Gravitational wave emission from a global string loop

Jorge Baeza-Ballesteros

In collaboration with E. Copeland, D. G. Figueroa and J. Lizarraga
Based on arXiv/2308.08456

IFIC, University of Valencia-CSIC

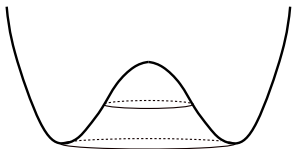First Nordic Cosmology Meeting - 25th October 2023

Cosmic strings in the early universe

Cosmic strings are **one-dimensional topological defects**

Cosmic strings in the early universe

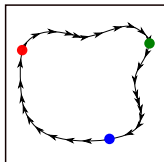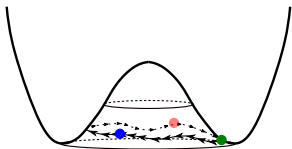Cosmic strings are **one-dimensional topological defects**

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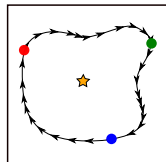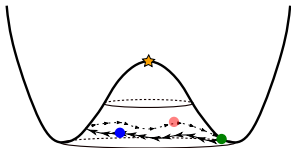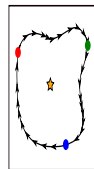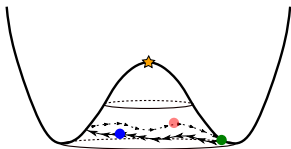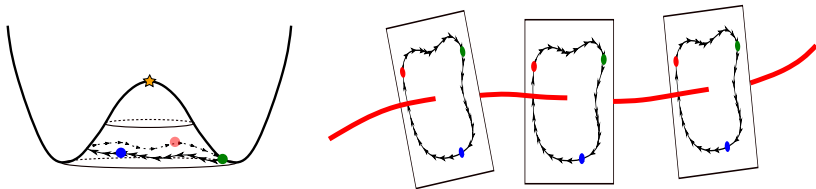
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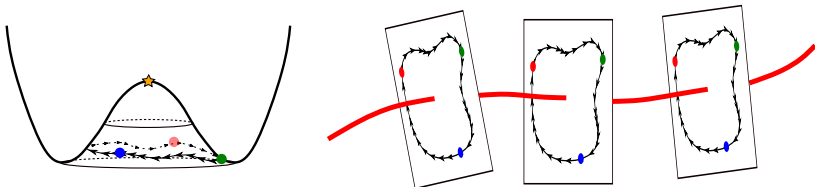
Detection: CMB, gravitational wave (GW) background...

Cosmic strings in the early universe

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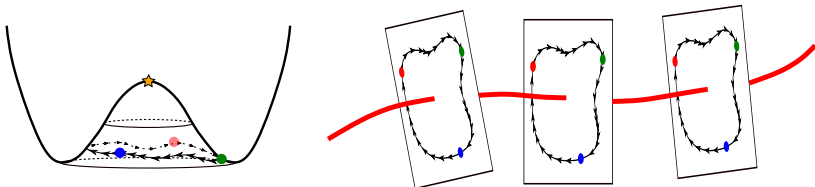Generated in **early-universe phase transitions** (e.g., **axion strings**)

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Need to constrain the GW signature from cosmic strings

The Nambu-Goto approximation

Traditional picture $\longrightarrow$ **Nambu-Goto approximation** (zero width)

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▶ String networks = Infinite strings + Loops
  ↳ Decay to GWs
  ↳ Decay to loops and GWs

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                                           $\rightarrow$ Decay to GWs

▶ String networks = Infinite strings + Loops

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▶ Loops decay via GWs radiated in all harmonic frequencies $\nu_j = j/T$, with $T = L_{\text{str}}/2$

$$P_j = \Gamma G \mu^2 \frac{j^{-q}}{\zeta(q)} \quad \longrightarrow \quad P_{\text{GW}} = \dot{E}_{\text{GW}} = \sum_{j=1}^{\infty} P_j = \Gamma G \mu^2$$

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Field-theory strings can also decay via **particle emission**

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Goal: Particle and GW emission using lattice simulations

Global string loops in flat spacetime

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$$V(\varphi) = \lambda \left(|\varphi|^2 - \frac{v^2}{2} \right)^2 \quad \longrightarrow$$

Massive ($m = \sqrt{2\lambda}v$)
and massless radiation
Global strings ($r_c \sim m^{-1}$)

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Lattice simulations with $\mathcal{C}$osmo$\mathcal{L}$attice [Figueroa et al, 2020, 2021]
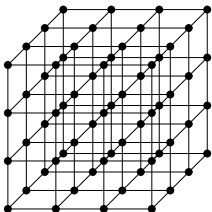
$$\equiv \quad \frac{L}{\delta x}$$

Dimensionless variables:
$$\tilde{x} = \sqrt{\lambda}v\, x$$
$$\tilde{t} = \sqrt{\lambda}v\, t$$
$$\tilde{\varphi} = \varphi/v$$

Initial conditions

We consider **two types of loops**:

Network loops
(from decay of networks)

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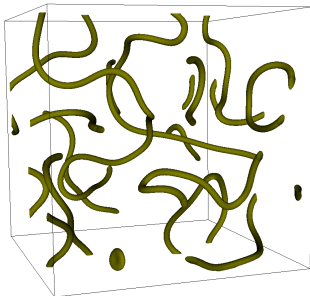
Network loops
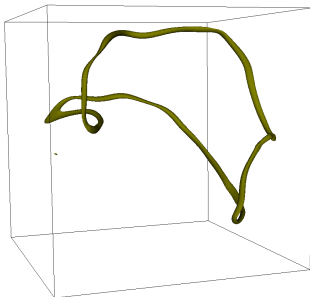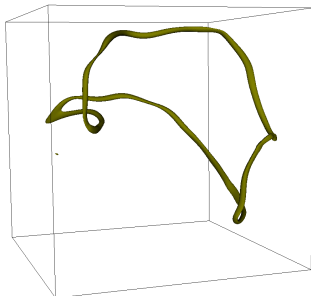(from decay of networks)

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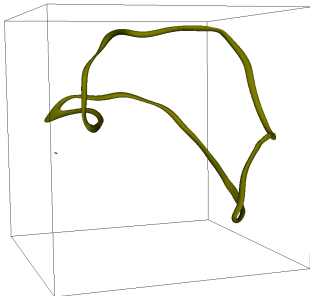(from decay of networks)

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<div align="center">

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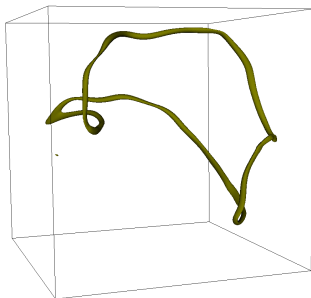(from decay of networks)

Artificial loops
(from intersection of strings)

</div>

Random initial conditions

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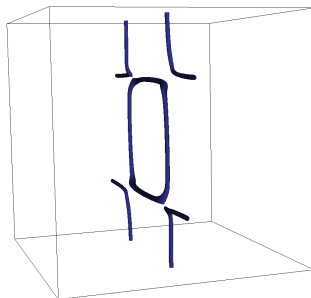
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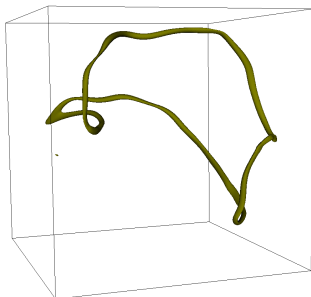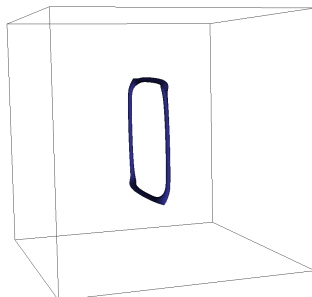(from intersection of strings)

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Control over initial conditions

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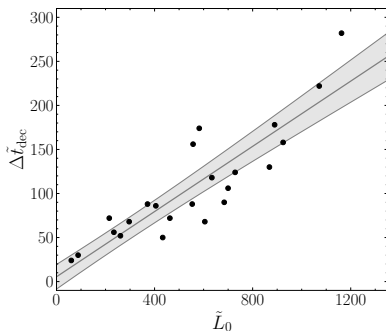

Random initial conditions

Control over initial conditions

Loop decay time

Decay time vs **initial length** ($L_0 \lesssim 1700 r_c$) $\longrightarrow$ linear relation
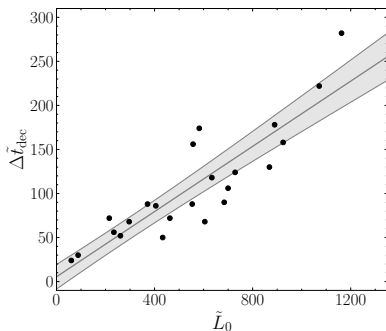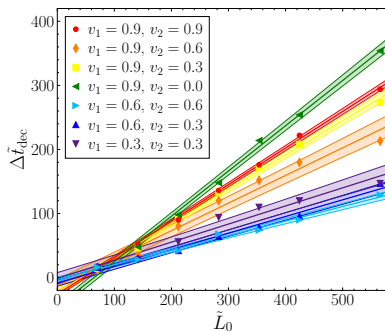

Network

Loop decay time

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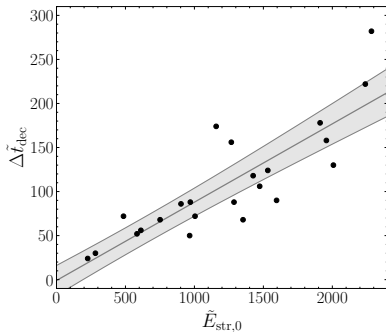
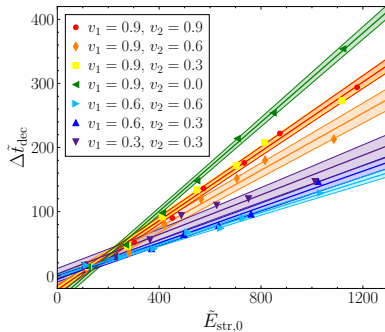**Network**

Artificial

Dependence on
initial conditions

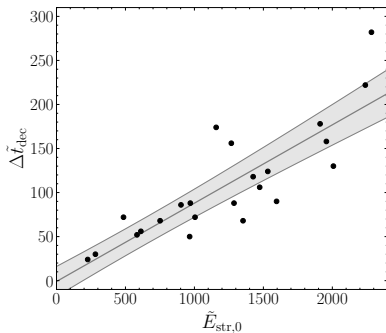# Loop decay time

Decay time vs **initial string energy** $\longrightarrow$ linear relation

Loop decay time

Decay time vs **initial string energy** $\longrightarrow$ linear relation

Network

Artificial
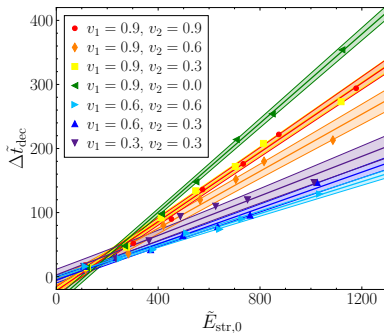
$$P_{\varphi} = -\frac{\mathrm{d}E_{\mathrm{str}}}{\mathrm{d}t} \approx (11.2 \pm 1.6)v^2 \qquad\qquad P_{\varphi} = -\frac{\mathrm{d}E_{\mathrm{str}}}{\mathrm{d}t} \approx (3-8)v^2$$

Loop decay time

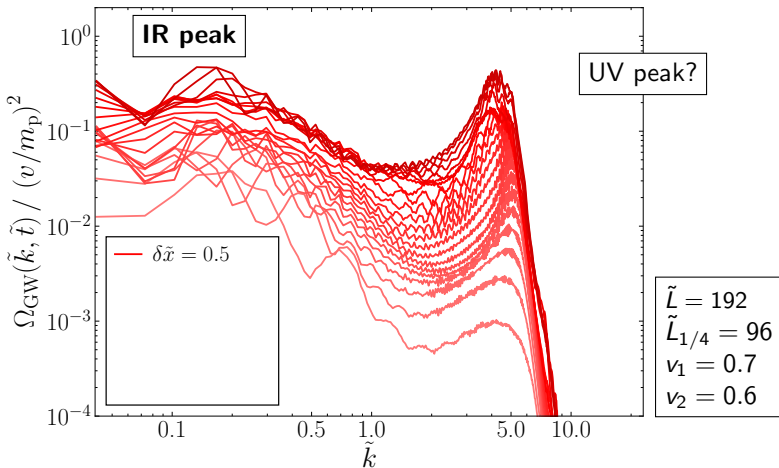Decay time vs **angular momentum** $\longrightarrow$ **universal scaling**

$$\vec{J} = -2 \int_{\text{str}} \mathrm{d}^3 x \, \mathrm{Re} \left[\vec{x} \times \dot{\varphi} \vec{\nabla} \varphi^* \right]$$

Distance to loop's
geometric center

Artificial

$v_1 = 0.9, \, v_2 = 0.9$
$v_1 = 0.9, \, v_2 = 0.6$
$v_1 = 0.9, \, v_2 = 0.3$
$v_1 = 0.9, \, v_2 = 0.0$
$v_1 = 0.6, \, v_2 = 0.6$
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$v_1 = 0.3, \, v_2 = 0.3$

$\Delta \tilde{t}_{\text{dec}}$

$\propto |\tilde{J}_0|^{3/5}$

$10^{-3} \times |\tilde{J}_0|$

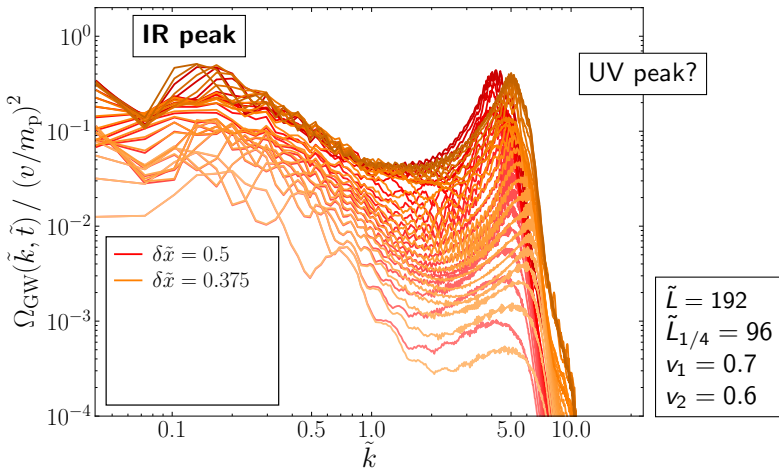# GW results: UV sensitivity of artificial loops

Fixed loop and lattice size + reduce lattice spacing

GW results: UV sensitivity of artificial loops

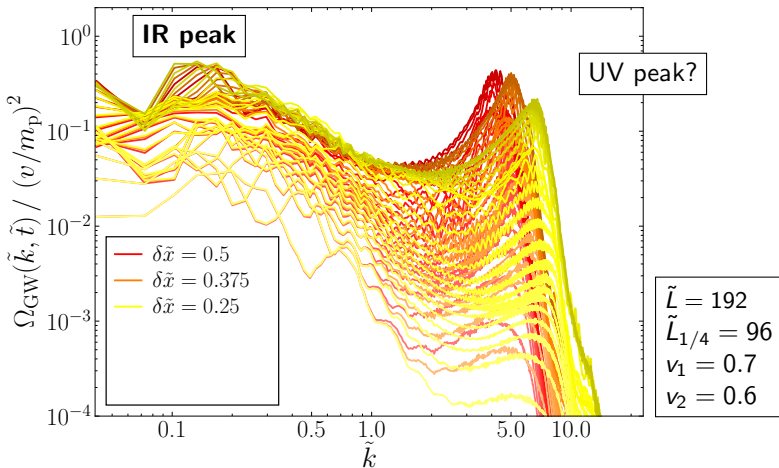Fixed loop and lattice size + reduce lattice spacing

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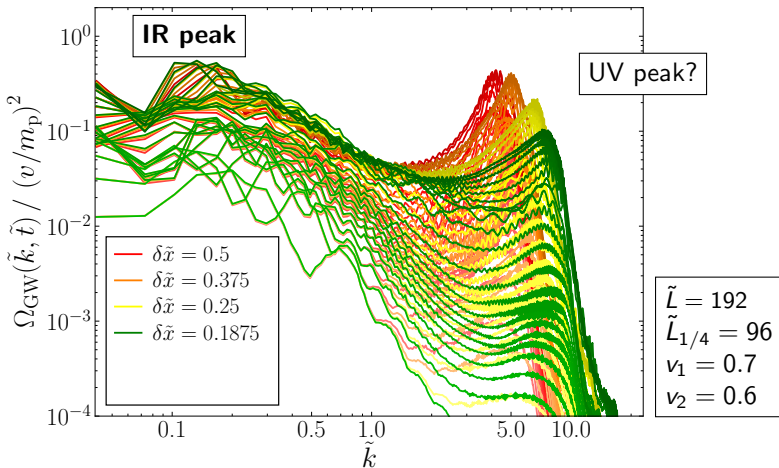Fixed loop and lattice size + reduce lattice spacing

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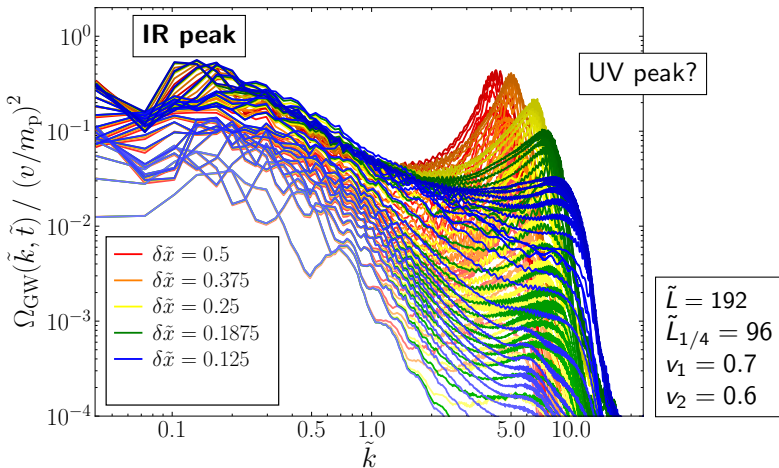Fixed loop and lattice size + reduce lattice spacing

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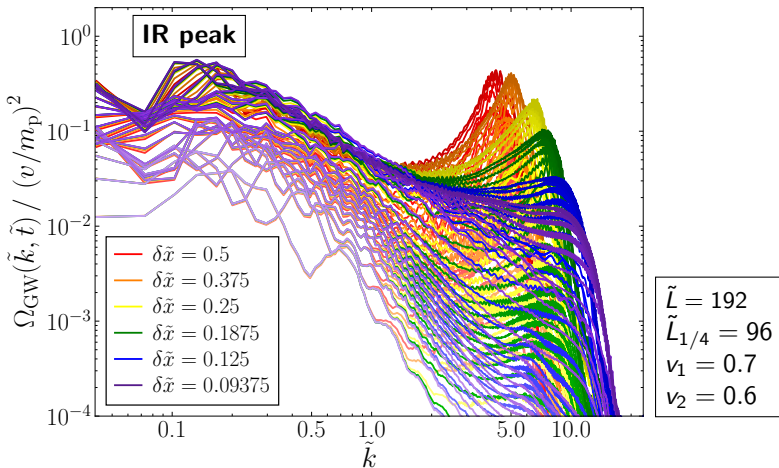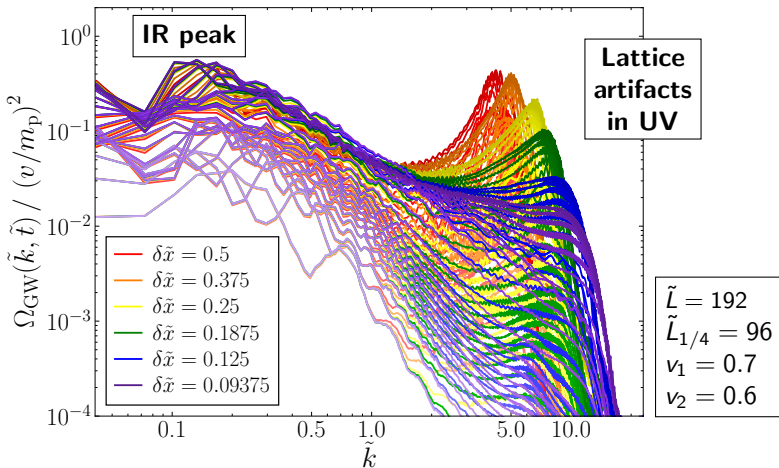Fixed loop and lattice size + reduce lattice spacing

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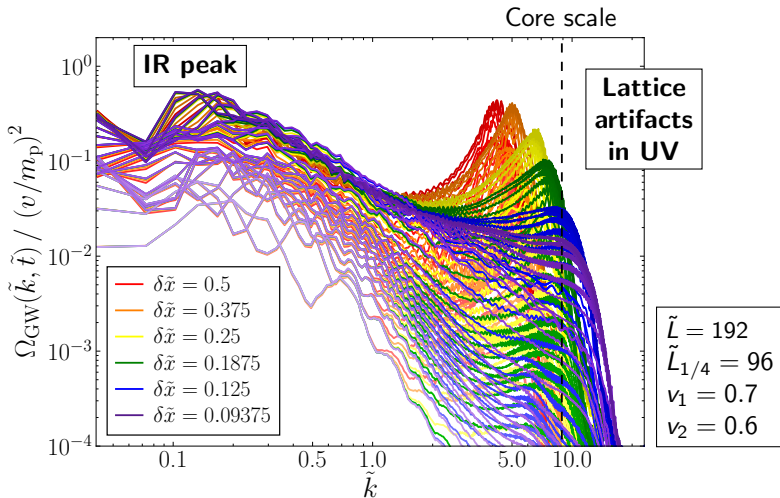
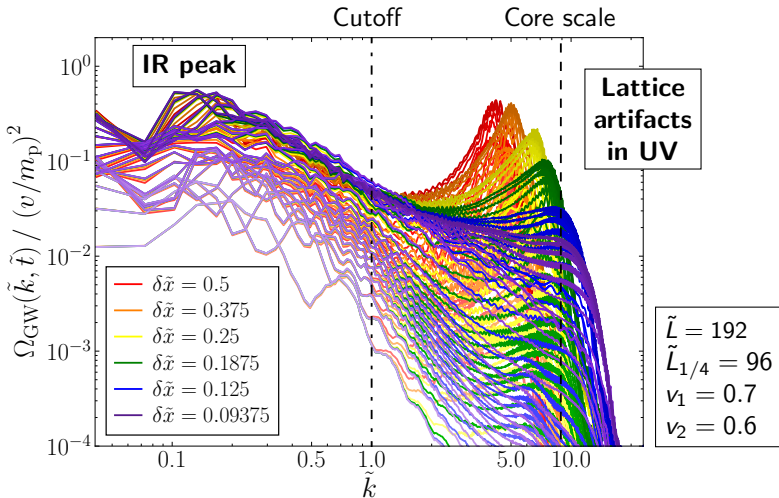Fixed loop and lattice size + reduce lattice spacing

GW results: UV sensitivity of artificial loops

Fixed loop and lattice size + reduce lattice spacing

GW results: UV sensitivity of artificial loops

Fixed loop and lattice size + reduce lattice spacing

Similar results for network loops

GW results: IR sensitivity of artificial loops

Fixed loop and lattice spacing + Increase box size

GW results: IR sensitivity of artificial loops

Fixed loop and lattice spacing + Increase box size

Loop length scale

$\tilde{L}_{1/4} = 96$
$\delta\tilde{x} = 0.25$
$v_1 = 0.7$
$v_2 = 0.6$

GW results: IR sensitivity of artificial loops

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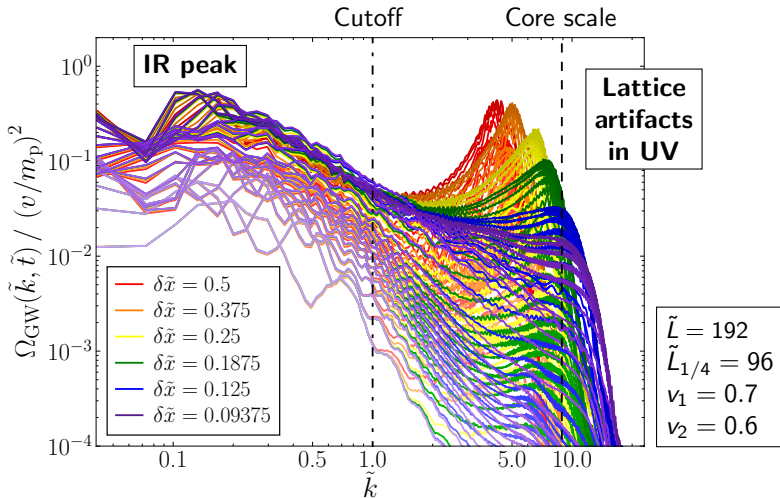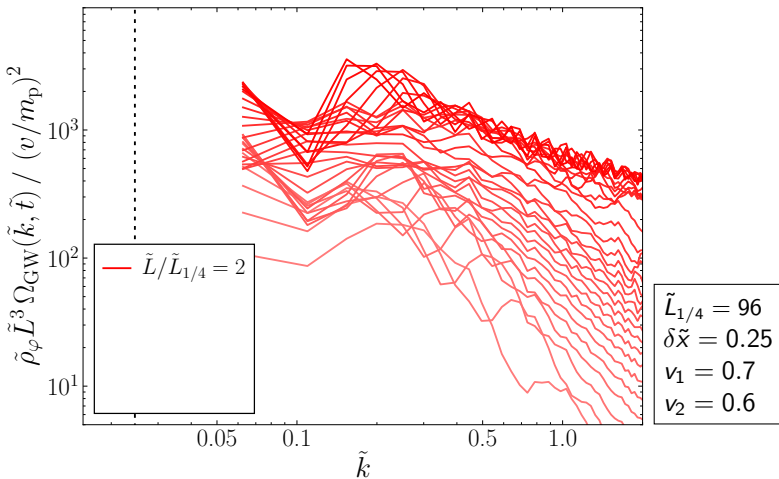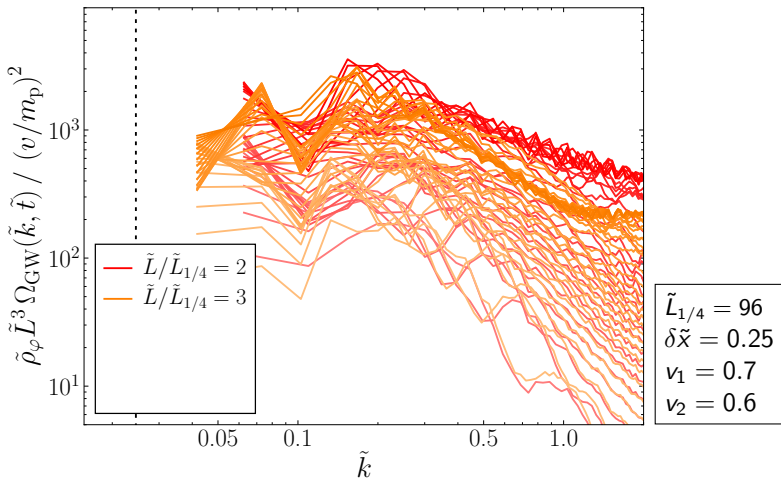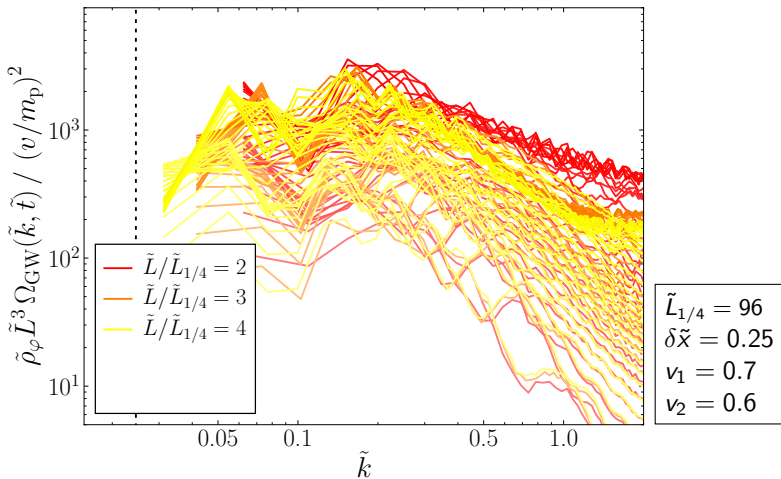
GW results: IR sensitivity of artificial loops

Fixed loop and lattice spacing + Increase box size

Loop length scale

Large effects for small L

$\tilde{\rho}_\varphi \tilde{L}^3 \Omega_{GW}(\tilde{k}, \tilde{t}) / (v/m_p)^2$

Legend:
- $\tilde{L}/\tilde{L}_{1/4} = 2$
- $\tilde{L}/\tilde{L}_{1/4} = 3$
- $\tilde{L}/\tilde{L}_{1/4} = 4$
- $\tilde{L}/\tilde{L}_{1/4} = 6$
- $\tilde{L}/\tilde{L}_{1/4} = 8$

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$\tilde{k}$
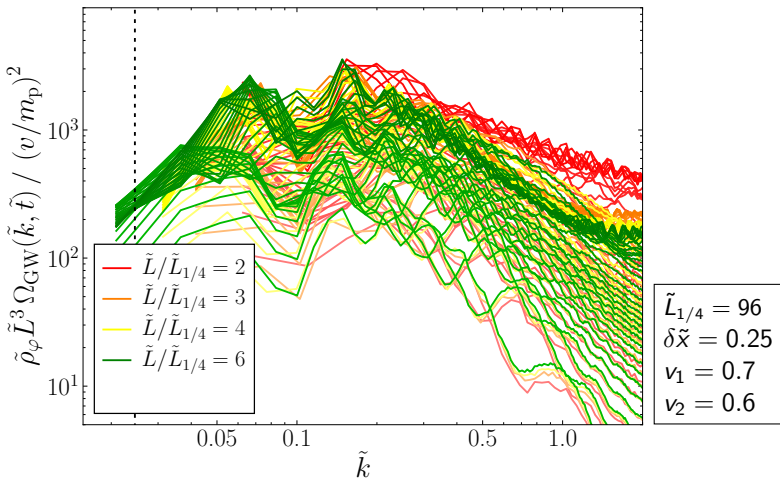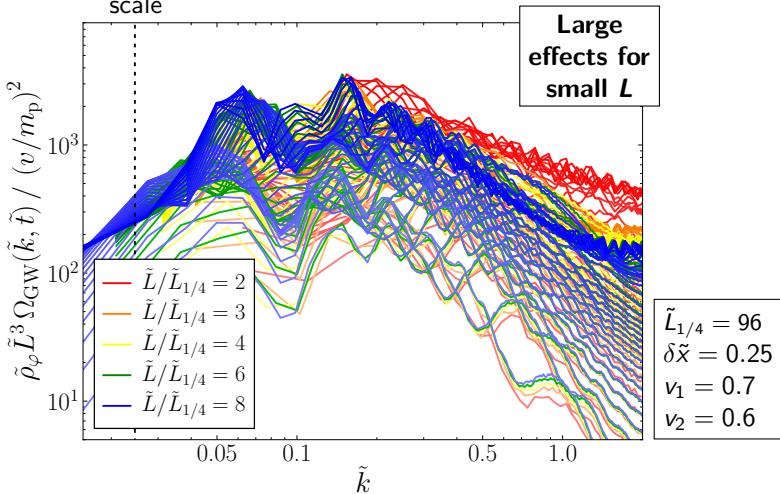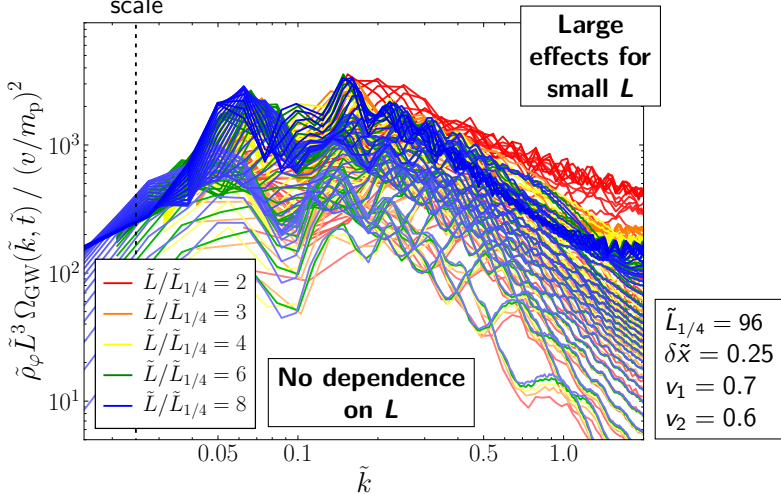
GW results: IR sensitivity of artificial loops

Fixed loop and lattice spacing + Increase box size

GW results: power spectrum of artificial loops

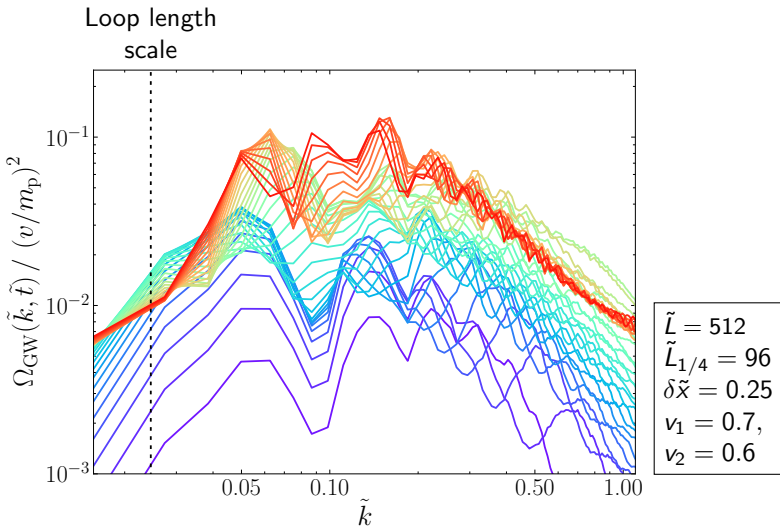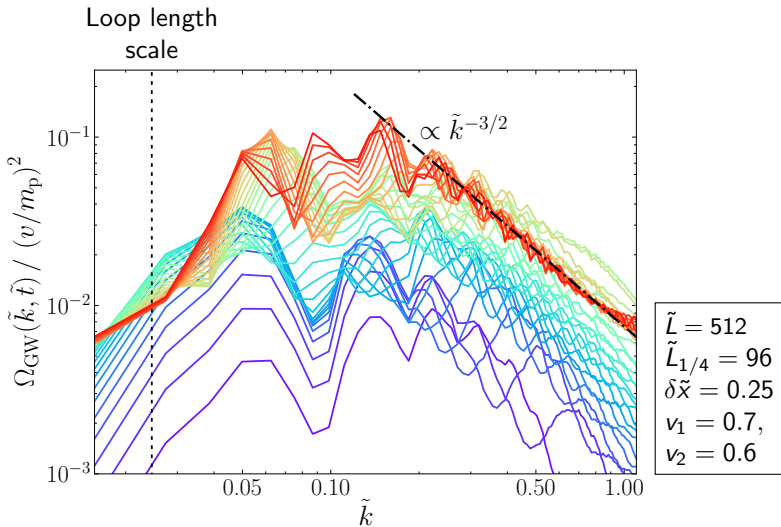Peaks at non harmonic frequencies + suppression at large scales

GW results: power spectrum of artificial loops

Peaks at non harmonic frequencies + suppression at large scales

GW results: radiation power

$$P_{\mathrm{GW}}(t) \equiv \frac{L^3 \rho_\varphi}{2T} \int_{t-T}^{t+T} \mathrm{d}t' \frac{\mathrm{d}}{\mathrm{d}t'} \int_0^{k_{\mathsf{cut}}} \Omega_{\mathrm{GW}}(k, t') \, \mathrm{d}\log k$$

GW results: radiation power

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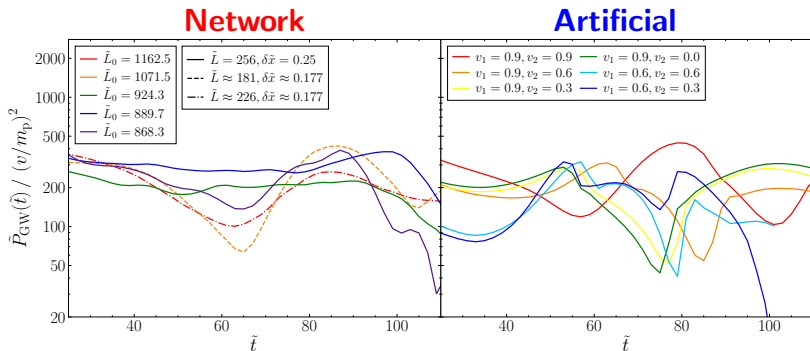
No dependence on string length

GW results: radiation power

Network

Artificial
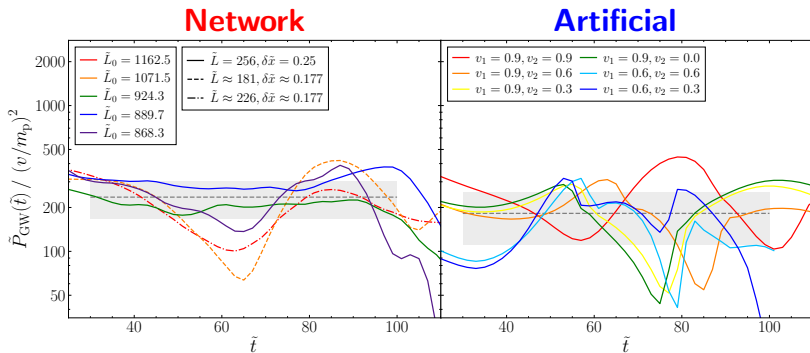
$$P_{\mathrm{GW}} = (240 \pm 80) v^2 (v/m_{\mathrm{p}})^2 \qquad P_{\mathrm{GW}} = (190 \pm 80) v^2 (v/m_{\mathrm{p}})^2$$

GW results: radiation power

Network

$$P_{\mathrm{GW}} = (240 \pm 80)v^2(v/m_{\mathrm{p}})^2$$

Artificial

$$P_{\mathrm{GW}} = (190 \pm 80)v^2(v/m_{\mathrm{p}})^2$$

$$\frac{P_{\mathrm{GW}}}{P_{\varphi}} \approx \mathcal{O}(10)\left(\frac{v}{m_{\mathrm{p}}}\right)^2, \quad v/m_{\mathrm{p}} \lesssim 10^{-6} - 10^{-3}$$

[Hindmarsh et al. (2019), Benabou et al. (2023)]

Summary and outlook

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**Outlook**: local strings, GWs from networks

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Outlook: local strings, GWs from networks

Thank you for your attention!

Time-evolution of the string length
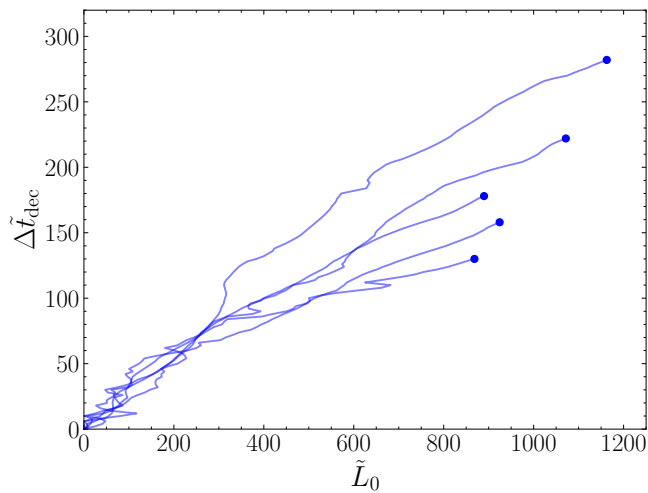
Fixed loop and lattice size + reduce lattice spacing

Coarse graining