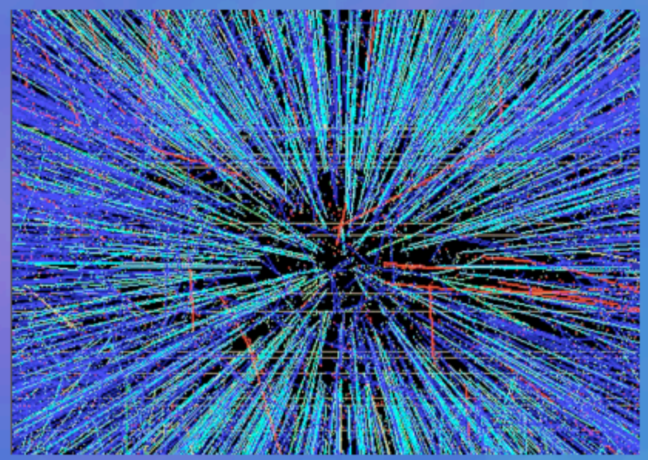
The Search for Cosmic Strings

Mia Ihm, Kirsten Howley, Lluvia Zuniga, Jodi Lamoureux, Professor George Smoot
Department of Astrophysics, Lawrence Berkeley National Laboratory, Berkeley, CA 94720

Background and Motivation

What's the Origin of Cosmic Strings?

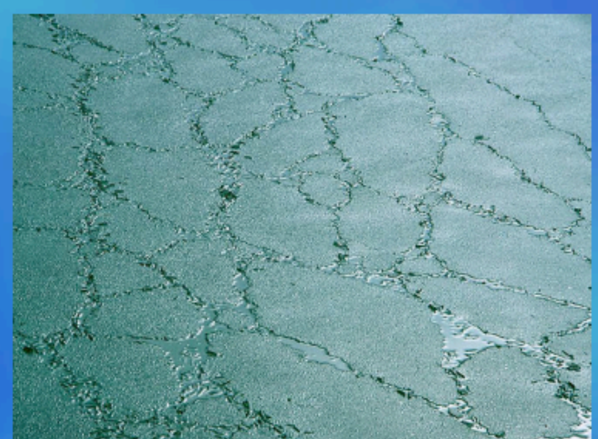


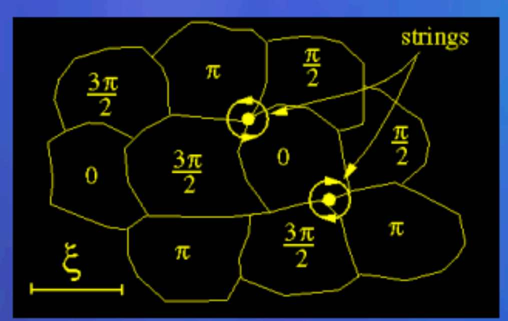
Cosmic strings are hypothetical remnants of the early universe whose formation is a predicted result of spontaneous symmetry breaking. Detectable cosmic strings, which are on an energy scale of $\sim 10^{15}$ GeV, may have formed during symmetry breakings which occurred in certain Grand Unified Theories (GUT) or at the end of inflation. Proof of their existence would excite both particle physicists and astronomers, for the strings could connect us directly with exotic matter and conditions of the moments right after the big bang.

Symmetry Breaking

Water Analogy

Symmetry breaking is characterized by phase transitions as matter changes to a less symmetric state. The phase transitions that occurred in the early universe are analogous to those of water. When liquid water has cooled significantly, it freezes into solid ice. Note that the liquid phase is more symmetric than the solid phase: in the liquid every direction is equivalent, but as the water freezes the molecules assemble into a crystal structure, and this directional symmetry is broken. Similarly, as the early universe expanded and cooled, it experienced a series of phase transitions.



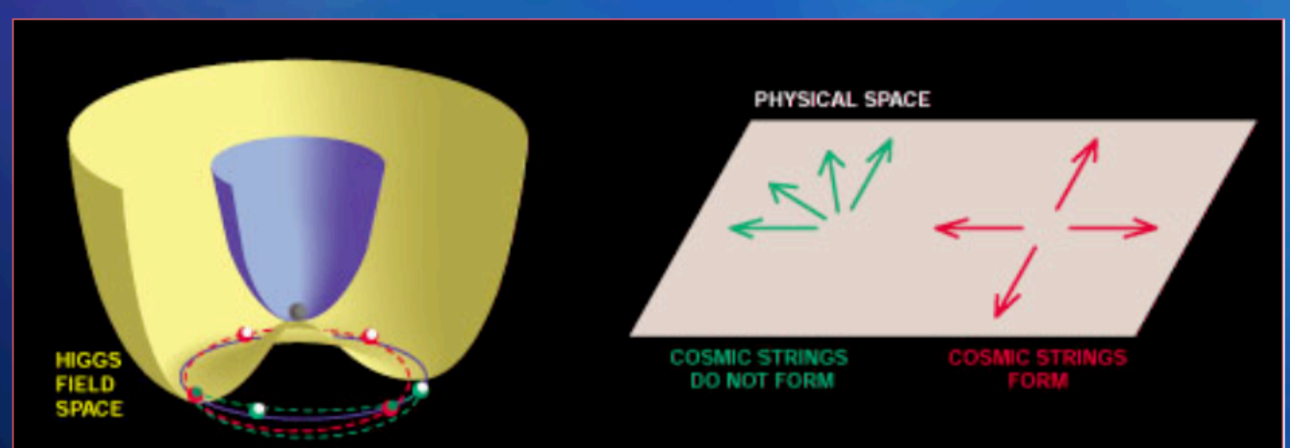


Formation of cosmic strings

Ice forming on a lake does not freeze uniformly, but in independent patches creating irregular boundaries, or cracks, between the regions. The formation of these cracks is analogous to the formation of topological defects in the early universe. Cosmic strings are linear *topological defects*; they are theorized to have formed when axial symmetry was broken. Trapped within these "liquid cracks" is the previous phase of the universe.

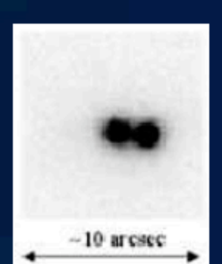
GUT Cosmic Strings

GUT Cosmic strings (predicted in some Grand Unified Theories) are an example of a topological defect that can result from the symmetry breaking at 10^{-35} seconds after the Big Bang. As spontaneous symmetry breaking occurred, the Higgs field takes on different orientations in unconnected regions of space. Along the boundaries, between these differently oriented regions of space, the previous vacuum energy (or phase) is trapped, and a defect is formed. In the case of a cosmic string, mass-energy is concentrated in a long, narrow strand with a radius a trillion times smaller than that of a hydrogen atom.



The figure above demonstrates the evolution of the complex scalar Higgs field. On the left, the temperature dependent potential V(ø) for high temperatures is indicated by the violet surface; the potential at lower temperatures is represented by the yellow surface, and takes the form of the "Mexican hat". For each of the two fields, the vacuum expectation value resides in the trough of the potential. As different regions of the space transit from the higher temperature violet potential (indicated by the grey ball) to the lower temperature yellow potential (red or green balls), an arbitrary direction for the phase of the field is chosen. As indicated by the physical space diagram on the right, these random orientations do not always line up; along these boundaries a cosmic string will form (red balls/lines).

Candidate Pairs

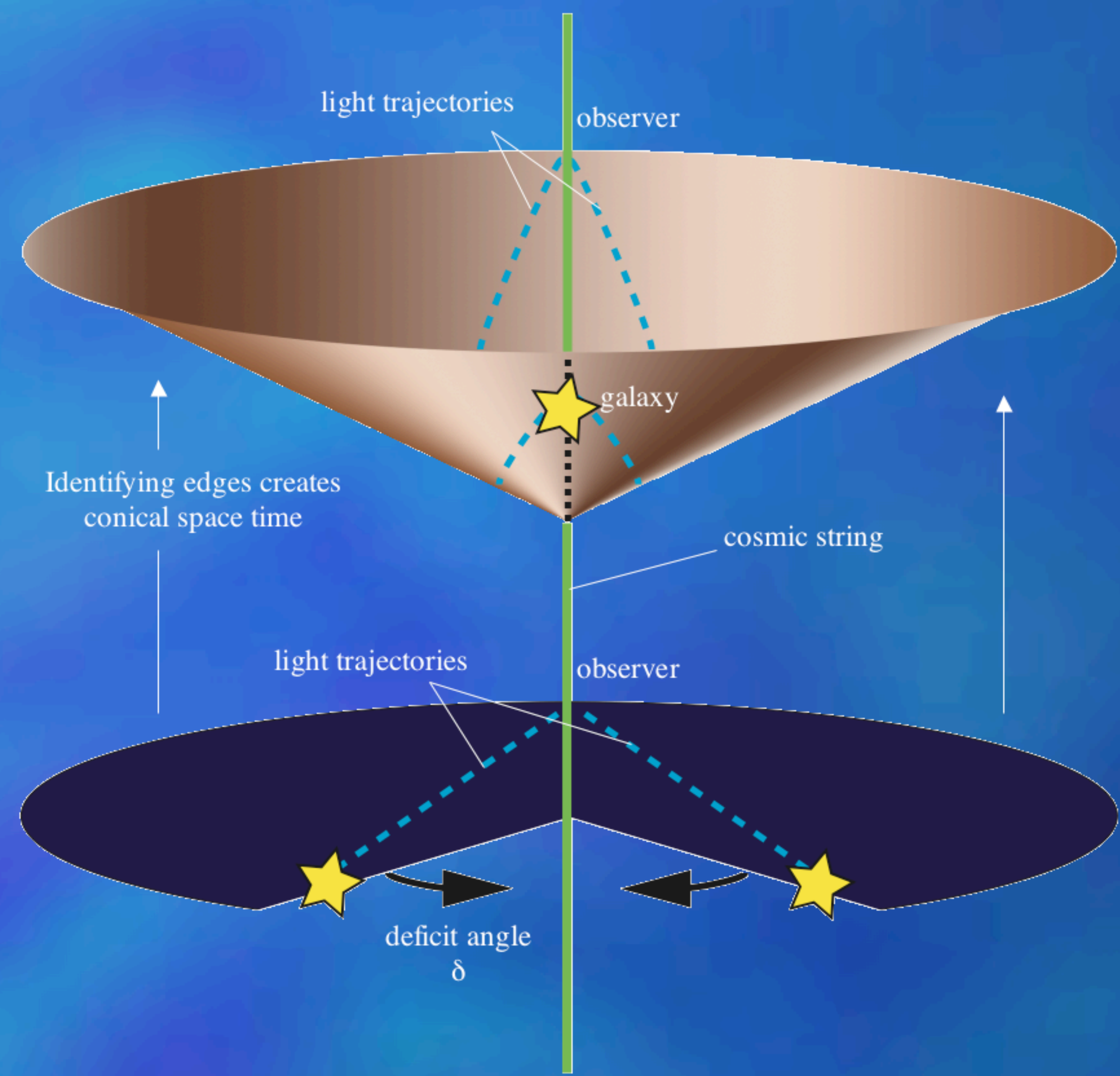


Observational interest in cosmic strings was recently rekindled by the discovery of Capodimonte–Sternberg–Lens Candidate, No.1, or **CSL-1**. This pair of galaxies share the same morphology and lie at a redshift of z=0.46. Further analysis shows that the unusual pair could be a result of gravitational lensing, a double image caused by a cosmic string.

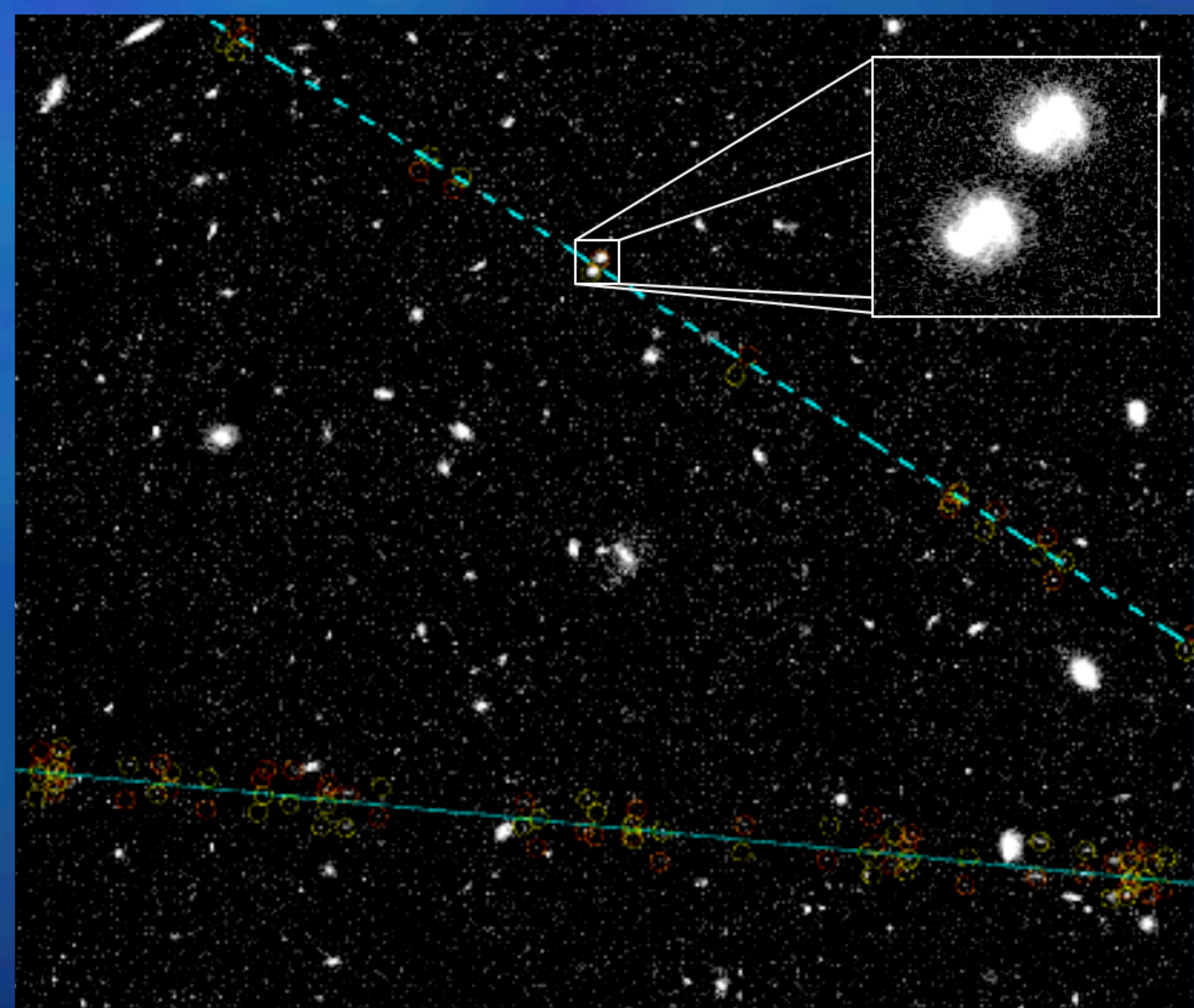
What Does a Cosmic String Do?

Gravitational Lensing by a Cosmic String

A cosmic string cuts out from flat space time a deficit angle $\delta = 8\pi G\mu/c^2$, where μ is the string's energy per unit length. If a string lies between an observer and a galaxy, light from the galaxy travels in two paths around the string. The observer will see an identical pair of galaxies, two distinct images of the same object.



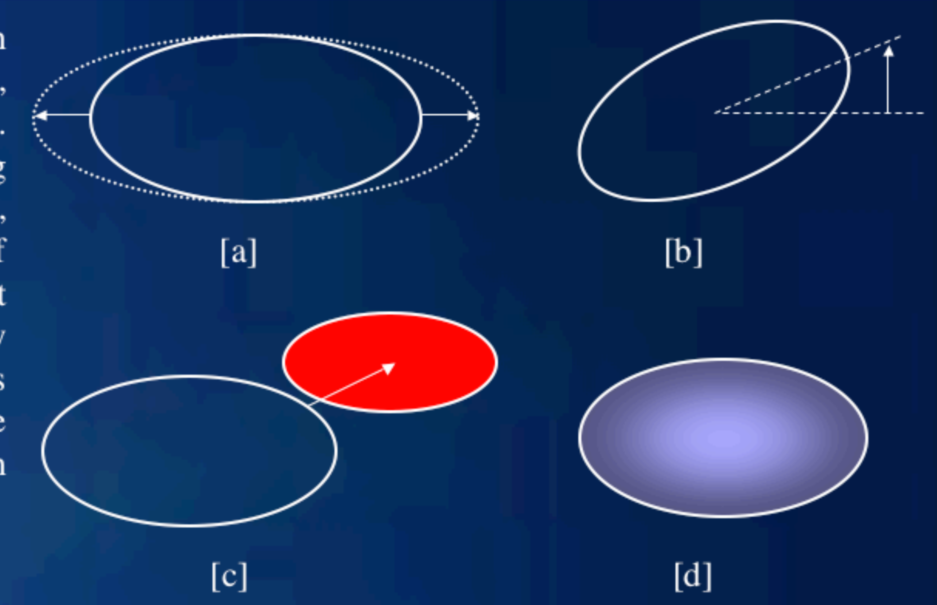
How a String Would Look



The field above shows two simulated cosmic strings at redshifts z=1.0 (dash) and z=0.5 (solid), placed in the GOODS' Hubble Deep Field North, section 33. The red and yellow circles identify lensed pairs that result from the string. A string can be detected by finding identical pairs that follow the line of the string.

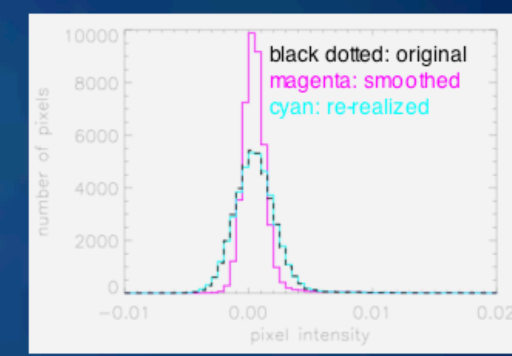
Detection Method

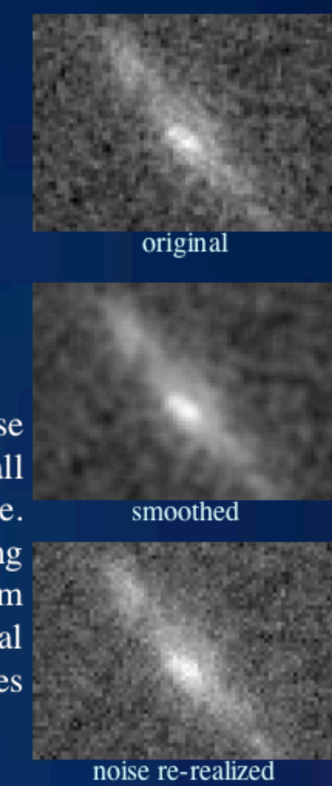
Our method for cosmic string detection involves finding pairs of similar galaxies, an indication of lensing by a string. Similarity can be measured by comparing ellipticities [a], angles of inclination [b], redshifts [c], and fluxes [d] of pairs of objects. Images from the Great Observatories Origins Deep Survey (GOODS) were searched for pairs. This survey used the Hubble Space Telescope to observe the Hubble Deep Field North and the Chandra Deep Field South.

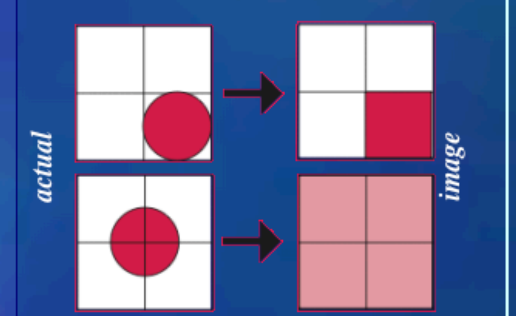


Smoothing and Noise

The accuracy of the images obtained by the Hubble Space Telescope is limited by the pixelization of the digital images. Depending on their placement within the pixels, two identical objects won't necessarily produce identical images, as illustrated below.

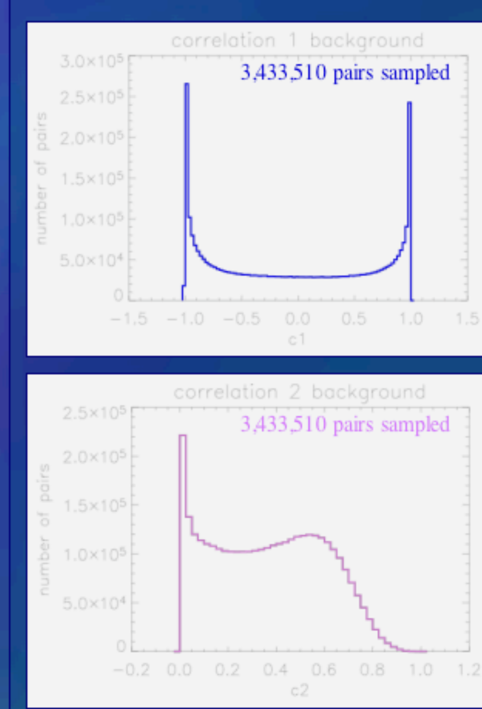






Smoothing helps to make up for these uncertainties by blurring the image, exhausting all possible positions the object can take. Background noise is then *re-realized* by adding intensity to each pixel, accounting for random noise and maintaining the flux of the original image. The top and bottom images of the galaxies to the right could be considered identical.

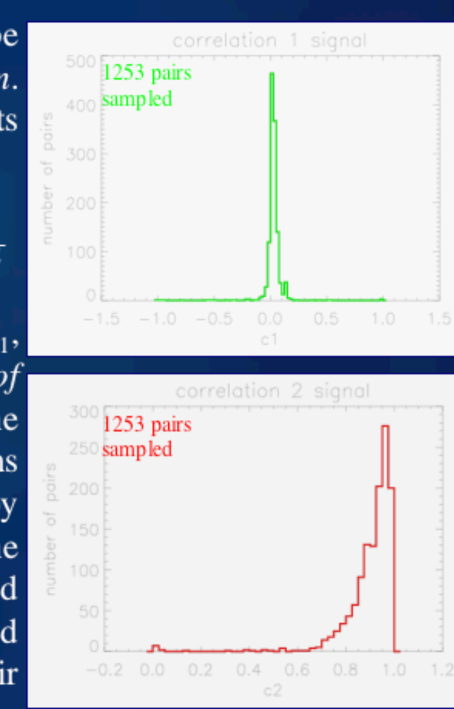
Correlation



The similarity between two objects can be assessed by calculating their *correlation*. Correlation coefficients between objects A and B were evaluated:

$$c_1 = \frac{\Sigma I_A^2 - \Sigma I_B^2}{\Sigma I_A^2 + \Sigma I_B^2}, \quad c_2 = \frac{2\,\Sigma (I_A I_B)}{\Sigma I_A^2 + \Sigma I_B^2}$$

Correlation of *fluxes* is described by c_1, while *shapes* (*ellipticity* and *angle of inclination*) are described by c_2. The plots on the left show the distributions expected as ***background***, obtained by correlating many random galaxies. The plots on the right display the expected ***signal*** from identical galaxies, obtained by correlating galaxies with their smoothed and re-realized counterparts.



Conclusions

We have not yet found a cosmic string of energy scale 10^{15} GeV and longer than 10" within the GOODS fields. However, this does not rule out the existence of cosmic strings. GOODS only covered a fraction of the sky, with 123 arcmin² in the north field and 140 arcmin² in the south field. More wide-field surveys can be searched for strings using this technique of finding pairs of galaxies that are morphologically similar.

Acknowledgements

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