Searching for Cosmic Strings in New Observational Windows

Robert Brandenberger
McGill University

IPMU, December 12, 2012

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!

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!

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.

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.

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..).

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

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..).

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

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:

$$V(\phi) = \frac{\lambda}{4}\left(|\phi|^2 - \eta^2\right)^2 \tag{1}$$

- Vacuum manifold $\mathcal{M}$: set up field values which minimize V.

Cosmic String I

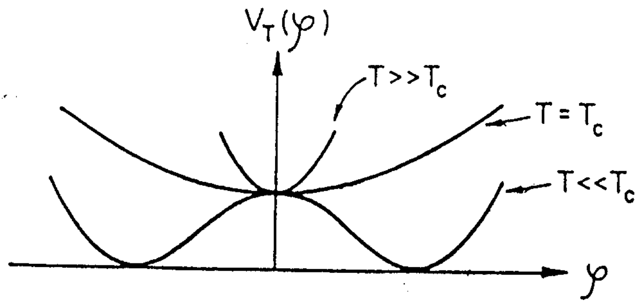
A. Vilenkin and E. Shellard, *Cosmic Strings and other Topological Defects* (Cambridge Univ. Press, Cambridge, 1994).

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

$$V(\phi) = \frac{\lambda}{4}\left(|\phi|^2 - \eta^2\right)^2 \tag{1}$$

- Vacuum manifold $\mathcal{M}$: set up field values which minimize V.

Scalar Field Potential



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:

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

- Vacuum manifold $\mathcal{M}$: set up field values which minimize V.
- At high temperature: $\phi = 0$.
- At low temperature: $|\phi| = \eta$ - but phase uncorrelated on super-Hubble scales.
- $\rightarrow$ defect lines with $\phi = 0$ left behind.

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:

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

- Vacuum manifold $\mathcal{M}$: set up field values which minimize V.
- At high temperature: $\phi = 0$.
- At low temperature: $|\phi| = \eta$ - but phase uncorrelated on super-Hubble scales.
- $\rightarrow$ defect lines with $\phi = 0$ left behind.

- Cosmic string core: points with $|\phi| \ll \eta$.
- Criterium for the existence of cosmic strings: $\Pi_1(\mathcal{M}) \neq \infty$.

- Cosmic string core: points with $|\phi| \ll \eta$.
- Criterium for the existence of cosmic strings: $\Pi_1(\mathcal{M}) \neq \infty$.

Cosmic String II

Symmetric cosmic string configuration (uniform along z axis, with core at $\rho = 0$):

$$
\begin{aligned}
\phi(\rho, \theta) &= f(\rho)\eta e^{i\theta} && (3)\\
f(\rho) &\rightarrow 1 \ \text{for } \rho > \mathrm{w} && (4)\\
f(\rho) &\rightarrow 0 \ \text{for } \rho < \mathrm{w} && (5)
\end{aligned}
$$

Important features:

- Width $w \sim \lambda^{-1/2}\eta^{-1}$
- Mass per unit length $\mu \sim \eta^2$ (independent of λ).

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 → network of cosmic strings persists at all times.

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 → network of cosmic strings persists at all times.

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

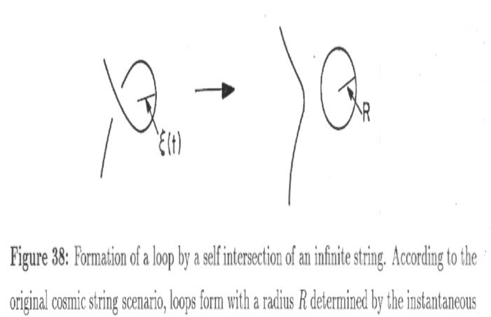


Figure 38: Formation of a loop by a self intersection of an infinite string. According to the original cosmic string scenario, loops form with a radius R determined by the instantaneous

Scaling Solution II

R. H. Brandenberger, Int. J. Mod. Phys. A **9**, 2117 (1994) [arXiv:astro-ph/9310041].

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:

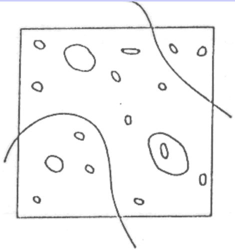


Figure 39. Sketch of the scaling solution for the cosmic string network. The box corresponds

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).
- → 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 $G\mu < 1.5 \times 10^{-7}$.

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).
- → 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 $G\mu < 1.5 \times 10^{-7}$.

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

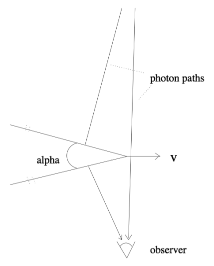
$$\alpha \, = \, 8\pi G\mu \, ,$$

Kaiser-Stebbins Effect

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

Photons passing by the string undergo a relative Doppler shift

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

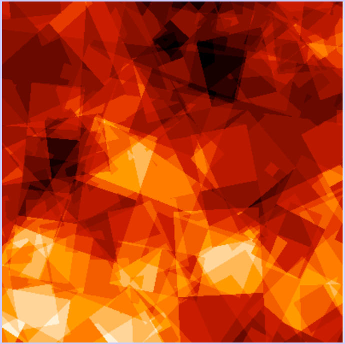


- → network of line discontinuities in CMB anisotropy maps.
- *N.B. characteristic scale: comoving Hubble radius at the time of recombination → need good angular resolution to detect these edges.*
- Need to analyze position space maps.

Signature in CMB temperature anisotropy maps

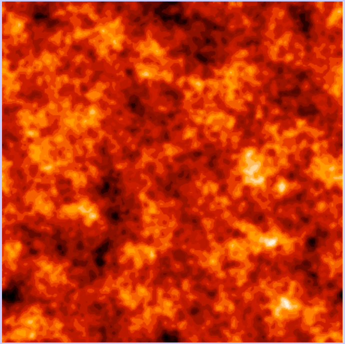
R. J. Danos and R. H. Brandenberger, arXiv:0811.2004 [astro-ph].

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



- → network of line discontinuities in CMB anisotropy maps.
- Characteristic scale: comoving Hubble radius at the time of recombination → 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.

Temperature map Gaussian + strings



- → network of line discontinuities in CMB anisotropy maps.
- Characteristic scale: comoving Hubble radius at the time of recombination → 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) → 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)]

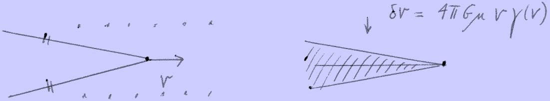
- → network of line discontinuities in CMB anisotropy maps.
- Characteristic scale: comoving Hubble radius at the time of recombination → need good angular resolution to detect these edges.
- Need to analyze position space maps.
- Edges produced by cosmic strings are masked by the “background" noise.
- Edge detection algorithms: a promising way to search for strings
- Application of Canny edge detection algorithm to simulated data (SPT/ACT specification) → 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).

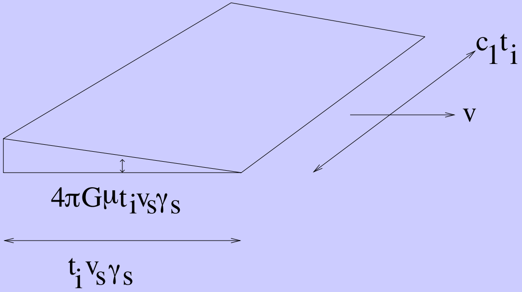
Consider a cosmic string moving through the primordial gas:

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 → 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:

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

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

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:

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

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

Gravitational accretion onto a wake (ctd.)

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

Result: $q_{nl}(t) \sim a(t)$.

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 $t_i < t$.

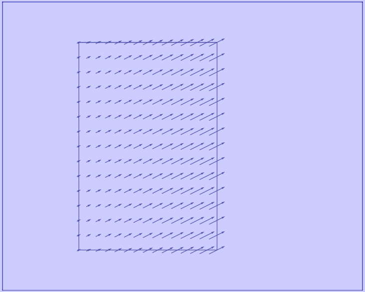
$$\begin{aligned}\frac{P}{Q} &\simeq \frac{24\pi}{25}\left(\frac{3}{4\pi}\right)^{1/2}\sigma_T f G\mu v_s \gamma_s \\ &\times \Omega_B \rho_c(t_0) m_p^{-1} t_0 \left(z(t)+1\right)^2 \left(z(t_i)+1\right)^{1/2} .\end{aligned}$$

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.
- → 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).
- → a detection of gravitational waves through B-mode polarization is more likely to be a sign of something different than inflation.
- If the spectrum of gravitational waves is blue this would rule out standard inflation and confirm a prediction first made in the context of superstring theory (R.B., et al, 2006).

Is B-mode Polarization the Holy Grail of Inflation?

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

- Cosmic strings produce direct B-mode polarization.
- → 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).
- → a detection of gravitational waves through B-mode polarization is more likely to be a sign of something different than inflation.
- If the spectrum of gravitational waves is blue this would rule out standard inflation and confirm a prediction first made in the context of superstring theory (R.B., et al, 2006).

Is B-mode Polarization the Holy Grail of Inflation?

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

- Cosmic strings produce direct B-mode polarization.
- → 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).
- → a detection of gravitational waves through B-mode polarization is more likely to be a sign of something different than inflation.
- If the spectrum of gravitational waves is blue this would rule out standard inflation and confirm a prediction first made in the context of superstring theory (R.B., et al, 2006).

Is B-mode Polarization the Holy Grail of Inflation?

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

- Cosmic strings produce direct B-mode polarization.
- → 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).
- → a detection of gravitational waves through B-mode polarization is more likely to be a sign of something different than inflation.
- If the spectrum of gravitational waves is blue this would rule out standard inflation and confirm a prediction first made in the context of superstring theory (R.B., et al, 2006).

Is B-mode Polarization the Holy Grail of Inflation?

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

- Cosmic strings produce direct B-mode polarization.
- → 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).
- → a detection of gravitational waves through B-mode polarization is more likely to be a sign of something different than inflation.
- If the spectrum of gravitational waves is blue this would rule out standard inflation and confirm a prediction first made in the context of superstring theory (R.B., et al, 2006).

Plan

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.
- CMB radiation passing through a cold gas cloud will be partially absorbed by exciting a 21cm transition. A hot gas cloud will produce 21cm radiation by a de-excitation transition.
- 21cm redshift surveys map the density distribution of neutral H.
- 21cm surveys: method to probe baryonic matter distribution before the epoch of star formation (i.e. in the "dark ages").

The Effect

- $10^3 > z > 10$: baryonic matter dominated by neutral H.
- Neutral H has hydrogen hyperfine absorption/emission line.
- CMB radiation passing through a cold gas cloud will be partially absorbed by exciting a 21cm transition. A hot gas cloud will produce 21cm radiation by a de-excitation transition.
- 21cm redshift surveys map the density distribution of neutral H.
- 21cm surveys: method to probe baryonic matter distribution before the epoch of star formation (i.e. in the "dark ages").

The Effect

- $10^3 > z > 10$: baryonic matter dominated by neutral H.
- Neutral H has hydrogen hyperfine absorption/emission line.
- CMB radiation passing through a cold gas cloud will be partially absorbed by exciting a 21cm transition. A hot gas cloud will produce 21cm radiation by a de-excitation transition.
- 21cm redshift surveys map the density distribution of neutral H.
- 21cm surveys: method to probe baryonic matter distribution before the epoch of star formation (i.e. in the "dark ages").

The Effect

- $10^3 > z > 10$: baryonic matter dominated by neutral H.
- Neutral H has hydrogen hyperfine absorption/emission line.
- CMB radiation passing through a cold gas cloud will be partially absorbed by exciting a 21cm transition. A hot gas cloud will produce 21cm radiation by a de-excitation transition.
- 21cm redshift surveys map the density distribution of neutral H.
- 21cm surveys: method to probe baryonic matter distribution before the epoch of star formation (i.e. in the "dark ages").

The Effect

- $10^3 > z > 10$: baryonic matter dominated by neutral H.
- Neutral H has hydrogen hyperfine absorption/emission line.
- CMB radiation passing through a cold gas cloud will be partially absorbed by exciting a 21cm transition. A hot gas cloud will produce 21cm radiation by a de-excitation transition.
- 21cm redshift surveys map the density distribution of neutral H.
- 21cm surveys: method to probe baryonic matter distribution before the epoch of star formation (i.e. in the "dark ages").

The Effect

- $10^3 > z > 10$: baryonic matter dominated by neutral H.
- Neutral H has hydrogen hyperfine absorption/emission line.
- CMB radiation passing through a cold gas cloud will be partially absorbed by exciting a 21cm transition. A hot gas cloud will produce 21cm radiation by a de-excitation transition.
- 21cm redshift surveys map the density distribution of neutral H.
- 21cm surveys: method to probe baryonic matter distribution before the epoch of star formation (i.e. in the "dark ages").

The Effect (II)

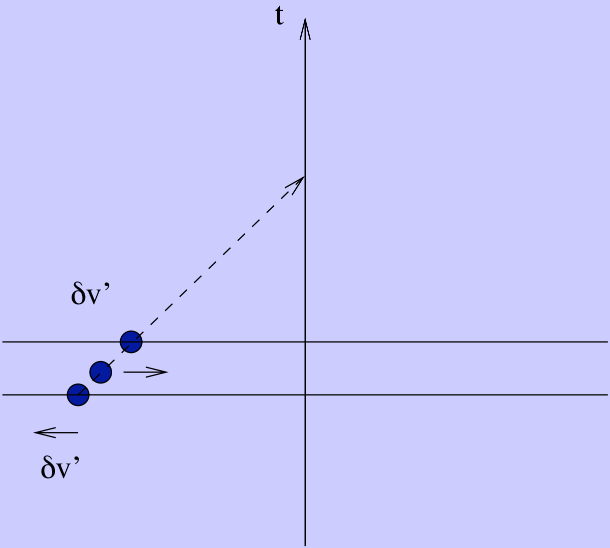
- String wake is a nonlinear overdensity in the baryon distribution with special geometry which emits/absorbs 21cm radiation.
- Whether signal is emission/absorption depends on the temperature of the gas cloud.
- At high redshifts the strings dominate the nonlinear structure and hence will dominate the 21cm redshift maps.

The Effect (II)

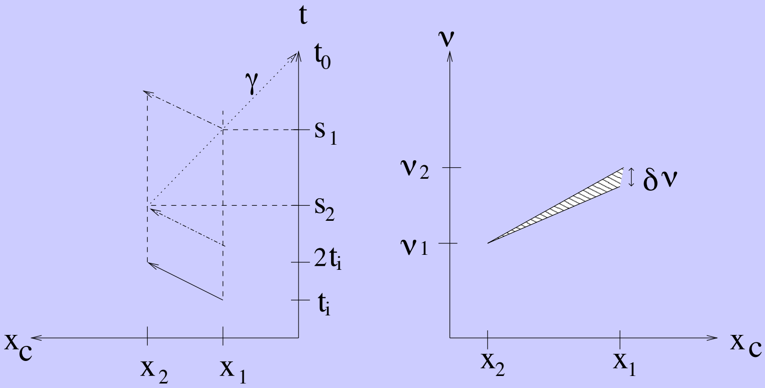
- String wake is a nonlinear overdensity in the baryon distribution with special geometry which emits/absorbs 21cm radiation.
- Whether signal is emission/absorption depends on the temperature of the gas cloud.
- At high redshifts the strings dominate the nonlinear structure and hence will dominate the 21cm redshift maps.

The Effect (II)

- String wake is a nonlinear overdensity in the baryon distribution with special geometry which emits/absorbs 21cm radiation.
- Whether signal is emission/absorption depends on the temperature of the gas cloud.
- At high redshifts the strings dominate the nonlinear structure and hence will dominate the 21cm redshift maps.


t
δv'
δv'

Geometry of the signal



Frequency dispersion

Frequency dispersion

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

Brightness temperature

Brightness temperature:

$$T_b(\nu) \,=\, T_S\bigl(1 - e^{-\tau_\nu}\bigr) + T_\gamma(\nu)e^{-\tau_\nu} \,,$$

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:

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

Brightness temperature

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:

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

Brightness temperature

Brightness temperature:

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

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.

Line profile:

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

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.

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.

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:

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

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):

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

Relative brightness temperature:

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

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

Critical curve (transition from emission to absorption):

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

Relative brightness temperature:

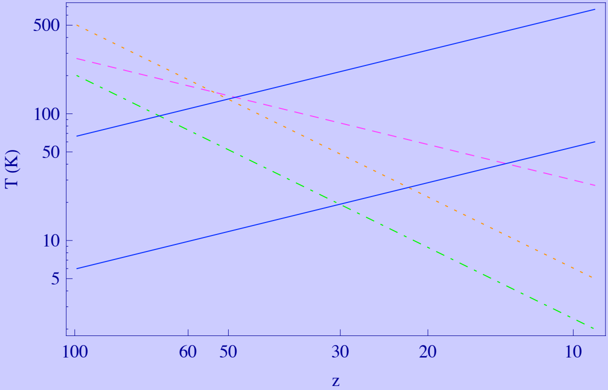
$$\begin{aligned} \delta T_b(\nu) &= [0.07\ \mathrm{K}] \frac{x_c}{1+x_c}\left(1-\frac{T_\gamma}{T_K}\right)(1+z)^{1/2} \\ &\sim 200 mK \quad \text{for} \quad z+1=30\,. \end{aligned}$$

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

Critical curve (transition from emission to absorption):

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

Scalings of various temperatures



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

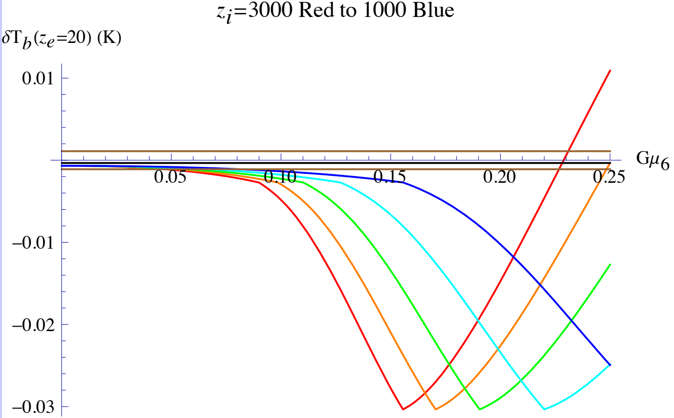
Extension 1: “Diffuse" Cosmic String Wakes

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

Plan

Conclusions

- 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.
- Cosmic string wakes produce distinct wedges in redshift space with enhanced 21cm absorption or emission.