Gravitational Waves from Cosmic Superstrings

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Summary :

Gravitational wave detection of string theory strings provides the best test of string theory.

There is a good chance LIGO can detect them. eLISA is even more promising.

Introduction
- Cosmic Strings
- Superstrings in String Theory
- Cosmic Superstrings

Binding to Galaxy
- Clustering like Dark Matter
- Local Number Density of Strings

Hunting Cosmic Superstrings in the Galaxy
- Gravitational Waves
- Micro-lensing

Conclusion

History of Cosmic Strings

• In late 1970s and early 1980s, it was proposed (by Kibble, Zeldovich, Vilenkin, ...) that cosmic strings are topological defects that would form a scaling network, independent of the initial production mechanism.

• They can generate density perturbation as seed for structure formation if $G\mu \simeq 10^{-6}$. So cosmic strings provide an alternative to inflation.

• In early 1990s, COBE data slightly disfavors cosmic strings. By late 1990s, Cosmic Microwave Background Radiation data (acoustic peaks) supports inflation and rules out cosmic string as an explanation to the density perturbation.

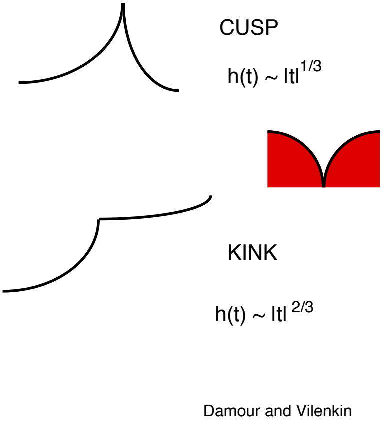
A scaling cosmic string network

- $\rho_{radiation} \propto a(t)^{-4}$ and $\rho_{matter} \propto a(t)^{-3}$.
- $\rho_{string} \propto a(t)^{-2}$. Even if initial production is small, they become important as universe expands.
- Loops get chopped off and they decay via gravitational radiation.
- They enter into a scaling network with $\Gamma \simeq 50$,

$$\Omega_{string} \simeq 8\pi\Gamma G\mu$$

- The observational bound is $G\mu < 10^{-9}$. (For cosmic strings to be responsible for the density perturbation for structure formation, $G\mu \sim 10^{-6}$.)

Strings have cusps and kinks, which emit gravitational waves.



LISA will see about one event per year if $G\mu \sim 10^{-7}$.

• String theory has been extensively studied in the past 40 years, but we have no observational evidence for it so far.

• In 1985, Witten attempted to identify the cosmic strings as fundamental strings in superstring (heterotic) theory, but failed : tension too big ($G\mu \simeq 10^{-3}$), and they are unstable.

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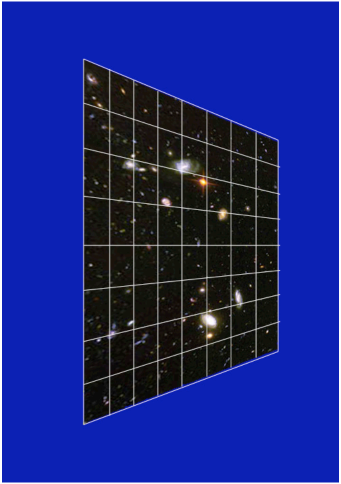
- In late 1990s, the brane world scenario appears. In 2002, we proposed that horizon-size strings in string theory could have been produced in the early universe, consistent with observation.

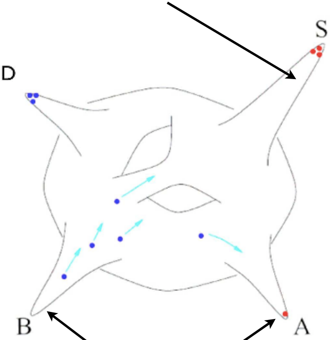
- They have rather different properties compared to that of the original cosmic strings. To distinguish them, we call them cosmic superstrings.

- Their gravitational wave detection (combined with micro-lensing) offers the best hope in testing string theory.

Brane World



Dozens to hundreds of Warped Throats



Cosmic superstrings at the bottoms of throats

Flux Compactification in Type IIB String Theory

- A typical 6-dimensional compactification with the right properties is a Calabi-Yau-like manifold with dozens to hundreds of such throats, each with its own warp factor $h_j \ll 1$.

- We live in $D3$-branes and there are no point-like ($D0$-) or membrane-like ($D2$-) defects.

- There are $D1$-branes (ie., D-strings) and fundamental strings (i.e., F-strings).

- Strings in the bulk : $G\mu \simeq GM_S^2 \simeq 10^{-6}$

- At the bottom of a throat : $G\mu \simeq GM_S^2 h_j^2$, where the warp factor h_j of the jth throat can be very small, $h_j \ll 1$.

• D-strings and F-strings can form bound states, with junctions and beads. So we have a tension spectrum.

• At the bottom of a (Klebanov-Strassler) throat, a bound state of p F-strings and q D-strings have tension

$$T_{p,q} \simeq \frac{M_s^2 h_i^2}{2\pi} \sqrt{\frac{q^2}{g_s^2} + (\frac{bN}{\pi})^2 \sin^2(\frac{\pi p}{N})}$$

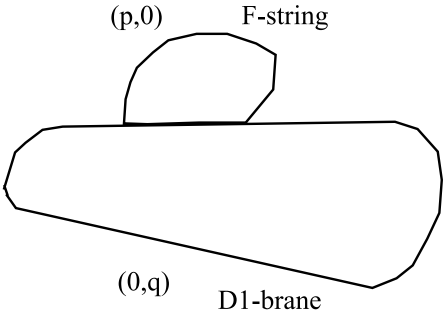
where $b = 0.93$, N an integer, and string coupling $g_s \sim 10$.

• A bead at a junction has mass

$$m_b = \frac{h_i M_s}{3} \sqrt{g_s/4\pi}\,(bN/\pi)^{3/2}$$

• If there are $D3$-branes at the bottom of a throat, only D-strings survive.

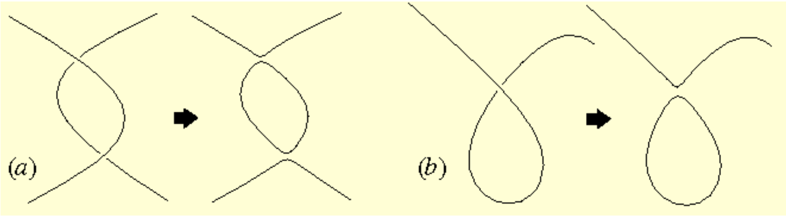
Ends of F-strings can end on a D-brane



Loops get formed from long (horizon-crossing) strings:

• The loops decay via gravitational radiation. Large loops live longer.

• The inter-commutation probability $P_{ic} = 1$ for ordinary strings, but $P_{ic} \leq 1$ for superstrings. It can be as small as $P_{ic} \simeq 10^{-3}$. (Jackson, Jones, Polchinski)



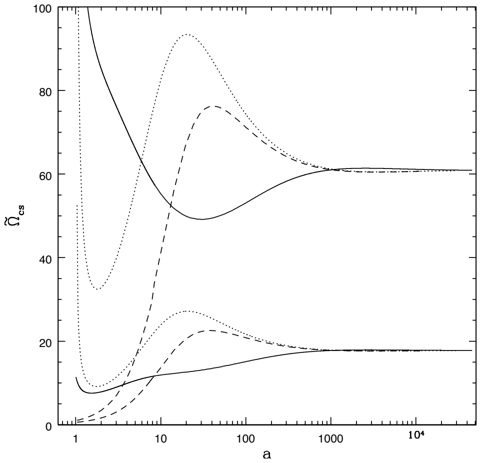
Cosmic Superstring Network

- Cosmic superstring tensions lowered by warping: no lower bound $0 < G\mu < 10^{-8}$.
- Multiple throats ($N_T \sim 10 - 10^2$), with a spectrum of bound strings ($N_s \sim 1 - 10$) in each throat.
- Intercommutation probability $10^{-3} < P_{ic} < 1$.
- Scaling solution, with $\Gamma \sim 50$,

$$\Omega_{strings} \sim 8\pi\mathcal{G}\Gamma G\mu$$

  where $\mathcal{G} = N_T N_s P_{ic}^{-\beta}$.
- $10^5 > \mathcal{G} > 1$ so $\mathcal{G} \simeq 10^3$ is easy.

$$\Omega_{strings} \simeq 8\pi\Gamma\mathcal{G}G\mu$$



Other Notable Properties

• Superstring loops are closed strings, in the same sector as gravitons.

• Cosmic superstrings in different throats evolve independently.

• Loops may emit axions, in addition to gravitational waves. This tends to decrease $\mathcal{G}$.

• With $\mathbf{Z}_N$ symmetry, a loop can have a membrane (domain wall) stretching inside it.

• A superstring loop can oscillate at the bottom of a throat : varying tension along the loop and in time.

Low tension loops dominate

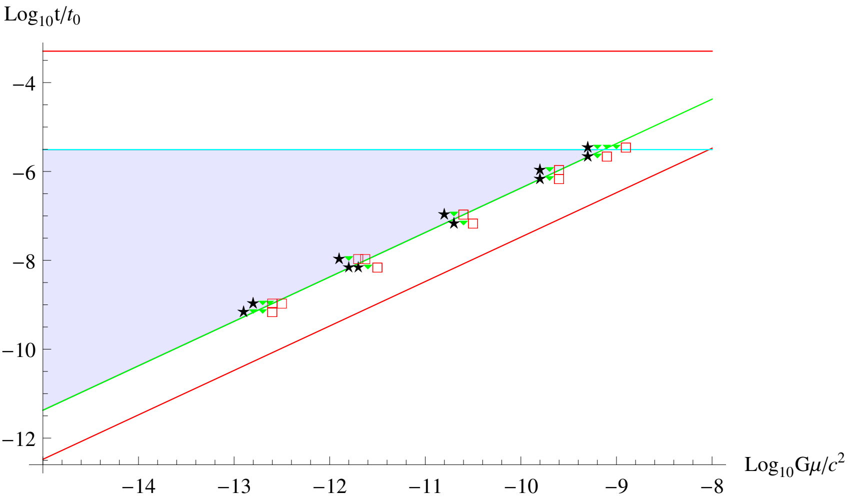
- Characteristic loop size at birth: $l = \alpha t$.
- Loop lifetime: $\tau = l/\Gamma G\mu = \alpha t/\Gamma G\mu$ (dimless $\Gamma \sim 50$).
- GUT scale $\sim M_s$: small α, large μ, $\Omega_{string} \sim \Omega_{long} > \Omega_{loop}$.
- Large $\alpha \sim 0.1$, small μ:
  - $H\tau \gg 1$ live many expansion times.

    $$\Omega_{long} \propto \Gamma G\mu, \qquad \Omega_{loops} \propto \sqrt{\alpha G\mu/\Gamma}$$
  - $\Omega_{string} \sim \Omega_{loops} \gg \Omega_{long}$
  - Relativistic center of mass motion damped.

Clustering like Dark Matter

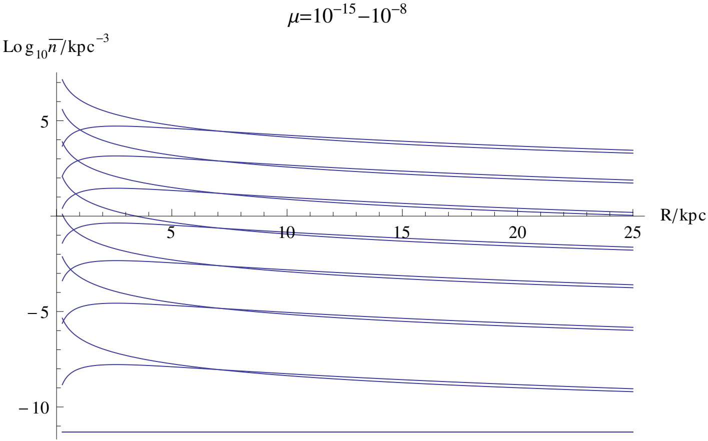
- Long-lived, slow moving ... $v_{rot} \sim 10^{-3}$ ... Cluster?
- Anisotropic GW emission: $\frac{\dot{P}}{\dot{E}} = \frac{\Gamma_P}{\Gamma_E} \sim \frac{1}{5}$.
- Rocket effect has to be taken into account.
- Radial infall model for CDM; r_{ta}; $\phi(x^\alpha)$; $g_{\mu\nu}(x^\alpha)$.
- Minimum rocket effect, maximum damping $\rightarrow$ maximum clustering.
- Enhancement: $\mathcal{F} \equiv \frac{\rho_{loop}}{\bar{\rho}_{loop}} = \frac{\rho_{loop}}{G\mu l_g}$

Maximum enhancement $\mathcal{F} \sim 10^{5.2}$



(Chernoff)

Local number density $\bar{n} = \rho_{loop}/\mu l_g$,
where $l_g = \Gamma G\mu t_0 \sim 20\mathrm{pc}(G\mu/10^{-10})$:

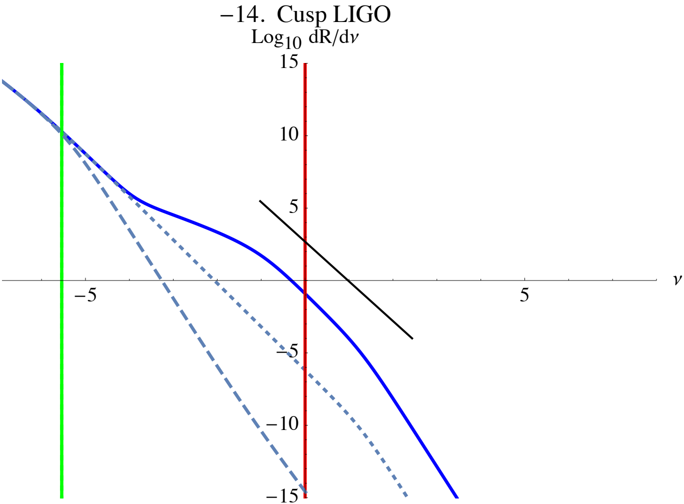


Gravitational Wave from Cusps and Kinks

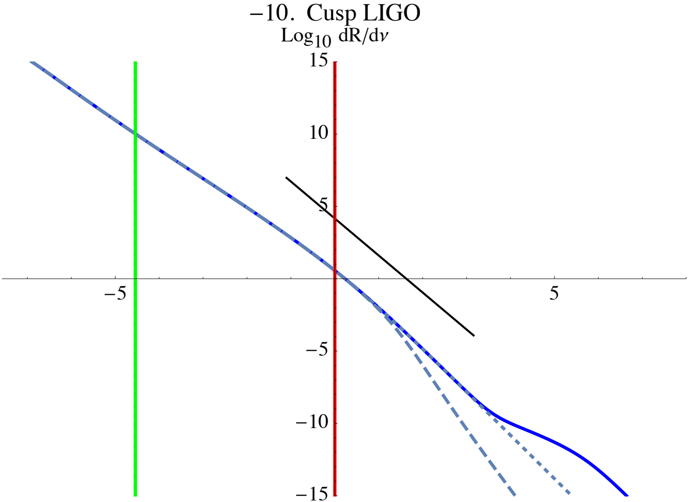
- $f_n = nf_1 = n\frac{2c}{l}$; fixed relative phase.
- $h_{LISA} \sim 10^{-23.8}$ at $f_* \sim 10^{-2.3}$ Hz.
- $n_* = \frac{f_*}{f_1} \gg 1$.
- f_* lies above galactic binary interference.
- Loop $l = \epsilon l_g$ with kink ($P_n \propto n^{-5/3}$).

Dashed:$z > 0.68$, dotted:homogeneous, solid:clustering

$G\mu = 10^{-14}, \quad \mathcal{G} \sim 100$



$G\mu = 10^{-10}, \quad \mathcal{G} \sim 100$



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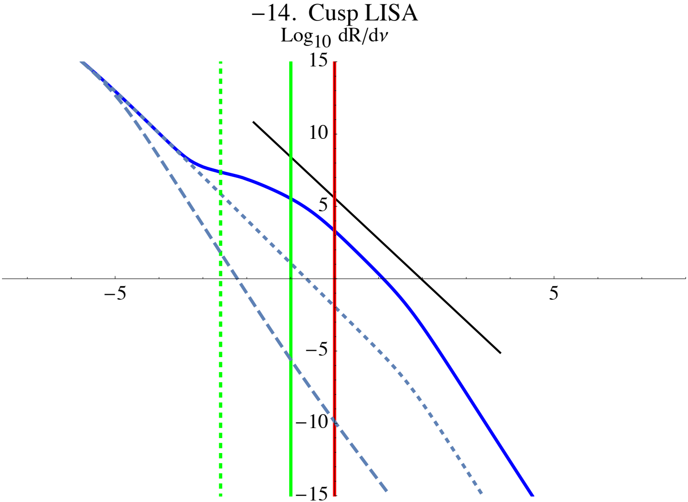
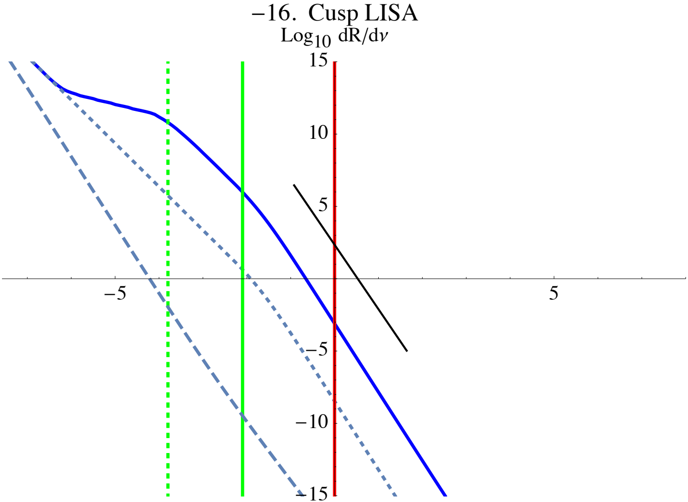
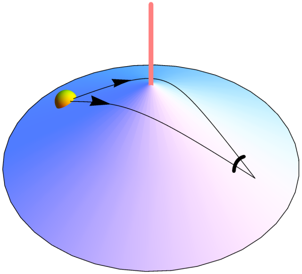


$G\mu = 10^{-16}, \quad \mathcal{G} \sim 100$

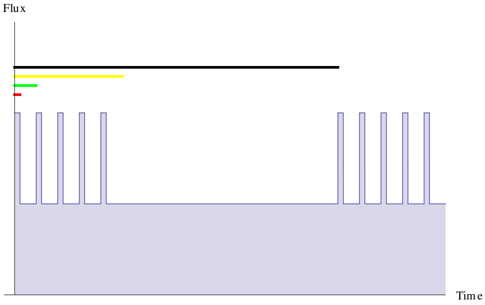


- Einstein deficit angle $\Theta_E = 8\pi G\mu$ in flat space.
- Source size: $\Theta_\odot/\Theta_E = 0.9\mu_{-13}R_{10}$.
- Resolved: double images. Unresolved: double flux.
- Range of interest: $10^{-13} < G\mu < 10^{-9}$.



Micro-Lensing

- Fingerprint: Achromatic, repetitive flux doubling. Lensing duration $\to \mu$. Lensing repetitions $\to l_g$. Direction!
- LSST or WFIRST has a very good chance.
- Exoplanet search can reach $G\mu \sim 10^{-18}$.



Conclusion

- Search for cosmic superstrings offers by far the best chance to test string theory. They have distinctive signatures.
- There is a good chance that upgraded LIGO + VIRGO + KAGRA will detect cosmic superstrings.
- LISA, eLISA, Taiji, Tianqin are very promising.
- The search is particularly powerful if GW search/detection is combined with micro-lensing. Search can reach $G\mu > 10^{-18}$. (Present bound $G\mu < 10^{-9}$.)

THANKS