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The Stochastic Gravitational Wave Background from Cosmic Strings

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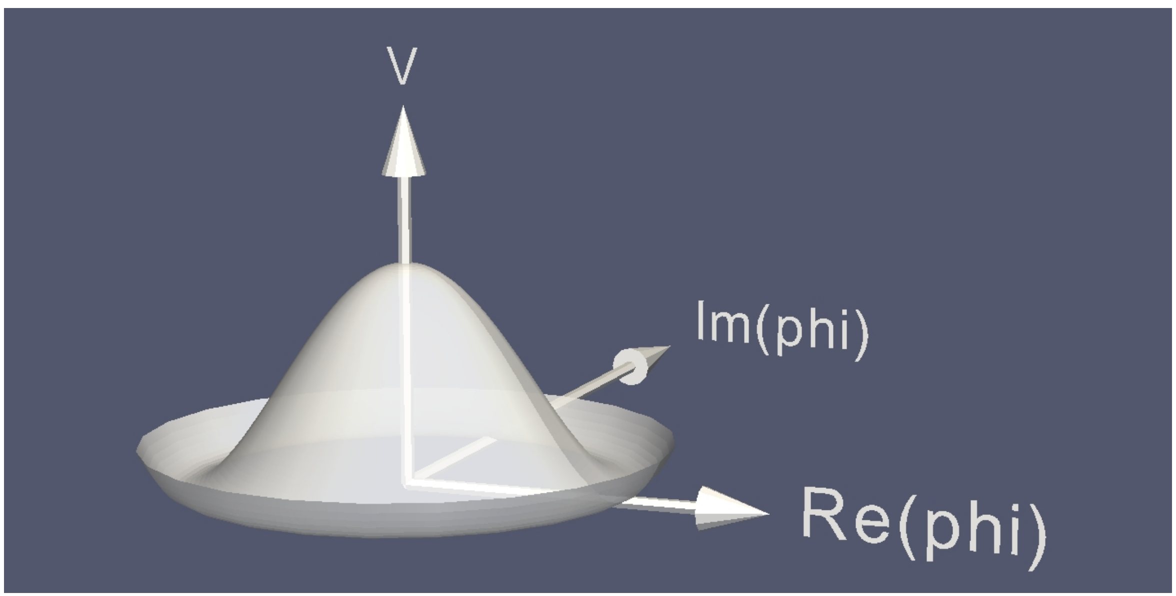
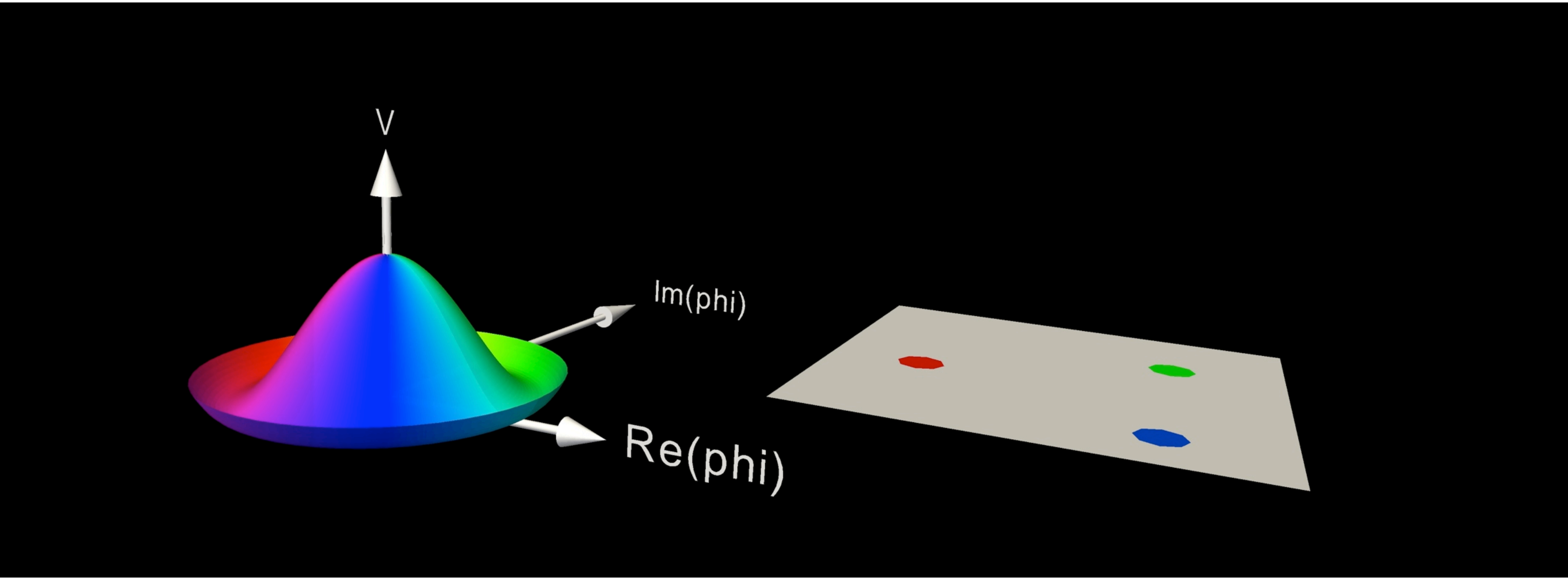
What is a cosmic string?

- Simplest model: Abelian Higgs model.

$$S_{AH} = \int d^4x \left[|D_\mu \phi|^2 - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{\lambda}{4} \left(|\phi|^2 - \eta^2 \right)^2 \right]$$



(Kibble '76).



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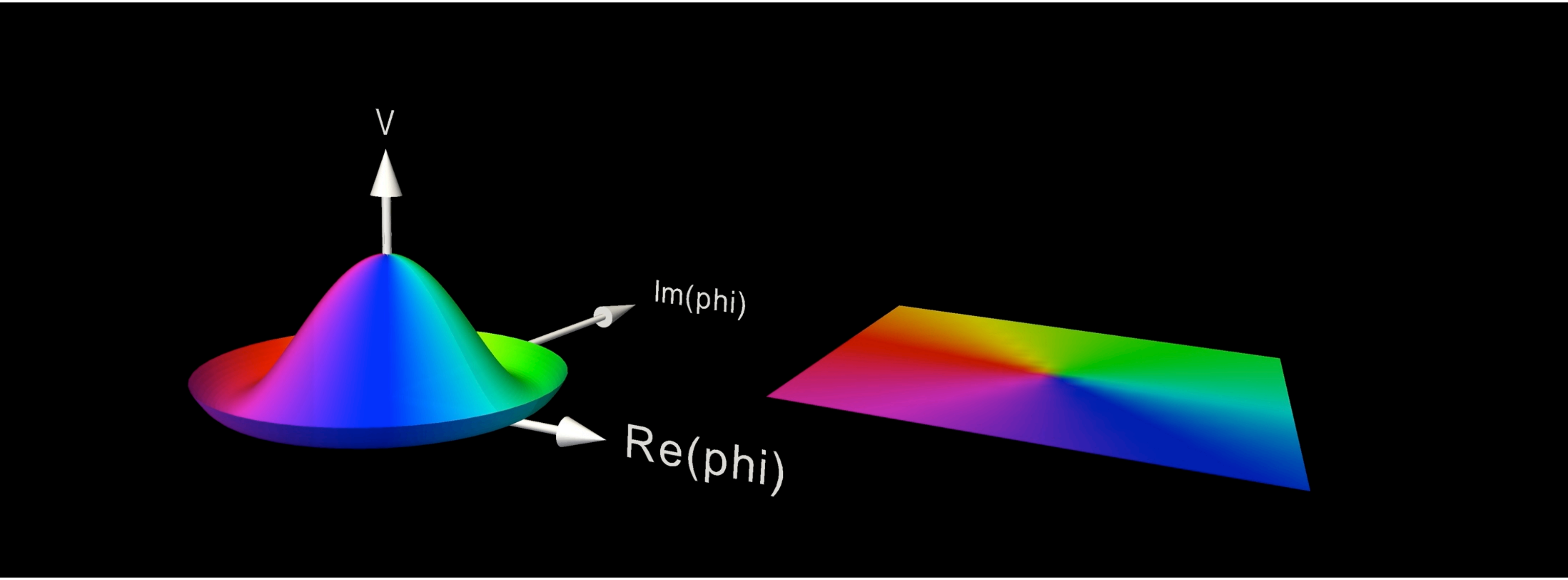

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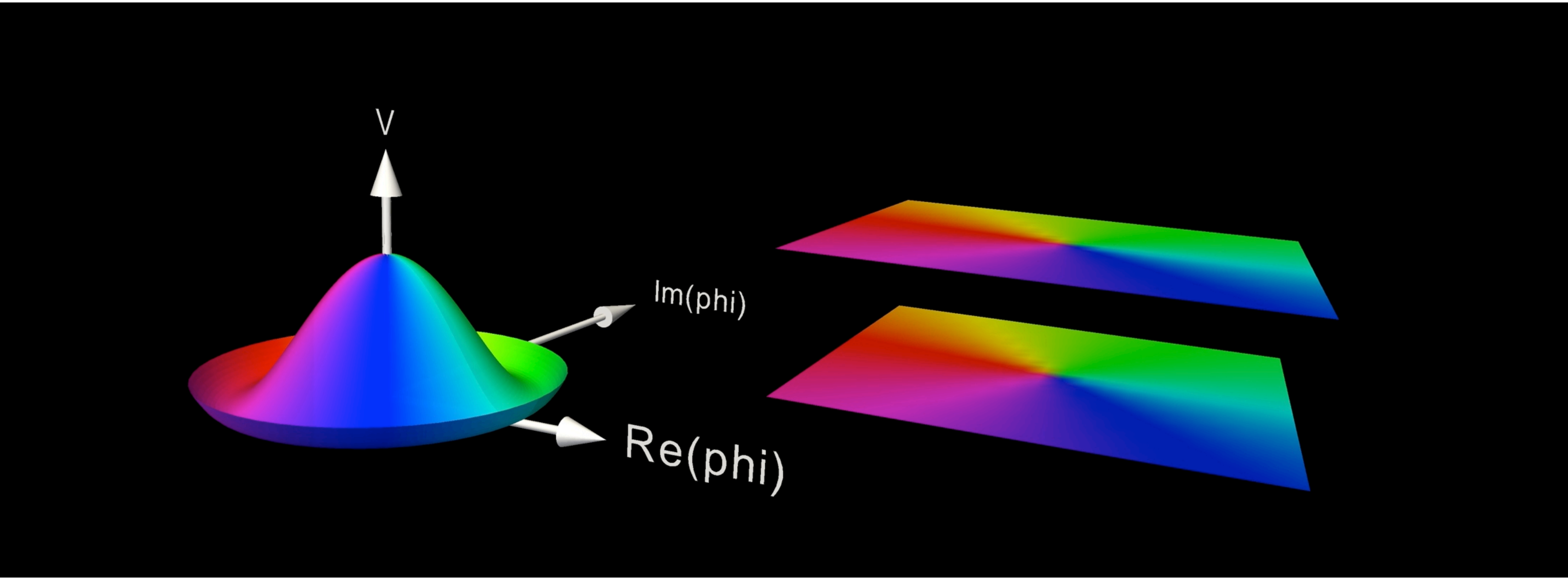

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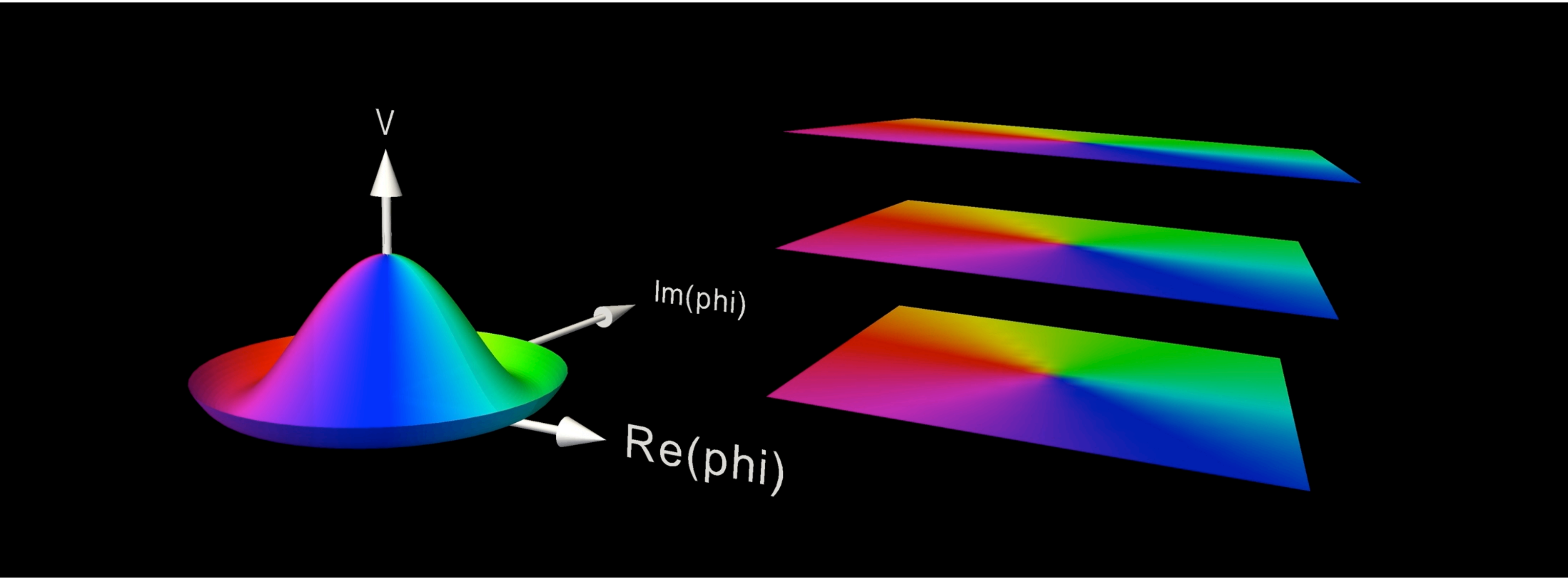

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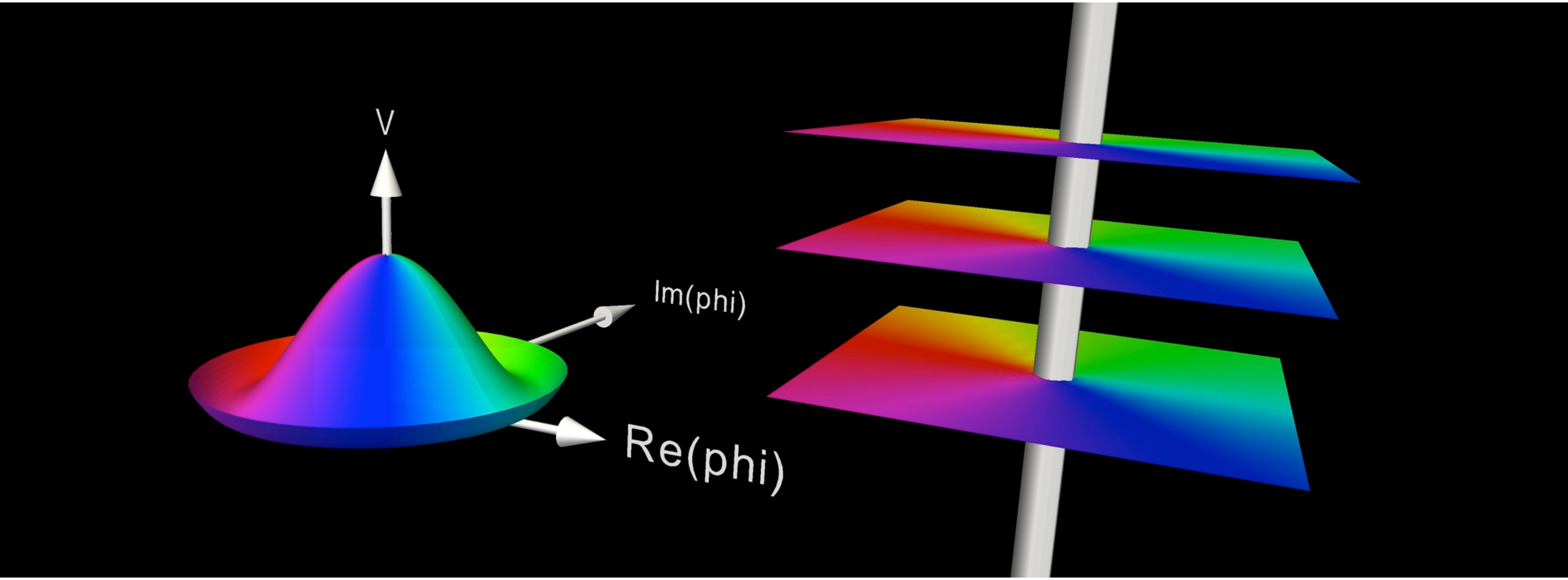


What is a cosmic string?

- Physical properties of the strings:
  - They are topological stable objects, they have no ends.
  - They have Tension = Energy density per unit length
  - They are not coupled to any massless mode, except gravity.

(This is the simplest version of strings that we will consider here)

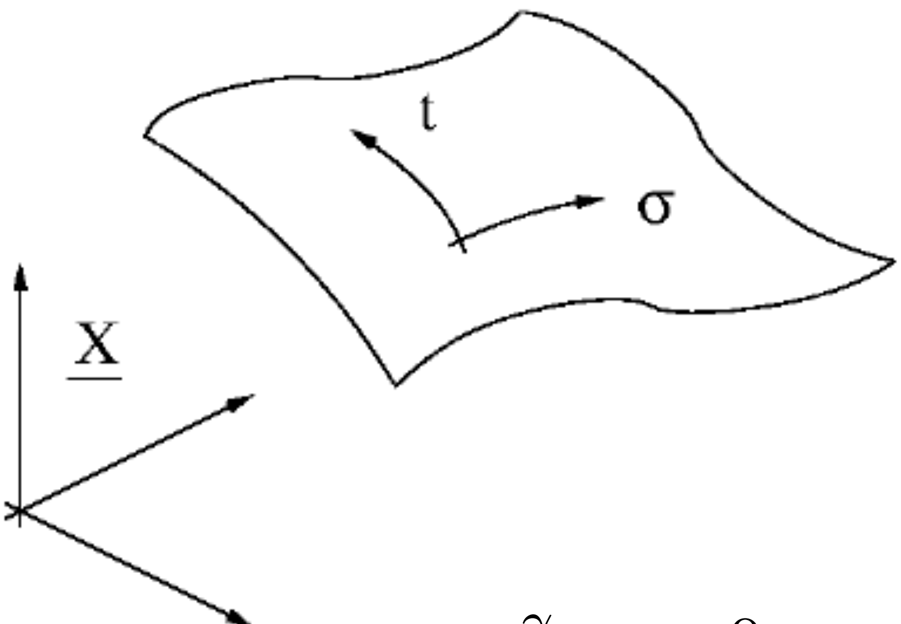
The String Scale

- Thickness, energy density and tension of the string are controlled by the symmetry breaking scale. η
- For a Grand Unified Theory scale: $\eta \approx 10^{16}\mathrm{GeV}$
- Thickness: $\delta = 10^{-30}\mathrm{cm}$
- Linear mass density: $\mu = 10^{22}\mathrm{gr/cm}$
- Tension : $T = 10^{37} N$
- Gravitational effects depend on: $\boxed{G\mu = \left(\frac{\eta}{M_{Pl}}\right)^2 \sim 10^{-6}}$

Cosmic String Dynamics

(Nambu,' 71; Goto '70).

- A relativistic string dynamics has an action of the form,



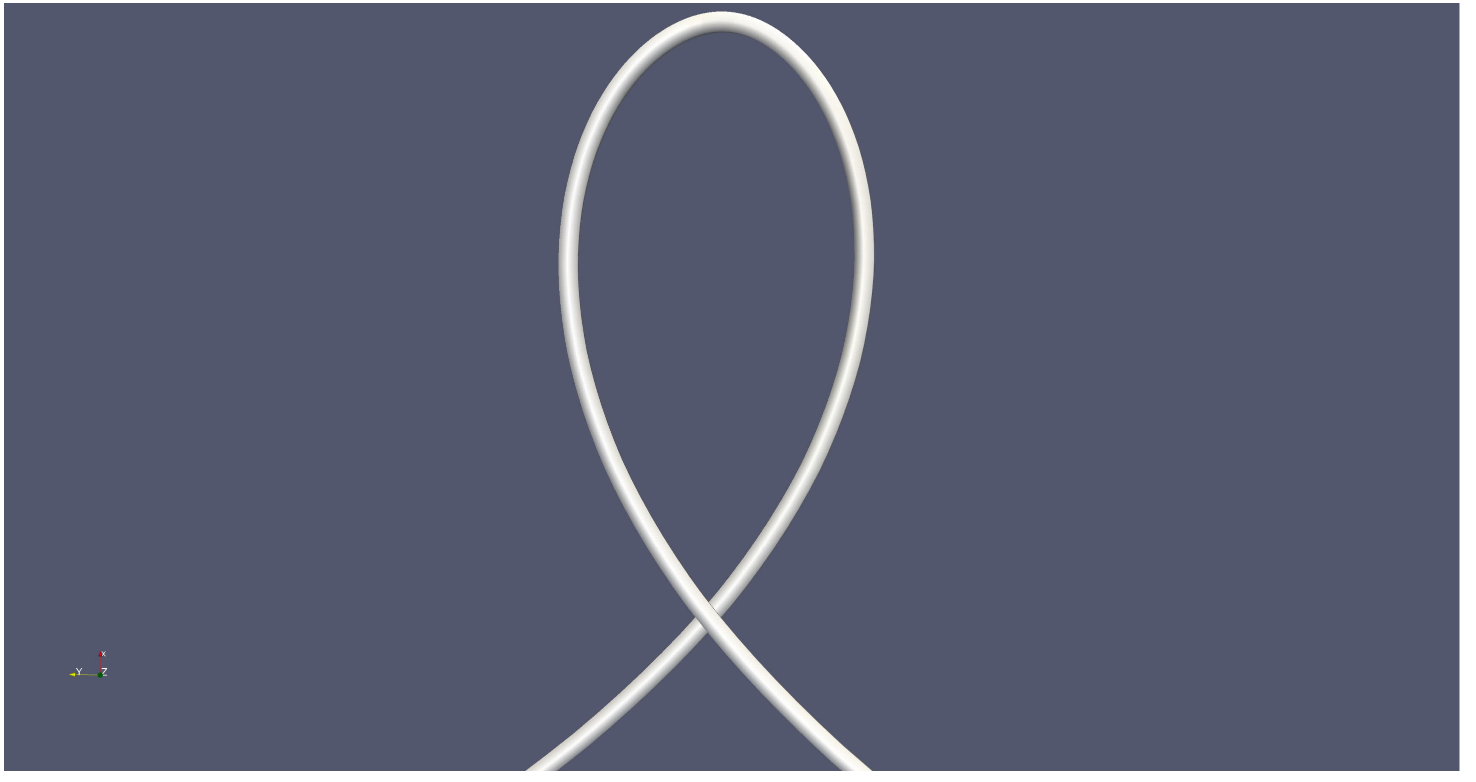
$$\boxed{S_{NG} = -\mu \int \sqrt{-\gamma}\; d^2\xi}$$

$$x^{\gamma}{}_{,\mathrm{uv}} = 0 \qquad\qquad x^{\gamma}(\mathrm{u},\mathrm{v}) = \frac{1}{2}\left[A^{\gamma}(\mathrm{v}) + B^{\gamma}(\mathrm{v})\right]$$

- This is a good approximation as long as the radius of curvature of the string is larger than its thickness.

Cosmic Loop Dynamics

- Strings can have intersections where they exchange partners.



- Once formed loops oscillate due to their tension.

Stochastic background of Gravitational Waves

- The whole network of strings contributes to the stochastic background of GW.

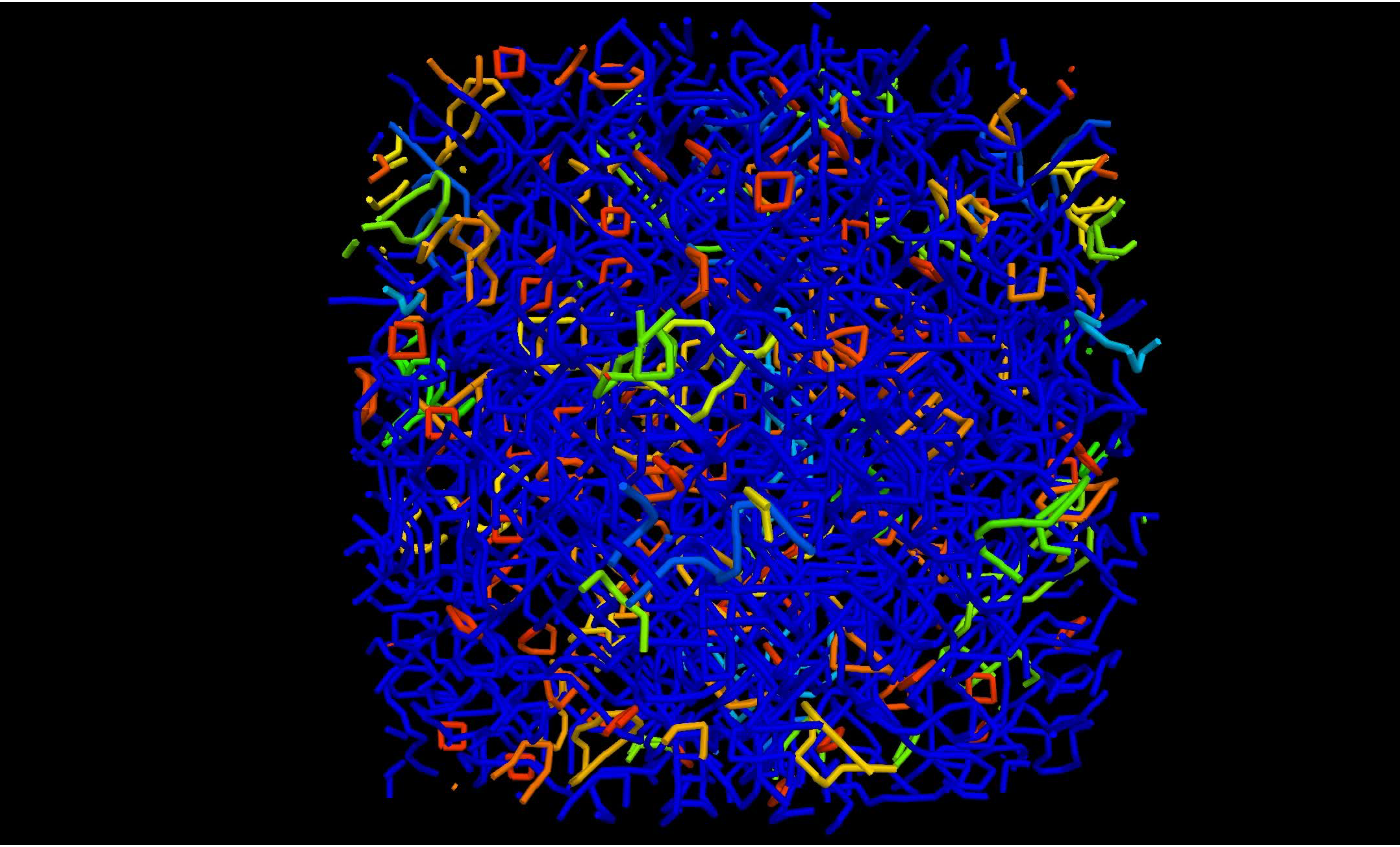
$$\boxed{\Omega_{gw}(\ln f) = \frac{8\pi G}{3H_o^2} f \int_0^{t_0} dt \left(\frac{a(t)}{a(t_0)}\right)^3 \int_0^{m_{max}} dm \; n(t,m) \left(\frac{dP}{df}\right)}$$

$n(t,m)$ ⟸ It depends directly on the number of loops.

$\left(\frac{dP}{df}\right)$ ⟸ It also depends on the spectrum of gw emission by the surviving loops.

Nambu-Goto Cosmic String Networks

(B-P., Olum and Shlaer '12).



The number of cosmic string loops

(B-P., Olum and Shlaer ‘13).

- We have been able to obtain from the simulations the scaling distribution of loops (See also Ringeval et al. ’05).

- This allows us to calculate the loop distribution of sizes at any moment in the history of the universe:

$$\boxed{\frac{n_r(t,l)}{a^3(t)} \approx \frac{0.18}{t^{3/2}(l+\Gamma\mu t)^{5/2}}}$$

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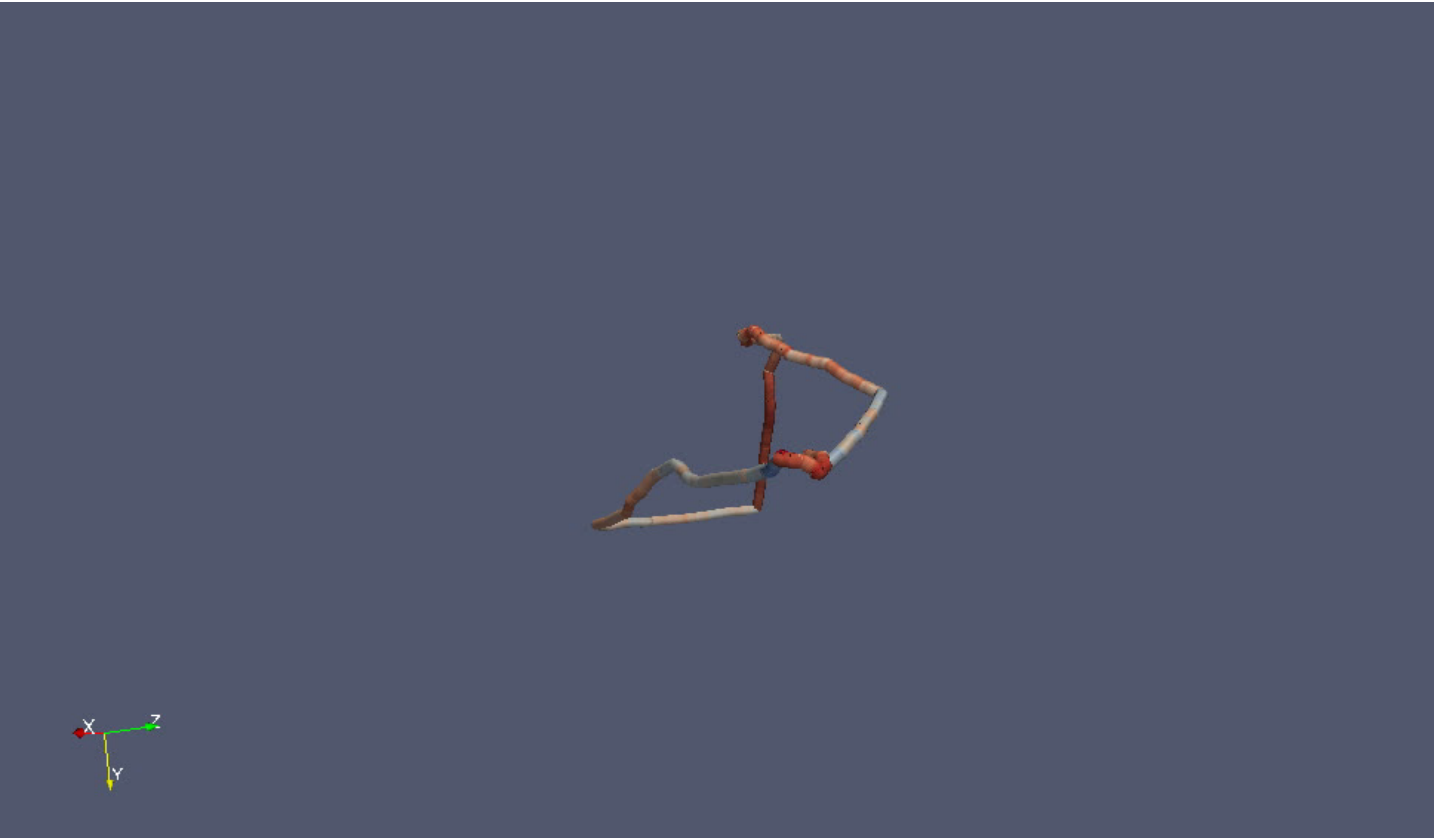
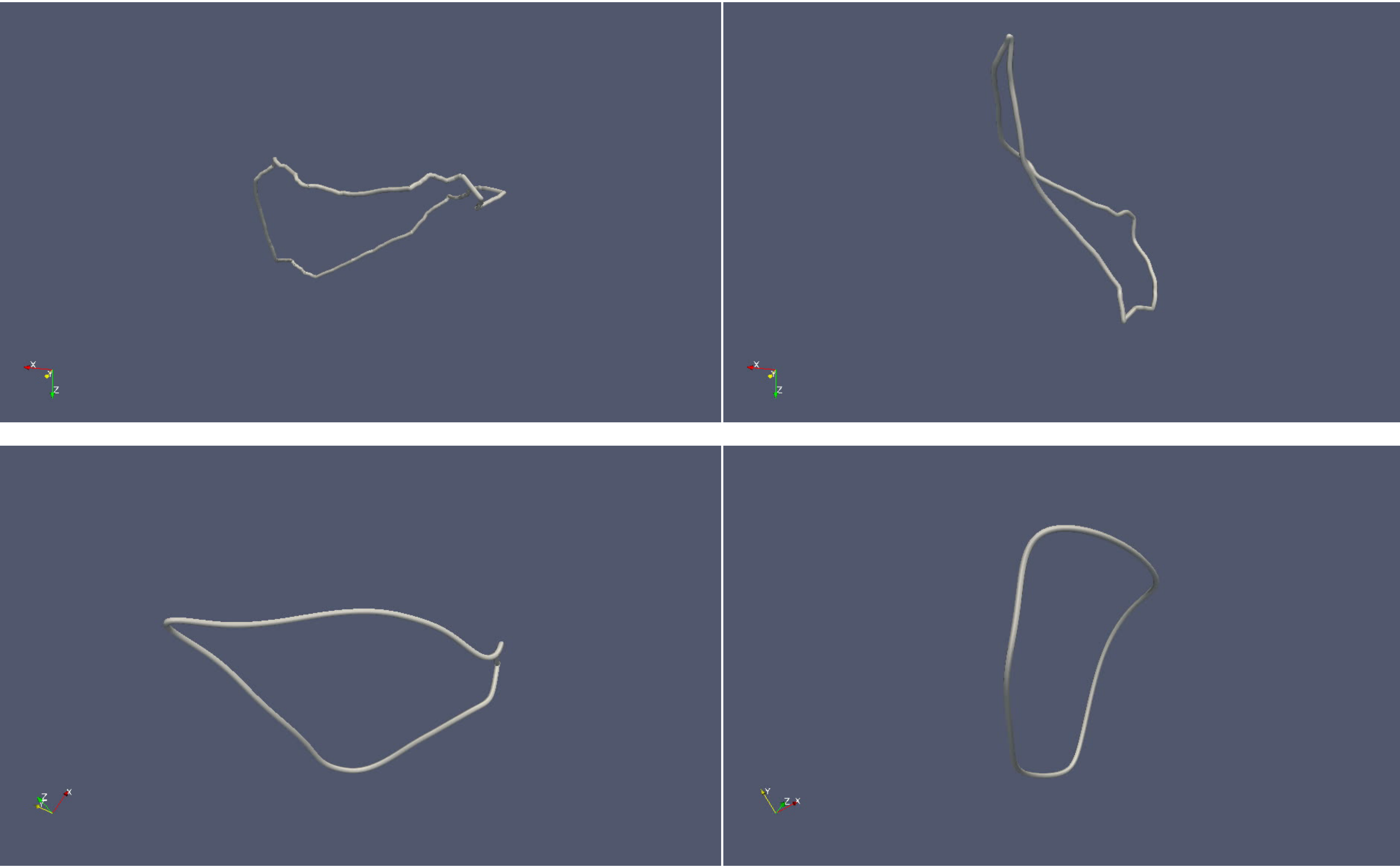
Loops from the Simulation

(B-P., Olum and Shlaer '12).



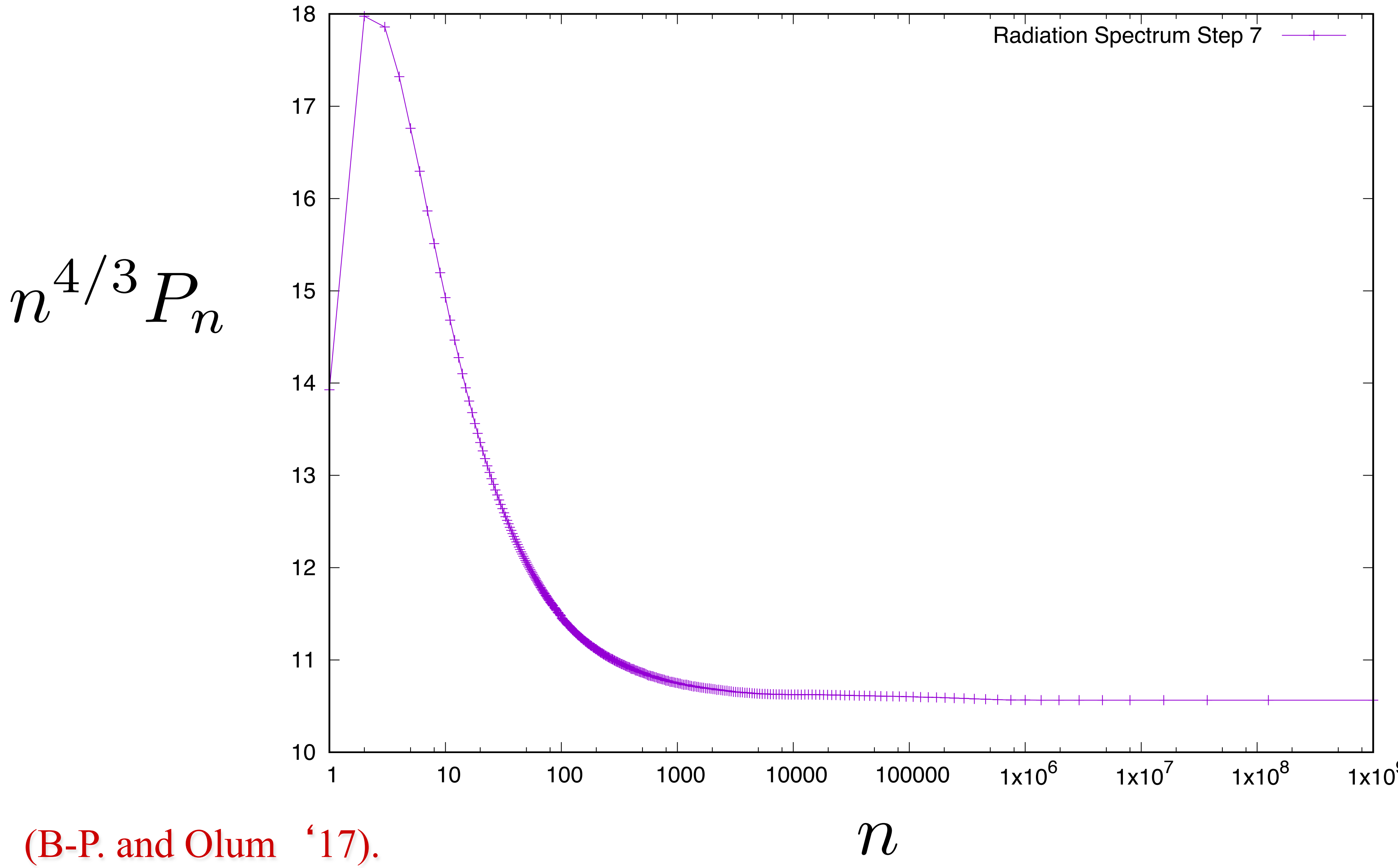
Smoothing the loops (Toy model)

(B-P., Olum '15).



Gravitational Radiation by Loops

- Averaging over more than 1000 loops we get a spectrum of the form.



(B-P. and Olum ‘17).

Stochastic background of Gravitational Waves

- The whole network of strings contributes to the stochastic background of GW.

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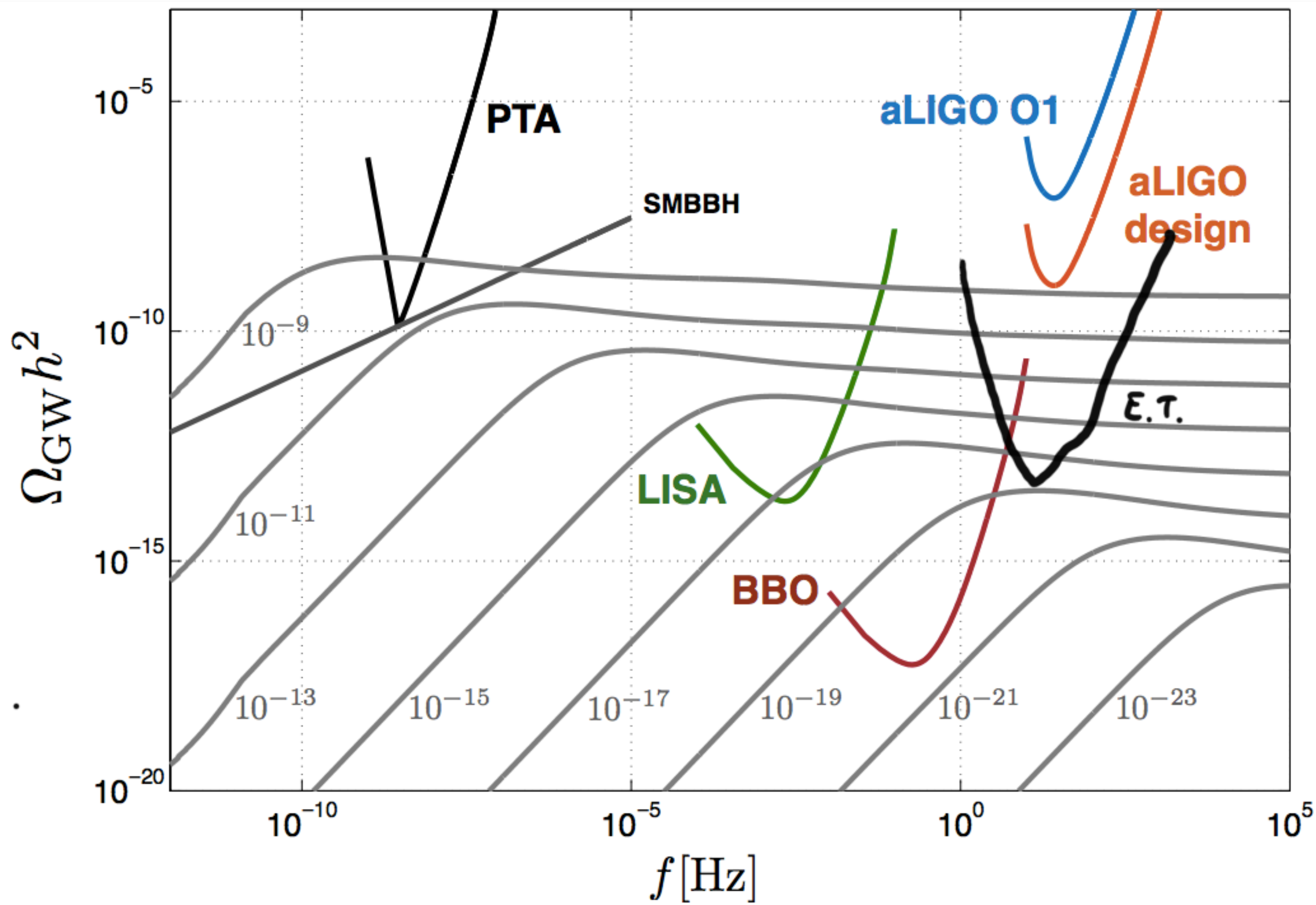
Observational Implications

(B-P. , Olum and Siemens '18).



Observational Implications

(B-P. , Olum and Siemens '17).

- Current limit from Parkes PTA (Australia)

$$\boxed{G\mu < 1.5 \times 10^{-11}}$$

- Similar results from the old NANOGrav (9 year)

$$G\mu < 4 \times 10^{-11}$$

- European Pulsar Timing.

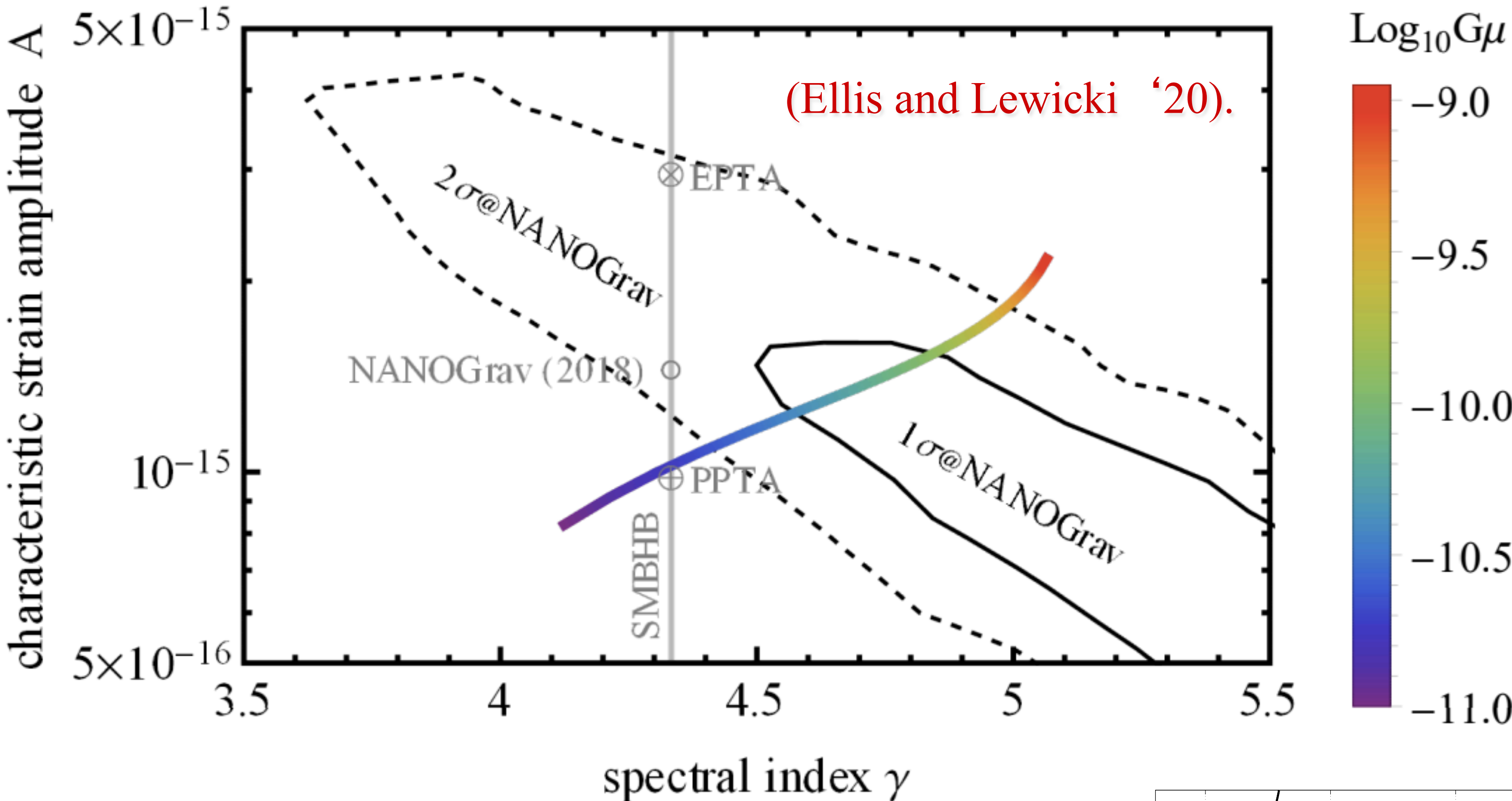
$$G\mu < 1.1 \times 10^{-10}$$

- LISA would be the relevant instrument for strings in the long run

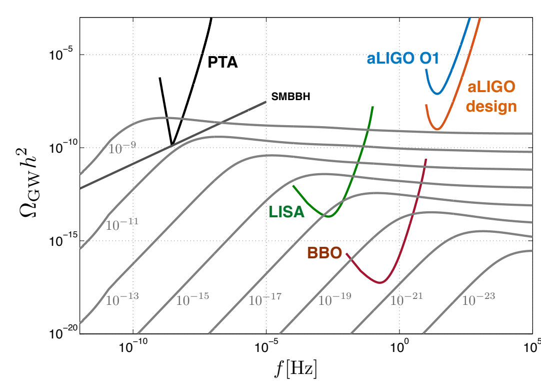
$$G\mu < 6 \times 10^{-18}$$

- These strings would not be seen in the CMB.

Implications from NANOGrav 12.5 year data



$$h_c(f) = A\left(\frac{f}{f_{\rm yr}}\right)^{(3-\gamma)/2}$$



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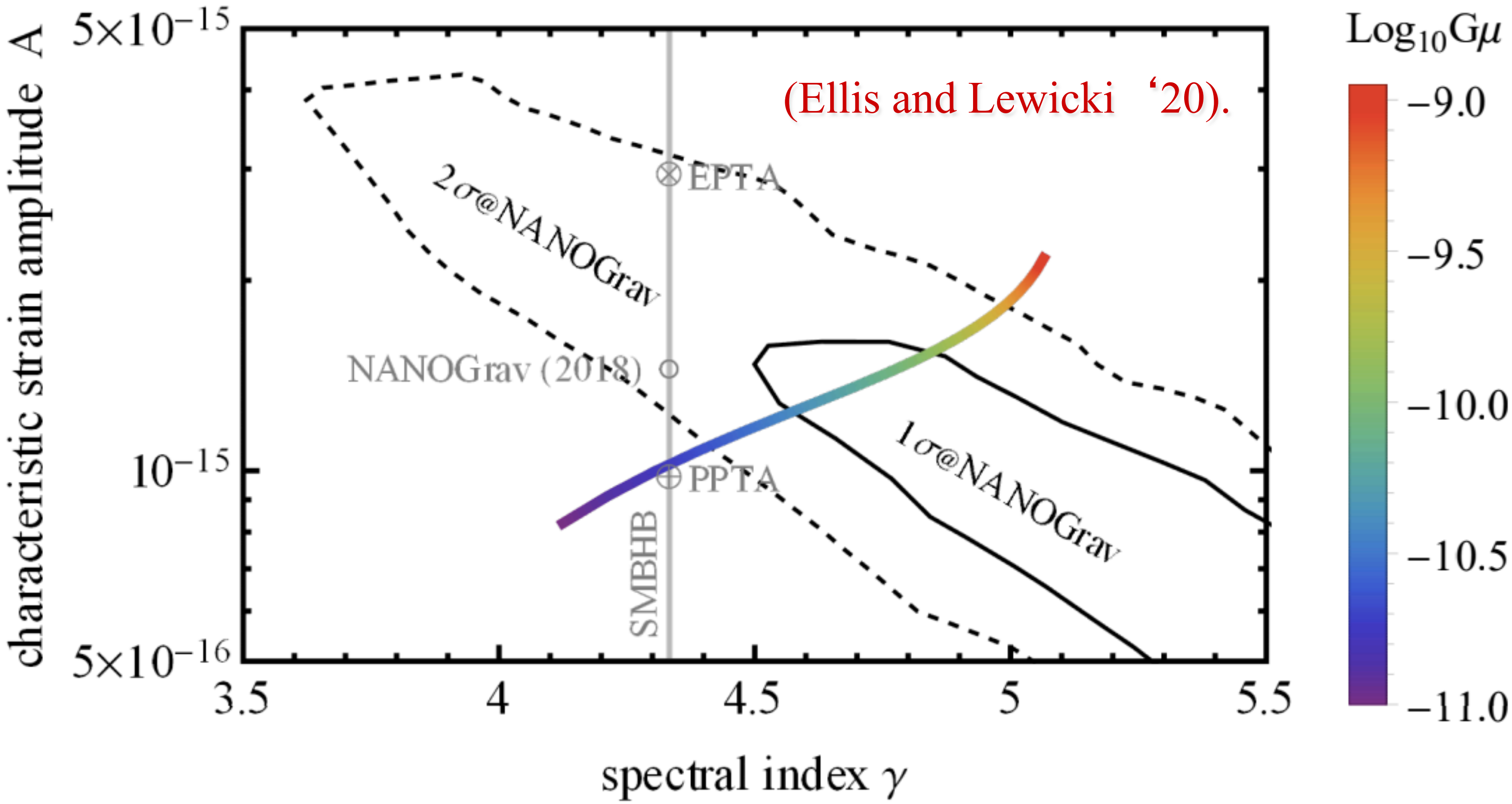


$$1\sigma : \boxed{G\mu \in \left(4\times 10^{-11}, 10^{-10}\right)}$$

$$2\sigma : G\mu \in \left(2\times 10^{-11}, 3\times 10^{-10}\right)$$

Including real backreaction

Real Gravitational Backreaction

- Recall the NG equations:

(Quashnock and Spergel '90).
(B-P. , Olum and Wachter '18; '19).

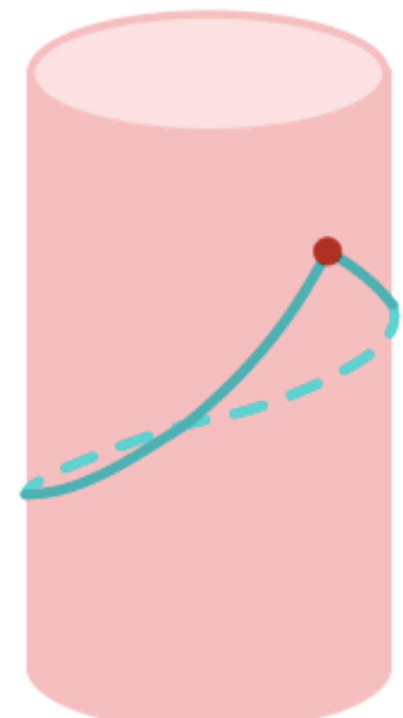
$$x^\gamma{}_{,\mathrm{uv}} = 0 \qquad\qquad x^\gamma(\mathrm{u},\mathrm{v}) = \frac{1}{2}\left[A^\gamma(\mathrm{v}) + B^\gamma(\mathrm{v})\right]$$

- We want to introduce the gravitational self-interaction at linear order:

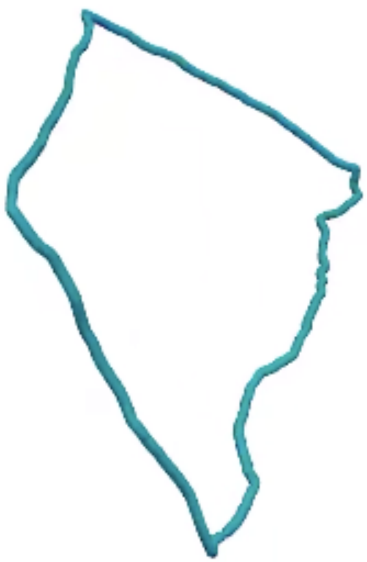
$$x^\gamma{}_{,\mathrm{uv}} = -\frac{1}{4}\Gamma^\gamma_{\alpha\beta}A'^\alpha B'^\beta$$

- Correction at the linear order in $G\mu$

- This captures the gravitational effect of the intersection of the worldsheet with the past lightcone of the observation points.



Real Loops with Real Backreaction



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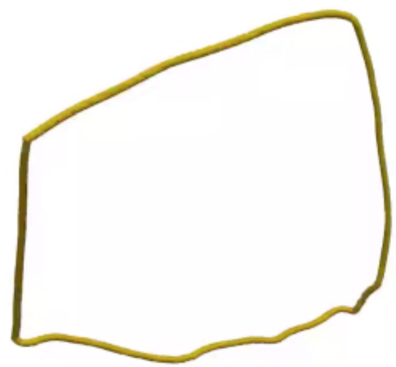

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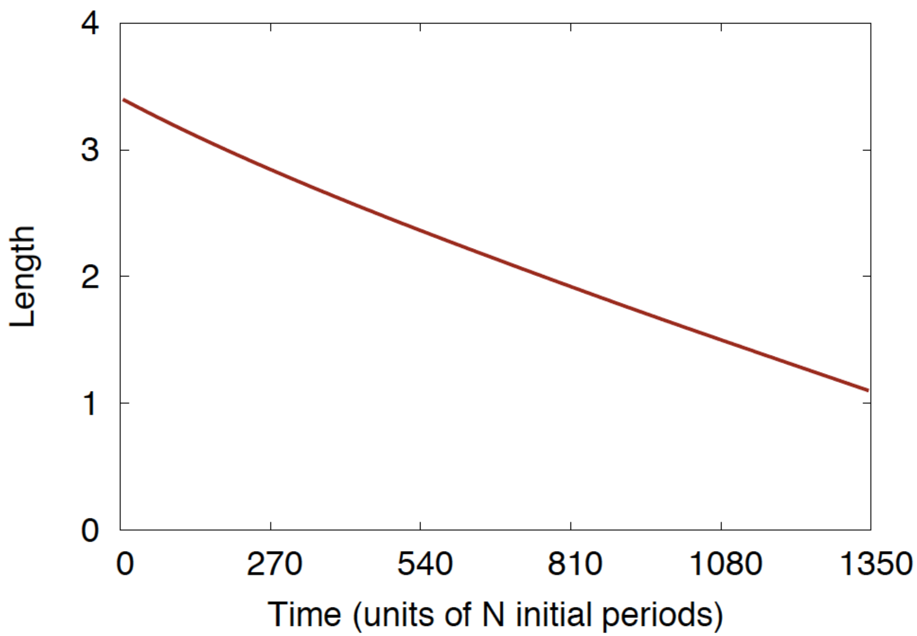
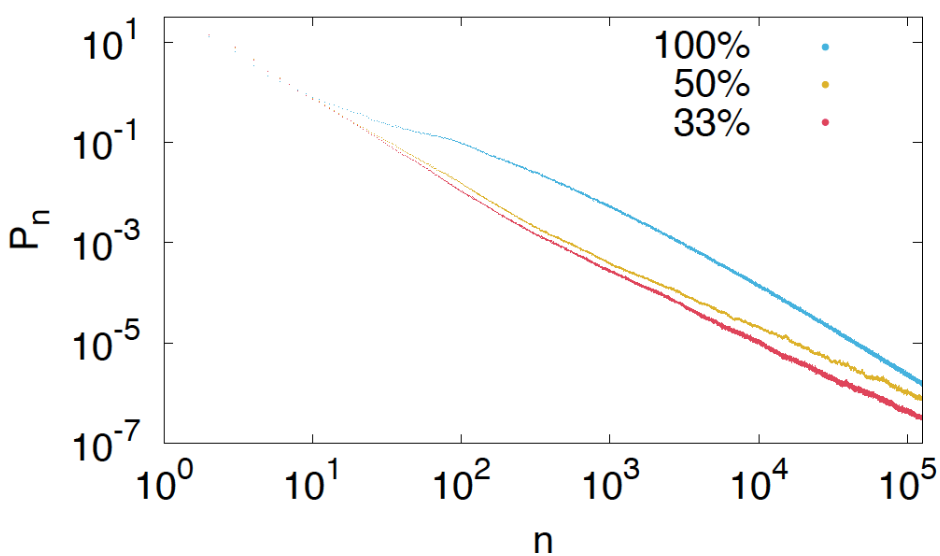
33%

Real Loops with Real Backreaction

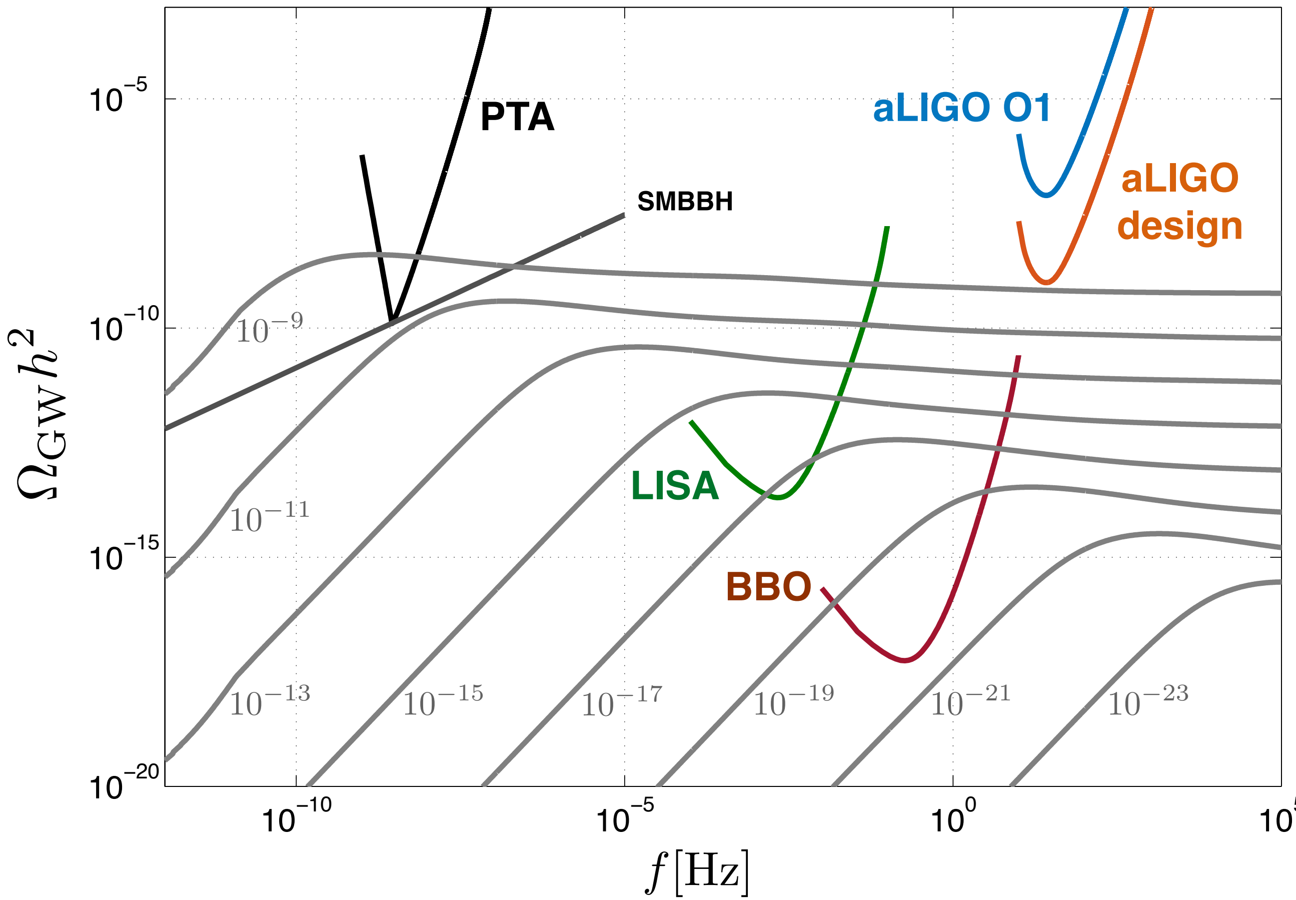


As the loop evolves with backreaction its length decreases.



Backreaction modifies the loop's power spectrum.

Observational Implications



How much does this picture change due to backreaction ?

Work in progress

Conclusions

- Cosmic Strings are predicted in many extensions of the SM.
- We are entering an era of precision cosmology in cosmic string simulations.
- All known effects taken into account except real backreaction.
  (Coming soon)
- We can impose important constraints on the scale of the string from current PTA observations.
- Future observatories like LISA and ET could detect or constrained these scenarios.
- This bounds have an impact on high energy physics of the early universe.

Thank you