Gravitational waves from cosmic strings

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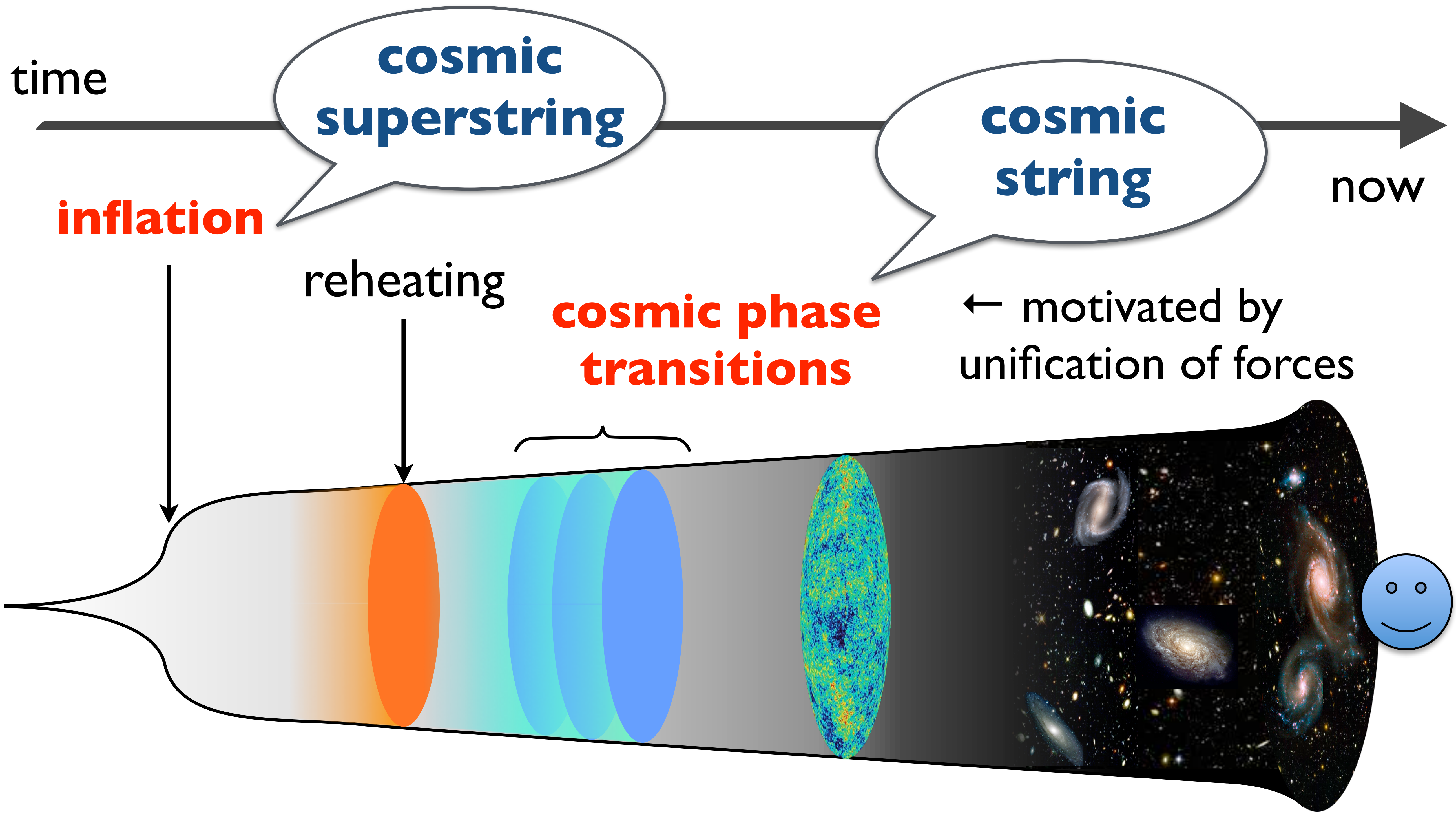
9 Nov 2023

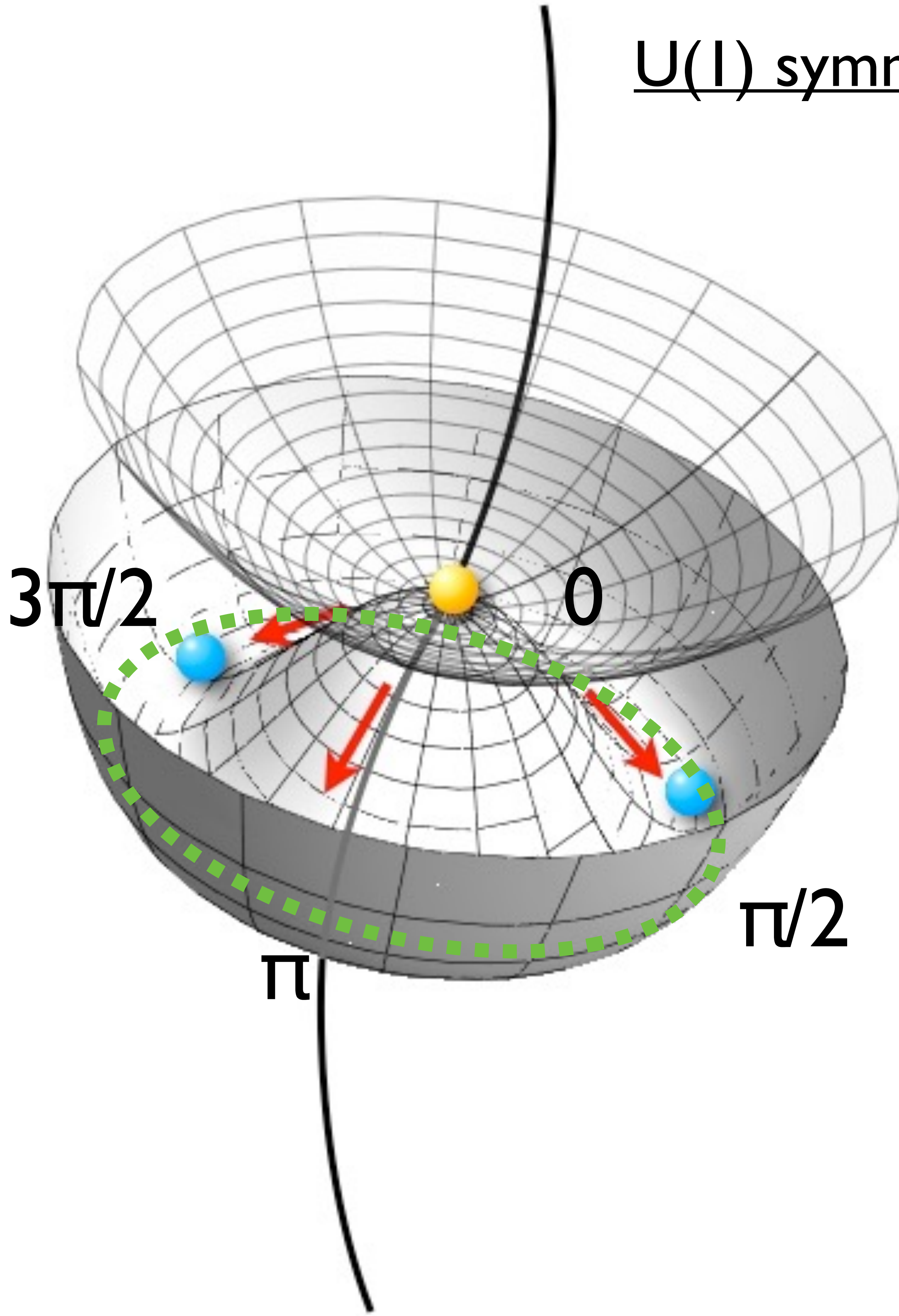
Gravitational Wave Probes of Physics Beyond the Standard Model
@ Osaka Metropolitan University

Cosmic strings may have been generated in the early Universe



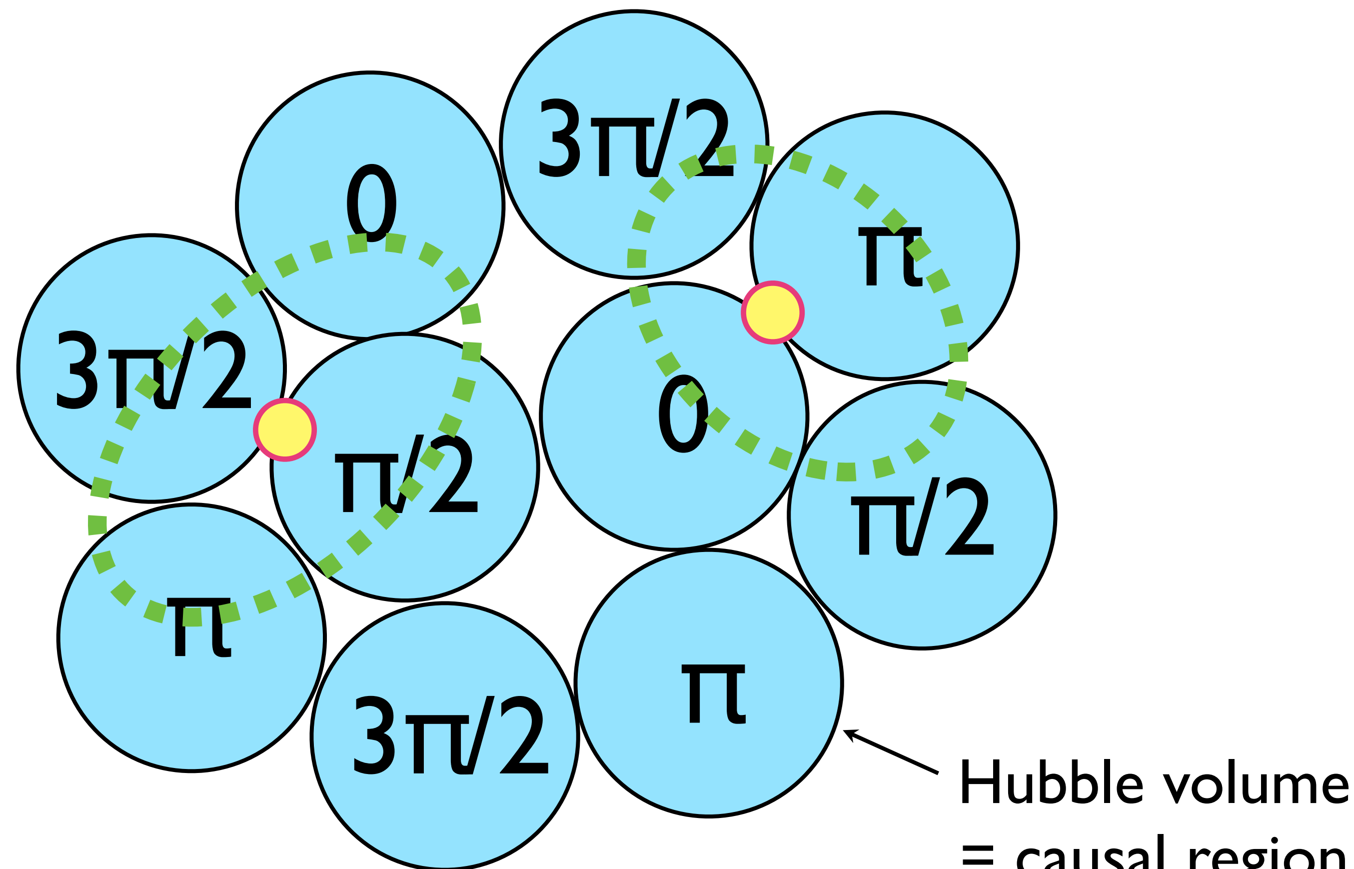
→ unique way to access the early universe physics

Generation of cosmic strings



<u>U(1) symmetry breaking</u>

High energy vacuum left in the Universe



Gμ : tension = line density

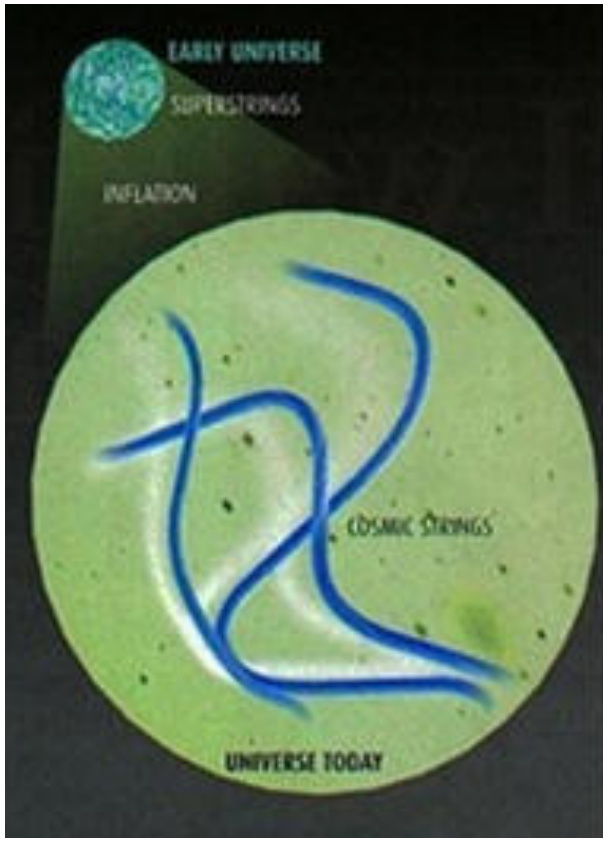
→ corresponds to the energy scale of the phase transition

e.g. GUT scale strings: $G\mu=10^{-6}$

Cosmic superstrings

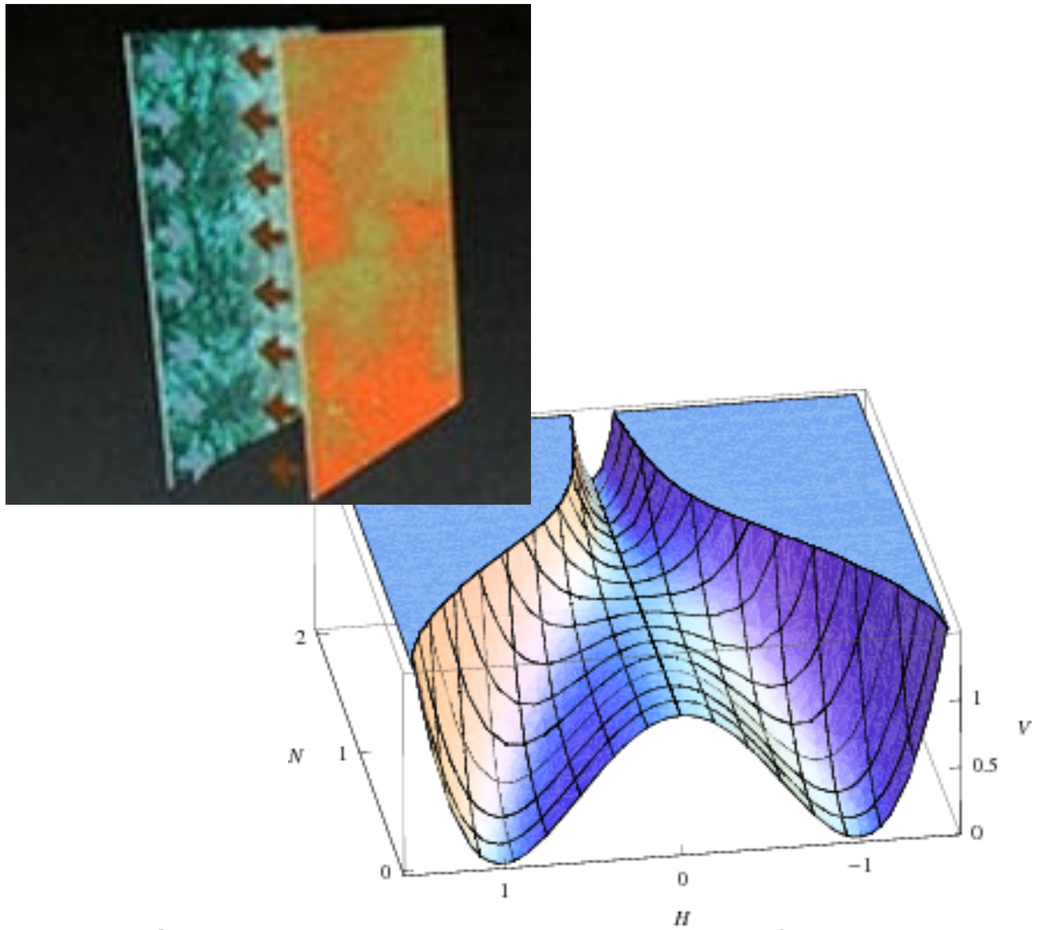
Cosmological size D-strings or F-strings remains after inflation

F-strings



Fundamental stings stretched
to the macroscopic scale

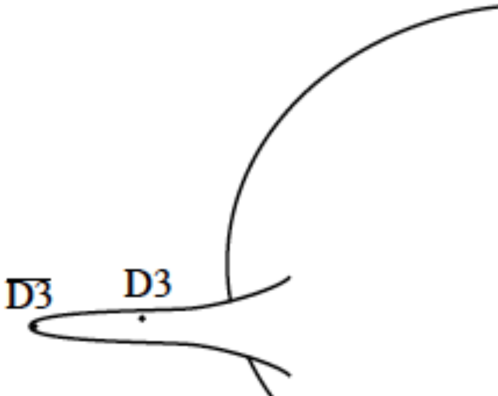
D-strings



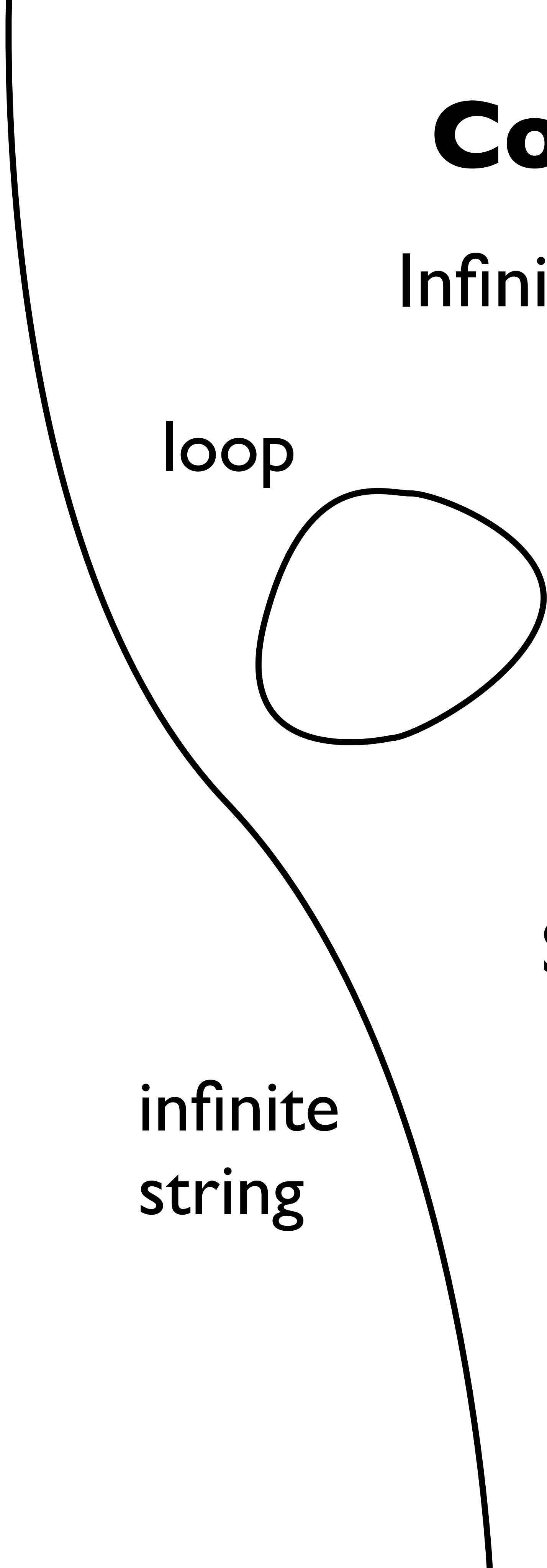
Strings remain after
D-brane-antibrane inflation

tension $\mu = \underline{e^{2A(x_\perp)}} \bar{\mu}$

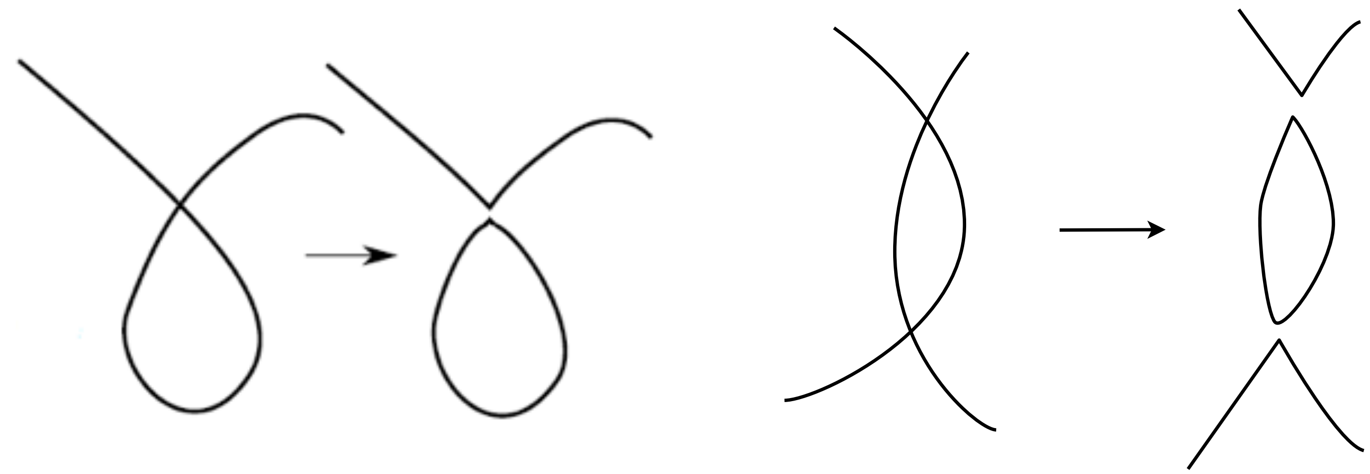
warp factor << 1



Cosmic string network



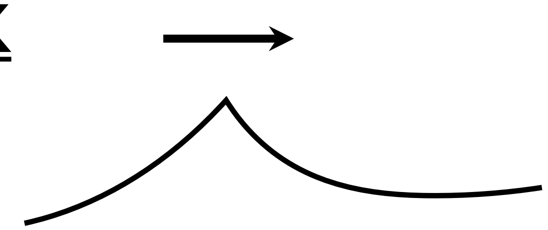
Infinite string becomes a loop by **reconnection**



Loops shrink by emiting GWs and evaporate

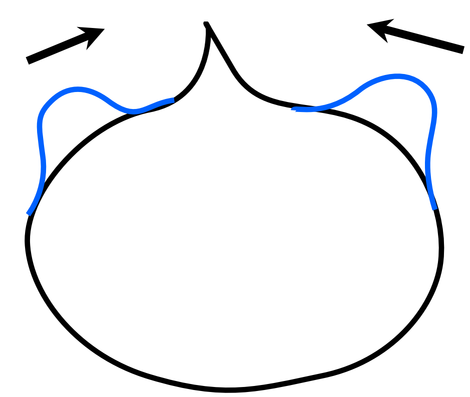
Strings emit strong **GWs** from singular points

kink



formed at reconnection

cusp



formed when waves collide
with a special condition

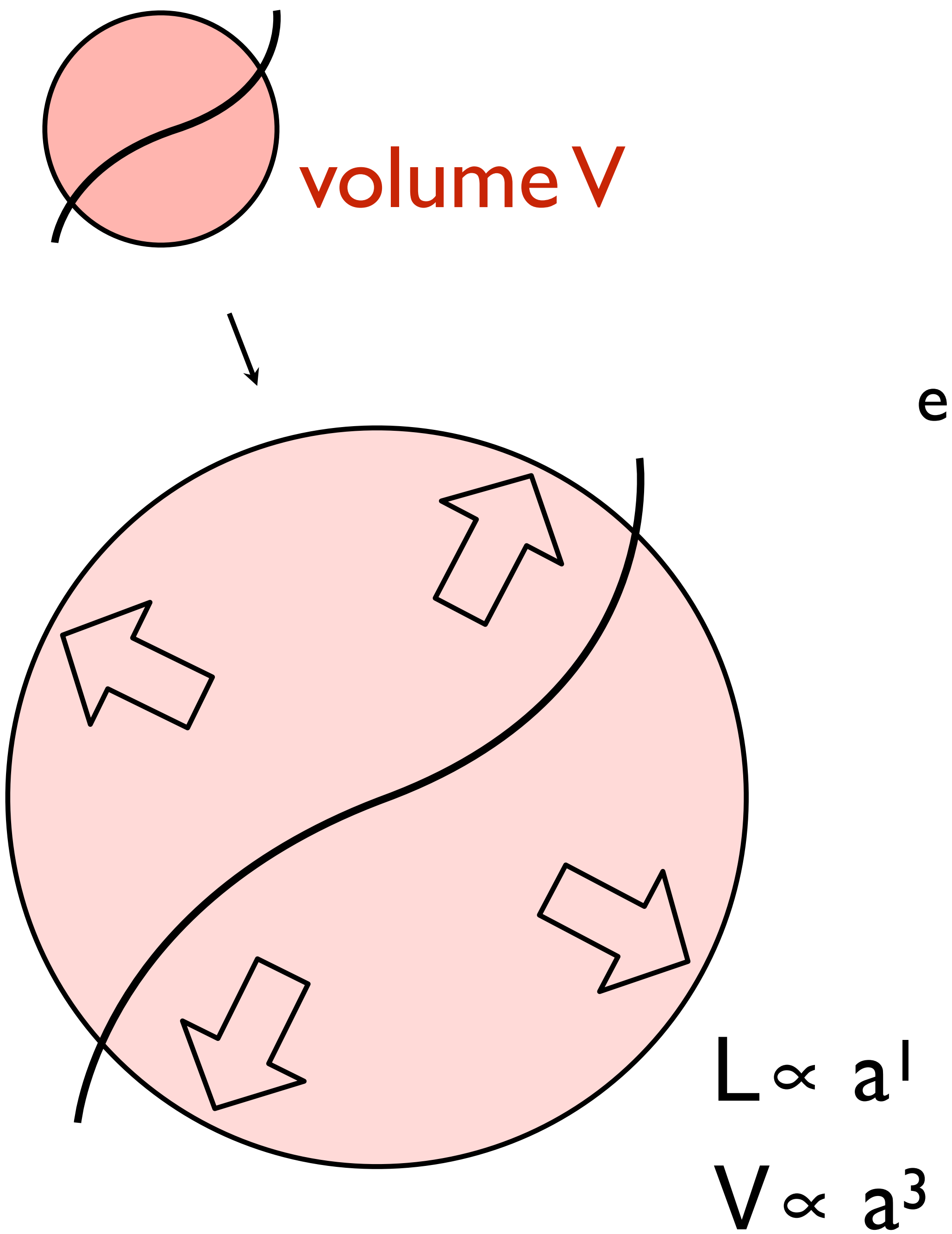
Evolution of cosmic string network

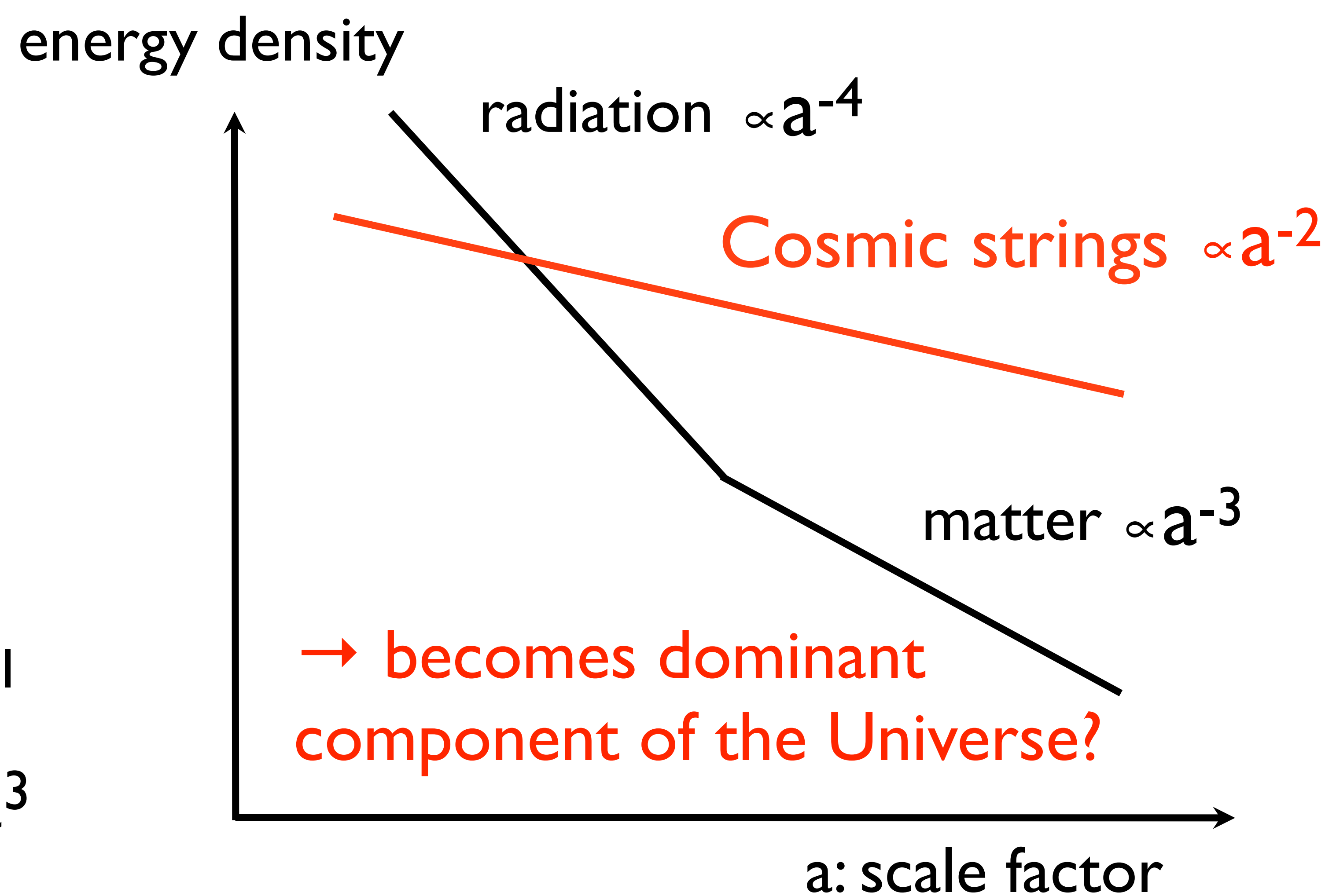
The energy density of cosmic strings

$\sim$ (line density × length)/volume $\propto a^{-2}$

(line density $\propto a^{1}$, volume $\propto a^{3}$)

a: scale factor of the Universe





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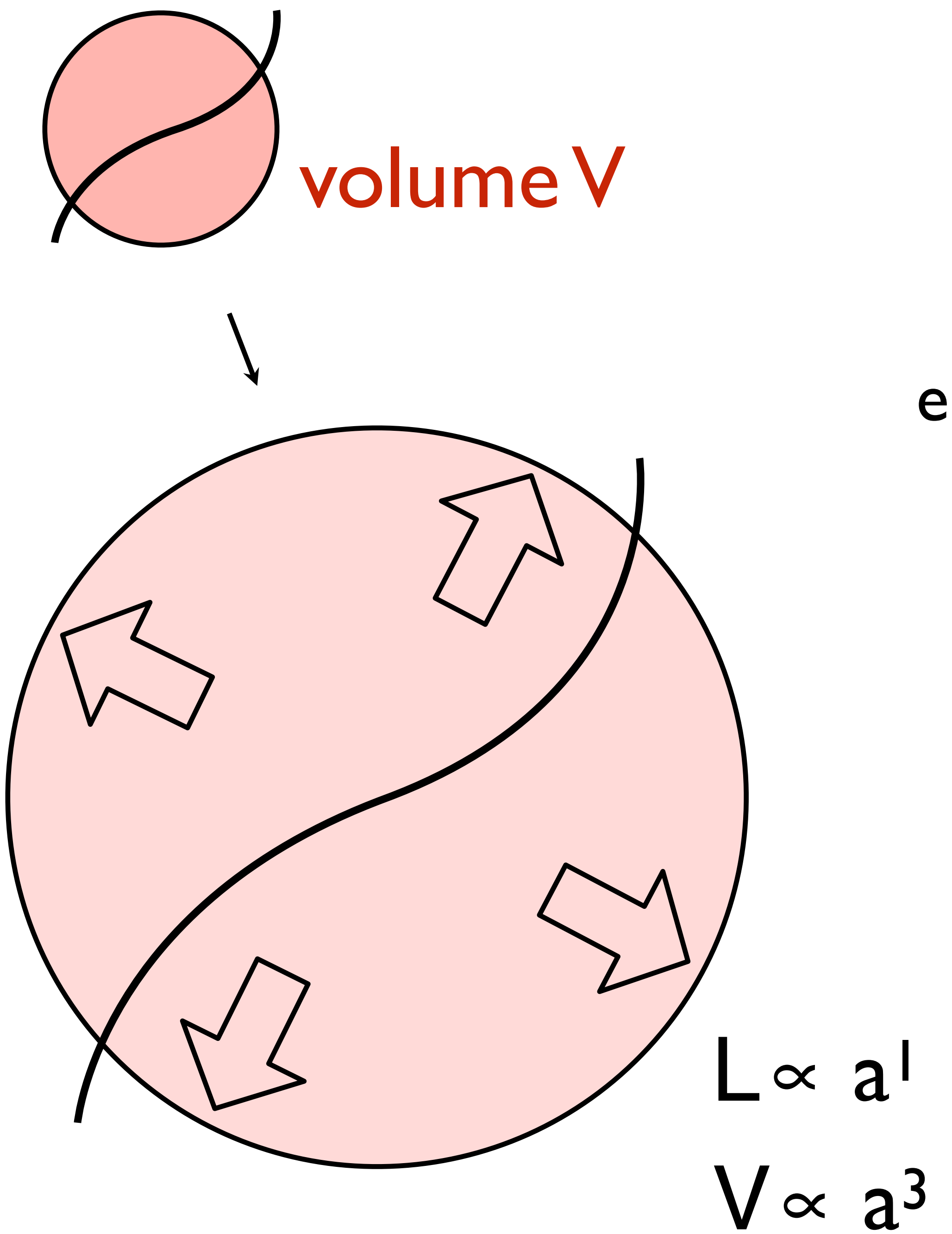
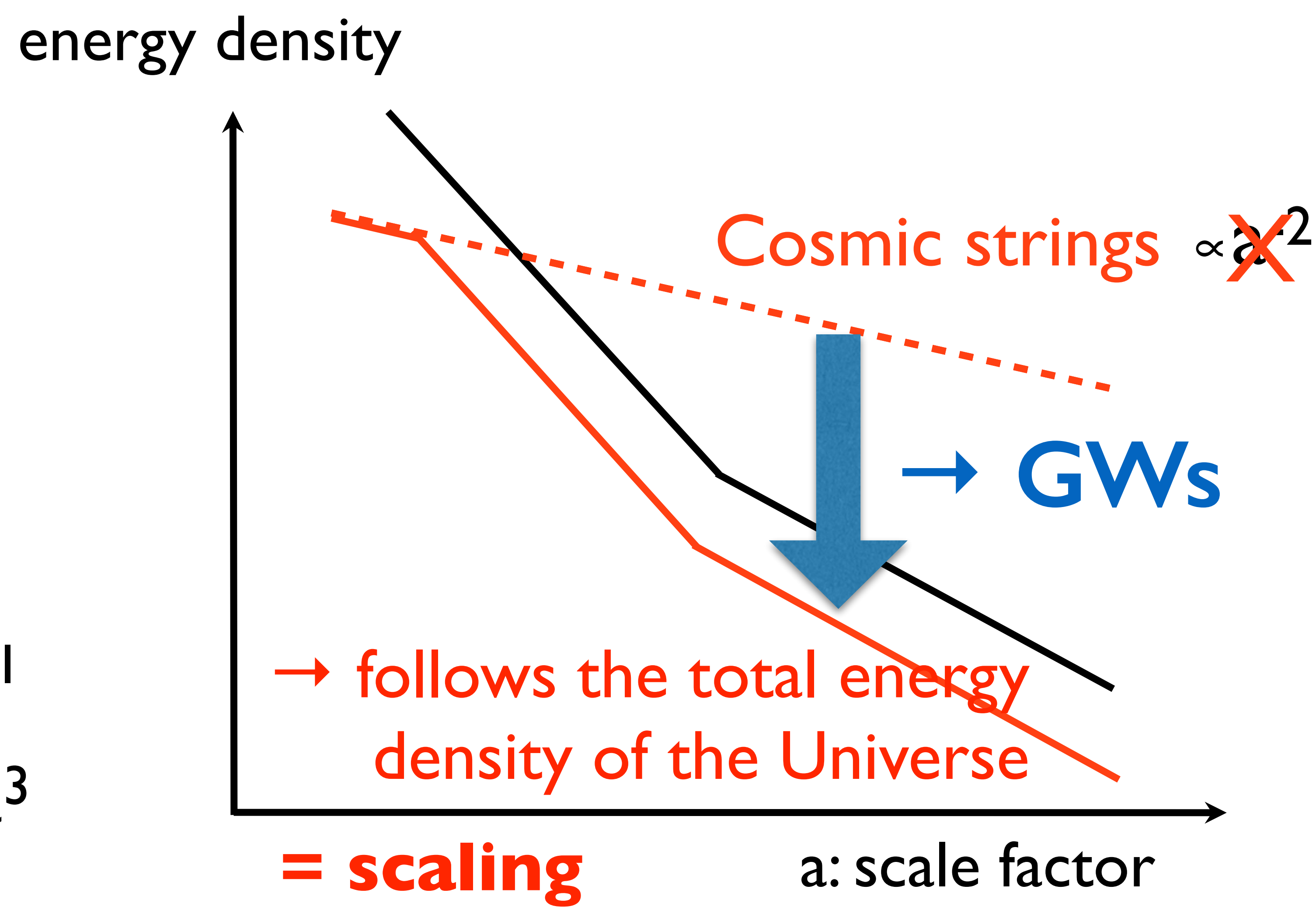


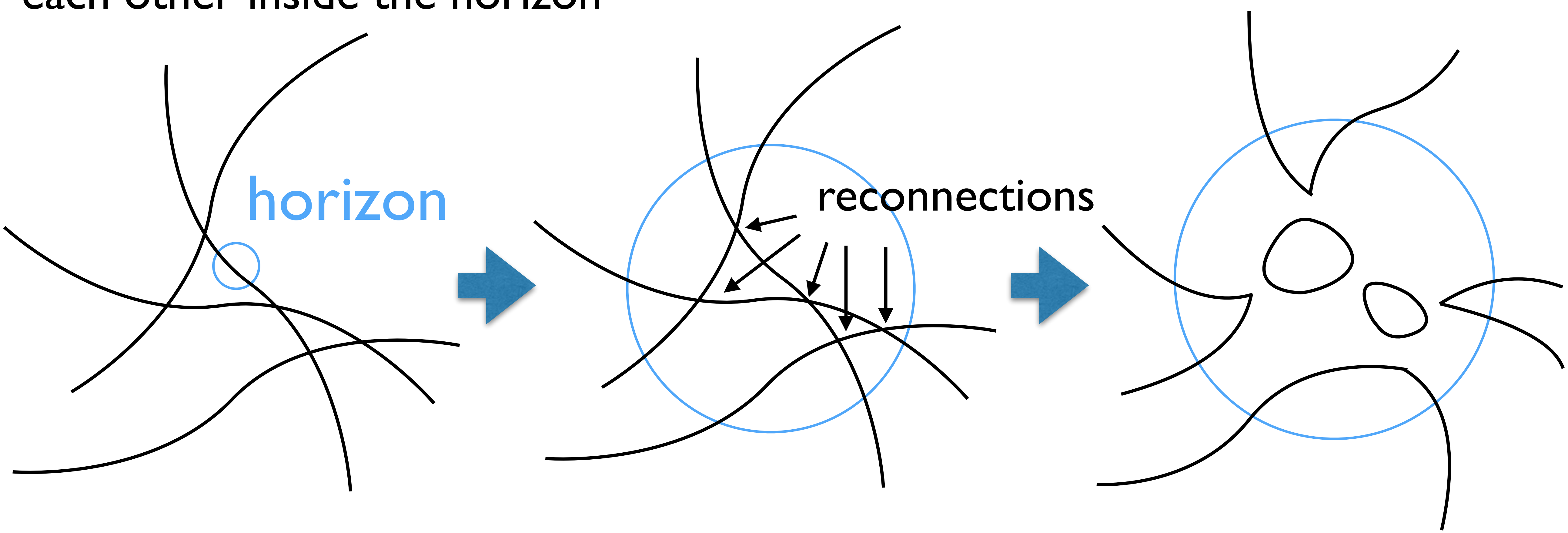


Scaling law

The Universe always has O(1-10) strings per horizon

Key point: string network keeps producing loops

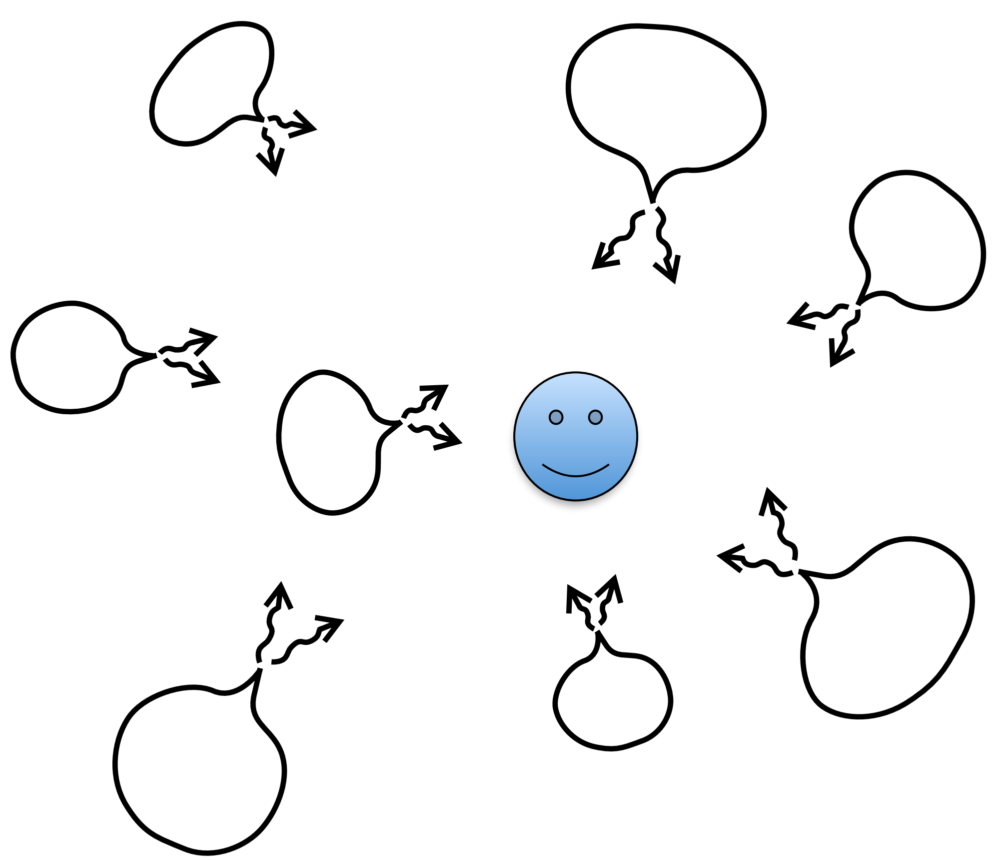
Strings can communicate each other inside the horizon



→ Loops evaporate after continuous GW emission

Gravitational wave signatures

	infinite strings	loops
cusp	little	**numerous**
kink	**numerous**	little



Overlapped GW bursts

→ **Stochastic GW background**

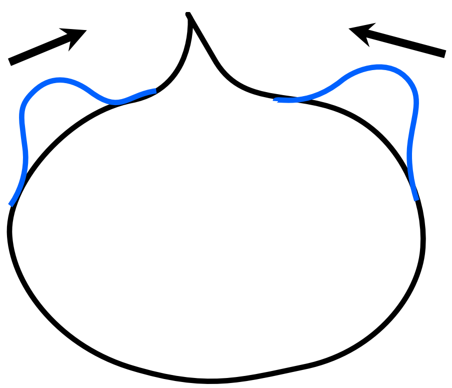
Strong GW bursts from loops nearby

→ **Rare bursts**

GW bursts from cusps and kinks

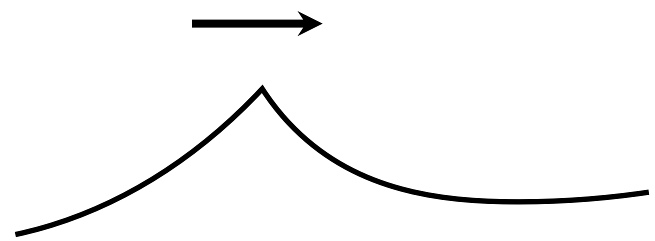
Damour & Vilenkin, PRL 85, 3761 (2000); PRD 64, 064008 (2001)

cusp



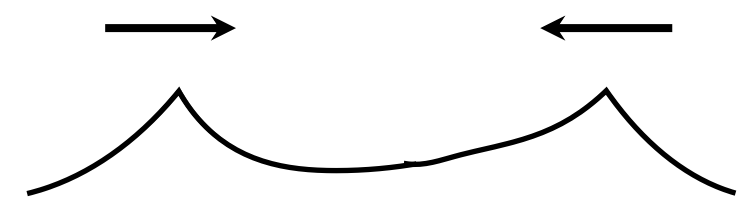
$$h(f) \propto f^{-4/3}$$

propagating kink



$$h(f) \propto f^{-5/3}$$

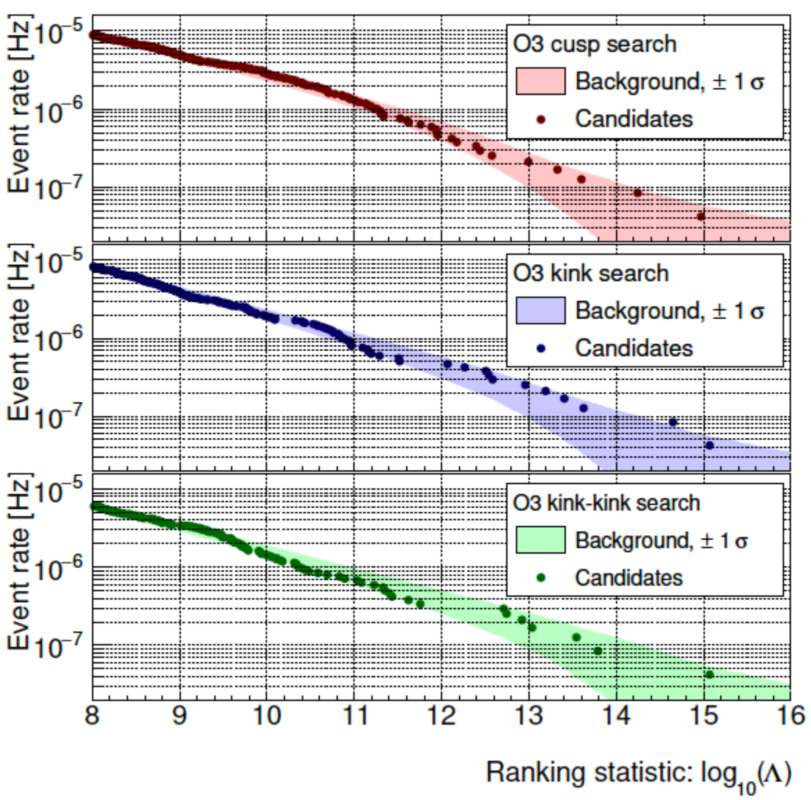
kink-kink collision



$$h(f) \propto f^{-2}$$

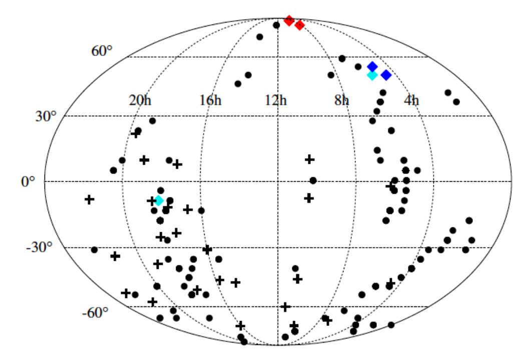
Template search by

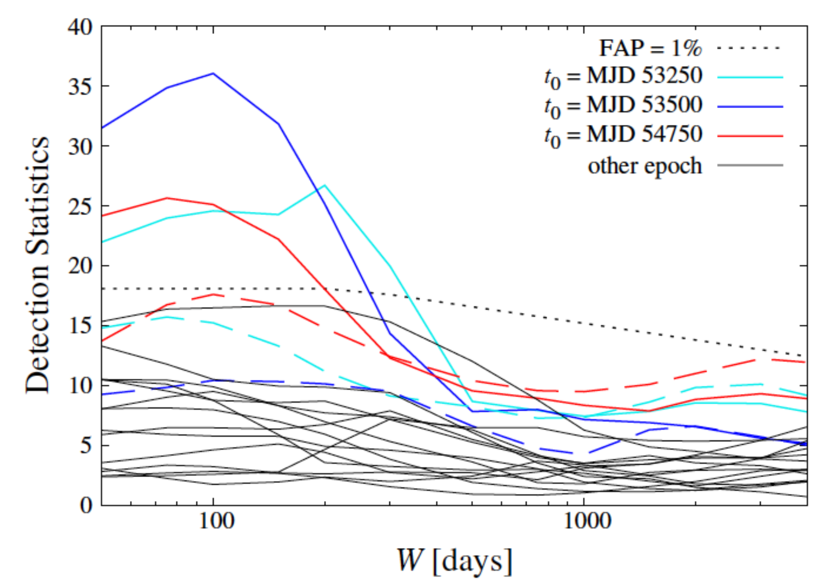
LVK



LVK collaboration, PRL 126, 241102 (2021)

PPTA (only for cusp)



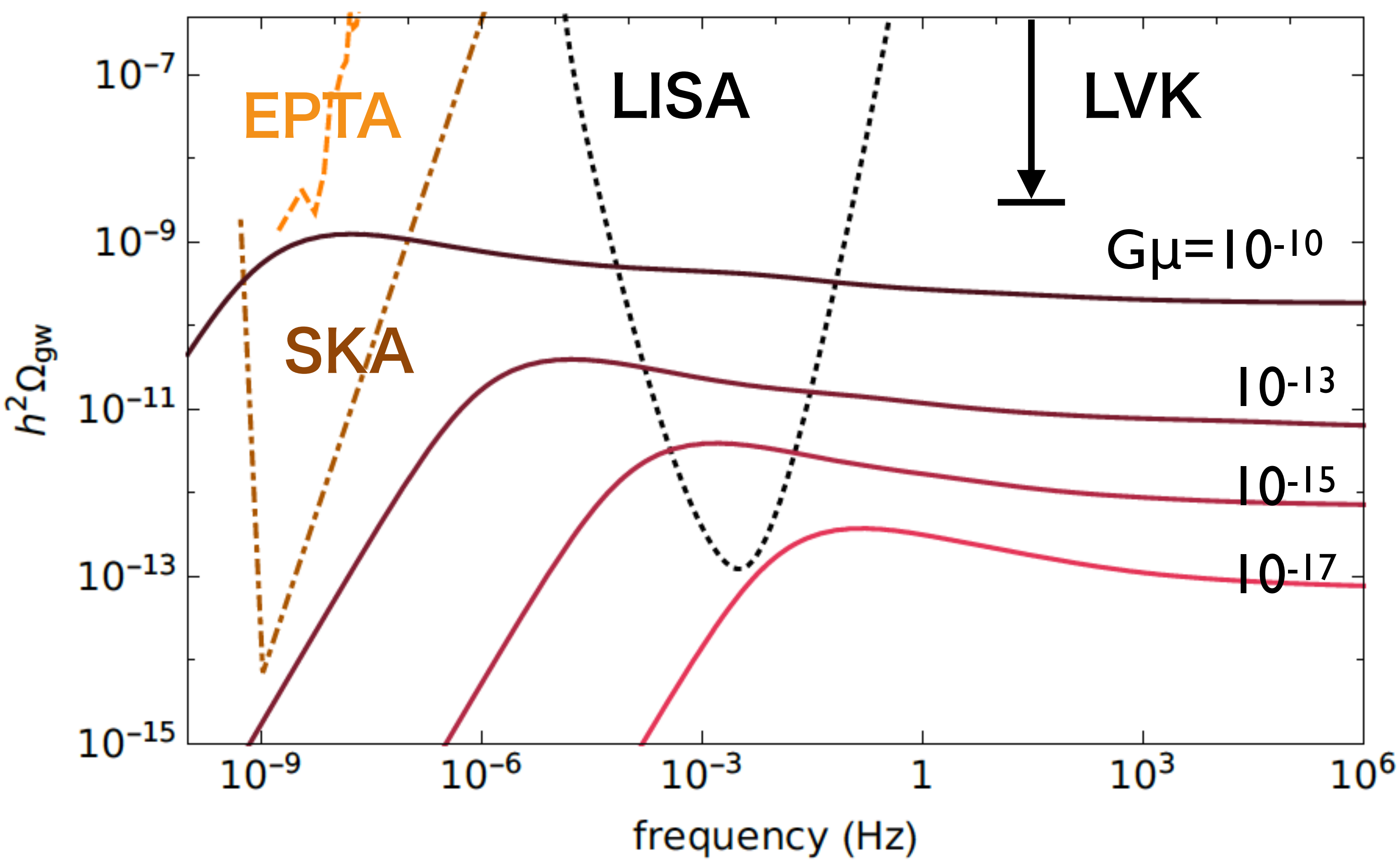


Yonemaru et al. (+SK), MNRAS 501, 1 (2021) 701

GW Background from cusps on loops

P. Auclair et al. (+SK) (LISA Cosmology Working Group), JCAP 04, 034 (2020)

Loop distribution obtained by simulation



NANOGrav 15-year $G\mu \sim 10^{(-11)-(-12)}$

(preference to superstring? $P \sim 10^{(-3)-(-1)}$)

Ellis et al. arXiv:2306.17147

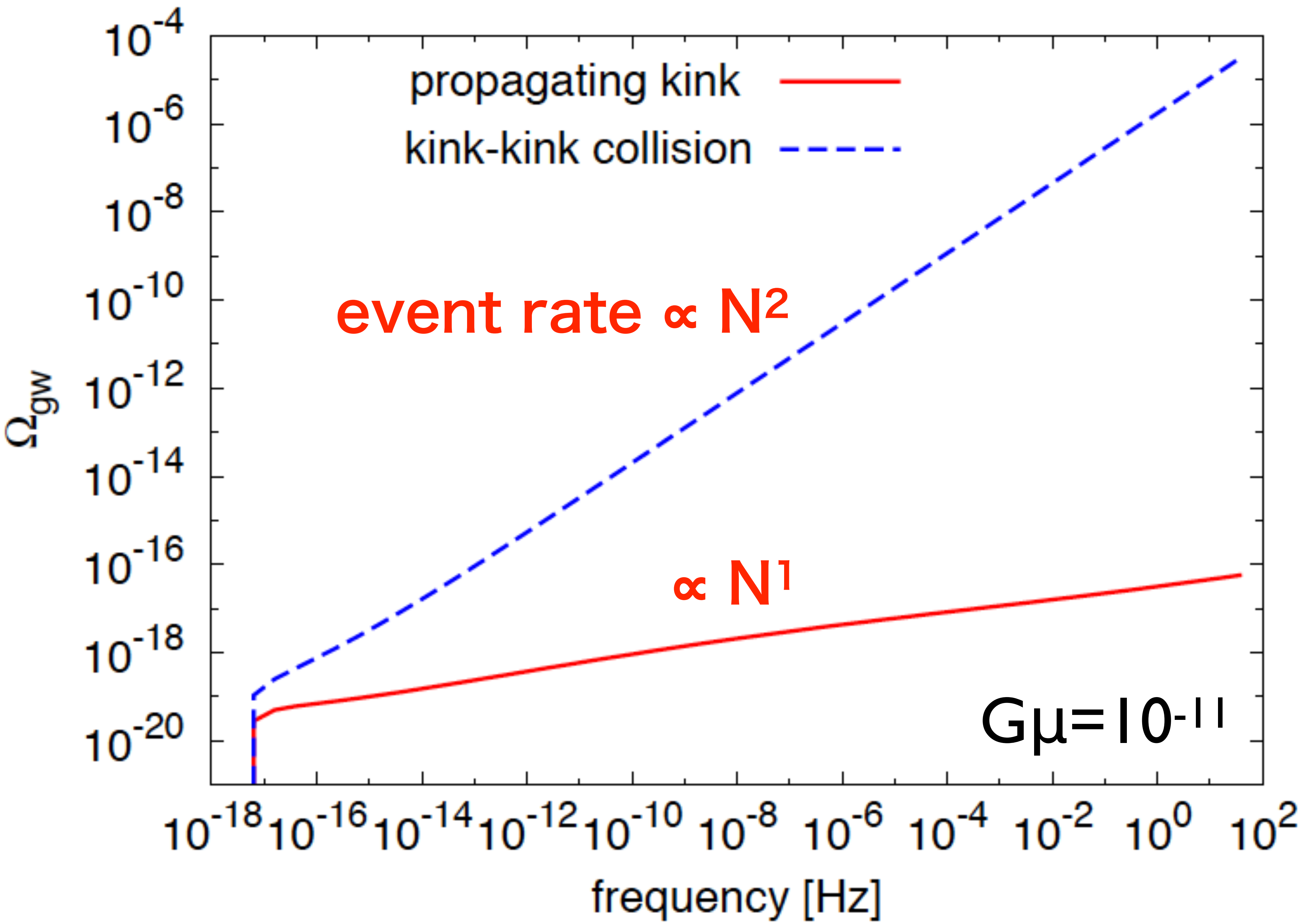
LVK $G\mu < 10^{-7}$

LVK collaboration,
PRL 126, 241102 (2021)

GW Background from kinks on infinite strings

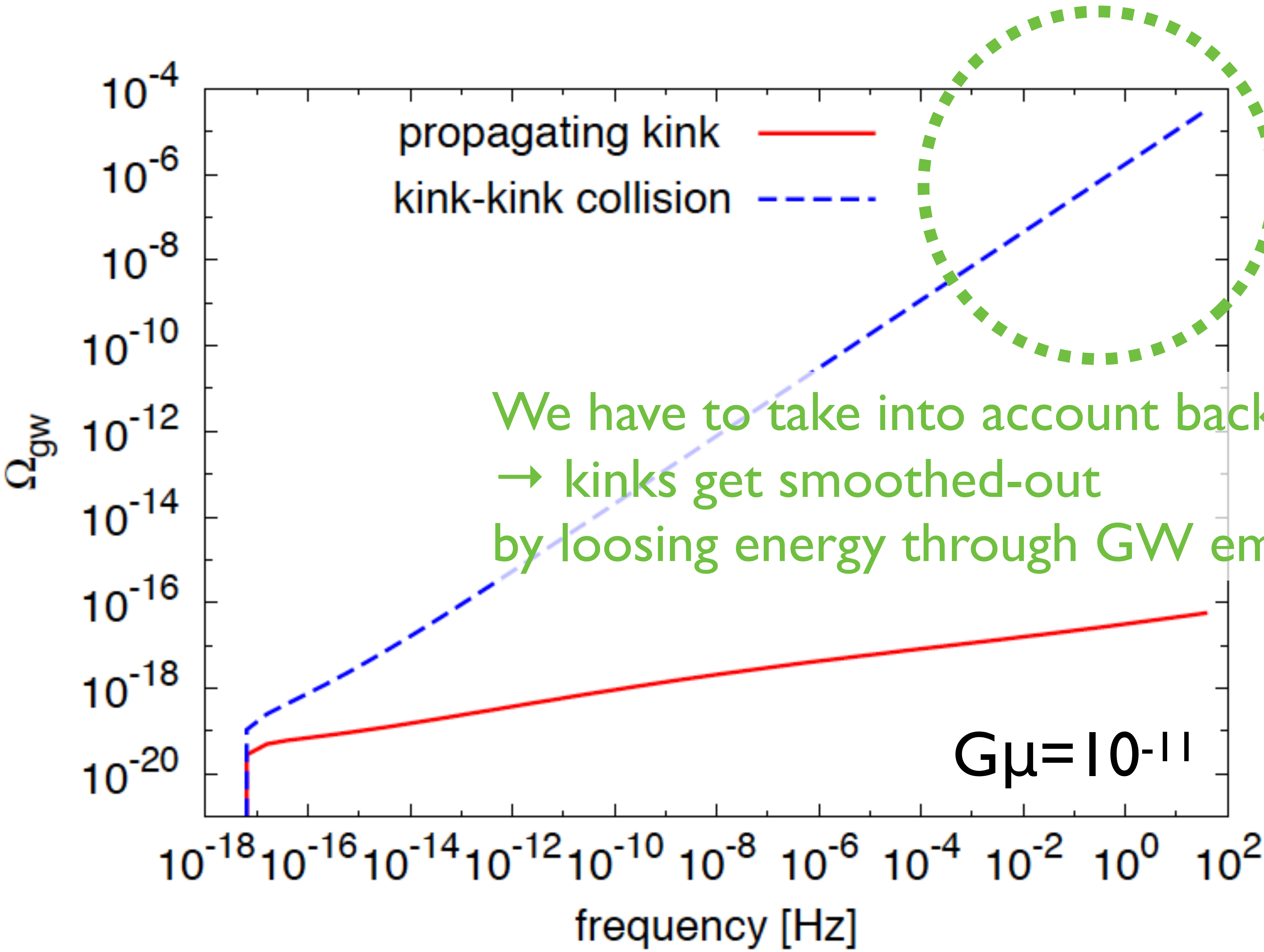
Matsui & SK, PRD,100,123515 (2019)

GWs are produced over wide range of frequencies



GW Background from kinks on infinite strings

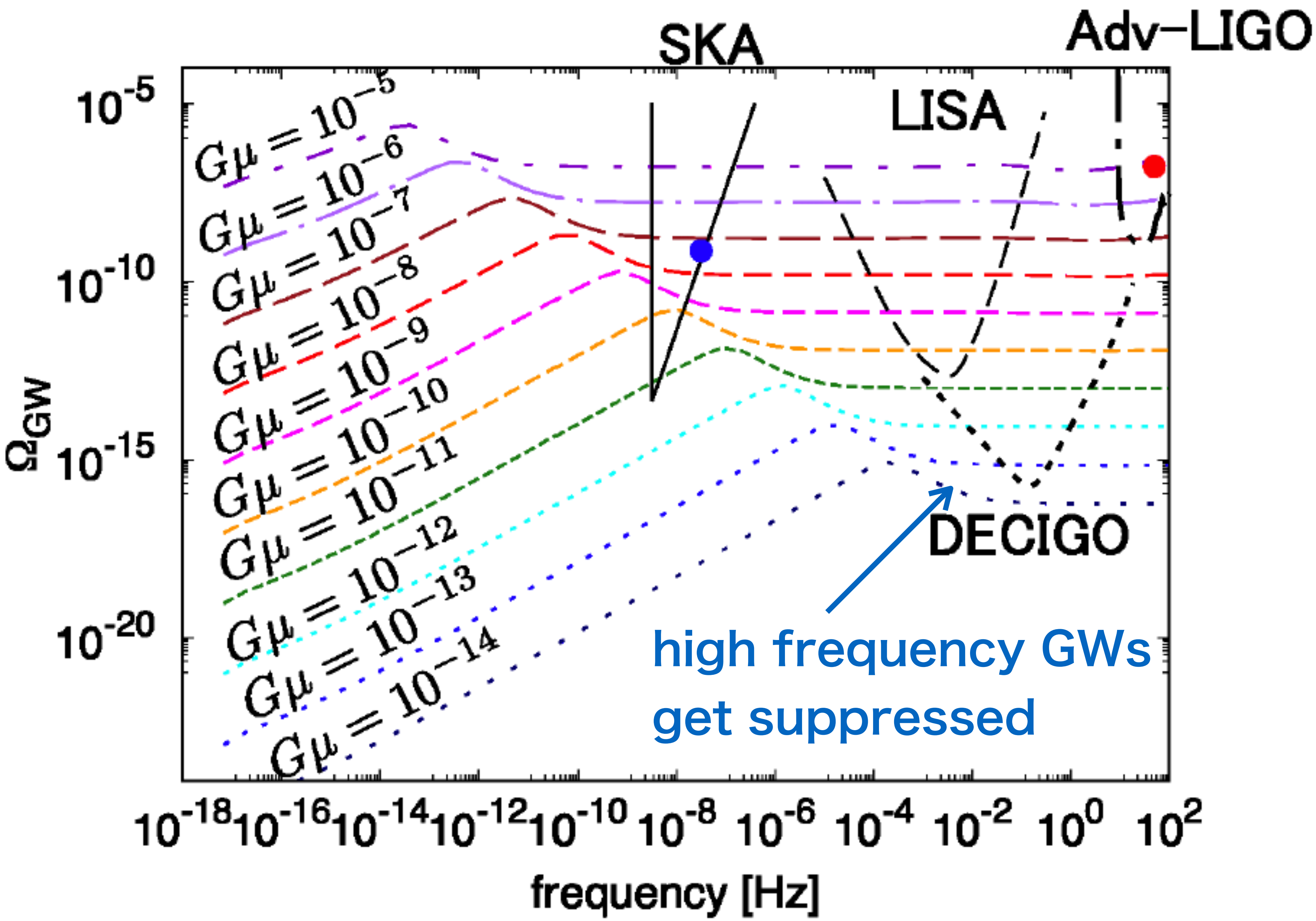
Matsui & SK, PRD,100,123515 (2019)



We have to take into account back reaction
→ kinks get smoothed-out
by loosing energy through GW emission

GW Background from kinks on infinite strings

Matsui & SK, PRD,100,123515 (2019)

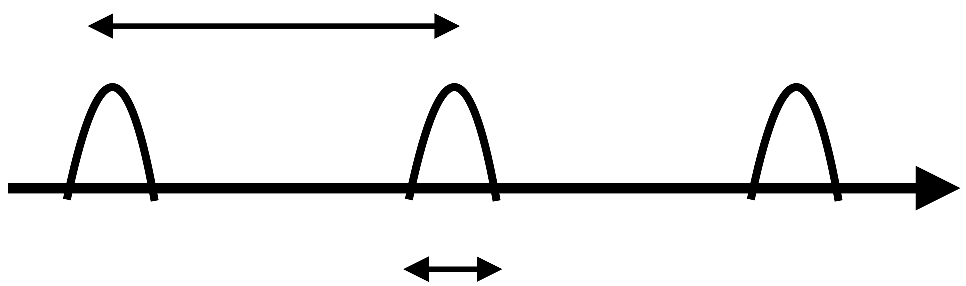


→ $O(10^2)$ smaller than GWs from cusps on loops
but infinite string contribution dominates at low frequencies

Burst or background?

Criteria of becoming a stochastic background

ΔT : average time interval between two events ~ (event rate)$^{-1}$



$\Delta\tau$: duration of the signal ~ (GW frequency)$^{-1}$

Duty Cycle $\equiv \dfrac{\Delta\tau}{\Delta T}$ ~ event rate/frequency

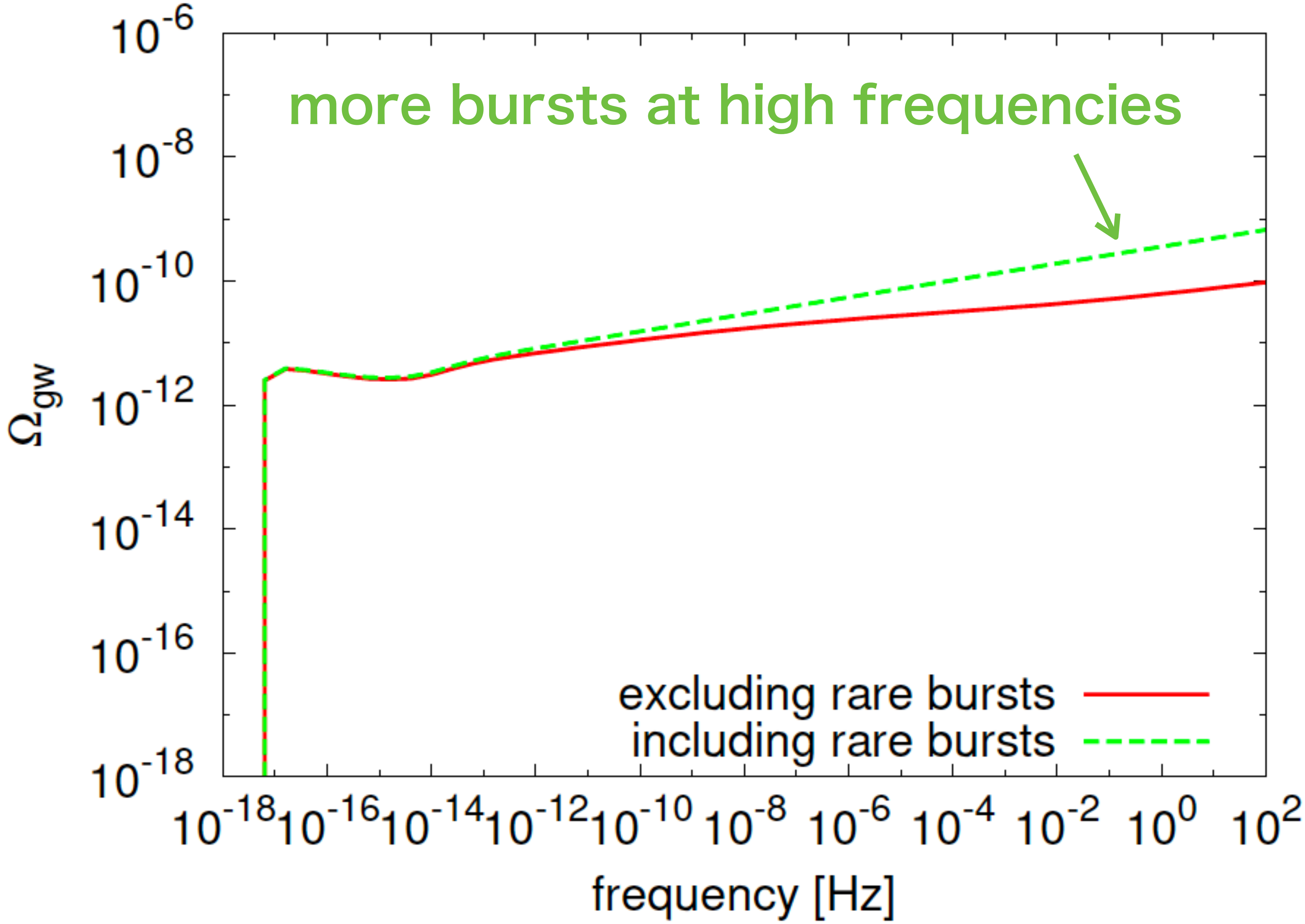
$DC \ll 1$ events do not overlap → burst events

$DC \gg 1$ events overlap → stochastic background

→ more likely to detect burst events at high frequencies

Burst or background?

e.g. Propagating kinks on infinite strings



$G\mu=10^{-7}$

Matsui et al. (+SK), JCAP 11 (2016) 005

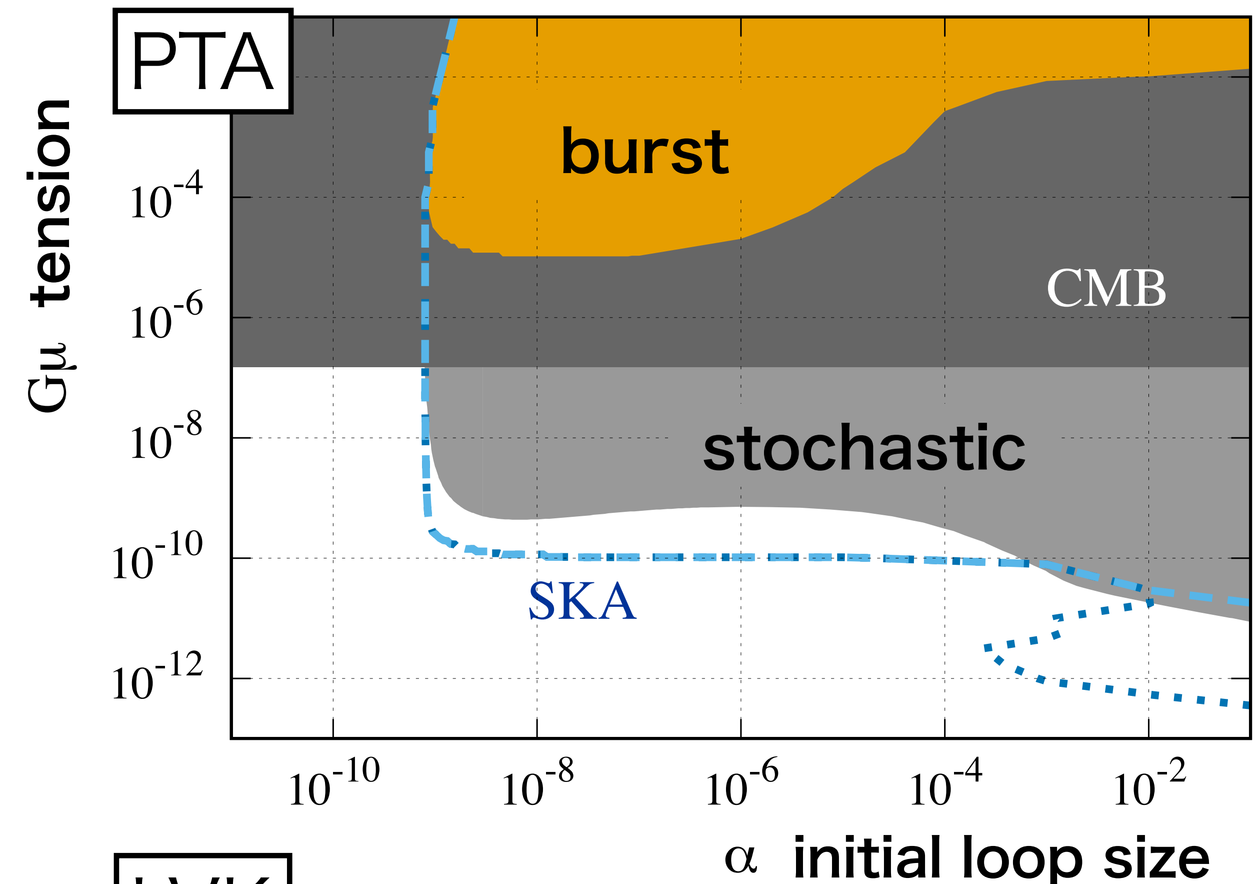
Burst or background?

Cusps on loops

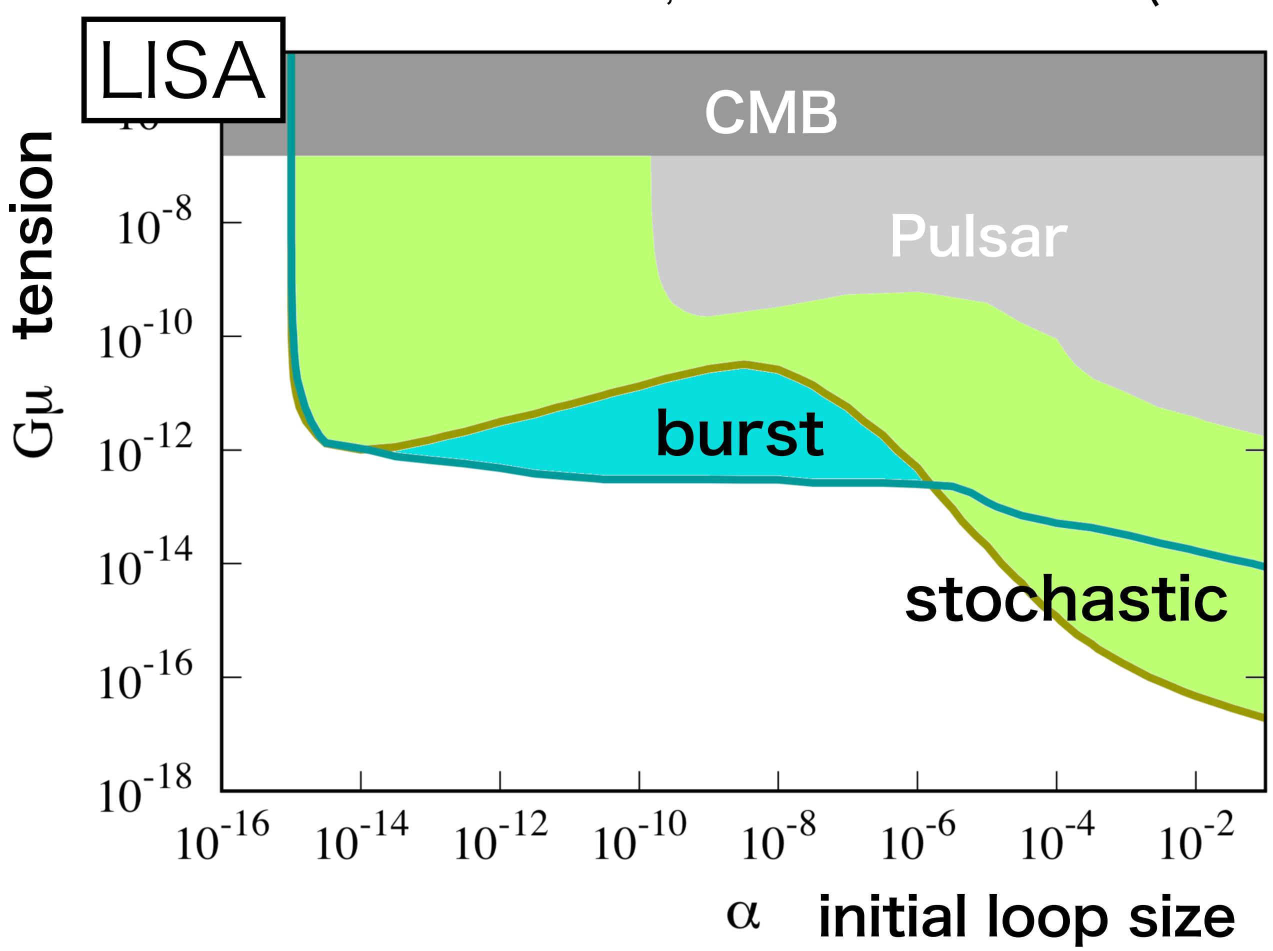
- It strongly depends on the initial loop size α.

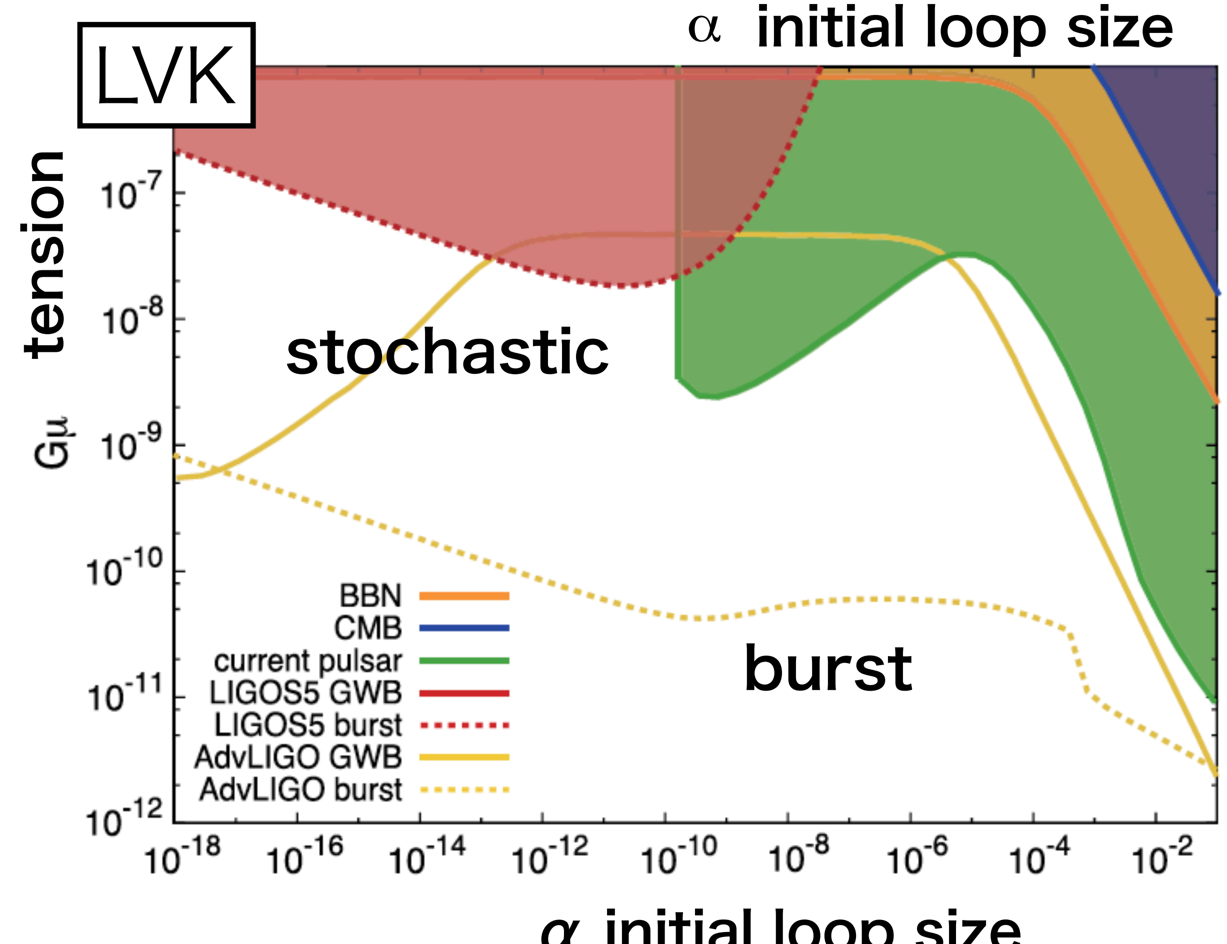
  (simulation indicates $\alpha \sim 0.05$ - 0.1)

- We can still see the tendency of more bursts for high frequency experiment.



SK et al., PRD 86 023503 (2012)





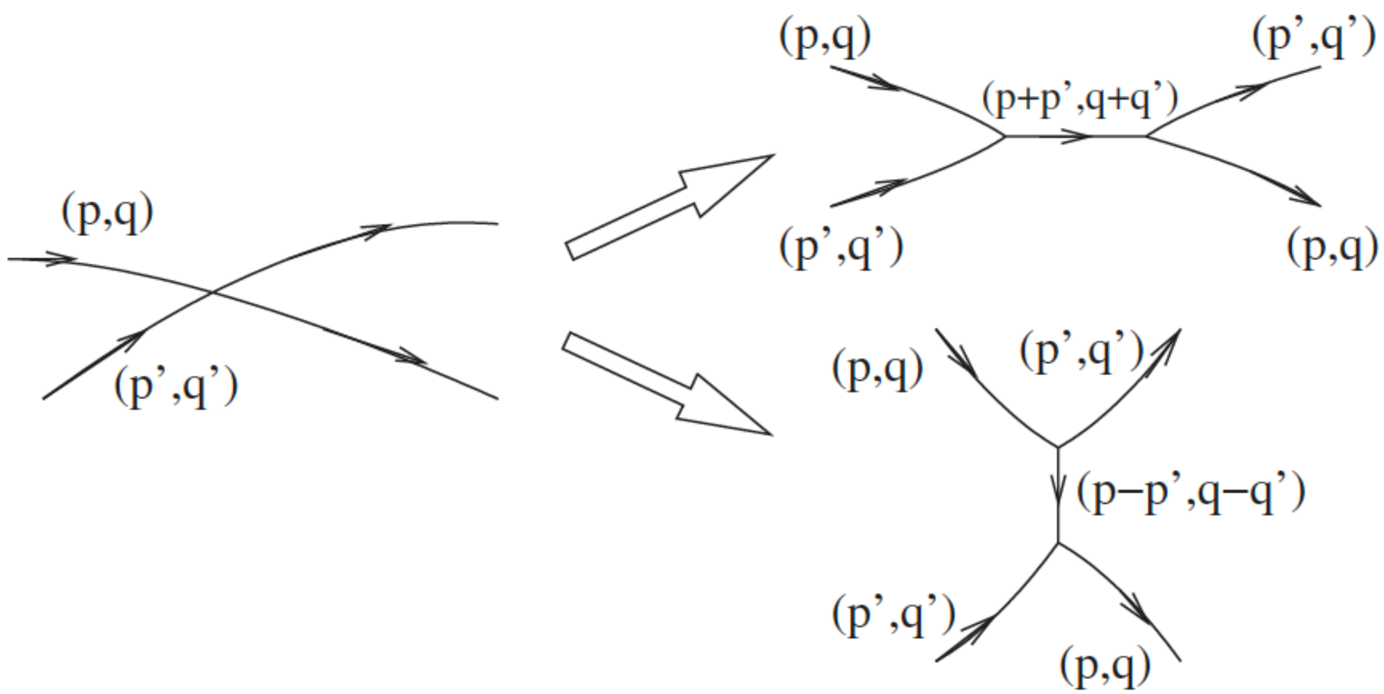
Difference in superstrings

1. Reconnection probability

field-theoretic strings	$p \sim 1$
superstrings	$p \ll 1$

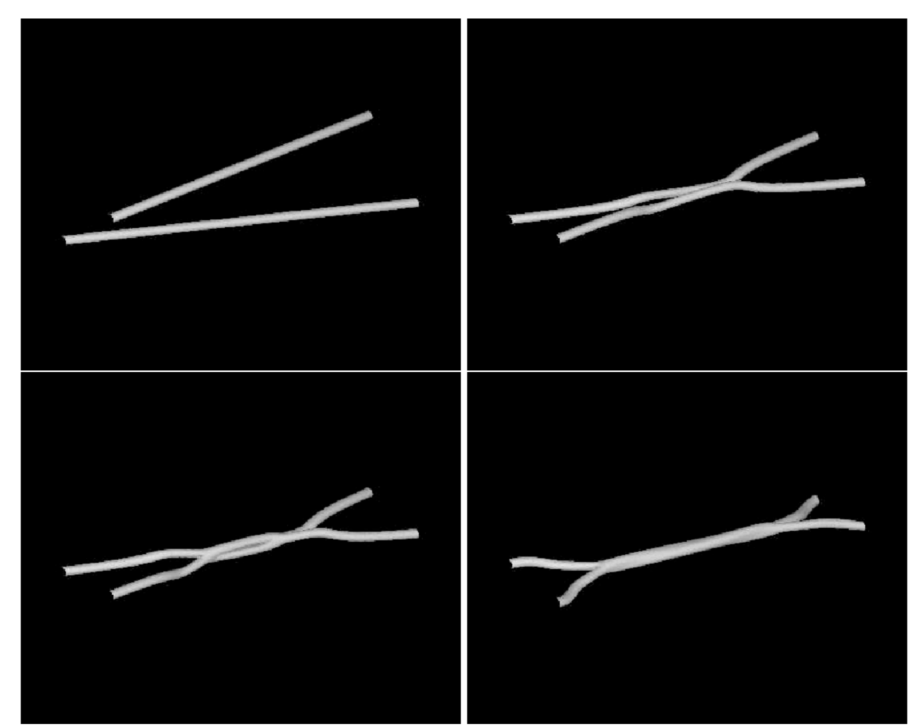
2. Strings can make bound state and form Y-junctions

Bound state between
p F-strings and q D-strings

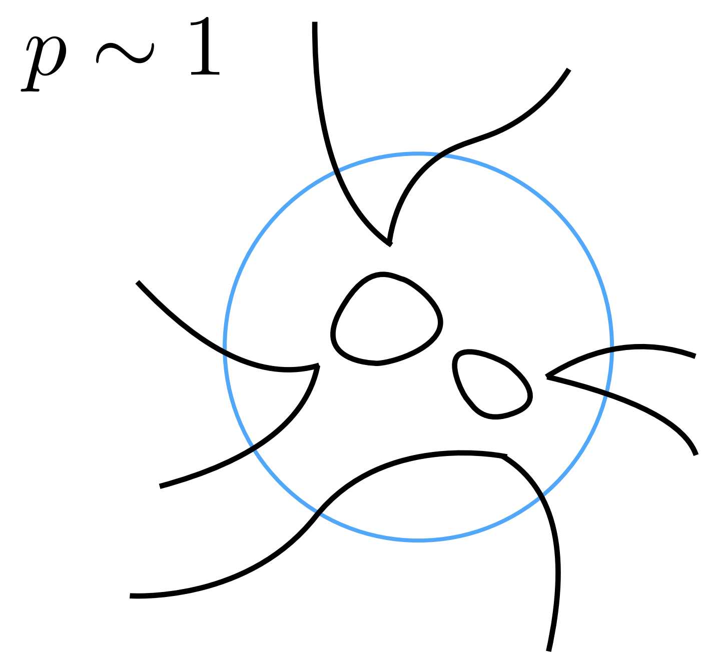


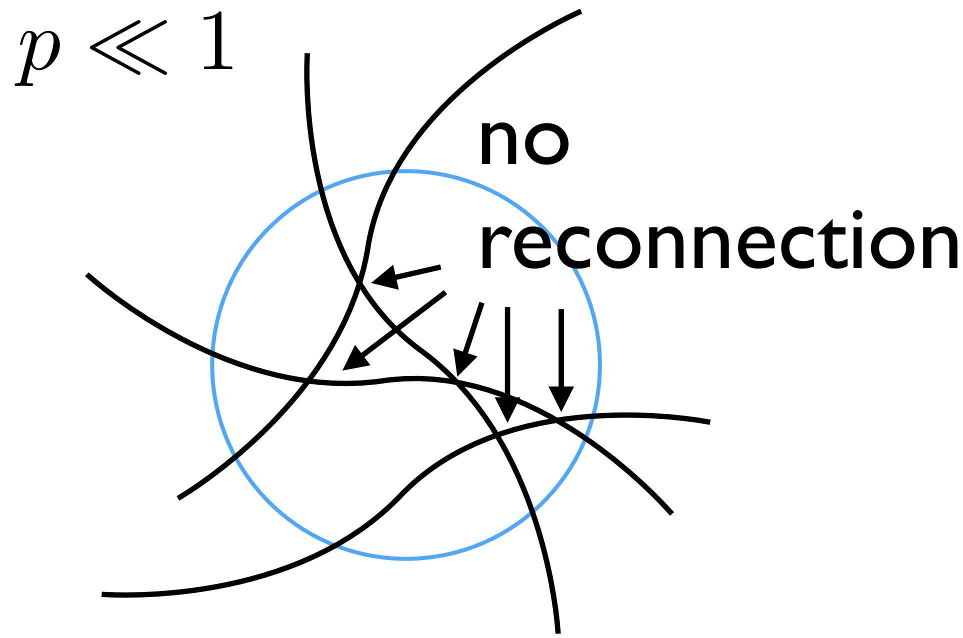
Avgoustidis & Shellard, PRD 78 103510 (2008)

It also happens to
Abelian-Higgs Type-I strings



Effect of small reconnection probability

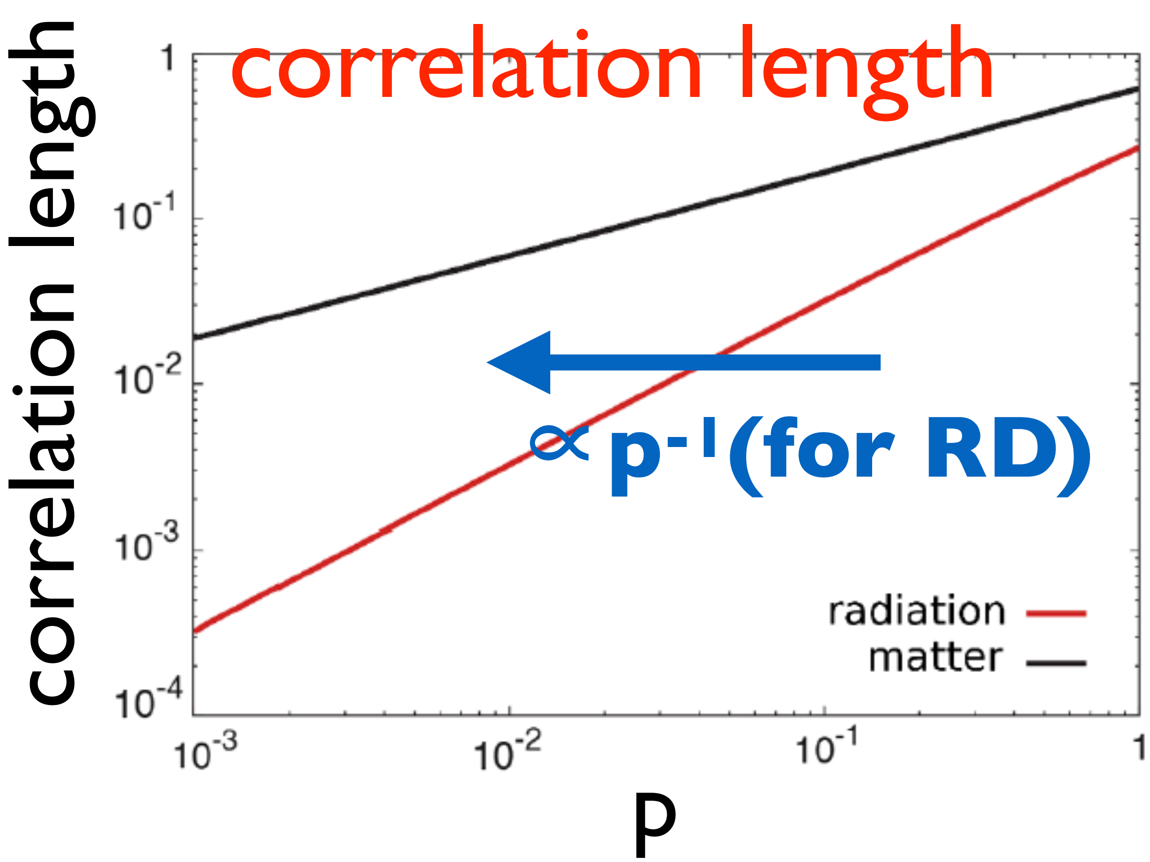


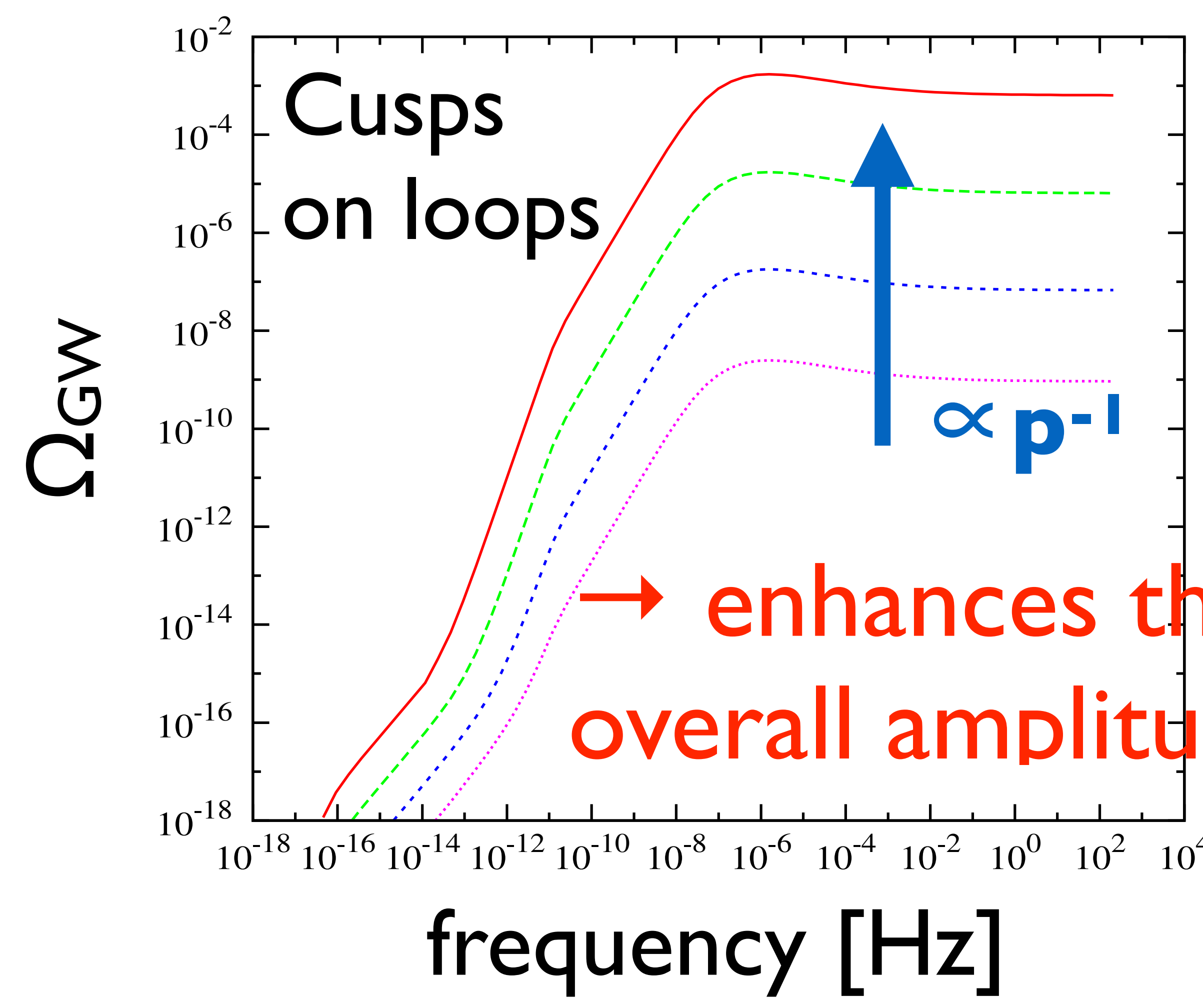


→ more strings
in the Universe

but the network still
follows the scaling law

→ smaller
correlation length



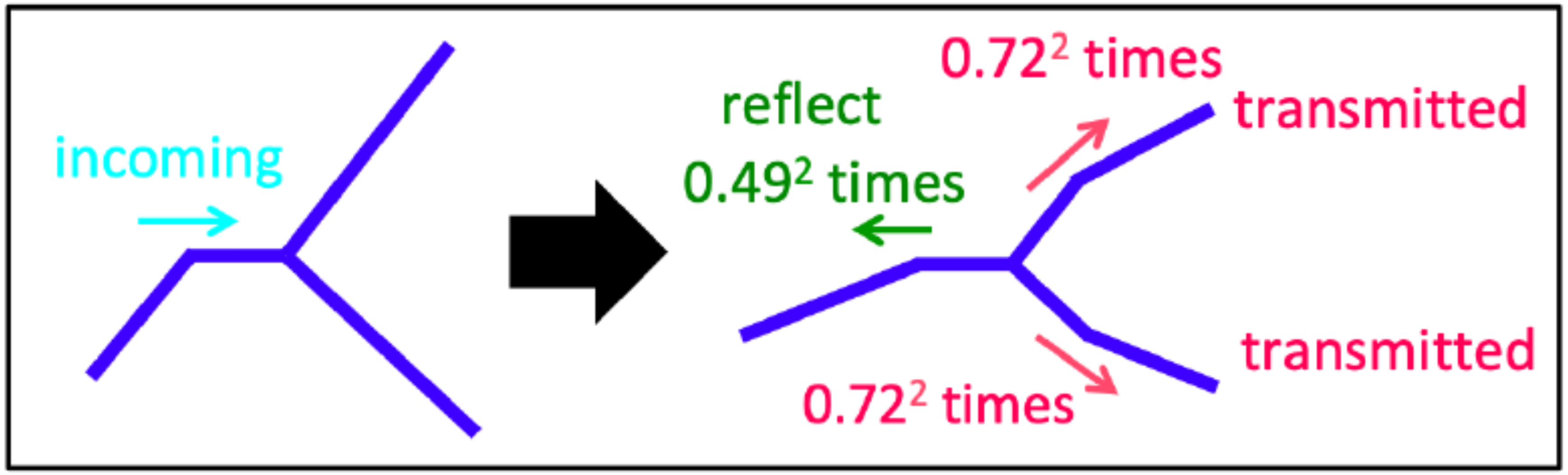


→ enhances the
overall amplitude

Kink proliferation by Y-junction

Binetruy et al. PRD 82, 083524 (2010)

A kink transforms to **3 daughter kinks** when it encounters to a Y-junction



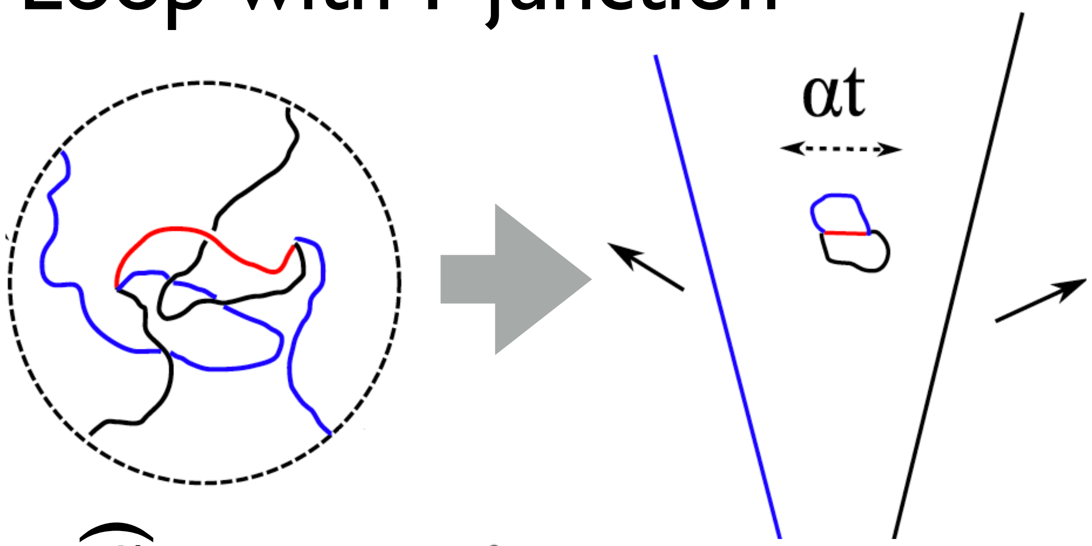
	infinite strings	loops
cusp	little	numerous
kink	numerous	~~little~~

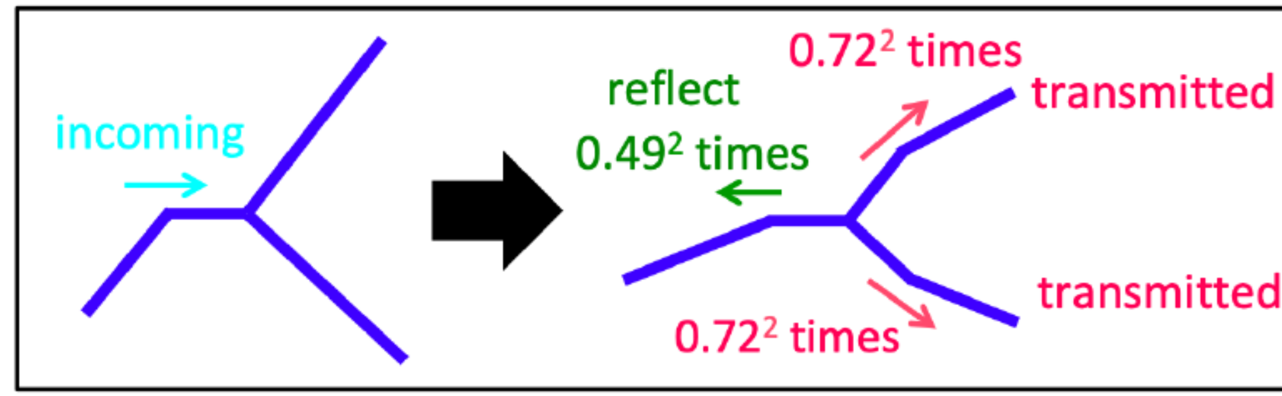
more numerous **numerous**

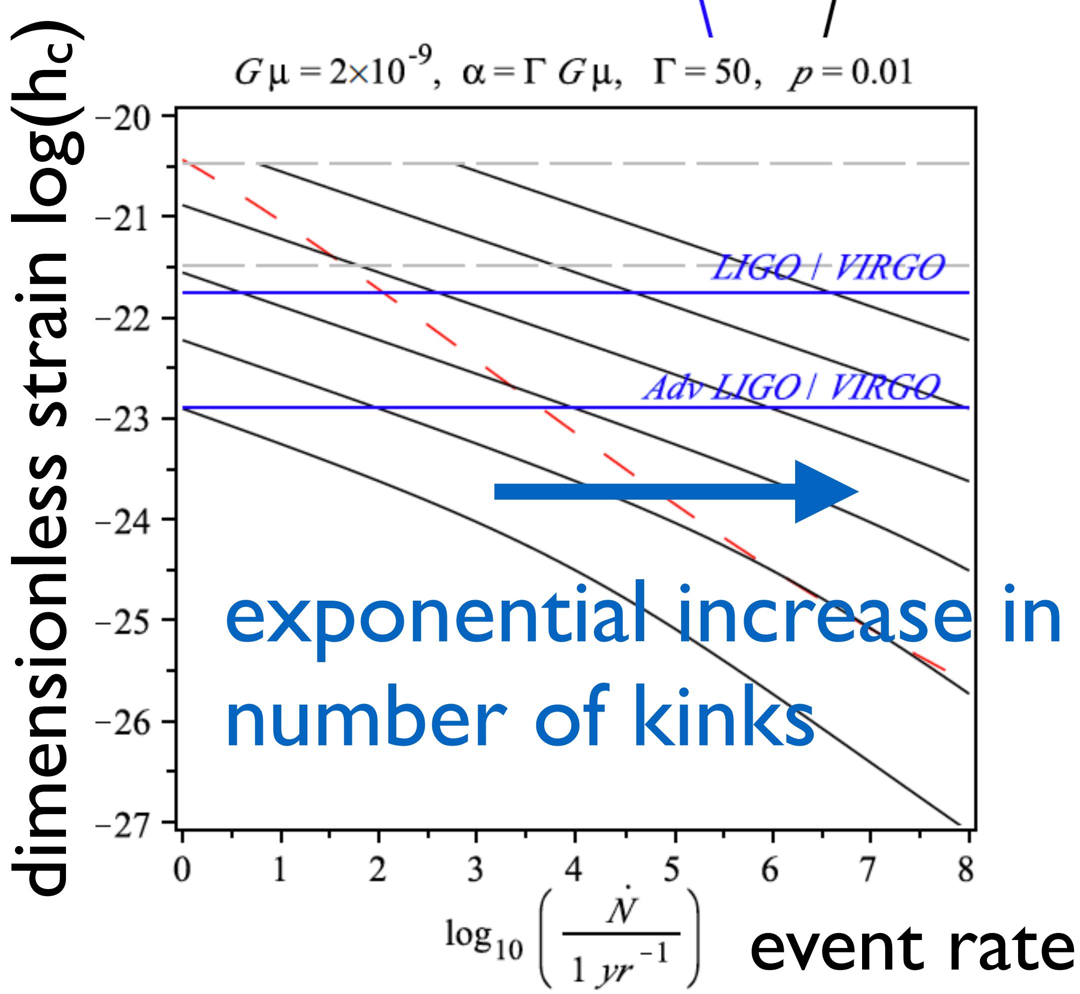
GW Background from kinks on superstring loops

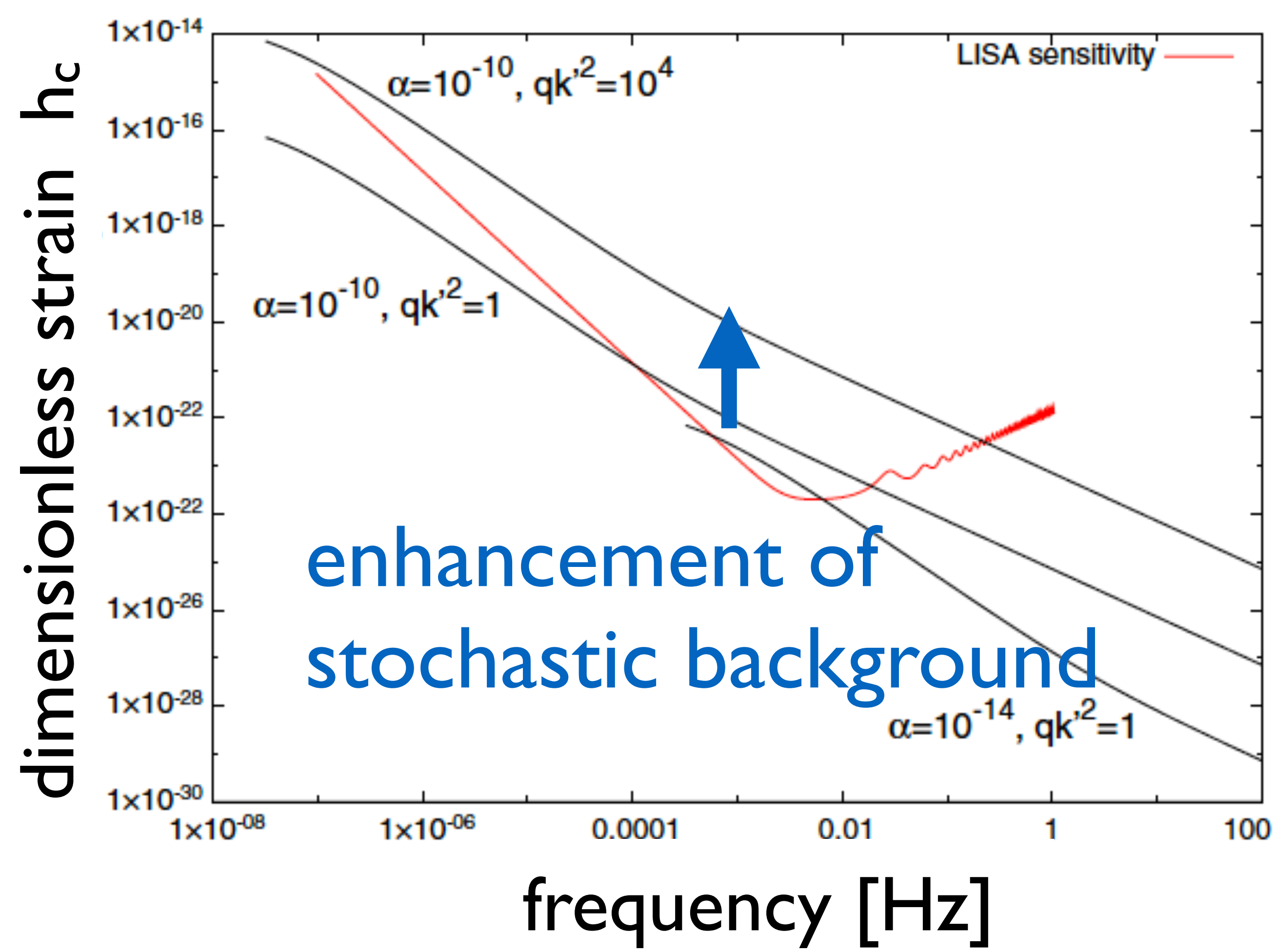
Loop with Y junction

Binetruy et al. PRD 82, 126007 (2010)



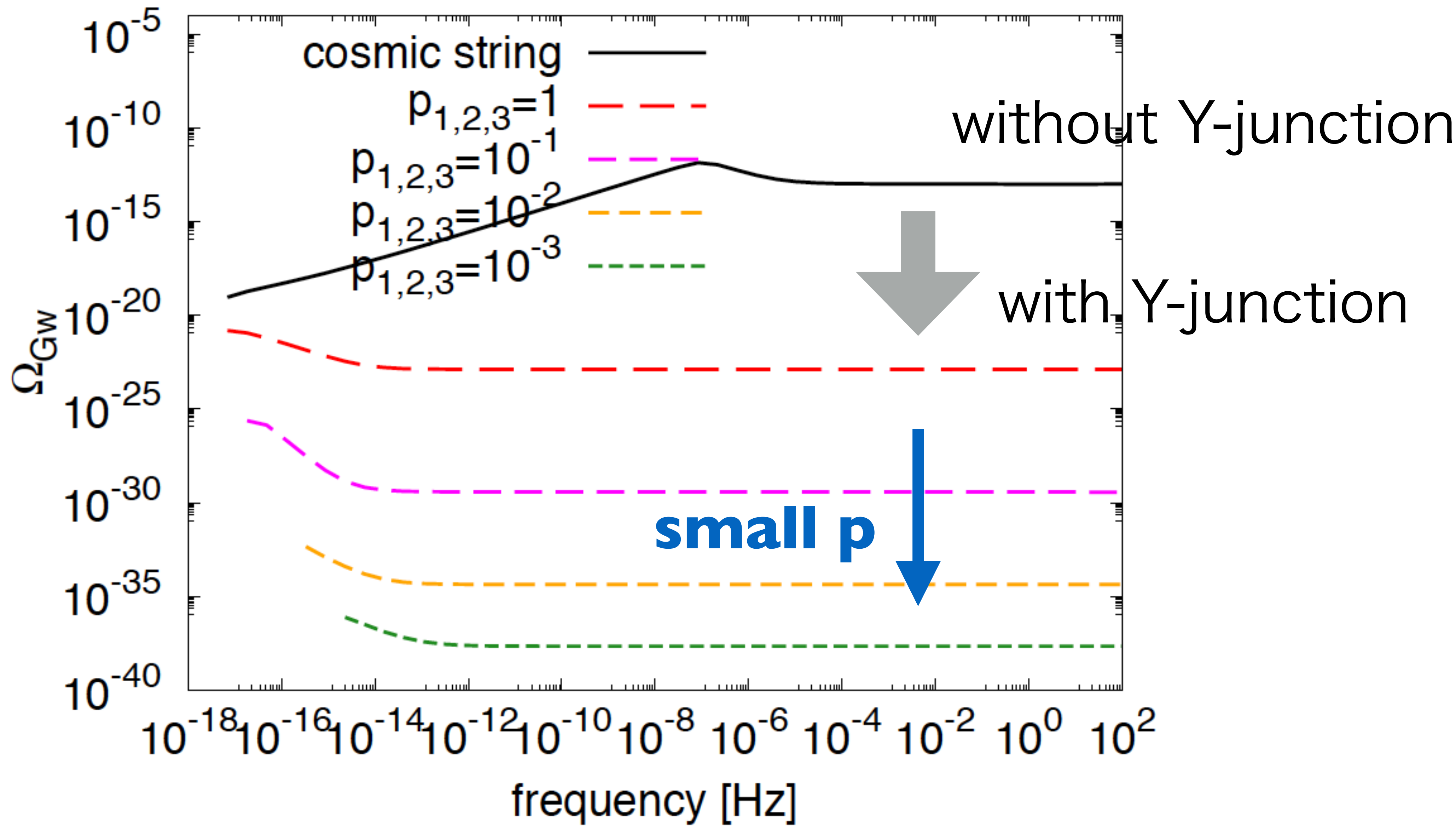






Note: no careful consideration about the sharpness of kinks

GW Background from **kinks on infinite superstrings**



GW amplitude get suppressed because
Y-junction reduces the sharpness of kinks

Matsui et al. (+SK), JCAP 11 (2020) 039

Summary

- Cosmic strings and superstrings predicts distinct **GW signals**
- There are various ways of emitting GWs, especially those from singular points (**cusps** and **kinks**) are strong
- **Infinite strings** have more kinks while **loops** has more cusps, but existence of **Y-junctions** may change this picture.
- We can search for both **burst events** and **a stochastic background**

→ can be tested by GW experiments, which provides insights into high-energy theories in the early universe!