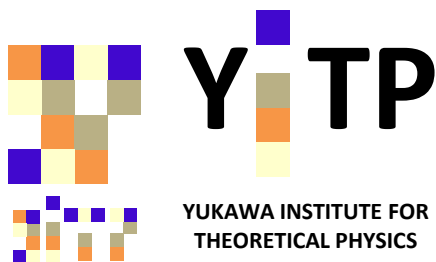


# Analytic model for CMB temperature angular power spectrum from cosmic (super-)strings

YAMAUCHI, Daisuke

Yukawa Institute for Theoretical Physics,  
Kyoto University



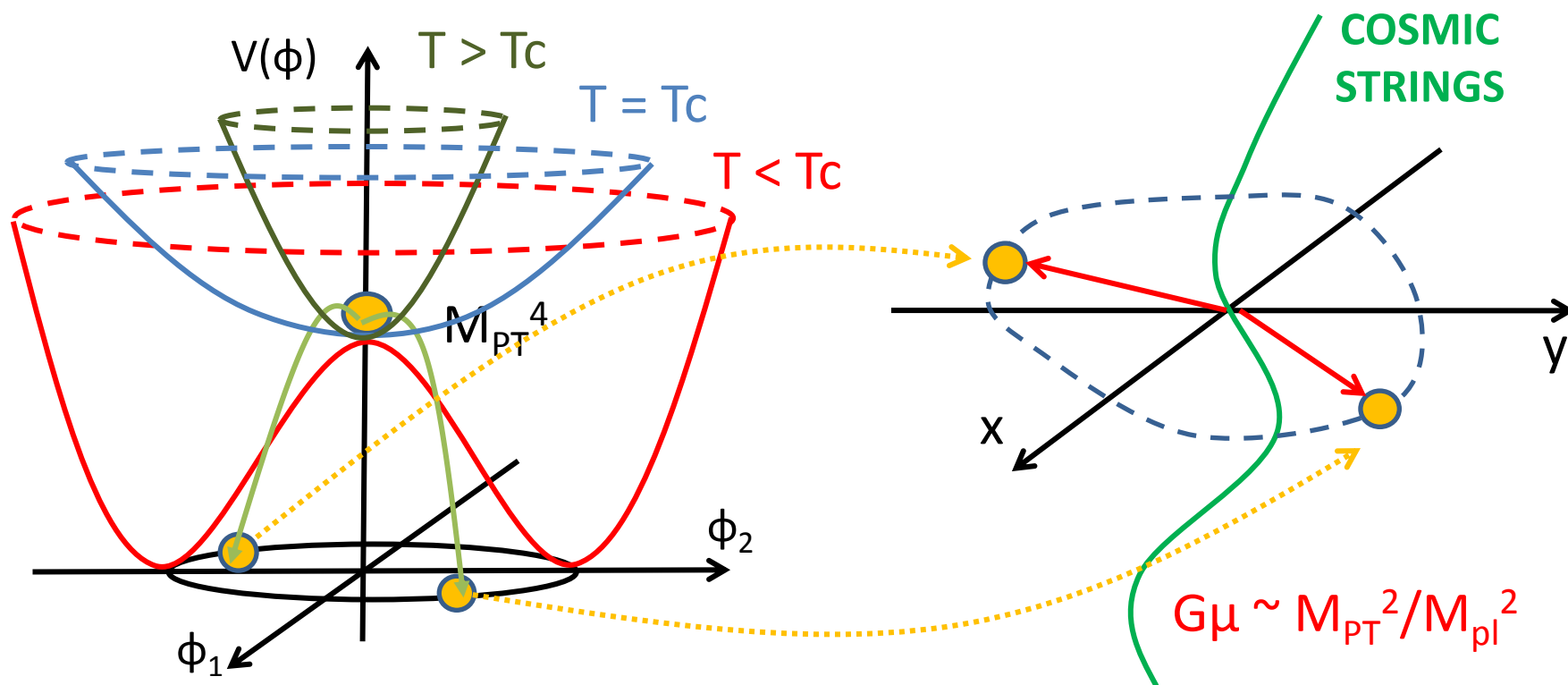
K. Takahashi (Nagoya), Y. Sendouda (Paris7,APC),  
C.-M. Yoo, A. Naruko, M. Sasaki (YITP)

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- JCAP10,003 (2009), 0811.4698 [astro-ph]
- JCAP05,033 (2010), 1004.0600[astro-ph.CO]

# 1.1 : Conventional (field theoretic) cosmic strings

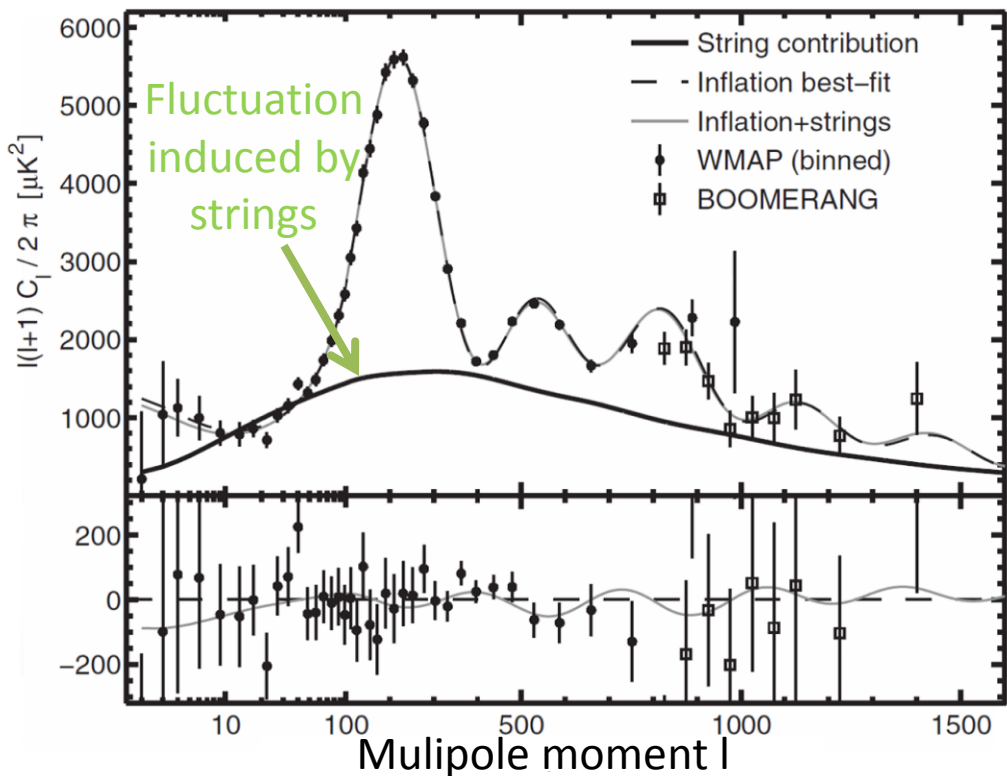
are line-like object formed in the early universe through spontaneous symmetry breaking. [Kibble ('76)]

→ The non-trivial phase mapping from the internal space [left] to the physical space [right] leads to the formation of a cosmic string.



Observational verification of the existence of cosmic strings will have profound implications to unified theories !

## 1.2 : CMB constraints for standard cosmic strings



- Cosmic strings are excluded as a dominant source of the observed large-angular-scale anisotropy.

$$G\mu < 0.7 \times 10^{-6} \quad (95\% \text{ C.L.})$$



- Cosmic strings could still be observable at small scales with future arcminutes experiments such as

[Bevis, Hindmarsh, Kunz and Urrestilla, PRL100, 021301 ('08)]

Cf. [Pogosian, Tye, Wasserman and Wyman, JCAP 02 ('09) 013, etc...]

- ✓ Atacama Cosmology Telescope (ACT : Fowler et al., 1001.2934)
- ✓ South Pole Telescope (SPT : Lueker et al., 0912.4317).

## 1.3 : COSMIC SUPERSTRINGS

*Fundamental strings and D-branes can be seen in the sky !?*

➤ Naively,  $G_4 \mu_s \approx \mathcal{O} \left( \frac{M_s^2}{M_{\text{pl}}^2} \right)$  [cf. Witten, 1985]

$$\longleftrightarrow G\mu_{\text{obs}} < 0.7 \times 10^{-6}$$

➤ The “warping” naturally leads to low tension cosmic strings:

[e.g. Randall-Sundrum('99), Giddings, Kachru, Polchinski('02),...]

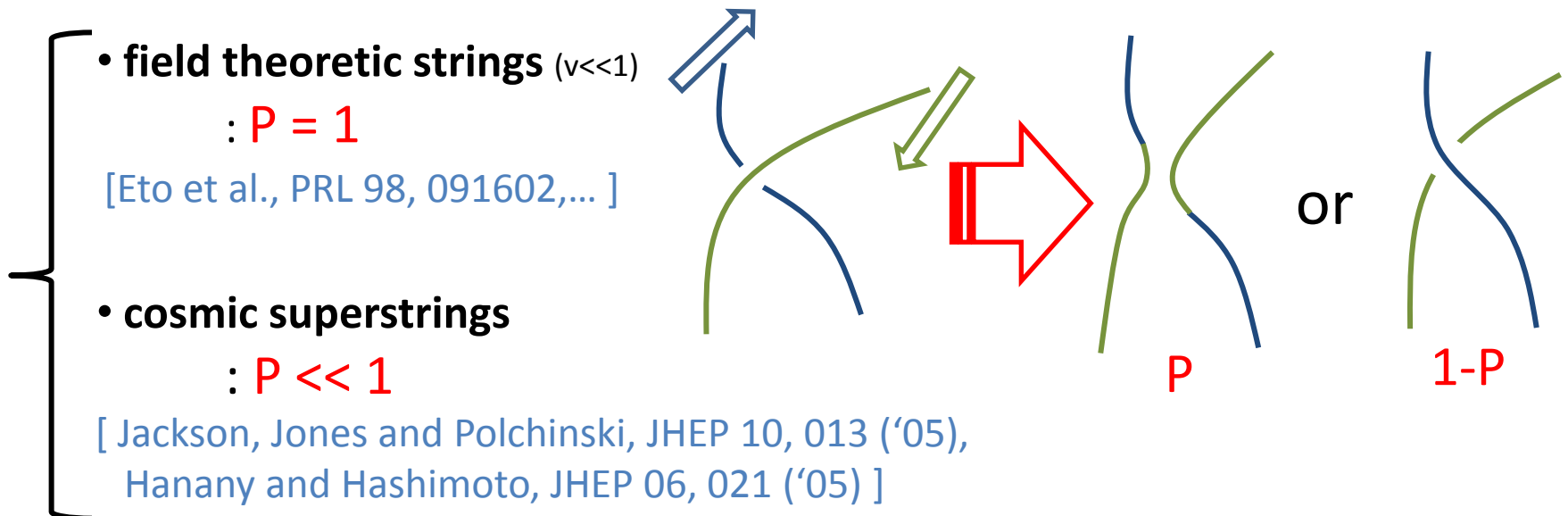
$$ds^2 = e^{2A(y)} g_{\mu\nu}^{(4)}(x) dx^\mu dx^\nu + e^{-2A(y)} g_{mn}^{(6)}(y) dy^m dy^n$$

$$\Rightarrow T_{\mu\nu} = -\mu_s e^{2A(y)} g_{\mu\nu}^{(4)} \delta^8(x, y)$$

In a more general point of view, COSMIC SUPERSTRINGS are reasonably plausible ( e.g. if a tachyonic phase transition occurs ).

➤ Recent developments in string cosmology suggest that inflation may be due to motions of branes in higher dimensions and various new types of strings, called **COSMIC SUPERSTRINGS**, may be formed at the end of inflation.

One of the differences between **COSMIC SUPERSTRINGS** and conventional **FIELD-THEORETIC STRINGS** is the value of **THE INTERCOMMUTING PROBABILITY  $P$  !**



# Goal

- ✓ To give an analytic method to calculate the **small scale** CMB temperature power spectrum due to strings.
- ✓ To investigate the spectrum on the intercommuting probability  $P$ , namely **COSMIC SUPERSTRINGS**.
- ✓ To discuss **an upper bound of  $G\mu$**  as a function of  $P$ .

## 2.1 : Evolution of cosmic (super-)string network

- A string network is assumed to consist of string segment with the correlation length  $\xi$ , and the root-mean-square velocity  $v_{\text{rms}}$  :

$$\rho_{\text{str}} = \frac{1}{\xi^3} \times \mu \xi = \frac{\mu}{\xi^2} \quad \xi = \frac{1}{H\gamma}$$

- The characteristic time scale of the interval of the loop formation :

$$\frac{\Delta\rho_{\text{str}}}{\Delta t} \approx - \frac{\mu \tilde{c} \xi \times (P v_{\text{rms}} / \xi)}{\xi^3}$$

✓ Velocity dependent one-scale model (VOS)

$$\left\{ \begin{array}{l} \frac{t}{\gamma} \frac{d\gamma}{dt} = \frac{1}{3} \left[ (1 - v_{\text{rms}}^2) \frac{-\tilde{c}P v_{\text{rms}} \gamma}{\text{Loop formation}} \right] \quad : \text{Energy conservation} \\ \frac{dv_{\text{rms}}}{dt} = (1 - v_{\text{rms}}^2) H \left[ \frac{k(v_{\text{rms}}) \gamma - 2v_{\text{rms}}}{\text{Curvature acceleration}} \right] \quad : \text{EOM} \end{array} \right.$$

$$k(v_{\text{rms}}) = \frac{2\sqrt{2}}{\pi} \frac{1 - 8v_{\text{rms}}^6}{1 + 8v_{\text{rms}}^6}$$

Assuming the **SCALING** (scale  $\propto 1/H$ ) is already realized by the last scattering surface,  $\mathbf{Y}$  and  $\mathbf{v}_{\text{rms}}$  are asymptotically constant in time:

$$\gamma \approx \sqrt{\frac{\pi\sqrt{2}}{3\tilde{c}P}} \quad \Rightarrow \quad \rho_{\text{str}} = \frac{\mu}{\xi^2} = \frac{\mu}{H^2} \gamma^2 \propto \frac{1}{P}$$

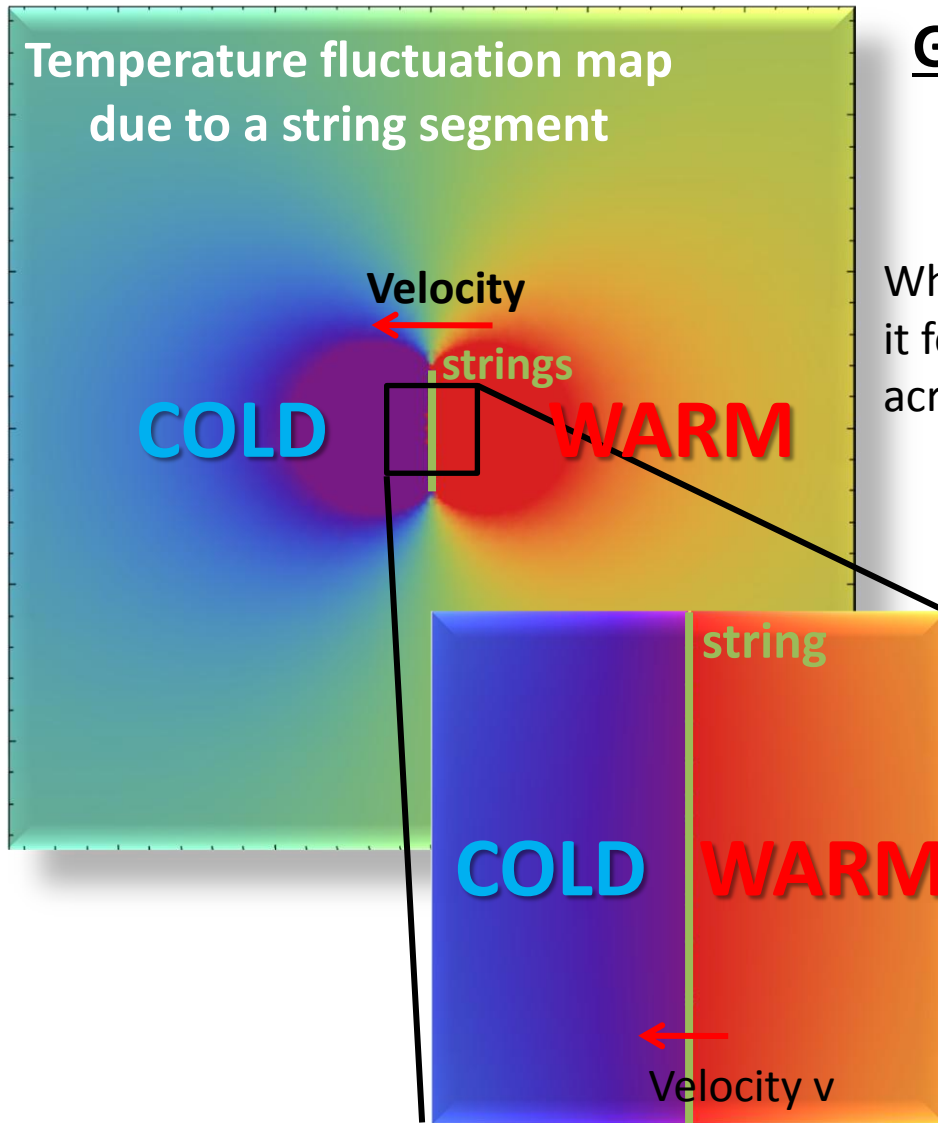
**: Scaling solution incorporating P**

[Takahashi, *DY* +('09), *DY* +('10)]

[see also Martins+Shellard ('96, '02), Avgoustidis+Shellard ('06)]



## 2.2 : Signal from straight strings



### Gott-Kaiser-Stebbins (GKS) effect

[Kaiser, Stebbins, Nature 310 ('84)391,  
Gott III, ApJ 288, 422 ('85)]

When a photon passes by a moving straight string, it feels a discontinuities of gravitational potential across the string segment :

$$\frac{\Delta T_{\text{GKS}}}{T} = 4\pi \frac{v}{\sqrt{1-v^2}} \alpha_{\text{seg}} G\mu$$

➤ The CMB photons are scattered by a number of moving string segments, hence the observed fluctuations appears as a superposition of the discontinuities.

$$\frac{\Delta T_{\text{total}}}{T} = \sum_i \left( \frac{\Delta T_{\text{GKS}}}{T} \right)_{(i)}$$

$i$  : segment index

## 3.1 : Analytic model for power spectrum due to CS

[DY, Takahashi, Sendouda, Yoo, Sasaki, 1006.0687]

In order to compute the angular power spectrum due to CS, we use what we call the *SEGMENT FORMALISM*, by adapting from the halo formalism for the Sunyaev-Zel'dovich effect :

[cf . Komatsu+Seljak (2002), Komatsu+Kitayama (1999),...]

$$C_\ell \approx \int_0^{z_{\text{LSS}}} dz \frac{dV}{dz} \int d\Theta \cdot \frac{dn}{d\Theta} \mathcal{G}_\ell(\Theta, z)$$

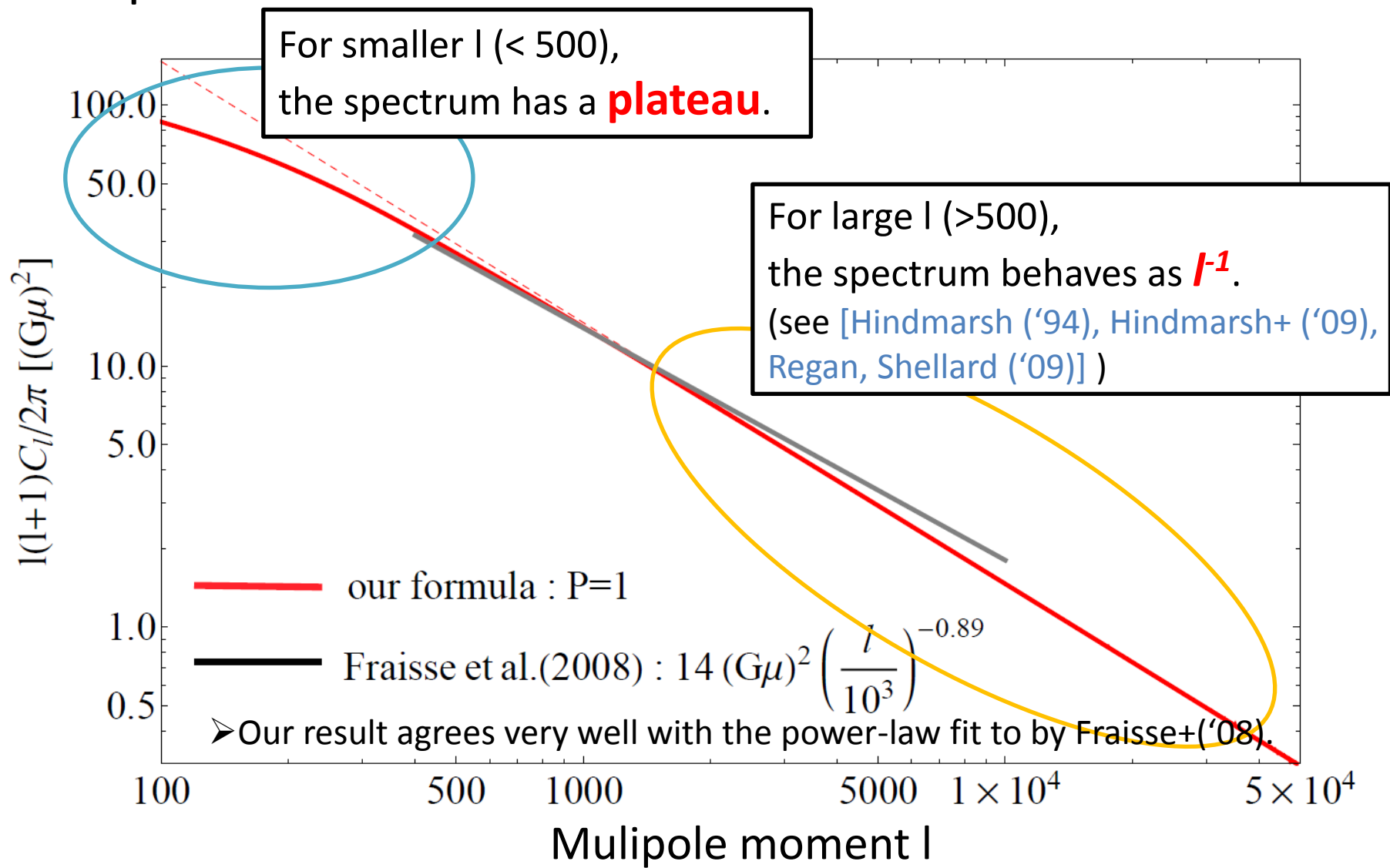
: differential comoving  
volume element at redshift  $z$

: comoving number density of segments with  
the configuration parameter  $[\Theta, \Theta+d\Theta]$

$$\text{with } \mathcal{G}_\ell(\Theta, z) = \int \frac{d\hat{\varphi}_\ell}{2\pi} |a_\ell(\Theta, z)|^2$$

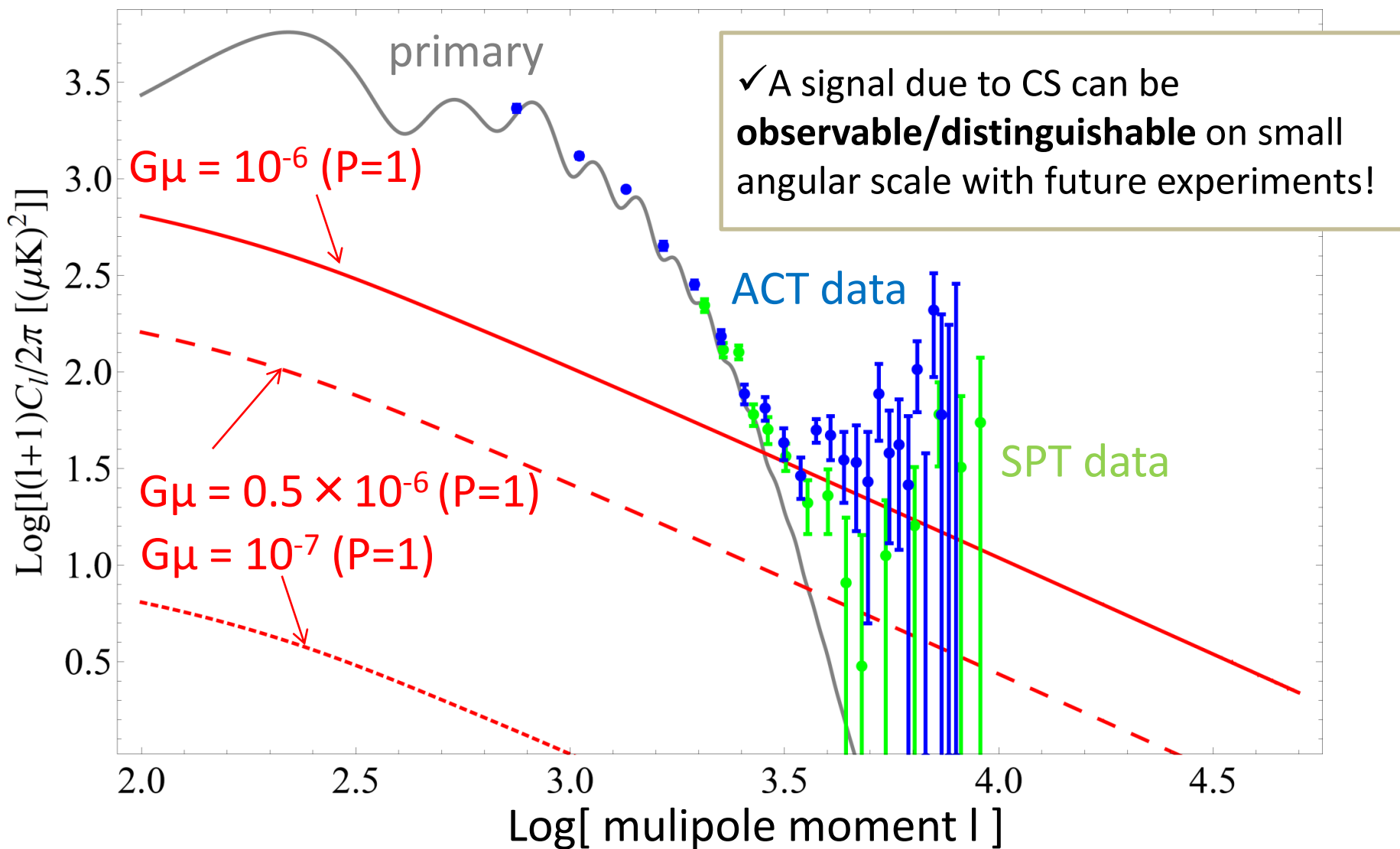
: power spectrum due to a string with configuration  
parameter vector  $\Theta$  and redshift  $z$

## 3.2 : Spectrum due to CONVENTIONAL STRINGS

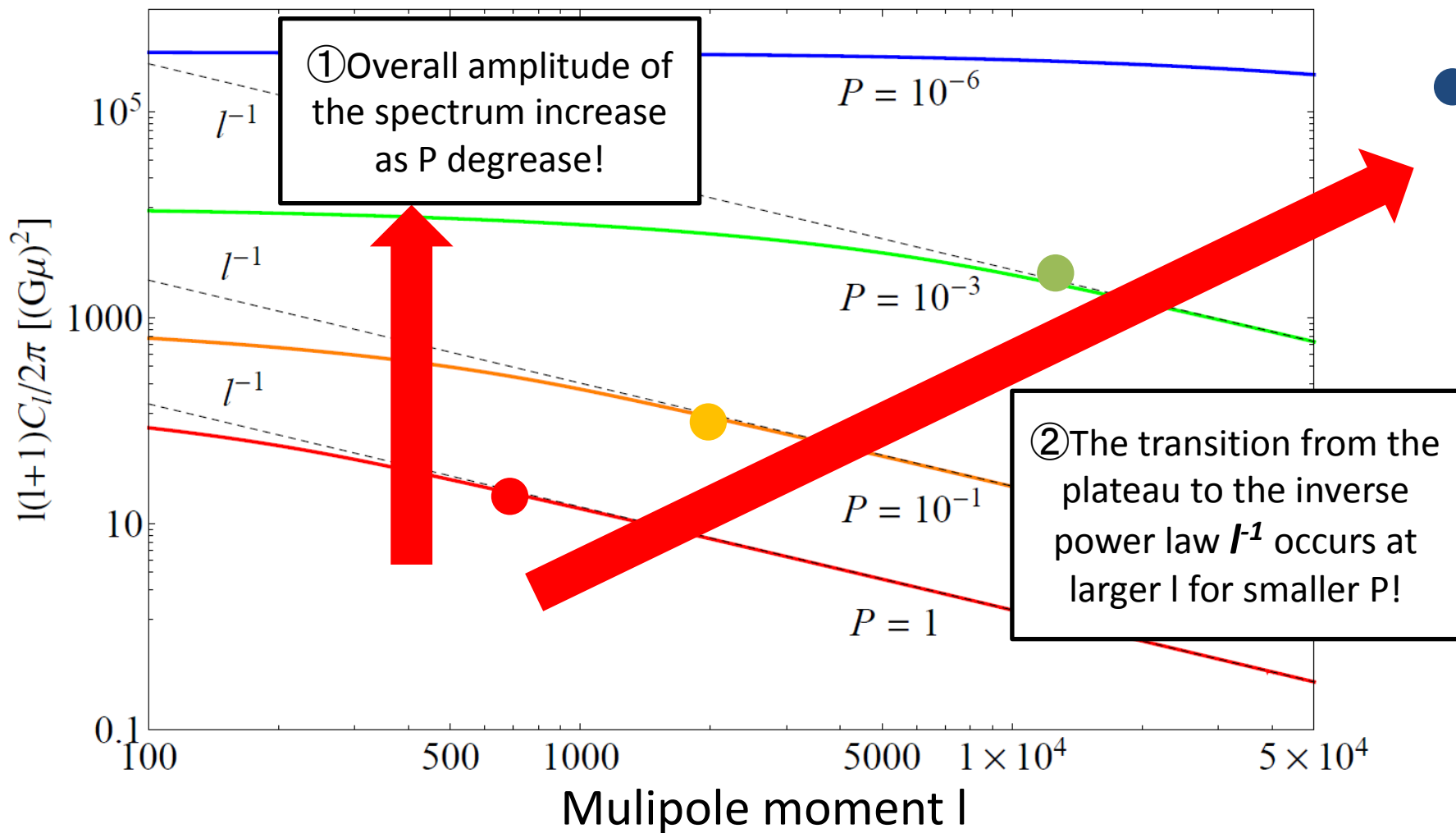


[ **DY**, Takahashi, Sendouda, Yoo, Sasaki, 1006.0687 ]

## 3.2 : Spectrum due to CONVENTIONAL STRINGS



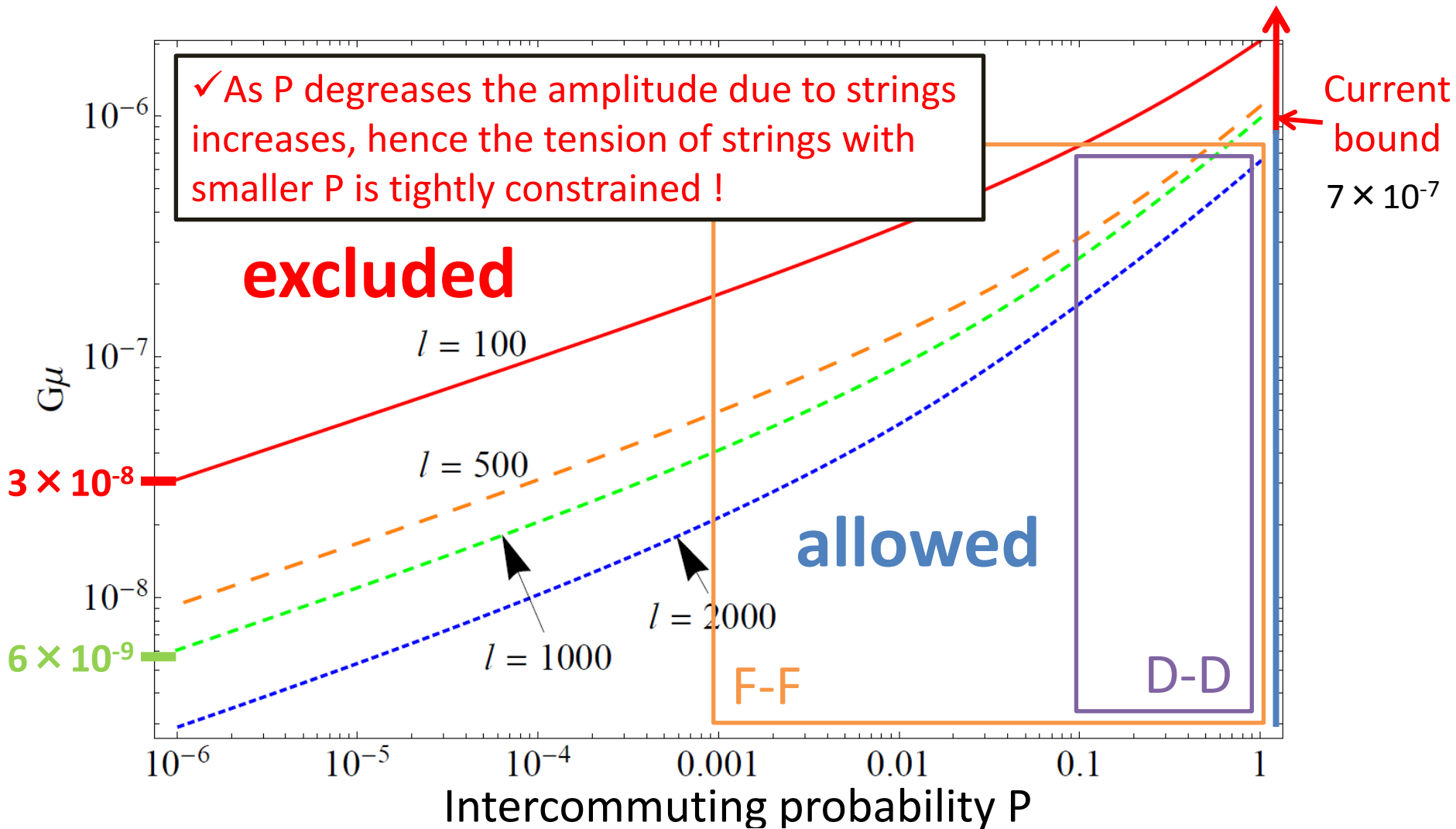
### 3.3 : Spectrum due to COSMIC SUPERSTRINGS



These properties of the power spectrum may become a useful tool to distinguish the value of  $P$ , namely COSMIC SUPERSTRINGS, in future experiments!

### 3.4 : Constraints on string tension $G\mu$

➤ Assuming that the fraction of the spectrum due to strings is less than 10% at various  $l$ ,



## 4 : Summary

- We presented a new analytic method to calculate the small angle CMB temperature power spectrum due to cosmic (super-)strings, and investigated the dependence of the power spectrum on the intercommuting probability  $P$ .
- The small angle power spectrum is found to behave as  $l^{-1}$  for large  $l$  and have a plateau for small  $l$ .
- Using our result, we discussed an upper bound on the dimensionless tension  $G\mu$  as a function of  $P$ . Assuming that the fraction of the CMB spectrum due to strings is less than 10%, strings with small  $P$  are more tightly constrained.
- These properties of the power spectrum are distinguishable features of cosmic superstrings.