CMB and Weak Lensing from Cosmic Strings

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Outline

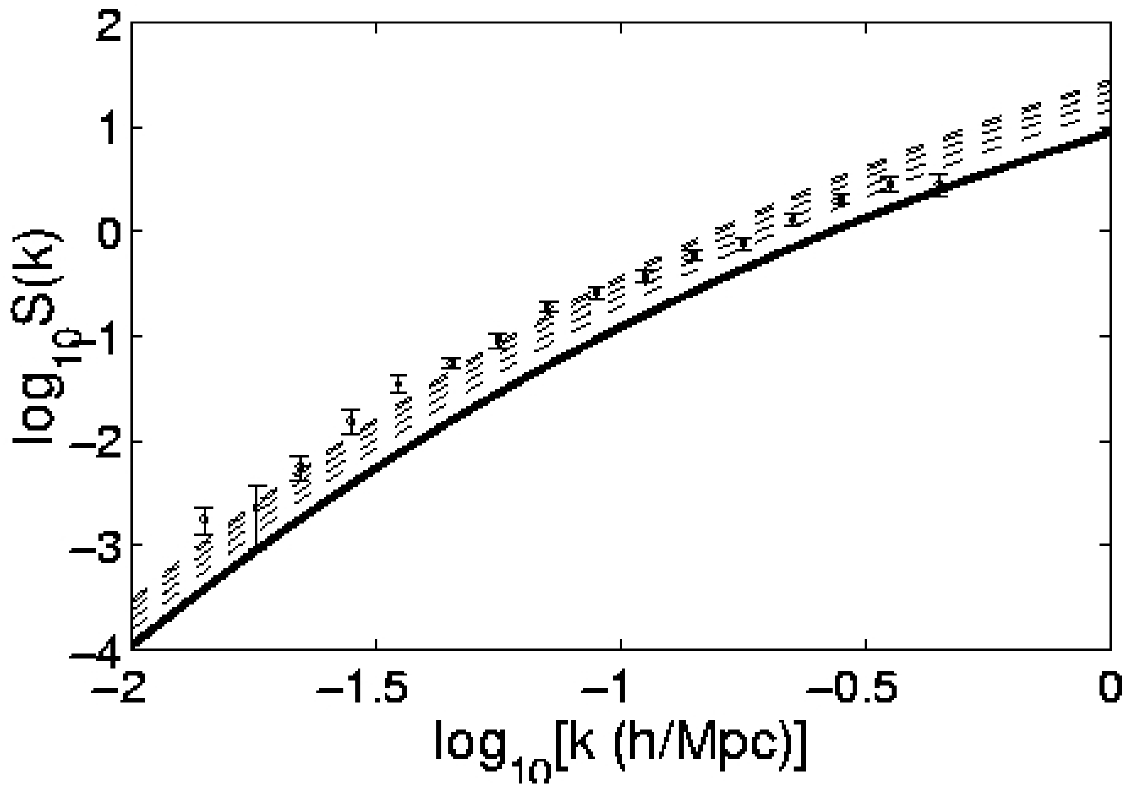
- Motivation

- CMB Fluctuations:
  - Method
  - Temperature
  - Polarization

- Weak Lensing:
  - Method
  - Preliminary results

Motivation

A long time ago, cosmic strings *on their own* could account for the observed matter power spectrum.



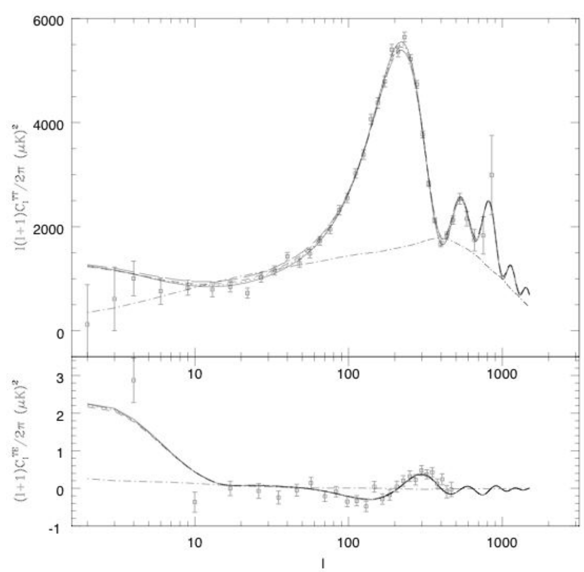
$P(k)$ for cosmic strings (Avelino et al. 1999) along with LSS data (Peacock & Dodds 1994)

High resolution CMB observations (Boomerang,...) refuted this hypothesis, but could not rule out the possible subdominant prexence of strings.

Until recently, such models were phenomological, but in the last few years fundamental physics has provided some convincing evidence for them:

- It was shown by Jeannerot, Rocher & Sakellariadou that all cosmologically viable SUSY GUTs predict the formation of topologically stable cosmic strings after inflation.

- Also, inflation models in braneworld scenarios predict the copious production of cosmic strings at the end of the inflationary phase; e.g. Sarangi & Tye, Polchinski. It is important to note the that these strings are not the traditional topological defects and differ in some important aspect from these.

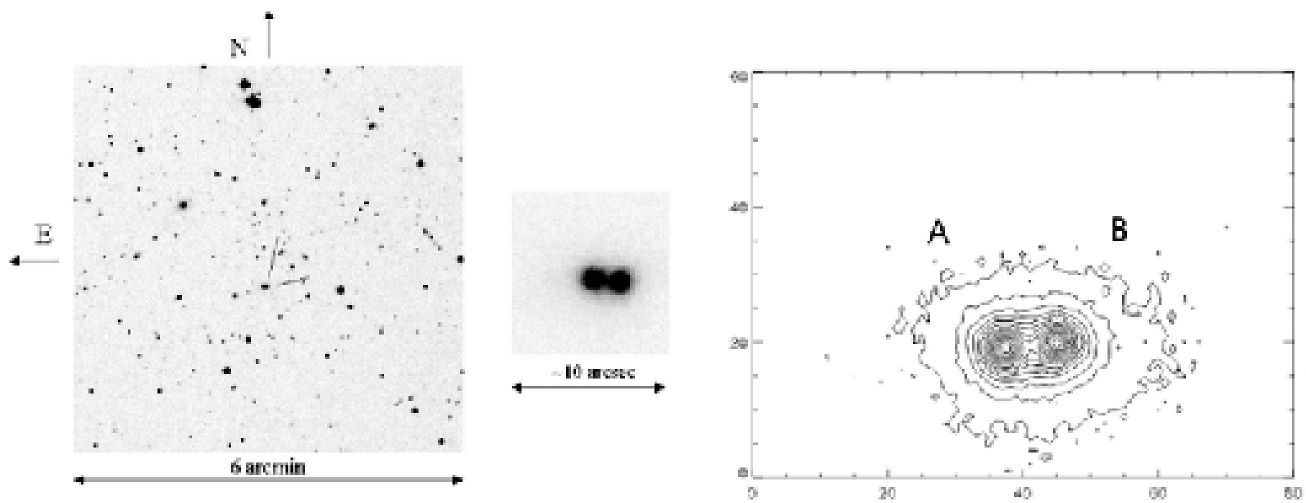


Pogosian et al. (2003)

A Cosmic String Gravitational Lens?

- A lensed galaxy has been observed, which seem to be explainable only by the presence of a cosmic string

- Follow-up observations determined that the galaxies were indeed identical and that there were a several other lens candidate in the vicinity.



R-band image of object CSL-1 (left and centre); contours of the near IR image (right); Sazhin et al. (2003)

CMB Maps from Cosmic Strings

ML & EPS Shellard, Phys. Rev. **D67**, 103512 (2003)

- Our goal was to produce realistic maps from high resolution cosmic string simulations using a full Boltzmann code.

- The cosmic string simulations used in our work are based on the Nambu-Goto action

$$\mathcal{S} = -\mu \int d^2\zeta \sqrt{-\gamma}\,.$$

  and hence treat the strings as 1D objects.

- The energy-momentum tensor of the strings

$$\Theta^{\mu\nu}\sqrt{-g} = \mu \int d\zeta (\epsilon \dot{x}_s^\mu \dot{x}_s^\nu - \epsilon^{-1} x_s'^\mu x_s'^\nu)\delta^{(3)}(\mathbf{x} - \mathbf{x}_s)$$

  is interpolated onto a 3D grid for the Boltzmann evolution.

- The scalar, vector and tensor systems of ODE's can each be written as

$$\dot{y}(\mathbf{k}, \eta) = \mathcal{A}(k, \eta) y(\mathbf{k}, \eta) + q(\mathbf{k}, \eta)$$

  with initial conditions $y(\mathbf{k}, 0) = c(\mathbf{k})$, where y is the vector whose components are the metric and matter perturbations and q contains the relevant components of the strings' EM tensor.

- The solution to this equation is:

$$y(\mathbf{k},\eta) = Y(k,\eta)\mathbf{c}(\mathbf{k},\mathbf{0}) + Y(k,\eta)\int_0^{\eta} Y^{-1}(k,\eta')q(\mathbf{k},\eta')d\eta'$$

  where Y is the solution to

$$\dot{Y}(k,\eta) = \mathcal{A}(k,\eta)Y(k,\eta)$$

  with initial conditions $Y(k,0) = \mathcal{I}$.

- Thus, after FFT the relevant perturbation grids back to real space, we can compute the temperature and polarization distributions:

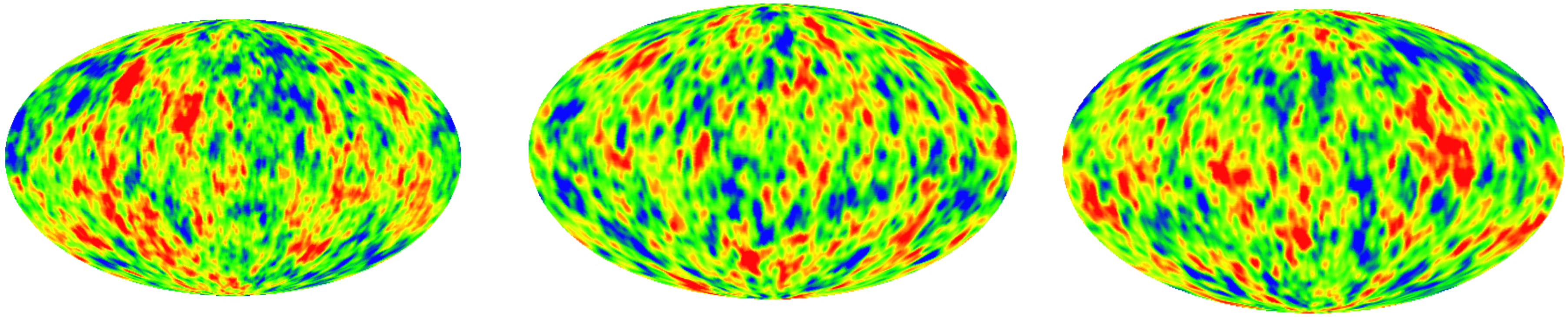
$$\frac{\delta T}{T} = \int_0^{\eta_0}\left(\dot{\tau}e^{-\tau}\left(\frac{\delta_\gamma}{4} - \mathbf{v_B}\cdot\widehat{n} + \Pi^I_{ij}\widehat{n}_i\widehat{n}_j\right) - \frac{1}{2}e^{-\tau}\dot{h}_{ij}\widehat{n}_i\widehat{n}_j\right)d\eta$$

$$Q = \int_0^{\eta_0}\dot{\tau}e^{-\tau}\Pi^Q_{ij}\widehat{n}_i\widehat{n}_j d\eta$$

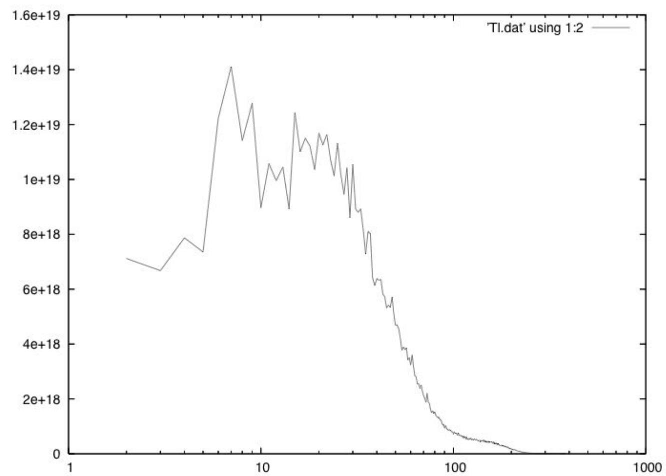
$$U = \int_0^{\eta_0}\dot{\tau}e^{-\tau}\Pi^U_i\widehat{n}_i d\eta$$

Results

ML & EPS Shellard, Phys. Rev. **D69**, 023003 (2004)
ML & EPS Shellard, in preparation
ML, EPS Shellard & E Komatsu, in preparation



Temperature Q U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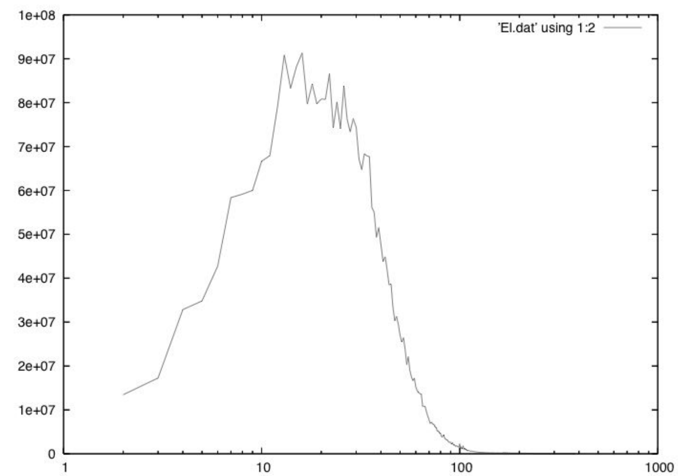
1.4e+19
1.2e+19
1e+19
8e+18
6e+18
4e+18
2e+18
0
1
10
100
1000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9e+07
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6e+07
5e+07
4e+07
3e+07
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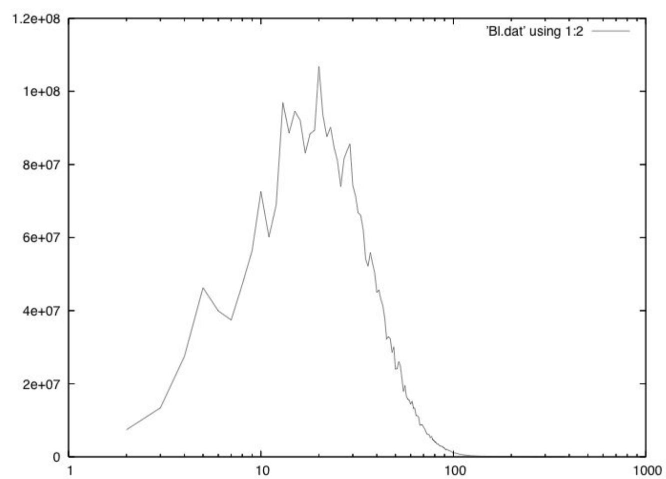
1e+07
0
1
10
100
1000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6e+07
4e+07
2e+07
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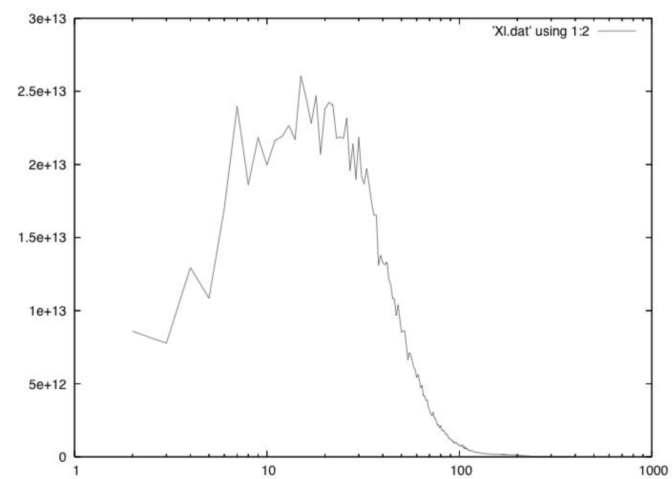
1
10
100
1000


'XI.dat' using 1:2
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2.5e+13
2e+13
1.5e+13
1e+13
5e+12
0
1
10
100
1000

Weak Lensing

ML, E Komatsu & EPS Shellard, in preparation

- The method initially developped to produce CMB maps can be very easily extended to study weak lensing.
- Weak lensing signal from strings may be important on scales where the CMB is more difficult to observe.
- Combination of several astrophysical signature increases chances of detection and ensures we are not confornted with a fluke.

The metric of a (spatially flat) FRW Universe is given by

$$g_{\mu\nu} = a(\eta)^2(\eta_{\mu\nu} + h_{\mu\nu}(\eta, \mathbf{x}))\,,$$

Given a null geodesic $g : x^\mu(\lambda)$, where λ is the affine parameter, the Minkowski space geodesic is identical, but with affine parameters realted by $d\lambda = a^2 d\widehat{\lambda}$.

The tangent vector to the geodesic is given by:

$$p^\mu = \frac{dx^\mu}{d\lambda} = \frac{1}{a^2}\frac{dx^\mu}{d\widehat{\lambda}}\,.$$

At the position of the observer, we can define two spacelike vectors n_a, $a = 1, 2$, which obey the following relations:

$$n_a^\mu n_{b\,\mu} = \delta_{ab} \;\text{ and }\; n_a^\mu u_\mu = n_a^\mu p_\mu = 0\,.$$

Choosing an observer at rest ($u^\mu = \frac{1}{a}(1, \mathbf{0})$), the above constraints impose the following form for the basis vectors:

$$p^\mu = \frac{1}{a^2}(1, \mathbf{n}) \;\text{ and }\; n_a^\mu = \frac{1}{a}(0, \mathbf{e}_a)\,,$$

with $\mathbf{e}_a.\mathbf{e}_b = \delta_{ab}$ and $\mathbf{n} = \mathbf{e}_1 \times \mathbf{e}_2$.

Our goal to compute maps and power spectrum of the shear field, $\gamma = (\gamma_1, \gamma_2)$, which is obtained from the amplification matrix:

$$\mathcal{A}_{ab} \equiv \frac{\mathcal{D}_{ab}(\lambda_S)}{\lambda_S} = \begin{pmatrix} 1-\kappa-\gamma_1 & \gamma_2 \\ \gamma_2 & 1-\kappa+\gamma_1 \end{pmatrix},$$

where κ is the convergence and the matrix $\mathcal{D}$ obeys the following evolution equation:

$$\mathcal{D}''_{ab} = \mathcal{R}_a^c \mathcal{D}_{cb}$$

and obeys the following initial conditions:

$$\mathcal{D}_{ab}(\lambda_O) = 0 \;\text{ and }\; \mathcal{D}'_{ab}(\lambda_O) = \mathcal{I}_{ab}\,,$$

while $\mathcal{R}_a b$ is obtained from the Riemann tensor in the following way:

$$\mathcal{R}_{ab} = R_{\mu\nu\alpha\beta} p^\nu p^\alpha n_a^\nu n_b^\beta$$

To zeroth order in the perturbation, we have, as in the Minkowski case, $\mathcal{R}_{ab} = 0$ The evolution equation then gives us

$$\mathcal{D}_{ab}^{(0)} = \lambda \mathcal{I}_{ab}\,.$$

Using this result, we obtain the following equation to first order:

$$\mathcal{D}_{ab}^{(1)\prime} = \lambda \mathcal{R}_{ab}^{(1)}\,,$$

to which the solution is

$$\mathcal{D}_{ab}^{(1)} = \int_0^{\lambda_S} \lambda(\lambda_S - \lambda)\mathcal{R}_{ab}^{(1)} d\lambda$$

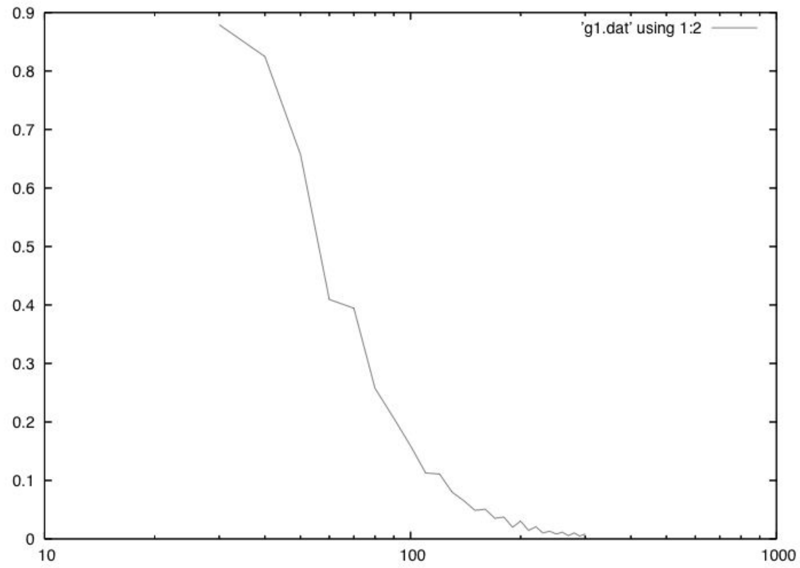
Choosing the conformal time for the affine parameter $\hat{\lambda} = \eta$ and the synchronous gauge $h_{0\mu} = 0$, the equation becomes, after integrating by parts and Fourier transforming:

$$\mathcal{D}_{ab}^{(1)} = \int_{\eta_S}^{\eta_0} \sum e^{-i\mathbf{k}.\mathbf{x}} \left[g_1 \left(k_l k_j \dot{h}_{ik} - k_l k_i \dot{h}_{jk} - k_j k_k \dot{h}_{il} + k_i k_k \dot{h}_{jl}\right) n^j n^k + (g_2 - g_3)\dot{h_{li}}\right] e_a^i e_b^l d\eta\,,$$

where the functions g_i are defined as:

$$g_1(\eta) = \textstyle\int_{\eta_S}^{\eta} \lambda(\lambda_S - \lambda) a^{-2} d\eta$$
$$g_2(\eta) = \textstyle\int_{\eta_S}^{\eta} \lambda(\lambda_S - \lambda) a^{-4} (\frac{\dot{a}}{a})^2 d\eta$$
$$g_3(\eta) = a^{-4}\frac{\dot{a}}{a}$$

Preliminary Results



γ_1 vs ℓ

Summary

- Cosmic strings, are generically formed in many fundamental theories and a confirmed detection would thus provide invaluable information on physics beyond the Standard Model.
- String-induced CMB fluctuations have a distinct signal (e.g. non-Gaussianities, B-mode polarization) which could be observed on small scales.
- Study of the weak lensing signal from strings will complement the information from the CMB.
- Various observational signatures used in conjunction should be used to
  - Increase our chance of detection.
  - Make sure we are not confronted with a fluke.