Signatures of Cosmic Strings in the 21-cm Sky

Robert Brandenberger
McGill University, Montreal, Canada

IAP Seminar, Sept. 13 2021

Plan

Outline

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.

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Relevance to Particle Physics I

- Cosmic string solutions exist 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.
- Seeing a cosmic string in the sky would provide a guide to particle physics beyond the Standard Model!

Relevance to Particle Physics 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: $G\mu \leq 1.3 \times 10^{-7}$ otherwise a 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 "Grand Unified" models.

Lowering the upper bound on the string tension by two orders of magnitude would rule out **all** grand unified models yielding cosmic string solutions.

Relevance to Cosmology

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)).
- **Seeds for high redshift supermassive black holes** (S. Bramberger, R.B., P. Jreidini and J. Quintin, 2015; R.B., B. Cyr and H. Jiao, 2021).
- Origin of globular clusters (A. Barton, R.B. and L. Lin, 2015; R.B., L. Lin and S. Yamanouchi, 2015).
- Origin of fast radio bursts (R.B., B. Cyr and A. Iyer, 2017).
- Global 21-cm absorption signal (EDGES) (R. Thériault, J. Mirocha and R.B. 2021)

Preview

Important lessons from this talk:

- Cosmic strings $\rightarrow$ nonlinearities already at high redshifts.
- Signatures of cosmic strings more pronounced at high redshifts.
- Cosmic string wakes lead to perturbations which are non-Gaussian.
- Cosmic string wakes 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).

Cosmic String Review

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

- 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 phase uncorrelated on super-Hubble scales.
- $\rightarrow$ defect lines with $\phi = 0$ left behind.
- Existence of cosmic strings requires: $\Pi_1(\mathcal{M}) \neq 1$.

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.

Sketch of the scaling solution:

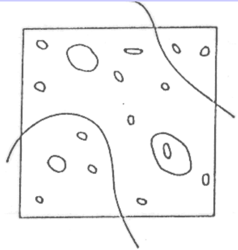


Figure 39. Sketch of the scaling solution for the cosmic string network. The box corresponds

Plan

Kaiser-Stebbins Effect

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

- Space away from the string is locally flat (cosmic string exerts no gravitational pull).
- Space perpendicular to a string is conical with deficit angle $\alpha = 8\pi G\mu$
- Photons passing by the string undergo a relative Doppler shift

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

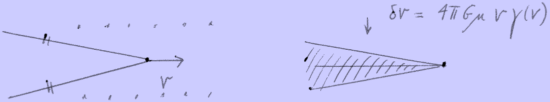
- $\rightarrow$ network of line discontinuities in CMB anisotropy maps.
- *N.B. characteristic scale: comoving Hubble radius at the time of recombination $\rightarrow$ need good angular resolution to detect these edges.*

Cosmic String Wake

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

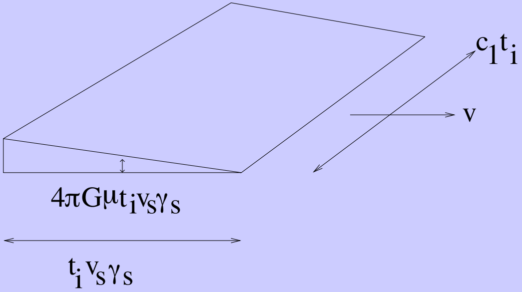
Consider a cosmic string moving through the primordial gas:

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

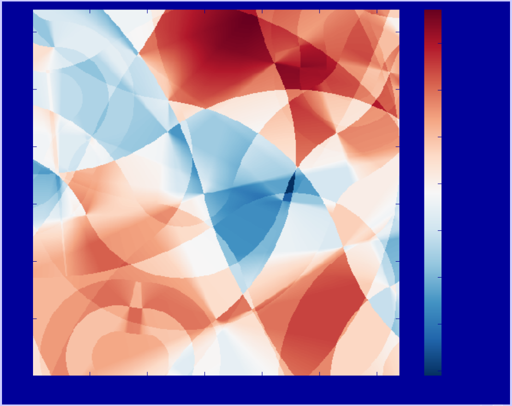
L. Perivolaropoulos, R.B. and A. Stebbins, Phys. Rev. D **41**, 1764 (1990).

- Initial overdensity $\rightarrow$ gravitational accretion onto the wake.
- Accretion computed using the Zeldovich approximation.
- **Result**: comoving thickness $q_{nl}(t) \sim a(t)$.

Plan

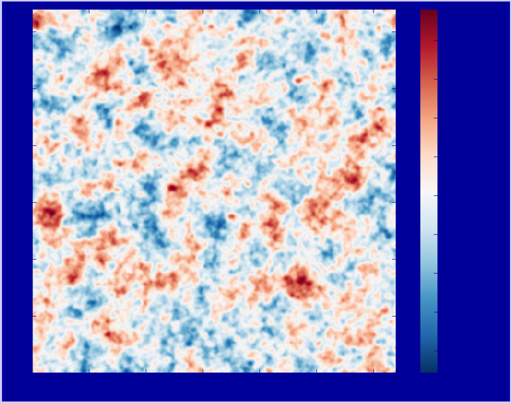
Temperature Map Strings from Strings, $G\mu = 10^{-7}$

L. Hergt et al., arXiv:1608.00004, 2016



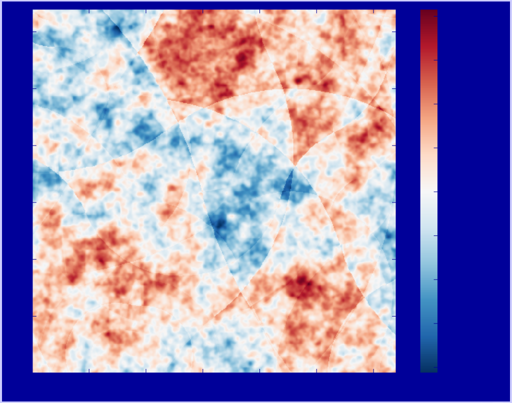
Temperature Map Gaussian

L. Hergt et al., 2016



Temperature Map Gaussian + Strings, $G\mu = 10^{-5}$

L. Hergt et al., 2016



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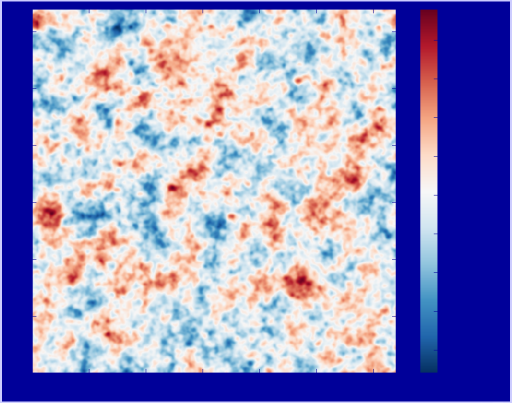
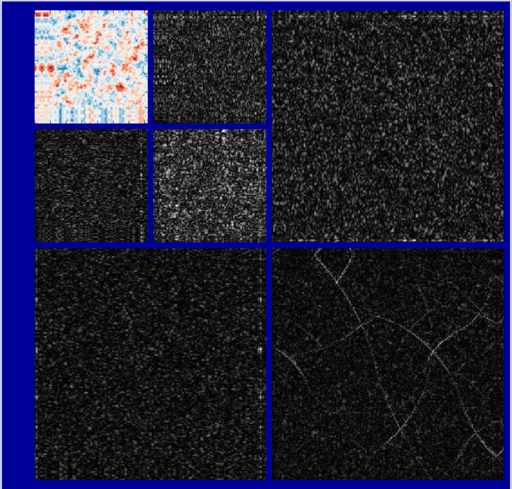


- **Signature:** Network of line discontinuities in CMB anisotropy maps.
- Characteristic scale: comoving Hubble radius at the time of recombination.
- Need good angular resolution to detect these edges.
- Need to analyze position space maps.
- Edges produced by cosmic strings are masked by the “background" noise.
- Wavelets and Curvelets: a promising way to search for strings.

Wavelet Analysis of Simulated CMB Data $G\mu = 10^{-7}$

L. Hergt et al., 2016



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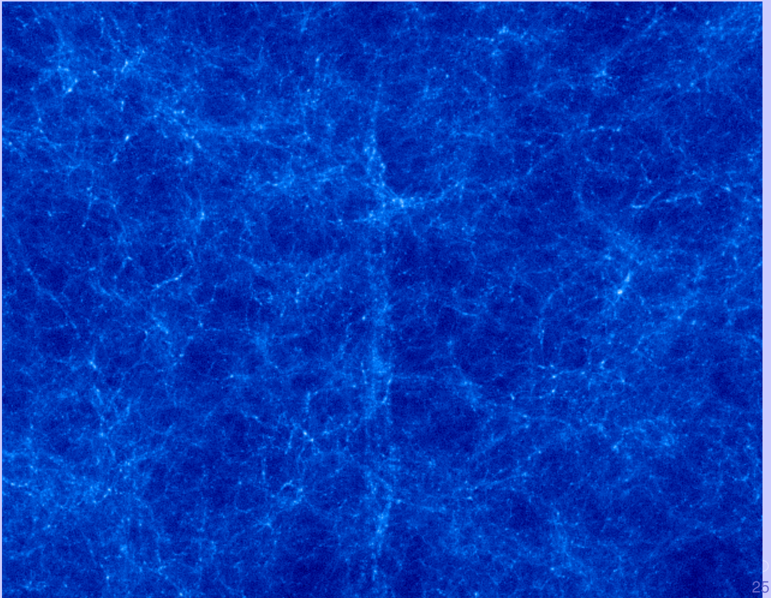
- Need to analyze position space maps.
- Edges produced by cosmic strings are masked by the “background" noise.
- Wavelets and Curvelets: a promising way to search for strings
- Application of Wavelet analysis to simulated data (SPT/ACT specification) $\rightarrow$ limit $G\mu < 3 \times 10^{-8}$ may be achievable [L. Hergt, R.B., A. Amara and A. Refregier, 2016]

Signature of Cosmic Strings in High z Large-Scale Structure Surveys

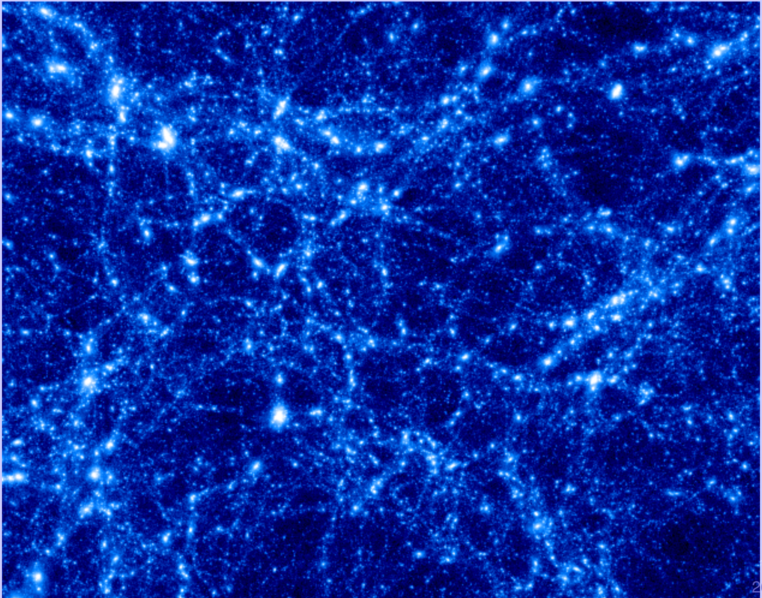
D. Cunha, J. Harnois-Deraps, R.B., A. Amara and A. Refregier, arXiv:1804.00083

- 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 $z = 7$ for $G\mu = 8 \times 10^{-7}$.
- Using adapted statistics the presence of string wakes is visible for significantly smaller values of $G\mu$. At the current resolution the limit is $z = 3$ for $G\mu = 10^{-7}$ (D. Cunha, arXiv:1810.07737).

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



Distribution of galaxies at $z = 0$ 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 $t_i < t$.

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

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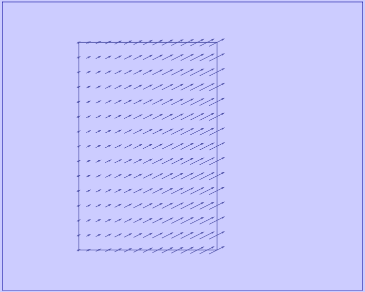
Signature in CMB Polarization II

Inserting numbers yields the result:

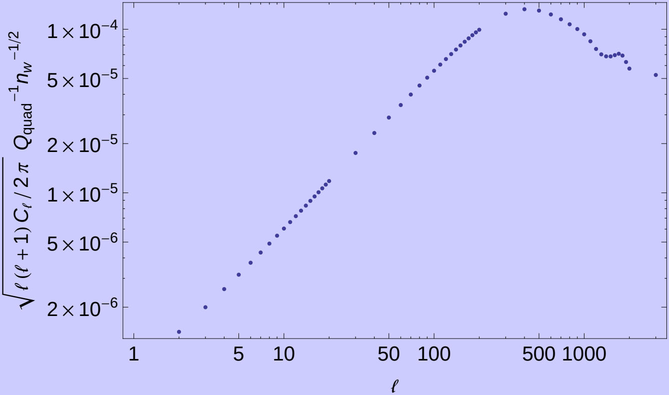
$$\frac{P}{Q} \sim fG\mu v_s\gamma_s\Omega_B\left(\frac{z(t)+1}{10^3}\right)^2\left(\frac{z(t_i)+1}{10^3}\right)^3 10^7 \, .$$

Characteristic pattern in position space:



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.
- 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

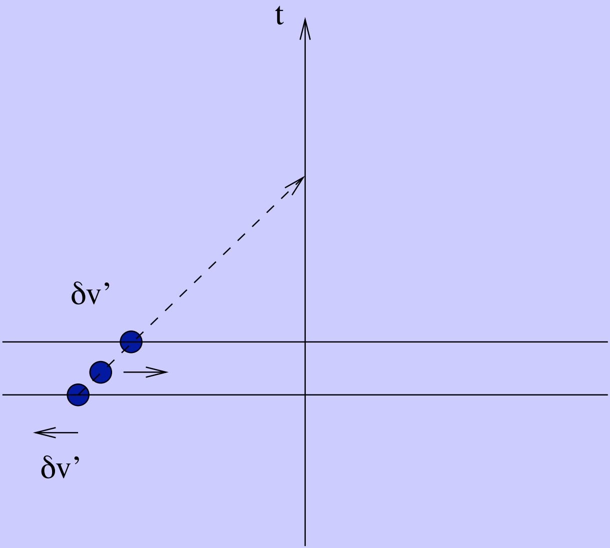
Motivation

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

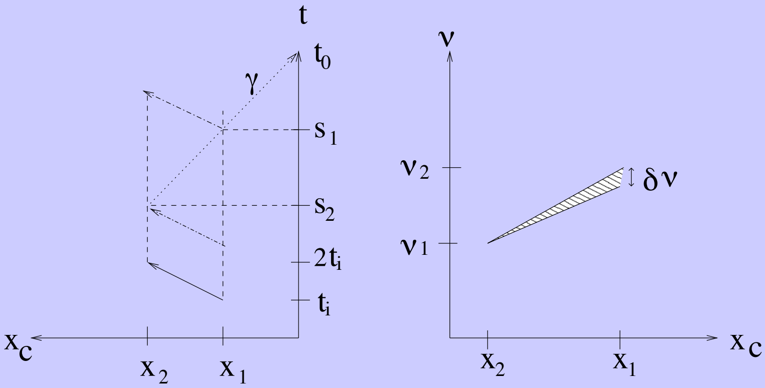
- 21 cm surveys: new window to map the high redshift universe, in particular the “dark ages".
- Cosmic strings produce nonlinear structures at high redshifts.
- These nonlinear structures will leave imprints in 21 cm maps. (Khatri & Wandelt, arXiv:0801.4406, A. Berndsen, L. Pogosian & M. Wyman, arXiv:1003.2214)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

The Effect

- 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



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:

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

Application to Cosmic String Wakes

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.

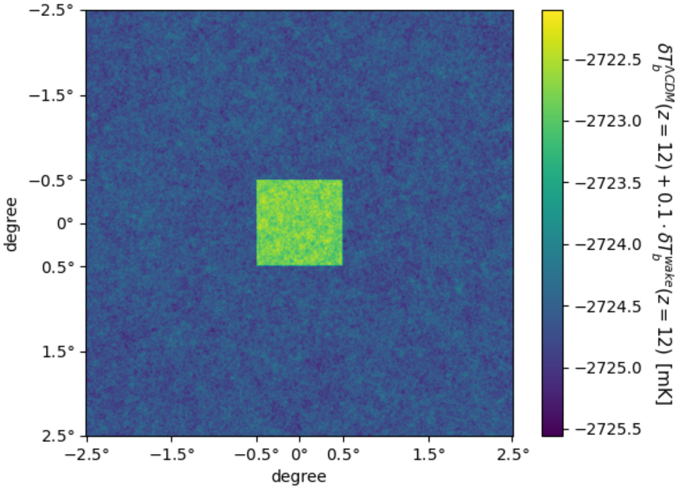
Relative brightness temperature:

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

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

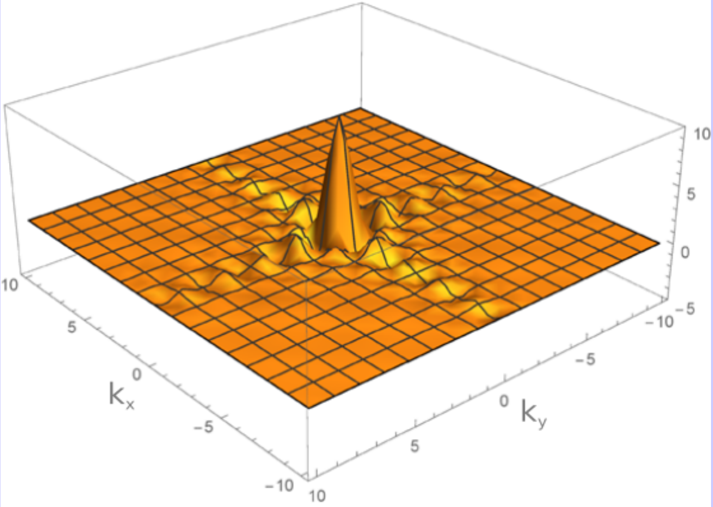
String Wake Signal + ΛCDM Fluctuations

D. Maibach, RB, D. Crichton and A. Refregier, 2107.07289



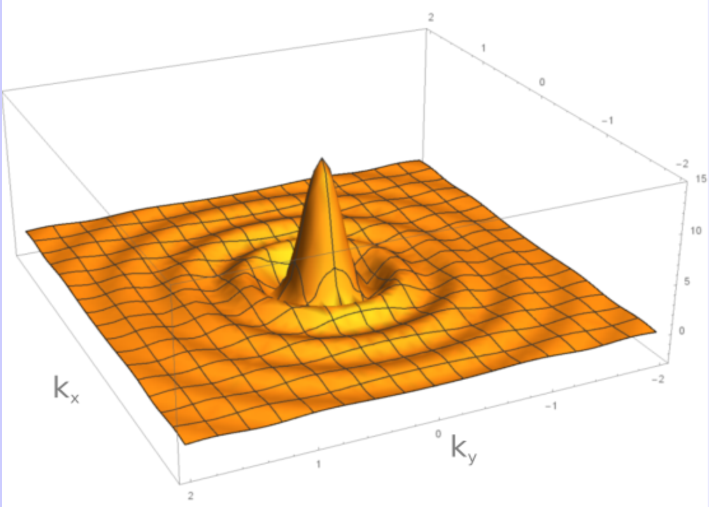
String Wake Signal in Fourier Space

D. Maibach, RB, D. Crichton and A. Refregier, 2107.07289



Signal from a Spherical Overdensity in Fourier Space

D. Maibach, RB, D. Crichton and A. Refregier, 2107.07289



Extracting the String Wake Signal from the Foregrounds

D. Maibach, RB, D. Crichton and A. Refregier, 2107.07289

Noise Sources Considered:

- Galactic Synchrotron
- Point Sources
- Galactic Free-Free
- Extra-Galactic Free-Free

$$C_l(\nu_1, \nu_2) = \sum_i A_i \left(\frac{l_{ref}}{l}\right)^{\beta_i} \left(\frac{\nu_{ref}^2}{\nu_1 \nu_2}\right)^{\alpha_i} \exp\left(\frac{-\log^2(\nu_1/\nu_2)}{2\xi^2}\right)$$

Extracting the String Wake Signal from the Foregrounds

D. Maibach, RB, D. Crichton and A. Refregier, 2107.07289

Noise Sources Considered:

- Galactic Synchrotron:
  $A = 1100[mK]^2, \ \beta = 3.3, \ \alpha = 2.8$
- Point Sources: $A = 57[mK]^2, \ \beta = 1.1, \ \alpha = 2.07$
- Galactic Free-Free: $A = 0.088[mK]^2, \ \beta = 3, \ \alpha = 2.15$
- Extra-Galactic Free-Free:
  $A = 0.014[mK]^2, \ \beta = 1, \ \alpha = 2.1$

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Extracting the String Wake Signal from the Foregrounds and Instrumental Noise

D. Maibach, RB, D. Crichton and A. Refregier, 2107.07289

Instrumental noise is modeled via a power spectrum following Alonso et al, 2017

$$P_T(l) = \frac{\lambda^2 T_{sys}^2 N_p}{A_e^2 \Delta\nu t_{tot} n(u = l/2\pi)}.$$

MWA specification.

Extracting the String Wake Signal: Three Point Statistic

D. Maibach, RB, D. Crichton and A. Refregier, 2107.07289

String Signal typically lies in a single redshift bin.

Focus on a single redshift bin.

Choose a statistic sensitive to the Fourier space ridges in the string signal.

$$< T(\vec{k}_1)T(\vec{k}_2)T(\vec{k}_3) > \text{ with } \vec{k}_1 \approx -\vec{k}_2,\ |\vec{k}_1| \approx |\vec{k}_3| \text{ and } \vec{k}_1 \cdot \vec{k}_3 \approx 0$$

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Extracting the String Wake Signal: Signal Processing Techniques

D. Maibach, RB, D. Crichton and A. Refregier, 2107.07289

- Wiener filterning
- Noise subtraction via modelling the redshift dependence of the noise pixel by pixel in the angular map.

Extracting the String Wake Signal: Result

D. Maibach, RB, D. Crichton and A. Refregier, 2107.07289

Result: Signal of a cosmic string with $G\mu = 10^{-7}$ is identifiable in a statistically significant way.

Plan

Sketch of the String Scaling Solution

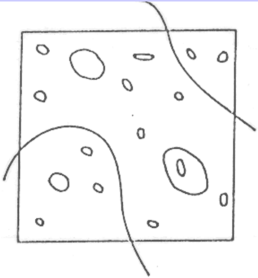

Figure 39. Sketch of the scaling solution for the cosmic string network. The box co
to one Hubble volume at arbitrary time t.

Scaling Distribution of Loops

- Loops form from the interactions of long strings.
- Once formed, loops oscillate and slowly decay by emitting gravitational radiation.
- The distribution of loops is universal (independent of the string tension)*
- * modulo the lower cutoff radius
- $\rightarrow$ **Signals of the cosmic string distribution have one free parameter only.**
- **Gravitational cutoff radius**: $R > \gamma G\mu t$
- Consider $t > t_{eq}$
- $n(R,t) = NR^{-5/2} t_{eq}^{1/2} t^{-2} \quad \gamma G\mu t < R < \alpha t_{eq}$
- $n(R,t) = \tilde{N} R^{-2} t^{-2} \quad R > \alpha t_{eq}$

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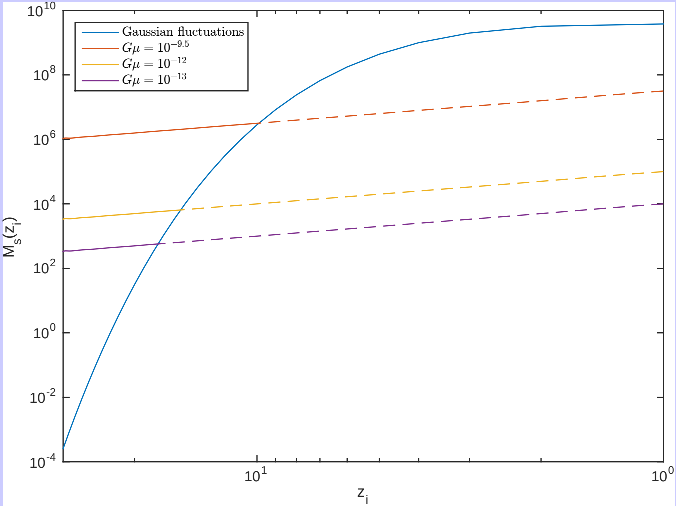
Loops as the Seeds for High Redshift Super-Massive Black Holes

A. Barton, R.B., P. Jreidini and J. Quintin, arXiv:1503.02317 (2015) .

- Observations: More than 40 black holes at $z > 6$ and mass $M > 10^9 M_0$ discovered.
- In the **standard ΛCDM** paradigm of structure formation nonlinearities form late.
- It is challenging to explain the origin of the massive seeds with only standard Gaussian fluctuations.
- Hypothesis: String Loops are the Seeds for the Accretion of high z super-massive black holes.

Nonlinear Mass with the Number Density of Galaxies

A. Barton, R.B., P. Jreidini and J. Quintin, arXiv:1503.02317 (2015) .



Loops as Seeds of Intermediate Mass and Mass Gap Black Holes

R.B., B. Cyr and H. Jiao, arXiv:2103.14057 (2021) .

- **LIGO Observation**: black holes merger event with masses in the mass gap region arXiv:2009.11075 (LIGO/Virgo collaboration).
- String loops yield seeds with a wide range of masses
- Normalization of $G\mu$: one seed of mass $M > 10^6 M_\odot$ per galaxy.
- $\rightarrow \ G\mu \sim 2 \times 10^{-13}$
- **Prediction**: Range of nonlinear seeds down $M \sim 10^{-2} M_\odot$ created.
- **Prediction**: $\sim 10^6$ mass gap black holes per large galaxy.

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Global 21-cm Signal from Superconducting Cosmic Strings

R. Thériault, J. Mirocha and R.B., arXiv:2105.01166

- In a subset of particle physics models, cosmic strings are superconducting (E. Witten, 1985).
- Superconducting strings emit electromagnetic radiation
- $\rightarrow$ excess of radio photons.
- $\rightarrow$ effect on global 21-cm signal.
- Effect of string wakes studied in O. Hernandez arXiv:1403.7522.

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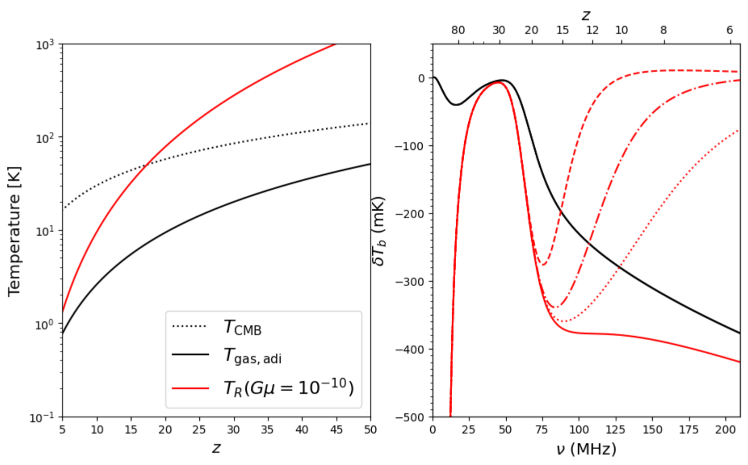

Plan

Conclusions I

- Cosmic strings $\rightarrow$ nonlinearities already at high redshifts.
- Signatures of cosmic strings more pronounced at high redshifts.
- Cosmic string wakes lead to perturbations which are non-Gaussian.
- Cosmic string wakes predict specific geometrical patterns in position space.
- Cosmic string loops may provide the seeds for **supermassive black holes**.

Conclusions II

- Cosmic string wakes produce distinct wedges in redshift space with enhanced 21cm absorption or emission.
- In the Dark Ages, the local 21-cm signal from cosmic strings is stronger than the signals from ΛCDM fluctuations.
- Using Wiener filtering and noise subtraction schemes the string signal can be extracted from the noise due to astrophysical and instrumental foreground for interferometric surveys such as MWA.
- Superconducting string loops influence the global 21-cm signal.