Forecast constraints on cosmic string parameters from observations of gravitational waves and CMB

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based on:
Kuroyanagi, KM, Sekiguchi, Takahashi & Silk, Phys. Rev. D86, 023503 (2012)
Kuroyanagi, KM, Sekiguchi, Takahashi & Silk, Phys. Rev. D87, 023522 (2013)

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1. introduction

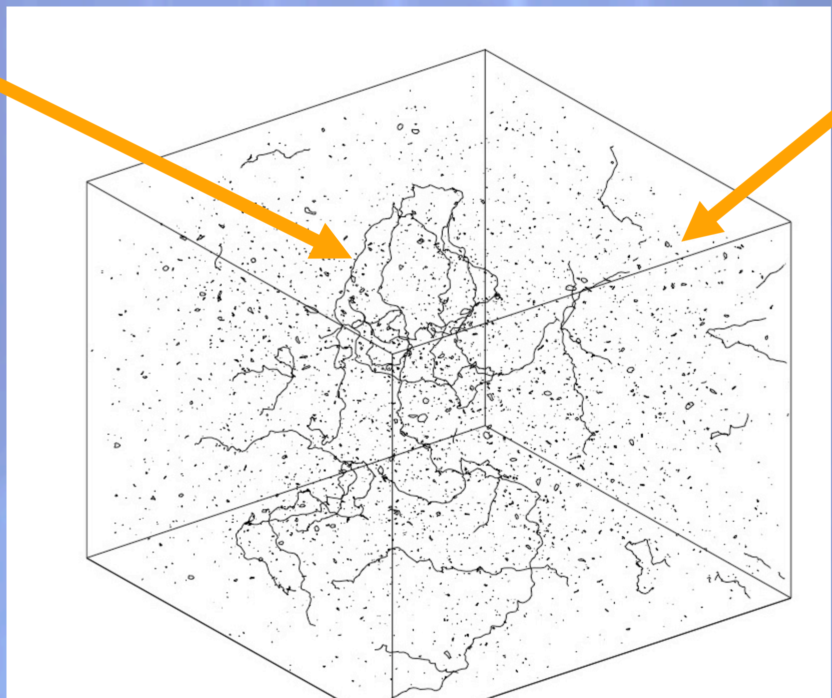
1. introduction

cosmic string ･･･ ”Strings” which contain large energy and randomly stretch across the universe.

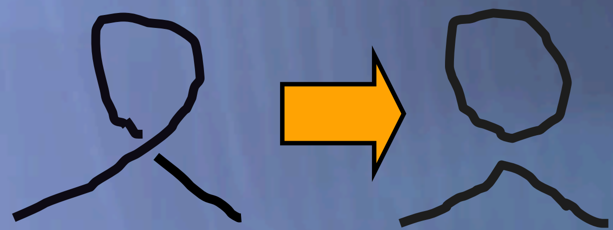
As a result of repeating collisions and reconnection, they form a “string network”.

infinite string

loop



Allen+,
PRL 64,119(‘90)



1. introduction

◆ How are they generated?

1. spontaneous symmetry breaking(SSB) (Kibble, J. Phys. A9, 1387 ('76))

→ appearance of 1-dim. topological defects = strings

↳ prediction from Grand Unified Theory (GUT) etc

2. inflation based on superstring theory

→ "strings" with cosmological length (cosmic superstring)

(Sarangi+, PLB 536, 185 ('02)
Jones+, PLB 563, 6 ('03)
Dvali+, JCP 0403, 010 ('04))

◆ Why are they important?

- They are related to
  - particle physics beyond Standard Model
  - inflation
- observational signals

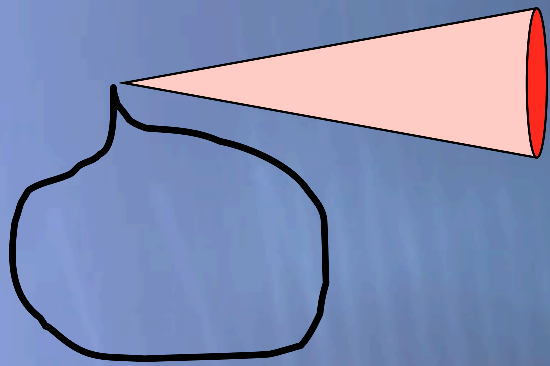
⇨ Cosmic strings are important observational probe for particle physics and cosmology

1. introduction

◆ signals from cosmic string

① gravitational wave (GW)

(Damour+ PRD 64, 064008 ('01) etc)



main GW source : loops

They emit "GW bursts" ← ・instantaneous emission ・beam-like

detected as

1. rare bursts : strong enough to be detected singly, but come to the earth infrequently.
2. GW background (GWB): consists of overlapping weak bursts.

② anisotropy of cosmic microwave background (CMB) (Pogosian+, PRD 60, 083504 ('99) etc)

↑ generated by complicated motion of strings

fluc. of temperature & polarization

← E-mode & B-mode

- 3 parameters which characterize cosmic strings

1. tension (mass per unit length) $G\mu$ (G:Newton constant)

   $\mu \sim E_{SSB}^2$ (E_{SSB} :energy scale of SSB)

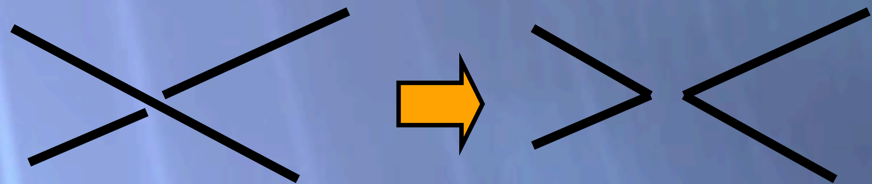
2. loop size α

   The size of a loop formed at time t is $l = \alpha t$
   α is not a parameter, but there is an uncertainty over many orders of magnitude (from $\alpha \sim (G\mu)^n$ to $\alpha \sim 0.1$).

   (Blanco-Pillado+, PRD 83, 083514 ('11), Siemens+, PRD 66, 043521 ('02) etc)

3. reconnection probability p

   $p = 1$ for strings from SSB
   $p \ll 1$ for cosmic superstrings



   As p decreases, interval and curvature radius of strings decrease.

1. introduction

- 3 parameters which characterize cosmic strings

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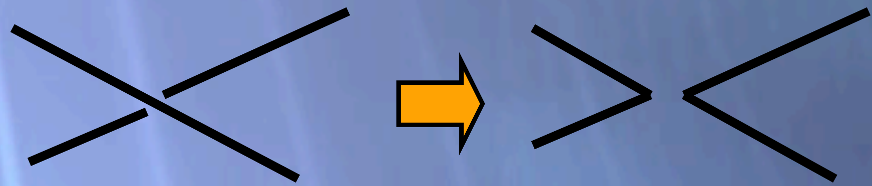

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deeply related to background physics

1. introduction

- experiments which can search cosmic strings

- GW experiments
  - direct detection by interferometers
    eg) ground : LIGO
    space : DECIGO
    - burst detection
    - GWB measurement
  - pulsar timing eg) SKA
    ··· extract the signal of GWB from fluctuations of time of arrival of pulses from pulsars
- observation of CMB eg) Planck, CMBPol
- ⋮

- How strongly will each experiment constrain $G\mu, \alpha, p$?
- Different experiments give us different information
  → How much will combining them tighten constraints?

↑ investigate using Fisher analysis

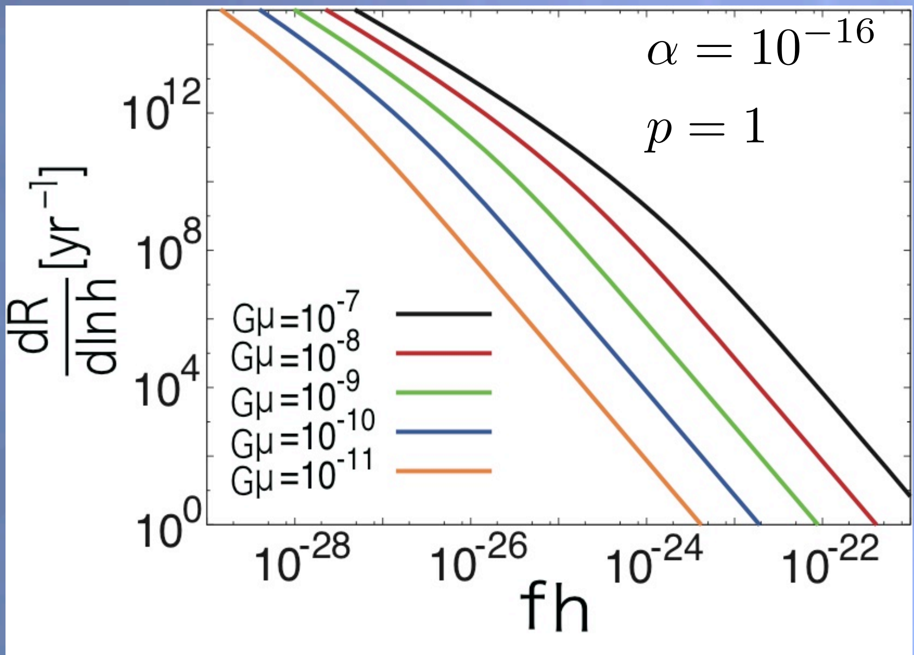
2. signals from cosmic strings

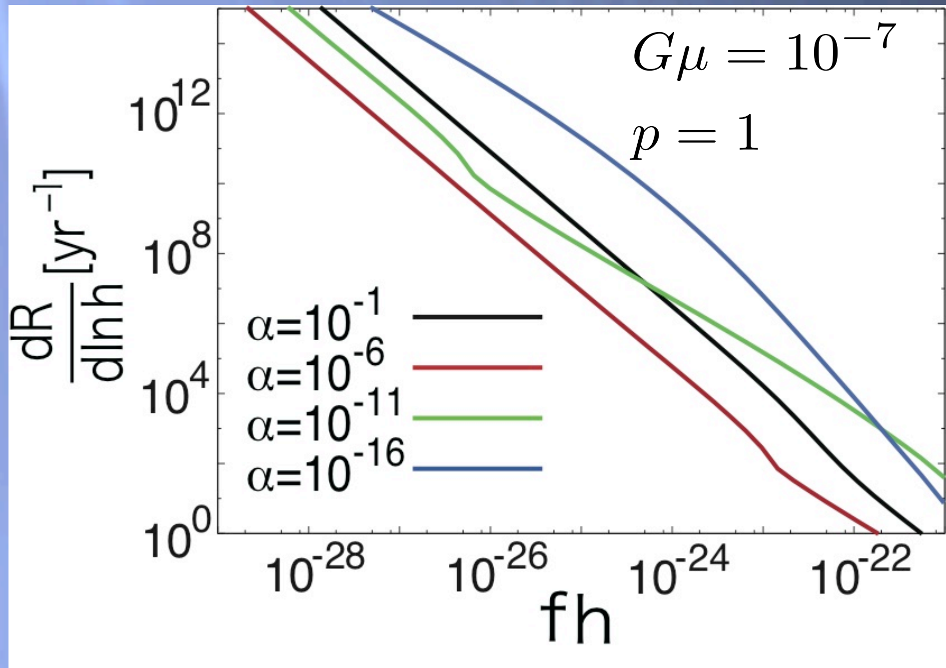
2. signals from cosmic strings

◆ rare bursts

$\frac{dR}{dh}(f,h)$: detection rate of bursts with frequency f and amplitude h (burst rate)

・parameter dependency





$f = 220\mathrm{Hz}$ (to which LIGO is sensitive)

・$p \searrow$ $\rightarrow$ burst rate $\nearrow$

2. signals from cosmic strings

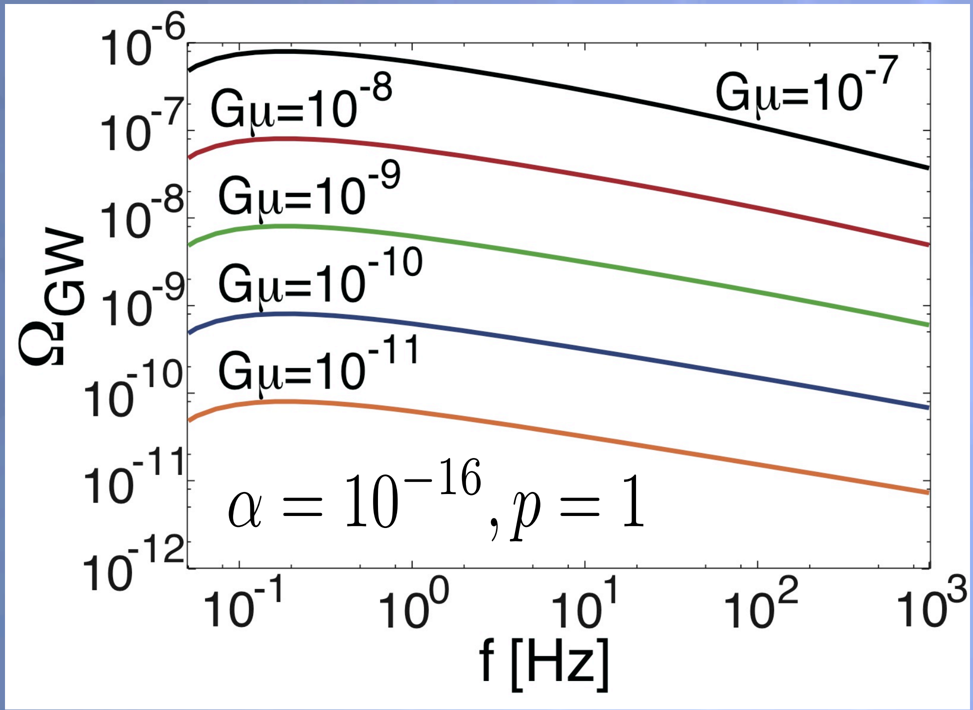
◆ GW background

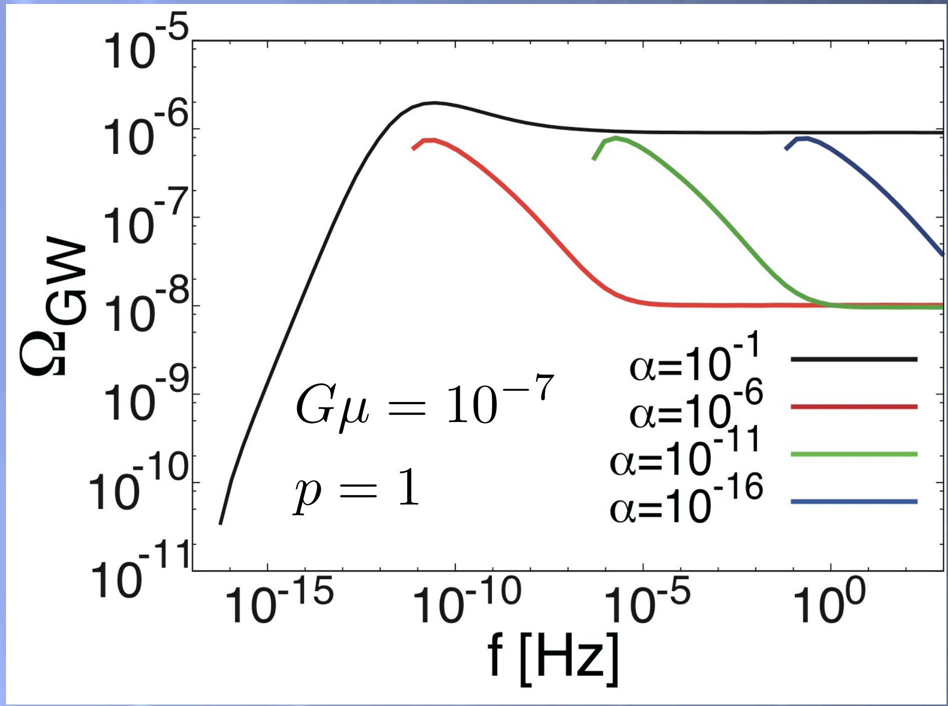
$$\Omega_{GW}(f) \equiv \frac{1}{\rho_{cr}} \frac{d\rho_{GW}(f)}{d \ln f}$$

(ρ_{cr}:critical density)

← sum of only overlapping bursts

・parameter dependency



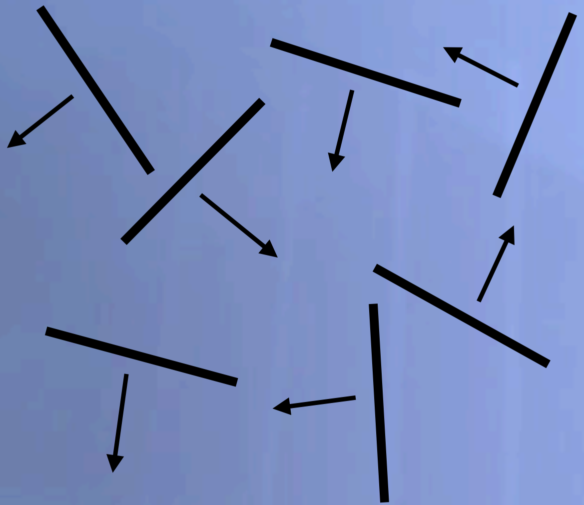


・$p \searrow \;\rightarrow\; \Omega_{GW} \nearrow$

2. signals from cosmic strings

◆ CMB anisotropy

method to calculate angular power spectra of CMB anisotropies



⋯ unconnected segment model (Pogosian+, PRD 60, 083504 ('99))

infinite string network

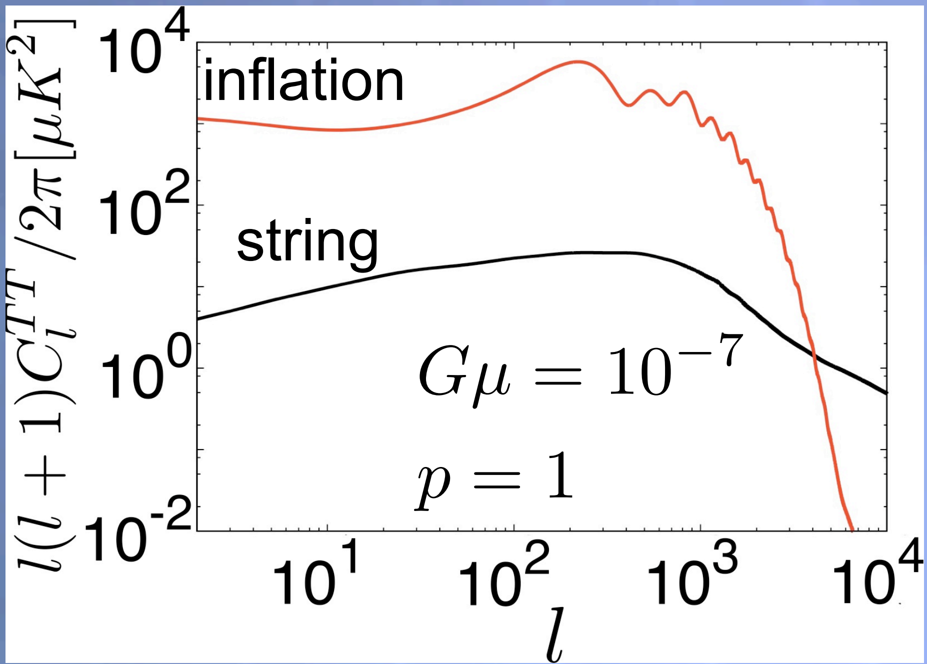
↓ approximate

ensemble of unconnected segment

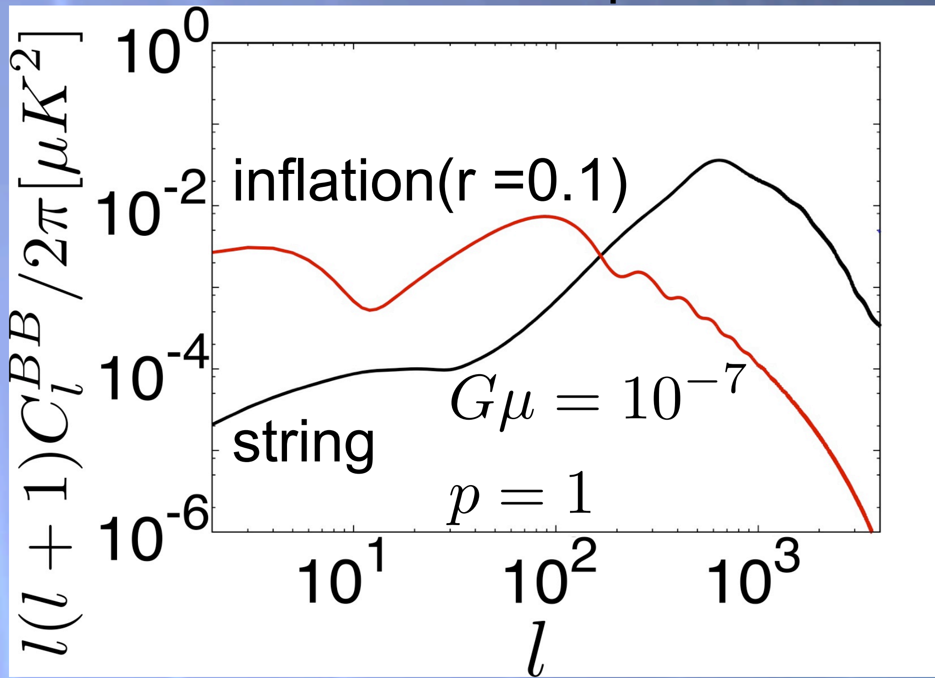
calculate $T_{\mu\nu}$

→ calculate CMB fluc.

temperature



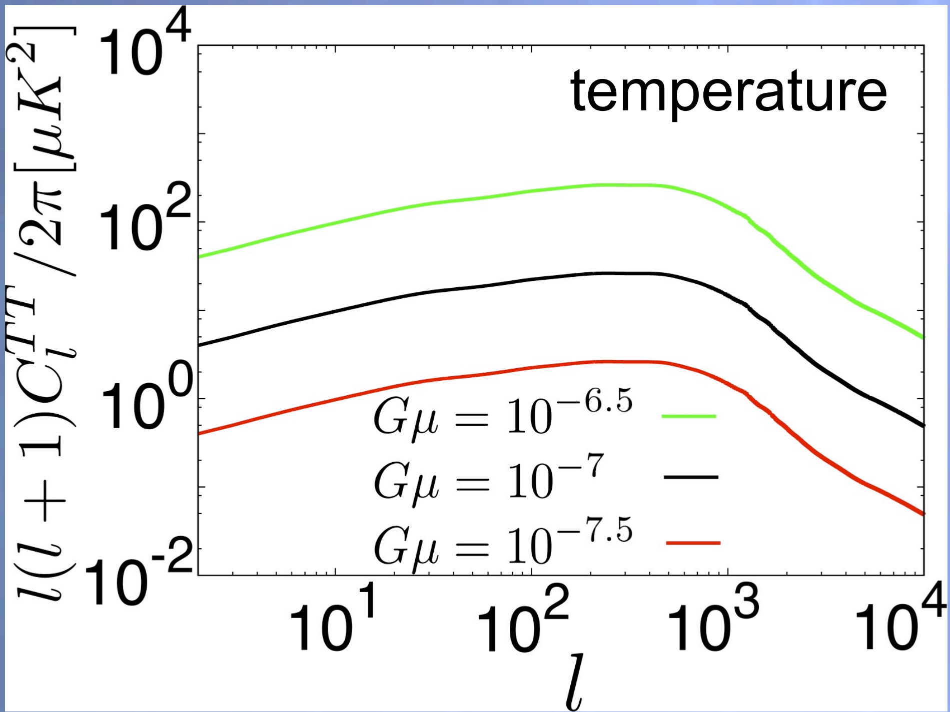
B-mode polarization

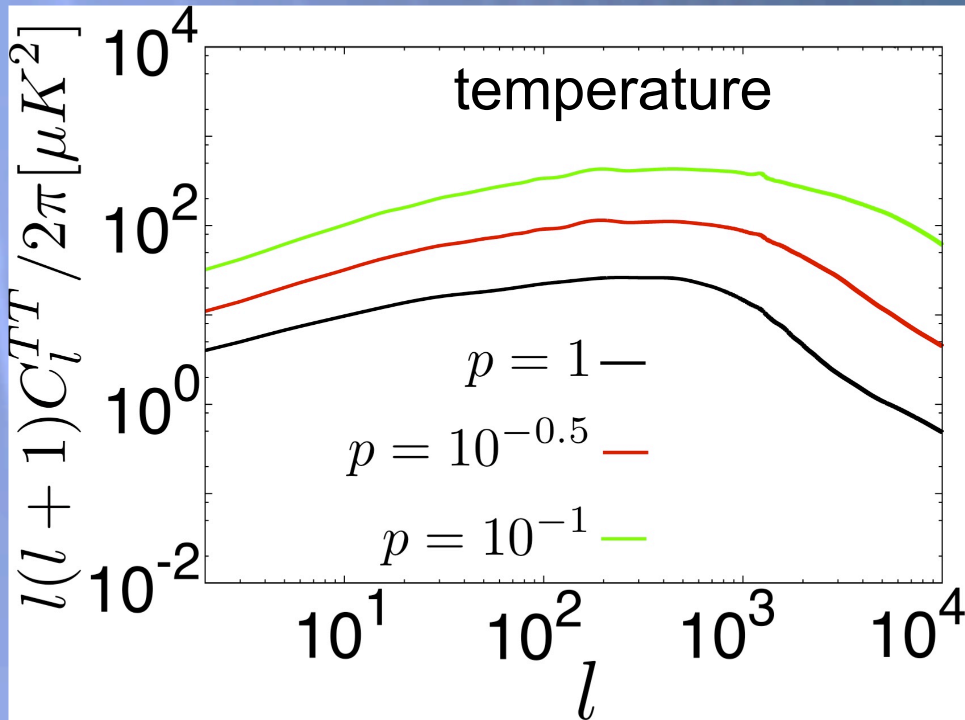


2. signals from cosmic strings

- parameter dependency of temperature power spectrum

(not depend on α)





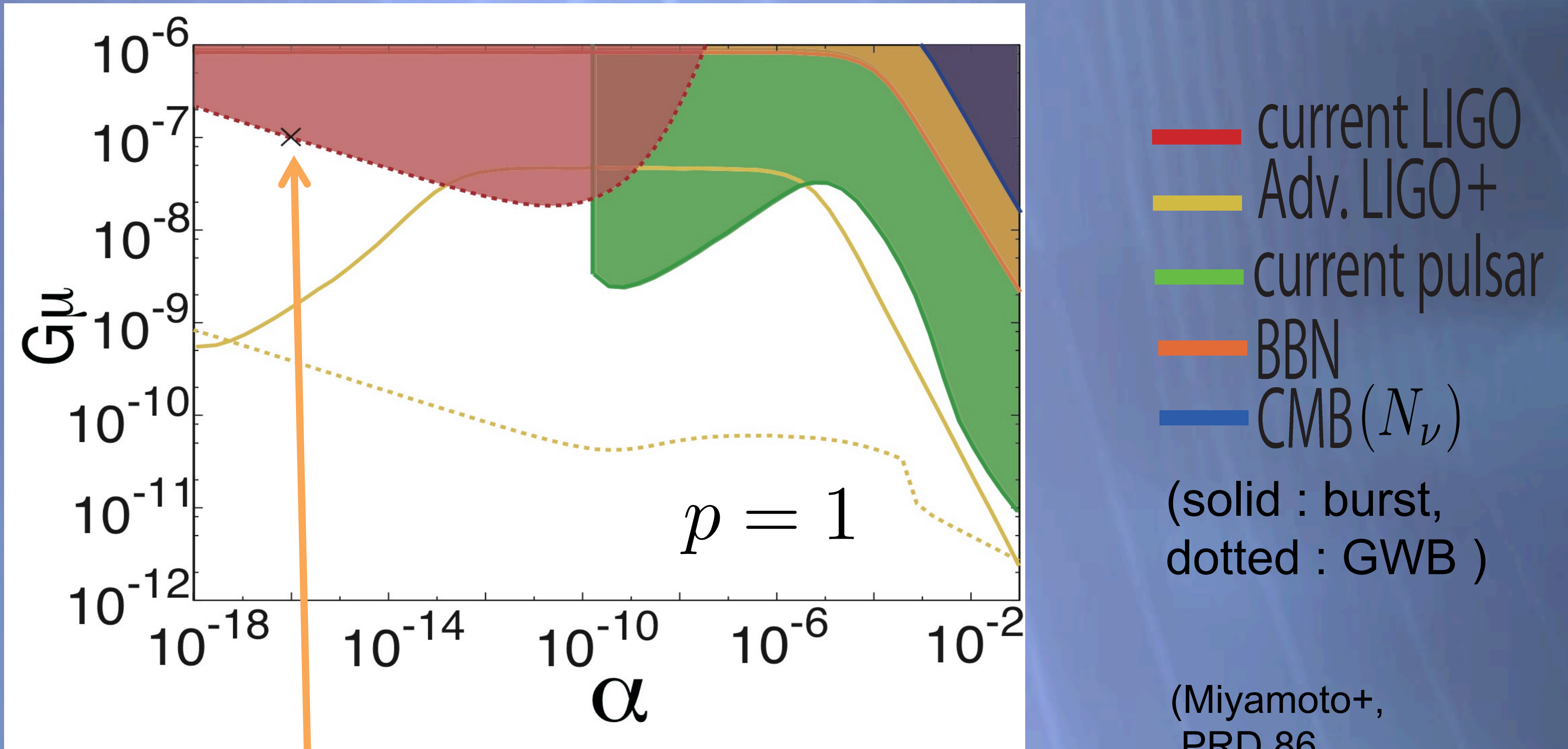
$p \searrow \rightarrow$
- string # density $\nearrow \rightarrow$ fluc. $\nearrow$
- fluc. on small scale $\nearrow$

3. future constraints on cosmic strings from gravitational wave direct detection experiments

3. future constraints on cosmic strings from GW direct detection

First, we consider constraints from future ground-based GW detectors

colored : excluded
above lines : future GW detectors (e.g. Adv. LIGO) can probe



(solid : burst,
dotted : GWB)

fiducial parameter set for Fisher analysis

(Miyamoto+,
PRD 86,
023503 ('12))

◆ Fisher analysis : method to forecast the determination accuracy of parameters in future experiments

$P[p|D]$: probability that the parameter is p when the data is D

⇕ proportional

$P[D|p]$: probability that the data is D when the parameter is p

($P[A|B]$:conditional prob. of A given B)

⇓

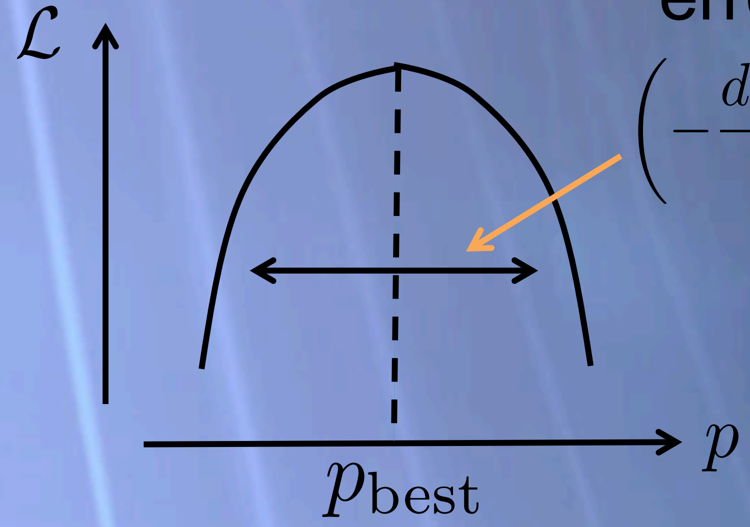
$\mathcal{L}(p,D) \equiv P[D|p]$: likelihood

If there are multiple parameters, the determination accuracy is given by the Fisher matrix

$$F_{ij} = -\left\langle \frac{\partial^2 \ln \mathcal{L}}{\partial p_i \partial p_j} \right\rangle$$

error

$$\left(-\frac{d^2 \ln \mathcal{L}}{dp^2}\right)^{1/2}$$



best fit parameter

3. future constraints on cosmic strings from GW direct detection

◆ Fisher matrix for rare burst detection

expectation value of # of bursts with amplitude $h_i \sim h_i + dh_i$

$$N_i = \Phi(h_i)dh_i, \Phi(h_i) = \frac{dR}{dh}(h_i)T \quad (T \text{ :observation time})$$

we observe k_i bursts in i-th amplitude bin ⇨ $\mathcal{L} = \prod_i \frac{(N_i)^{k_i} e^{N_i}}{k_i!}$ (Poisson distribution) ⇨

$$F_{ij} = \int dh \frac{\partial \Phi}{\partial p_i} \frac{\partial \Phi}{\partial p_j} \frac{1}{\Phi}$$

(Miyamoto+, PRD 86, 023503 ('12))

◆ Fisher matrix for GW background detection

$$\mathcal{L} = \prod_{I>J} \frac{1}{\sqrt{2\pi\sigma_{IJ}^2}} \exp\left[\frac{(S_{IJ} - \langle S_{IJ}\rangle)^2}{2\sigma_{IJ}^2}\right]$$

S_{IJ} : cross correlation signal between detector I and J $S_{IJ} \propto \Omega_{GW}$

σ_{IJ} : noise determined by the sensitivity curves of detector I and J

⇨

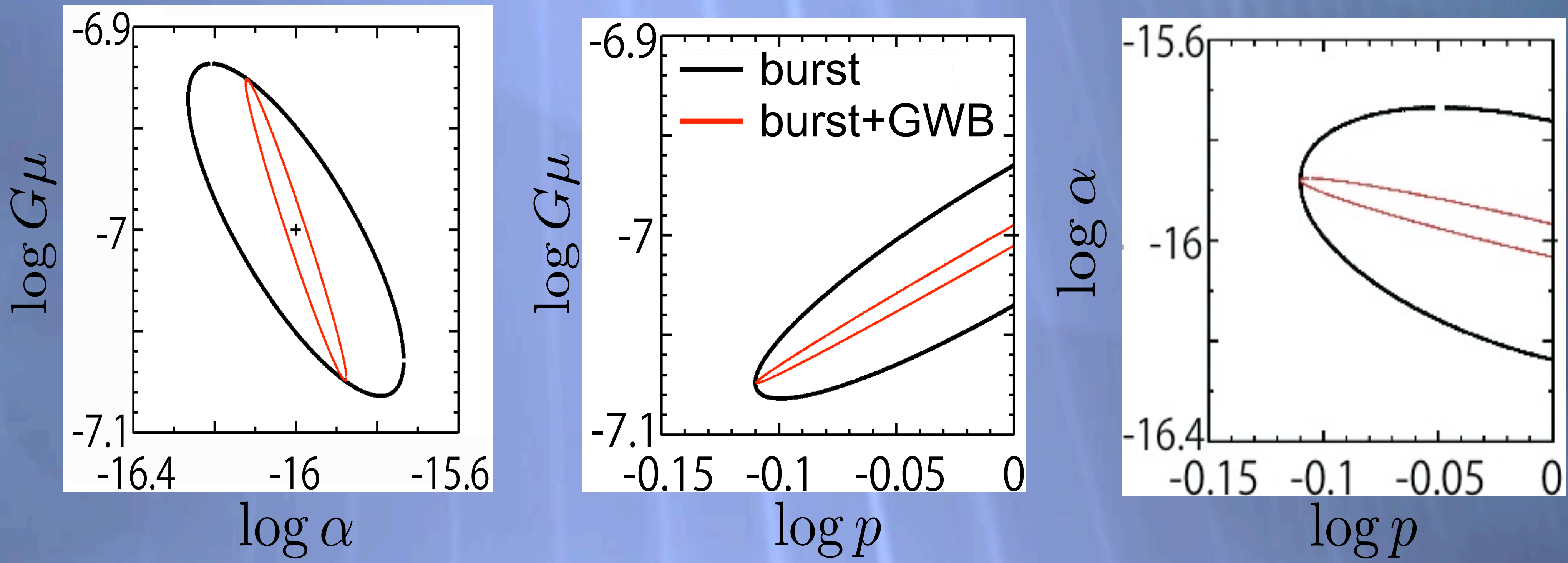
$$F_{ij} = \left(\frac{3H_0^2}{10\pi^2}\right)^2 2T \sum_{I>J} \int_0^\infty df \frac{|\gamma_{IJ}|^2 \partial_{p_i}\Omega_{GW}(f)\partial_{p_j}\Omega_{GW}(f)}{f^6 S_{n,I}(f) S_{n,J}(f)}$$

(Seto, PRD 73, 063001 ('06), Kudo+, PRD 73, 064006 ('06))

3. future constraints on cosmic strings from GW direct detection

◆ constraints from the GW detector network (LIGO, Virgo, KAGRA)

fiducial parameter : $G\mu = 10^{-7}, \alpha = 10^{-16}, p = 1$



(Miyamoto+, PRD 86, 023503 ('12))

LIGO etc. detect 1.8×10^5 bursts and GWB with SNR=187

The burst rate and the GWB spectrum give us different information

⇨ Combining them leads to breaking of parameter degeneracy and better constraints

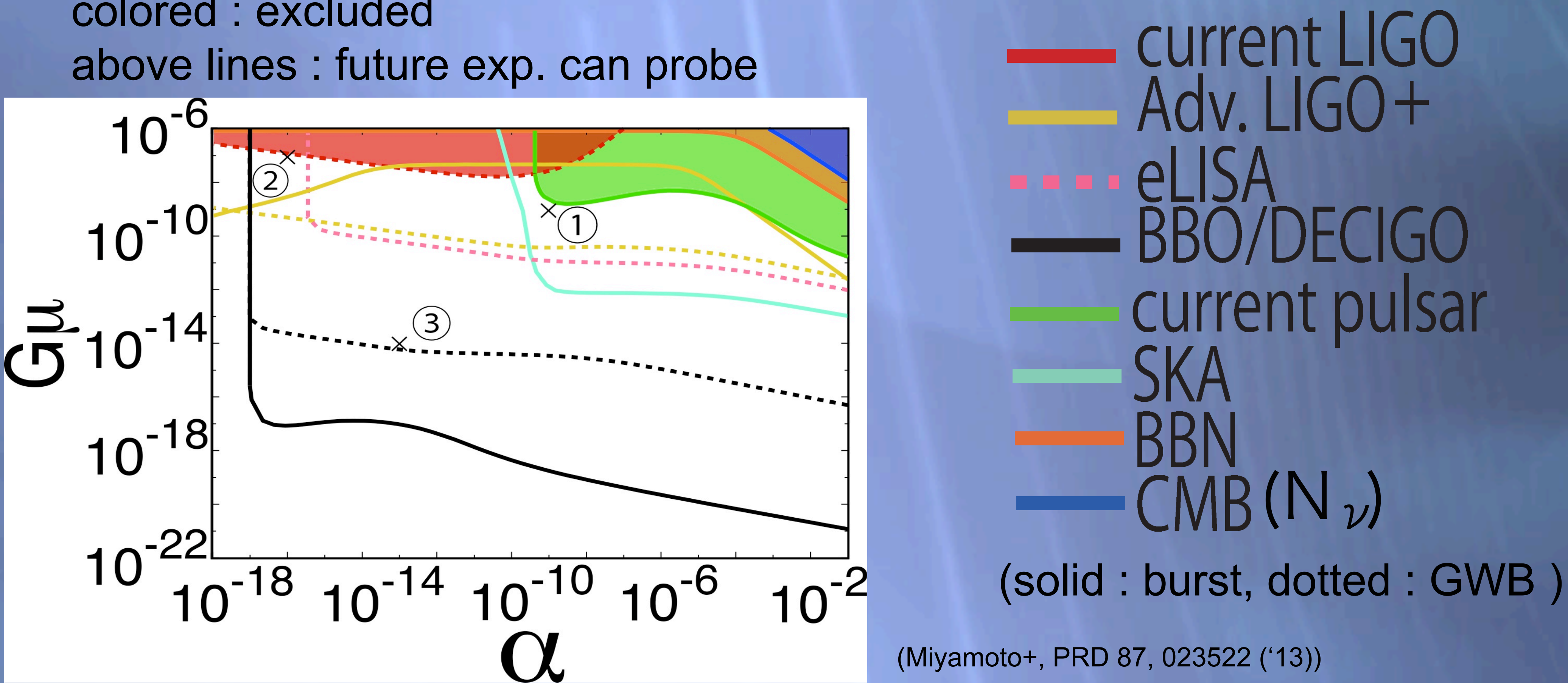
4. future constraints on cosmic strings from gravitational wave direct detection, pulsar timing and CMB experiments

4. constraints on cosmic strings from GW direct detection, pulsar timing and CMB

We consider pulsar timing exp. and CMB exp. in addition to GW direct detection exp.

colored : excluded

above lines : future exp. can probe



(Miyamoto+, PRD 87, 023522 ('13))

current CMB constraint: $G\mu < 1.4 \times 10^{-7}$

Planck B-mode measurement can probe $G\mu > 2.4 \times 10^{-8}$

We perform Fisher analysis choosing some fiducial parameter sets

4. constraints on cosmic strings from GW direct detection, pulsar timing and CMB

Fisher matrix for pulsar timing experiment

fluctuation of arrival time of pulses from i-th pulsar : $R_i(t)$

cross correlation between 2 pulsars : $r_i \equiv \frac{1}{N}\sum_{a=0}^{N-1} R_{i_1}(t_a)R_{i_2}(t_a)$

⇓ extract contribution from GW

signal : $S = \frac{\frac{1}{N_p}\sum_{i=0}^{N_p-1}(r_i-\bar{r})(\zeta(\theta_i)-\bar{\zeta})}{\sigma_r\sigma_\zeta}$

(Hellings+, ApJ 265, L39 ('83)
Jenet+, ApJ 625, L123 ('05))

$$F_{ij} = \frac{1}{N^2}\frac{\partial\langle S\rangle}{\partial p_i}\frac{\partial\langle S\rangle}{\partial p_j},\; N^2 = \langle S^2\rangle - \langle S\rangle^2$$

Fisher matrix for CMB experiment (Zaldarriaga+, ApJ 448, 1 ('97))

$$F_{ij} = \sum_l \sum_{X,X'} \frac{\partial C_l^X}{\partial p_i}\mathrm{Cov}^{-1}(C_l^X, C_l^{X'})\frac{\partial C_l^{X'}}{\partial p_j} \quad (X = TT, EE, BB, TE\,)$$

$$\mathrm{Cov}(C_l^X, C_l^{X'}) = \left\langle \left(C_l^X - \langle C_l^X\rangle\right)\left(C_l^{X'} - \left\langle C_l^{X'}\right\rangle\right)\right\rangle$$

determined by noise power spectra

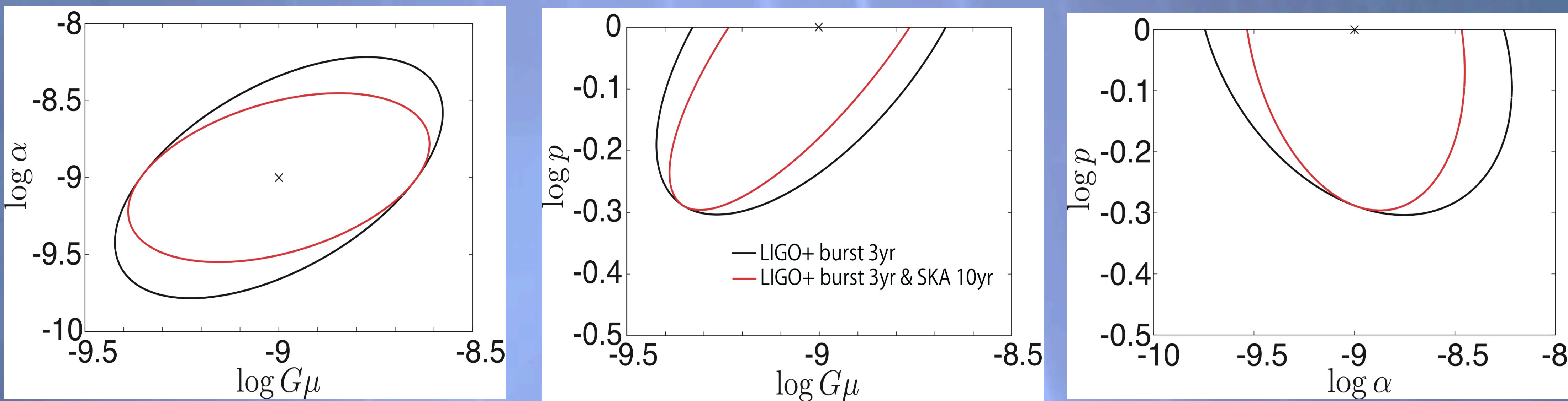
4. constraints on cosmic strings from GW direct detection, pulsar timing and CMB

case 1: $G\mu = 10^{-9}, \alpha = 10^{-9}, p = 1$

- CMB experiments cannot detect strings even in the future
- Pulsar timing exp. and ground-based interferometers (LIGO, KAGRA, Virgo) can detect GWs from strings

LIGO etc. detect 168 bursts and SKA detects GWB with SNR=33

- constraints from 3yr run of ground-based interferometers and 10yr run of SKA



4. constraints on cosmic strings from GW direct detection, pulsar timing and CMB

case 2: $G\mu = 10^{-7}, \alpha = 10^{-16}, p = 1$

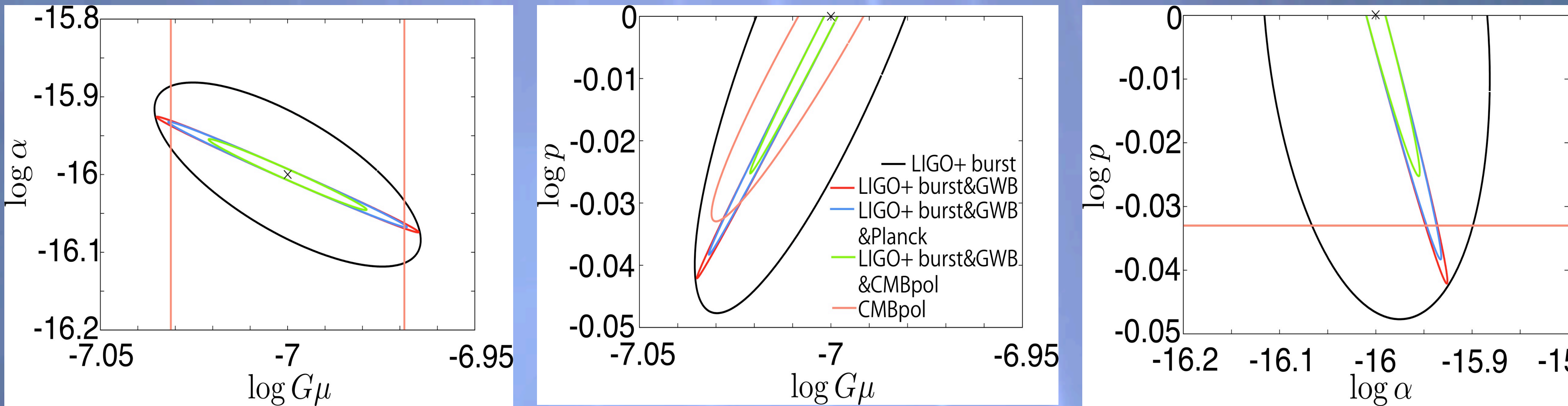
Pulsar timing exp. cannot detect GWs from string (f is too high)

Ground-based GW detectors (LIGO, KAGRA, Virgo) and CMB exp. can detect string signals.

LIGO etc. detect 1.8×10^5 bursts and GWB with SNR=187

CMB satellites detect string signals (small scale T fluc. and B-mode)

- constraints from ground-based GW detectors (3yr run) and CMB satellites



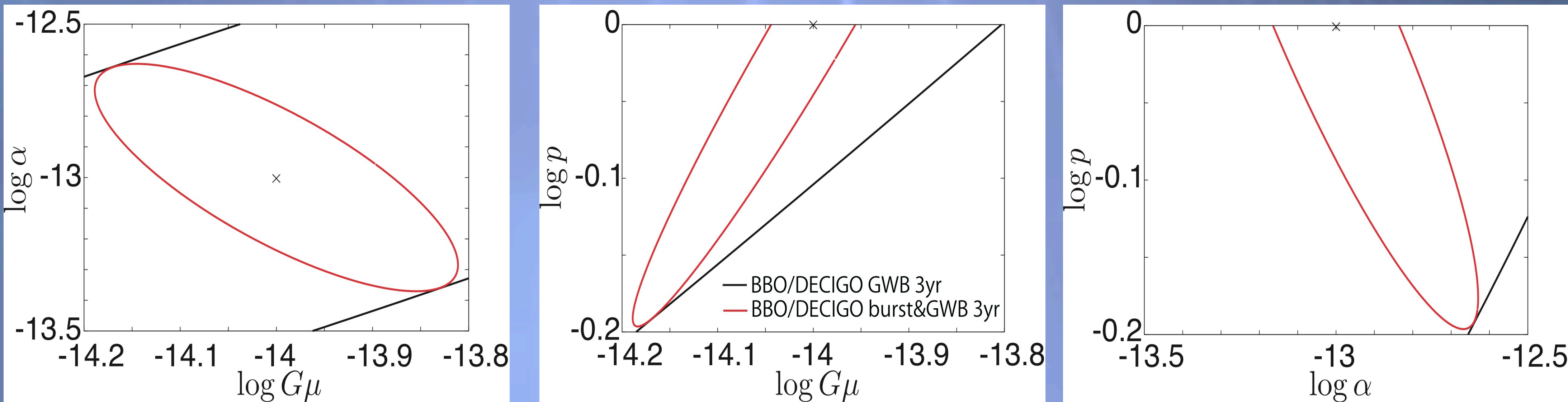
4. constraints on cosmic strings from GW direct detection, pulsar timing and CMB

case 3: $G\mu = 10^{-14}, \alpha = 10^{-13}, p = 1$

$G\mu$ is so small that only space-borne interferometers, such as BBO and DECIGO, can detect string signatures.

BBO/DECIGO etc. detect 35 bursts and GWB with SNR=510

◆ constraints from 3yr run of BBO/DECIGO



5. summary

5. summary

- Cosmic strings are important probes of cosmology and particle physics (if they exists).

- We investigated how strongly future GW direct detection experiments, pulsar timing experiments and CMB experiments will constrain the cosmic string parameters, tension $G\mu$, loop size α and reconnection probability p .

- We found that different types of experiments complement each other for constraining string parameters.
  We saw that GW direct detection experiments are powerful, because they intrinsically have two ways of observation, burst detection and background measurement.
  (Especially, space-borne interferometers are extremely powerful.)