cosmic strings are predicted in many particle physics models beyond the “Standard Model".
- Cosmic strings are predicted to form at the end of inflation in many inflationary models.
- Cosmic strings may survive as cosmic superstrings in alternatives to inflation such as string gas cosmology.
- In models which admit cosmic strings, cosmic strings inevitably form in the early universe and persist to the present time.
- It would be nice to see a cosmic string in the universe!

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Relevance to Particle Physics and Cosmology II

- 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).
- Existing upper bound on the string tension rules out large classes of particle physics models.

It is interesting to find ways to possibly lower the bounds on the string tension.

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Relevance to Particle Physics and Cosmology III

Cosmic strings can produce many good things for cosmology:

- String-induced mechanism of baryogenesis (R.B., A-C. Davis and M. Hindmarsh, 1991).
- Explanation for the origin of primordial magnetic fields which are coherent on galactic scales (X.Zhang and R.B. (1999).
- Explanation for cosmic ray anomalies (R.B., Y. Cai, W. Xue and X. Zhang (2009).
- Origin of supermassive black holes (R.B., in prep..).

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Preview

Important lessons from this talk:

- Cosmic strings → nonlinearities already at high redshifts.
- Signatures of cosmic strings more pronounced at high redshifts.
- Cosmic strings lead to perturbations which are non-Gaussian.
- Cosmic strings predict specific geometrical patterns in position space.
- 21 cm surveys provide an ideal arena to look for cosmic strings (R.B., R. Danos, O. Hernandez and G. Holder, 2010).

Plan

Cosmic String I

A. Vilenkin and E. Shellard, *Cosmic Strings and other Topological Defects* (Cambridge Univ. Press, Cambridge, 1994).

- Cosmic strings form after symmetry breaking phase transitions.
- Prototypical example: Complex scalar field ϕ with “Mexican hat" potential:

$$V(\phi) = \frac{\lambda}{4}\left(|\phi|^2 - \eta^2\right)^2$$

- Vacuum manifold $\mathcal{M}$: set up field values which minimize V.
- At high temperature: $\phi = 0$.
- At low temperature: $|\phi| = \eta$ - but by causality the phase on scales larger than the horizon is uncorrelated.
- There are lines where $|\phi| = 0$: narrow tubes of trapped potential energy: cosmic strings.
- Mass per unit length $\mu \sim \eta^2$ (independent of λ).

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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.

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Scaling Solution I

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

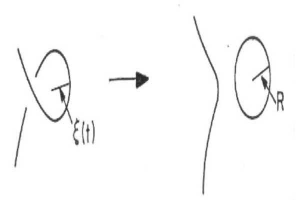

Figure 38: Formation of a loop by a self intersection of an infinite string. According to the original cosmic string scenario, loops form with a radius R determined by the instantaneous

Scaling Solution II

Analysis of the Boltzmann equation shows that $\xi(t) \sim t$ for all $t > t_c$:

- If $\xi(t) << t$ then rapid loop production and $\xi(t)/t$ increases.
- If $\xi(t) >> t$ then no loop production and $\xi(t)/t$ decreases.

Sketch of the scaling solution:

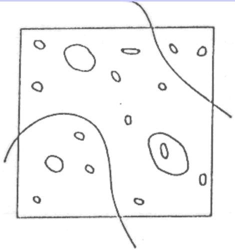

Figure 39. Sketch of the scaling solution for the cosmic string network. The box corresponds

History I

- Cosmic strings were popular in the 1980's as an alternative to inflation for producing a scale-invariant spectrum of cosmological perturbations.
- Cosmic strings lead to incoherent and active fluctuations (rather than coherent and passive like in inflation).
- Reason: strings on super-Hubble scales are entropy fluctuations which seed an adiabatic mode which is growing until Hubble radius crossing.
- Boomerang CMB data (1999) on the acoustic oscillations in the CMB angular power spectrum ruled out cosmic strings as the main source of fluctuations..
- Interest in cosmic strings collapsed.

History II

- Supergravity models of inflation typically yield cosmic strings after reheating (R. Jeannerot et al., 2003).
- Brane inflation models typically yield cosmic strings in the form of cosmic superstrings (Sarangi and Tye, 2002; Copeland, Myers and Polchinski, 2004).
- String Gas Cosmology may lead to a remnant scaling network of cosmic superstrings (R.B. and C. Vafa, 1989: A. Nayeri, R.B. and C. Vafa, 2006).
- $\rightarrow$ renewed interest in cosmic strings as supplementary source of fluctuations.
- Best current limit from angular spectrum of CMB anisotropies: $\sim$ 5% of the total power can come from strings (see e.g. Dvorkin, Hu and Wyman, 2011).
- Leads to limit $G\mu < 1.5 \times 10^{-7}$.

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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

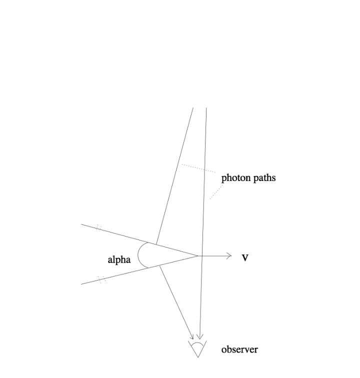
$$\alpha = 8\pi G\mu ,$$

Kaiser-Stebbins Effect

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

Photons passing by the string undergo a relative Doppler shift

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

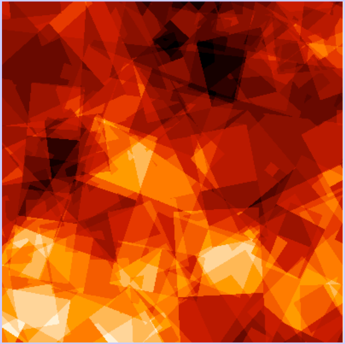


- $\rightarrow$ network of line discontinuities in CMB anisotropy maps.
- *N.B. characteristic scale: comoving Hubble radius at the time of recombination $\rightarrow$ need good angular resolution to detect these edges.*
- Need to analyze position space maps.

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



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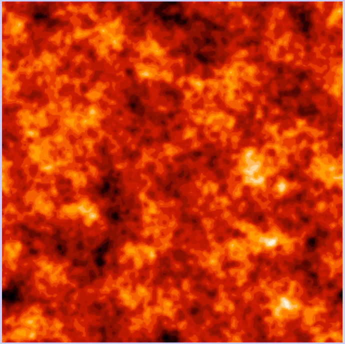
Temperature map Gaussian + strings



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- Edge detection algorithms: a promising way to search for strings
- Application of Canny edge detection algorithm to simulated data (SPT/ACT specification) $\rightarrow$ limit $G\mu < 2 \times 10^{-8}$ may be achievable [S. Amsel, J. Berger and R.B. (2007), A. Stewart and R.B. (2008), R. Danos and R.B. (2008)]

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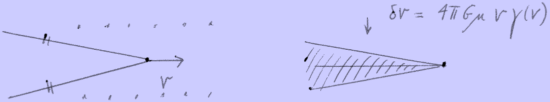
Cosmic String Wake

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

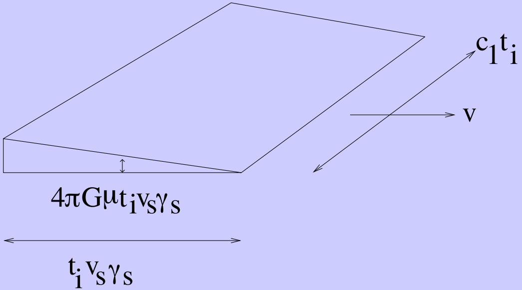
Consider a cosmic string moving through the primordial gas:

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 → 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:

$$w(q,t) = a(t)\big(q - \psi\big),$$

- Gravitational accretion → ψ grows.
- Turnaround: $\dot{w}(q,t) = 0$ determines $q_{nl}(t)$ and thus the thickness of the gravitationally bound region.

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Plan

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 $t_i < t$.

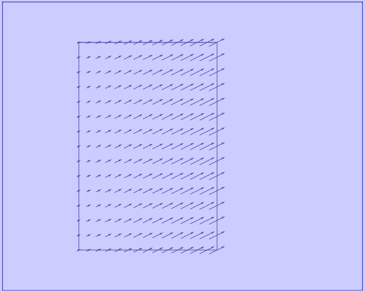
$$
\begin{aligned}
\frac{P}{Q} &\simeq \frac{24\pi}{25}\left(\frac{3}{4\pi}\right)^{1/2}\sigma_T f G\mu v_s\gamma_s \\
&\times\Omega_B\rho_c(t_0)m_p^{-1}t_0\left(z(t)+1\right)^2\left(z(t_i)+1\right)^{1/2}.
\end{aligned}
$$

Signature in CMB Polarization II

Inserting numbers yields the result:

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

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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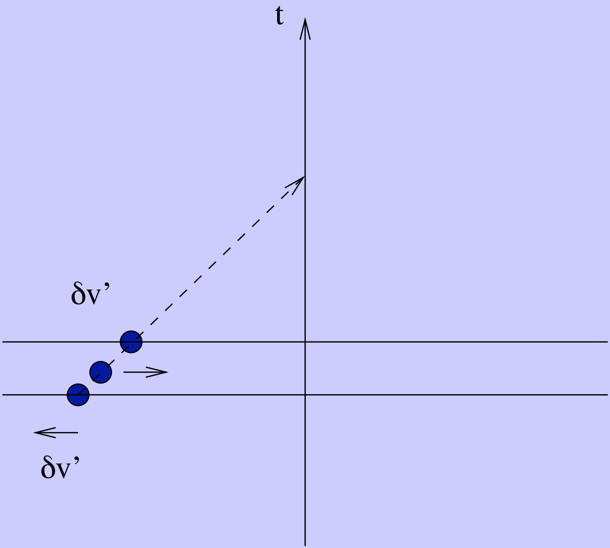
Motivation

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 → potentially more data than the CMB.
- → 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} column number density of hydrogen atoms.
Frequency dispersion

$$\frac{\delta\nu}{\nu} = 2\sin(\theta) \tan\theta \frac{Hw}{c} \, ,$$

Line profile:

$$\phi(\nu) = \frac{1}{\delta\nu} \text{ for } \nu \, \epsilon \, [\nu_{10} - \frac{\delta\nu}{2}, \nu_{10} + \frac{\delta\nu}{2}] \, ,$$

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:

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

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

Relative brightness temperature:

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

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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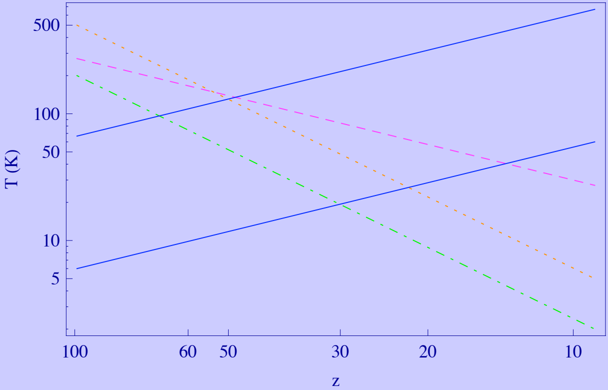
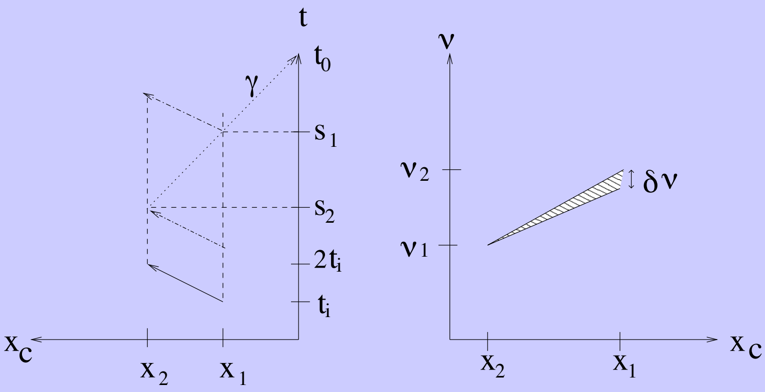
Scalings of various temperatures



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

Geometry of the signal



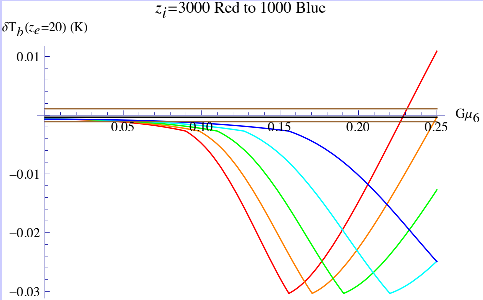
Extension 1: "Diffuse" Cosmic String Wakes

O. Hernandez and R.B., arXiv:1203.2307 .

- Wakes also form for $T_K < T_g$, but no shock heating
- The wakes are more dilute $\rightarrow$ thicker but less dense.

$$h_w(t)|_{T_K<T_g} = h_w(t)|_{T_g=0} \frac{T_g}{T_K}$$

- This allows the exploration of smaller values of $G\mu$.


z_i=3000 Red to 1000 Blue
$\delta T_b(z_e=20)$ (K)
0.01
−0.01
−0.02
−0.03
0.05
0.10
0.15
0.20
0.25
$G\mu_6$

Extension 2: Cosmic String Loops

M. Pagano and R.B., arXiv:1201.5695 (2012) .

- Cosmic string loops sees nonlinear objects at high redshift.
- Spherical accretion
- Average overdensity 64 (compared to 4 for a wake)
- $\rightarrow$ higher brightness temperature!
- But: no string-specific geometrical signal
- $\rightarrow$ harder to identify loop signals compared to wake signals.

Plan

Conclusions

- Cosmic strings $\rightarrow$ nonlinearities already at high redshifts.
- Signatures of cosmic strings more pronounced at high redshifts.
- Cosmic strings lead to perturbations which are non-Gaussian.
- Cosmic strings predict specific geometrical patterns in position space.
- 21 cm surveys provide an ideal arena to look for cosmic strings.
- Cosmic string wakes produce distinct wedges in redshift space with enhanced 21cm absorption or emission.