Searching for Cosmic Strings in New Observational Windows

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Outline

Plan

Relevance to Particle Physics

- 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.
- By searching for cosmological signatures of strings we can constrain particle physics models beyond the Standard Model.

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 ($\mu \sim \eta^2$).
- Cosmol. signatures of strings are proportional to $G\mu$.
- 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 $G\mu$.

Relevance to Cosmology

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..).

It is interesting to find evidence for the possible existence of cosmic strings.

Preview

Important lessons from this talk:

- 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 (R.B., R. Danos, O. Hernandez and G. Holder, 2010).

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Scaling Solution

Correlation length $\xi(t) \sim t$ for all $t \gg t_c$:
Sketch of the scaling solution:

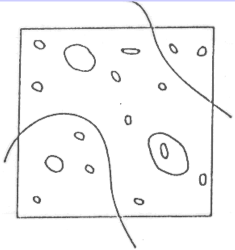


Figure 39. Sketch of the scaling solution for the cosmic string network. The box corresponds to one Hubble volume at arbitrary time t.

One Scale Toy Model

Toy model for the distribution of long strings:

- Divide the time interval into Hubble expansion times.
- In each Hubble expansion time the network of long strings is described by a set of straight string segments with length $\xi(t) = c_1 t$.
- Fixed number N of segments per Hubble volume.
- Random centers, velocity vectors and tangent vectors.

Plan

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

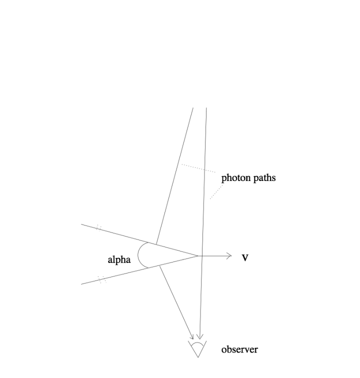
$$\alpha = 8\pi G\mu ,$$

Kaiser-Stebbins Effect

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

Photons passing by the string undergo a relative Doppler shift

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



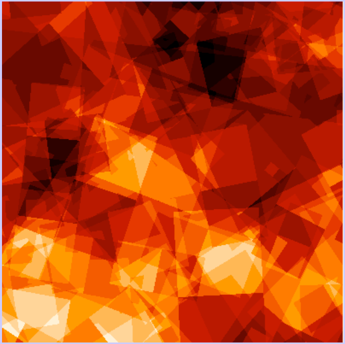
Signatures of Cosmic Strings in CMB Temperature Maps

- $\rightarrow$ 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



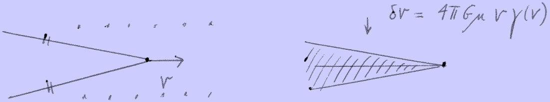
- $\rightarrow$ network of line discontinuities in CMB anisotropy maps.
- Characteristic scale: comoving Hubble radius at the time of recombination $\rightarrow$ need good angular resolution to detect these edges.
- Need to analyze position space maps.
- Edges produced by cosmic strings are masked by the “background" noise.
- 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)]

Cosmic String Wake

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

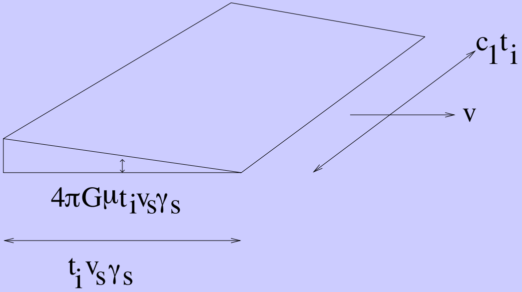
Consider a cosmic string moving through the primordial gas:

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:

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

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

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No Direct Effect of Wakes

F. Duplessis and R.B., arXiv:1302.3467 [astro-ph.CO].

Model: wakes form and fragment into spherical clumps whose radius at time t equals the width of the wake at time t.

- Wake temperature obtained by conversion of infall kinetic energy into thermal energy.
- Halo temperature given by virialization of the energy in the clumps.
- Result: for $z > 5$, $T < 700K$ for a value of $G\mu = 10^{-7}$, too low for atomic cooling.
- $\rightarrow$ no independent star formation in the clumps produced by wakes.

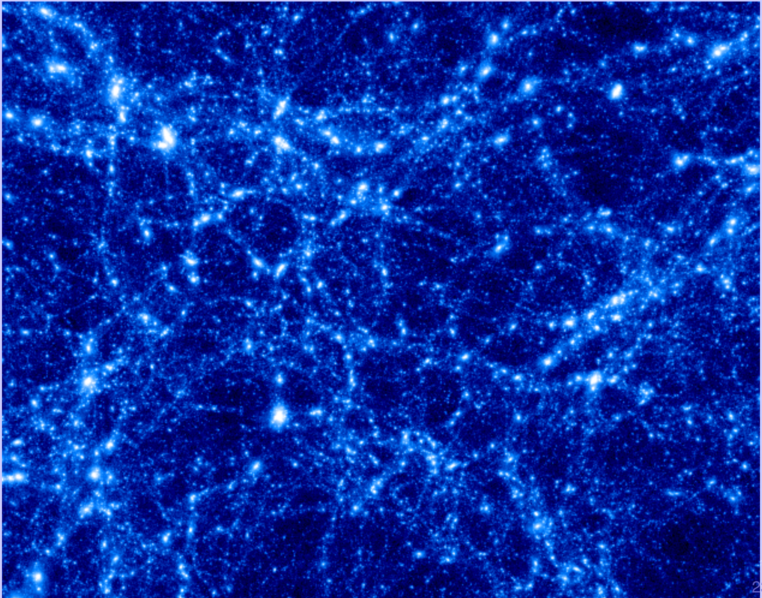
Note: See B. Shlaer, A. Vilenkin and A. Loeb (arXiv:1202.1346) for a similar analysis for string loops.

Indirect Signal of Wakes

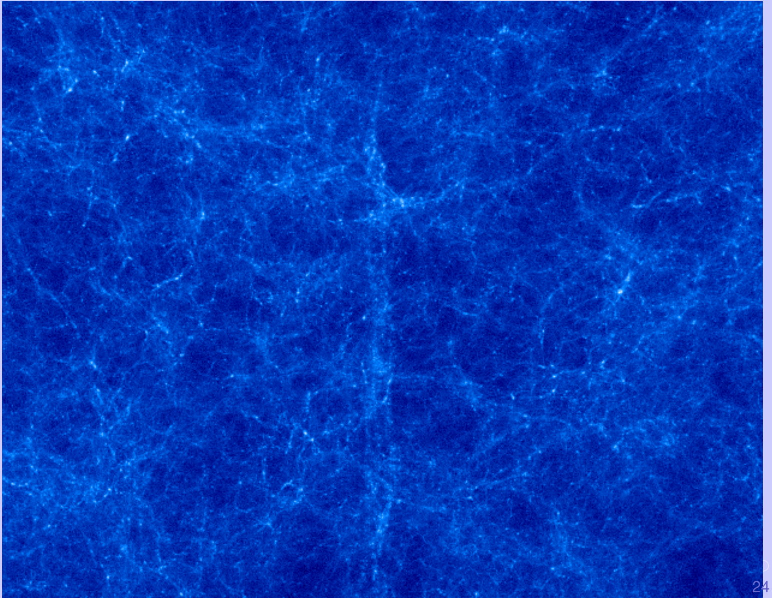
Y. Omori, R.B., in preparation.

- The presence of a string wake causes a displacement in the distribution of galaxies formed by the Gaussian fluctuations.
- N-body simulation of structure formation in a ΛCDM cosmology with the addition of a string wake.
- By eye the effect of the wake is visible at redshift of $z = 3$ for $G\mu = 10^{-5}$.
- Using adapted statistics the presence of string wakes should be visible for significantly smaller values of $G\mu$.

Distribution of galaxies at $z = 0$ for $G\mu = 10^{-5}$.



Distribution of galaxies at $z = 3$ for $G\mu = 10^{-5}$.



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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 $t_i < t$.

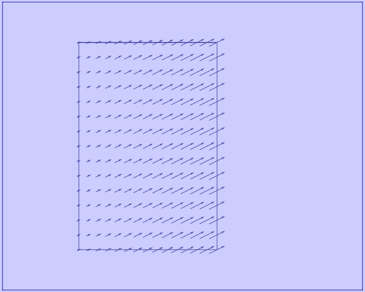
$$\frac{P}{Q} \simeq \frac{24\pi}{25}\left(\frac{3}{4\pi}\right)^{1/2}\sigma_T f G\mu v_s\gamma_s \times\Omega_B\rho_c(t_0)m_p^{-1}t_0\left(z(t)+1\right)^2\left(z(t_i)+1\right)^{1/2}.$$

Signature in CMB Polarization II

Inserting numbers yields the result:

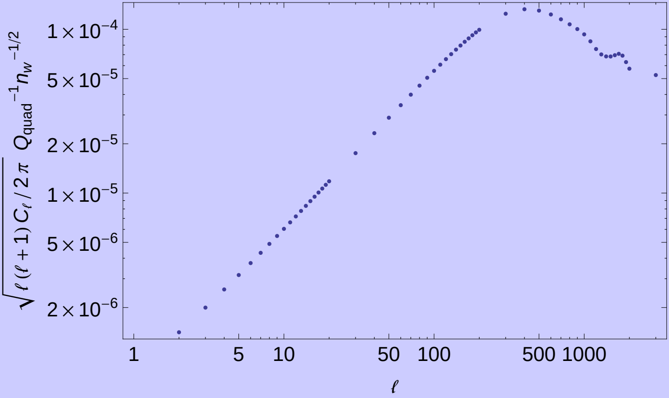
$$\frac{P}{Q} \sim fG\mu v_s \gamma_s \Omega_B \left(\frac{z(t)+1}{10^3}\right)^2 \left(\frac{z(t_i)+1}{10^{1/2}}\right)^3 10^7 \, .$$

Characteristic pattern in position space:



Angular Power Spectrum of B-Mode Polarization from Strings

R.B., N. Park and G. Salton, arXiv:1308.5693 [astro-ph.CO].



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).
- $\rightarrow$ a detection of gravitational waves through B-mode polarization is more likely to be a sign of something different than inflation.

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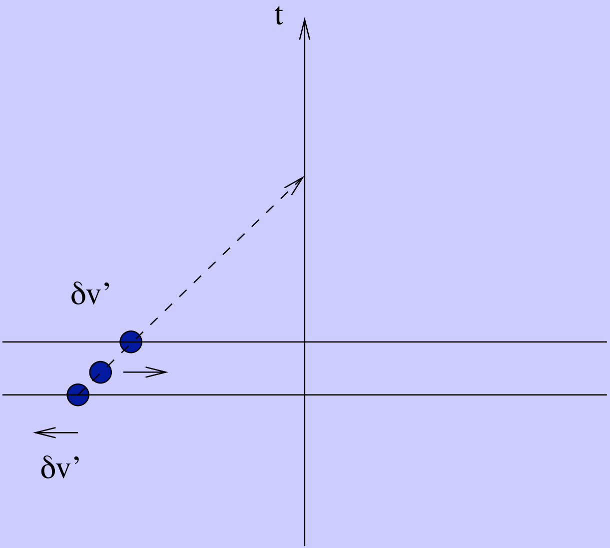
Motivation

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

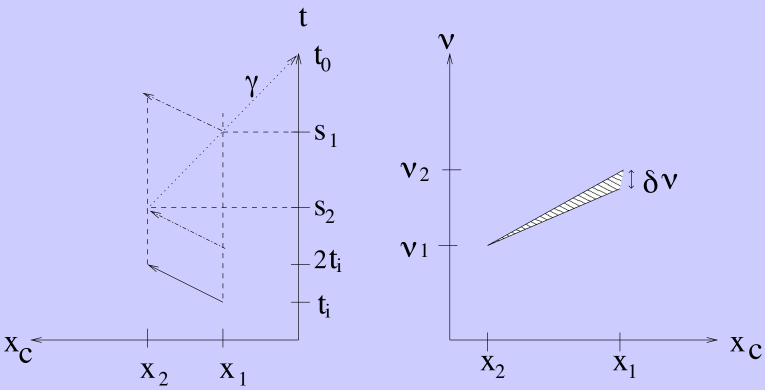
- 21 cm surveys: new window to map the high redshift universe, in particular the “dark ages".
- Cosmic strings produce nonlinear structures at high redshifts.
- These nonlinear structures will leave imprints in 21 cm maps. (Khatri & Wandelt, arXiv:0801.4406, A. Berndsen, L. Pogosian & M. Wyman, arXiv:1003.2214)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

Geometry of the signal



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:

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

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:

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

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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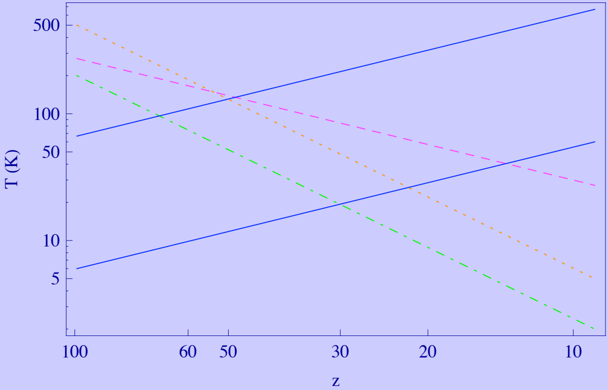
Scalings of various temperatures



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

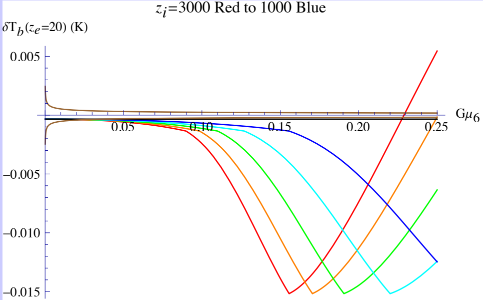
Extension 1: “Diffuse" Cosmic String Wakes

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)
0.005
−0.005
−0.010
−0.015
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.