Gravitational Waves from Low-Scale Cosmic Strings

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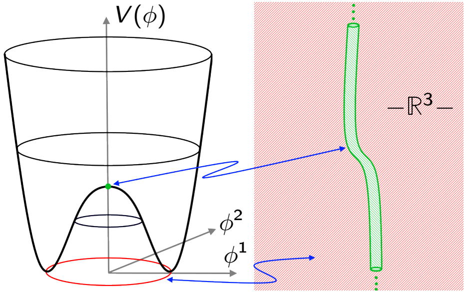
Cosmic Strings

- Consider spontaneous symmetry breaking in the early universe
- If $\pi_1(\mathcal{M}) \ncong \{\mathbb{1}\}$ (e.g. $U(1) \to \mathbb{1}$):
  Tube-like regions in space occur in which transition is topologically forbidden

Cosmic String from $U(1)$-symmetry breaking



- Cosmic strings: 1D field-configuration in which symmetry is unbroken, vacuum is not assumed
- String tension (energy per unit length): $G\mu = GE/l \propto \eta^2 > 10^{-34}$
- String width $\delta \propto \frac{1}{\eta} < 10^{-3} r_{\mathrm{Proton}}$

Network Evolution

- Interested in dynamics on scales $\gg \delta \rightarrow$ neglect internal structure and approximate strings as 1D
- Dynamics of string described by Nambu-Goto action $\Rightarrow$ Only free parameter: string tension $G\mu$
- String network chops off loops that decay via gravitational radiation

Radiating String Loop [Daniel Dominguez (CERN)]

- Loops oscillate with discrete frequencies $f_j = \frac{2j}{l}$
- $\Omega(f) = \sum_j \Omega^{(j)}(f)$ with $\Omega^{(j)}(f) = p_j \Omega^{(1)}\left(\frac{f}{j}\right)$
- Henceforth, focus on fundamental frequency $f = \frac{2}{l}$
- Total power $P = \Gamma G\mu^2$ and $E = \mu l$
- Loops shrink due to GWs: $l(t) = l(t_0) - \Gamma G\mu(t - t_0)$

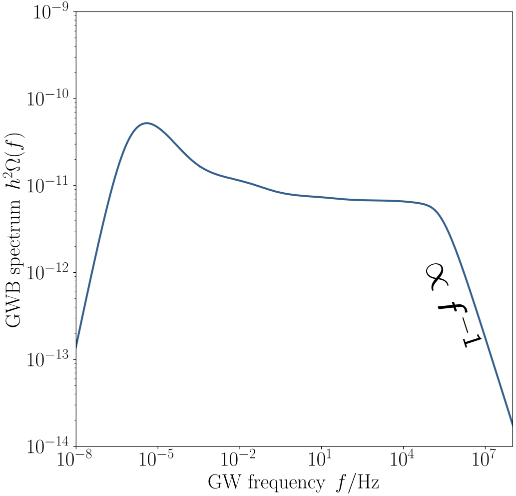
Existence of a Maximum Frequency

- Distribution of production length of string loops at given time sharply peaked around fixed fraction of $H^{-1} \propto t \implies$ At given time t, loops are produced with single length $l_*(t) = 2\alpha t$, with $\alpha \simeq 0.05$
- Smallest loops produced at earliest times $l_{\mathrm{ini}} \equiv l_*(t_{\mathrm{ini}}) = 2\alpha t_{\mathrm{ini}}$
- Length of those shortest strings today $l_{\mathrm{min}} = l_{\mathrm{ini}} - \Gamma G\mu\,(t_0 - t_{\mathrm{ini}})$
- If strings have not decayed until today $l_{\mathrm{min}} > 0$, then there exists maximum frequency in spectrum

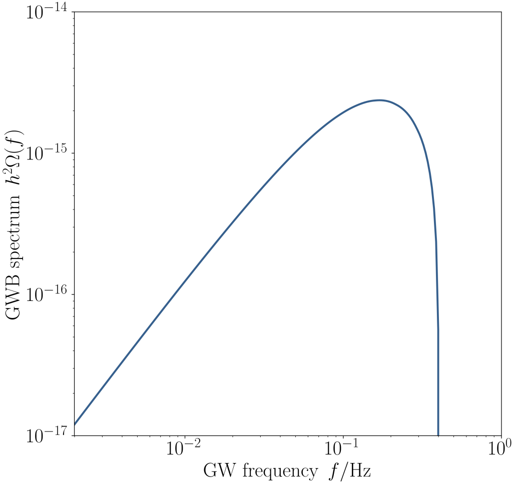
$$f_{\mathrm{cut}} = \frac{2}{l_{\mathrm{min}}} \simeq \frac{2}{l_{\mathrm{ini}} - \Gamma G\mu t_0}. \tag{1}$$

Existence of a Maximum Frequency

Standard fundamental spectrum
without cutoff frequency:



Fundamental spectrum
with cutoff frequency:



Existence of a Maximum Frequency

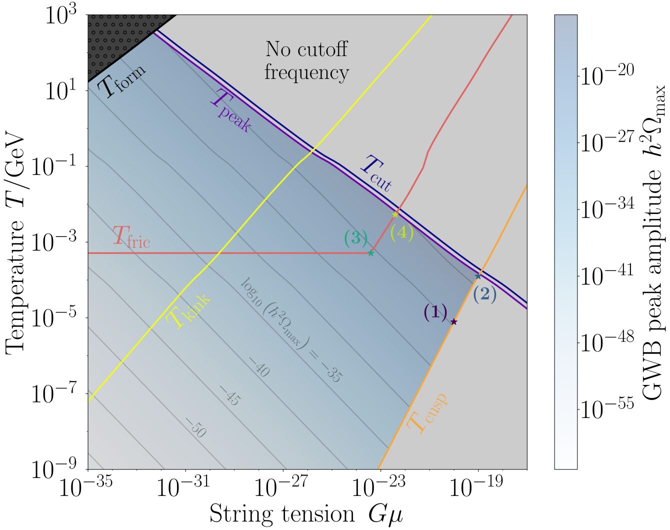
- Distribution of production length of string loops at given time sharply peaked around fixed fraction of $H^{-1} \propto t \implies$ At given time t, loops are produced with single length $l_*(t) = 2\alpha t$, with $\alpha \simeq 0.05$
- Smallest loops produced at earliest times $l_{\rm ini} \equiv l_*(t_{\rm ini}) = 2\alpha t_{\rm ini}$
- Length of those shortest strings today $l_{\rm min} = l_{\rm ini} - \Gamma G\mu\,(t_0 - t_{\rm ini})$
- If strings have not decayed until today $l_{\rm min} > 0$, then there exists maximum frequency in spectrum

$$f_{\rm cut} = \frac{2}{l_{\rm min}} \simeq \frac{2}{l_{\rm ini} - \Gamma G\mu t_0}. \tag{1}$$

- This is the case for large values of $l_{\rm ini}$ and low $G\mu$.
- Rephrase in terms of temperature: Maximum in spectrum if $l_{\rm ini} = \alpha t_{\rm ini} > \Gamma G\mu t_0$ or equivalently

$$T_{\rm ini} < T_{\rm cut} = \sqrt{\frac{\alpha}{\Gamma G\mu}\frac{M_*}{2t_0}} \overset{g_*=100}{\simeq} 3.33 \times 10^{-4}\mathrm{GeV}\sqrt{\frac{10^{-20}}{G\mu}} \tag{2}$$

Parameter Space



Parameter Space - Formation, Friction and Particle Radiation Cutoffs

- String loops can only start oscillating after string network **formation** at $\mu = \sqrt{\rho_c}$

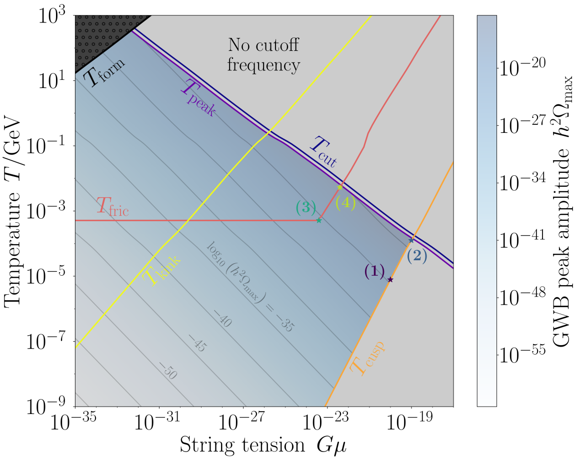
$$T_{\text{ini}} \leq T_{\text{form}} \tag{3}$$

- **Thermal friction** strongly dampens string motion, suppresses GW emission $\Rightarrow$ Thermal friction needs to be subdominant

$$T_{\text{ini}} \leq T_{\text{fric}} \tag{4}$$

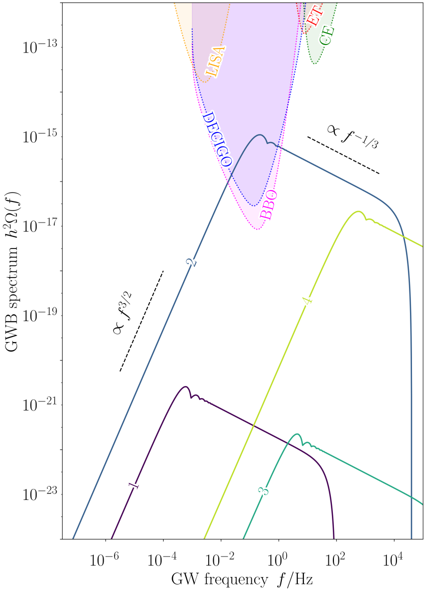
- Strings can also decay via **particle radiation**: Dominant for small loops $\Rightarrow$ Need to consider large enough loops

$$T_{\text{ini}} \leq T_{\text{rad}} \tag{5}$$

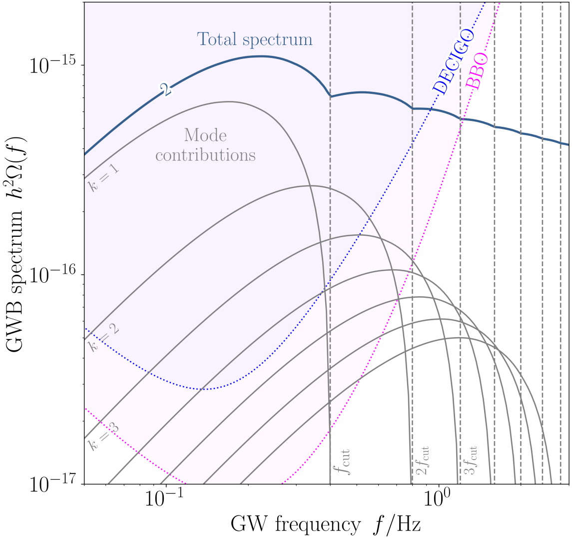


- Full (numerically computed) spectra including contributions from 10^5 modes
- Despite low tensions: GWs **measurable in future experiments**
- Spectra qualitatively different from standard case, in particular, **oscillatory feature around peak**

№	$\log_{10}(G\mu)$	$\log_{10}(T_{\rm ini}/\mathrm{GeV})$
1	-20	-5.107
2	-19	-3.903
3	-23.4	-3.292
4	-22.4	-2.277



Benchmark Scenario 2 - $G\mu = 10^{-19}$, $T_{\rm ini} = 1.250 \times 10^{-4}\,\mathrm{GeV}$

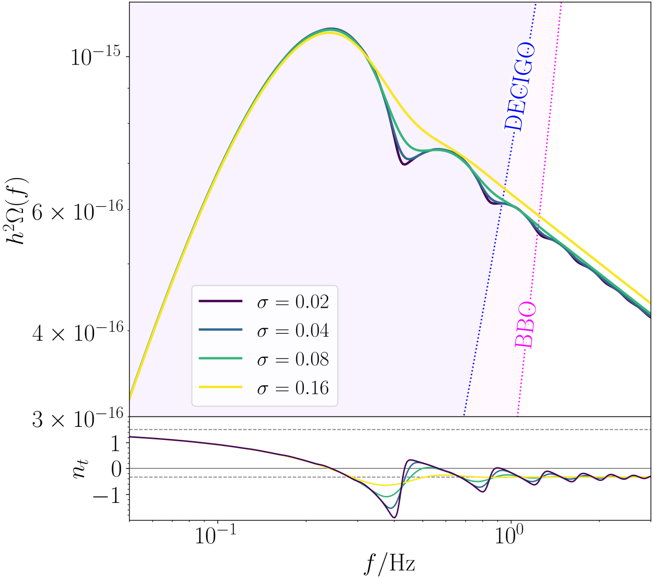


- $\Omega(f) = \sum_j \Omega^{(j)}(f)$
- $\Omega^{(j)}(f) = p_j \Omega^{(1)}\left(\frac{f}{j}\right)$
- "Dip frequencies" $f_n = n f_{\rm cut}, \; n \in \mathbb{N}$
- E.g. in Benchmark scenario $f_{\rm cut} \simeq 0.4\mathrm{Hz}$

Conclusion

- Found new feature of GW spectrum from cosmic strings arising for **small** $G\mu$ **and** $T_{\rm ini}$ because none of the strings loops have fully decayed yet
- Distinct feature in GW spectrum: **Oscillatory shape of spectrum** with dips at multiples of frequency of first dip.

Backup Slides


$h^2\Omega(f)$
10^{-15}
6×10^{-16}
4×10^{-16}
3×10^{-16}
DECIGO
BBO
$\sigma = 0.02$
$\sigma = 0.04$
$\sigma = 0.08$
$\sigma = 0.16$
n_t
1
0
-1
10^{-1}
10^{0}
$f\,/\mathrm{Hz}$