Probing cosmic string properties through Pulsar Timing Array

Use of anisotropy of the gravitational wave background

Sachiko Kuroyanagi

(Nagoya U.)

in collaboration with
K. Takahashi, H. Kumamoto, N. Yonemaru

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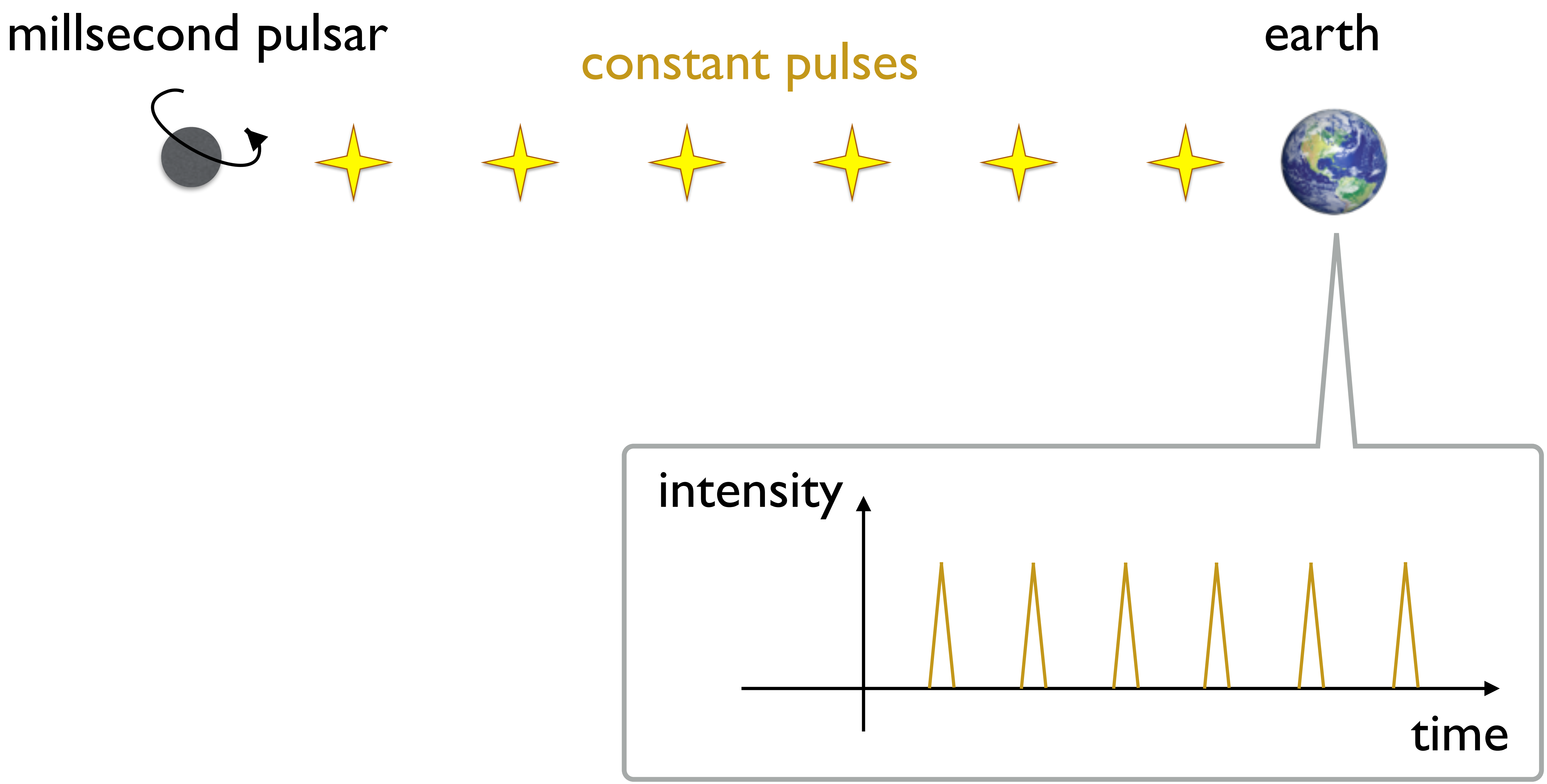
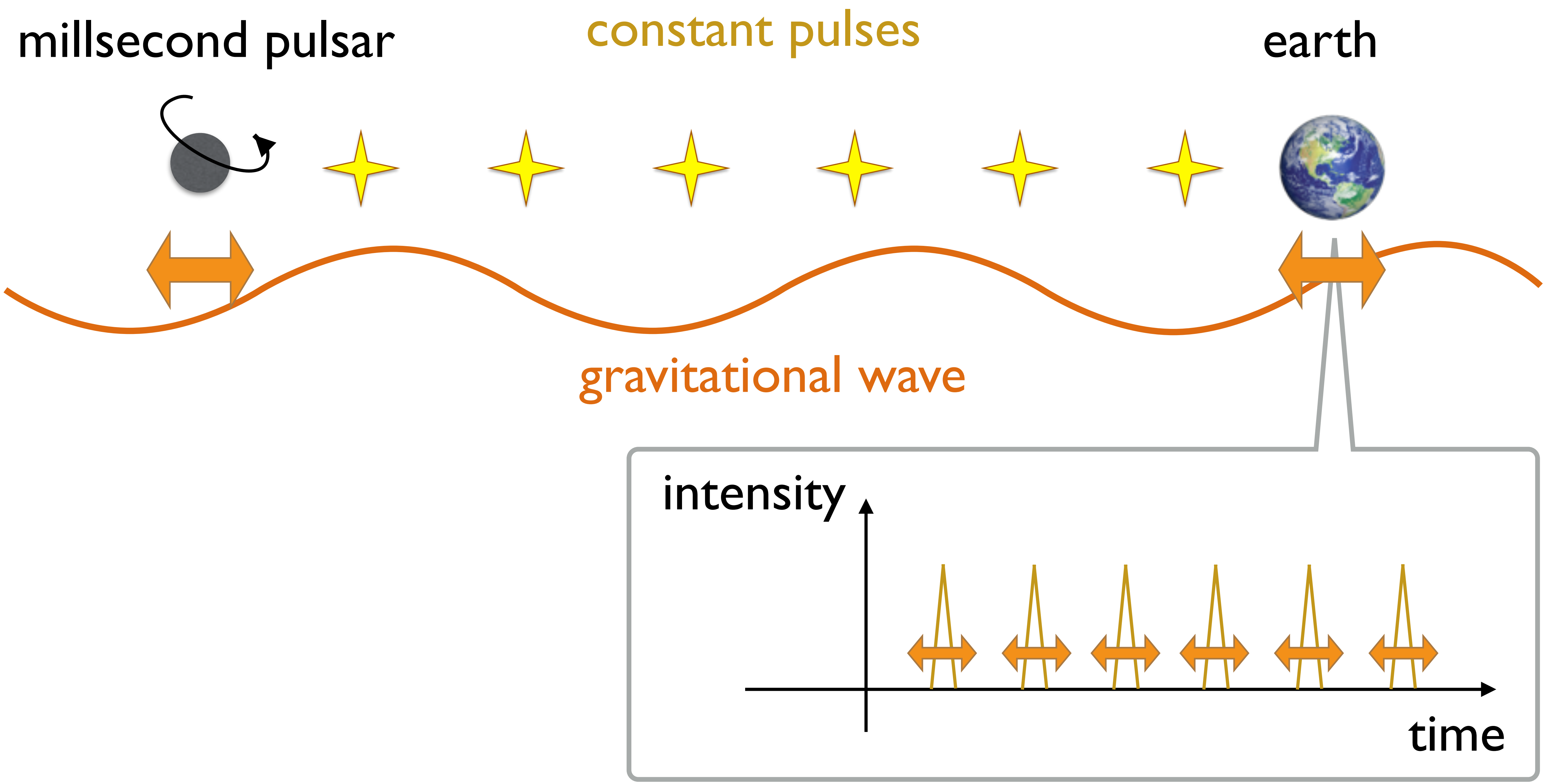
Pulsar timing array

- Robust and unique test of gravitational waves

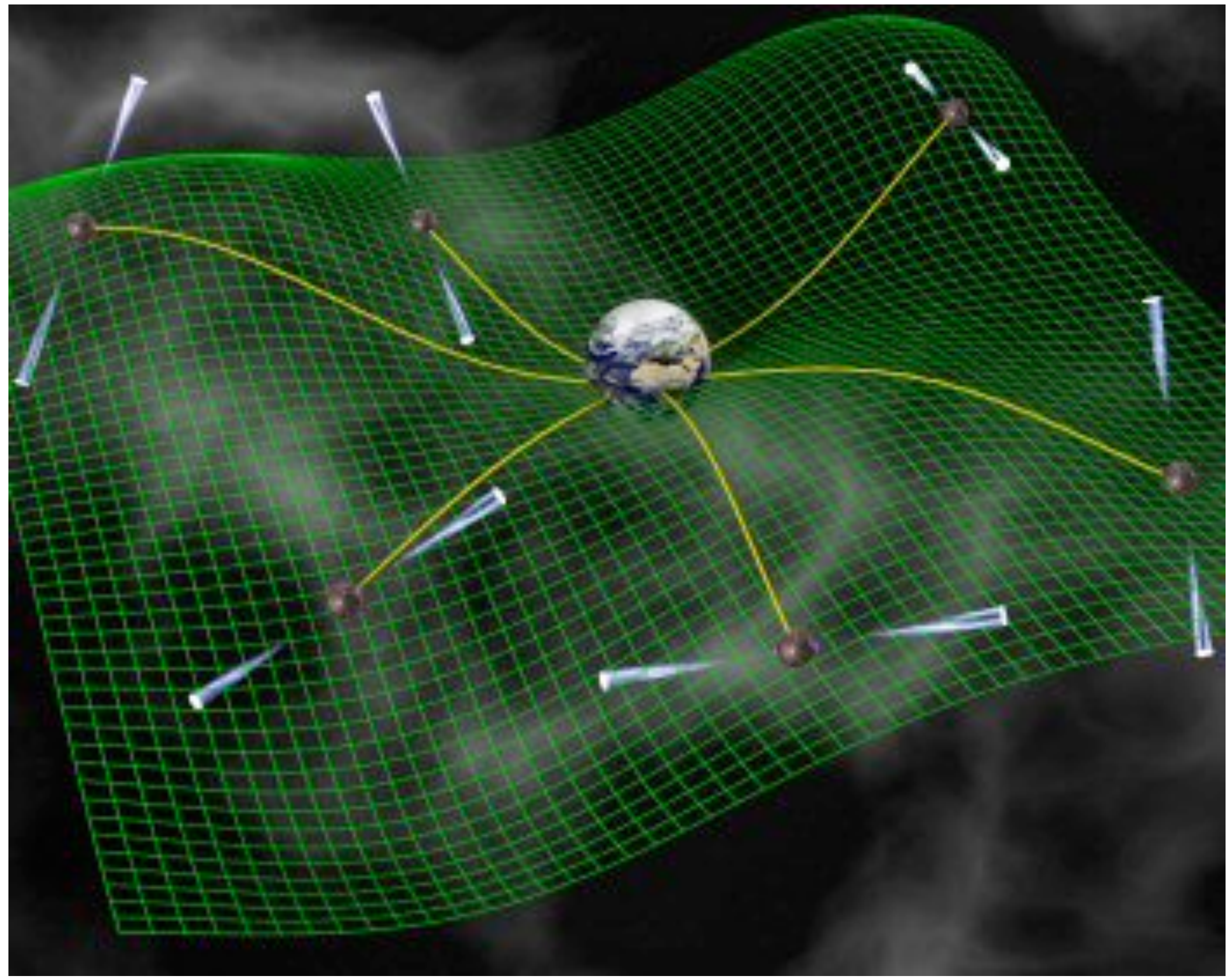


Pulsar timing array

- Robust and unique test of gravitational waves

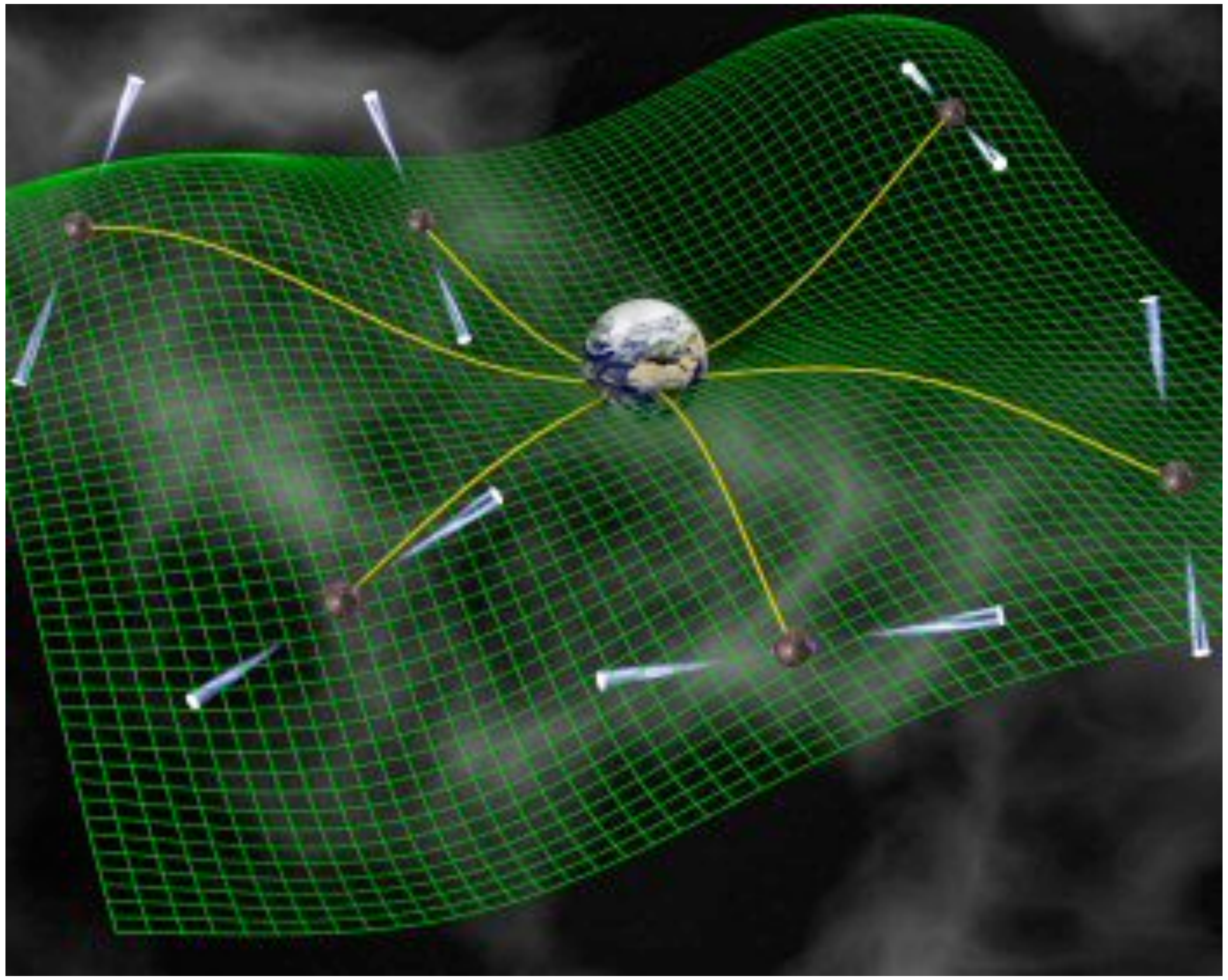


Pulsar timing array



- Correlation analysis with multiple pulsars to remove noises associating with individual pulsars
- Frequency $\propto$ (Observation time)$^{-1}$

Pulsar timing array



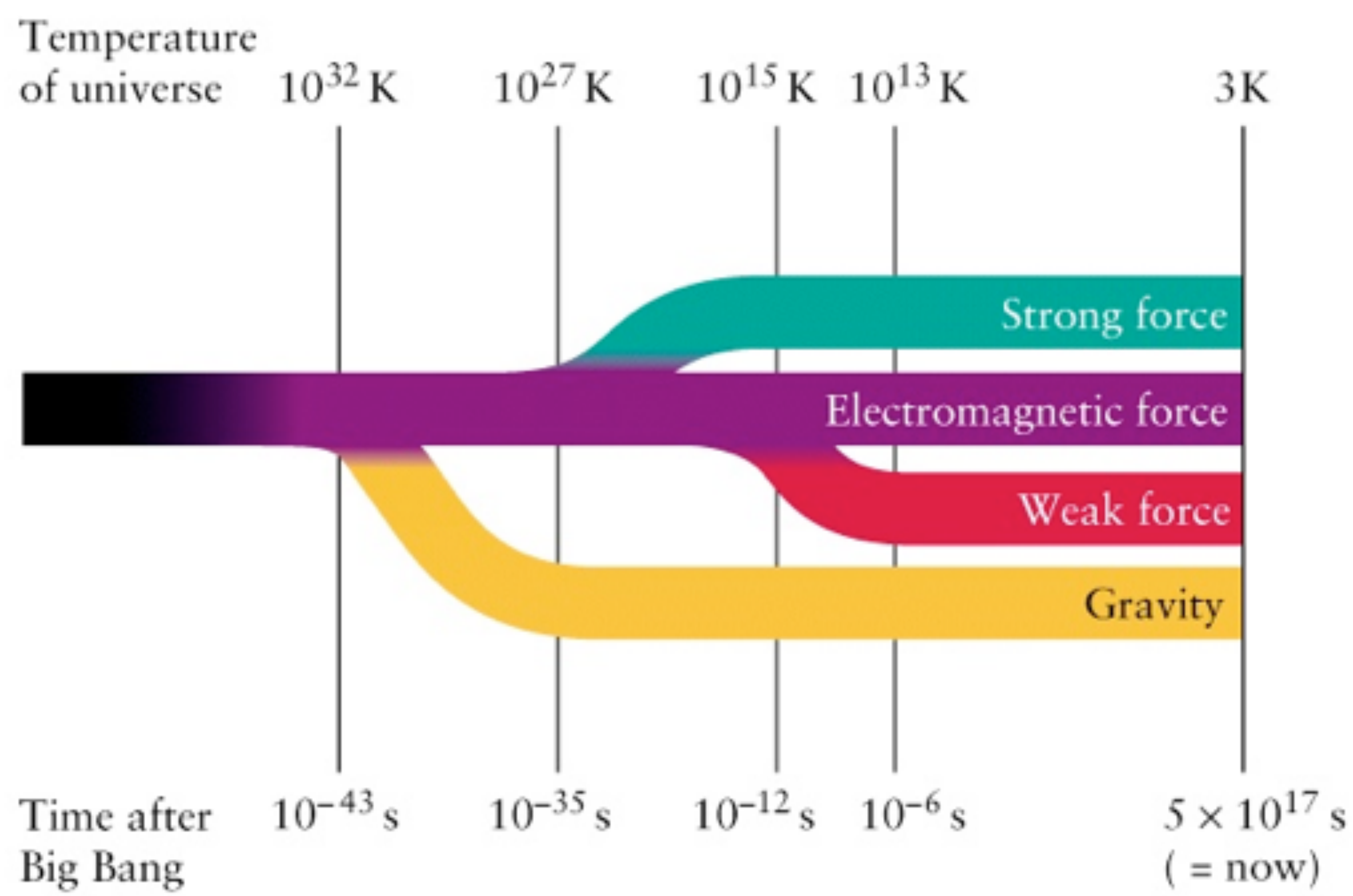
- expected to detect gravitational waves from super massive black hole binaries or maybe from exotic sources (e.g. cosmic strings)

Cosmic string？

One dimensional topological defect
generated in the early universe

Generation mechanism

1: Phase transition



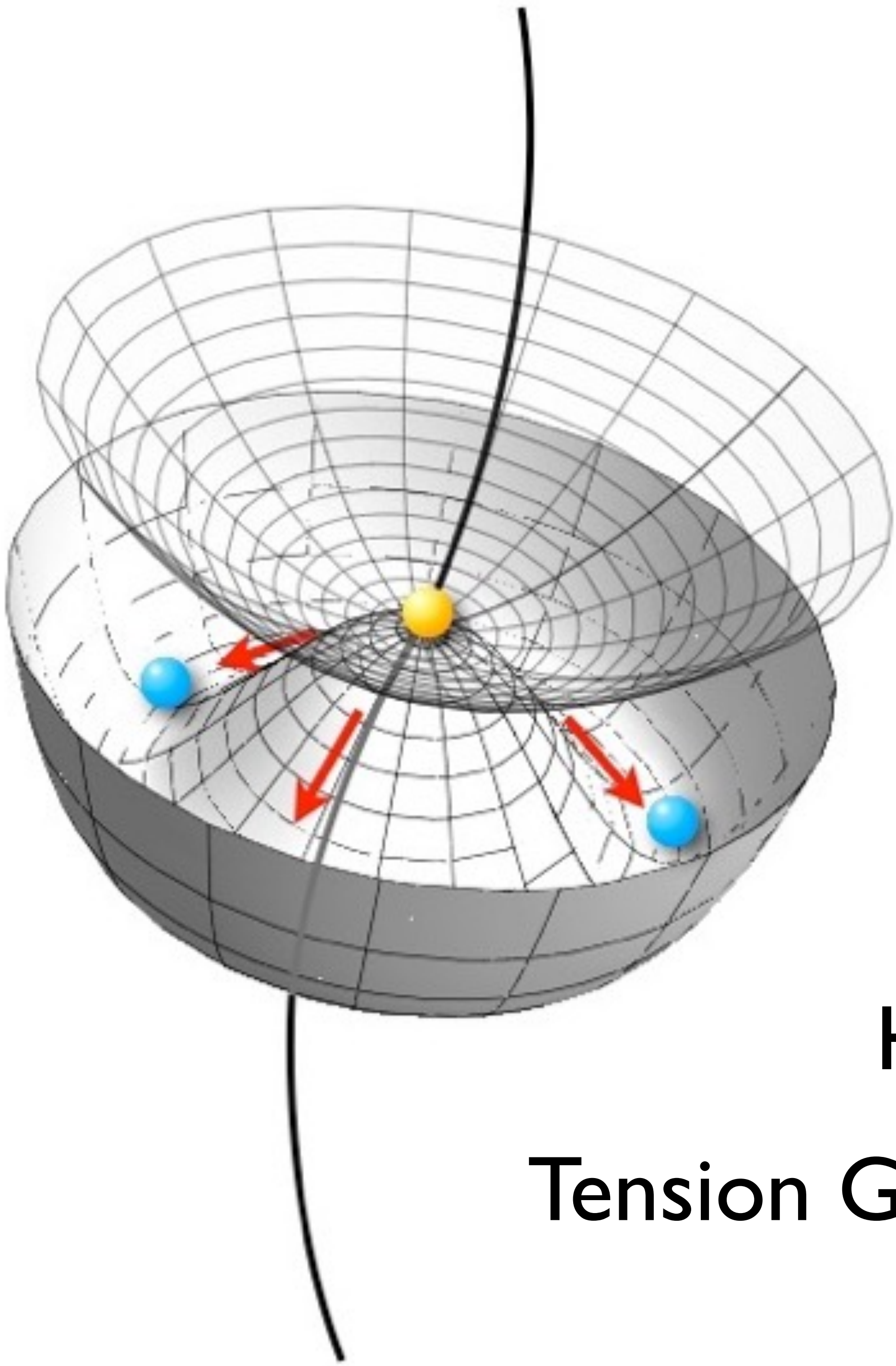
2: Cosmic superstrings

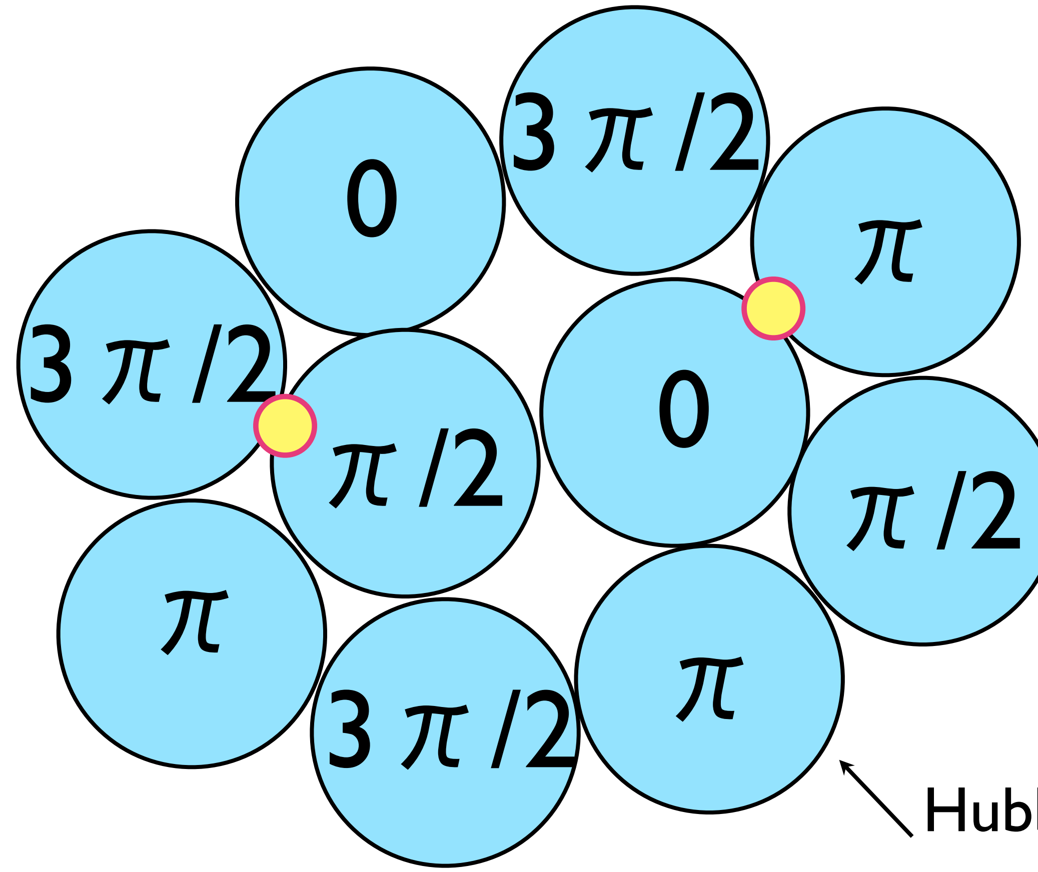
Cosmological size D-strings or F-strings remains after inflation

→ could provide some insight into fundamental physics

Generation mechanism 1: phase transition

The Universe has experienced symmetry breakings.





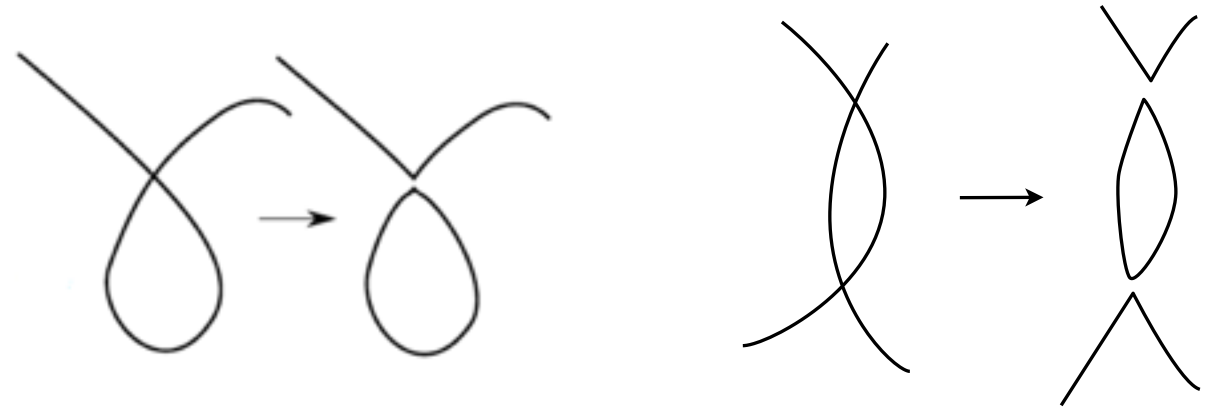
High energy vacuum remains at the center

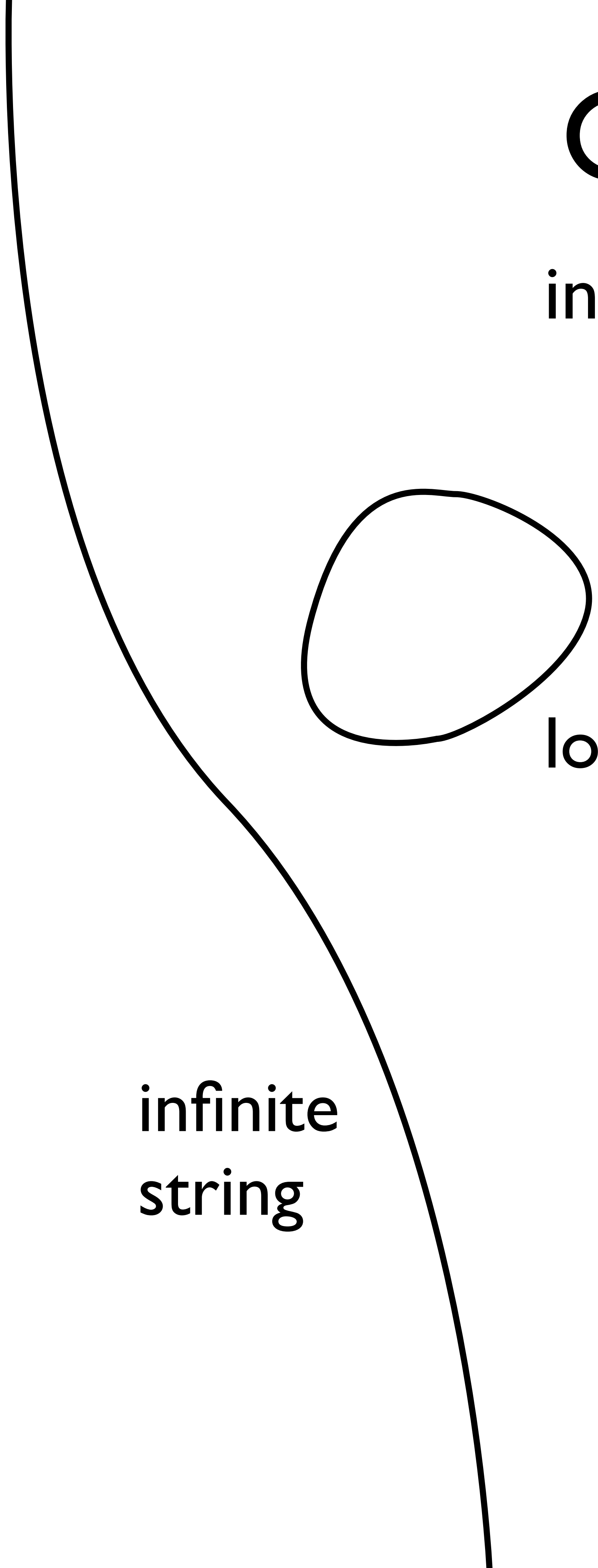
Tension Gμ ~ potential energy of the true vacuum

~ the energy scale of the phase transition

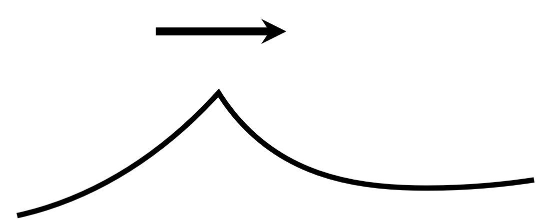
Cosmic string ?

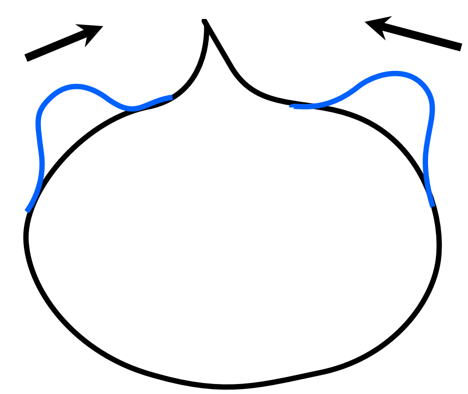
infinite string becomes a loop by reconnection





strings emit gravitational waves
especially from singular structures





loops lose energy and shrink by emitting
gravitational waves and eventually evaporate

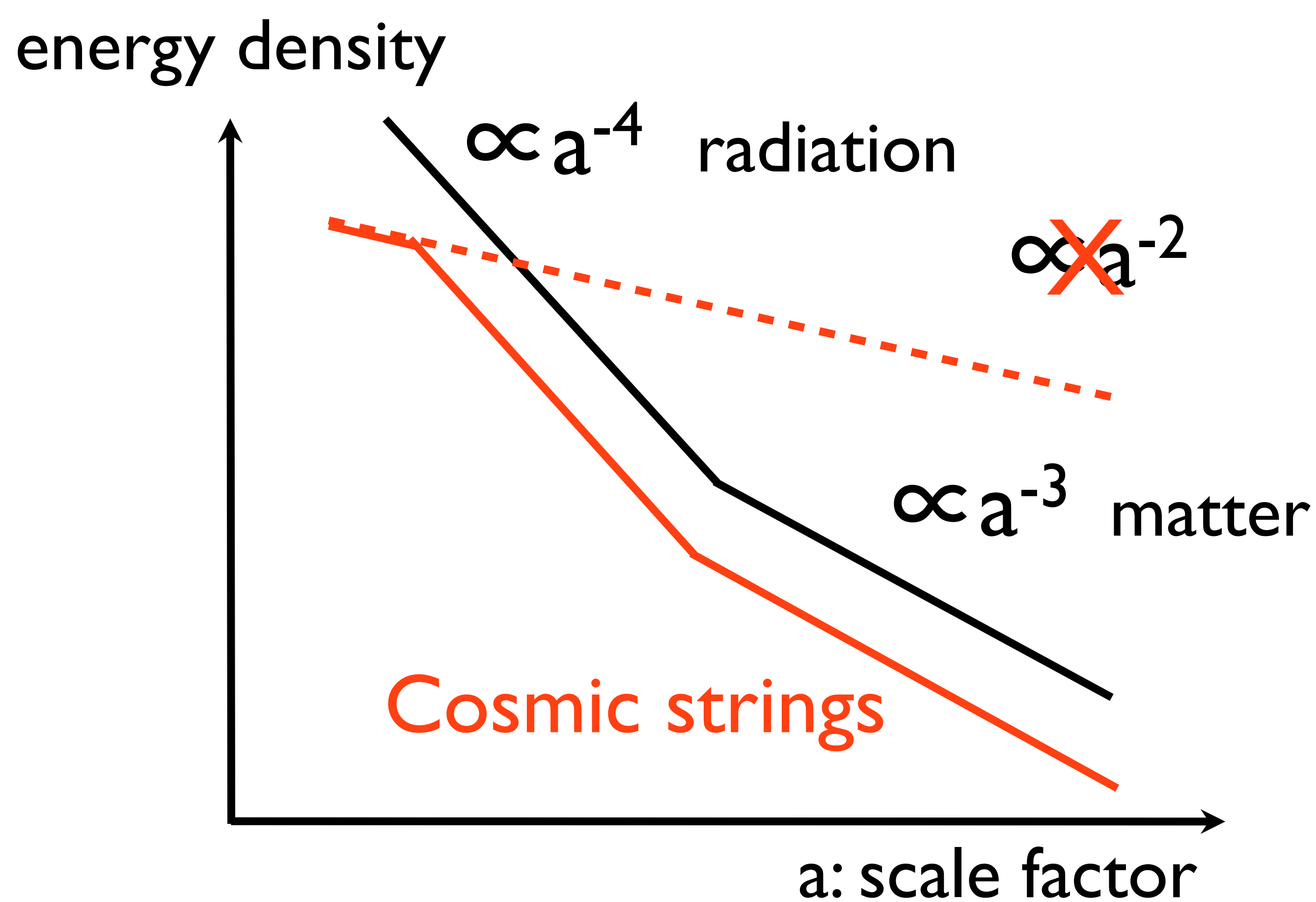
Evolution of cosmic strings

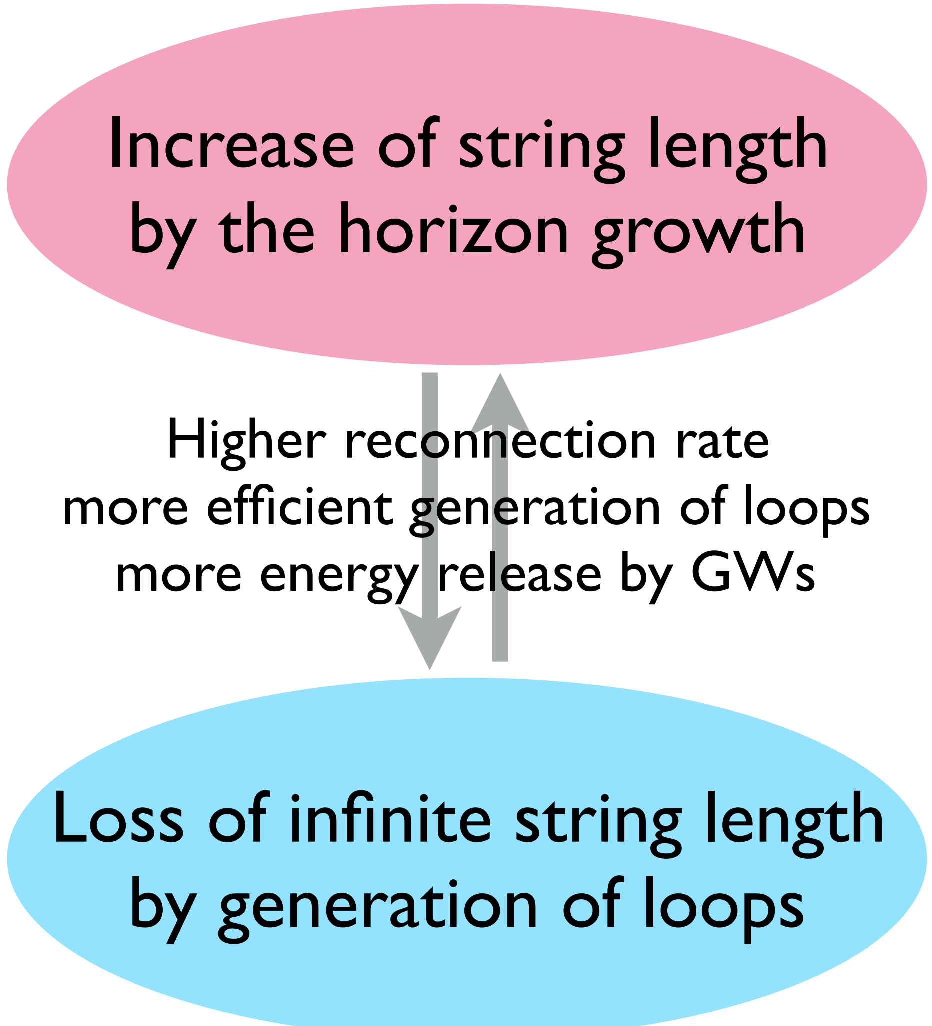
The energy density of cosmic strings

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

Scaling law

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



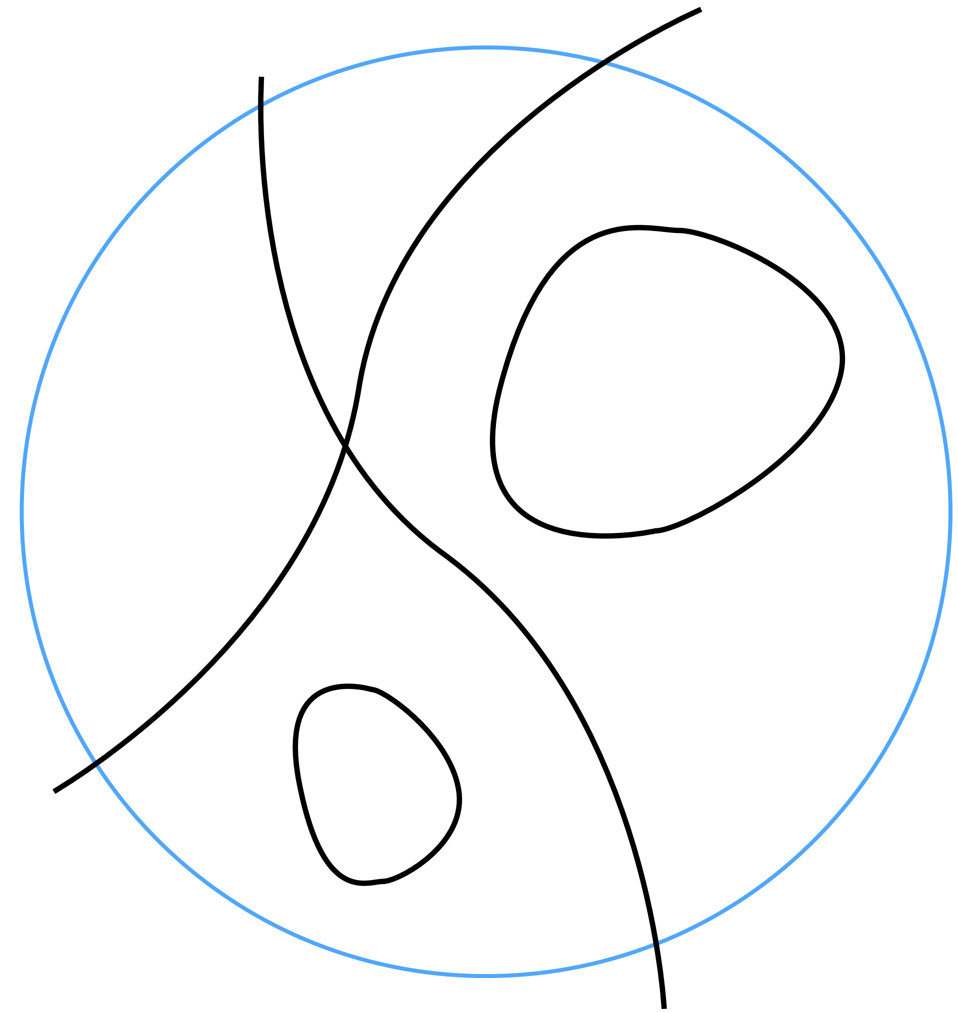


Cosmic string loops generate scale invariant GWs

Early Universe

→ high frequency GWs

Late Universe



→ low frequency GWs

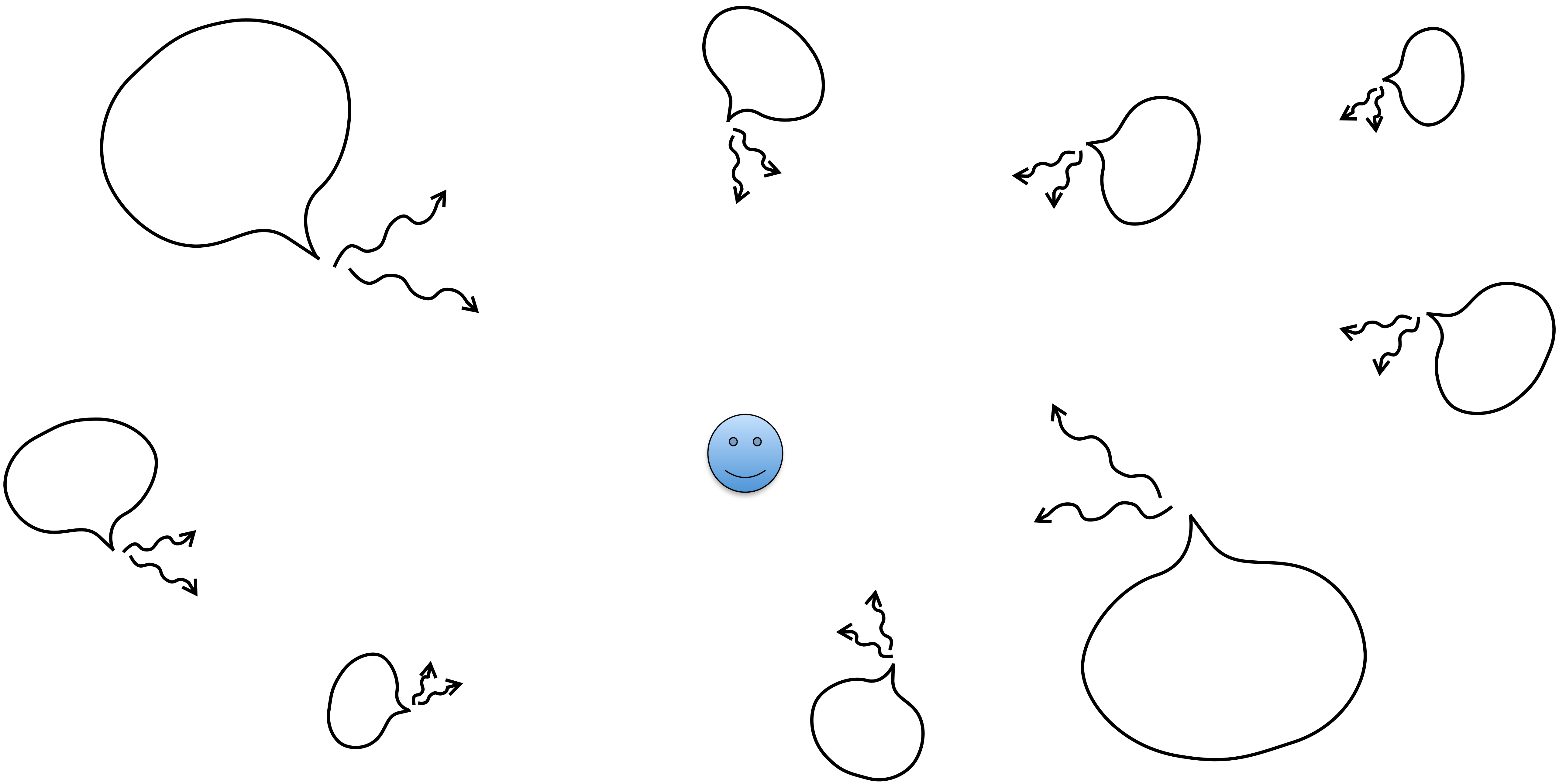
GW frequency ~ 1/L

GW amplitude $\Omega_{GW} \equiv \frac{1}{\rho_c} \frac{d\rho_{GW}}{d\ln k}$ ~ constant

$\rho_c \propto a^{-4}$ for RD

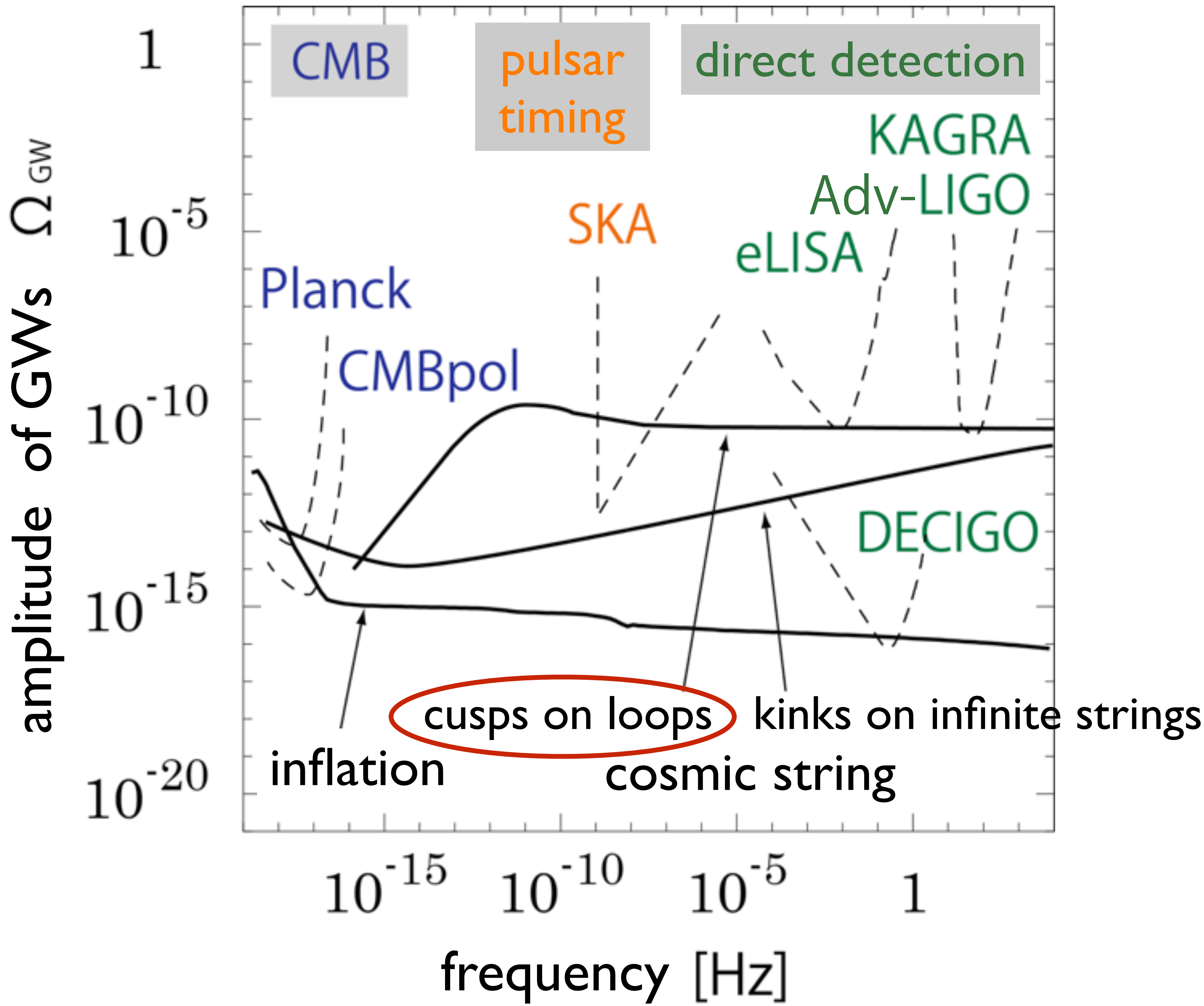
$\rho_{GW} \propto a^{-4}$

Gravitational waves from cosmic string loops



Gravitational waves coming from different directions overlap each other and form gravitational wave background

Spectrum and Sensitivities



What determines the GW amplitude?

3 main parameters to characterize cosmic string

- $G\mu$: tension = line density

  Generation mechanism

- α : initial loop size $L \sim \alpha H^{-1}$

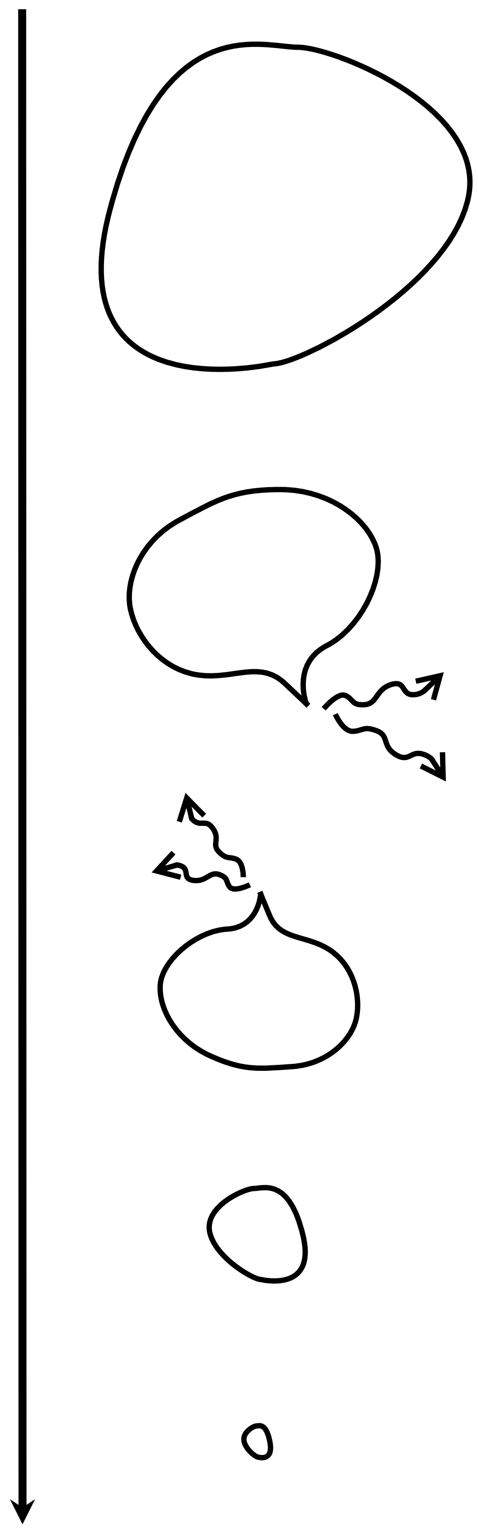
  Network evolution

- p : reconnection probability

  Phase transition origin: p=1

  Cosmic superstring: p<<1

Evolution of a loop



Initial loop length = αt_i

t_i : time when the loop formed

GW power $P = \Gamma G \mu^2$ Γ: numerical constant ∼50-100

From the energy conservation law
(energy of loop at time t =μl)

= (initial energy of the loop =$\mu\alpha t_i$) − (enegry released to GWs =PΔt)

Loop length at time t $l(t, t_i) = \alpha t_i - \Gamma G \mu (t - t_i)$

Lifetime of the loop = $\frac{\text{(initial loop energy)}}{\text{(energy release rate per time)}}$

$$= \frac{\mu \alpha t_i}{\Gamma G \mu^2} = \frac{\alpha t_i}{\Gamma G \mu}$$

Amplitude of GW background

$\propto$ amplitude of single burst $h \propto G\mu$

$\propto$ number density of loops n_l

depends on **Lifetime of the loop** $= \dfrac{\alpha t_i}{\Gamma G\mu}$

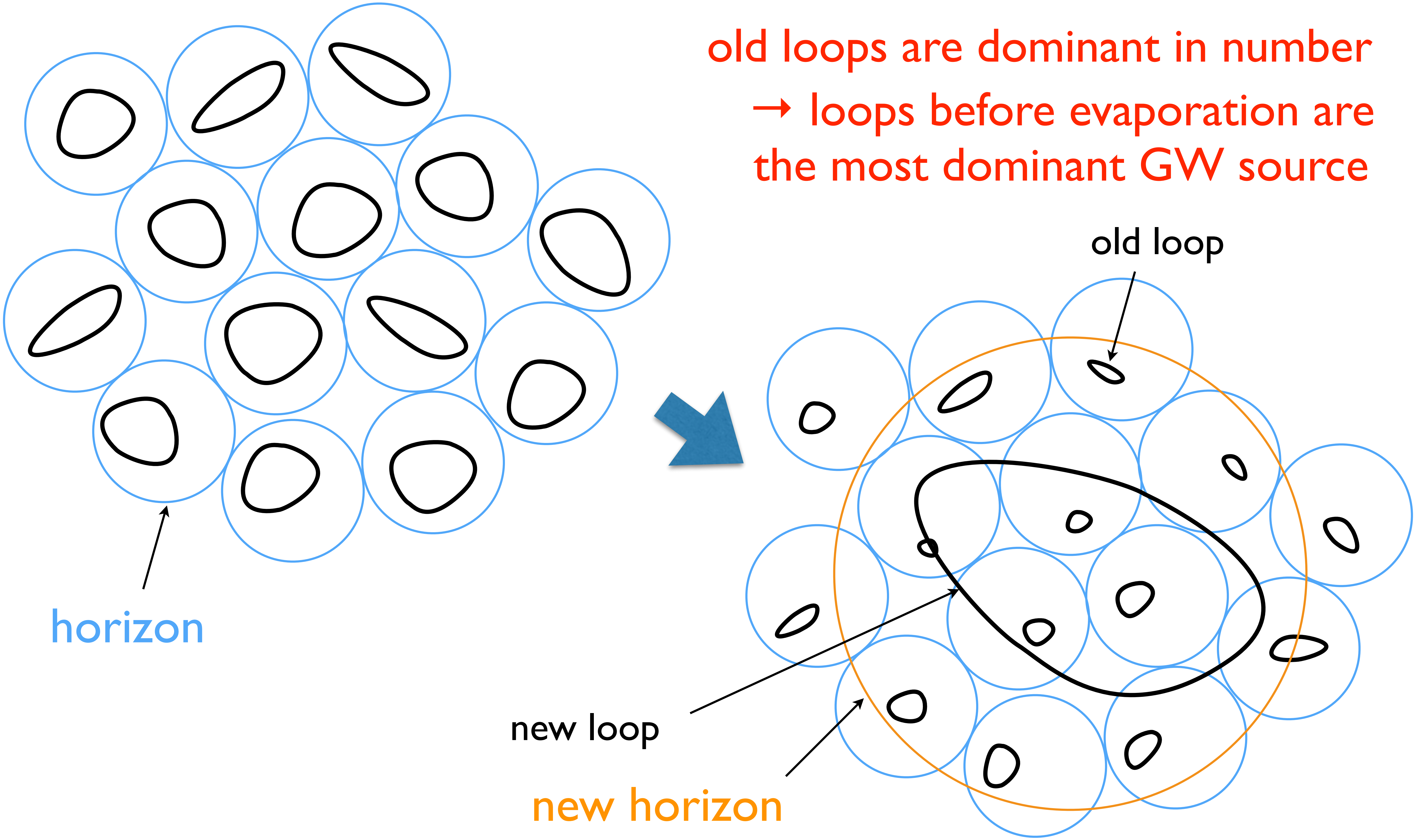
$\alpha \ll \Gamma G\mu$	$\alpha \gg \Gamma G\mu$
Loops evaporate soon after the generation	Loops remain for a while → the string network consists of old and new loops
$n_l \propto$ const	$n_l \propto \alpha^{1/2}$

Number density of loops

$\alpha \gg \Gamma G\mu$ → the network consists of old and new loops

old loops are dominant in number

→ loops before evaporation are the most dominant GW source



GW spectrum

$\alpha \gg \Gamma G\mu$

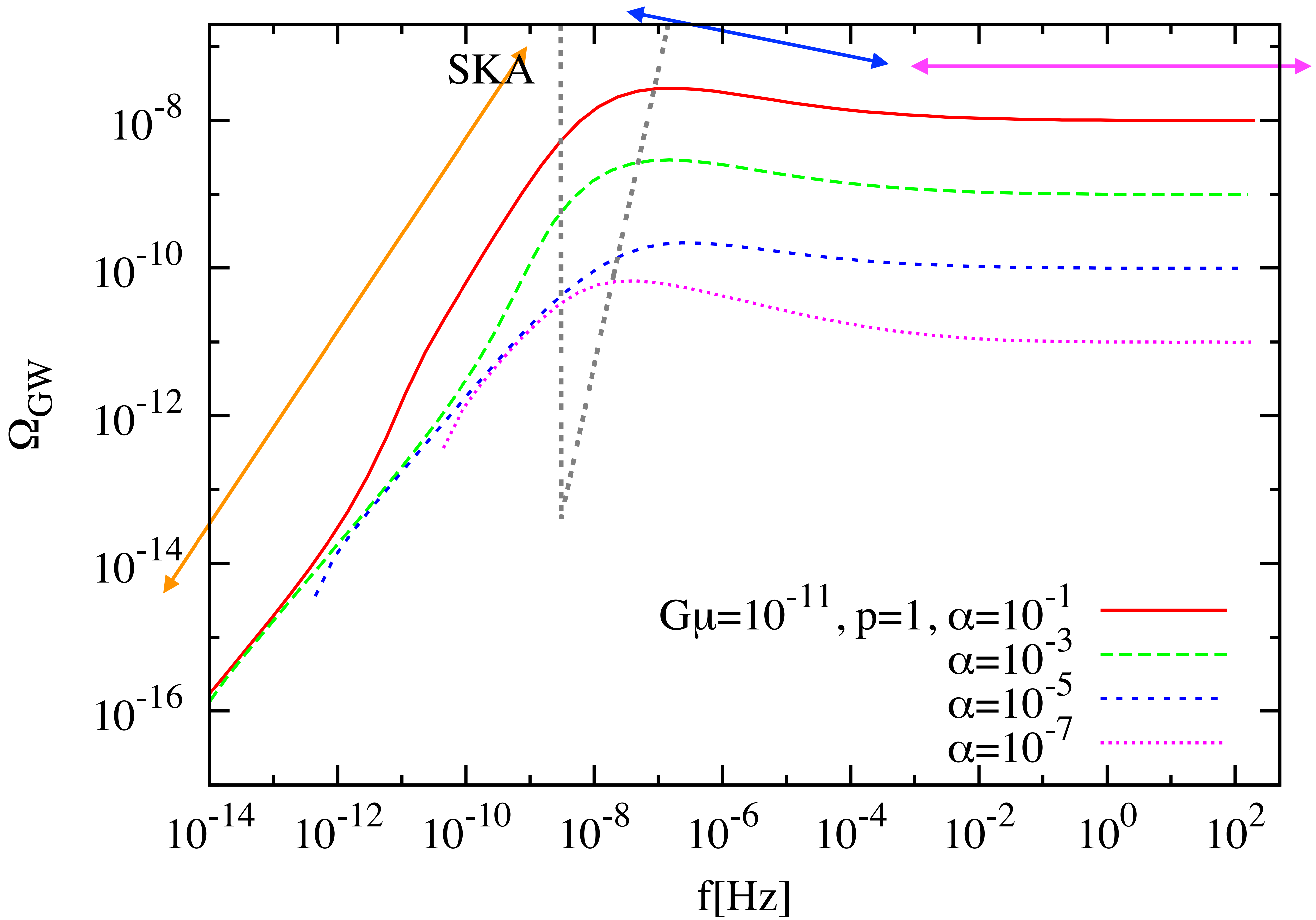
Loops remain for a while

$n_l \propto \alpha^{1/2}$

loops which evaporate in MD

GWs from loops which still exists

loops which evaporate in RD

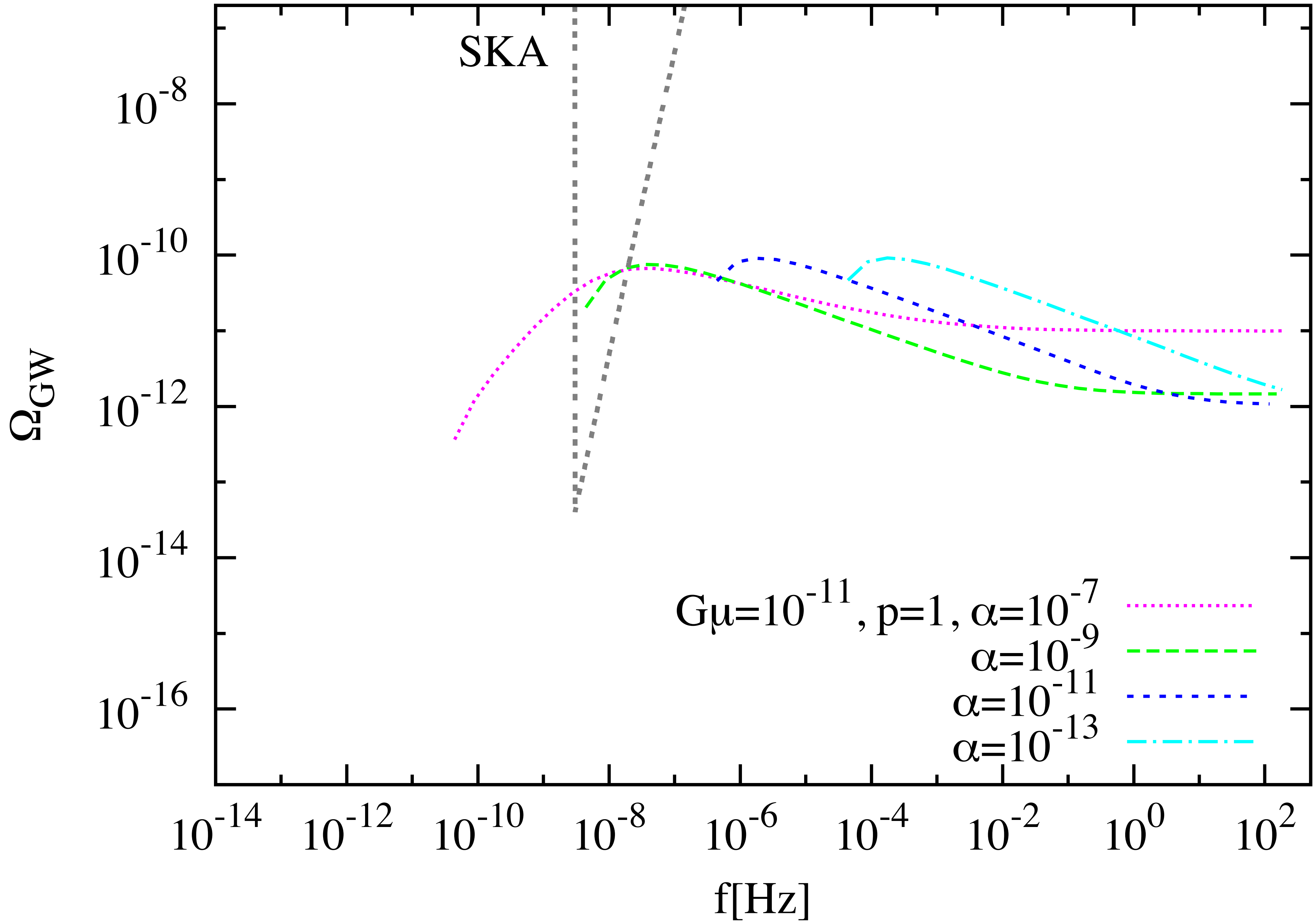


GW spectrum

$\alpha \ll \Gamma G\mu$

Loops evaporate soon after the generation

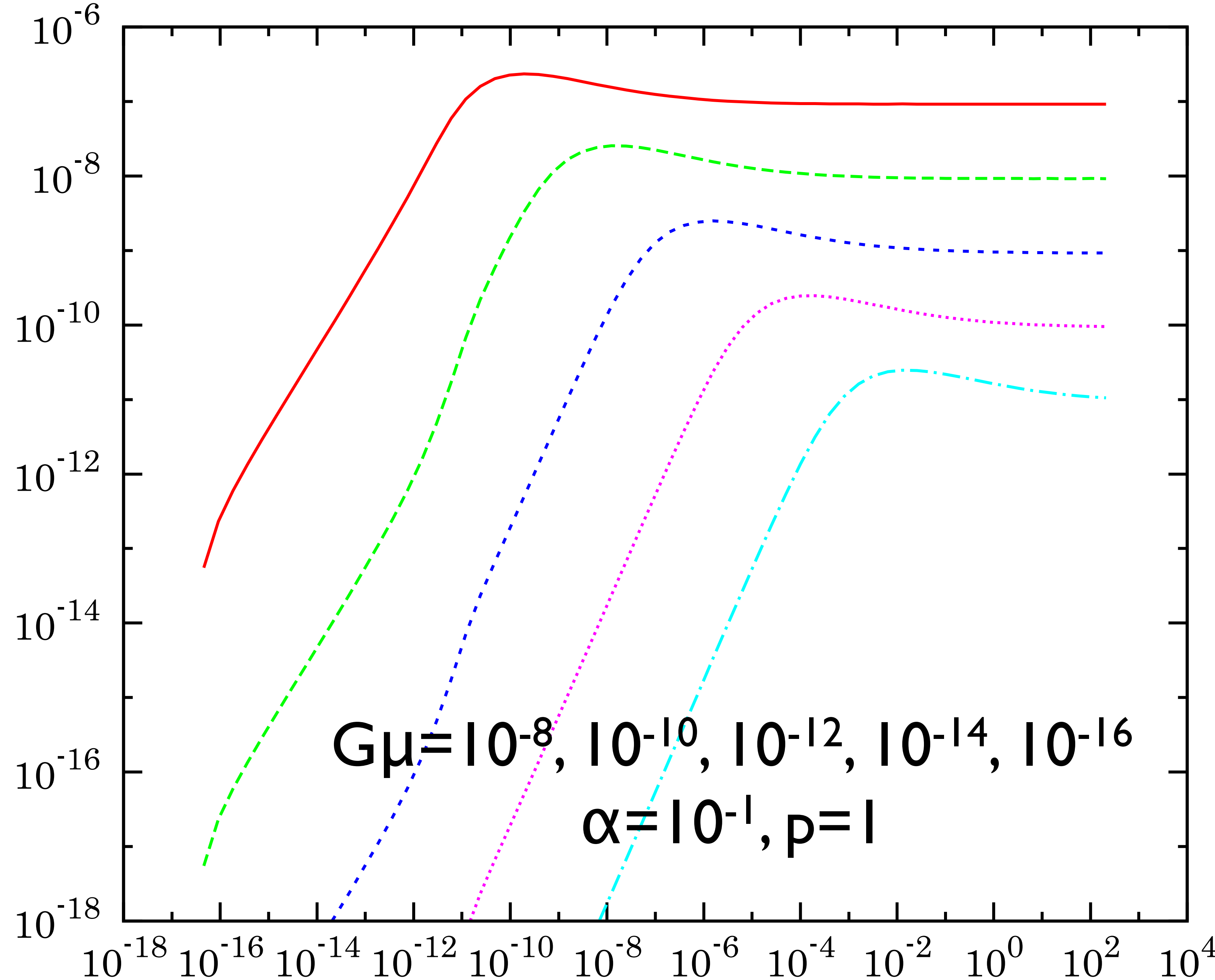
$n_l \propto$ const



GW spectrum

$\alpha \gg \Gamma G\mu$

dependence on Gμ

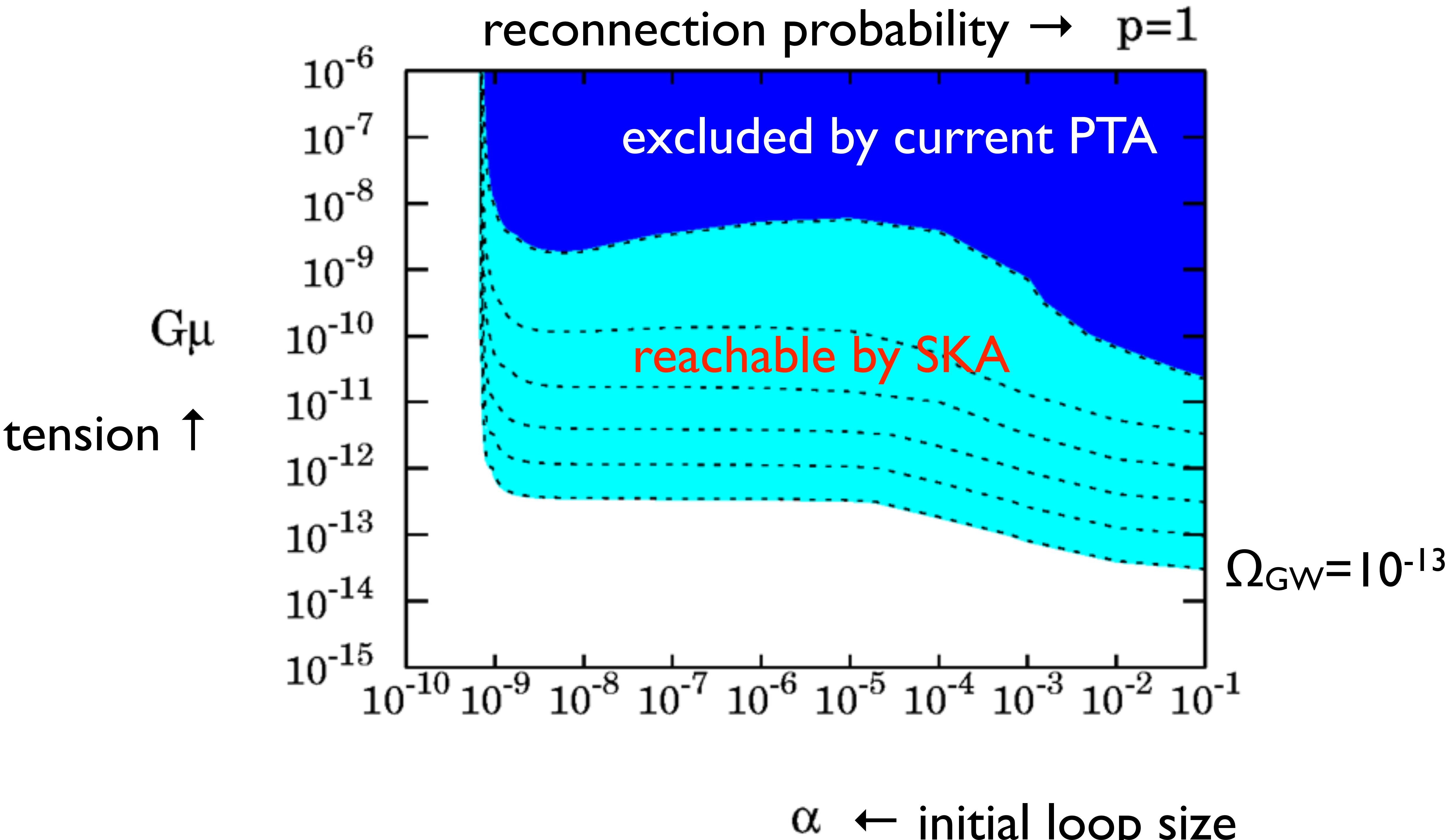


GW power from cusps

$h^2 \propto (G\mu)^2$

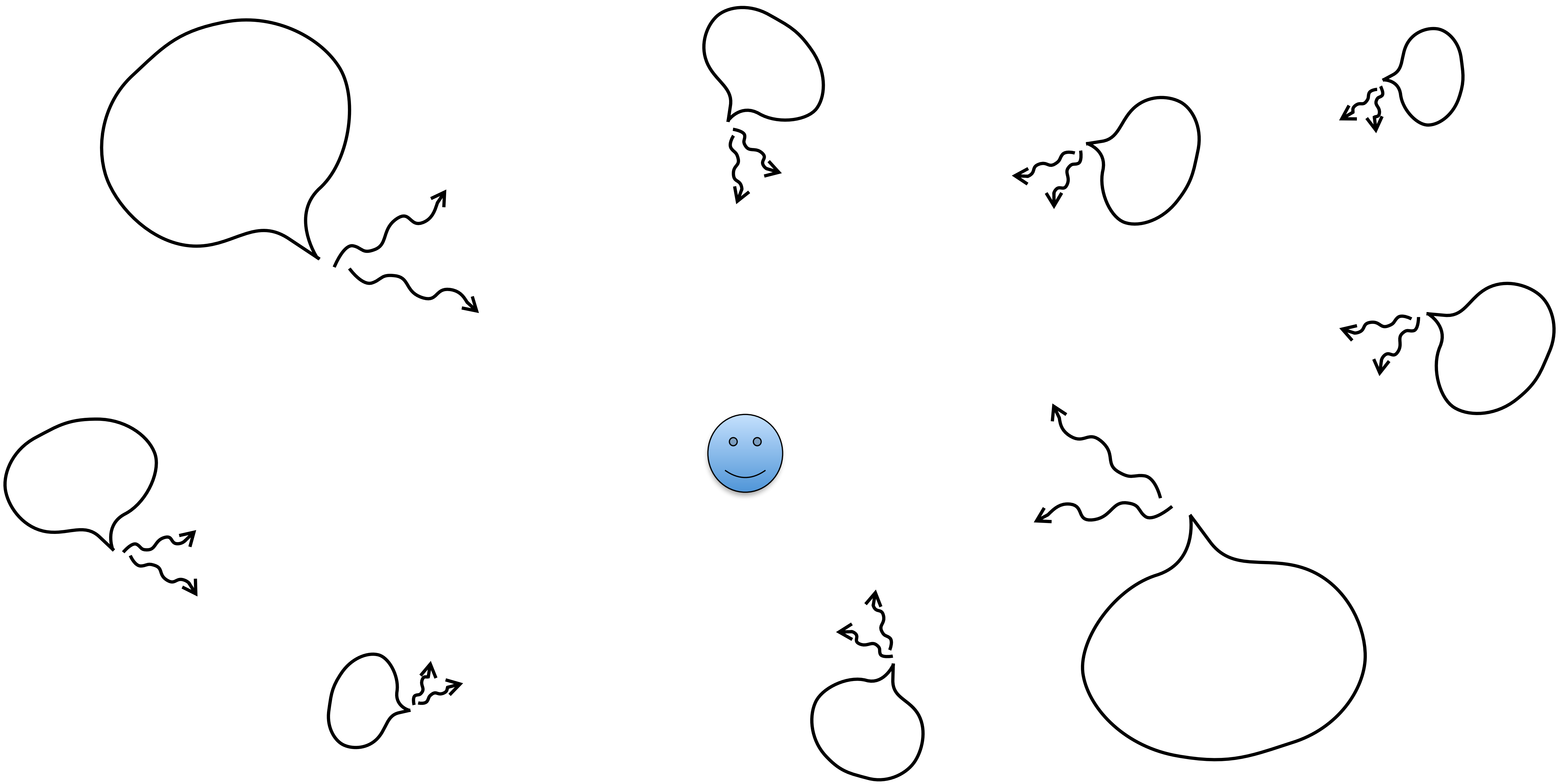
life time of loops $\propto (G\mu)^{-1}$

Detectability in Gμ - α plane



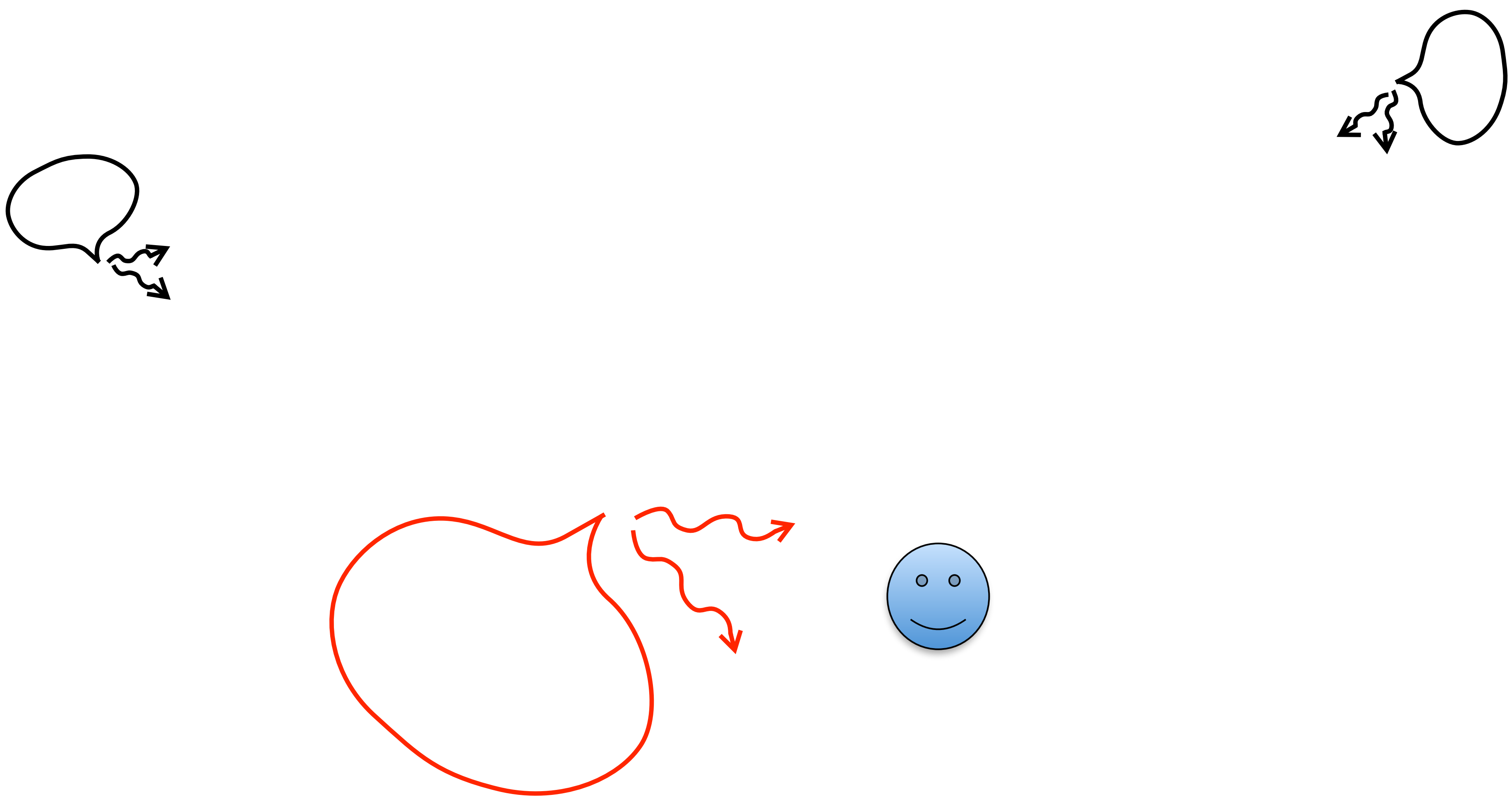
SKA will cover a large parameter space of cosmic string parameters

Gravitational waves from cosmic string loops



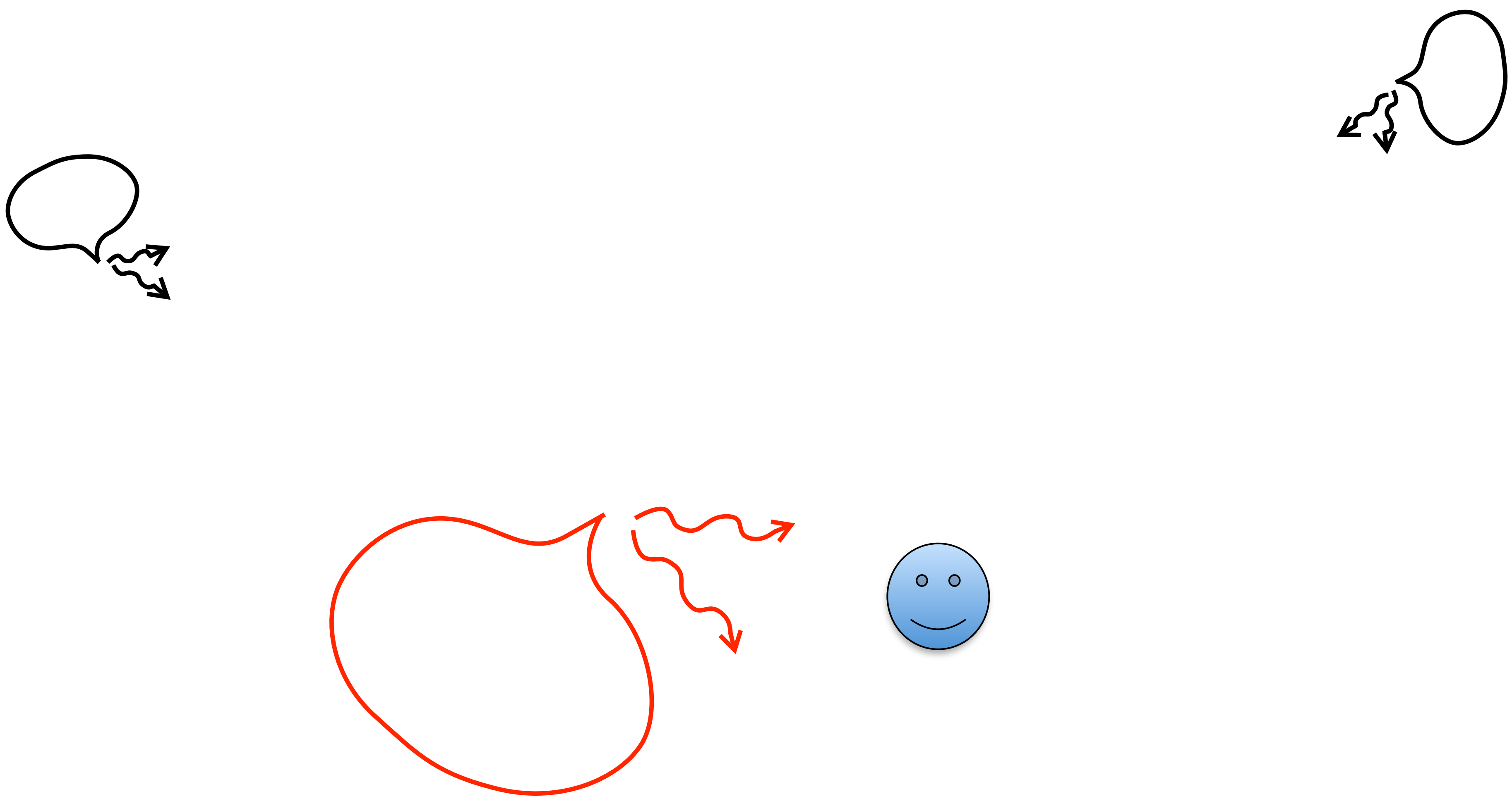
Gravitational waves coming from different directions overlap each other and form gravitational wave background

Anisotropy of gravitational wave background



If there is very few loops,
gravitational wave background becomes anisotropic

Anisotropy of gravitational wave background



Can we extract information of cosmic strings from anisotropy of the gravitational wave background?

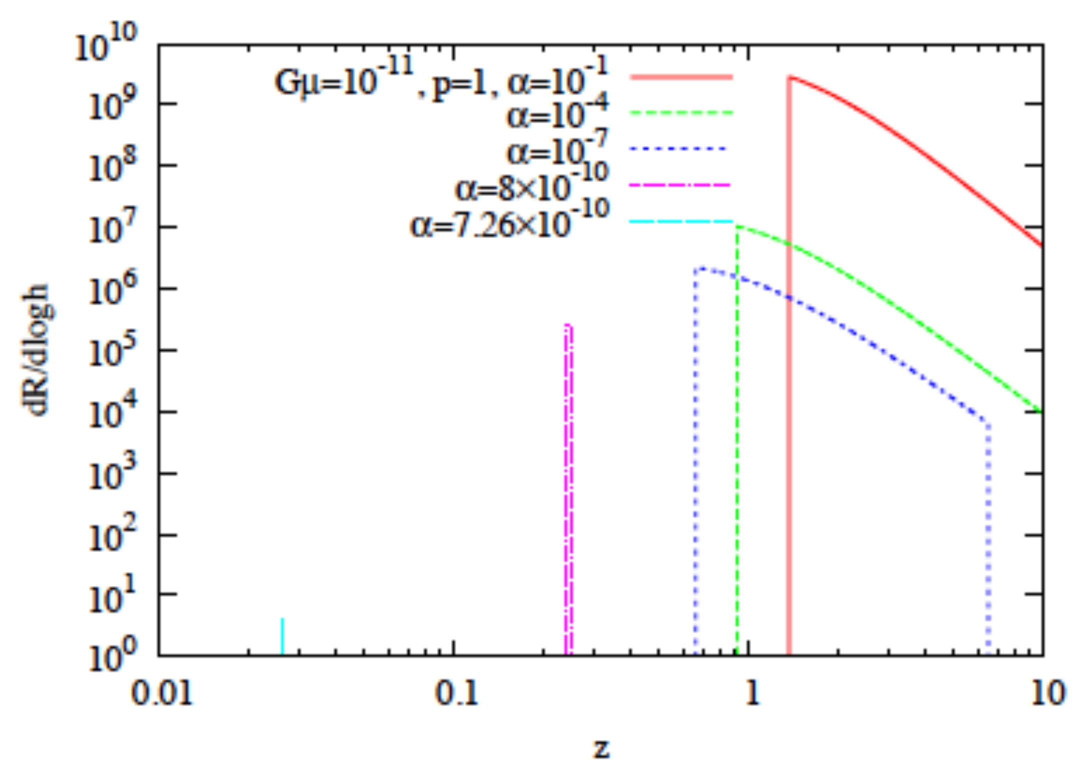
Anisotropy level depends on distribution of loops

→ depends on properties of cosmic string

3 main parameters to characterize cosmic string

- $G\mu$: tension = line density → Generation mechanism
- α : initial loop size $L \sim \alpha H^{-1}$ → Network evolution
- p : reconnection probability → Phase transition origin: p=1; Cosmic superstring: p<<1

Assuming the values of parameters and using theoretical evolution model, we can predict number density and redshift distribution of gravitational wave bursts from cosmic string loops



Anisotropy test

- Formulations are constructed by

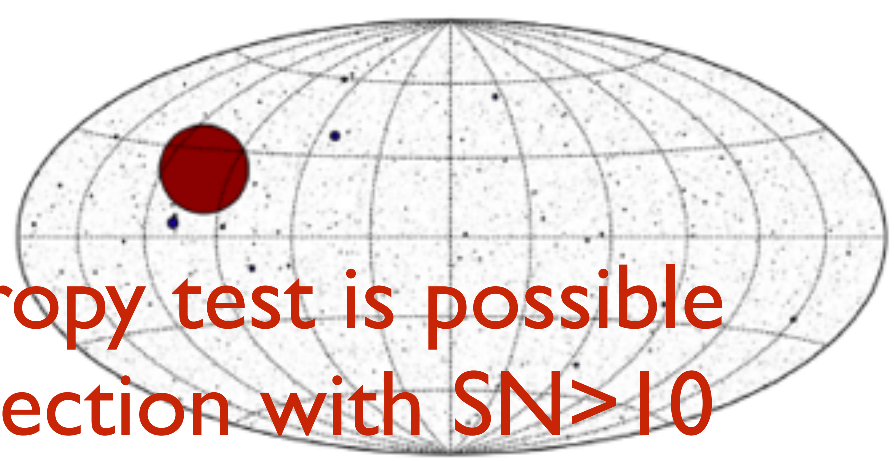
  Mingarelli et. al., PRD 88, 062005 (2013)

GW amplitude: $\Omega_{\rm gw}(f) = \frac{8\pi^2}{3H_0^2} f^3 H(f) \int d\hat{\Omega} P(\hat{\Omega})$

$P(\hat{\Omega}) \equiv \sum_{lm} c_l^m Y_l^m(\hat{\Omega})$ ← Spherical harmonic expansion

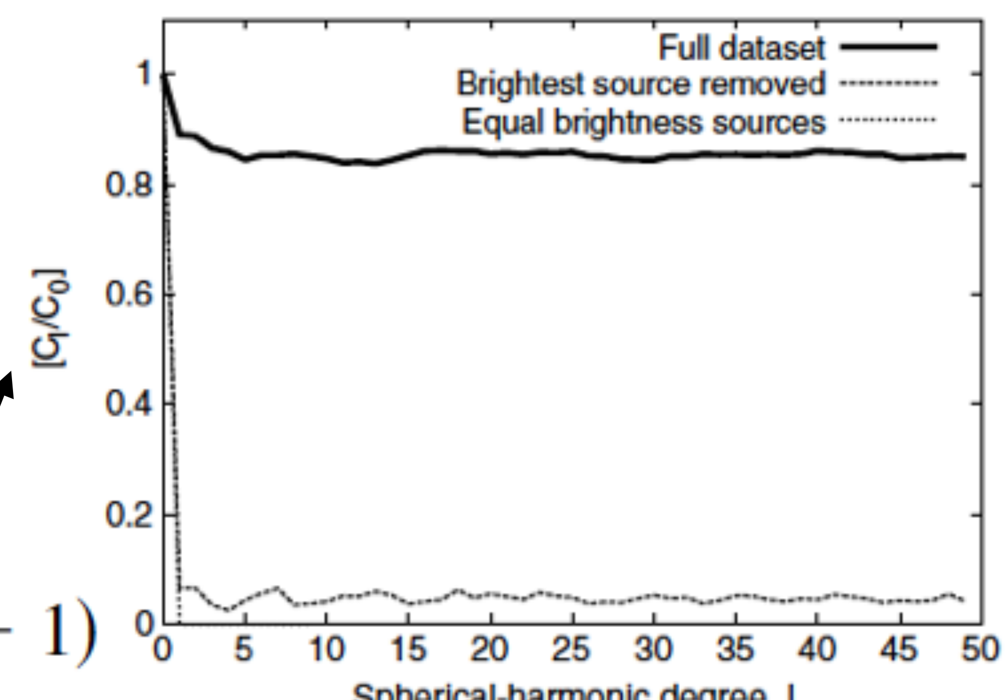
- Simulation study in a context of GWs from SMBH binaries

  Taylor & Gair, PRD 88, 084011 (2013)



Anisotropy test is possible for detection with SN>10

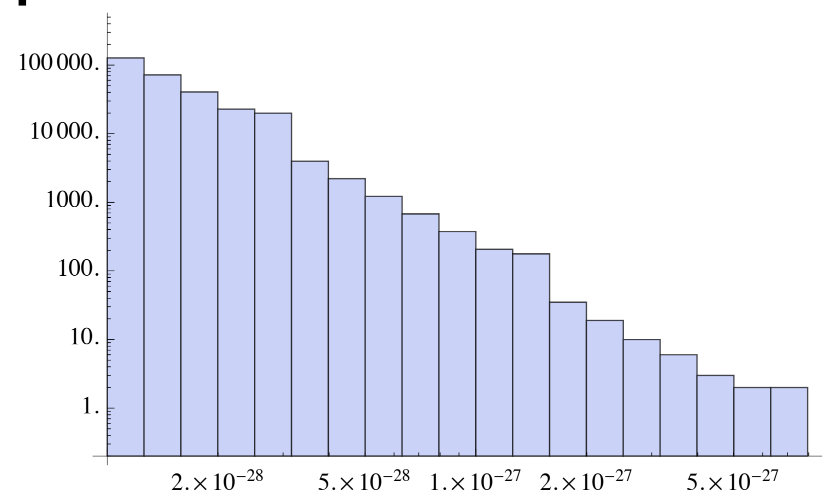
angular power spectrum: $C_l = \sum_m |c_{lm}|^2/(2l+1)$



Predictions for cosmic strings

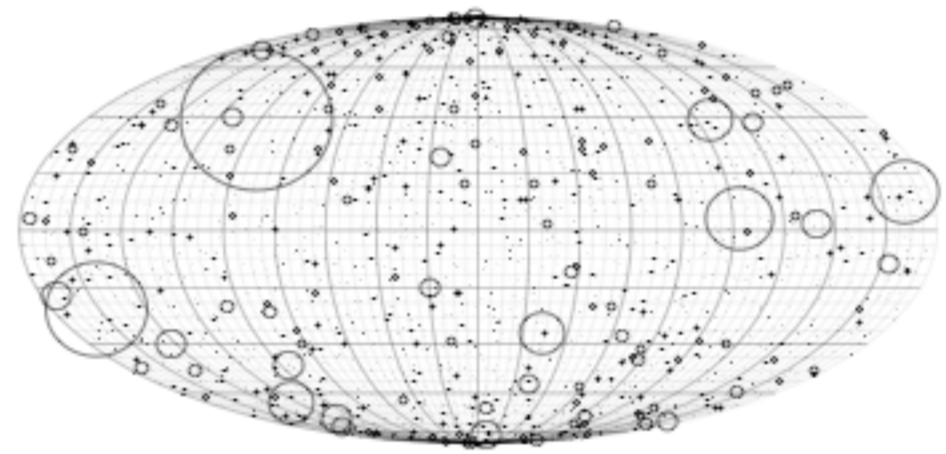
1. predict rate of GW bursts

rate per year
for fixed frequency



amplitude

2. randomly distribute the source



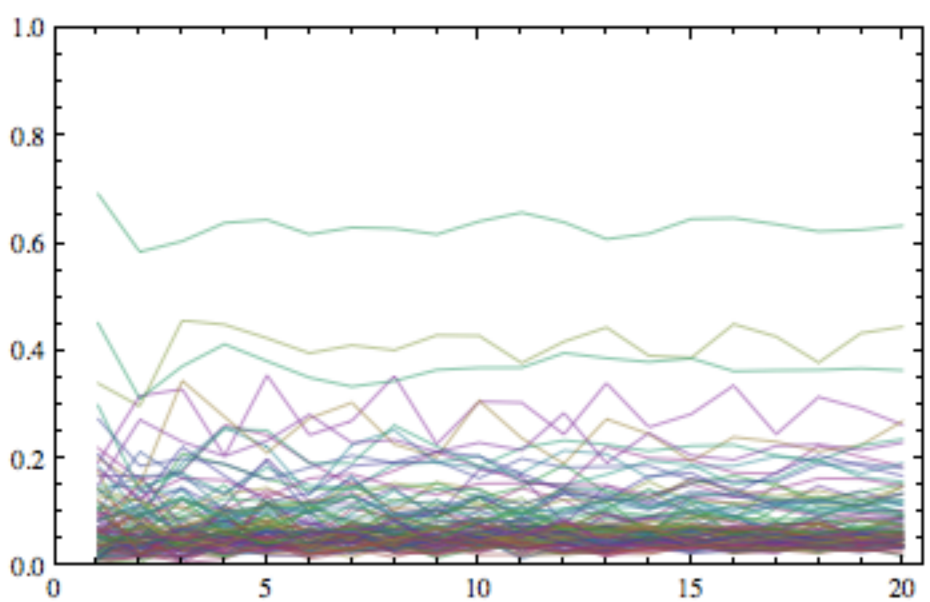
3. make100 realizations

$$c_{lm} = \sum_{i=1}^{N} \rho_i Y_{lm}(\hat{\Omega}_i)$$

$$C_l = \sum_m |c_{lm}|^2/(2l+1)$$

4. calculate anisotropy levels

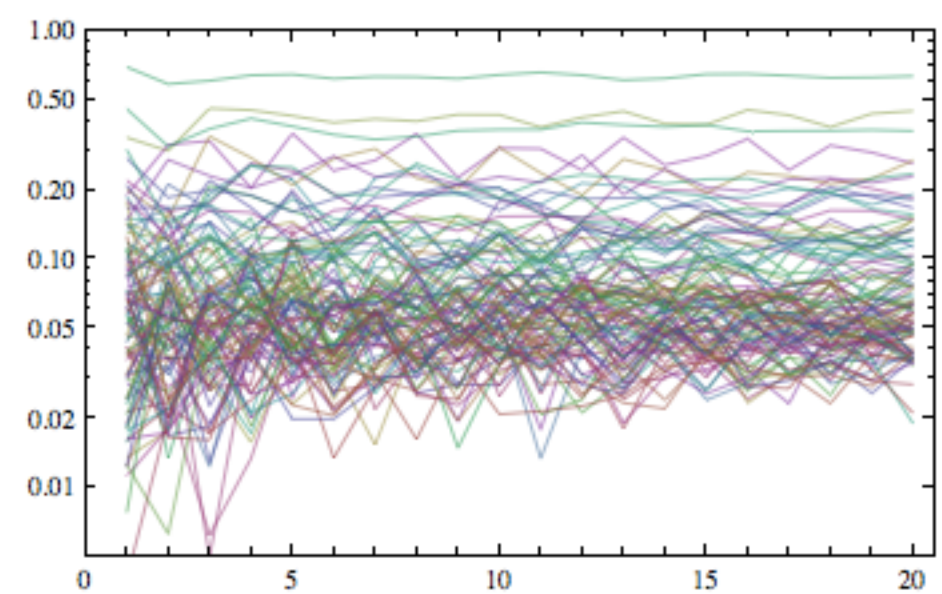
C_l/C_0



l: multipole

log normal distribution?

C_l/C_0

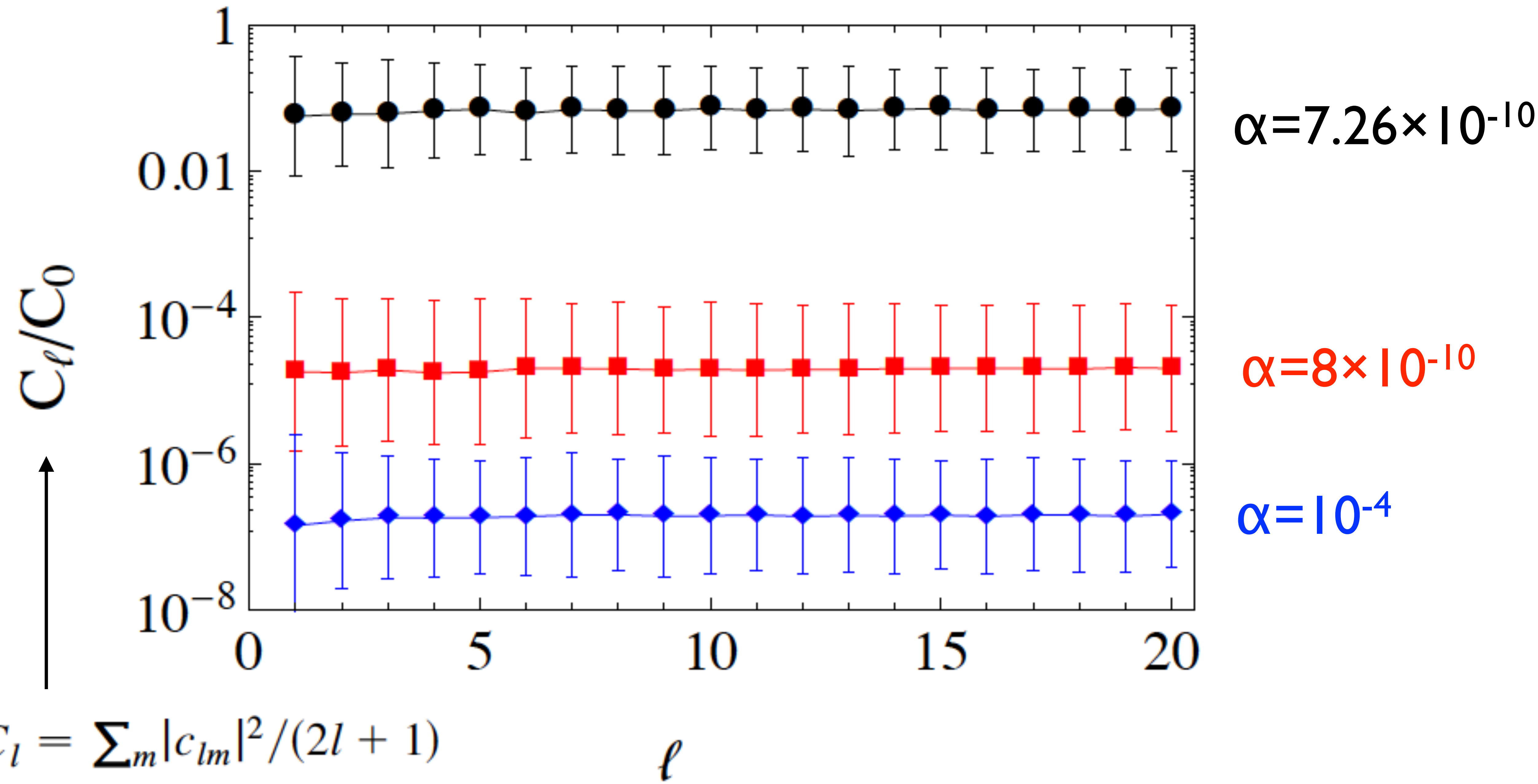


l: multipole

assumed $f=(10\text{yr})^{-1}$
$G\mu = 10^{-11}$, $p=1$

Anisotropy level

with 2σ error bar

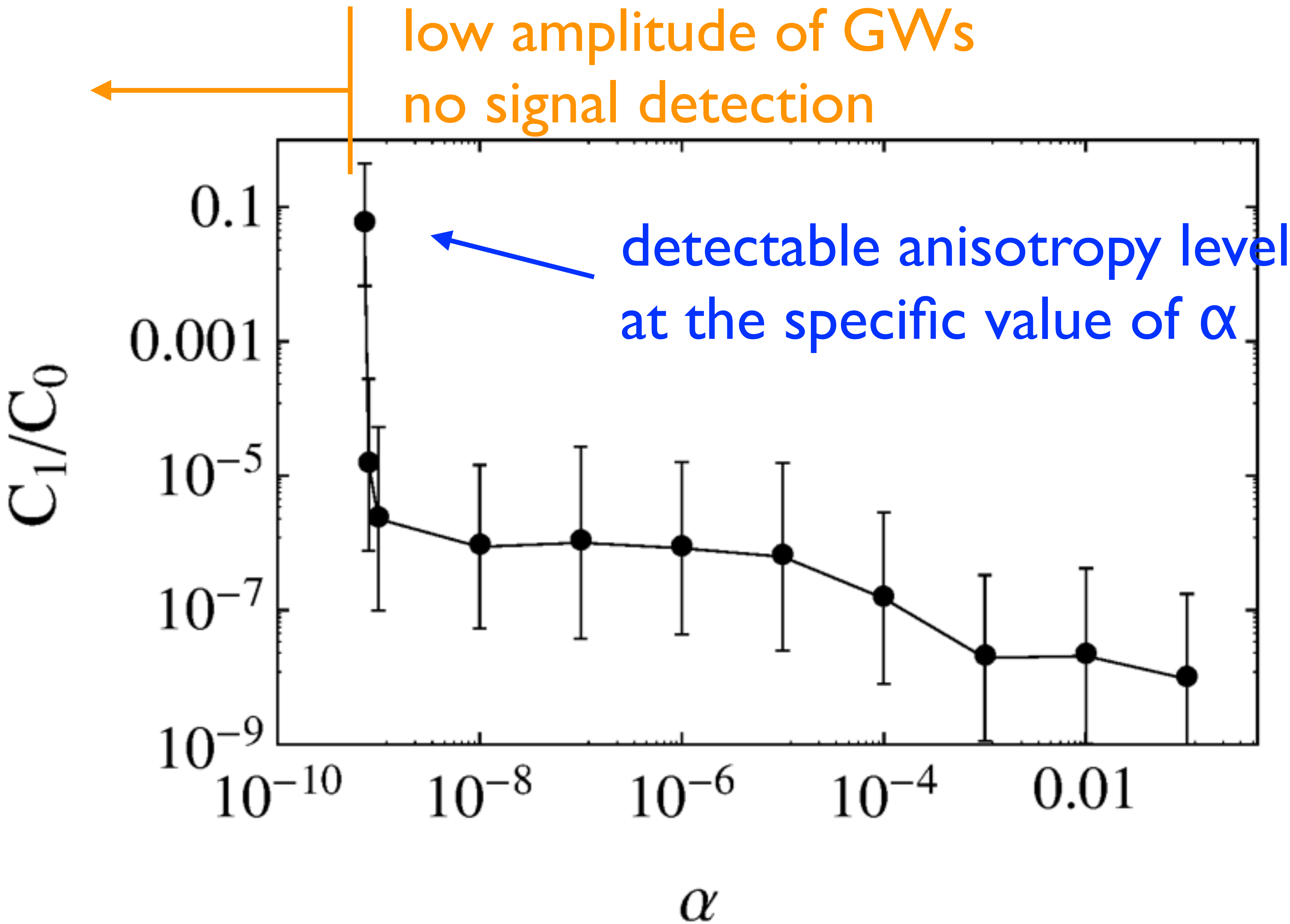


$C_l = \sum_m |c_{lm}|^2/(2l+1)$

We get large anisotropy for smaller value of α

(smaller initial loop size)

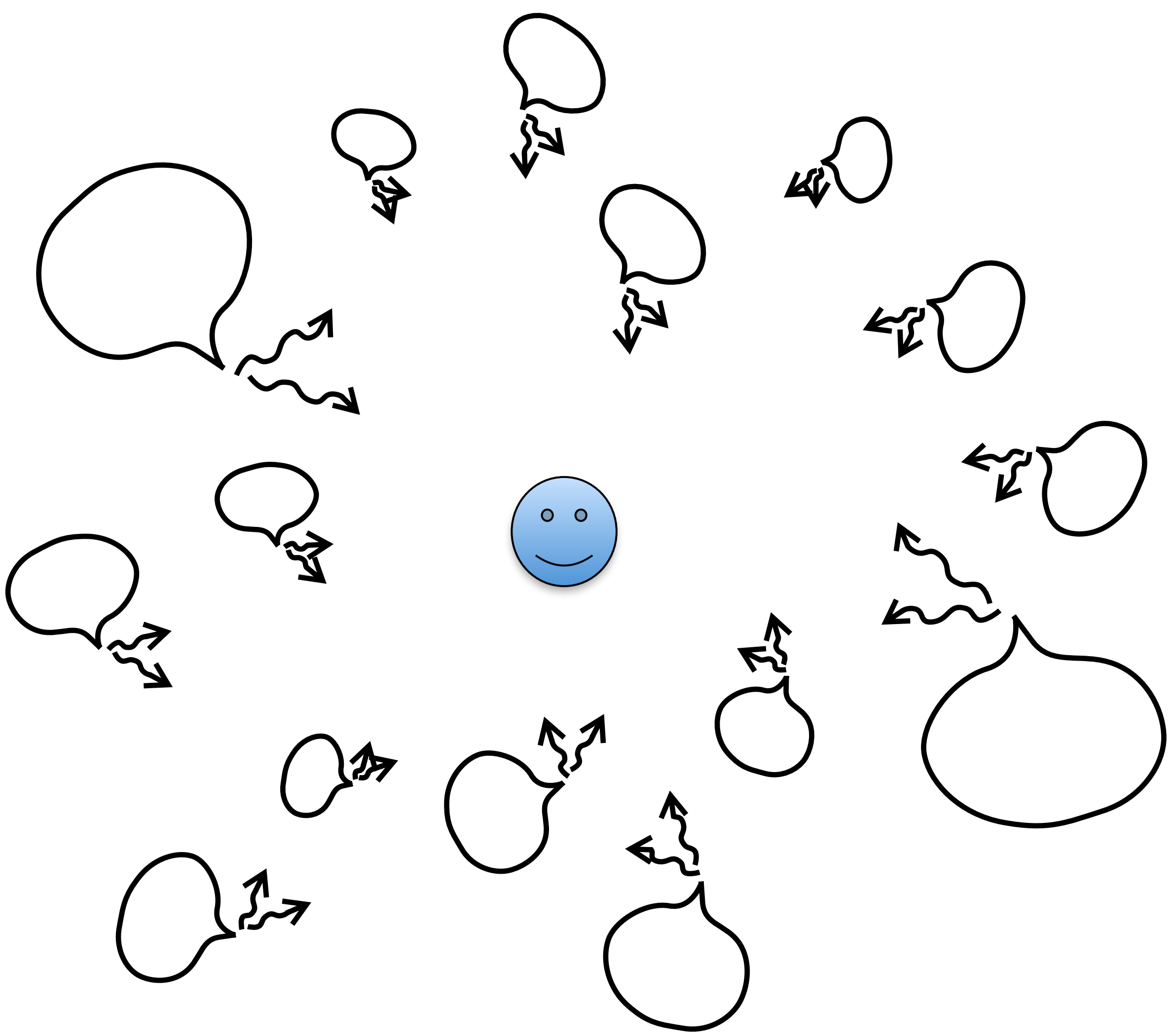
Dipole component α dependence



Interpretation

large α = long lifetime

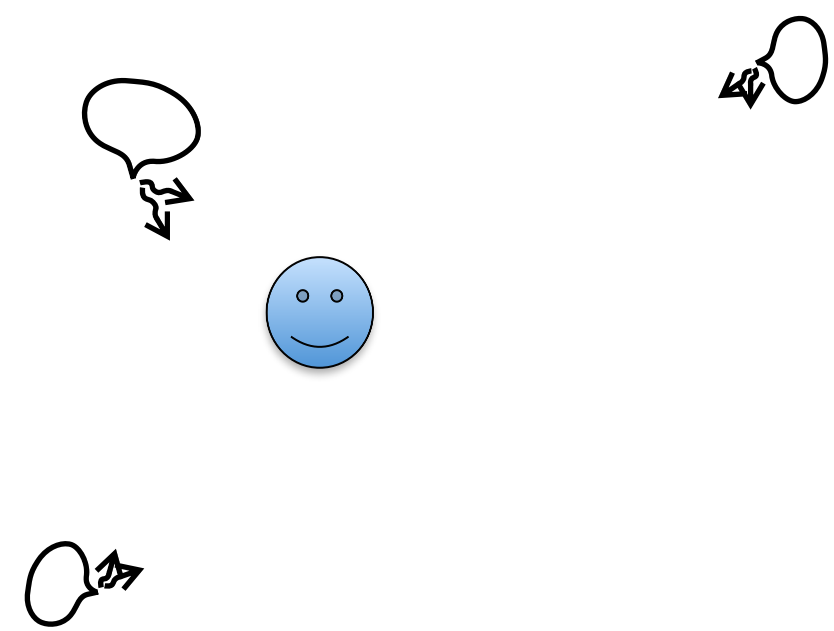
network consists of mixture of old and new loops



→ **isotropic GWs**

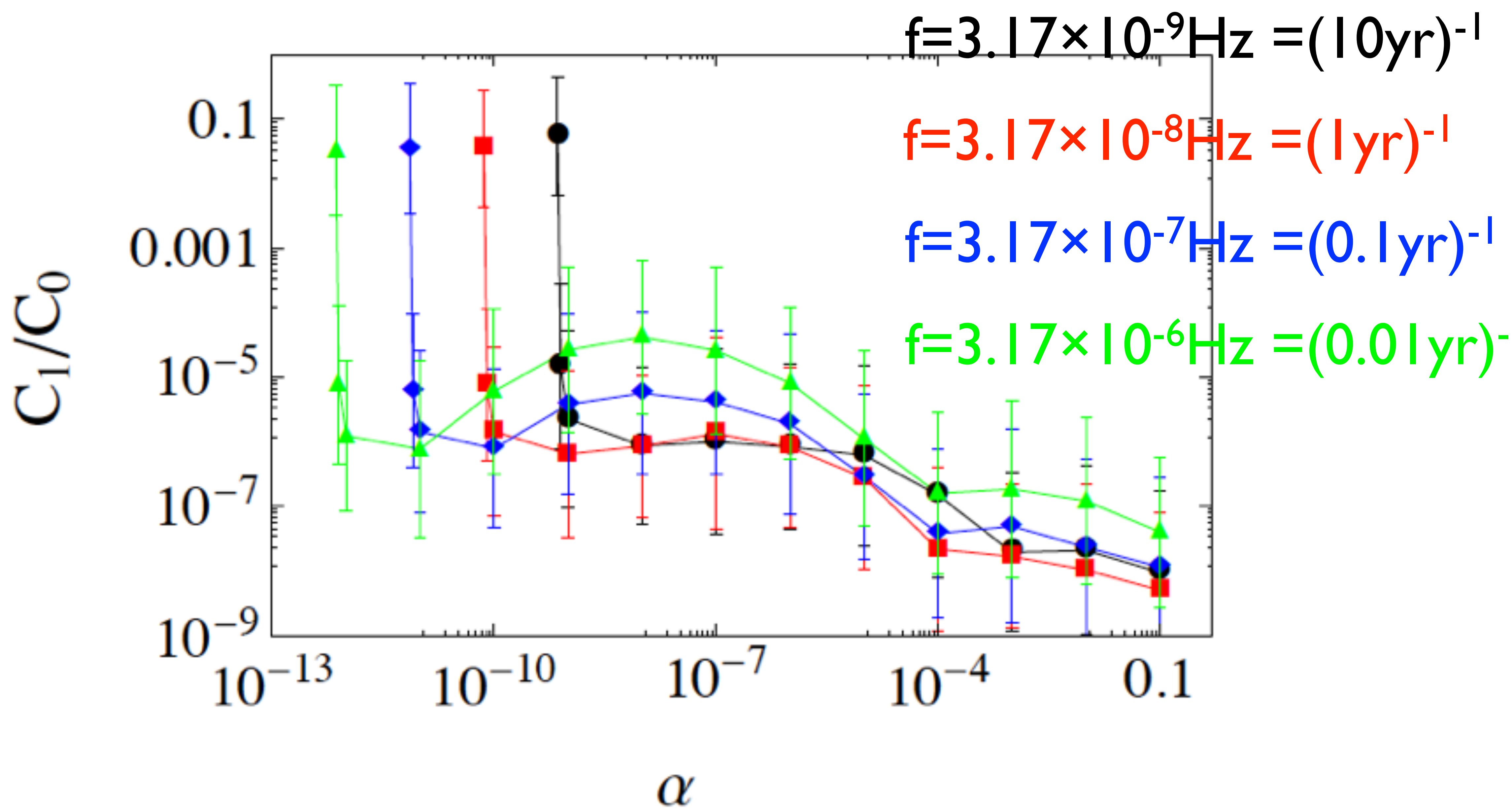
small α = short lifetime

loops evaporate soon after their formation



→ **anisotropic GWs**

Observation frequency dependence

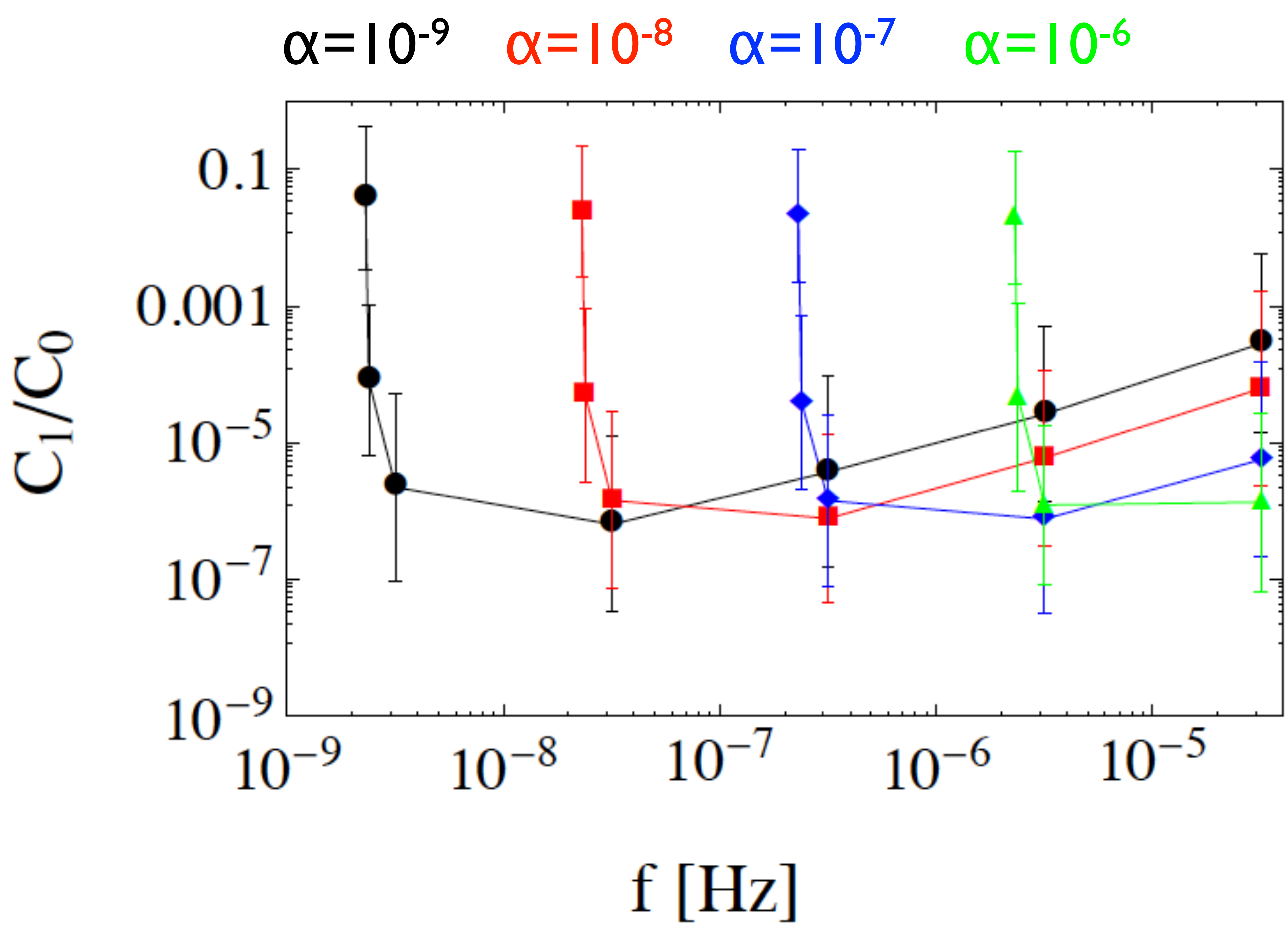


The peak position changes for different observation frequency

When loops evaporate soon after the formation by emitting GWs,

frequency of GWs ~ (initial loop size)$^{-1}$ $\propto$ α^{-1}

Observation frequency dependence



By checking anisotropy for different frequency bands, it may be possible to obtain implication on the value of α

Summary

- Testing the existence of cosmic string by PTA is important for obtaining implication on fundamental physics.
- SKA will cover a large parameter space of cosmic string parameters.
- Anisotropy of the gravitational wave background can be used to extract information on the initial loop size, which is important for understanding cosmic evolution of string network.