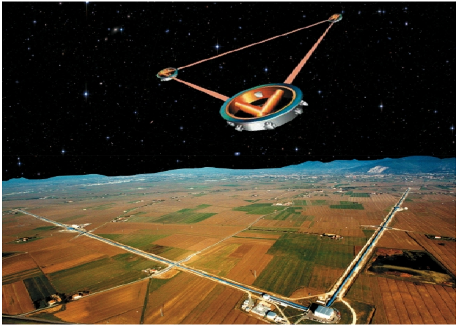
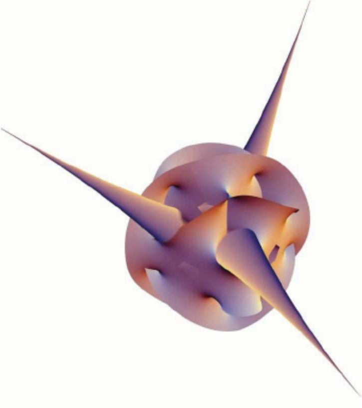
Gravitational Waves and Kaluza-Klein Modes from Cosmic Super-Strings





Jean-François Dufaux

OUTLINE

Cosmic super-strings are fundamental objects of string theory produced in the early universe, that have a cosmological size and evolve until the present epoch as a network of cosmic strings

Observational signatures of string theory??

In particular, cosmic strings are important sources of gravitational waves

Cosmological GW backgrounds and eLISA

[Binétruy, Bohé, Caprini, JFD '12] - arXiv:1201.0983, submitted to JCAP

Distinguishing cosmic super-strings from "traditional" cosmic strings??

Production of Kaluza-Klein modes by cosmic super-strings

[JFD '11] - arXiv:1109.5121, submitted to PRL

[JFD '12] - arXiv:1201.4850, submitted to PRD

PLAN

1) Cosmic strings and super-strings

- Cosmic strings
- Cosmic super-strings
- Cosmological evolution and loop number density

2) Gravitational waves (GW) from cosmic strings

- From LISA to eLISA
- Cosmological sources of GW
- GW background from cosmic strings
- Detection prospects

3) Kaluza-Klein (KK) modes from cosmic super-strings

- KK coupling to cosmic strings
- KK emission from cusps
- Cosmological consequences
- Constraints on cosmic super-strings

Cosmic Strings and Super-Strings

Cosmic Strings [Kibble '76], ...

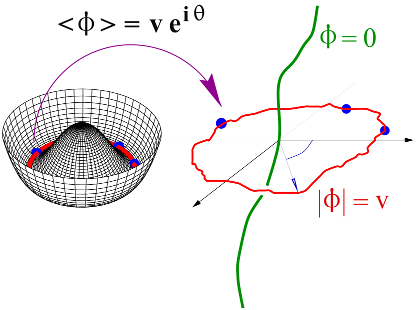
Linear topological defects

Formed at <u>any</u> symmetry-breaking phase transition provided the vacuum manifold is not simply connected

Example: Abelian-Higgs model

$U(1)$ gauge symmetry with

$$V(\Phi) = \frac{\lambda}{4} \left(|\Phi|^2 - v^2\right)^2$$



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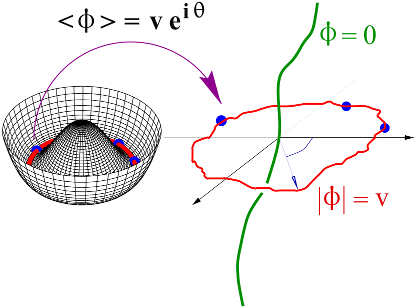

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$$S_{NG} = \mu \int d\tau d\sigma \sqrt{-\gamma} \quad \text{where string tension: } \mu = E/L \sim v^2$$

and $\gamma_{\alpha\beta} = \partial_\alpha X^\mu \partial_\beta X_\mu$ is induced metric on string worldsheet $X^\mu(\tau, \sigma)$

Cosmic Strings

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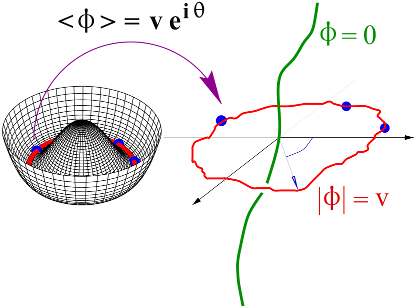

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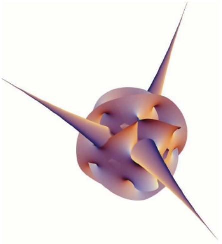
Current constraint (CMB, gravitational lensing, pulsar timing):

$$G\mu < \text{few} \times 10^{-7} \qquad \left(\Leftrightarrow \;\; \mu \lesssim 10^{18}\,\text{kg/cm}\,!!\right)$$

Cosmic Super-Strings (F-strings, D-strings)



[Witten '85],
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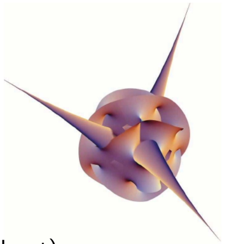

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Tension? If $\mu \sim 1/\alpha'$ and $V_6 \sim \alpha'^3$: $G\mu \gg 10^{-5}$ (ruled out)

Different for large extra dimensions or warped throats:

$$ds_{10}^2 = e^{-2A(y)}\,\eta_{\mu\nu}\,dx^\mu\,dx^\nu + g_{ab}(y)\,dy^a\,dy^b \quad \Rightarrow \quad G\mu \propto e^{-2A_b} \ll 1$$

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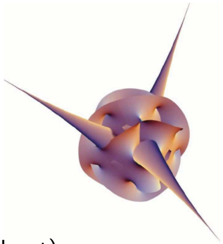

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- Brane/anti-brane annihilation at the end of brane inflation
- Hagedorn phase transition after inflation ($T_H \sim \sqrt{\mu}$, multi-throat models)

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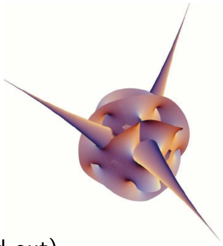

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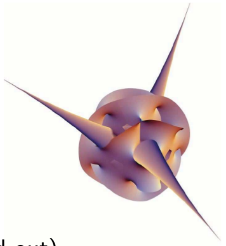

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"Particular" properties?

- Reconnection probability smaller than unity
- Different kinds of strings with junctions between them

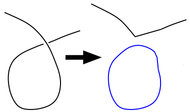
Cosmological Evolution of Cosmic String Networks

Scaling regime (attractor): the network of **long strings** ($L > t$) looks statistically the same at any time when measured in units of $H^{-1} \sim t$

$$\frac{\rho_{\rm long}}{\rho_{\rm tot}} = \text{constant} \propto G\mu/p^{\beta} \qquad (\beta = 1 \text{ usually expected})$$

$\Rightarrow$ Long strings must continually loose energy (otherwise $\rho_{\rm long} = \frac{\mu L}{L^3} \propto a^{-2}$)

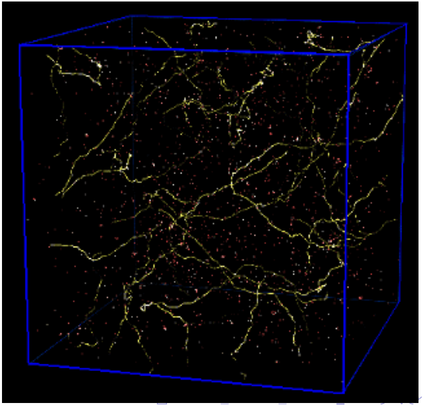
$\Rightarrow$ Production of **loops** ($L < t$) by reconnection of long strings:



The loops oscillate relativistically under the effect of their tension and decay away into **gravitational waves**

Thus GW are continually emitted via the continuous production of loops

$$\rho_{\rm long} \longrightarrow \rho_{\rm loop} \longrightarrow \rho_{gw} \propto a^{-4}$$

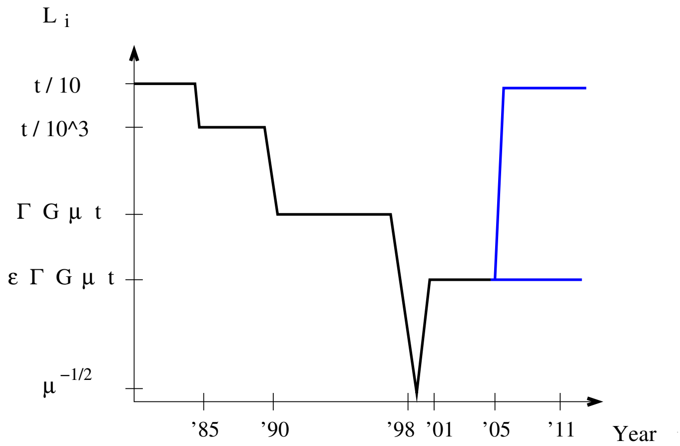


The Scale(s) of Loop Production

Charactersitic initial size of loops when produced from long string network:

$$L_i \sim \alpha\, t \qquad \Rightarrow \text{ Lifetime: } \tau \sim \frac{\alpha\, t}{\Gamma G \mu} \qquad \left(\frac{dE_{gw}}{dt} = \Gamma G \mu^2 \text{ with } \Gamma \sim 50 \right)$$

Results in literature differ by orders of magnitude



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Currently two main scenarios (UK Vs. Tufts):

- **Short-lived loops** (L_i set by network's small-scale structure)
  [Ringeval, Sakellariadou, Bouchet '05], [Martins, Shellard '05]

$$L_i \sim \epsilon\, \Gamma G\mu\, t \;\; \text{with} \;\; \epsilon \leq 1 \qquad \Rightarrow \;\; \tau \sim \epsilon\, t < t$$

- **Long-lived loops** (L_i set by network's large-scale properties)
  [Olum, Vanchurin, Vilenkin '05 '06], [Blanco-Pillado, Olum, Shlaer '11]

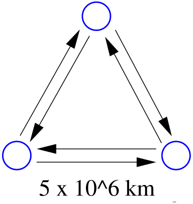
$$L_i \sim 0.1\, t \qquad \Rightarrow \;\; \tau \sim t/(10\Gamma G\mu) \gg t$$

Long-lived loops have larger number density $\Rightarrow$ produce more GW

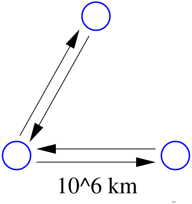
GW Background from Cosmic Strings

From LISA (ESA + NASA) to eLISA/NGO (ESA only)

LISA ($\sim 1.5 \times 10^9$ euros)



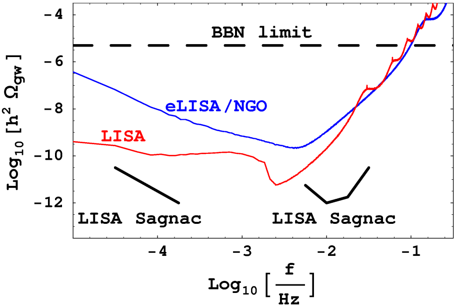
eLISA ($\sim 10^9$ euros)



Sensitivity curves

$$h^2\,\Omega_{gw}(f) = \frac{h^2}{\rho_c}\,\frac{d\rho_{gw}}{d\log f}$$

Sagnac calibration of instrumental noise **[Hogan, Bender '01]** is lost for eLISA



Cosmological Sources of Gravitational Waves (GW)

- First-order phase transitions
- Cosmic (super-)strings
- Inflation with:
  - $\hookrightarrow$ particle production during inflation
  - $\hookrightarrow$ equation of state $w > 1/3$ after inflation
- Preheating after Inflation
- Non-perturbative decay of other scalar fields, e.g. SUSY flat directions
- Unstable domain walls and hybrid defects
- Scalar field relaxation after global phase transitions
- Primordial black holes
- Alternatives to inflation (pre-big-bang, ekpyrotic/cyclic cosmology)
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Each source leads to GW with specific spectral properties, which may allow to disentangle different cosmological signals from each other and from astrophysical and instrumental backgrounds

GW Background from Cosmic Strings: Literature

- Extensively studied in the 80's and beginning of 90's, see in particular **[Caldwell, Allen '92]** for a review.
- More recently, **[Damour, Vilenkin '00 '01 '05]** pointed out that the GW signal from cosmic strings includes strong infrequent bursts, that:
  (i) can be looked for individually
  (ii) should not be included in stationary and nearly Gaussian background
- GW background further studied in **[Hogan et al '06 '07]**, **[Siemens et al '06 '10]**, ...

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We made the following improvements:

- Two main methods used in the literature shown to be equivalent, up to an overall normalization constant
- Studied how the results depend on spectrum emitted by individual loops and on removing of the rare bursts
- Improved model for the cosmological evolution (Λ-CDM cosmology and variation of g_*)
- Studied how the results depend on cosmological evolution of early universe
- Predictions for eLISA and other experiments

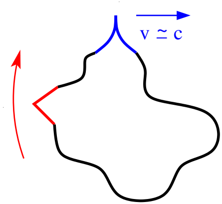
GW Spectrum Emitted by Individual Loops

A loop of (invariant) length L oscillates (quasi-)periodically with period $T_L = L/2$.

Emits GW at frequencies $f_{em} = 2n/L$ where $n = 1, 2, 3, \ldots$ are harmonics of loop oscillation.

Power emitted:

$$\frac{E_{gw}}{dt} = \sum_n P_n \, G\mu^2 = \Gamma \, G\mu^2$$



High-frequency spectrum: $P_n \propto n^{-1-q}$ for $n \gg 1$

Cusp: piece of string with instantaneous velocity $v \simeq c$, $q = 1/3$

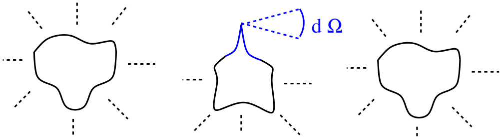
Kink: shape-discontinuity propagating along string with $v = c$, $q = 2/3$

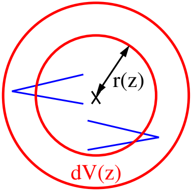
BUT: full spectrum for "realistic" population of loops is unknown

Limiting cases:

$$\begin{cases} P_n = \Gamma/3n^{4/3} & \text{(loops with cusps)} \\ P_n = 2\Gamma/3n^{5/3} & \text{(loops with kinks and no cusp)} \\ P_1 = \Gamma \ \text{ and } \ P_{n\geq 2} = 0 & \text{(only fundamental mode)} \end{cases}$$

Removing Rare GW Bursts from Cusps and Kinks





Present-day amplitude and rate of GW bursts produced by cusp or kink on loops of length L at redshift z: $\quad ((1+z)f = f_{em} > 2/L)$

$$h(f,z,L) = \frac{G\mu L}{r(z)\ [Lf(1+z)]^q} \quad , \quad d\dot{N}(f,z,L) = \frac{d\Omega}{4\pi}\,\frac{N_q}{(1+z)\ T_L}\, n(L,z)\, dV(z)\, dL$$

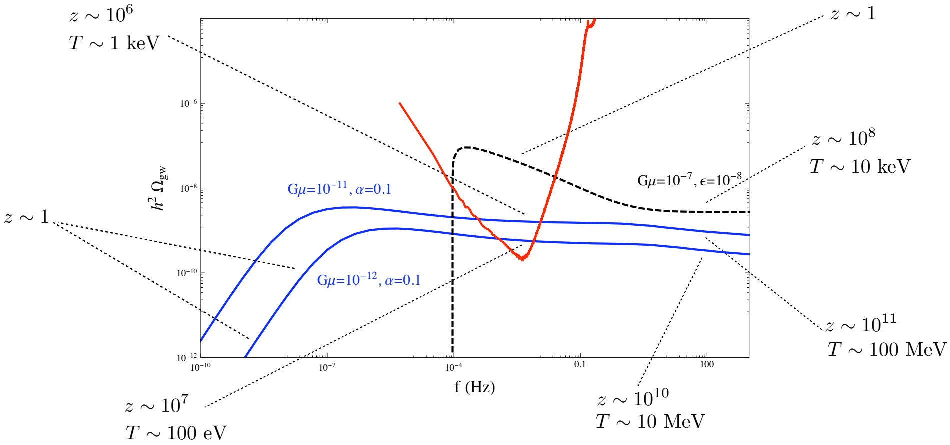
The bursts with amplitude $h(f,z,L) > h_b(f)$ "arrive separately" at a detector:

$$\int\int_{h(f,z,L)>h_b(f)} \frac{d\dot{N}}{dzdL}(f,z,L)\, dz\, dL = f$$

Spectrum of GW background from the superposition of many bursts:

$$\Omega_{gw}(f) \propto \frac{f}{H_0^2} \int\int_{\begin{cases} h(f,z,L) < h_b(f) \\ Lf(1+z) > 2 \end{cases}} \frac{d\dot{N}}{dzdL}(f,z,L)\, h^2(f,z,L)\, dz\, dL$$

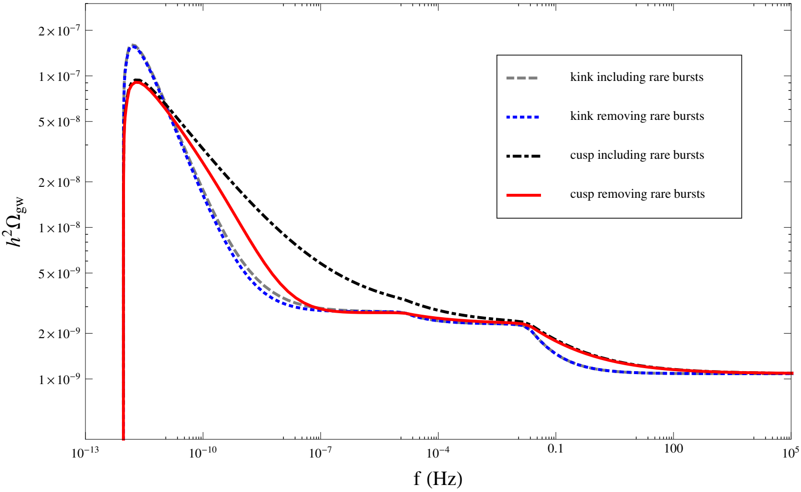
Typical Shape of the GW Spectrum



Dependence on the Spectrum Emitted by Individual Loops

Present-day GW spectra for short-lived loops

$(\alpha = \Gamma G\mu,\ G\mu = 10^{-7},\ p = 1)$



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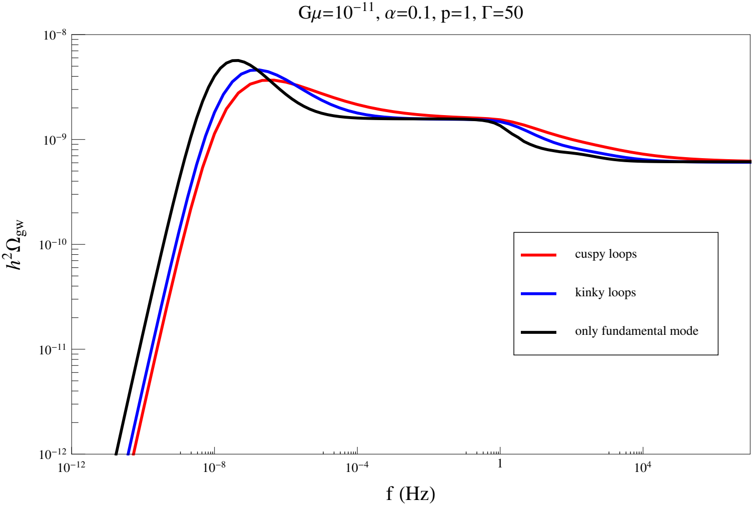
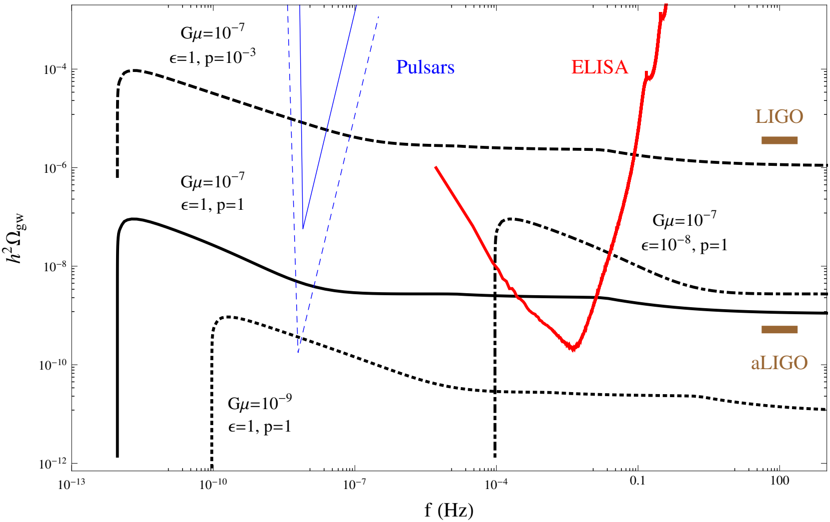
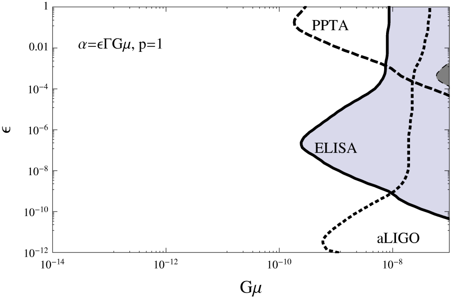
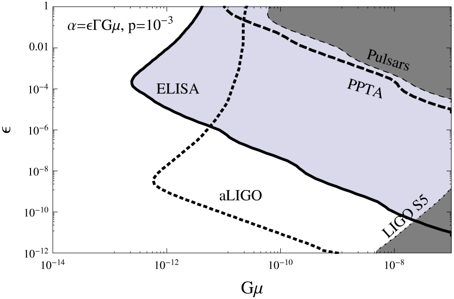


Comparison with Observations for Short-Lived Loops

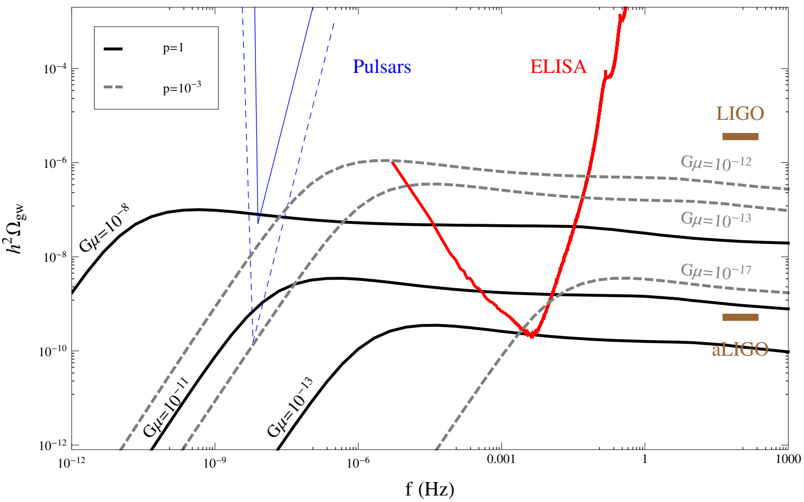


Accessible Regions in Parameter Space for Short-Lived Loops





Comparison with Observations for Long-Lived Loops



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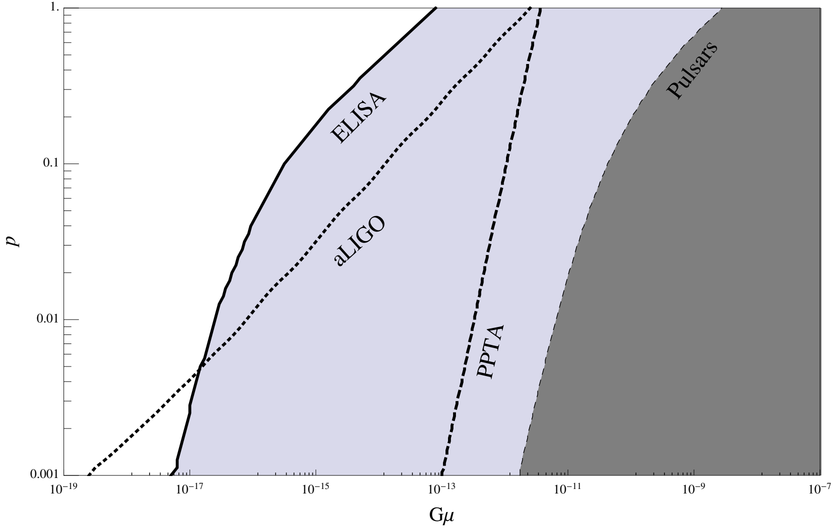
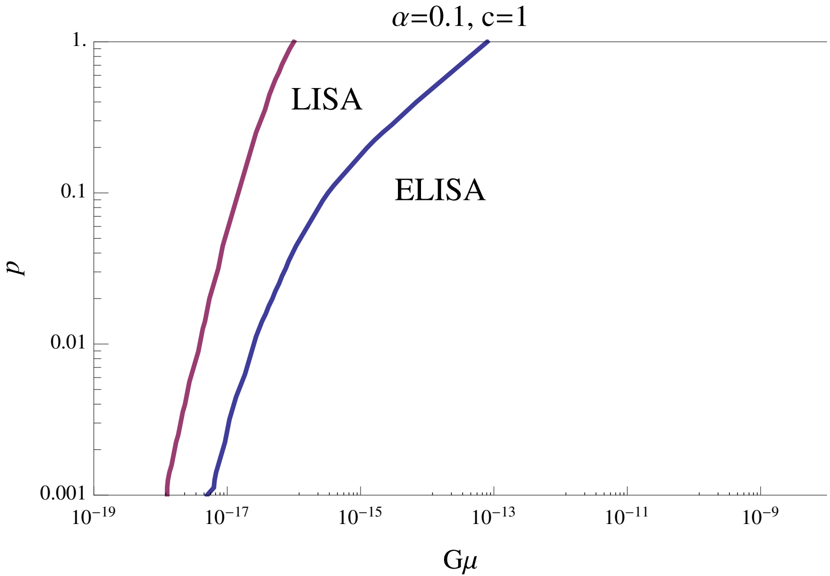


GW Background from Cosmic Strings: Conclusion

- The results are relatively **independent** of the particular spectrum emitted by each individual loop
- The **frequency dependence** of the GW background is well determined
- Significant regions of the parameter space are accessible **simultaneously** by different experiments $\Rightarrow$ **Distinctive feature**
- **eLISA** is able to probe new regions of parameter space
- For **cosmic super-strings** produced in the simplest models of brane inflation ($10^{-13} \lesssim G\mu \lesssim 10^{-7}$), most of the parameter space is accessible
- Observations of the GW background from cosmic strings would also provide informations about the **thermal history of the early universe**

Comparison of eLISA and LISA for Long-Lived Loops



Kaluza-Klein Modes from Cosmic Super-Strings

Tension of Cosmic Super-Strings

Depends on energy scale at which cosmic strings form in early universe

- In models of brane inflation with CMB anisotropies generated from the inflaton's quantum fluctuations:

  $$10^{-13} \lesssim G\mu \lesssim 10^{-6}$$

  May be looked for through their gravitational effects, in particular with upcoming GW experiments

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- Cosmic super-strings can also be produced in models of brane inflation at lower energy, see e.g. **[Kofman, Mukohyama '08]**.

  Or at Hagedorn phase transitions after inflation, **[Polchinski '04], ...**

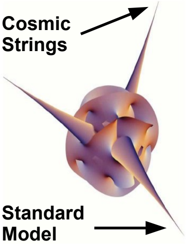
  In these cases:

$$10^{-34} \lesssim G\mu \lesssim 10^{-13}$$

  The gravitational effects of light cosmic strings are much weaker

$\Rightarrow$ **How to look for light cosmic super-strings??**

Particle Production by Cosmic Super-Strings??



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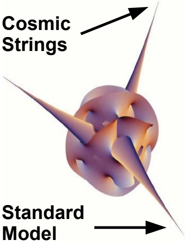


Stable cosmic super-strings are decoupled from other degrees of freedom, in particular from the Standard Model fields

But always couple to 10-D metric $\Rightarrow$ massless 4-D graviton + KK modes

$$\frac{g_s^{-x}}{2\pi\sqrt{\alpha'}} \int d\tau d\sigma \sqrt{-\gamma} \quad \text{with} \quad \gamma_{\alpha\beta} = g_{AB}\,\partial_\alpha X^A\,\partial_\beta X^B$$

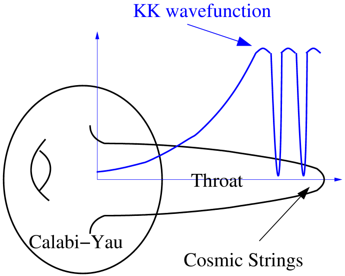
$$ds_{10}^2 = g_{AB}\,dx^A\,dx^B = e^{2A(y)}\,g_{\mu\nu}^{(4)}\,dx^\mu\,dx^\nu + \hat{g}_{ab}(y)\,dy^a\,dy^b$$

Consider spin-2 KK modes:

$$g_{\mu\nu}^{(4)} = \eta_{\mu\nu} + \sum_{\bar{n}} \Phi_{\bar{n}}(y)\,h_{\mu\nu}^{\bar{n}}(x) \quad \text{with} \quad \partial^\mu h_{\mu\nu}^{\bar{n}}(x) = \eta^{\mu\nu} h_{\mu\nu}^{\bar{n}}(x) = 0$$

Cosmic Super-Strings and Kaluza-Klein (KK) Modes

2 ways to make string tension μ small enough to satisfy observational bounds



Warped throat:

$$ds_{10}^2 = e^{-2A(y)}\,\eta_{\mu\nu}\,dx^\mu\,dx^\nu + g_{ab}(y)\,dy^a\,dy^b$$

$\Rightarrow \quad G\mu \propto e^{-2A_b} \ll 1$

KK mass: $m \sim e^{-A_b}/R < \sqrt{\mu}$ (R: curvature)

KK coupling to strings: $\propto \sqrt{G}\,e^{A_b} \gg \sqrt{G}$

Flat internal space with large volume:

d large extra dimensions with size $R \gg \sqrt{\alpha'}$

$\Rightarrow \quad G\mu \propto (\sqrt{\alpha'}/R)^d \ll 1 \qquad$ ($\sqrt{\alpha'}$: fundamental string length)

KK mode coupling to cosmic strings: $\propto \sqrt{G}$ only

BUT: dense spectrum of very light modes, $m \sim 1/R \ll \sqrt{\mu}$

KK Production by Loops

Production of spin-2 KK modes with mode numbers $\bar{n}$:

$$\left(\Box_4 + m_{\bar{n}}^2\right)\, h^{\bar{n}}_{\mu\nu}(x) = -\,\frac{\lambda_{\bar{n}}}{\sqrt{\mu}}\, T^{\mathrm{TT}}_{\mu\nu}(x) \qquad (m_{\bar{n}} \neq 0)$$

$$E_{\bar{n}} = \frac{\lambda_{\bar{n}}^2}{2\mu} \int \frac{d^3\mathbf{k}}{(2\pi)^3} \left(T^{\mu\nu}(\omega_k, \mathbf{k})\, T^{*}_{\mu\nu}(\omega_k, \mathbf{k}) - \frac{1}{3}\, |T^{\lambda}_{\lambda}(\omega_k, \mathbf{k})|^2 \right)$$

$$T_{\mu\nu}(\omega_k, \mathbf{k}) = \int d^4x\, T_{\mu\nu}(t, \mathbf{x})\, e^{ik_\lambda x^\lambda} \quad , \quad k^\lambda = (\omega_k, \mathbf{k}) \quad , \quad \omega_k = \sqrt{k^2 + m_{\bar{n}}^2}$$

$L \gg 1/m_{\bar{n}} \quad \Rightarrow \quad k_\lambda x^\lambda \gg 1 \quad \Rightarrow$ **stationary phase approximation**

KK Production by Loops

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$$T_{\mu\nu}(\omega_k, \mathbf{k}) = \int d^4x\, T_{\mu\nu}(t, \mathbf{x})\, e^{ik_\lambda x^\lambda} \quad , \quad k^\lambda = (\omega_k, \mathbf{k}) \quad , \quad \omega_k = \sqrt{k^2 + m_{\bar{n}}^2}$$

$L \gg 1/m_{\bar{n}} \quad \Rightarrow \quad k_\lambda x^\lambda \gg 1 \quad \Rightarrow$ **stationary phase approximation**

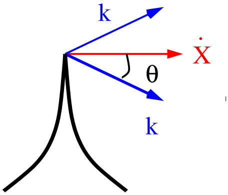
General solution for Nambu-Goto loop: $\mathbf{X}(t, \sigma) = \frac{1}{2}\left[\mathbf{X}_+(\sigma_+) + \mathbf{X}_-(\sigma_-)\right]$

with $X^0 = t$, $\sigma_\pm = t \pm \sigma$ and $|\mathbf{X}_+{}'| = |\mathbf{X}_-{}'| = 1$

$$k^\lambda X'_{\pm\,\lambda} = \sqrt{|\mathbf{k}|^2 + m_{\bar{n}}^2} - |\mathbf{k}| \cos\left(\hat{\mathbf{k}}, \mathbf{X}_\pm{}'\right) \approx 0$$

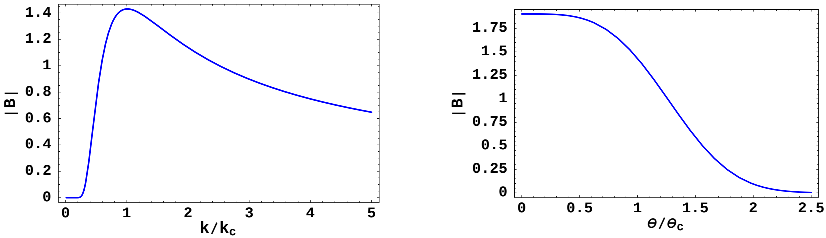
$\mathbf{X}_+{}' \parallel \mathbf{X}_-{}' \quad \Rightarrow \quad |\dot{\mathbf{X}}| = 1$: **cusp**

$\left(\hat{\mathbf{k}}, \mathbf{X}_\pm{}'\right) = \theta \ll 1$ and $m_{\bar{n}} \ll |\mathbf{k}|$



KK Emission from Cusps

Spectrum and angular distrib. of $dE_{\bar{n}}/d^3\mathbf{k}$ $\quad (k_c = m_{\bar{n}}\sqrt{m_{\bar{n}} L},\ \theta_c = (m_{\bar{n}} L)^{-1/2})$



Nambu-Goto description valid for $m_{\bar{n}} < \sqrt{\mu} \;\Rightarrow\; E_{KK} = \sum_{\bar{n}}^{m_{\bar{n}} < \sqrt{\mu}} E_{\bar{n}}$

Power emitted ($N_c \sim 1$ cusp per loop oscillation period):

$$\frac{dE_{KK}}{dt} = \Gamma_{KK} \frac{\mu^{3/4}}{\sqrt{L}} \quad \text{with} \quad \Gamma_{KK} \approx 10\, N_c\, g_s^{2-5x/4} \sim 1$$

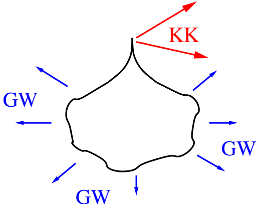
(g_s: string coupling ; $x = 0$ for F-strings and $x = 1$ for D-strings)

$dE_{gw}/dt = \Gamma\, G\mu^2$: **KK emission dominates for small loops or light strings**

Cosmological Consequences of KK Emission

Depend on loop number density, which is modified by KK emission

KK emission (in addition to GW)
$\Rightarrow$ loop lifetime decreases
$\Rightarrow$ loop number density decreases



Note: KK modes are light $\Rightarrow$ also produced in early universe
$\Rightarrow$ must decay mostly and relatively quickly in Standard Model fields
See e.g. reheating after brane inflation **[JFD, Kofman, Peloso '08]**

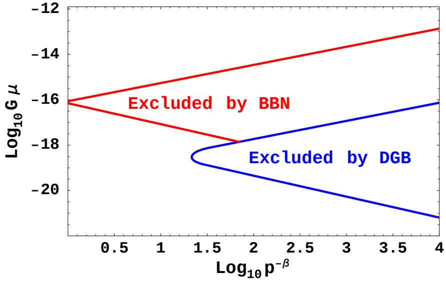
KK modes from cusps decay at "recent" epochs $\Rightarrow$ **observational constraints**

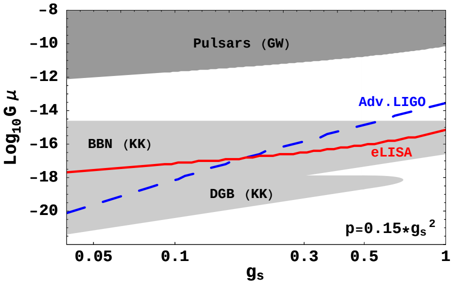
KK energy converted into photon background by electromagnetic cascade

- $\Rightarrow$ Diffuse gamma-ray background (EGRET, Fermi-LAT)
- $\Rightarrow$ Photo-dissociation of light elements (BBN abundances)

Constraints from BBN and diffuse gamma-ray background (DGB)

Constraints from KK emission for $L_i \sim 0.1\,t$ and $\Gamma_{KK} = 1 \longrightarrow$





Constraints from KK emission Vs. GW reach for F-strings in Klebanov-Strassler throat

Reconnection probability from **[Jackson, Jones, Polchinski '04]**

KK spectrum from **[JFD, Kofman, Peloso '08]**

KK Modes from Cosmic Super-Strings: Conclusion

Cosmic super-strings couple generically to tower of light (compared to $\sqrt{\mu}$), hence cosmologically relevant, KK modes

- They are produced by cusps, in a way largely **independent of compactification details**
- This leads to **constraints on cosmic super-strings that are complementary to the ones that can be obtained with GW experiments**
- KK modes are also expected to play an important role in early, **friction-dominated epoch** of cosmic super-string evolution
- KK emission **modifies loop number density**, mainly at early times or for small tensions $\Rightarrow$ Other cosmological consequences??
- Production of **other KK modes and string states**??
- **Other cosmological consequences of KK emission**, e.g. production of cosmic rays or dangerous relics??