Cosmic Strings

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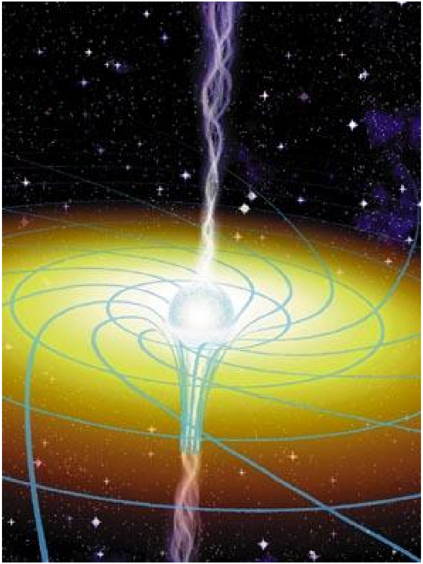
String Theory!!

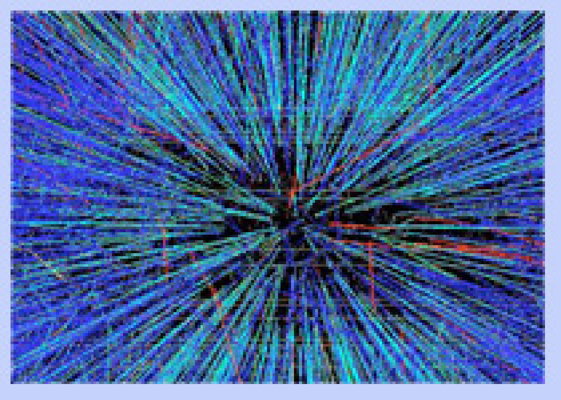
Cosmology



Outline

- Why Cosmic Strings?
- What is a "Topological Defect"?
- Examples of Cosmological Defects
- Brief History
- Importance to String Theory
- Geometry of Cosmic Strings
- Observation of Cosmic Strings
- Conclusion
- References

Why Cosmic Strings?

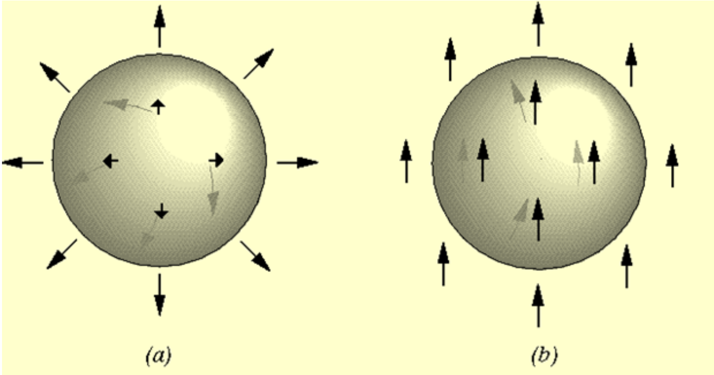


- Most promising among all types of cosmological defects
- Only type of string which can be detected in the near future

What is a "Topological Defect"?

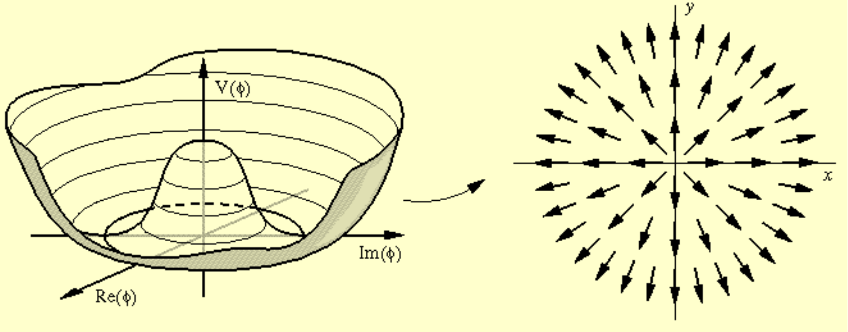
- Mathematical Topological Defect
  Solution of a system of PDE's or a QFT whose boundary condition has a non-trivial homotopy group preserved by the the differential equations.
- Cosmological Topological Defect
  stable configurations of matter created by the phase transitions due to symmetry-breakings in the very early universe.

Examples of Cosmological Defects: Monopoles



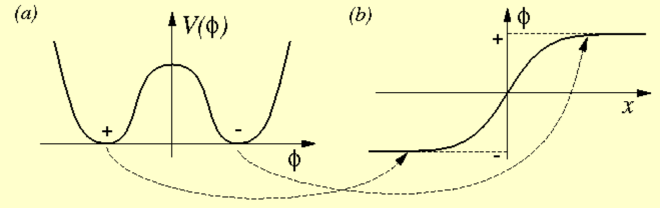
- Point-like objects from a broken spherical-symmetry
- Supermassive
- Magnetic charge

Examples of Cosmological Defects: Cosmic Strings



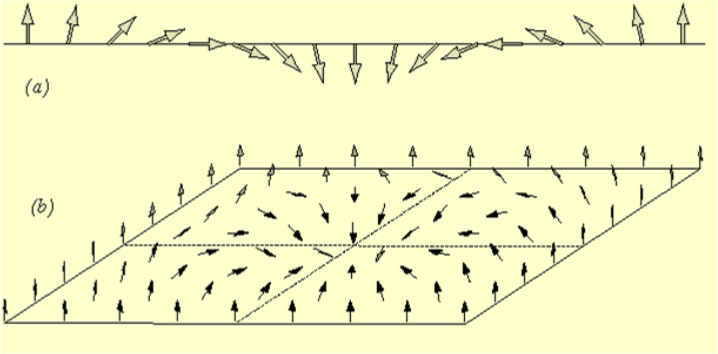
- 1D objects: lines
- Result of an axial symmetry-breaking

Examples of Cosmological Defects: Domain Walls



- 2D objects
- Result of a discrete symmetry-breaking
- Resemble walls of a closed-cell foam
- Divide universe into discrete cells

Examples of Cosmological Defects: Textures



- Complicated objects
- Result of a fully broken-symmetry

Brief History

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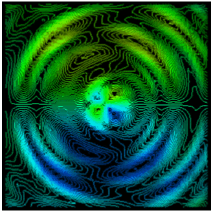
- CMB data from COBE, BOOMERanG, and WMAP excluded them as the main source, though they can still count for a few percent of these perturbations.
- In 2003, Polchinski described how cosmic strings could be created from fundamental strings. Jeanerott *et. al.* demonstrated their formation in SUSY GUT's.

Benefits for the String Theory

Biggest problem of the string theory is how to connect its mathematical structure to observation. Cosmic string is the best candidate so far to resolve this problem.

Benefits for the String Theory



- Macroscopic strings are possible.
  String energy density μ is proportional to the square of the symmetry-breaking scale η. If we take Planck's scale strings, they will be very heavy and thus could only exist in the first few Planck's times.However, in the models with large compact dimensions, the scale could go to as low as the GUT scale.
- Discovery of richer families of defects like D-Strings.
- For deriving standard model from M-theory we have to go through GUT's. All of them predict formation of cosmic strings at the end of inflation.

Geometry of Cosmic Strings

- Energy-momentum tensor

$$T^{\mu}_{\nu} = \rho(r) diag[1, 0, 0, -1], \tag{1}$$

$\rho(r) = \rho_0$ for $r < R$ and zero otherwise

- The effective gravitational mass of the string vanishes, i.e. $\rho + 3p = \rho - \rho = 0$.
- Spacetime line element

$$ds^2 = dt^2 - dr^2 - f^2(r) d\theta^2 - dz^2. \tag{2}$$

- Nontrivial components of the Einstein tensor

$$G^0_0 = G^3_3 = -\frac{f''}{f} = 8\pi\rho(r) \tag{3}$$

Geometry of Cosmic Strings

- Solution

$$f(r) = \begin{cases} k^{-1}\sin kr & \text{for } r < R \\ A + Br & \text{for } r > R \end{cases}, \tag{4}$$

  $k = \sqrt{8\pi\rho_0}$.

- Final form after imposing boundary conditions

$$f(r) = (r - R)\cos(kR) + \frac{\sin kR}{k}. \tag{5}$$

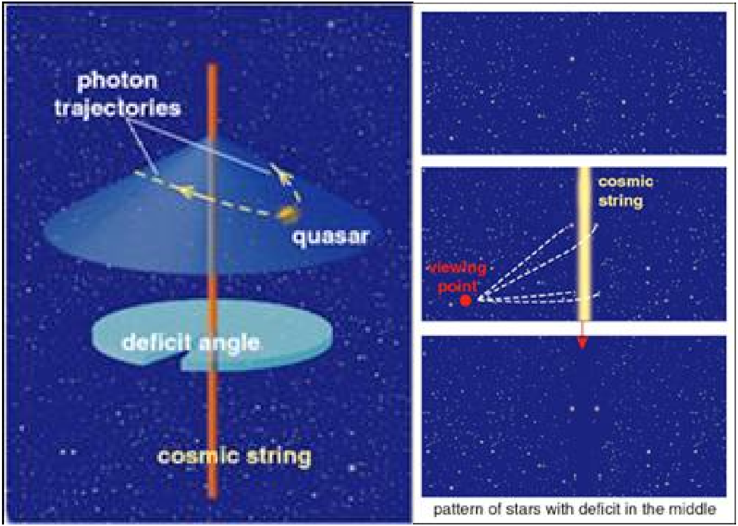
- $r \gg R$ and $kR < 1$

$$f(r) = (1 - 4\pi\rho_0 R^2)r = (1 - 4\pi\mu)r. \tag{6}$$

- Final form of the line element

$$ds^2 = dt^2 - dr^2 - (1 - 8\pi\mu)r^2 d\theta^2 - dz^2. \tag{7}$$

Geometry of Cosmic Strings



Geometry of Cosmic Strings

- Transforming to Minkowskian only possible *locally*
- $\phi = (1 - 4\mu)\theta$:

$$\rightarrow ds^2 = dt^2 - dr^2 - r^2 d\phi^2 - dz^2. \tag{8}$$

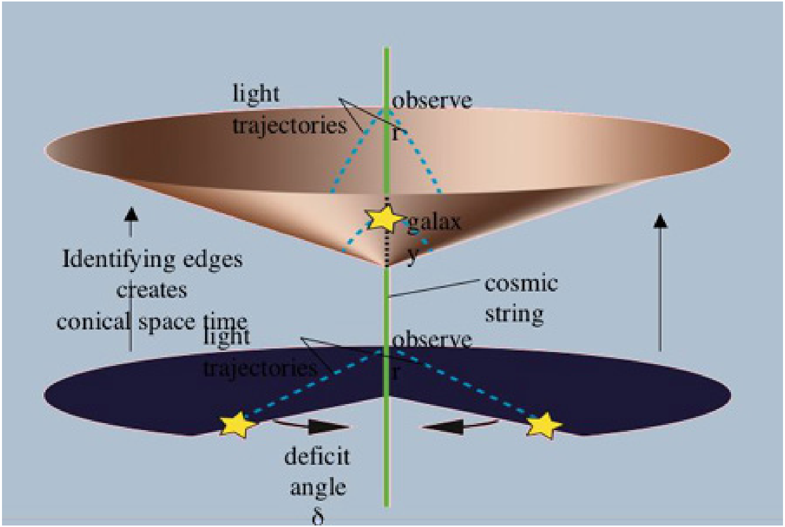
- ϕ only goes from 0 to $(1 - 4\mu)2\pi$
- Circumference of a circle of radius $r = a$ in a t=const., z=const. plane

$$C = (2\pi - 8\pi\mu)a, \tag{9}$$

- Conical spacetime with a "deficit angle"

$$\Delta\theta = 8\pi\mu = 5.2'' \left(\frac{\mu}{10^{-6}}\right). \tag{10}$$

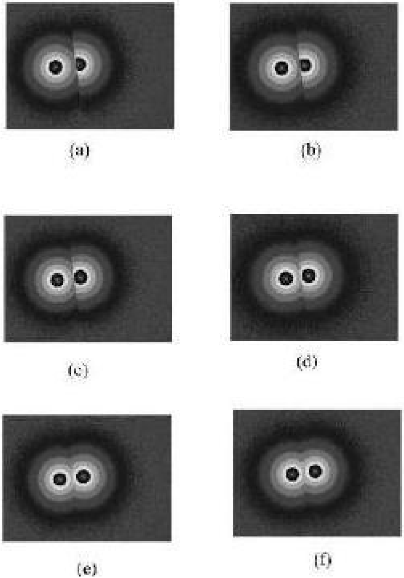
Geometry of Cosmic Strings



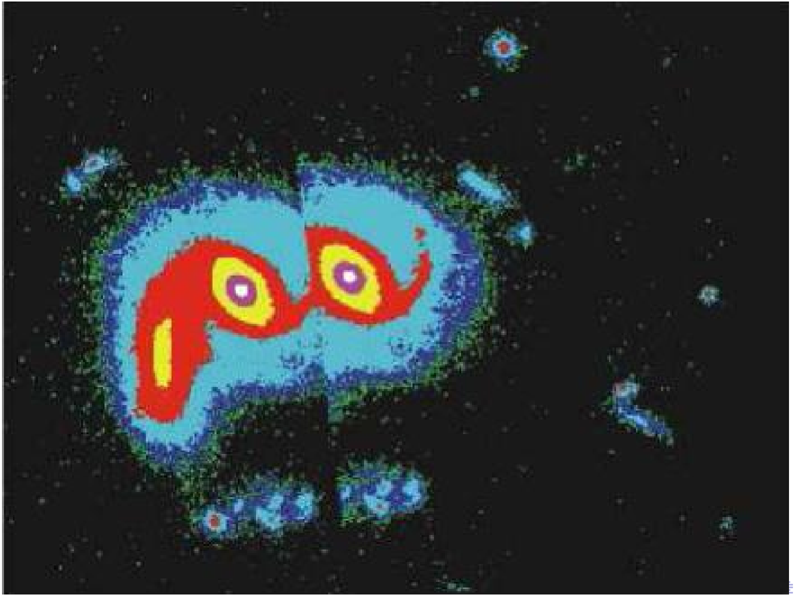
Geometry of Cosmic Strings

- As a light ray gets from very far away close to the string and then again to very far away, ϕ changes by π and hence θ changes by $\pi(1 + 4\mu)$.
- Light deflection is $\delta\theta = 4\pi\mu$, independent of the impact parameter
- two distinct images of the same size
- GUT-string, $\delta\theta \sim 10^{-5}$ rad $\rightarrow$ Observable
- Standard string, $\delta\theta \sim 10^{-31}$ rad $\rightarrow$ Not Observable

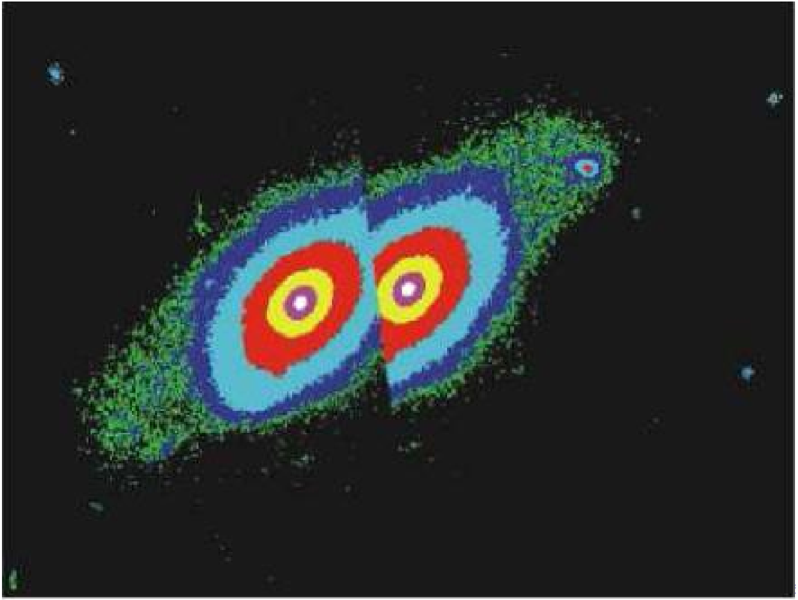
Observation: A source lensed by CS



Observation: A Spiral Galaxy Lensed



Observation: A Spiral Galaxy Lensed tilted axis

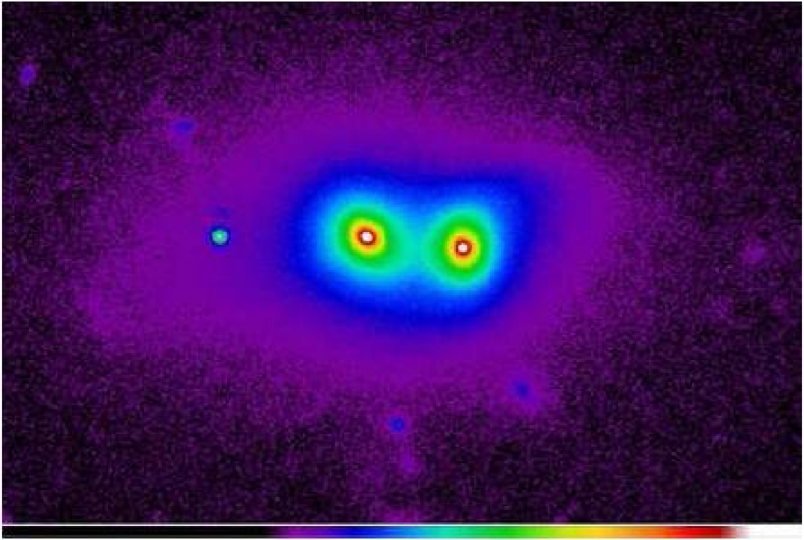


Observation: CSL1-4

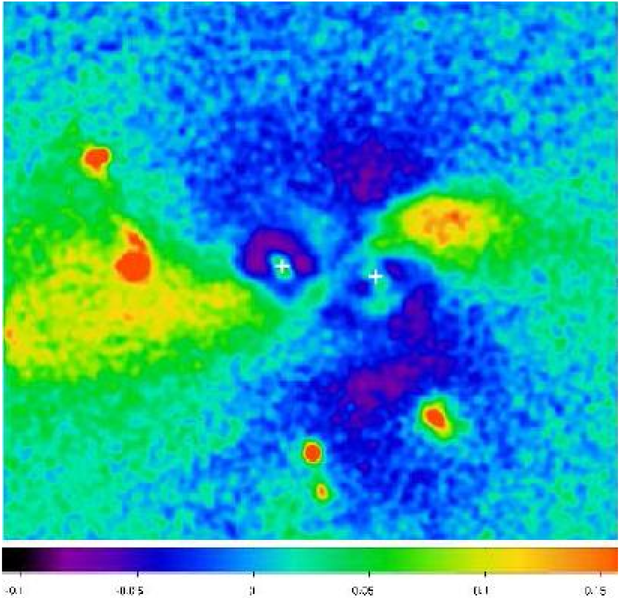
Pair of galaxy images from OACDF.
Possible explanation:

- Just one galaxy whose image is obscured by dust.
- Two similar galaxies.
- One galaxy with a conventional lensing object.

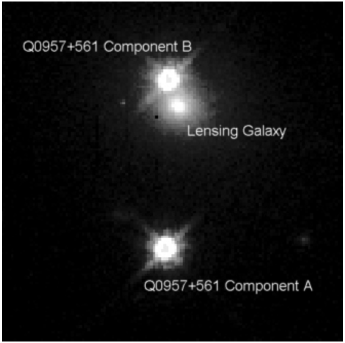
Observation: CSL-1 image from 6 HST images 2006



Observation: Normalized Residual

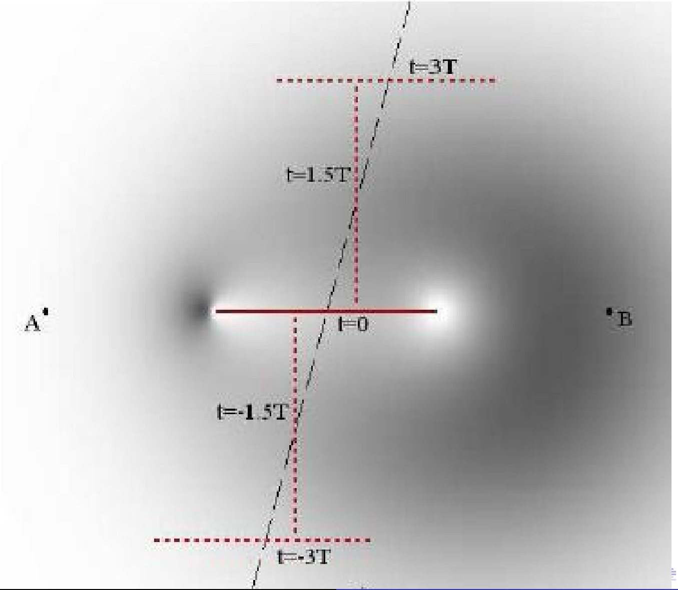


Observation: Loop

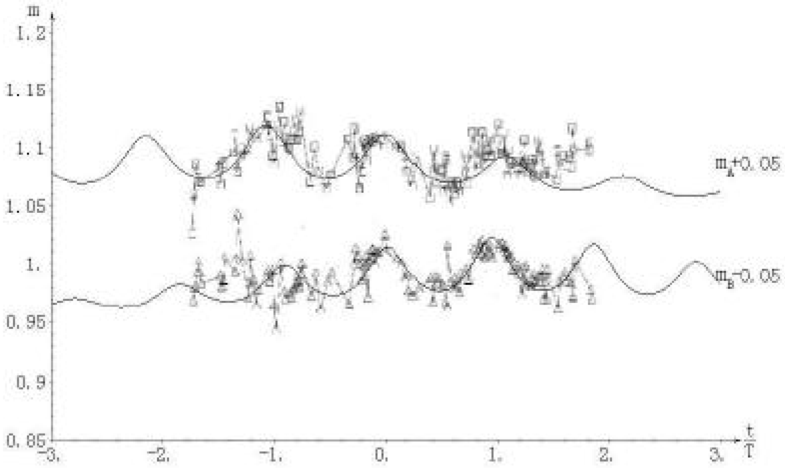


- Double image of the quasar Q0951+561
- Two images have a delay of 417 days due to light path difference
- This was not observed from Sep 94 to Jul 95
- Understood if we assume a loop 3 kpc away from us passed with a speed 0.7

Observation: Lens Galaxy and the Loop



Observation: Prediction of the Quasar image magnification oscillation



Conclusion

- Cosmic strings are the only possible observable type of cosmological defects.
- They are also the earliest possible observable type of superstrings.
- String theory certainly predicts them and if observed, we gain a lot of knowledge about fundamental theory itself.
- The spacetime around it is *weird*. There exist a deficit angle which is measurable in principle.
- So far we have had one possible indirect observation of cosmic string loop out of data from double images of the quasar system Q0951+561.
- Lensing measurements are possible only if $\mu \sim 10^{-7}$. Otherwise we have to wait for gravitational wave results from LISA, LIGO, VIRGO, etc.