Gravitational Wave Bursts from Cosmic Superstrings

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Cosmic superstrings are strings in string theory. They have properties quite different from conventional cosmic strings (vortices, or topological defects). These properties enhance their detection probability.

Gravitational wave burst detection of string theory superstrings will provide the best evidence of string theory.

There is a good chance LIGO (+VIRGO+KAGRA) can detect some of them.

LISA (launch date 2028 ?) (or Tianqin, Taiji, DeciGO, . . .) is even more promising.

D. Chernoff and H.T. : ArXiv:1412.0579 and to appear.

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.

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• 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

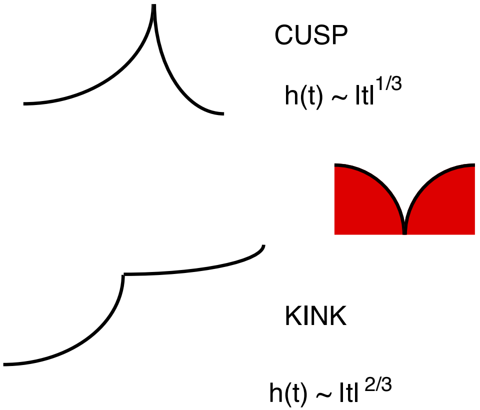
- $\rho_{radiation} \propto a(t)^{-4}$ and $\rho_{matter} \propto a(t)^{-3}$.
- $\rho_{string} \propto a(t)^{-2}$. Even if initial production is small, they become important as universe expands.
- Loops get chopped off and they decay via gravitational radiation.
- They enter into a scaling network,

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

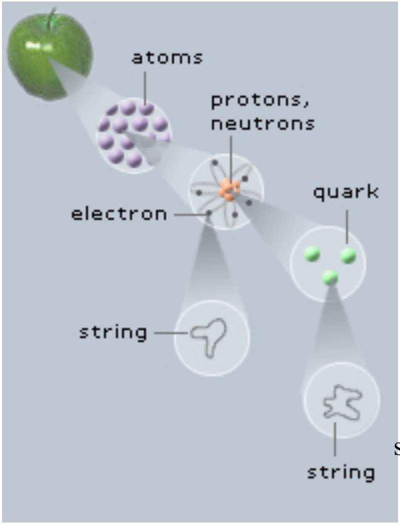
where $\Gamma \simeq 50$.

- The present 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 wave bursts.



Damour and Vilenkin



String Theory

弦理论

String theory has
9 spatial dimensions.

3 dimensions are large, spanning our universe.

The other 6 dimensions are very small, compactified into a Calabi-Yau manifold.

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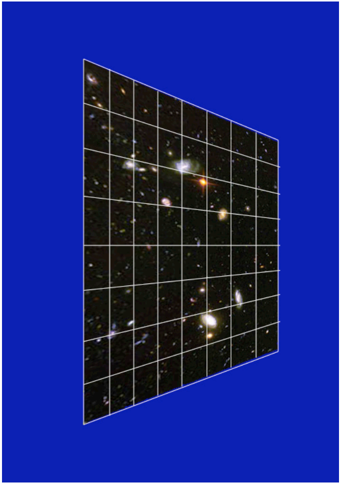
- In late 1990s, the brane world scenario appears. In 2002, we proposed that horizon-size strings in string theory could have been produced in the early universe after inflation, consistent with observation.

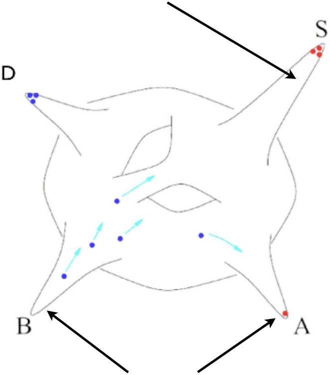
- The cosmic superstrings have rather different properties compared to that of the original cosmic strings.

- Their gravitational wave burst detection (combined with micro-lensing) offers the best hope in finding evidence for 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

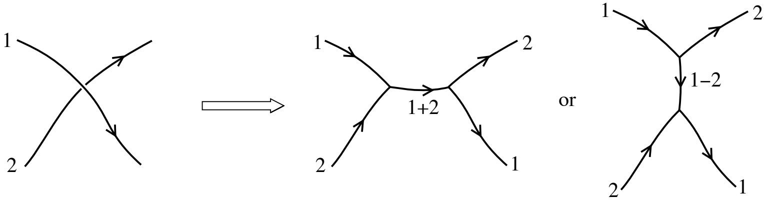
$$m_b = \frac{h_i M_s}{3} \sqrt{g_s/4\pi}\,(bN/\pi)^{3/2}$$

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

Junctions

During the evolution, they can form bound states with different tensions. Zipping and unzipping happen repeatedly.

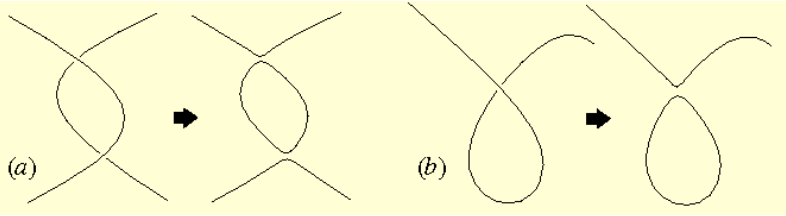
Strings in the picture shown are parts of closed string loops or part of horizon-size strings.



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)



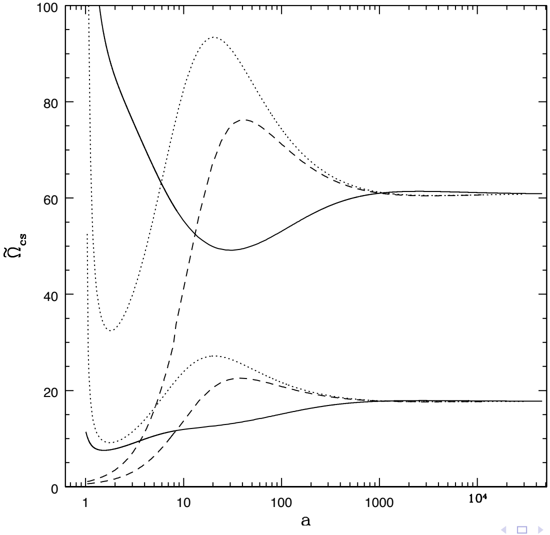
Cosmic Superstring Network

- 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,

$$\Omega_{superstrings} \sim \mathcal{G}\Omega_{string}$$

- $10^5 > \mathcal{G} > 1$ so $\mathcal{G} \simeq 10^3$ is easy.

$$\Omega_{superstrings} \simeq \mathcal{G}\Gamma G\mu$$



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.

2 Key Points :
String density is enhanced:

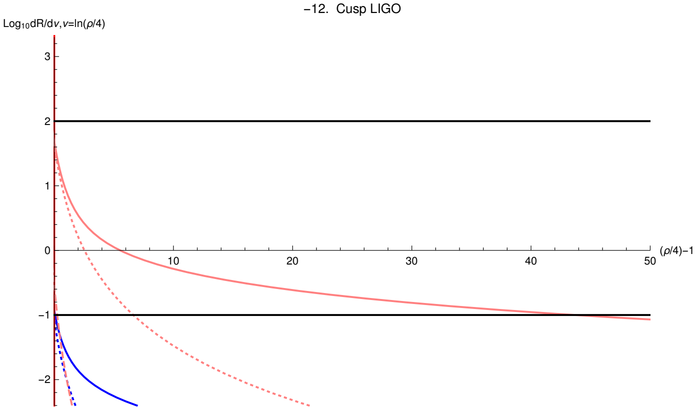
$$\Omega_{superstring} \simeq \mathcal{G}\Omega_{string}$$

where $1 \ll \mathcal{G} \lesssim 10^4$
Below, we choose $\mathcal{G} = 100$.

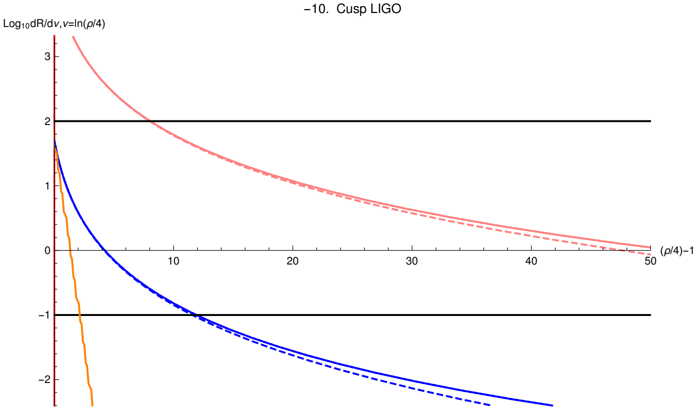
Low tension strings loops live long, so their relativistic motions get damped. So they cluster, just like dark matter.

String density in galaxy is enhanced by up to 10^5 for $G\mu < 10^{-10}$.

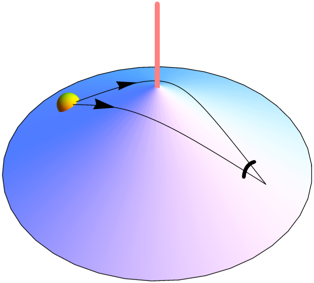
$G\mu = 10^{-12}$ LIGO-VIRGO-KAGRA



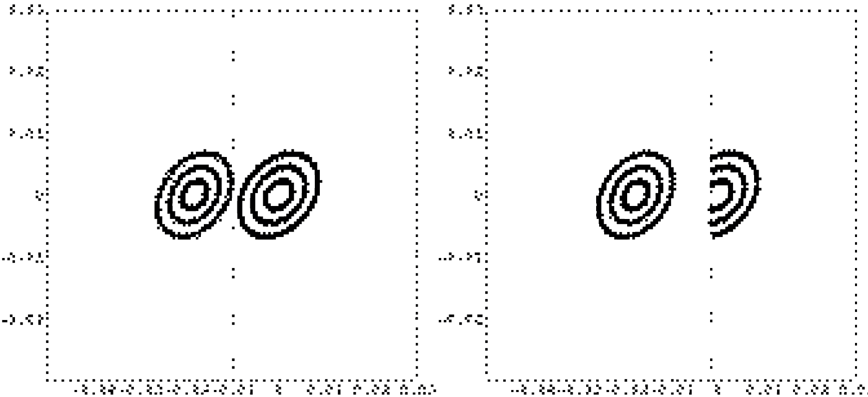
$G\mu = 10^{-10}$ LIGO-VIRGO-KAGRA



- 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: $10^{-18} < G\mu < 10^{-9}$.

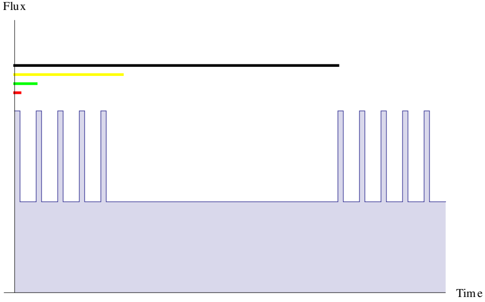


Lensing by a straight string



Micro-Lensing

- Fingerprint: Achromatic, repetitive flux doubling. Lensing duration $\rightarrow \mu$. Lensing repetitions $\rightarrow l_g$. 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 find signatures of string theory. Some features are very distinct.
- There is a good chance that upgraded LIGO + VIRGO + KAGRA will detect cosmic superstrings.
- LISA (also Taiji, Tianqin, DeCiGo) 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

Kuroyanagi et al
Blanco-Pillado et al.