# *Cosmic string network*

Takashi Hiramatsu

*Yukawa Institute for Theoretical Physics (YITP)*
*Kyoto University*

D. Yamauchi (ICRR), C.-M. Yoo(YITP),
K. Takahashi(Kumamoto), Y. Sendouda(Hirosaki)

# Cosmic strings

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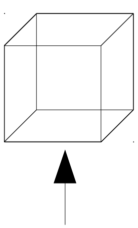
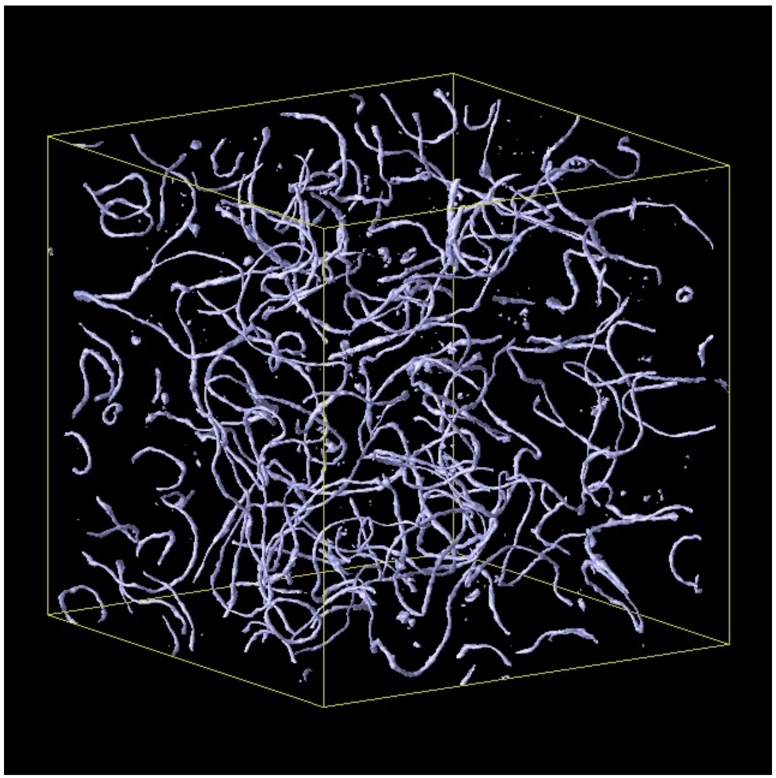
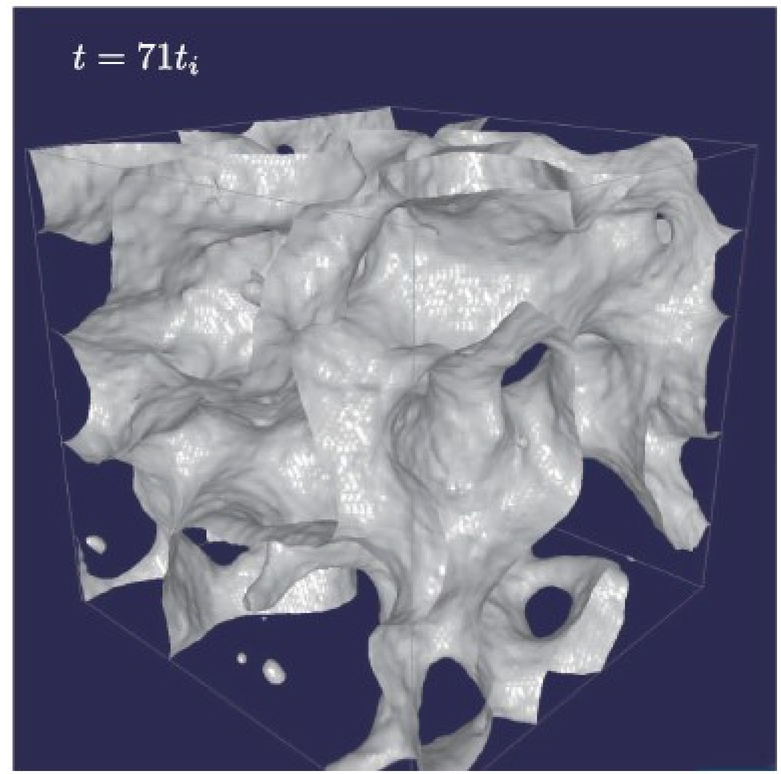
1-dimensional topological defect, produced through the spontaneous symmetry breaking (SSB) of the vacuum state of some kinds of fields.



our universe
(visible region)



cosmic strings




domain walls

It's possible for various kinds of field to exist in the early epoch of the universe, and some of them can be responsible for the formation of CSs.

# Cosmic strings

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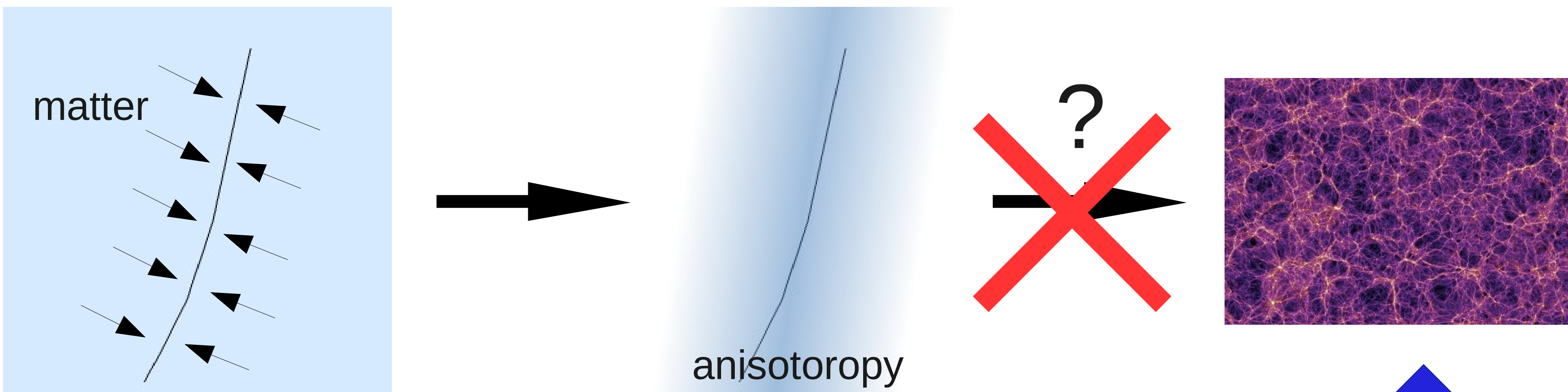
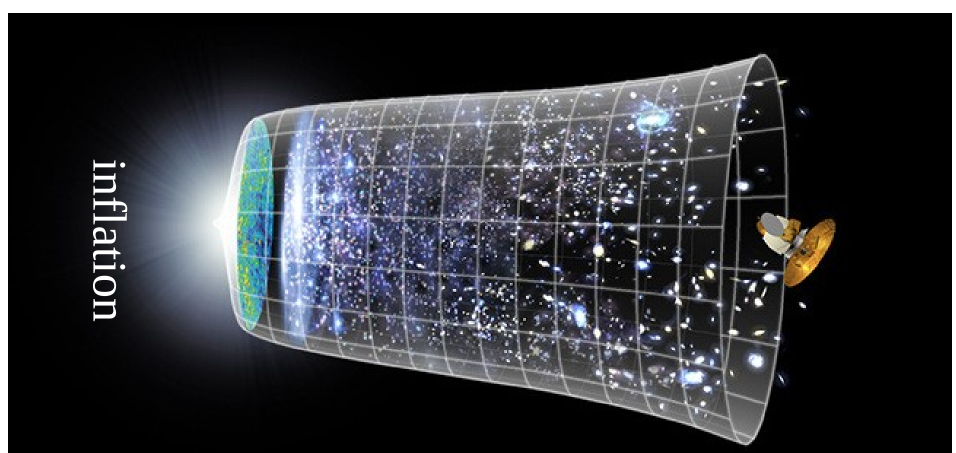
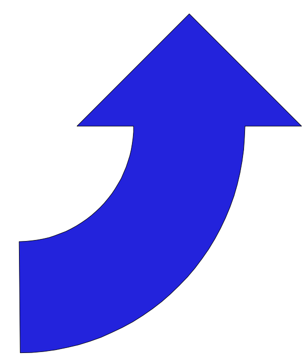
- Why CSs have been considered in cosmology ? → originally as the seed of LSS
- This role was replaced by inflation after COBE satellite's observation in 1990s which clarified an evidence of acoustic peak in CMB angular power spectrum. That has been manifestly confirmed by WMAP, a following mission of COBE in early 2000s.
- In fact, CS cannot create characteristic peaks in the power spectrum. COBE/WMAP restricts the amount of CS in our universe at most to 10% of the whole energy.



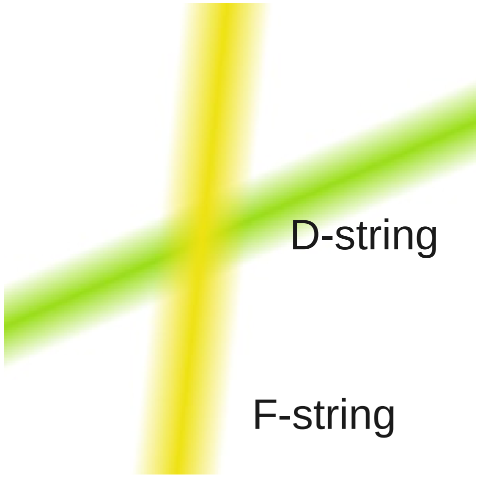

COBE (1989~1993)
= COsmic Background
Explorer
WMAP (2001~2010)
= Wilkinson Microwave
Anisotropy Probe



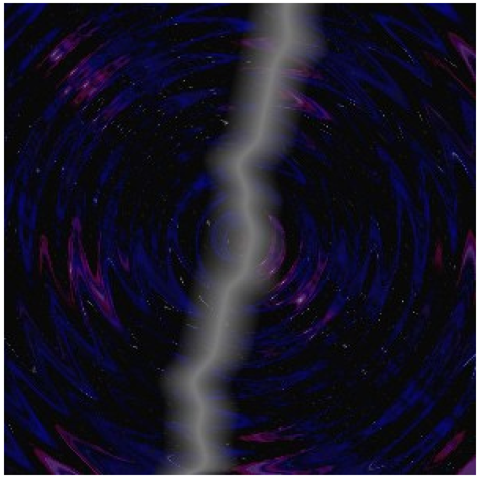



# Cosmic strings

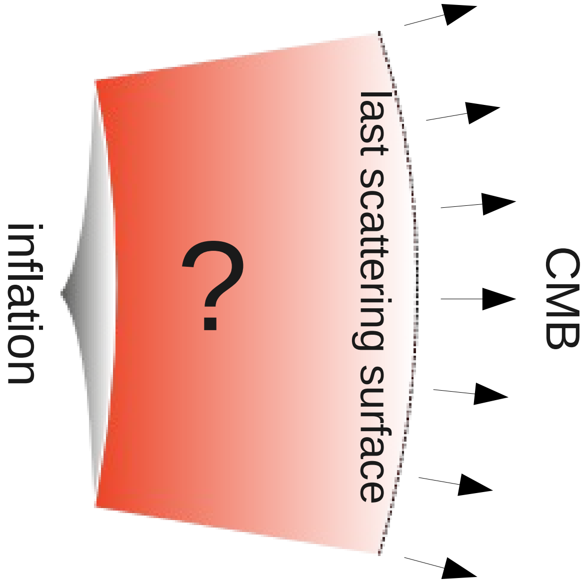
- CSs is still important possible probe for high-energy phenomena in early universe, extending the limit of our scope up to the time just after inflation.
  - Relation with superstring : macroscopic object of super strings is called cosmic superstring.
  - Possible source of gravitational waves
  - Various unobserved physics lying in invisible age




Cosmic superstrings



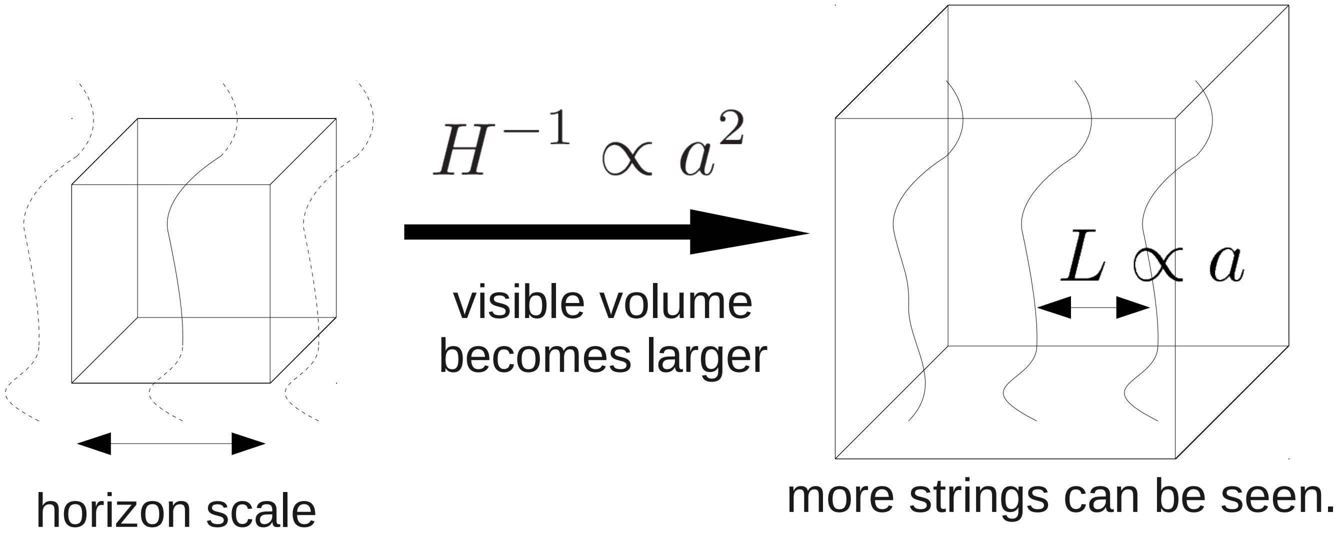
Gravitational wave source




Invisible age

# Scaling property

According to naive consideration of string evolution, strings are fobidden to survive.




If (comoving) separation of strings is fixed at the SSB, strings dominate the universe.

*linear energy density of a string*

$$\rho_{\mathrm{str}} = \frac{\mu L}{L^3} \propto L^{-2} \propto a^{-2}$$

cf. $\rho_{\mathrm{rad}} \propto a^{-4}$

# Scaling property

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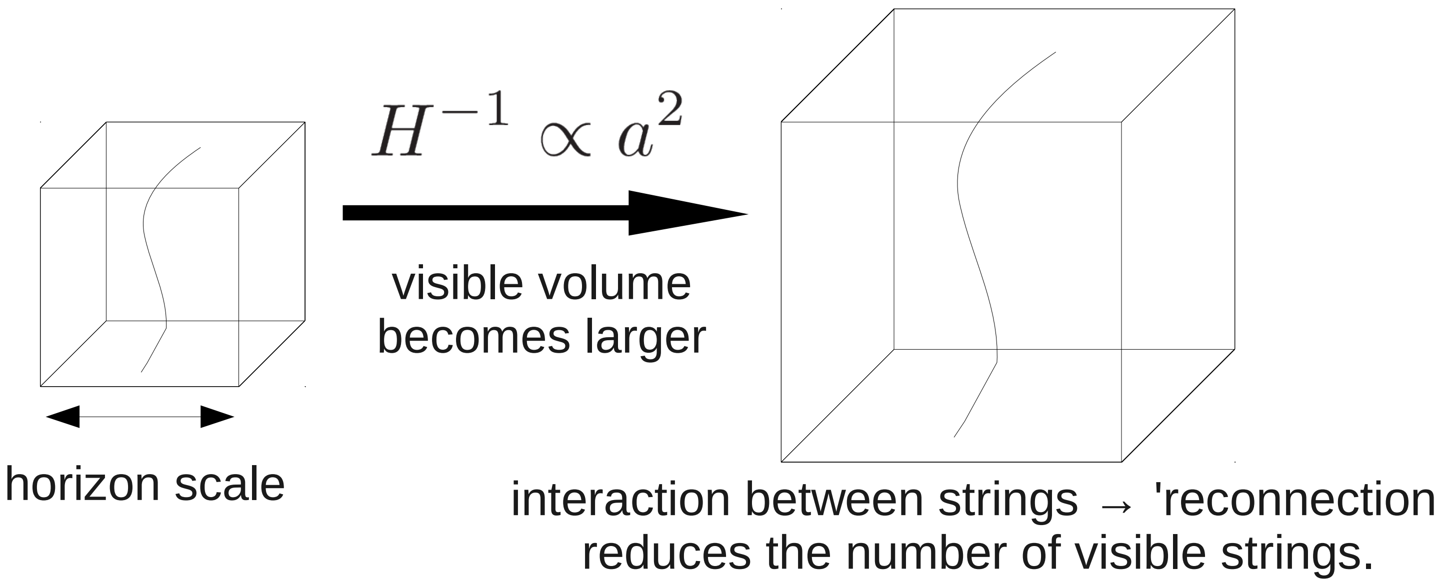
Self-similarity of string evolution inner the Horizon can avoid to overclose the universe.




If the self-similarity is maintained, a horizon-sized string exists in a horizon-scale box

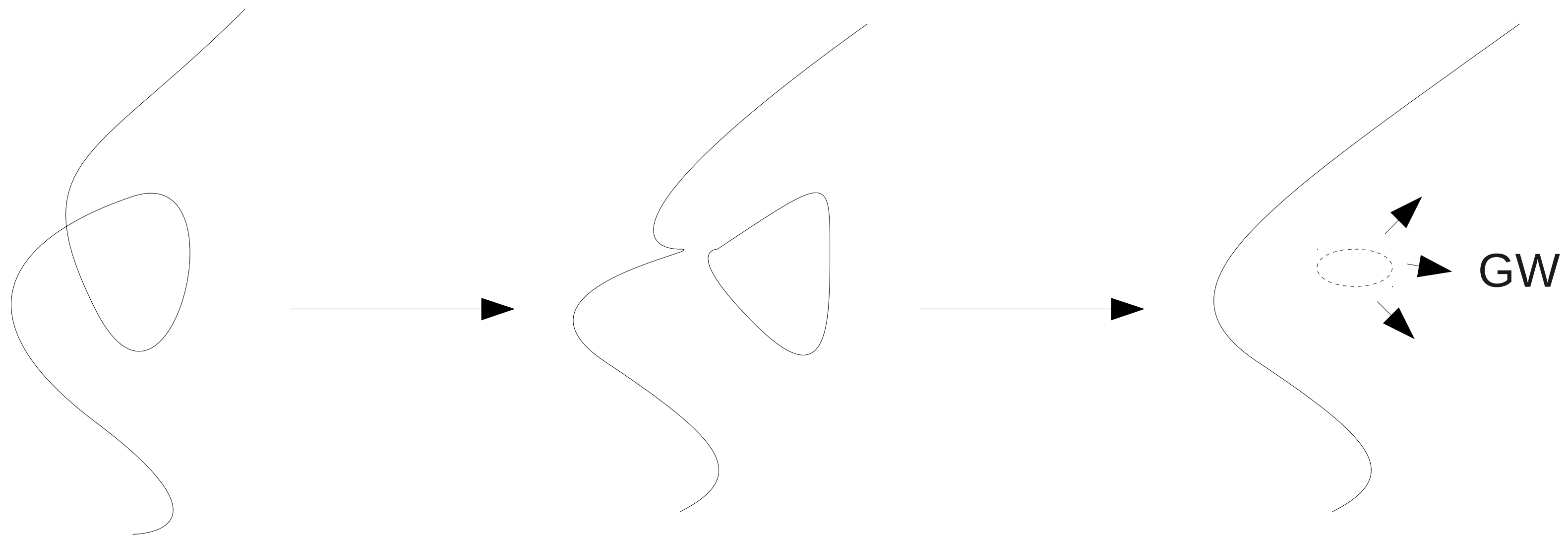
*linear energy density of a string*

$$\rho_{\rm str} = \frac{\mu H^{-1}}{H^{-3}} \propto H^2 \propto a^{-4}$$

cf. $\rho_{\rm rad} \propto a^{-4}$

# Reconnection

In order to have the scaling property, the reconnection process of strings has to take place efficiently.




reconnection

loop production

loops radiate GWs and collapse, reducing string energy density

# String network simulations



## Nambu-Goto simlations (early 1990s ~)

- Study the motion of strings by solving the EOM of strings.
- No thickness, no interactions between strings.
- Reconnection process is artificially imposed, taking place with a given probability.
- Enables to perform the quite large scale simulations.
- Has a great compatibility with analytic treatments.

## Field-theoretic simulations (early 2000s ~)

- Solving the field equations of scalar fields coupling with the gauge fields.
- Interactions of strings are determined from the potential and the gauge couplings. Reconnection is completely controled by the field interactions.
- The scale of simulations is highly restricted by the limitation of computer resources.
- Focusing on details of string interactions, small-scale simulations has also been done in a varity of situations.

# Field-theoretic : Abelian Higgs model

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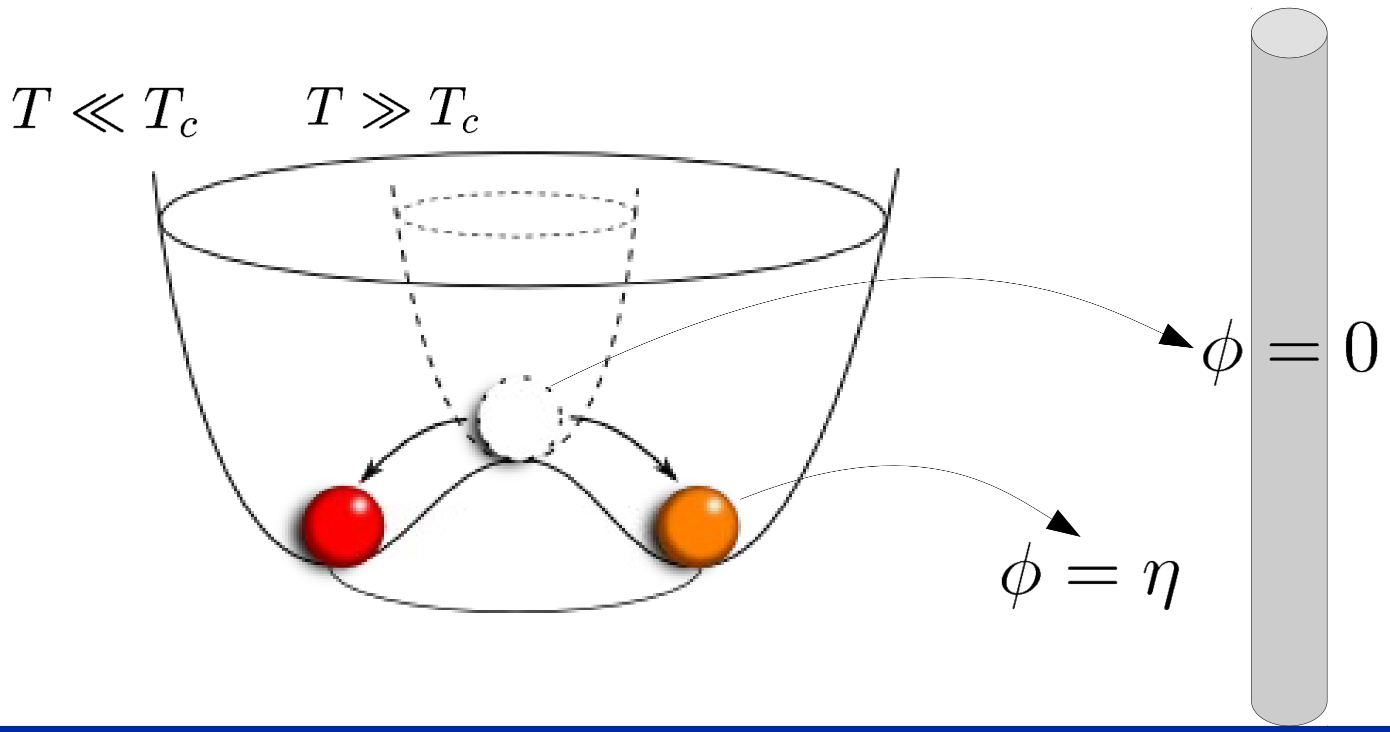
- complex scalar + local U(1) gauge

$$S = -\int dx^4 \sqrt{-g} \left( \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + (D_\mu \phi)^* (D^\mu \phi) + V(\phi) \right)$$

gauge　　scalar

$$V(\phi; T) = \frac{\lambda}{2}(\phi^* \phi - \eta^2)^2 + \frac{\lambda}{3} T^2 \phi^2$$

$$D_\mu \equiv \partial_\mu - ieA_\mu$$
$$F_{\mu\nu} \equiv \partial_\mu A_\nu - \partial_\nu A_\mu$$



# Classification of strings

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- After SSB, gauge field acquires its mass, and then
  - Scalar mass : $m_s = \sqrt{\lambda}\eta$
  - Gauge mass : $m_v = \sqrt{2}e\eta$
- Classified by $\beta^2 \equiv \lambda/2e^2 = m_s^2/m_v^2$

Type-I $\beta < 1$

Not so well studied in cosmological context.
cf. $\beta \ll 1$ is predicted for stings associated with SSB of flat direction in MSSM
**Cui, Martin, Morrissey, Wells, PRD 77 (2008) 043528**

Critical coupling $\beta = 1$

Most of field-theoretic simulations so far have been done wth this condition. cf. Hindmarsh, Bevis, Shellard, Vilenkin, Martin, de Putter, Achucarro, Vachaspati, Davis, ...

Type-II $\beta > 1$

Large β limit corresponds to global strings involving axion production
cf. Allen, Kawasaki, Saikawa, Shellard, Sikivie, Yamaguchi, Yokoyama, Yamaguchi, Vilenkin, ...

# Our studies

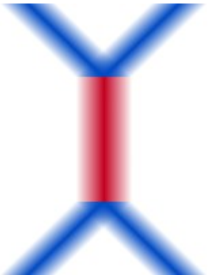


*How does type-I string network evolve ?*

classical field

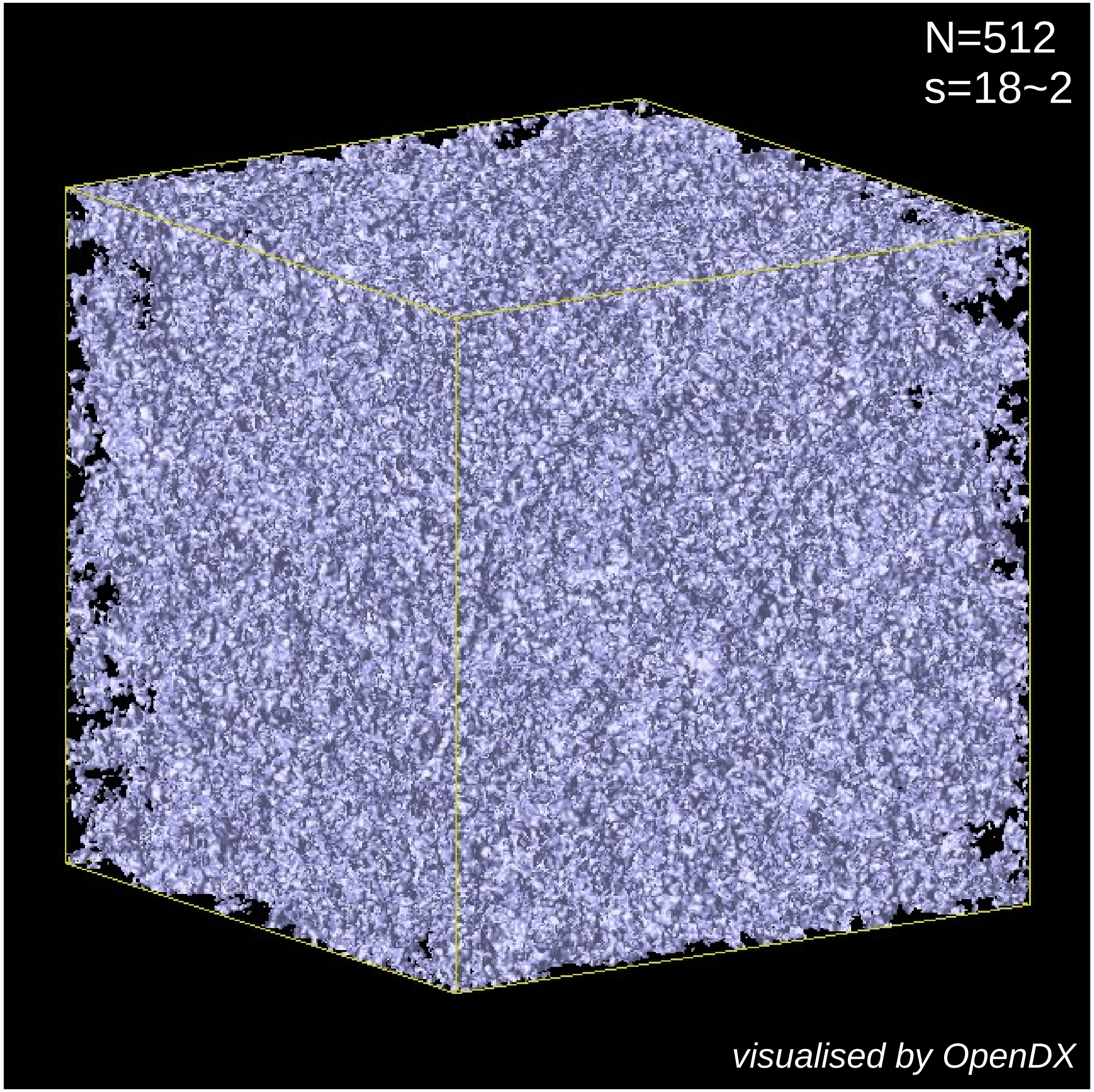
- Strong coupling with gauge fields doesn't prevent scaling ?
- Type-I string has peculiar properties
  - low velocity collision of strings produces a bound state

    Bettencourt et al., PRL 78 (1997) 2066
    Salmi et al., PRD 77 (2008) 041701R




  - Small effective reconnection rate ? Achuccaro, de Putter, PRD 74 (2006) 121701
- Are there any more efficient energy release mechanism than loop production involving the strong gauge coupling ?

# Numerical simulation : network




$$\lambda = 1.0, \beta = 0.1$$

CPU : Opteron 6172*2
(2.1GHz, 24 cores)
MEM : DDR3-1333 128GB
HDD : 21TB+7TB

# Numerical simulation : colliding strings

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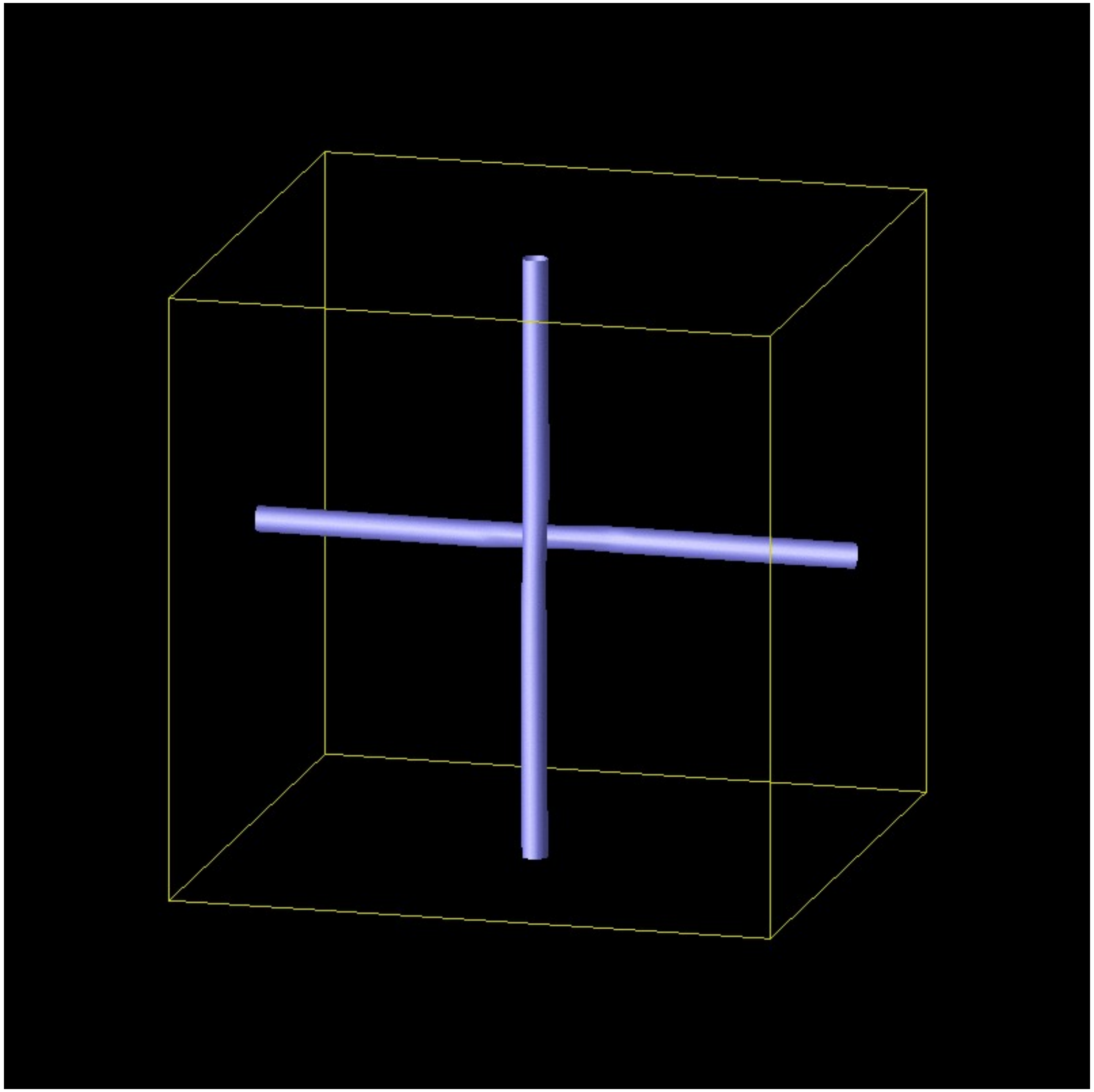
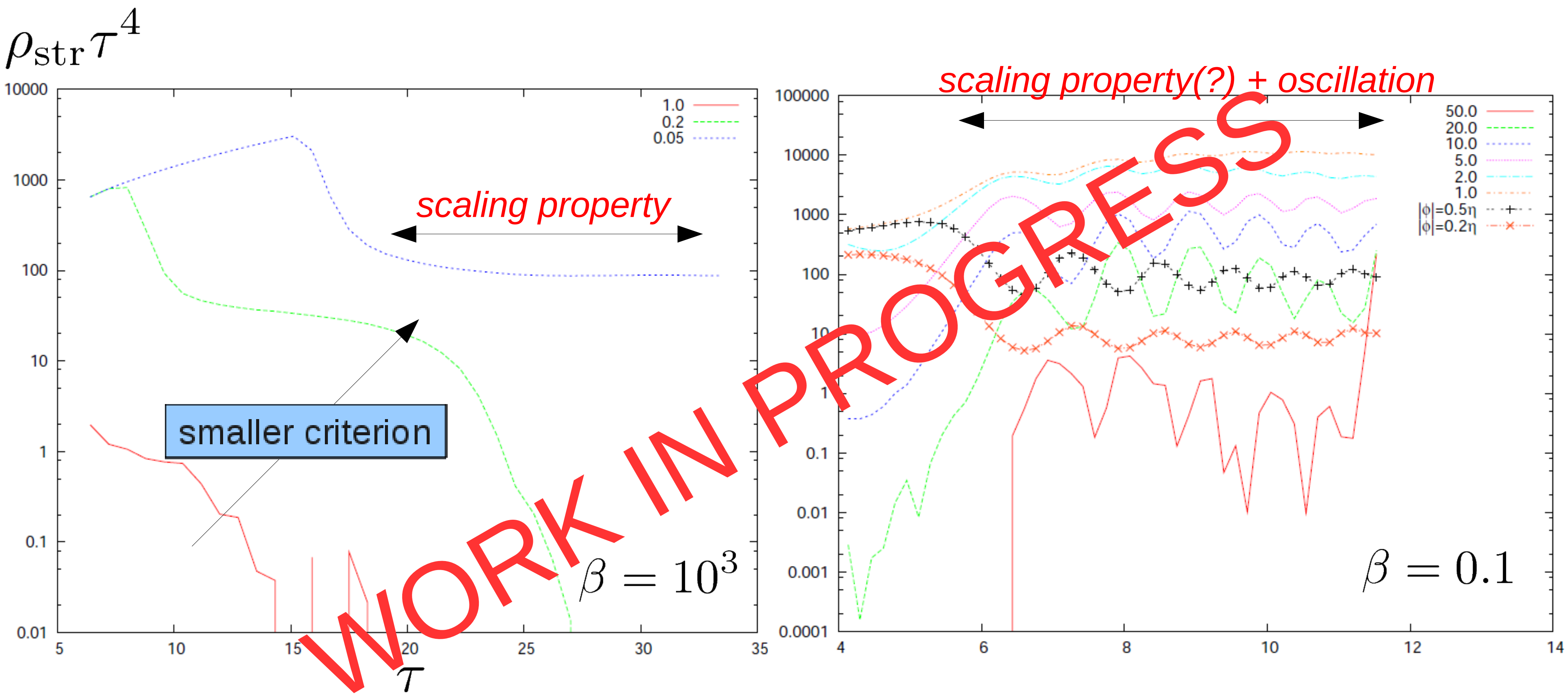


# Results : String energy – time evolution




- scaling property is observed at late time
- for Type-I, can see heavy oscillations