2015/07/03 seminar@Waseda U.

Cosmic strings and their future detectability

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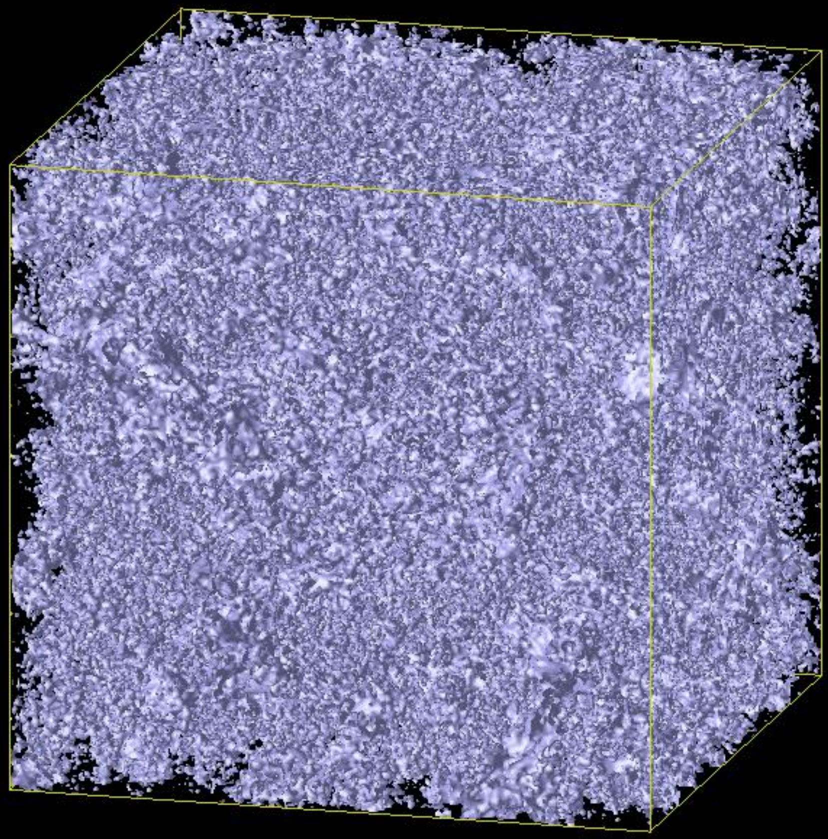
Cosmic strings

... are something like rubber bands, which

- Are 1-dimensional objects
- Have a tension
- Are VERY USEFUL!

Cosmic strings



… are something like rubber bands, which

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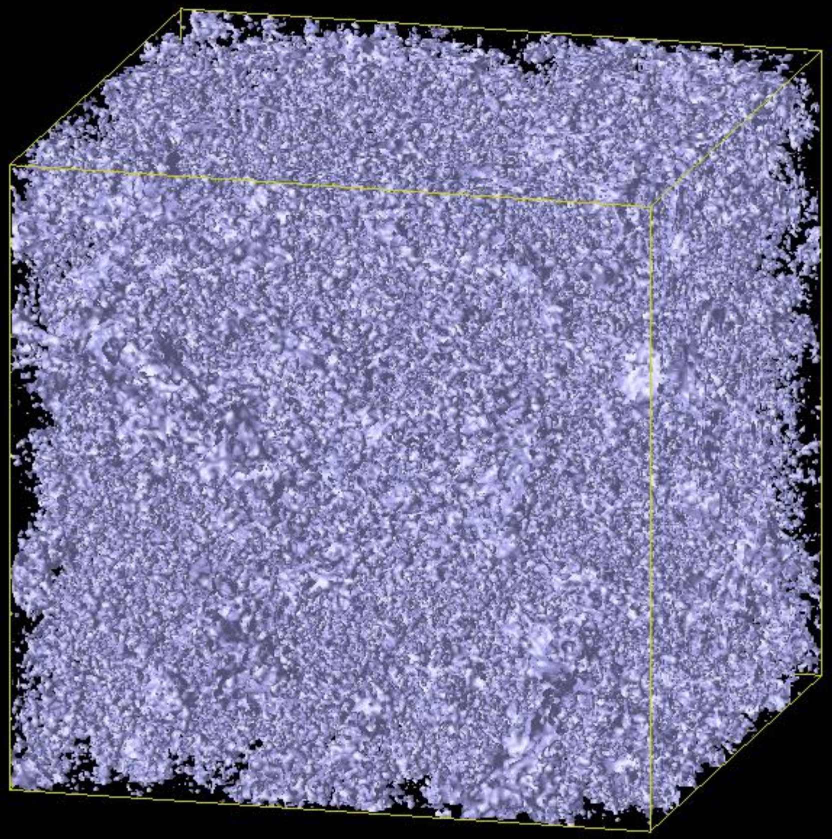
Hiramatsu+Sendouda+Takahashi+**DY**+Yoo, 1307.0308

Cosmic strings



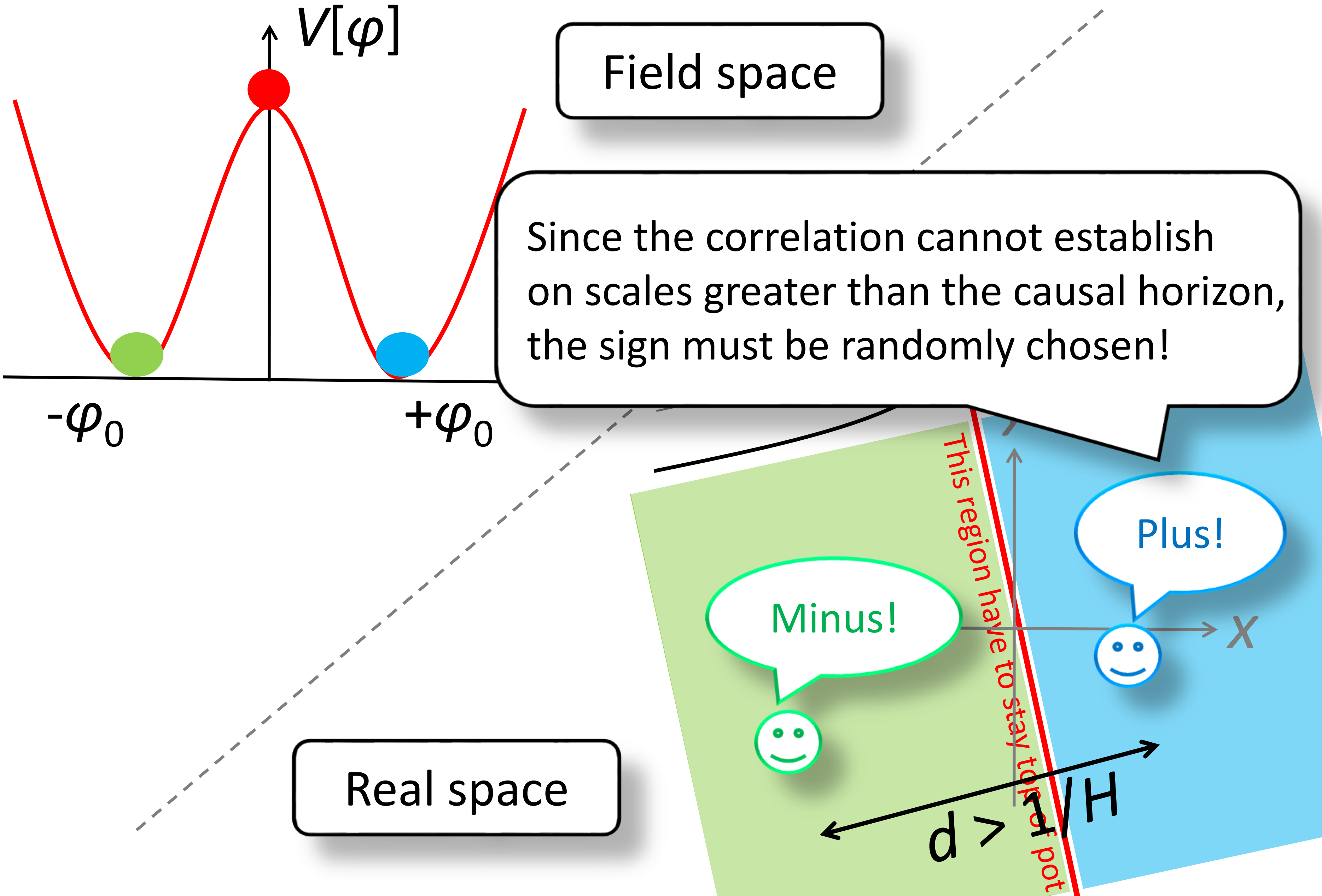
Phase transition

Scalar field settles down to true vacuum due to Hubble friction

Strings begin to appear

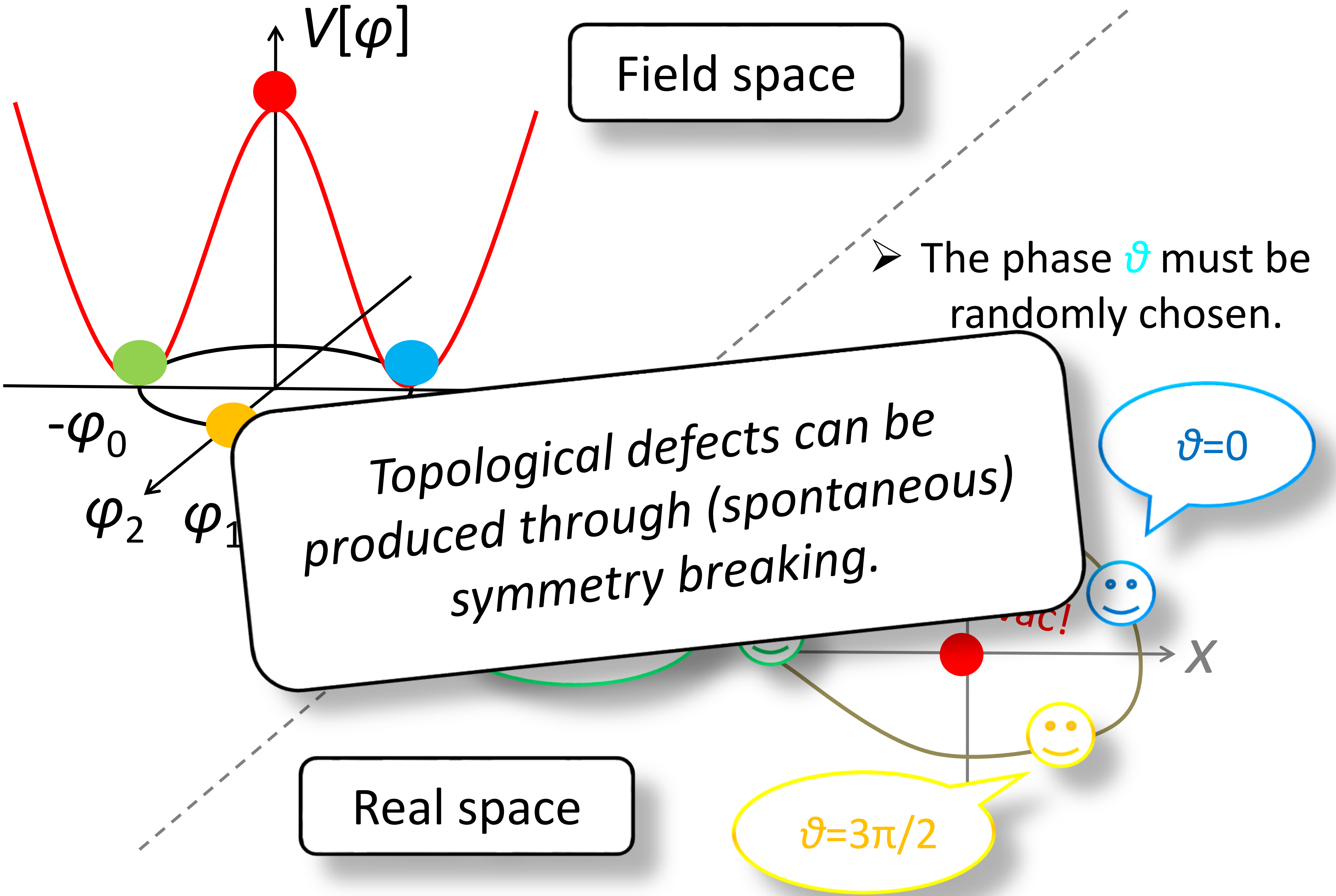
Hiramatsu+Sendouda+Takahashi+**DY**+Yoo, 1307.0308

[Exercise 1]



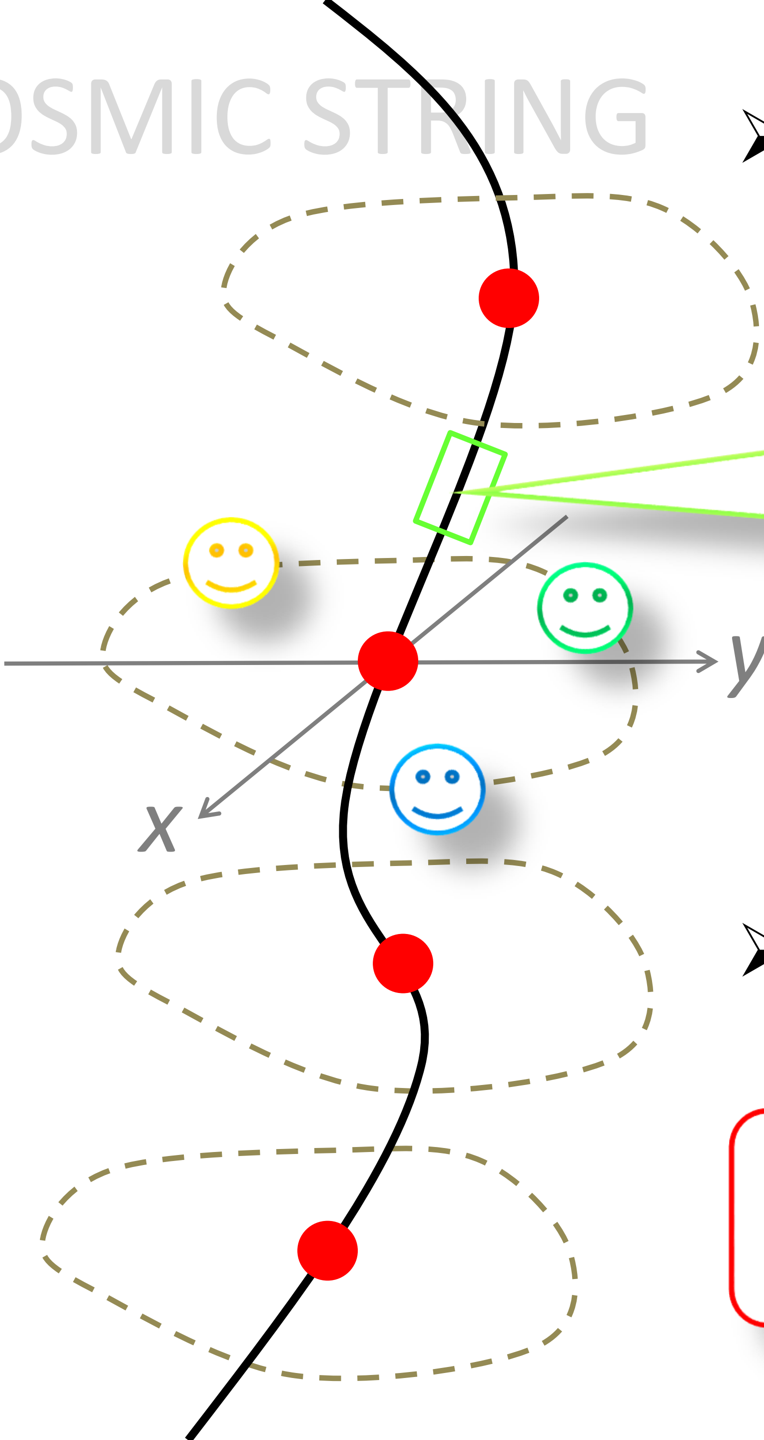
$V[\varphi]$
$-\varphi_0$
$+\varphi_0$
Field space
Since the correlation cannot establish on scales greater than the causal horizon, the sign must be randomly chosen!
This region have to stay top of pot
Minus!
Plus!
x
$d > 1/H$
Real space

[Exercise 2]

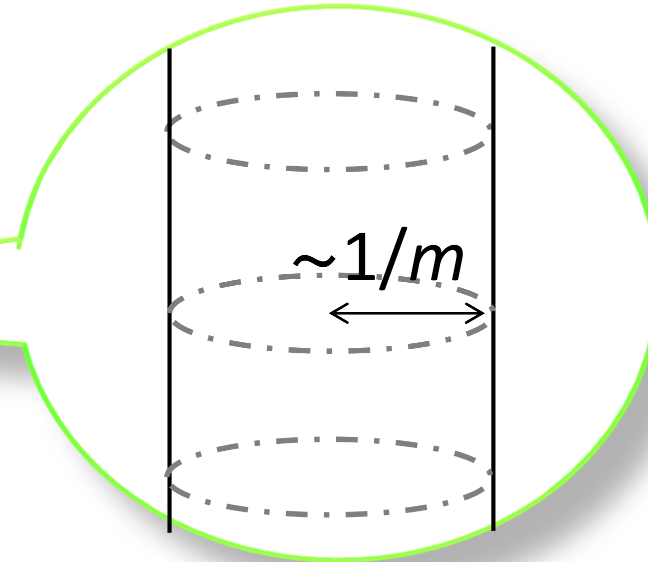


Topological defects can be produced through (spontaneous) symmetry breaking.

COSMIC STRING



- Inner structure



[Nielsen+Olsen (1973)]

- String tension

: energy-density per unit length

$\mu \sim (\text{phase transition energy})^2$

Why are cosmic strings still interesting?

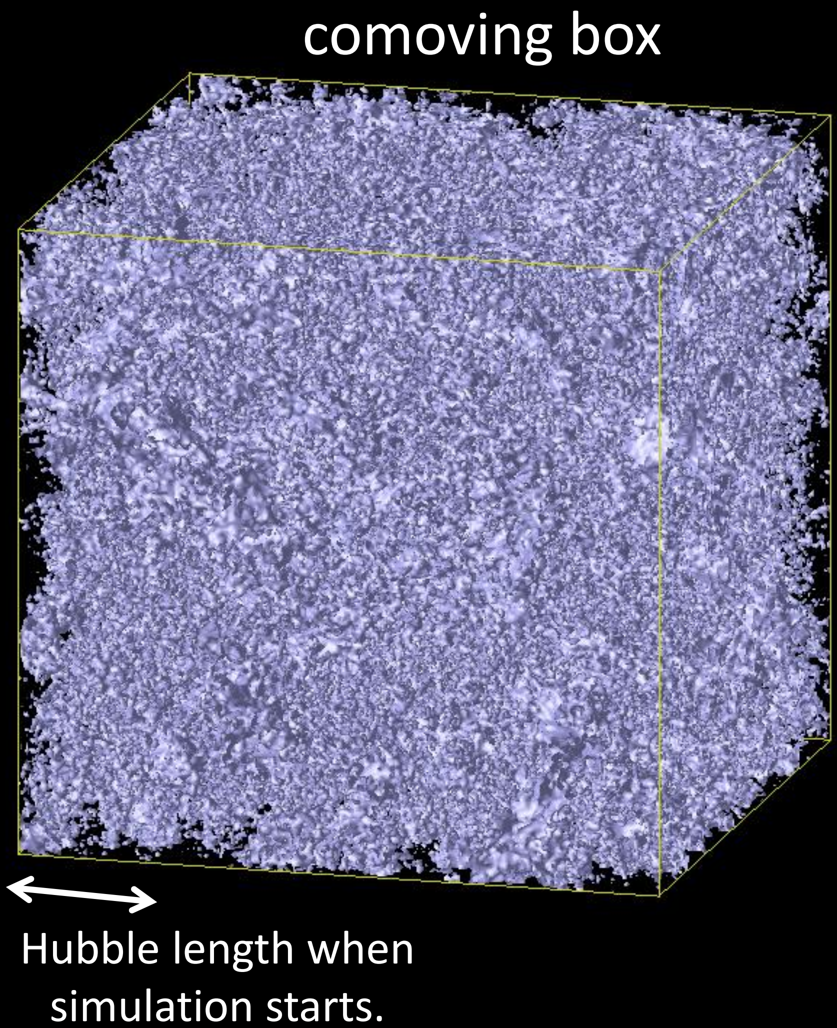
$\mu \sim$(phase transition energy)^2

Cosmic strings have a potential to reveal
the high-energy physics during phase transition!

For GUT scale…

$$G_N \mu = 10^{-6} \left(\mu/(10^{-3} M_{pl})^2\right)$$

Contents

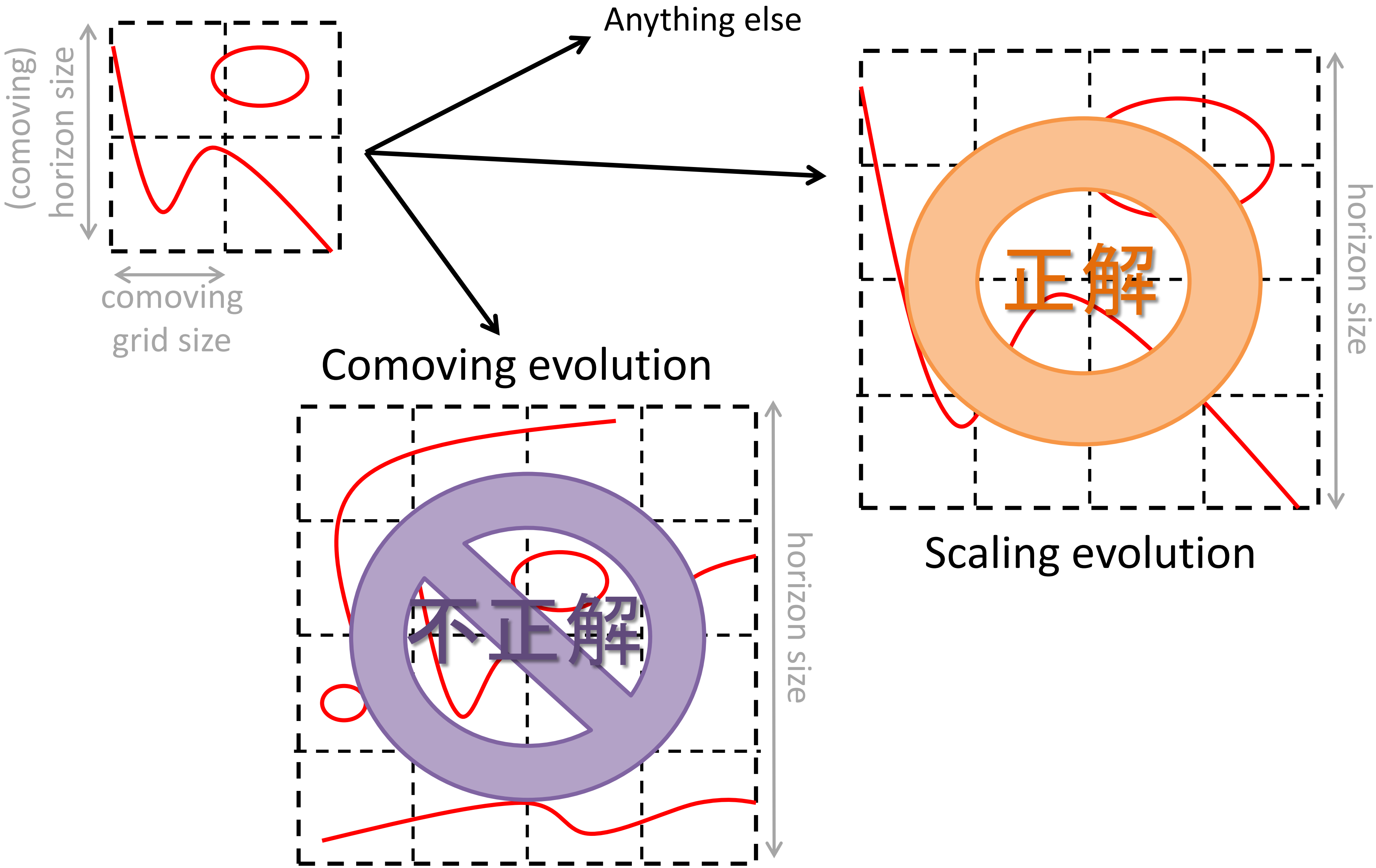


Question1

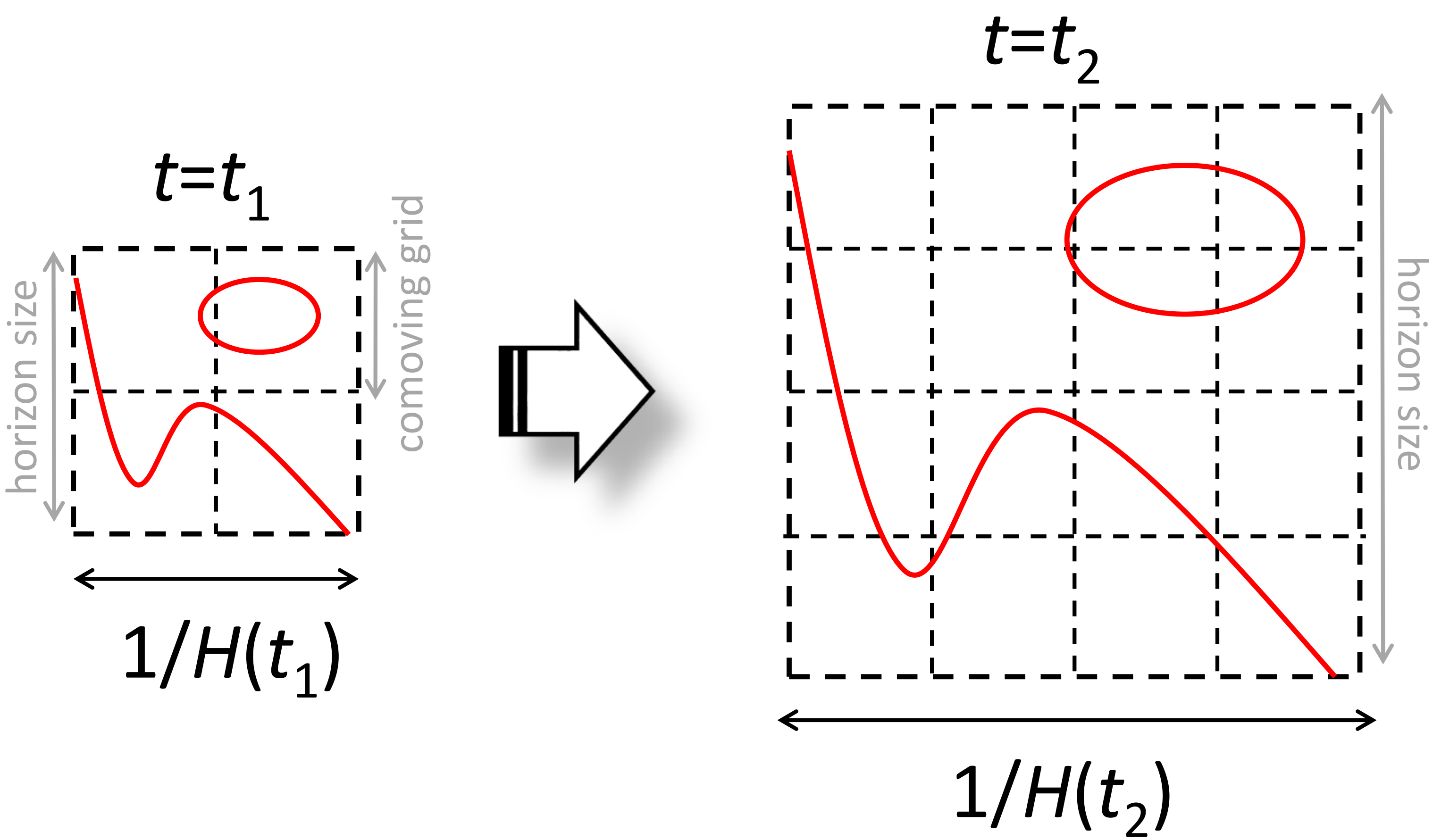
- How does string network evolve?
  - ✓ Comoving : $L_{str} \propto a(t)$?
  - ✓ Scaling : $L_{str} \propto 1/H(t)$?
  - ✓ Anything else ?

Hiramatsu+Sendouda+Takahashi+**DY**+Yoo, 1307.0308

Q1 : How does a string network evolve?



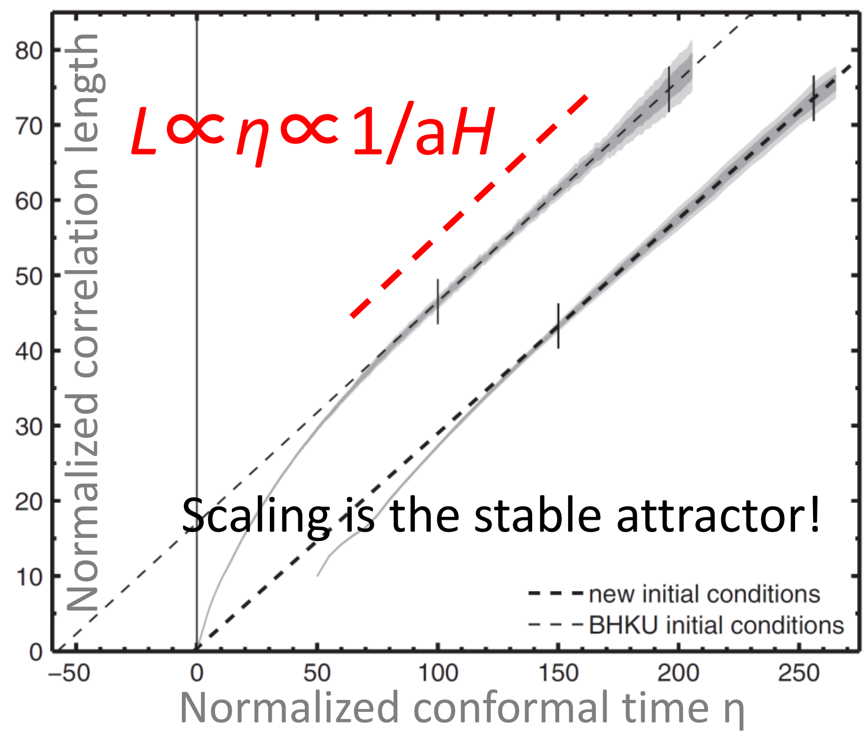
Scaling



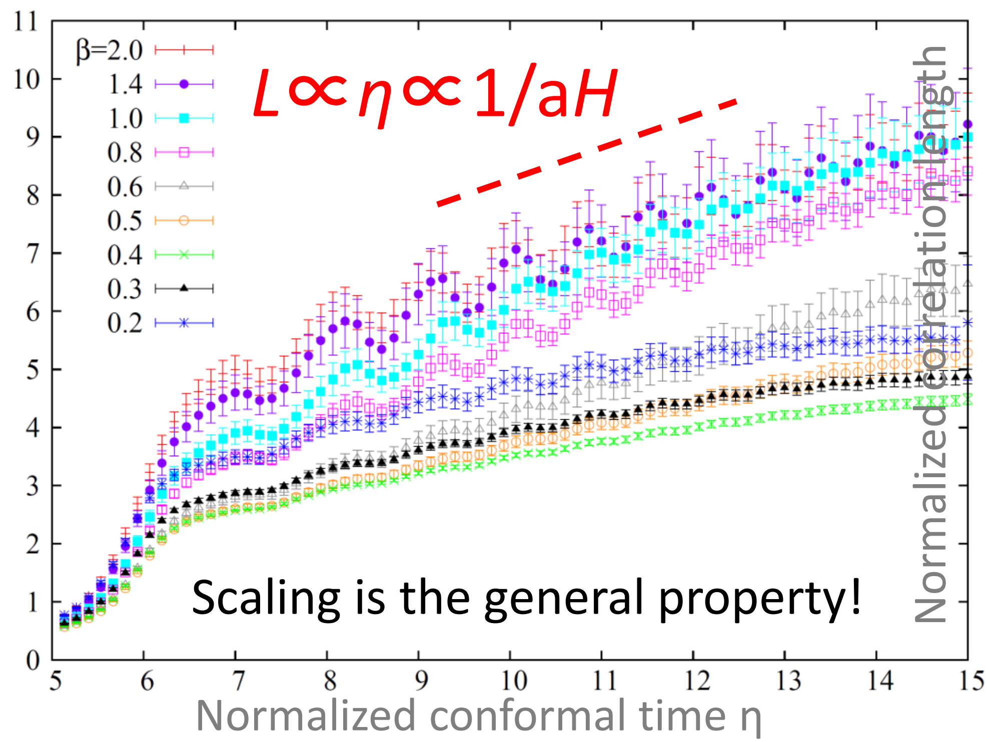
- Number of strings inside the Hubble volume is always O(1)!
- Length of a string is always given by Hubble length 1/H.

Scaling

[Bevis+, 1005.2663]



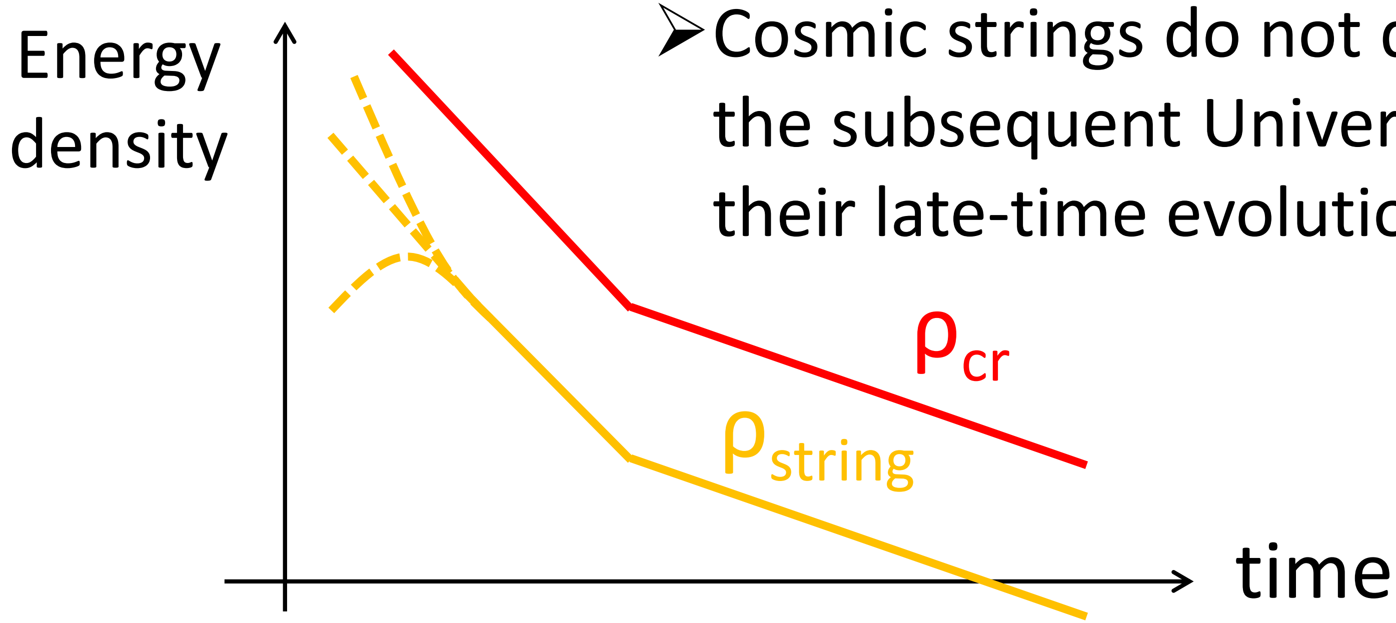
[Hiramatsu+**DY**+, 1307.0308]



- ➢ Number of strings inside the Hubble volume is always O(1)!
- ➢ Length of a string is always given by Hubble length 1/H.

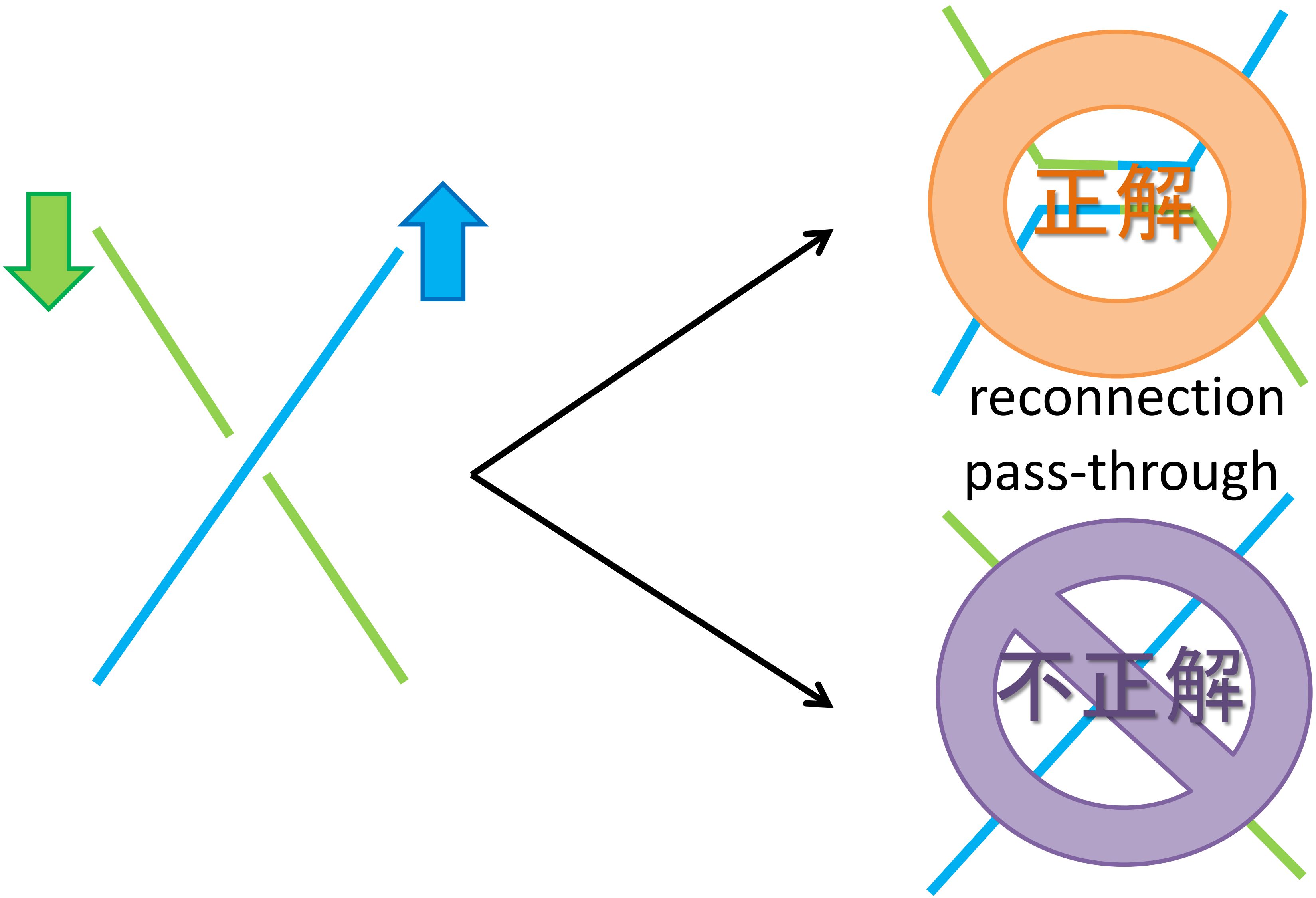
Scaling

$$\frac{\rho_{\text{string}}(\mathrm{t})}{\rho_{\text{cr}}(\mathrm{t})} = \frac{\mu \times \underbrace{L(t)}_{\sim 1/H(t)} \times \underbrace{n_{\text{string}}(t)}_{\sim 1/H^3(t)}}{(3/8\pi G_N)H^2(t)} \sim G_N\mu = \text{const.}$$



- Cosmic strings do not dominate the subsequent Universe due to their late-time evolution.

Q2 : What happens when 2 strings collide?



[cf. Salmi+, 0712.1204]

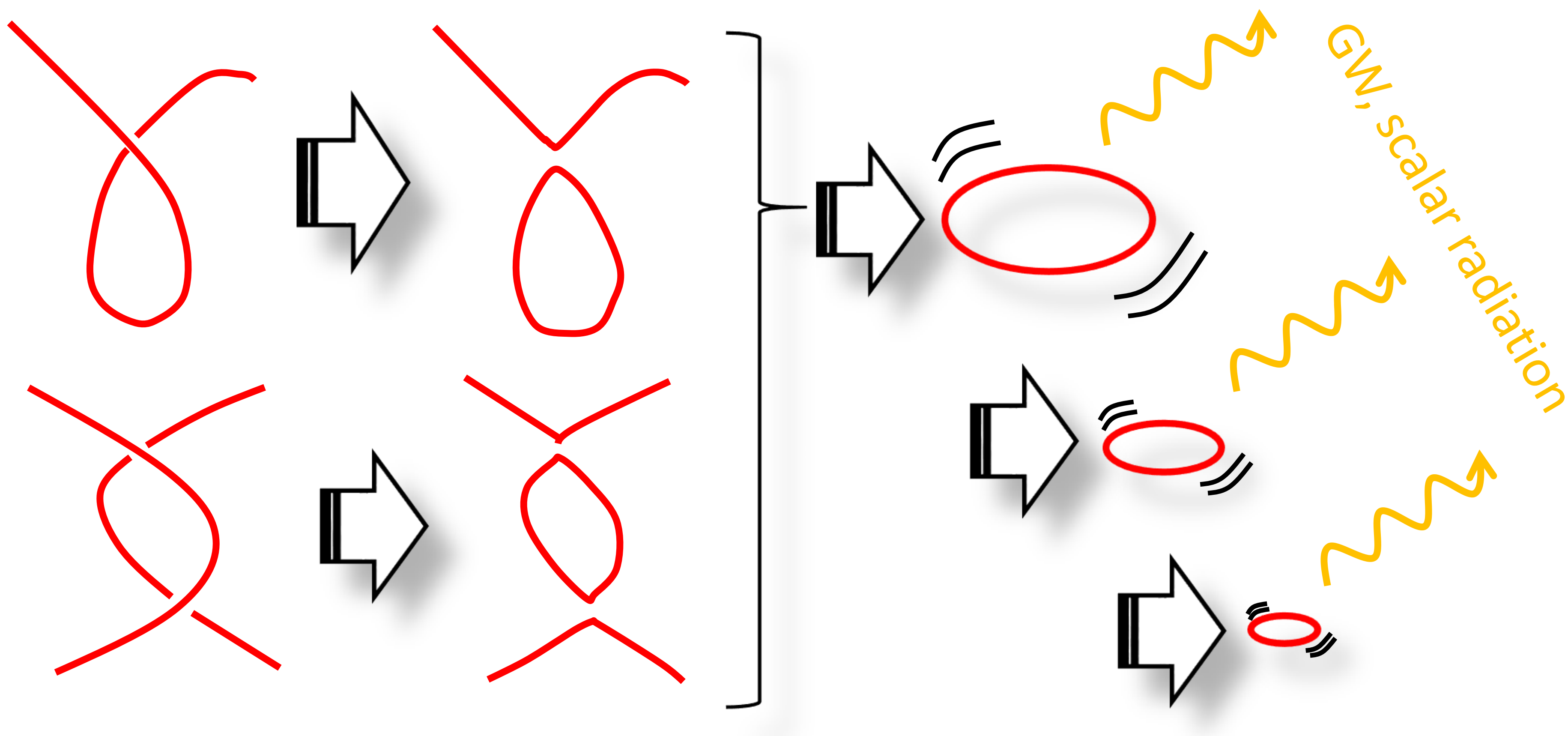
Reconnection

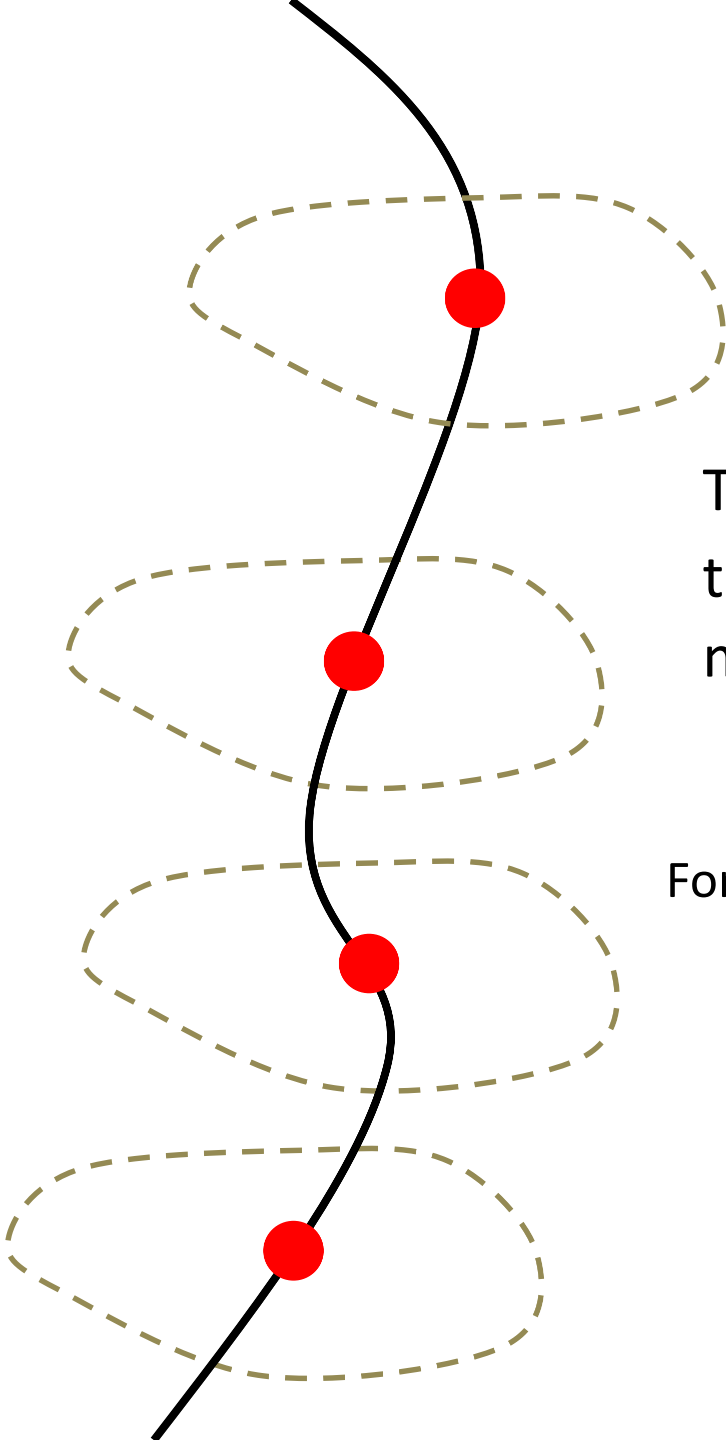
- Reconnection almost always happens! (P~1)
- But in some case, a junction may form:

[Hiramatsu+**DY**+Steer, in progress]

Loop formation and energy loss

When a string crosses itself, a loop separate from the string.
The energy of long strings is converted into small string loops,
which eventually shrink due to GW & scalar radiation.





String gravity

The nonvanishing energy-momentum tensor, $T_{\alpha\beta}$, modifies the spacetime metric $g_{\alpha\beta}$ through the Einstein eq.

For a static straight string lying along z-axis,

$$T^0{}_0 = T^z{}_z = \mu\, \delta^2(\boldsymbol{x}\text{-}\boldsymbol{x}_{\mathrm{str}})$$
$$T^x{}_x = T^y{}_y = 0$$

[Vilenkin (1981)]

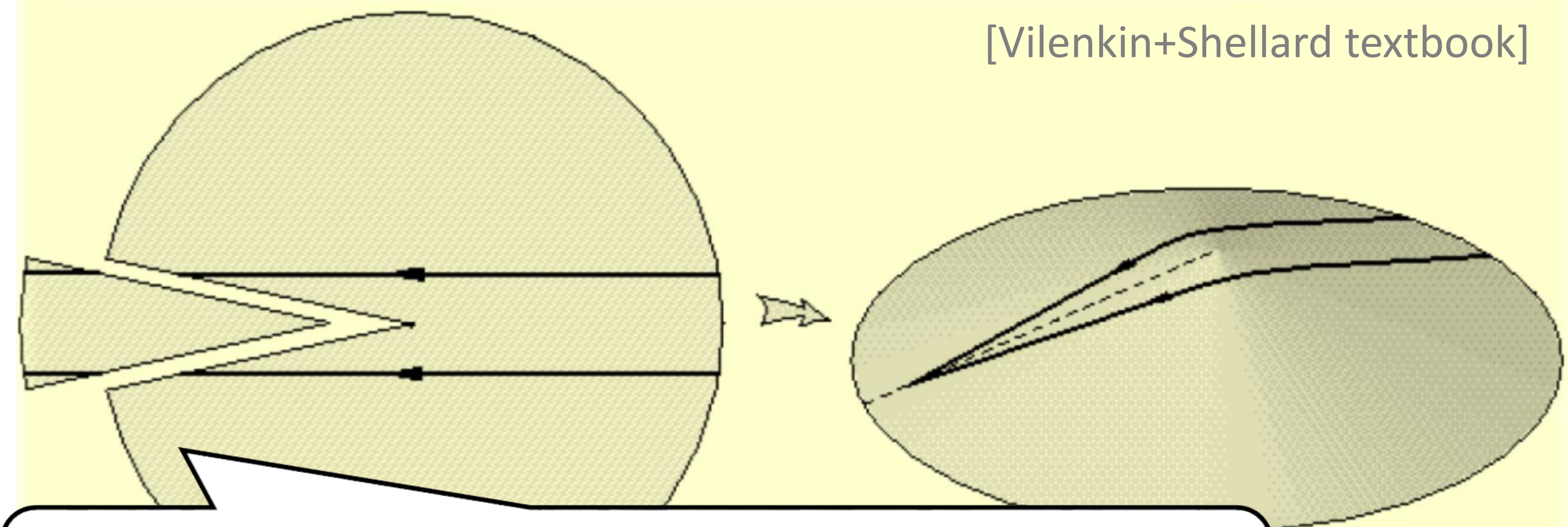
Conical structure

The spacetime around a straight cosmic string is “locally” flat.

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + \mathrm{d}z^2 + \mathrm{d}r^2 + r^2\mathrm{d}\theta^2$$

$$0 \leq \theta \leq 2\pi(1 - 4G\mu)$$

[Vilenkin+Shellard textbook]

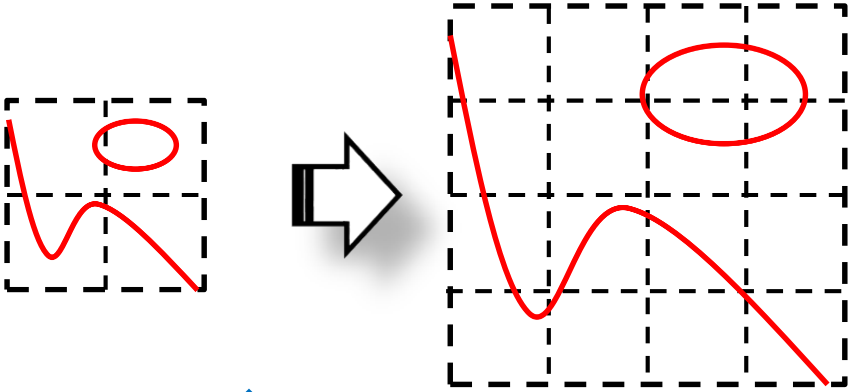


An angular wedge of width Δ=8πGμ is removed from the space and the remaining edges identified.

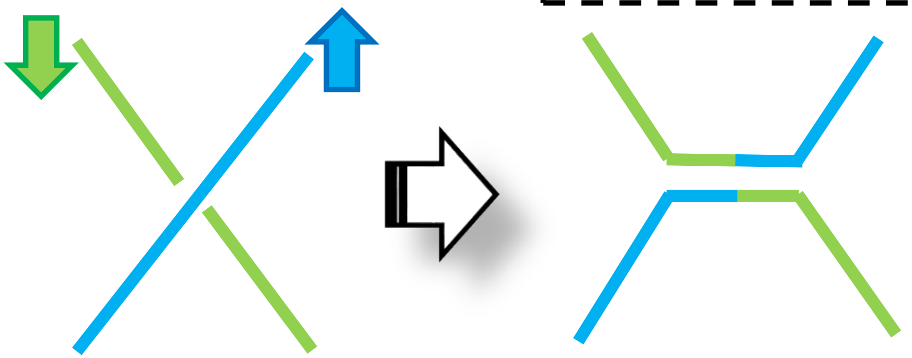
Take-home message

➢ We can obtain the robust predictions because…

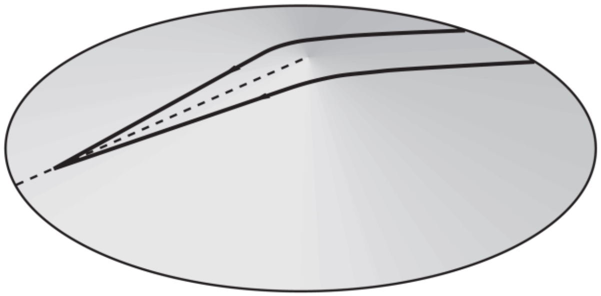
1. Scaling



2. Reconnection



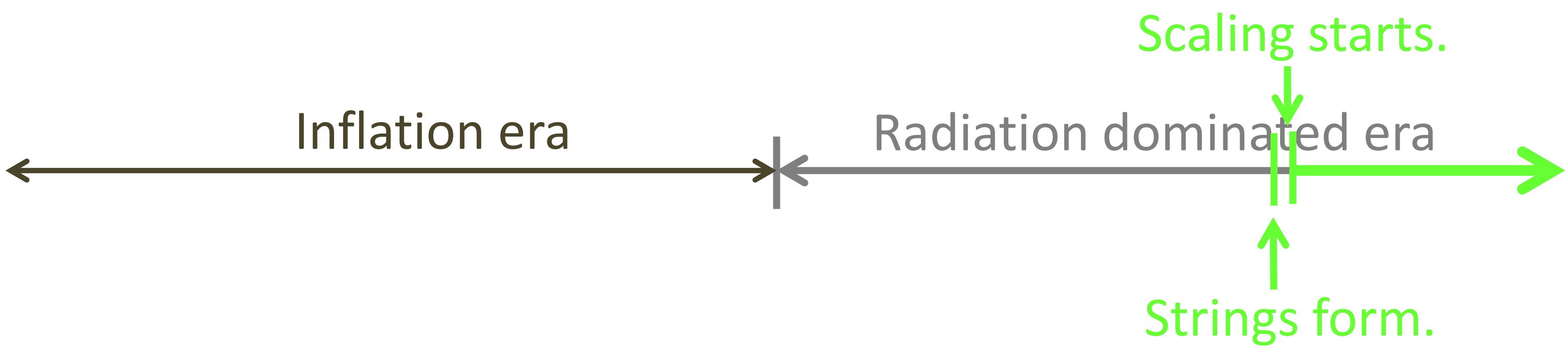
3. Conical structure



SOME LOOPHOLES

[Lazarides+Shafi(1984), Shafi+Vilenkin(1984), Yokoyama (1988),...]

When do strings form?



- Standard cosmic strings are produced at the phase-transition during radiation-dominated era.

⇒ The scaling can be achieved just after the formation.

[Lazarides+Shafi(1984), Shafi+Vilenkin(1984), Yokoyama (1988),...]

When do strings form?

Strings form.

Scaling starts.

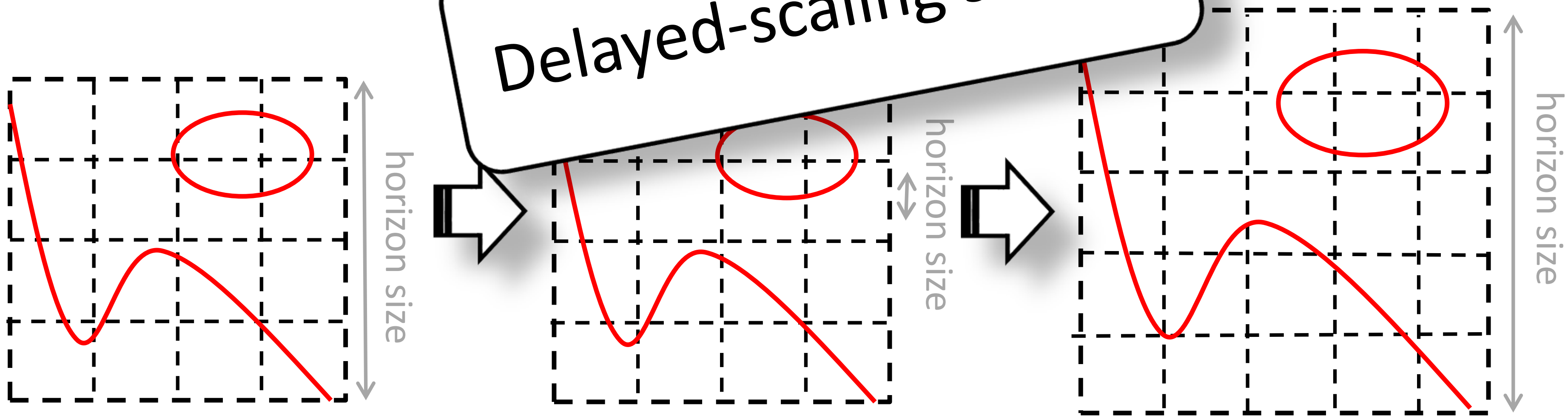
Inflation era

Radiation dominated era

They are diluted and the mean separation expands exponentially until end of inflation.

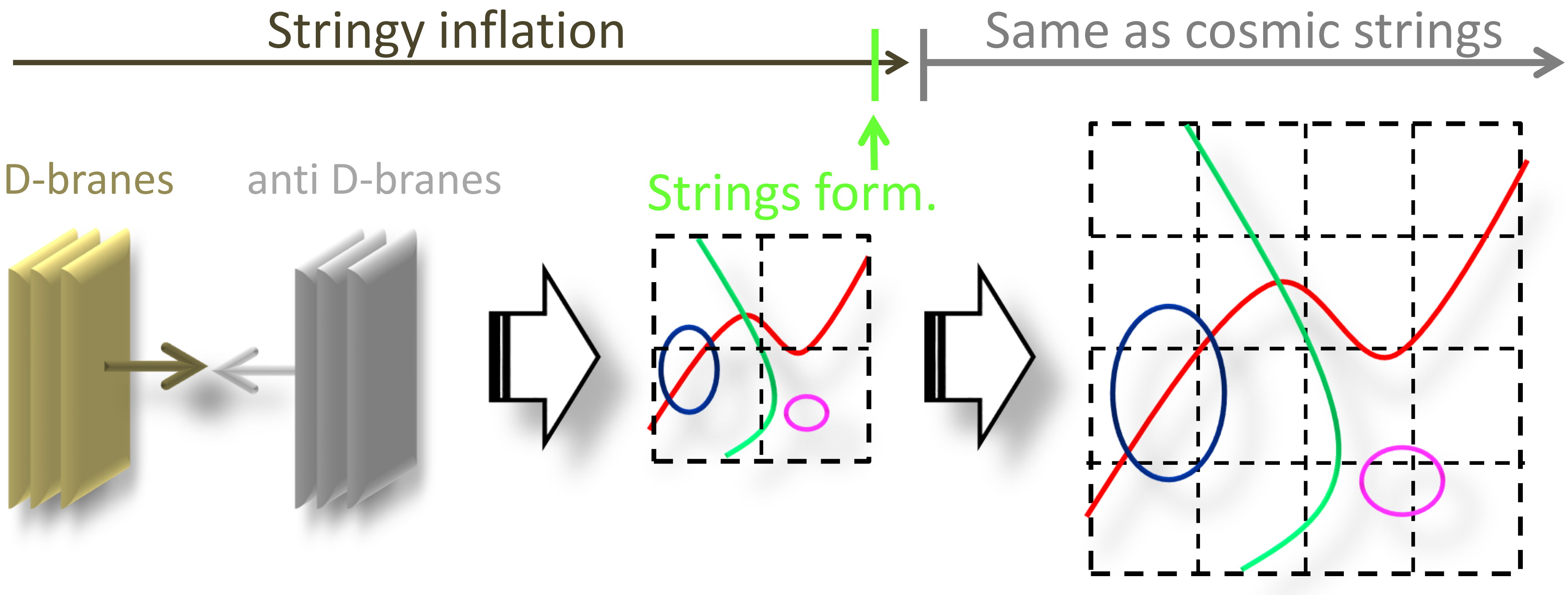
The network enters the scaling regime at the la... because L>>1/H and ... occur.

Delayed-scaling strings



Cosmic superstrings : Observable remnants of string theory

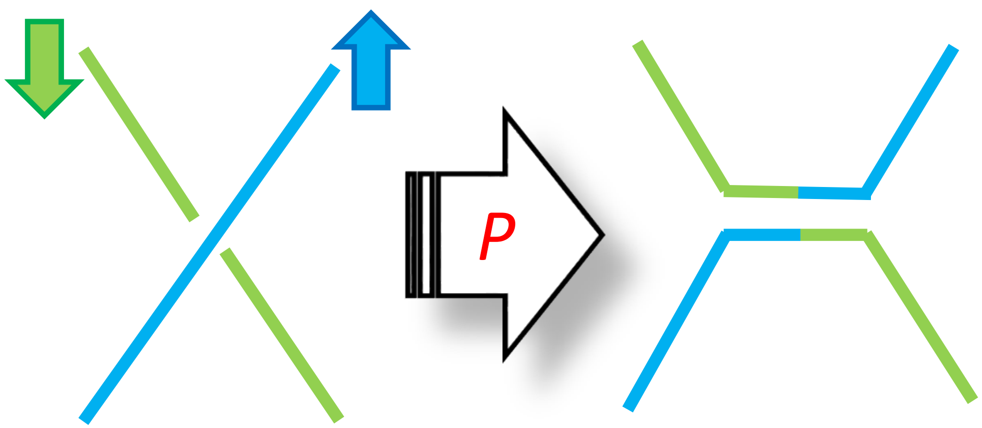
- Fundamental strings, which are elementary objects in string theory, could stretch to macroscopic scale by the expansion of the Universe (without suffering instability).



[original:Witten(1985)] [Sarangi+Tye(2002), Jones+(2003), Dvali+Vilenkin(2004)]

Cosmic superstrings : Observable remnants of string theory

- There are several differences from the standard cosmic strings:
  - ✓ Reconnection probability P



For standard strings

$P \sim 1$

For cosmic superstrings

$P << 1$

  - ✓ Appearance of bound states
  - ✓ Multiple tension network
  - ✓ …

[original:Witten(1985)] [Sarangi+Tye(2002), Jones+(2003), Dvali+Vilenkin(2004)]

Contents

Observational prospects for strings

- Cosmic Microwave Background
- Gravitational waves
- Weak/strong gravitational lensing
- 21cm line
- …

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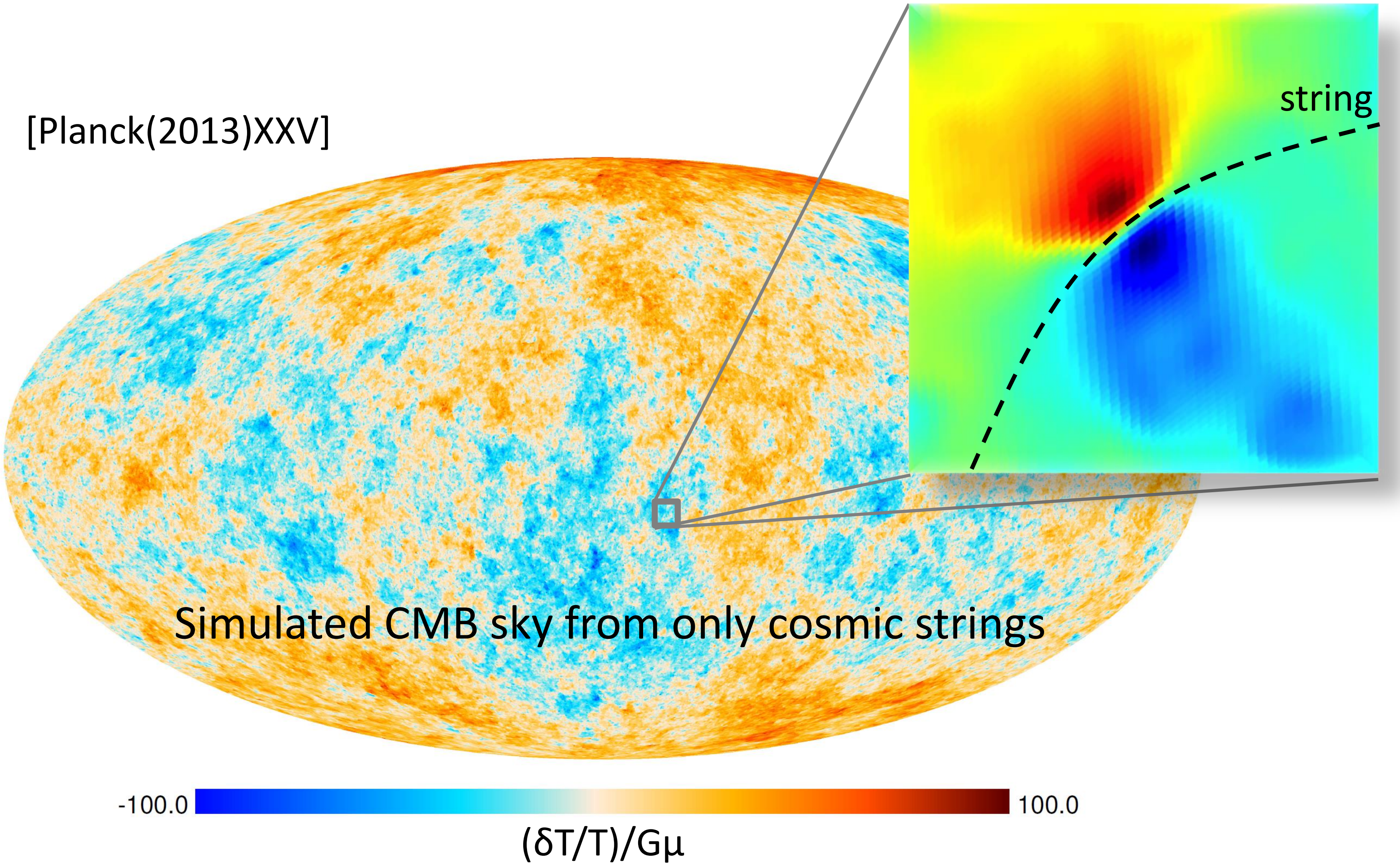
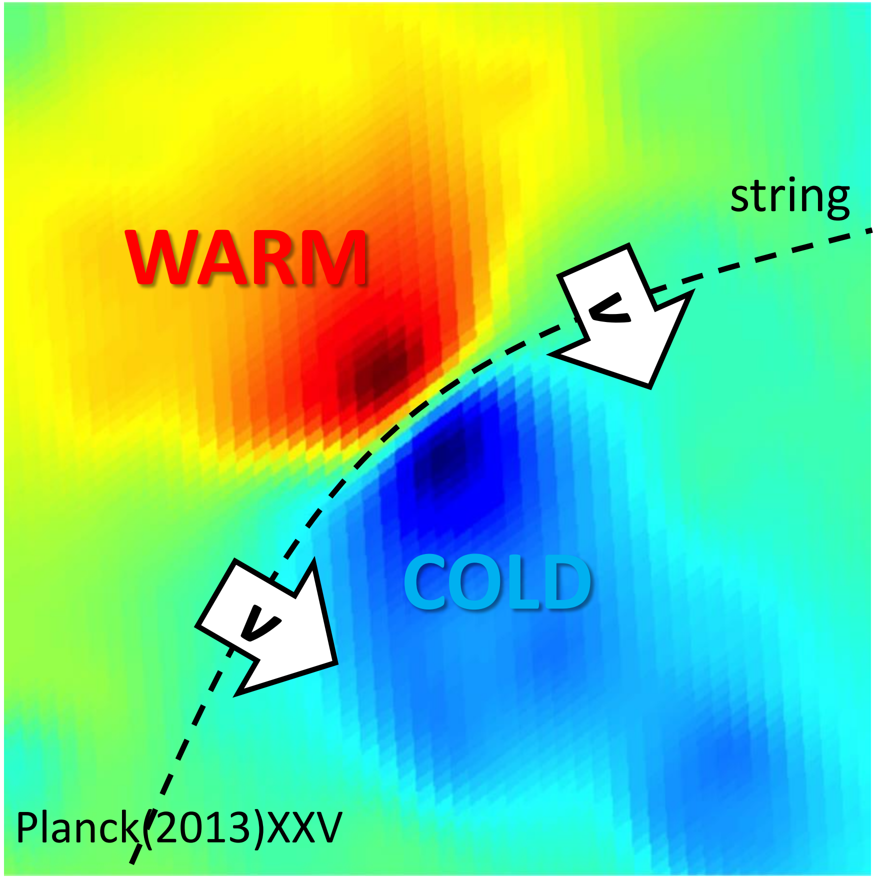
Cosmic strings on the CMB sky

[Planck(2013)XXV]



CMB temperature anisotropies



Cosmic strings create line-like discontinuities in the CMB signal (through Integrated Sachs-Wolfe).

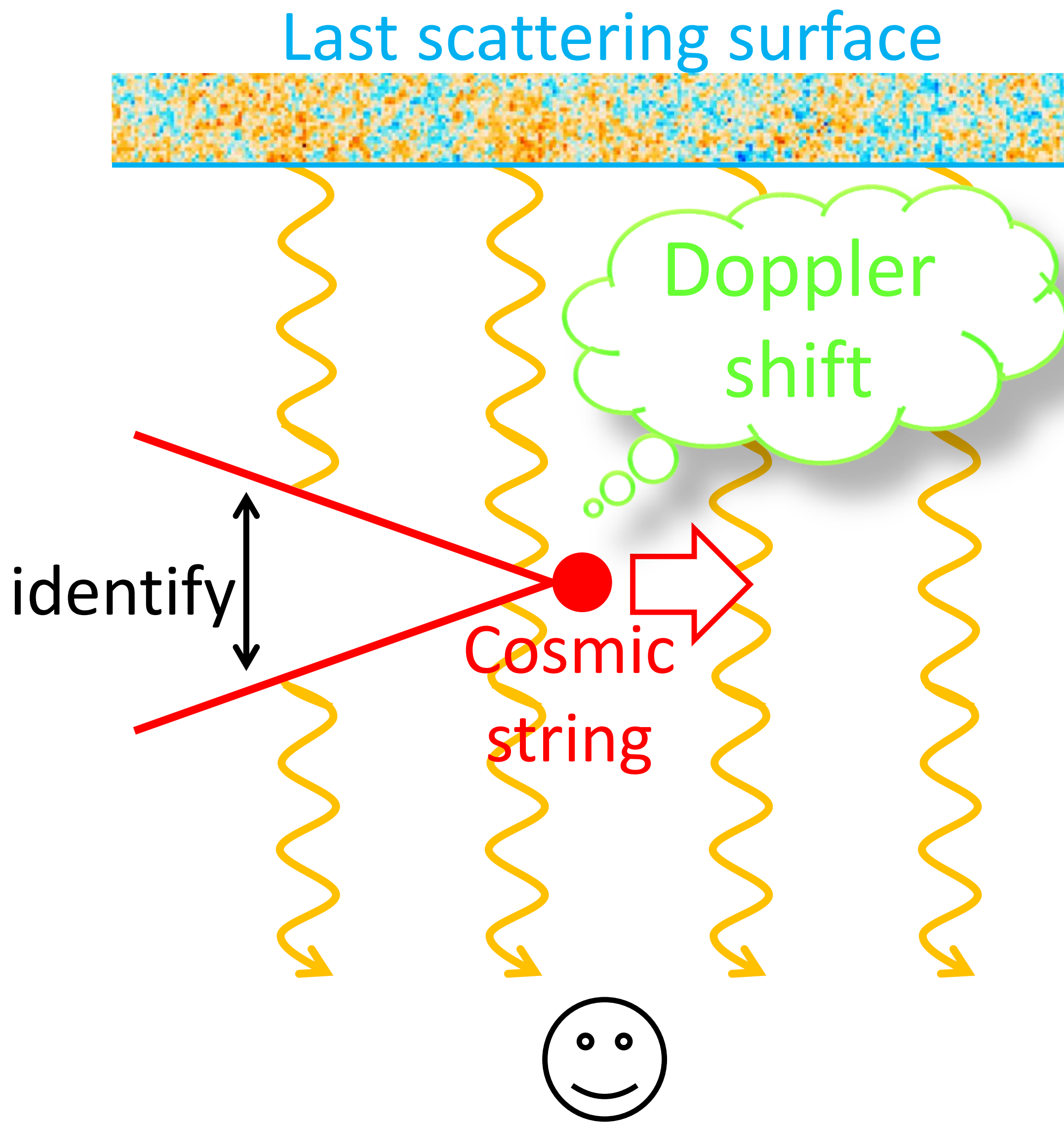
[Kaiser+Stebbins (1984), Gott III(1985)]

$$\frac{\delta T}{T} = 8\pi G\mu \frac{v}{\sqrt{1-v^2}}$$

[For curved strings, **DY**+, 1004.0600,
For kinks/cusps, Takahashi+**DY**+, 0811.4698]

[For curved strings, **DY**+, 1004.0600]

CMB temperature anisotropies



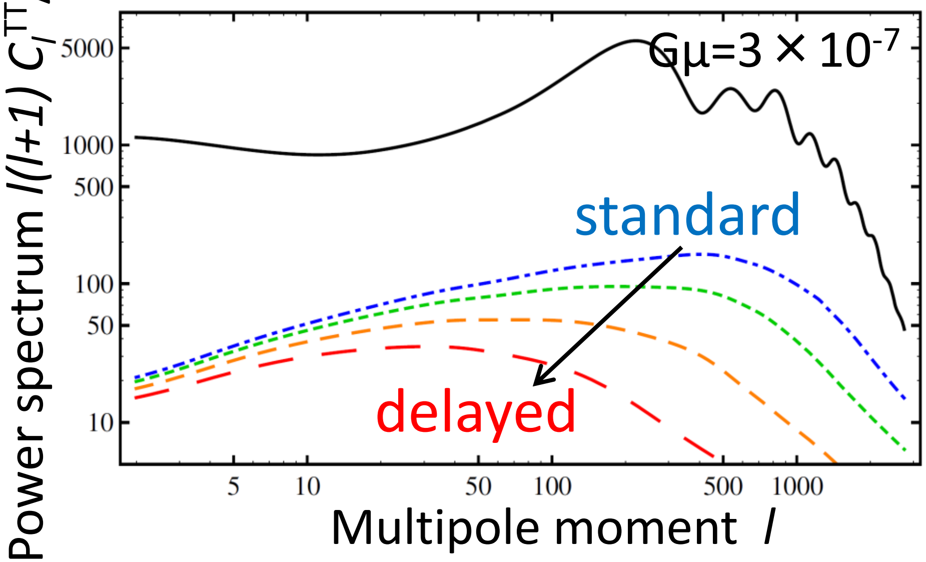
- As the string moves across the line of sight, the CMB photons are boosted towards the observer.

A relative CMB temp shift across the string

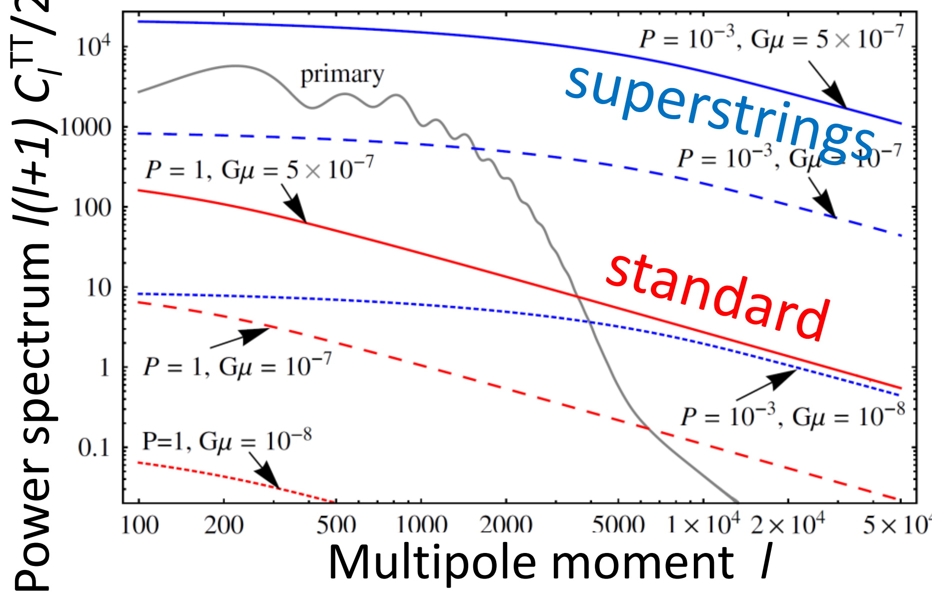
[Kaiser+Stebbins (1984), Gott III(1985)]

CMB temperature power spectrum

Delayed scaling scenario
[Kamada+**DY**+, 1407.2951]



Cosmic superstrings
[**DY**+, 1006.0687]



The observations of the acoustic oscillation in the CMB have excluded strings as the dominant source of the CMB anisotropies:

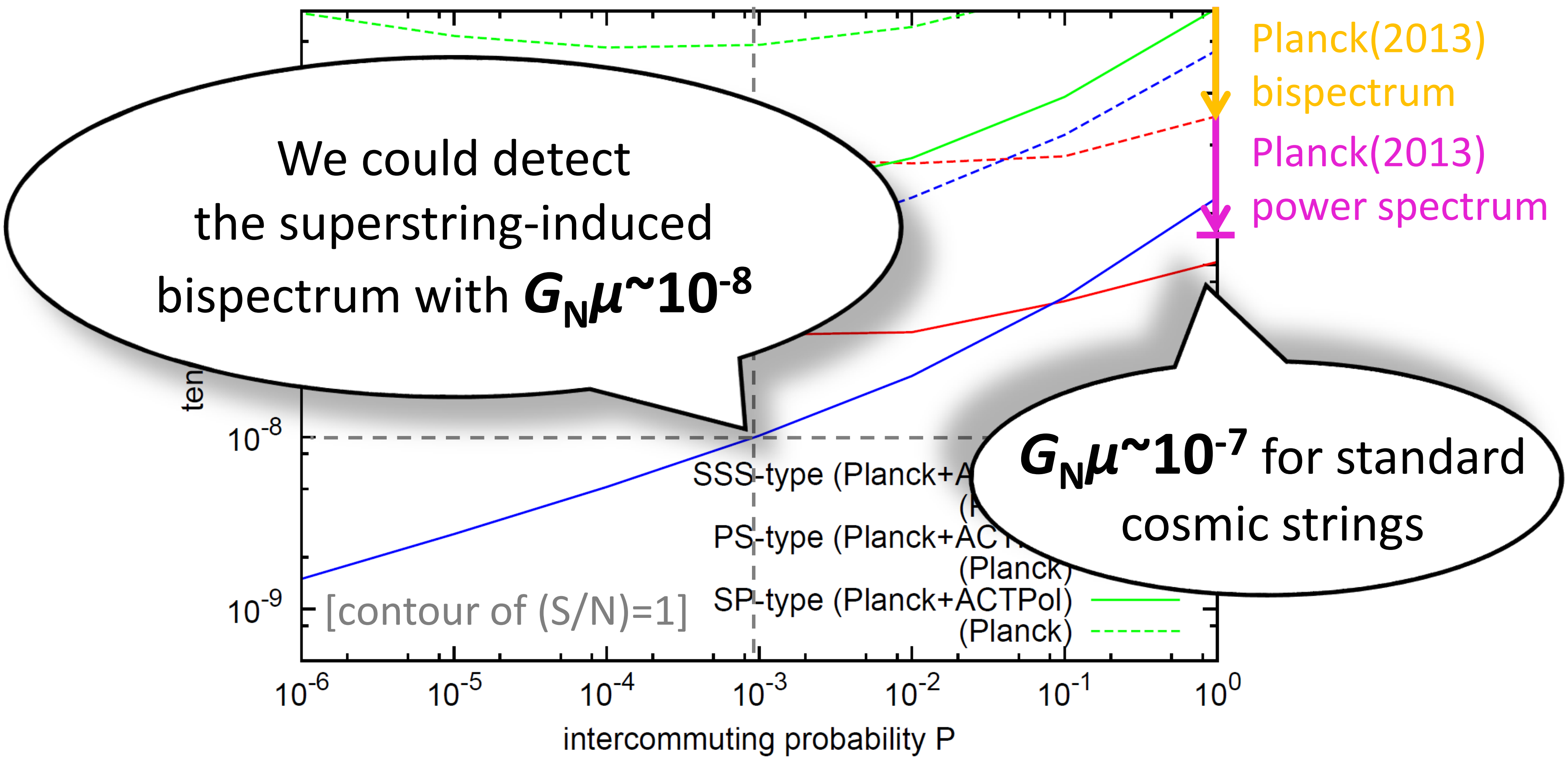
$$G_N\mu < 1.3\times10^{-7}$$ (95%CL, standard) [Planck(2013)XXV]

[**DY**+Sendouda+Takahashi, 1309.5528]

Detectability from future CMB obs.

(1) String-induced temprature 3-point functions

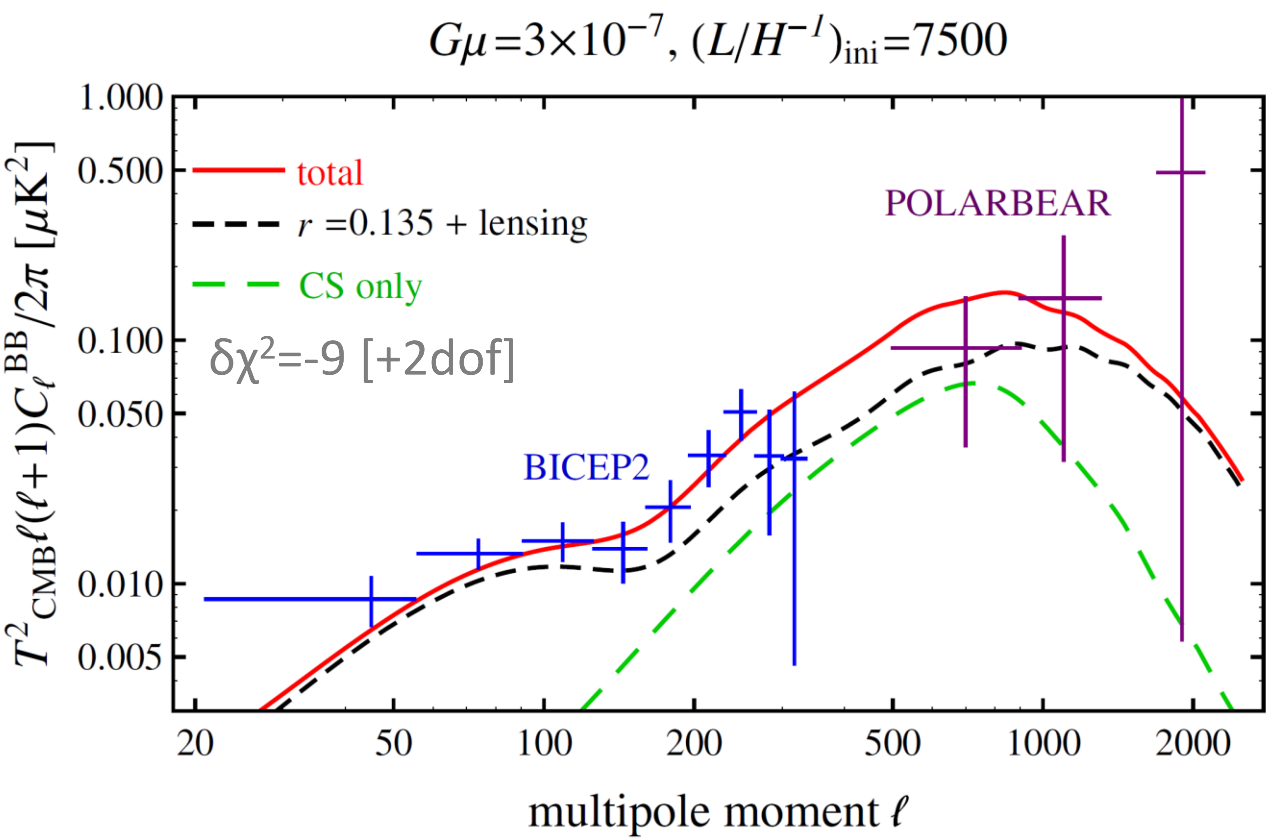
= (SSS-type) + (PS-type) + (SP-type)



Detectability from future CMB obs.

(2) String-induced B-mode polarization

The presence of delayed-scaling strings improves the fit to the BICEP2+POLARBEAR data, although more data are required.

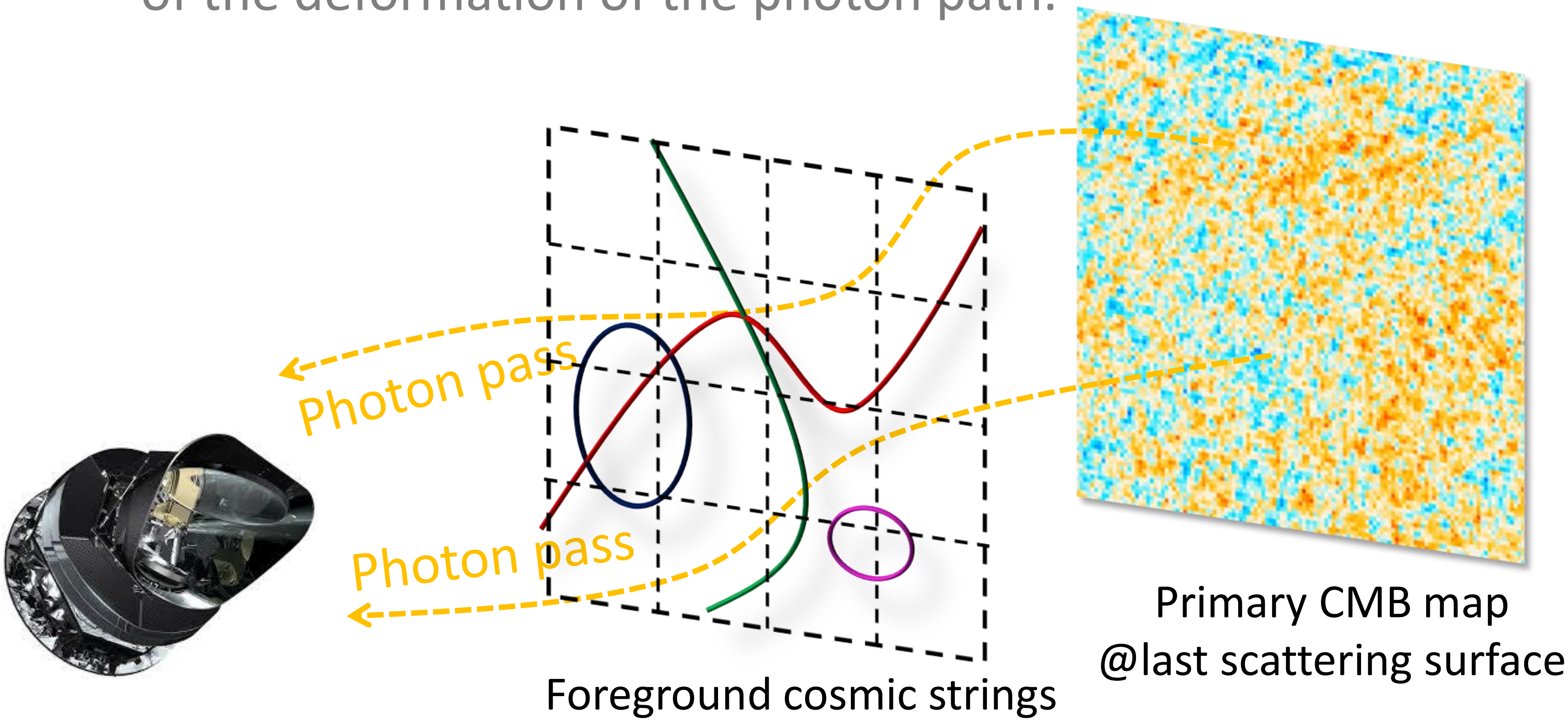


[Namikawa+**DY**+Taruya, 1205.2139, 1308.6068]

Detectability from future CMB obs.

(3) String-induced CMB lensing

:can provide a evidence for the intervening strings along a line of sight by measuring the spatial patterns of the deformation of the photon path.

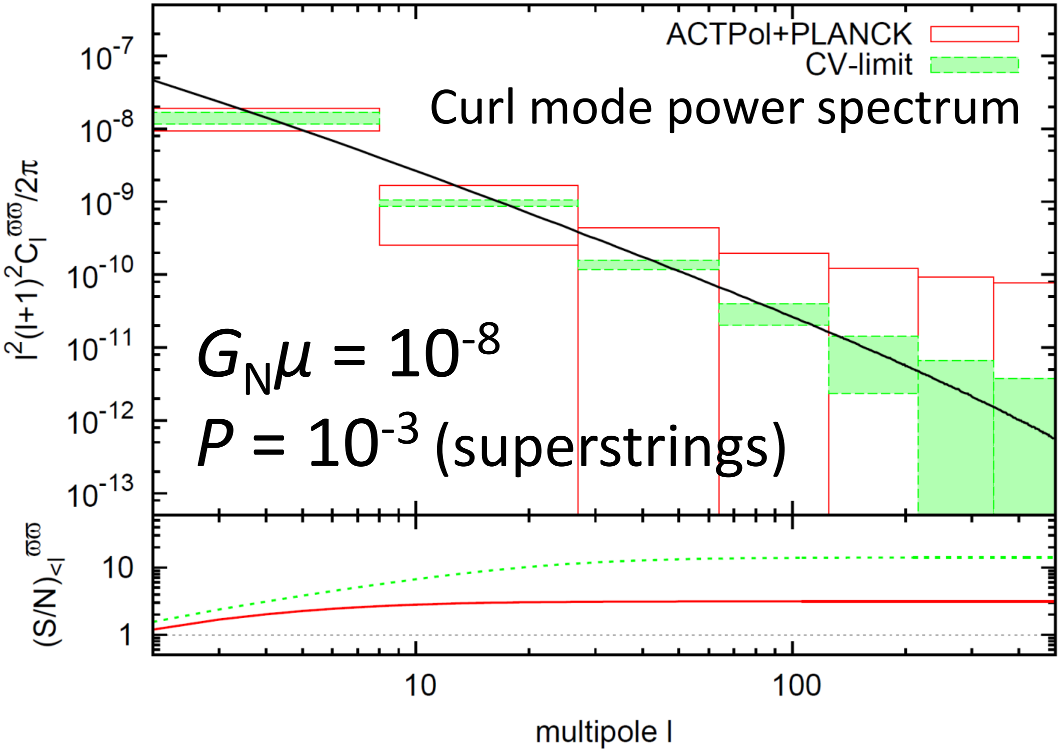


[Namikawa+**DY**+Taruya, 1205.2139, 1308.6068]

Detectability from future CMB obs.

(3) String-induced CMB lensing

Strings continuously generate vector and tensor pert. even at late time, which induce the parity-odd mode signal.



- **Planck (current)**

  $G_N\mu < 3\times10^{-8}\,(P/10^{-3})$

  [95%C.L., curl-mode]

- **Future**

  $G_N\mu < 2\times10^{-9}(P/10^{-3})$

  [(S/N)=1, curl-mode]

[For parity-even mode for CMB lensing, **DY**+Takahashi+Sendouda+Yoo, 1110.0556]

Observational prospects for strings

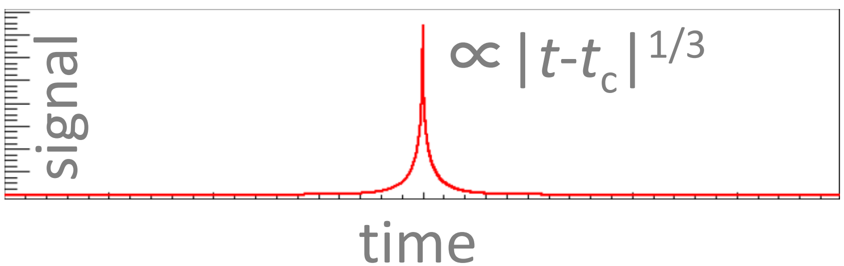
- Cosmic Microwave Background
- Gravitational waves
- Weak/strong gravitational lensing
- 21cm line
- ...

Gravitational waves from strings

- Oscillating loops of string can generate a potentially observable GW.

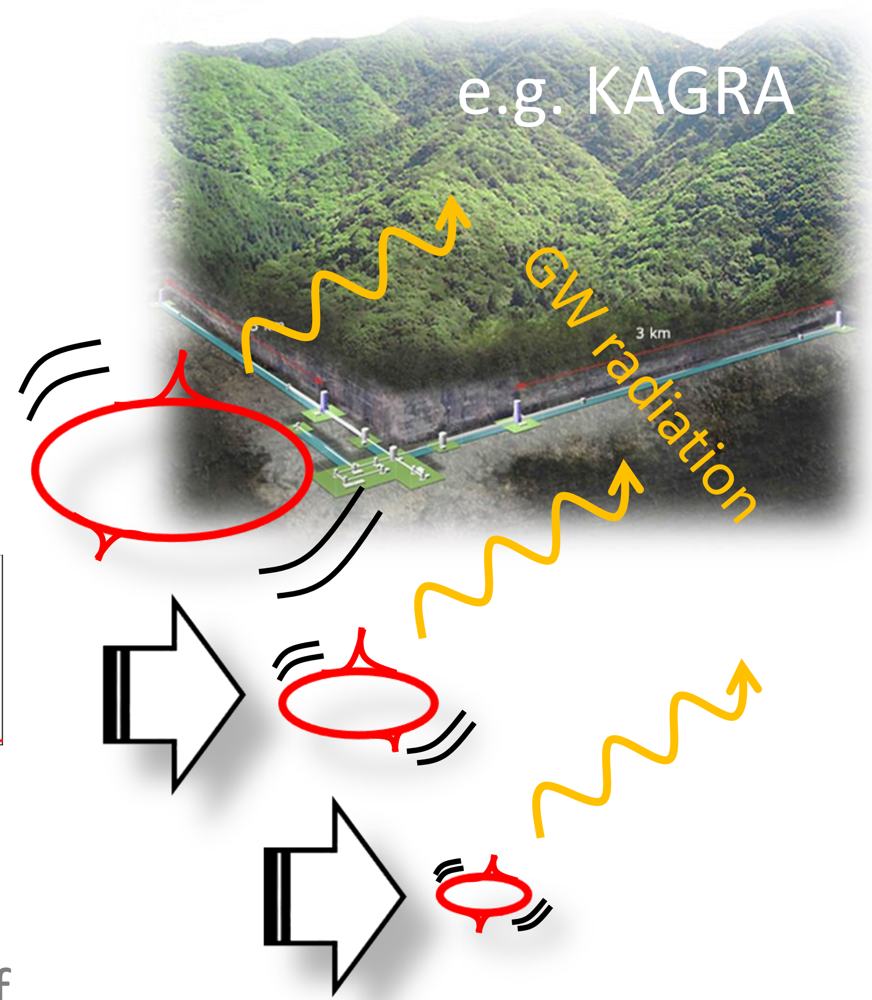
✓GW burst

: GW with shot duration [<1s]



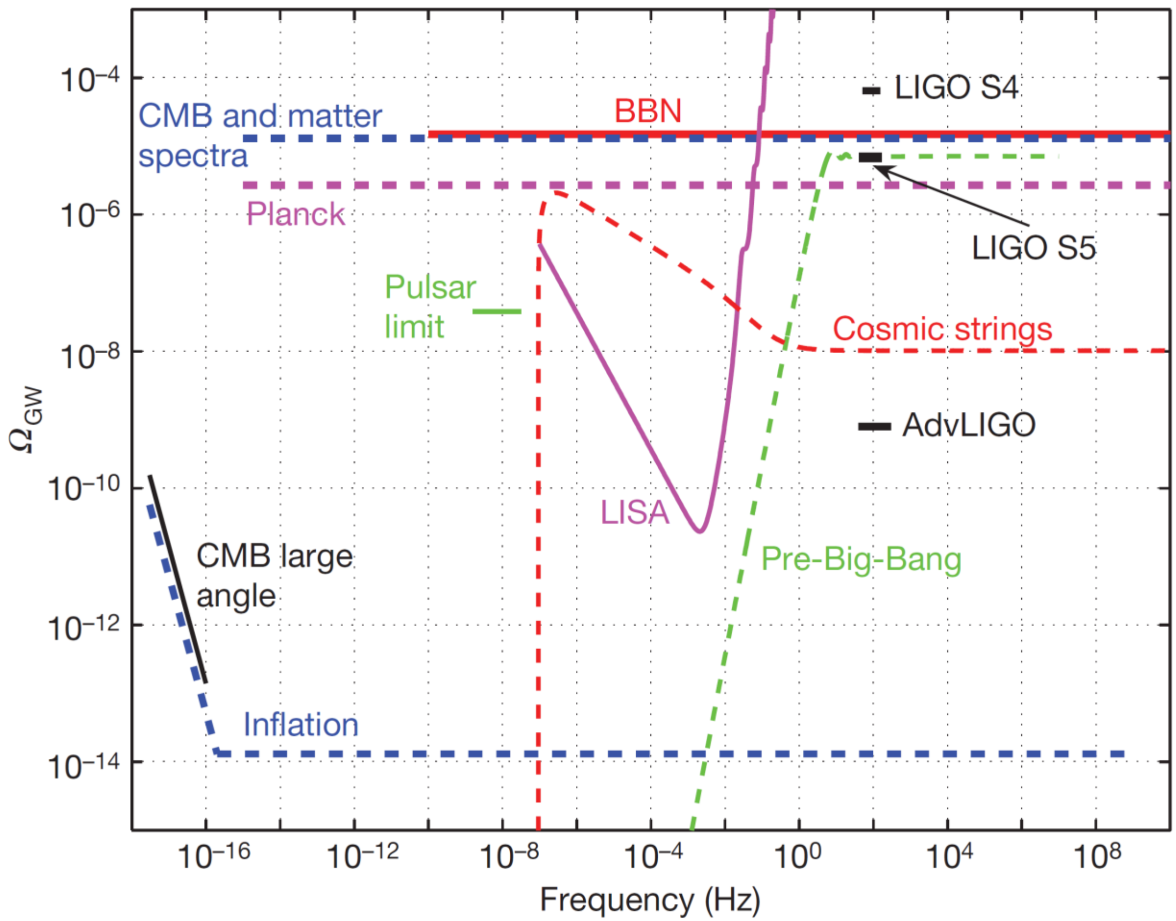
✓Stochastic background

: produced by superposition of bursts from a string network.



[LIGO+Virgo collaborations, 0910.5772]

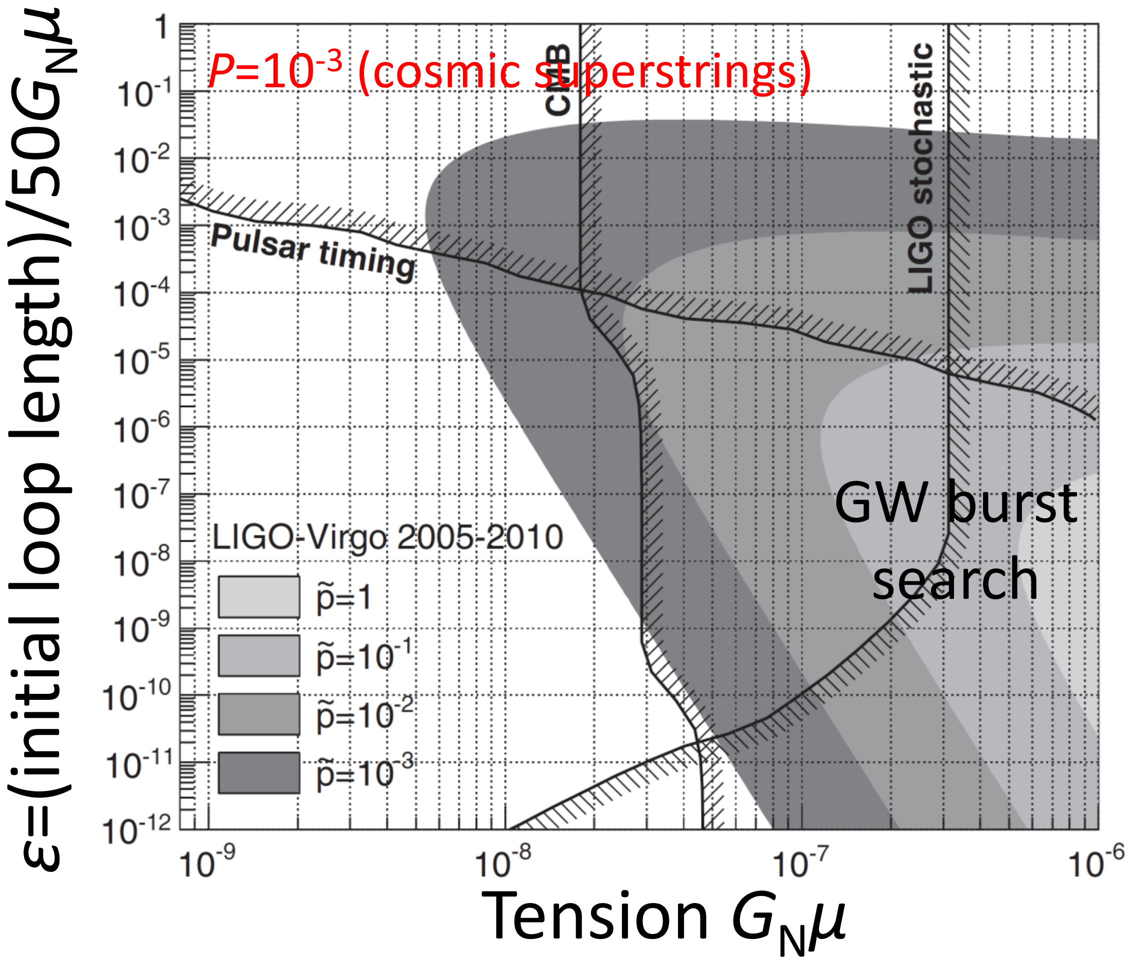
Stochastic background : $\Omega_{GW}=(1/\rho_c)d\rho_{GW}/d\log f$



$$\Omega_{BBN} = \int \Omega_{GW}(f)\, d(\ln f) < 1.1\times 10^{-5}(N_\nu - 3)$$

[LIGO+Virgo collaborations, 1310.2384]

Constraints on tension and initial loop length



- Note : the amplitude of GW strongly depends on the loop distribution.
- The allowed parameters: (P=10^{-3} case)

$$G_N\mu < 10^{-11}$$
(long loop model)

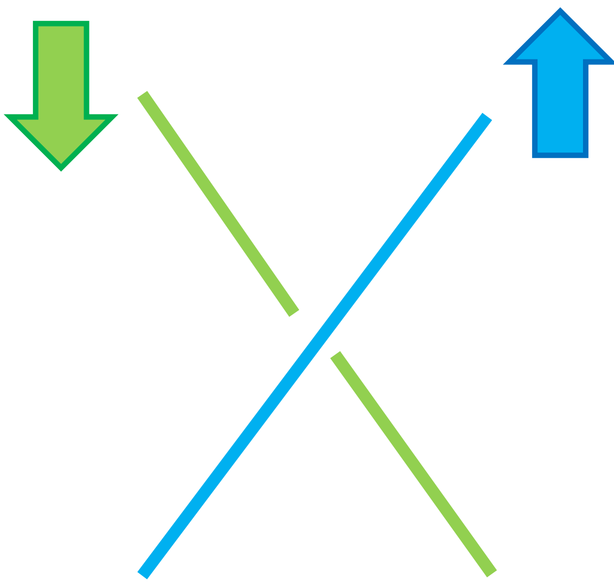
$$G_N\mu < 3 \times 10^{-8}$$
(small loop model)

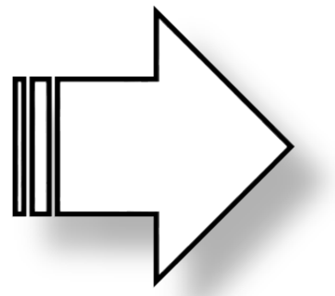
[For delayed-scaling strings, Deno+**DY**+Yokoyama, in progress…]

Contents

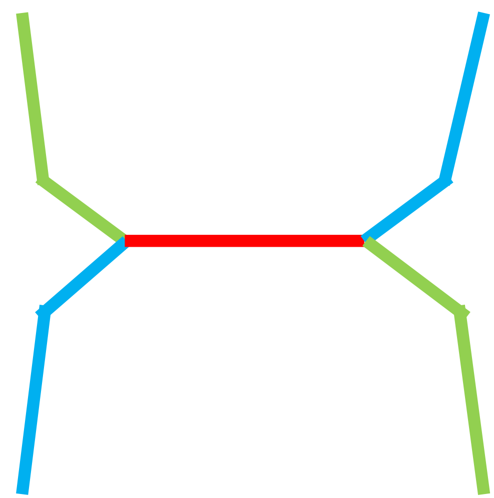
Can we see bound states in a network?

When two (type-I or super-)strings collide, bound states and Y-junctions would be produced.





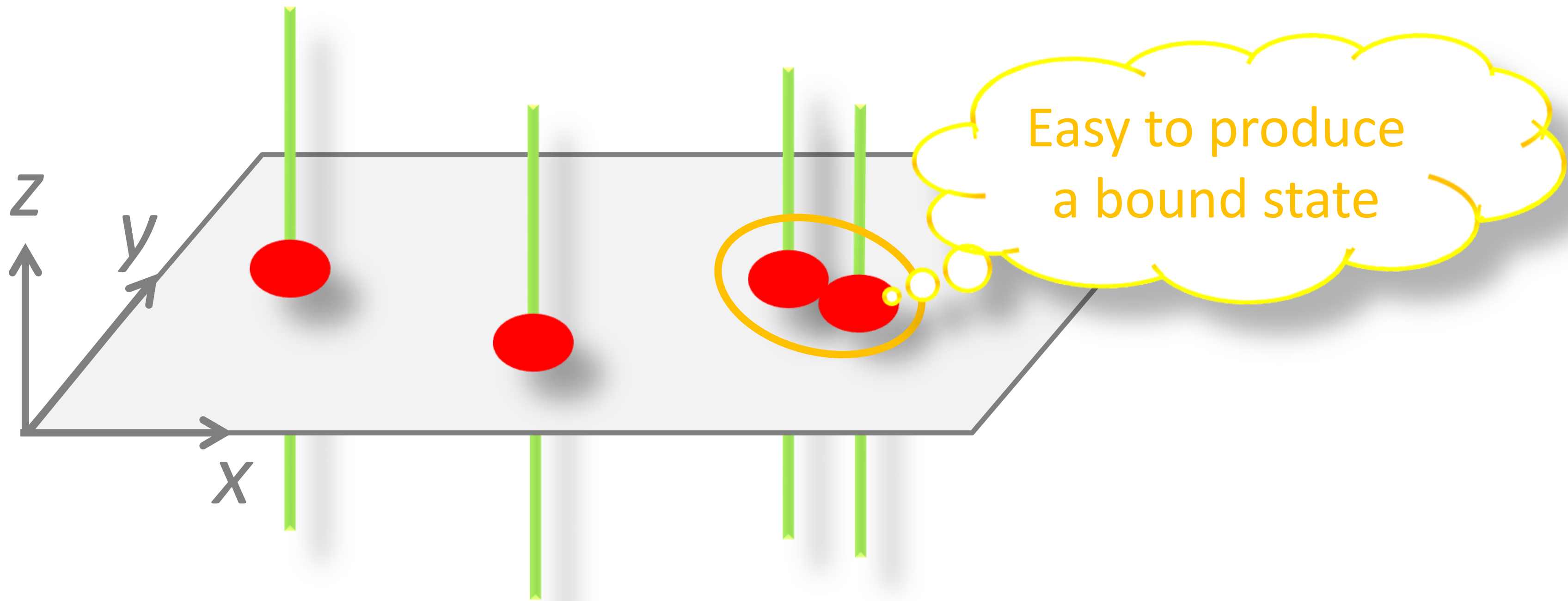
- Nearly parallel
- Low relative velocity



It is open question whether the (type-I) string network can dynamically create the bound states.

But 3-dim simulation requires heavy computational costs…

- 2-dim toy model : Impose translation sym along z-axis



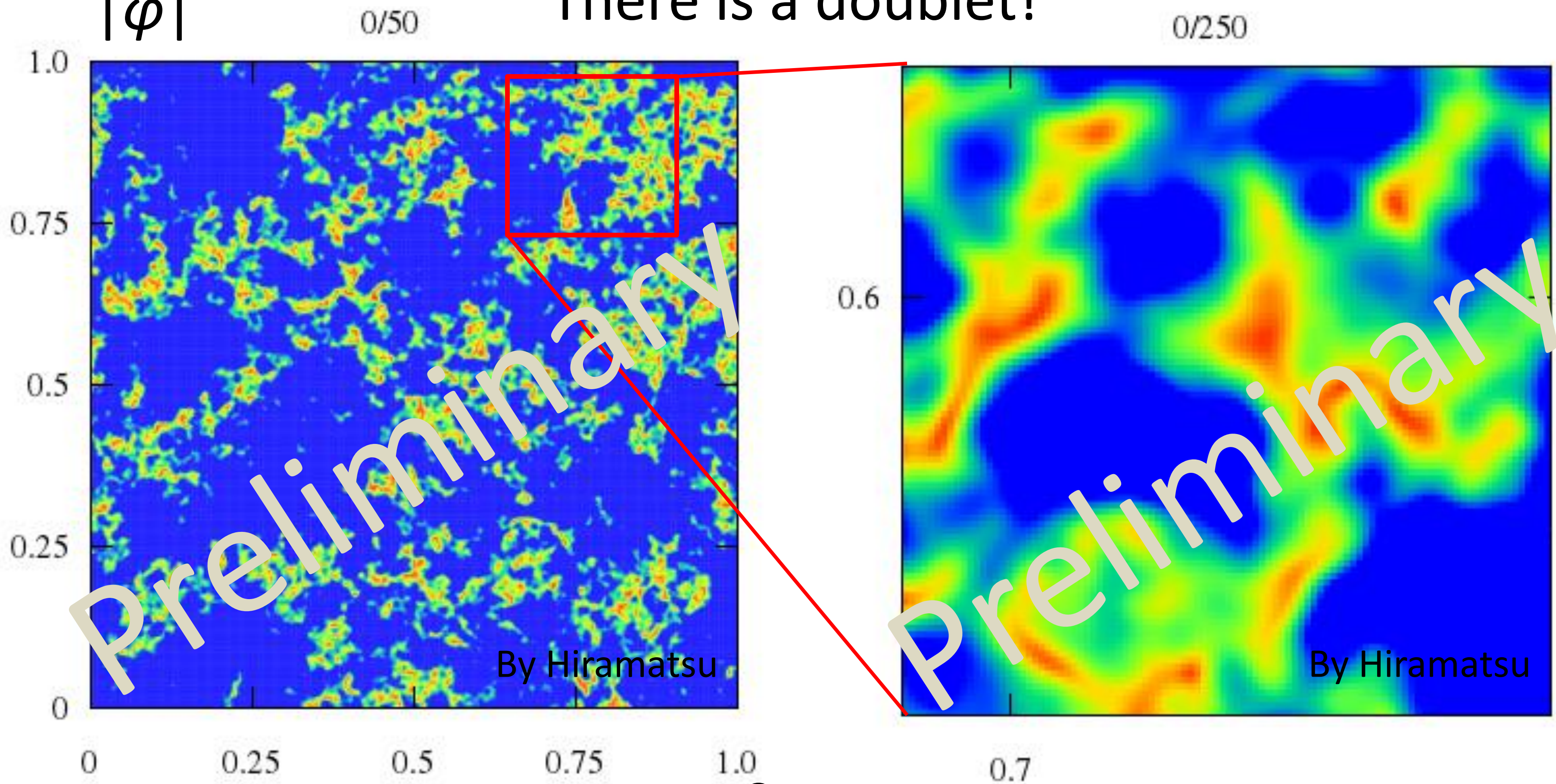
merits

- Reduce the computational costs
- Restrict the spatial degree-of-freedom
- Enhance the production rate of bound states
- May lead to the maximum fraction of bound state

Anyway, you can see bound states!

$|\varphi|$

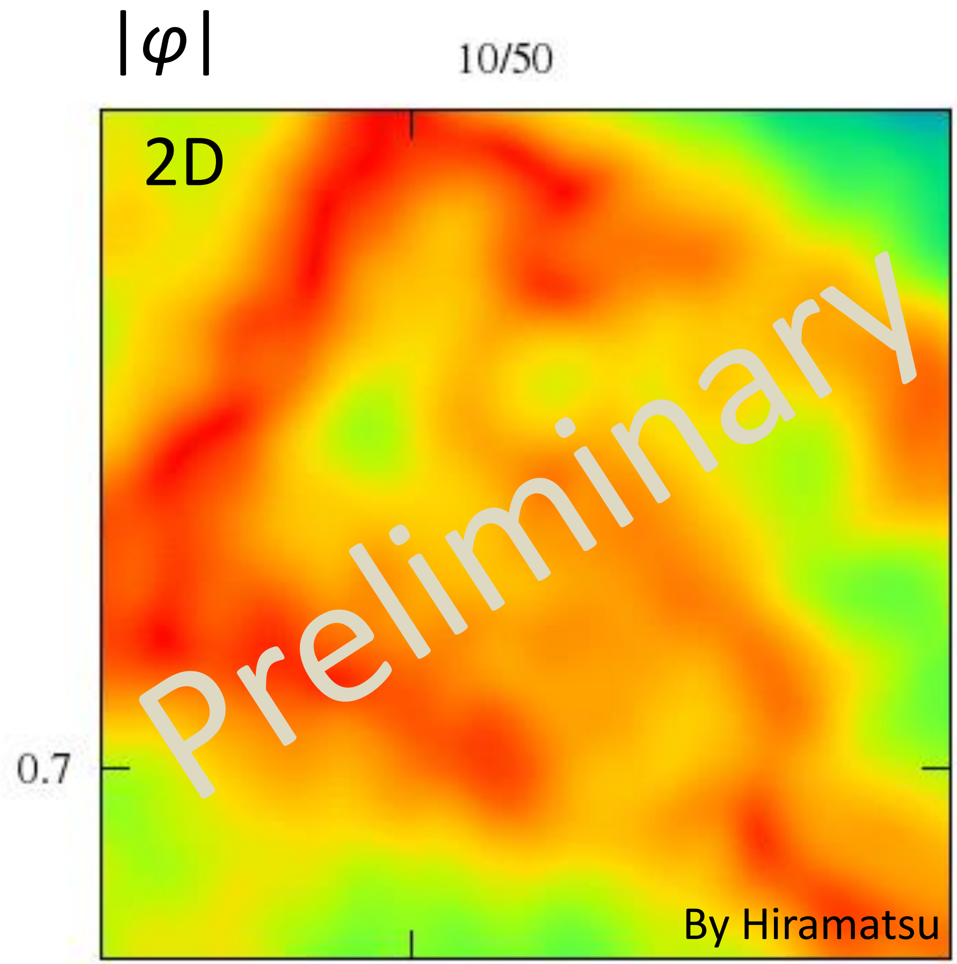
There is a doublet!



β=0.1

[Hiramatsu+**DY**, work in progress…]

Anyway, you can see bound states!



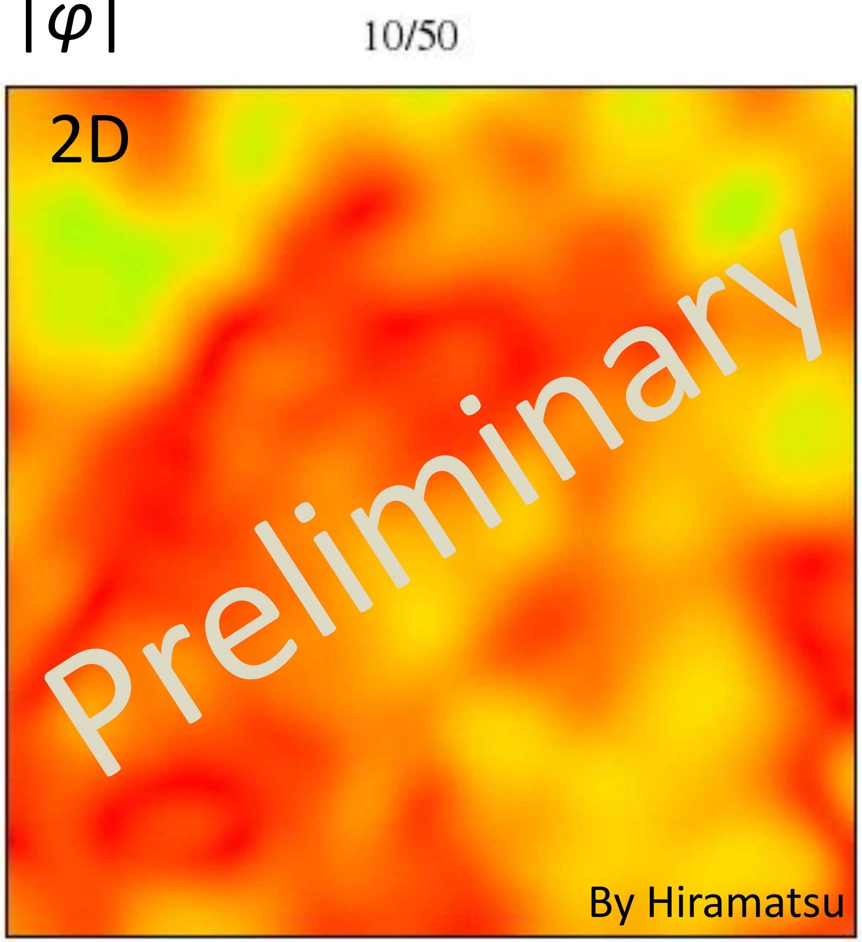
β=0.1

...and a triplet!

[Hiramatsu+**DY**, work in progress…]

Anyway, you can see bound states!

$|\varphi|$



β=0.05

Type-I string network in 2-D simulations have the bound states!

- ✓ The evolution of the network with bound states
- ✓ How large is the fraction of higher winding strings ?

[Hiramatsu+**DY**, work in progress…]

Summary

Cosmic strings are line-like objects, which are expected to be produced

- ✓ at PT after inflation via SSB (for standard ones)
- ✓ at PT during inflation via SSB (for delayed-scaling ones)
- ✓ at the end of stringy inflation (for superstrings)

Summary

A cosmic string network has the unique properties:

- ✓ Scaling attractor
- ✓ Reconnection
- ✓ Conical structure

Thanks to these, we can obtain the robust predictions.

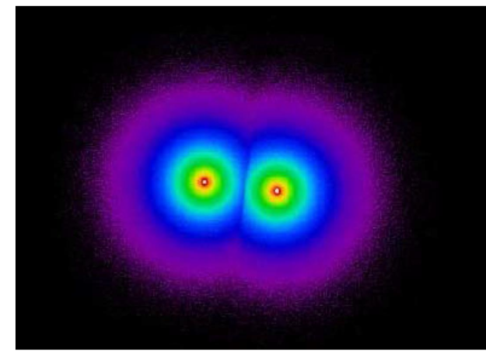
Summary

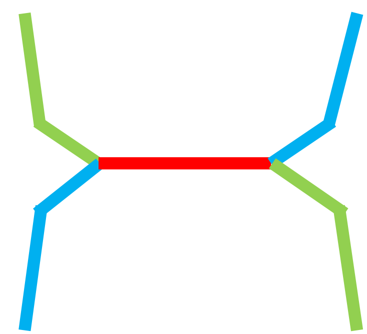
The presence of cosmic strings would leave a variety of traces such as

- ✓ Cosmic microwave background
- ✓ Gravitational waves
- ✓ Weak/strong gravitational lensing
  [**DY**+Namikawa+Taruya 1205.2139, Yoo+**DY**+ 1209.0903]
- ✓ 21cm line [Square Kilometre Array]

Future

- Modeling for loop distributions
  - The constraint from GW amplitude strongly depends on it!
- Formulation for strong lensing
  - E.g. double images
- Bound states / Y-junctions
  - Observational consequence?





Thank you!

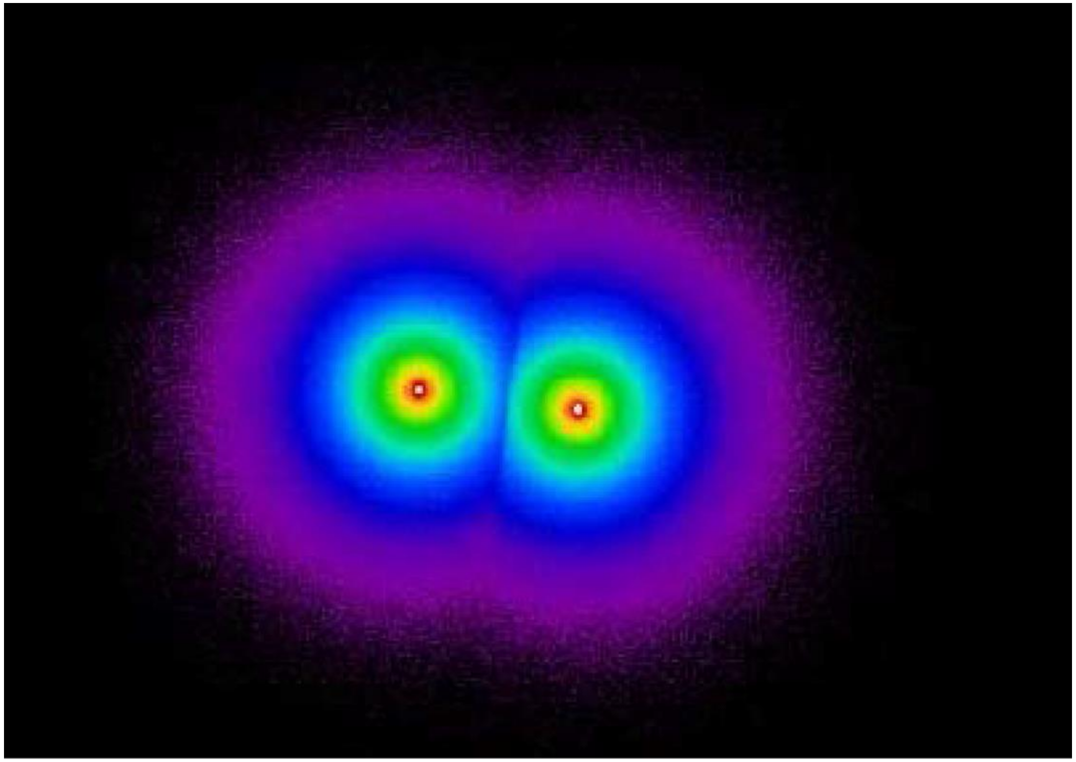
Summary

Anyway,…

Cosmic strings are fun!

Direct detection : strong lensing

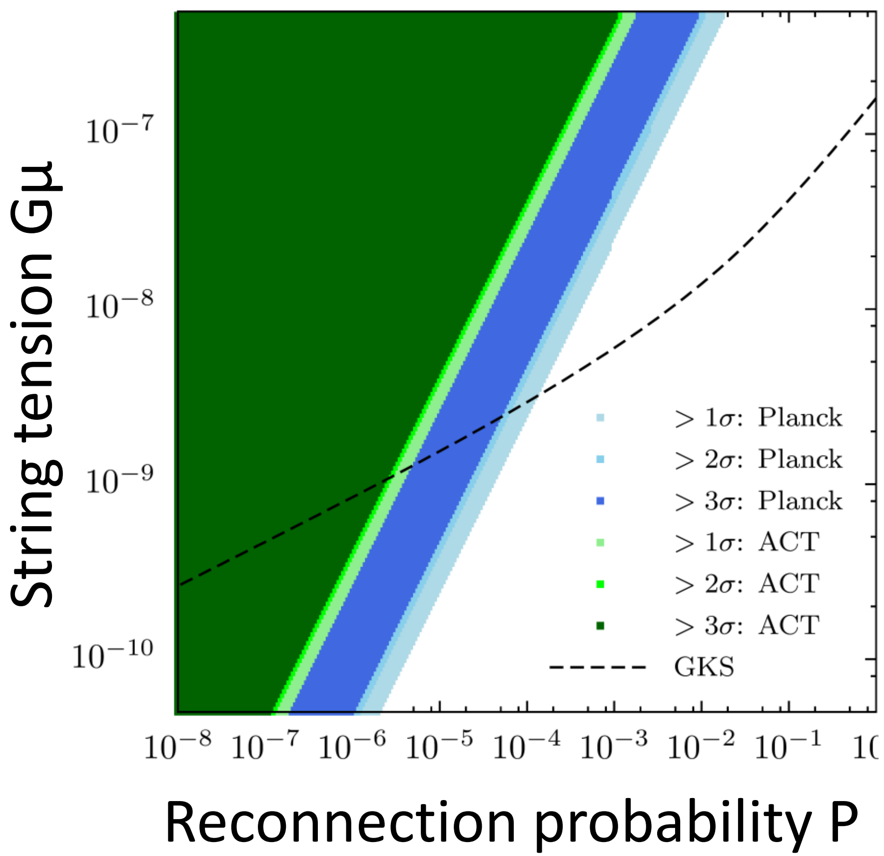
The string with the deficit angle creates the double image with the very similar amplitude with a separation angle of order $G\mu$.



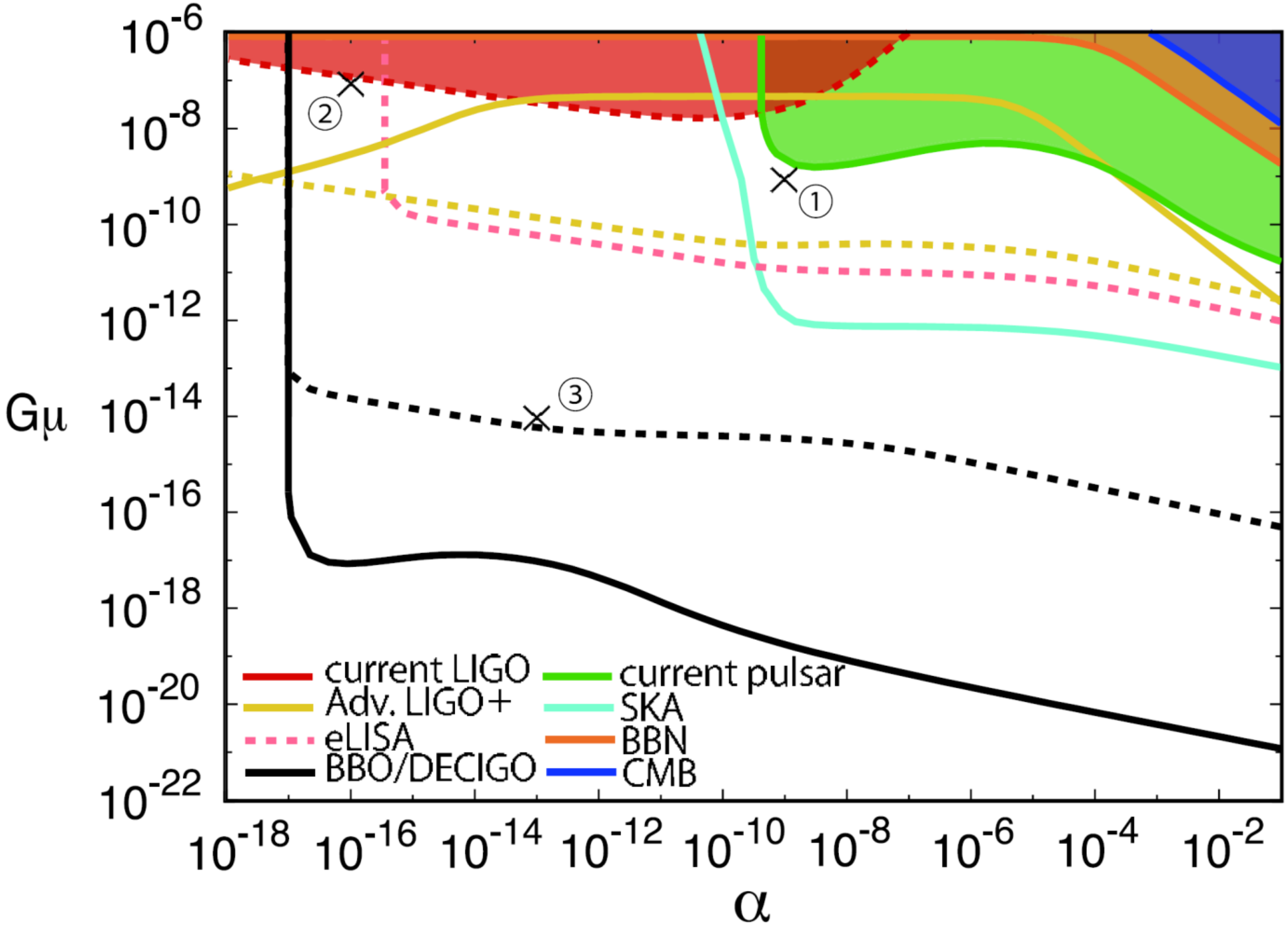
Detectability from future CMB obs.

(2) String-induced CMB lensing

$$G\mu P^{-1} \leq 3.4 \times 10^{-5}$$ (95%CL, Planck curl-mode)



- ➢ Curl mode is more sensitive to small values of P compared to the power spectrum.

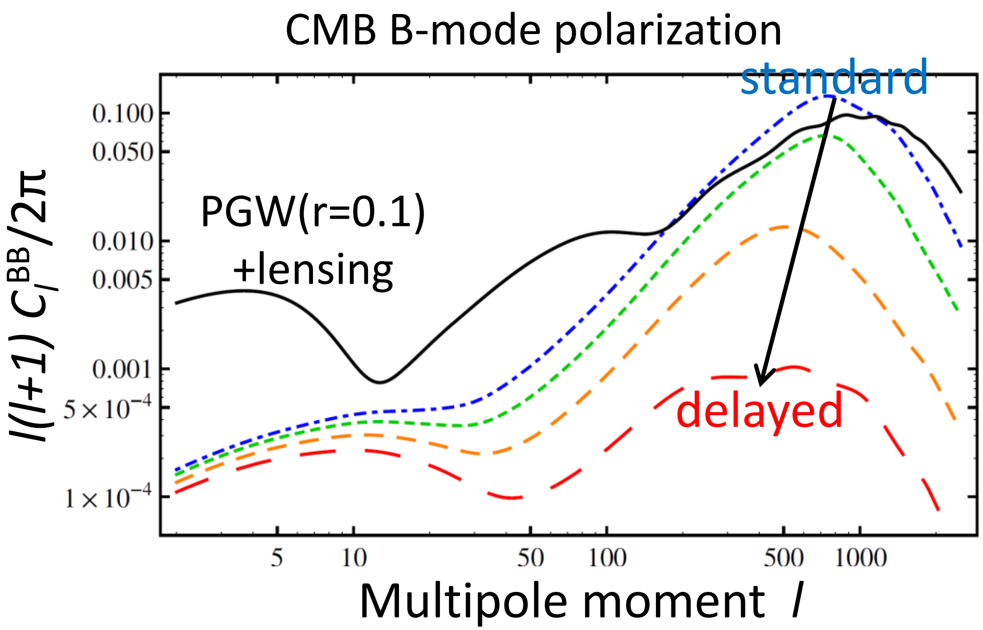


10^{-6}
10^{-8}
10^{-10}
10^{-12}
Gμ
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^{-22}
10^{-18} 10^{-16} 10^{-14} 10^{-12} 10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2}
α
1
2
3
current LIGO
Adv. LIGO+
eLISA
BBO/DECIGO
current pulsar
SKA
BBN
CMB

(a) $p = 1$

Other possibilities from CMB

- Non-Gaussianity
  - ✓ ISW-lensing non-Gaussianity [**DY**+, 1309.5528]
- B-mode polarization
  - ✓ Vector/tensor modes →
    [Kamada+**DY**+, 1407.2951]
  - ✓ Lensing-induced B-mode
    [**DY**+, 1110.0556]



- CMB lensing reconstruction
  - ✓ Vector/tensor modes [Namikawa+**DY**+Taruya, 1205.2139, 1308.6068]

2-D is NOT real world!!!

In 2-D system, it is probably impossible to obtain the true features of the string network.

- ✓ It is definitely impossible to construct the web-like string network.
- ✓ There are no energy release mechanisms which corresponds to the loop production in the 3-D cases. The only mechanism is pair annihilation!