

# Probing leptogenesis with gravitational waves

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Based on an upcoming work with  
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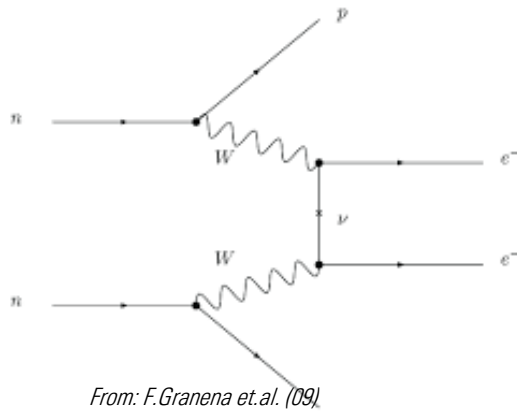


# Motivation

Neutrinos: A window to BSM physics

Approaching a golden era of precision cosmology: Use gravitational wave (GW) experiments as a complementary probe of neutrino physics?

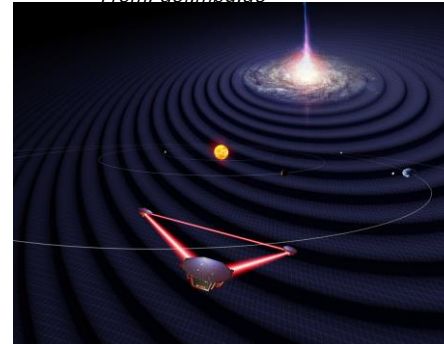
Many ongoing searches and experiments (see e.g. David Wark and Subir Sarkar's talks)



Can we learn something (complementary) from GW experiments:

- 1) Majorana mass vs. Dirac mass?
- 2) Origin/ mass scale of right-handed neutrinos?
- 3) How the baryon asymmetry of the universe was generated?

From: aei.mpg.de



From: Nanograv.org



# Neutrinos and the baryon asymmetry of the universe

## *Sakharov's conditions*

- 1) Baryon-number violation
- 2) C and CP-symmetry violation
- 3) Interaction out-of equilibrium

Leptogenesis (LG): Introducing singlet neutrinos

- 1) Majorana mass (L violation) + Sphalerons
- 2) CP violation via Yukawa couplings
- 3) Rate of Yukawa interactions --> out of equilibrium.



This talk:

Consider LG scenarios where gauged  $U(1)_{B-L}$  is spontaneously broken and detectable GWs from cosmic strings are produced.

(We also consider leptogenesis with FOPT in our work, but not in this talk).

$$\mathcal{L} \supset \underbrace{Y_M \Phi \bar{N}^c N}_{\text{Yukawa}} + \bar{N}^c i \gamma^\mu D_\mu N$$

In the models we consider, the  $U(1)_{B-L}$  breaking gives the RHNs mass.

# Outline

- 1) Cosmic strings: origin and dynamics
- 2) Cosmic strings as a non-thermal source for leptogenesis
- 3) Conclusions

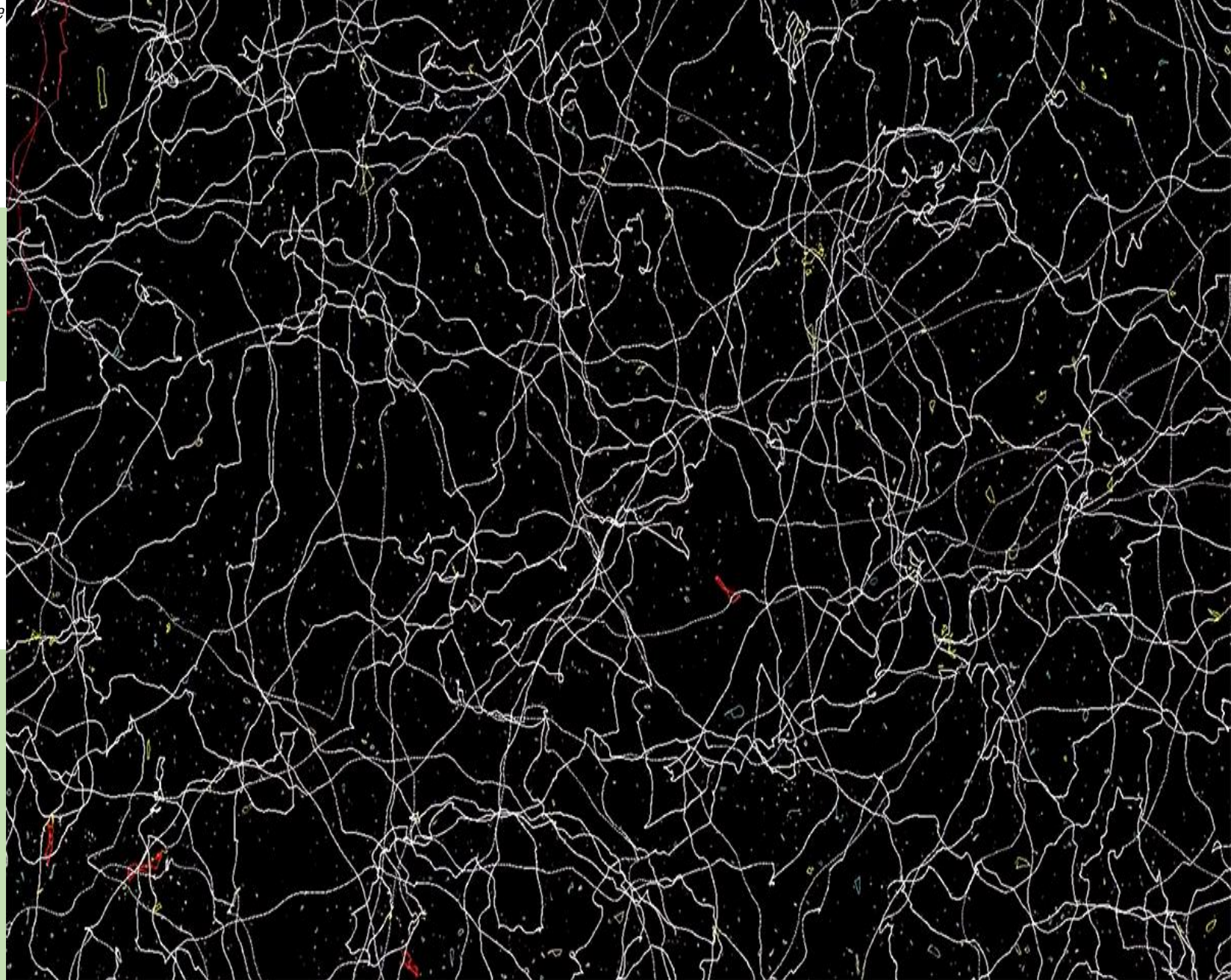
# Cosmic string basics:

Cosmic strings are topological defects.  
Arise in symmetry-breaking phase transitions in the early universe when:

$$G \rightarrow H \text{ and } \pi_1(G/H) \neq 0.$$

Similar objects observed in condensed matter systems.

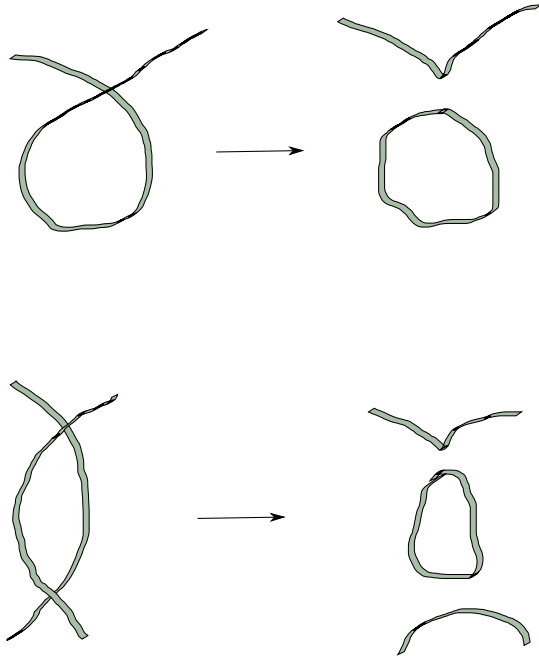
The universe is in the *unbroken* phase inside the string: can have zero modes on the string.



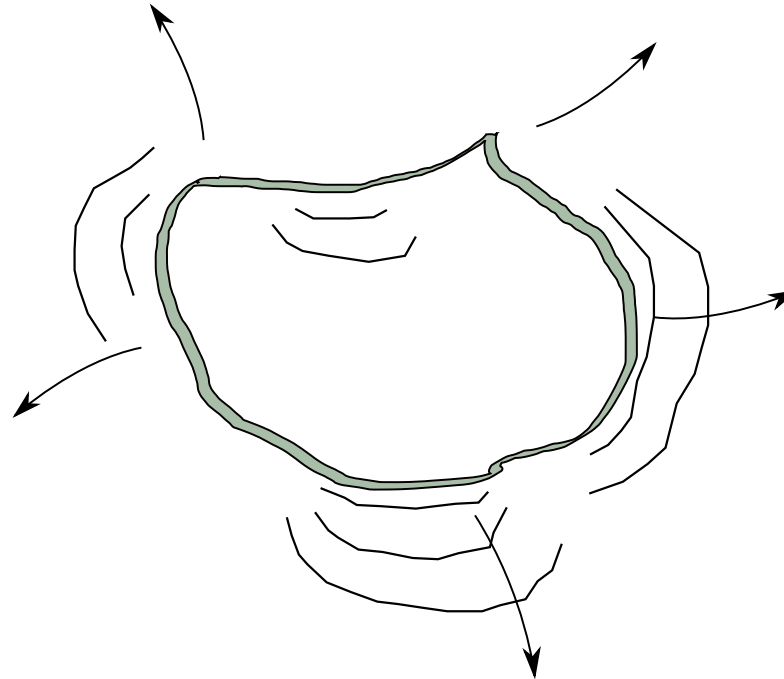
# Cosmic string dynamics and loop production

Vilenkin and Shellard (1994)  
Martins & Shellard (1996)

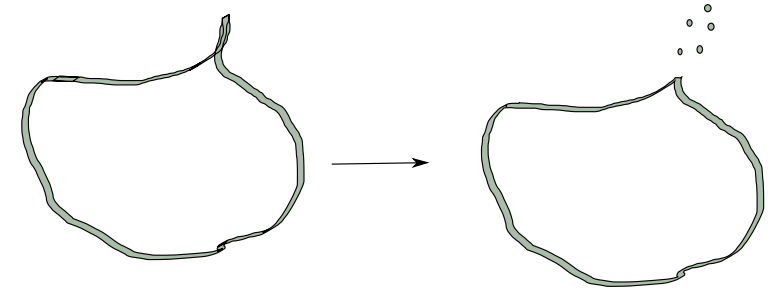
Intersect and create loops:



Wiggle and emit GWs:



Produce Particles:



Mechanisms:

Cusp evaporations

Kink collisions

Final collapse

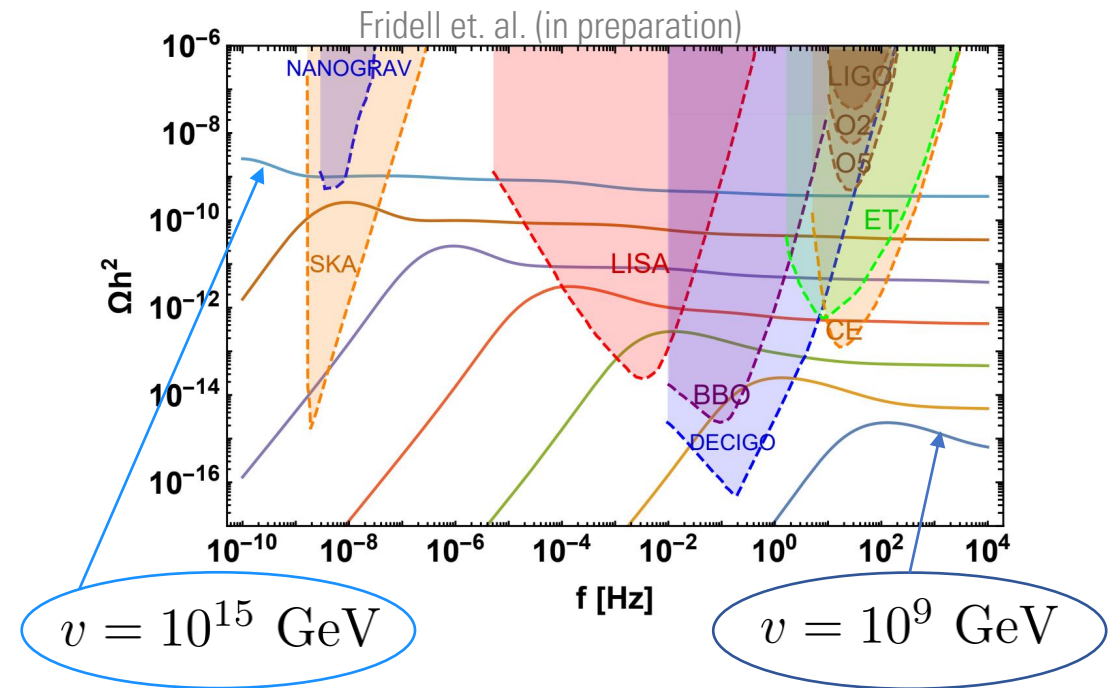
# $U(1)_{B-L}$ strings and leptogenesis

Right-handed neutrinos (RHN) couple to  $U(1)_{B-L}$  gauge field and the symmetry-breaking scalar field:

$$\mathcal{L} \supset Y_M \Phi \overline{N^c} N + \overline{N^c} i \gamma^\mu D_\mu N$$

A cosmic string arising from  $U(1)_{B-L}$  - breaking can source RHNs!

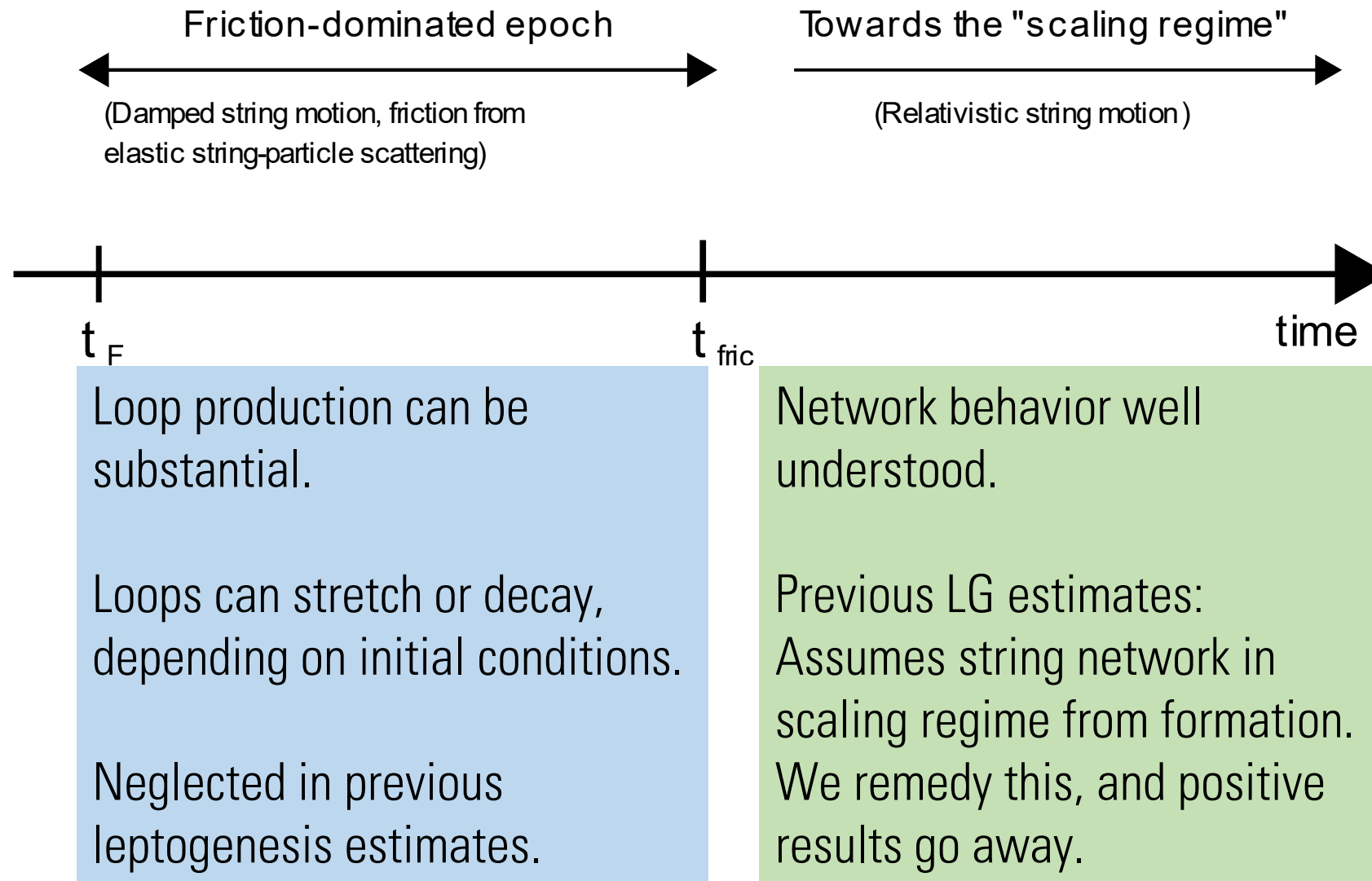
Stochastic GWs from strings (magnitude signal set by string tension)  $\mu \sim v^2$



Connects neutrino masses, leptogenesis w/ non-thermal source, and gravitational wave experiments.

# Cosmic string evolution

Vilenkin and Shellard (1994)  
Martins & Shellard (1996)



# Leptogenesis with cosmic strings (general case)

$$\frac{dE_\phi}{dy} = -\frac{1}{Hy} [\Gamma_{\phi N} + \Gamma_{\phi R}] E_\phi,$$

$$\frac{dE_N}{dy} = -\frac{1}{Hy} \left[ -\Gamma_{\phi N} E_\phi + \Gamma_N (E_N - E_N^{\text{eq}}) - E_X y^3 a_I^3 \frac{dn_N^{\text{cs}}(y)}{dt} \Theta(y - y_{\text{fric}}) \right],$$

$$\frac{dN_{B-L}}{dy} = -\frac{1}{Hy} [\epsilon D (N_N - N_N^{\text{eq}}) + W N_{B-L}],$$

$$\frac{dE_R}{dy} = \frac{a_I}{H} [\Gamma_N (E_N - E_N^{\text{eq}}) + \Gamma_{\phi R} E_\phi].$$

- Changes as string network evolves.
- Different for strings with different small-scale structure.

# Leptogenesis with cosmic strings (radiation domination)

$$\frac{dN_{N1}}{dz} = -(D + S)(N_{N1} - N_{N1}^{\text{eq}}) + \frac{dN_{N1}^{\text{CS}}}{dz}$$

$$\frac{dN_{B-L}}{dz} = -\epsilon D(N_{N1} - N_{N1}^{\text{eq}}) - W N_{B-L}$$

Davis & Earnshaw (1993)  
Lew & Riotto (1994)  
Jeannerot (1996)  
Sahu, Bhattacharjee & Yajnik (2004+2006)

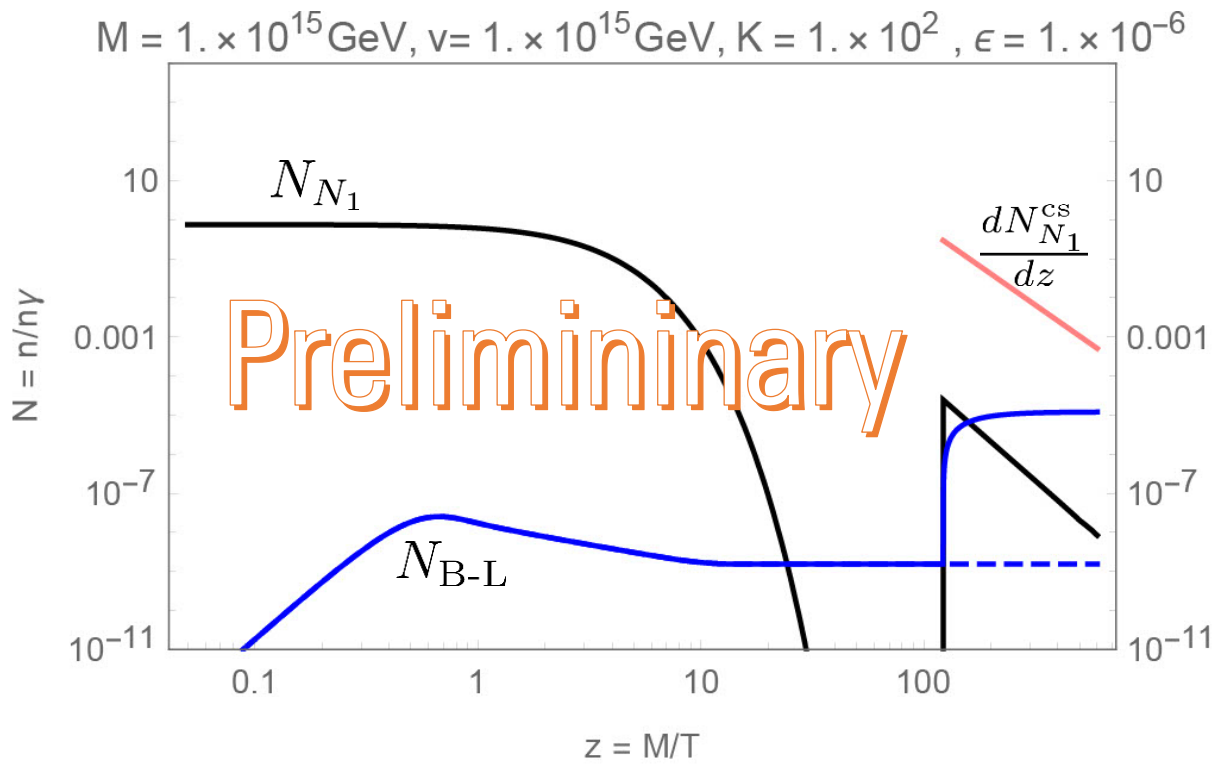
We have calculated the  
calculated the injection  
rate for different epochs of  
network evolution.

Based on field-theory simulations of loop evolution by  
Matsunami et. al. (PRL 2019).

We have considered loops  
with small-scale structure  
dominated by cusps, kinks,  
and loops primarily  
decaying via emission of  
GWs.

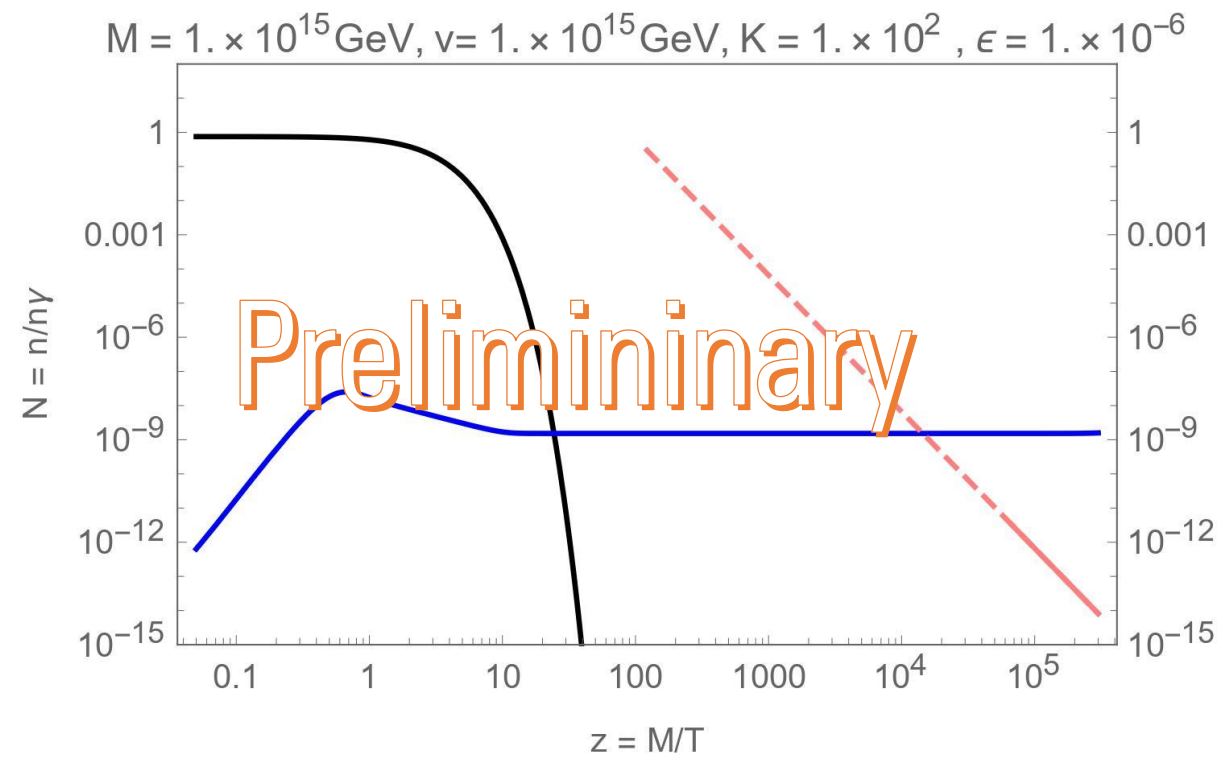
# Example of overestimate v.s. more careful estimate of CS contribution from big collapsing loops produced during linear scaling

“Overestimate”



Turn on RHN injection too early, achieve false enhancement of BAU.

“Conservative estimate”



Turn on RHN injection when first loops produced during linear scaling collapse.

# Considered scenarios

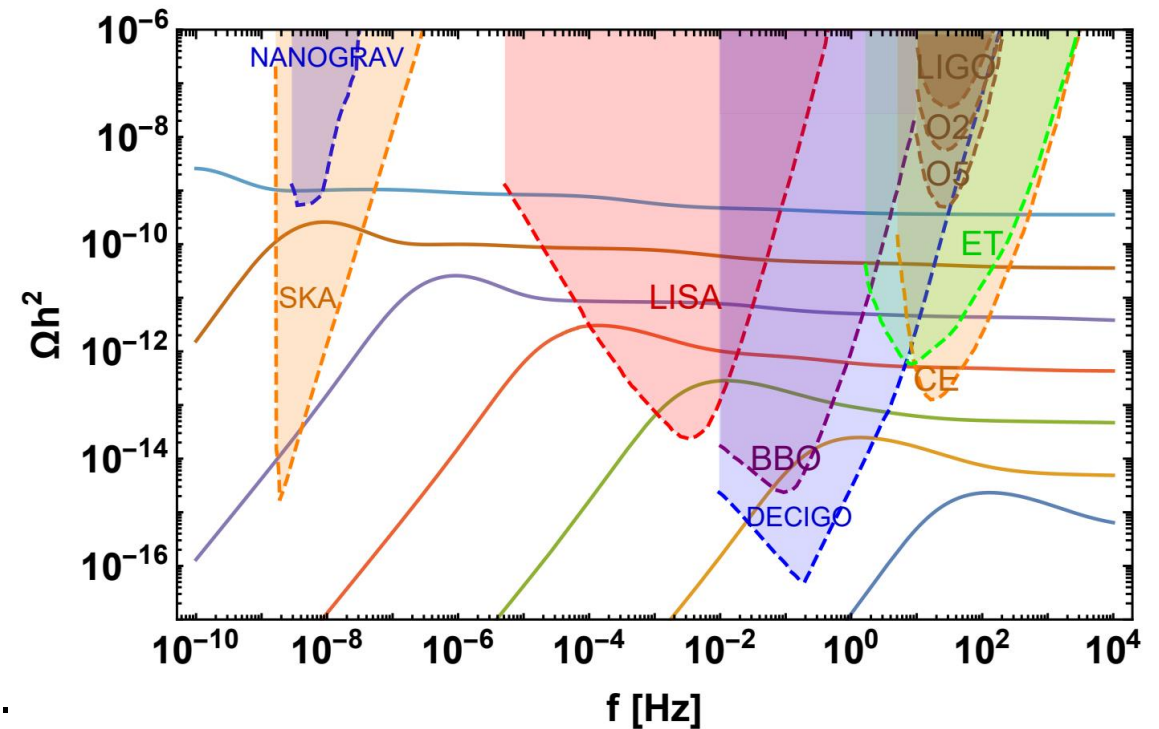
Network epoch	Size of loops	Small-scale structure	Particle-emission mechanism
Stretching (friction)	-	-	Final collapse
Kibble (friction)	-	-	Final collapse
Linear scaling	small	cusps	Final collapse
Linear scaling	small	cusps	Cusp evaporations
Linear scaling	big	cusps	Final collapse
Linear scaling	big	cusps	Cusp evaporations
Linear scaling	small	kinks	Final collapse
Linear scaling	small	kinks	Kink-kink collisions
Linear scaling	big	kinks	Final collapse
Linear scaling	big	kinks	Kink-kink collisions
Linear scaling	small	-	Final collapse
Linear scaling	big	-	Final collapse

# Preliminary comments on CS impact on BAU

- Loops formed during linear scaling generally little/ no effect on the BAU, contrary to previous estimates.
- Preliminary estimates for loops produced during friction epoch also suggest no large effects.
- Different scenario: Loop decaying to scalar decaying to RHNs.

# Summary

- Considered gauged  $U(1)_{B-L}$  breaking in the early universe, which gives right-handed neutrino masses.
- Network of cosmic strings form after the  $U(1)_{B-L}$  phase transition.
- The cosmic strings can source gravitational waves *and* right-handed neutrinos, which may affect leptogenesis predictions.
- We have calculated the injection rate of RHNs from cosmic strings for different epochs of network evolution and for different types of loops.
- Currently finalizing parameter scans of BAU from leptogenesis with RHN injection from cosmic strings.



# Conclusions

- Interesting possibilities to probe leptogenesis with gravitational waves; e.g. potential impact of RHN injection from cosmic strings.
- A positive measurement of GWs from gauge cosmic strings could shed light on the mass scale of right-handed neutrinos, and the nature of leptogenesis.



SFB 1258

Neutrinos  
Dark Matter  
Messengers



# Thank you for your attention!